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By

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ABSTRACT

The densities and kinematic viscosities of the quinary regular system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4) + cyclooctane (5) and all its corresponding quaternary, ternary, and binary sub-systems have been measured at 293.15 K, 298.15 K, 308.15 K, and 313.15 K over the entire composition range. The experimental data reported herein are considered valuable additions to the literature.

The experimental data gathered in the present study were utilized in testing the predictive capabilities of some well know viscosity models available in the literature. In addition, a new multi-layer artificial neural network (ANN) has been developed for the prediction of the kinematic viscosities of multi-component regular liquid mixtures. The concept of modular neural networks has been successfully applied to the design of the current network. *Only* a part of the experimental binary data was required for the training of the developed network. The remaining data on the binary systems were used for testing the ANN-based model.

The developed neural network resulted in excellent viscosity predictions for the cyclooctane-containing systems. The predictive capability of the ANN in the case of the cyclooctane-containing systems was superior to the predictive capabilities of the other tested models for all systems.

The predictive version of the McAllister three-body interaction model was the best to predict the kinematic viscosities of non-cyclooctane-containing systems. The predictive version of the McAllister three-body model worked very well when the molecular diameter ratio between system components was less than 1.5.

The reliable and accurate data resulting from the present study helped in both critically testing existing viscosity models and in developing a new model that is based on the ANN. Results of the present study are promising for continued work in the same area.

DEDICATION

This thesis is dedicated to my parents who have given and are still giving me unlimited help and support. To them I shall always be grateful. Thank you for your continuous prayers that reached me overseas.

ACKNOWLEDGEMENTS

I would like to, first and always, express all praise and thanks to HIS ALMIGHTY, ALLAH, who gave me the strength and energy to start and complete the present study.

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INTRODUCTION

1.1 General

Viscosity is an important physical property which characterizes a simple fluid's resistance to flow. Fluids are classified either as Newtonian fluids or non-Newtonian fluids. Newtonian fluids are defined as those fluids that obey Newton's law of viscosity. Obviously, non-Newtonian fluids do not obey that law. According to Newton's law of viscosity, the absolute viscosity is a proportionality constant in an equation that relates the shear stress and the shear rate, or velocity gradient. Newton's law is given by,

$$\tau = -\eta \frac{dv}{dy} \tag{1.1}$$

The shear stress, τ, appearing in equation (1.1) is the force applied to the fluid per unit area.

Viscosities of liquid mixtures are required in many engineering applications involving mass and heat transfer processes. Accurate viscosity data are needed for the design of most of fluid flow equipment.

The almost complete lack of knowledge regarding the structure of liquids and the complex nature of, and the little knowledge we currently have about the intermolecular forces in liquid systems, immensely contribute to the current unsatisfactory state-of-the-art regarding the prediction of physical properties of liquid systems.

Asfour (1979), during his study of diffusion in liquid mixtures, suggested breaking down liquid mixtures into three categories; *viz.*, (i) *n*-alkane solutions, (ii) regular mixtures, and (iii) associated solutions. Such a classification has led to success by Asfour (1979), Asfour (1985), Asfour and Dullien (1981), Dullien and Asfour (1985), Asfour and Dullien (1986) in dealing with the diffusion in liquids problem. Asfour *et al*. (1991) proposed extending that classification to the study of viscosities of liquid systems. Asfour and co-workers were met with a great deal of success when they extended the Asfour (1979) classification of liquid systems to the study of viscosity of liquid mixtures; e.g., Asfour *et al*. (1991), Wu and Asfour (1992), Nhaesi and Asfour (1998), Nhaesi and Asfour (2000a and b), and Nhaesi, *et al*. (2005).

Models available in the literature for calculating the viscosities of liquid mixtures may be divided into two categories; *viz.*, *correlative or predictive.* Correlative models contain adjustable parameters whose values are determined from fitting those models to experimental mixture data. Predictive models employ molecular properties for the prediction of the dependence of a physical property, e.g., viscosity on composition. The predictive models can further be classified into either semi-theoretical or empirical. The former are normally developed on some theoretical basis and require limited experimental data; e.g., pure component properties for the prediction of the physical property of interest on composition. The latter employ experimental data for developing those models.

In the present study, four well known viscosity models were subjected to testing of their predictive capability. The selected models cover both categories; i.e. semi-theoretical and empirical models. The models employed in the present study are: (i) the predictive version of the generalized McAllister’s three-body interaction model, (ii) a generalized corresponding states principle GCSP, (iii) a group contribution GC-UNIMOD model, and (iv) the Allan and Teja correlation. In addition, an artificial neural network based model has been developed and used for predicting the kinematic viscosity of the investigated systems. Results from the neural network are reported and compared to the results obtained from the remaining models. Experimental data at different temperature levels obtained during the current study were utilized in testing the above-named models.

McAllister (1960) utilized Eyring’s absolute rate theory to develop a correlative model for calculating the dependence of the kinematic viscosity of liquid binary mixtures on composition. The McAllister model was extended by Chandramouli and Laddha (1963) to ternary liquid systems. The McAllister equation contains adjustable parameters that require costly and time consuming experimental data for determining their values. The correlative nature of the McAllister model drastically limits its use.

In order to overcome this problem, Asfour *et al.* (1991) proposed a technique for predicting the McAllister model parameters for the case of *n*-alkane binary mixtures using pure component viscosities and molecular parameters. This in effect successfully converted the McAllister model from being a *correlative* model to a *predictive* model. This evidently makes the McAllister, in its new form, much more useful than before.

Nhaesi and Afour (1998) extended the Asfour *et al*. (1991) technique to include binary and ternary regular solutions. Following that, Nhaesi and Asfour (2000b) reported a generalized form of the McAllister three-body model for the prediction of the viscosity of multi-component liquid mixtures. The model has been tested by other researchers; e.g. Giner *et al*. (2006) and Bandres *et al*. (2009) and proved to be successful.

The Generalized Corresponding States Principle (GCSP) was first developed by Teja and Rice (1981) for the prediction of the viscosities of multi-component *n*-alkane liquid systems.. Their method requires the knowledge of the critical properties of pure components and the concept of the reference fluid. The problem encountered with the application of the GCSP method for mixtures of more than two components is the proper choice of the reference fluids. It was shown by Wu and Asfour (1992) in their study of *n*-alkane mixtures that the results significantly depended on the different reference fluid combinations. There was no optimum selection reported by Teja and Rice (1981) for the choice of the best reference fluid combination. Wu and Asfour (1992) overcame the problem of the reference fluid selection by proposing a "*pseudo-binary*" model that they incorporated into the GCSP and called their method the modified GCSP (MGCSP). The incorporation of the "*pseudo-binary*" model proposed by Wu and Asfour (1992) resulted in a method, the MGCSP, where the results did not depend on the selection of the reference fluids, especially for the case of multi-component liquid system (Wu *et al*. 1998). The MGCSP was successfully extended by Nhaesi and Asfour (2000a) to include multi-component regular solutions.

A Group Contribution GC-UNIMOD was proposed by Cao *et al.* (1992), (1993a), and (1993b) is a modified version of the original group contribution approach first developed by Langmuir (1925). The theoretical basis for that method assumes that the physical property of a compound is represented by the summation of the contribution made by the different chemical groups contained in that compound. Moreover, the contribution of one chemical group is independent of the contribution of other groups.

The GC-UNIMOD assumes that the contribution of one chemical group in one component is the same as it is in all other components. Evidently, this is not a good assumption and there are no theoretical or experimental evidence that supports such an assumption. This, obviously, does not make that method very reliable.

Allan and Teja (1991) reported their Antoine-type equation for viscosity of liquid mixtures. That equation mainly depends on the number of carbon atoms contained in the pure components constituting a mixture. The trial and error procedure involved in the calculation of the effective carbon number of any component in the mixture in the Allan and Teja correlation is rather cumbersome and is time consuming. This dramatically limited the applicability of that method.

The artificial neural network has been considered in the present study due to its fast computation as well as for its ability to successfully represent the highly non-linear relationships involved; i.e., the viscosity-composition relationship. In the present study, an artificial neural network using back-propagation learning algorithm has been developed. The network was trained on only half of the reported data on binary systems. Then the network was tested and generalized to predict the kinematic viscosities of the quinary regular system and all the corresponding quaternary, ternary, and binary sub-systems involved in the present study. Results of the network are reported and compared with results from the previously mentioned tested models.

1.2 Objectives

The present study is part of an on-going research program in our laboratory aiming at building up an extensive database for viscosity-composition data at different temperatures of liquid systems containing components with different chemical structures and molecular sizes.

The primary objective of the present work is to experimentally measure and report: (i) the densities, kinematic viscosities, and absolute viscosities of the pure components constituting the systems under investigation, and (ii) the dependence of the densities and viscosities of the quinary regular system: benzene (1) + toluene (2) + ethylbenzene (3) + heptanes (4) + cyclooctane (5), and its corresponding quaternary, ternary, and binary sub-systems on concentration, over the entire composition range, at the temperatures of 293.15 K, 298.15 K, 308.15 K, and 313.15 K. The present study also aims at:

(a) Employing the experimental data gathered in the present investigation to critically test some of the viscosity models available in the literature.

(b) Developing an artificial neural network for predicting the viscosities of multi-component regular liquid systems using part of the reported experimental data, and using the other part of the data for validating the model.

(c) Comparing the predictive capabilities of the tested models.

1.3 Contributions and Significance

Viscosities of liquid mixtures are required in many engineering applications. However, costly and time consuming experiments are required in order to collect such data. In addition, data on the viscosities of multi-component liquid mixtures are very scarce in the literature. Such data are also needed for the development and testing of mathematical models that describe the dependence of viscosity on composition, especially for the case of multi-component liquid systems .Therefore, the viscosity and density-composition data reported herein are considered a valuable contribution to the literature.

The following contributions have been made during the course of the present study:

i. Kinematic viscosity, density, and absolute viscosity composition data of multi-component liquid regular solutions have been accurately measured and reported.
ii. Some viscosity models available in the literature were subjected to critical testing using the experimental reported data.
iii. An artificial neural network has been developed for predicting the viscosities of multi-component regular solutions.
iv. The predictive capability of the developed network has been tested and compared to the other tested models.

CHAPTER 2

LITERATURE SURVEY

2.1 General

Viscosity is a transport property that is generally defined as the resistance of a fluid to flow under applied shear stresses. It may be considered an important key parameter in many engineering process design and development.

The prediction of viscosity of pure components as well as those of liquid mixtures has attracted the attention of many researchers over the years. In spite of all the earlier efforts, complete description of the viscosity of multi-component liquid mixtures remains insufficient. This can be attributed to the difficulty of understanding the structure of the liquids. That is why accurate and reliable viscosity data, especially for liquid mixtures are needed.

Our laboratory has successfully continued to establish an extensive database that contains accurate density and viscosity-composition data at different temperature levels.

Viscosity models for calculating the viscosities of pure components as well as liquid systems have been reported in the literature. Reid *et al.* (1987), Monnery *et al.* (1995), Mehrotra *et al.* (1996), and Poling *et al.* (2001) represent some examples of such reviews.

Monnery *et al.* (1995) classified models that attempt to estimate the viscosity of liquid mixtures as empirical or semi-theoretical models. The semi-theoretical models can further be classified into, *predictive*, where molecular parameters and pure component properties are employed in calculating the viscosities of mixtures and *correlative*, where the experimental mixture data are used.

The semi-theoretical class of models results from a combination of theoretical formulation of the model and determination of the values of the parameters contained in those models by using experimental data. The McAllister model (1960) is an excellent example of those models.

In the present chapter, some viscosity related properties used in the current study are first quickly described, followed by an overview of different classes of liquids. Then, an up-to-date review of the most important viscosity models in the literature from the present author's standpoint is presented.

2.2 Density, Viscosity, and Related Properties

2.2.1 Density

Density is considered a property of interest in the present study since the kinematic viscosities of different fluids, v, is the transport property to be measured. In order to determine the value of the absolute viscosity, η, one employs the following relationship which utilizes the value of the density, ρ,

$$\eta = v \rho \tag{2.1}$$

Densities in the present study were measured at the same conditions for each pure component and for the mixtures. Densities have also been required for the calculation of the excess volumes of mixing as is explained in Section 2.2.2.

2.2.2 Excess volume of mixing

Excess volume is a term that accounts for the departure from ideality when two liquids are mixed. If the liquids were ideal, then the sum of the molar volumes of the liquids constituting a mixture, each multiplied by its respective mole fraction in the solution, has to equal the molar volume of the mixture. Since the molecules of each liquid are of different sizes and shapes, the difference between the molar volume of the mixture will deviate, either positively or negatively, from the sum of the molar volumes of the components of the liquid mixtures each multiplied by its respective mole fraction. The following expression was utilized for calculating the excess volume of mixing, V^E

$$V^E = V - \sum_i x_i V_i \tag{2.2}$$

where V is the mixture's molar volume, x_i, and V_i are the pure components' mole fraction and molar volume, respectively.

The above equation may be rewritten as

$$V^E = \frac{\sum_i x_i M_i}{\rho} - \sum_i \frac{x_i M_i}{\rho_i} \tag{2.3}$$

where, M_i and ρ_i are the molecular weight and density of the pure component i and ρ is the density of the mixture.

2.2.3 Excess free energy of viscous flow

The absolute rate theory developed by Eyring (1936) states that,

$$\eta = \left(\frac{\lambda}{\alpha}\right)^2 \left(\frac{h N}{V}\right) exp\left(\frac{\Delta^* G}{RT}\right) \tag{2.4}$$

These terms will be explained in detail in the section dealing with the models based on absolute rate theory.

Taking the logarithms of both sides of equation (2.4) and after rearrangement, the above equation may be rewritten as follows:

$$\frac{\Delta^{*}G}{RT} = \ell n\left(\eta V\right) + 2\ell n\left(\frac{\lambda}{\alpha}\right) - \ell n\left(h\, N\right) \tag{2.5}$$

Heric and Brewer (1967) defined another excess free energy term, $\Delta^{*}G^{E}$, to be subtracted from the actual free energy, $\Delta^{*}G$, to account for the non-ideality in the solution as follows:

$$\Delta^{*}G^{E} = \Delta^{*}G - \Delta^{*}G^{i} \tag{2.6}$$

where $\Delta^{*}G^{i}$ is defined as the excess molar free energy for ideal solutions and is calculated with the help of the following simple mixing rule as suggested by Reed and Taylor (1959),

$$\Delta^{*}G^{i} = \sum_{i} x_{i}\ \Delta^{*}G_{i} \tag{2.7}$$

Substituting equations (2.5) and (2.7) into equation (2.6) yields,

$$\frac{\Delta^{*}G}{RT} = \ell n\left(\eta V\right) + 2\ell n\left(\frac{\lambda}{\alpha}\right) - \ell n\left(h\, N\right) - \sum_{i} x_{i}\left[\ell n\left(\eta_{i}\, V_{i}\right) + 2\,\ell n\left(\frac{\lambda_{i}}{\alpha_{i}}\right) - \ell n\left(h\, N\right)\right]$$

(2.8)

But since

$$\ell n\left(\frac{\lambda}{\alpha}\right) = \sum_{i} x_{i}\,\ell n\left(\frac{\lambda_{i}}{\alpha_{i}}\right) \tag{2.9}$$

Therefore, equation (2.8) can be simplified as

$$\frac{\Delta^{*}G}{RT} = \ell n\left(\eta V\right) - \sum_{i} x_i \ell n\left(\eta_i V_i\right) \qquad (2.10)$$

Equation (2.10) relates the excess molar free energy, $\Delta^{*}G^{E}$, to the molar volumes.

2.3 Classes of Liquid Mixtures

Asfour (1979) classified liquid solutions into three categories; *viz.*, *n*-alkane systems, regular solutions, and associated mixtures. This classification helped Asfour (1985), Dullien and Asfour (1985), and Asfour and Dullien (1986) to successfully deal with diffusion in liquid diffusion problems. Extension of such a classification to the viscosity of liquid mixture problems has led to promising results. Asfour and co-workers; e.g. (Asfour *et al.* (1991), Wu and Asfour (1992), Nhaesi and Asfour (1998), Wu *et al.* (1998), Nhaesi and Asfour (2000 a and b), and Nhaesi *et al.* (2005) successfully employed that classification in the study of viscosities of liquid mixtures.

2.4 Semi-Theoretical Models of Viscosity of Liquid Mixtures

2.4.1 The absolute rate theory based models

Eyring (1936), Ewell and Eyring (1937), and Kincaid *et al.* (1941), developed one of the most popular liquid theories; the absolute rate theory. Eyring suggested that a single molecule requires a potential energy change of $\Delta^{*}G_{o}$ in order to move from one equilibrium position to another passing the energy barrier as shown in Figure 2.1a. Such successive movements of liquid molecules are treated as if they were a chemical reaction.

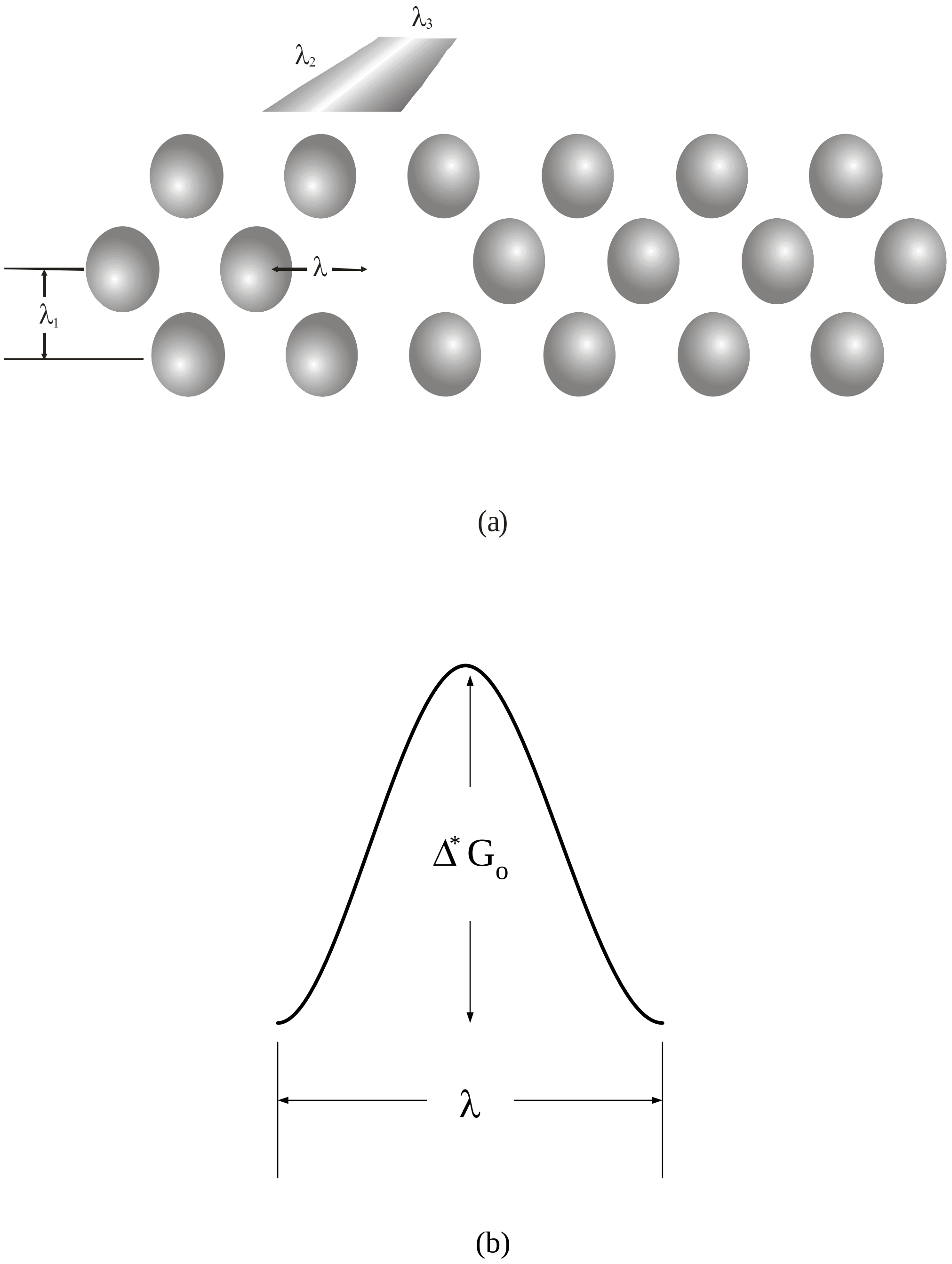

Figure 2.1: The Eyring Molecular Model of Liquid Viscosity

Figure 2.1b shows liquid molecules as described by Eyring (1936), in layers. A distance λ_1 between two adjacent layers experiencing shear forces and an average area occupied by one molecule of $\lambda_2\ \lambda_3$ are assumed. Where λ_2 is the average distance between neighboring molecules and λ_3 is the average distance between molecules normal to the direction of motion.

A vacant site is required for the molecule to successively move from one position to another. Eyring's viscosity equation for liquids was derived as:

$$\eta = \frac{h\lambda_1}{\lambda_2\lambda_3\lambda^2} exp\left(\frac{\Delta G_0}{KT}\right) \tag{2.11}$$

where η is the absolute viscosity, h is Planck's constant, K is Boltzman's constant, and λ is the average distance between equilibrium positions in the direction of motion.

Assuming that $\lambda_1 = \lambda$, and taking V_0, the effective volume of a molecule, to be equal to $\lambda_1\ \lambda_2\ \lambda_3$, equation (2.11) becomes

$$\eta = \frac{h}{V_0} exp\left(\frac{\Delta^* G_0}{RT}\right) \tag{2.12}$$

The above equation may be rewritten in the form of molar properties as

$$\eta = \frac{hN}{V_m} exp\left(\frac{\Delta^* G}{RT}\right) \tag{2.13}$$

where N is Avogadro's number, V_m is the molar volume of the liquid, and

$\Delta^* G$ is the molar activation energy of viscous flow.

2.4.1.1 McAllister's model

A. Binary mixtures

McAllister (1960) developed his successful model, on the basis of Eyring's absolute rate theory, in terms of the kinematic viscosity of binary liquid mixtures as follows:

$$v = \frac{hN}{M_{avg}} exp\left(\frac{\Delta^{*}G}{RT}\right) \tag{2.14}$$

where

$$M_{avg} = \sum_{i} x_i M_i \tag{2.15}$$

where the subscript *i* denotes component type 1 or 2, *x* is the mole fraction and *M* is the molecular weight.

In a binary mixture of molecules of the type 1 and 2, McAllister assumed that different possible types of interactions may occur in a solution with respect to the molecule movement. McAllister (1960) assumed a *three-body* collision (or interaction). Figure 2.2 depicts the different types of molecular interactions in a binary mixture (occurs in one plane) and Table 2.1 shows the different types of molecular interactions along with their corresponding free energies of activation and their fraction of total occurrences.

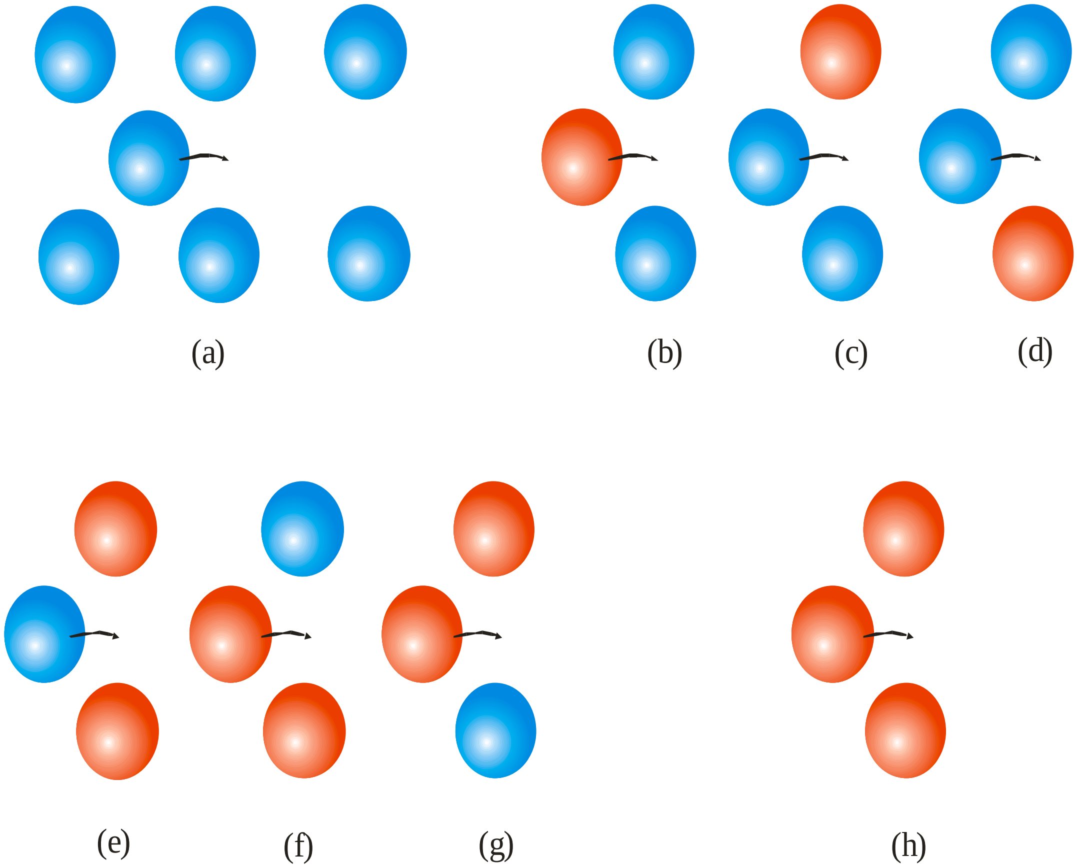

Figure 2.2: Different Types of Molecular Interactions Involved in Binary Mixtures (Three-Body Interaction Model)

Table 2.1: Different Types of interactions in a binary mixture of molecules 1 and 2, their corresponding free energy of activation and their total of fractional occurrences (Three-Body Interaction Model)

Type of Interaction	Free Energy of Activation	Fraction of Total Occurrences
1-1-1	$\Delta^{*}G_{1}$	x_1^3
2-2-2	$\Delta^{*}G_{2}$	x_2^3
1-2-1	$\Delta^{*}G_{121}$	$x_1^2 x_2$
1-1-2	$\Delta^{*}G_{112}$	$2x_1^2 x_2$
2-1-1	$\Delta^{*}G_{211}$	
2-1-2	$\Delta^{*}G_{212}$	$2x_1 x_2^2$
2-2-1	$\Delta^{*}G_{221}$	
1-2-2	$\Delta^{*}G_{122}$	$x_1 x_2^2$

According to McAllister (1960), the free energy of activation of the mixture is given by,

$$\Delta^* G = x_1^3 \Delta^* G_1 + x_1^2 x_2 \Delta^* G_{121} + 2x_1^2 x_2 \Delta^* G_{112} + x_1 x_2^2 \Delta^* G_{212} + 2x_1 x_2^2 \Delta^* G_{122} + x_2^3 \Delta^* G_2 \tag{2.16}$$

Many assumptions were made by McAllister in order to derive his *cubic equation.* These were,

(i) All types of interactions are only three bodied and are taking place in one plane.

(ii) The ratio between the radii of the two types of molecules is taken arbitrarily to be 1.5; otherwise different additional interactions have to be considered (a four-body interaction model).

(iii) The free energies of activation are additive, and the probability of interaction is proportional to the mole fractions of the molecules involved.

(iv) Due to the difficulty in differentiating between $\Delta^* G_{121}$ and $\Delta^* G_{112}$ and similar terms, it was assumed that

$$\Delta^* G_{121} = \Delta^* G_{112} = \Delta^* G_{12} \tag{2.17}$$

$$\Delta^* G_{212} = \Delta^* G_{122} = \Delta^* G_{21} \tag{2.18}$$

On the basis of the above assumptions, equation (2.16) may be rewritten as

$$\Delta^* G = x_1^3 \Delta^* G_1 + 3x_1^2 x_2 \Delta^* G_{12} + 3x_1 x_2^2 \Delta^* G_{21} + x_2^3 \Delta^* G_2 \tag{2.19}$$

Applying equation (2.14) to each type of interaction involved in the mixture, i.e. one can re-write an equation for the kinematic viscosity of the pure component 1 as follows:

$$\nu_1 = \frac{hN}{M_1} exp\left(\frac{\Delta^* G_1}{RT}\right) \tag{2.20}$$

Similarly, for component 2

$$\nu_2 = \frac{hN}{M_2} exp\left(\frac{\Delta^* G_2}{RT}\right) \tag{2.21}$$

For interactions of types 12 and 21,

$$\nu_{12} = \frac{hN}{M_{12}} exp\left(\frac{\Delta^* G_{12}}{RT}\right) \tag{2.22}$$

and

$$\nu_{21} = \frac{hN}{M_{21}} exp\left(\frac{\Delta^* G_{21}}{RT}\right) \tag{2.23}$$

one also has the following relationship:

$$M_{12} = \frac{2M_1 + M_2}{3} \tag{2.24}$$

similarly,

$$M_{21} = \frac{2M_2 + M_1}{3} \tag{2.25}$$

$$\Delta^* G_{12} = \frac{2\Delta^* G_{112} + \Delta^* G_{121}}{3} \tag{2.26}$$

and

$$\Delta^{*}G_{21}=\frac{2\Delta^{*}G_{122}+\Delta^{*}G_{212}}{3} \tag{2.27}$$

Substituting equation (2.19) into equation (2.14) one obtains:

$$\nu=\frac{hN}{M_{ave}}\,exp\left(\frac{\left[x_1^3\Delta^{*}G_1+3x_1^2x_2\Delta^{*}G_{12}+3x_1x_2^2\Delta^{*}G_{21}+x_2^3\Delta^{*}G_2\right]}{RT}\right) \tag{2.28}$$

Taking the logarithms of equations (2.20) through (2.23) and combining them in order to eliminate the free energies, then substitute all of that along with equations (2.15), (2.24), and (2.25) with some mathematical manipulations, one can obtain the final form of the McAllister three-body model for binary mixtures as follows:

$$\begin{aligned}\ell n\,\nu &= x_1^3\ell n\,\nu_1+3x_1^2x_2\ell n\,\nu_{12}+3x_1x_2^2\ell n\,\nu_{21}+x_2^3\ell n\,\nu_2-\ell n\left[x_1+\frac{x_2M_2}{M_1}\right]\\ &\quad+3x_1^2\ell n\left[\frac{(2+M_2/M_1)}{3}\right]+3x_1x_2^2\ell n\left[\frac{(1+2M_2/M_1)}{3}\right]+x_2^3\ell n\,(M_2/M_1)\end{aligned} \tag{2.29}$$

Equation (2.29) is a cubic equation which can have a maximum, a minimum, neither or both for *v* as a function of *x*. It should also be noted that the equation has only two adjustable parameters; *viz.*, ν_{12} and ν_{21} which can be determined by fitting the equation to experimental data.

McAllister (1960) suggested a *four-body* interaction model to be applied for the case of mixtures having large differences in their molecular size. McAllister followed a similar procedure to that he had followed in deriving his three-body interaction model. The final form of his "*quartic equation*" is as follows:

$$\begin{aligned}\ell n\nu = {} & x_1^4\ell n\nu_1 + 4x_1^3x_2\ell n\nu_{1112} + 6x_1^2x_2^2\ell n\nu_{1122} + 4x_1x_2^3\ell n\nu_{2221} \\ & + x_2^4\ell n\nu_2 - \ell n\left[x_1 + \frac{x_2M_2}{M_1}\right] + 4x_1^3x_2\ell n\left[\frac{(3 + M_2/M_1)}{4}\right] \\ & + 6x_1^2x_2^2\ell n\left[\frac{(1 + M_2/M_1)}{2}\right] + 4x_1x_2^3\ell n\left[\frac{(1 + 3M_2/M_1)}{4}\right]\end{aligned} \tag{2.30}$$

Table 2.2 shows the different types of interactions involved along with their corresponding free energies and fractional occurrences.

The above equation, equation (2.30), contains three adjustable parameters; namely, ν_{1112}, ν_{1122}, and ν_{2221} which again have to be determined from viscosity-composition data.

The presence of the adjustable parameters in both the three-body and the four-body models limits the use of the McAllister model because of the need for costly and time consuming viscosity-composition data to determine the values of these parameters. It should be pointed out here that the McAllister adjustable parameters are highly temperature dependent which, again, is considered a major draw back of his models.

Table 2.2: Different Types of interactions in a binary mixture of molecules 1 and 2, their corresponding free energy of activation and their total of fractional occurrences (Four-Body Interaction Model)

Type of Interaction	Free Energy of Activation	Fraction of Total Occurrences
1-1-1-1	$\Delta^{*}G_{1}$	x_1^4
2-2-2-2	$\Delta^{*}G_{2}$	x_2^4
1-1-1-2	$\Delta^{*}G_{1112}$	$4x_1^3x_2$
1-2-1-1	$\Delta^{*}G_{1211}$	
2-1-1-1	$\Delta^{*}G_{2111}$	
1-1-2-1	$\Delta^{*}G_{1121}$	
2-2-2-1	$\Delta^{*}G_{2221}$	$4x_1x_2^3$
2-1-2-2	$\Delta^{*}G_{2122}$	
1-2-2-2	$\Delta^{*}G_{1222}$	
2-2-1-2	$\Delta^{*}G_{2212}$	
1-1-2-2	$\Delta^{*}G_{1122}$	$6x_1^2x_2^2$
1-2-1-2	$\Delta^{*}G_{1212}$	
2-2-1-1	$\Delta^{*}G_{2211}$	
2-1-2-1	$\Delta^{*}G_{2121}$	
1-2-2-1	$\Delta^{*}G_{1221}$	
2-1-1-2	$\Delta^{*}G_{2112}$	

2.4.1.2 The Asfour *et al* (1991) technique

Realizing the importance of the McAllister model, Asfour *et al.* (1991) proposed their technique which converts the McAllister model from a correlative model into a predictive model. This was achieved by providing means for predicting the values of the adjustable parameters from pure component and molecular properties. This obviously eliminates the need for costly and time consuming experimental data.

Asfour *et al.* (1991) successfully applied their technique to *n*-alkane mixtures. They employed kinematic viscosity-composition data reported by Cooper (1988) and Wu (1992). They plotted the lumped parameter $\left(\frac{\nu_{12}}{(\nu_1^2\nu_2)^{1/3}}\right)$ versus the inverse of the absolute temperature, (1/*T*). From the plot shown in Figure 2.3, horizontal straight lines were obtained which confirmed that the lumped parameter is independent of temperature. Asfour *et al*. (1991) plotted the lumped parameter against a fraction of the number of carbon atoms of the *n*-alkanes constituting a binary system as shown in Figure 2.4. A straight line relationship resulted. They suggested the following equation:

$$\frac{\nu_{12}}{(\nu_1^2\nu_2)^{1/3}} = 1 + 0.044\frac{(N_2 - N_1)^2}{(N_1^2 N_2)^{1/3}} \tag{2.31}$$

where N_1 and N_2 are the numbers of carbon atoms per molecule of components 1 and 2, respectively.

Equation (2.31) permits the calculation of the value of the McAllister parameter, ν_{12}, by knowing the pure component kinematic viscosities and the number of carbon atoms of the involved substances. Furthermore, they suggested the following equation for

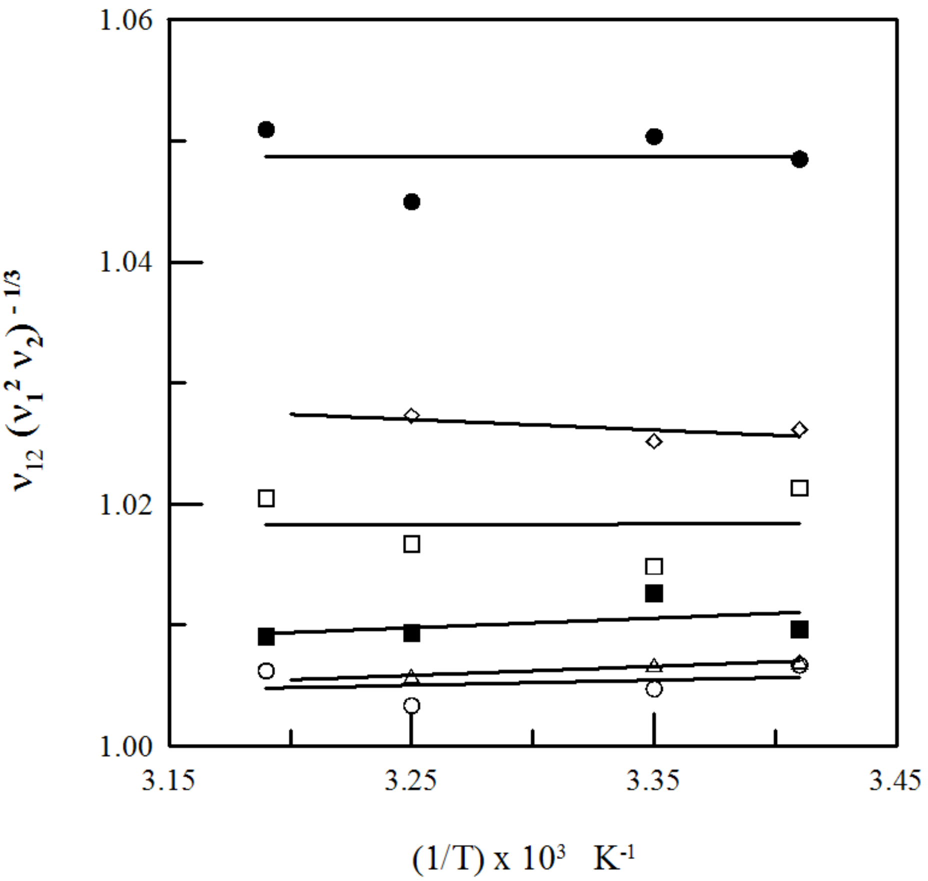

Figure 2.3: Lumped Parameters, $\left(\frac{\nu_{12}}{\left(\nu_1^2\nu_2\right)^{1/3}}\right)$, Variation With (1/*T*) or *n*-alkane Systems (For which $|N_2 - N_1| \le 3$, Asfour *et al*. (1991)

△ **Hexane (A) - Heptane (B)**
◇ **Hexane (A) - Octane (B)**
○ **Heptane (A) - Octane (B)**
● **Heptane (A) - Decane (B)**
■ **Tetradecane (A) - Hexadecane (B)**
□ **Octane (A) - Decane (B)**

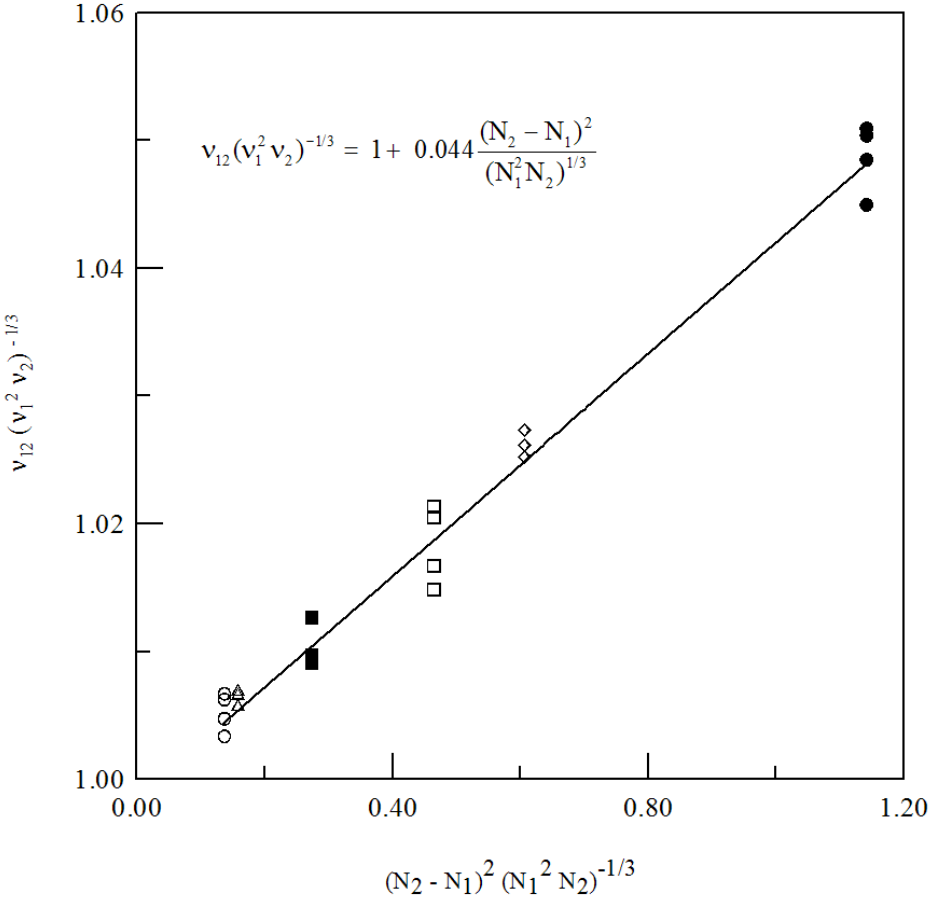

Figure 2.4: Lumped Parameter Variations, $\left(\frac{\nu_{12}}{(\nu_1^2\nu_2)^{1/3}}\right)$, with $\left(\frac{(N_2 - N_1)^2}{(N_1^2 N_2)^{1/3}}\right)$ For *n*-alkane Systems (Asfour *et al.*(1991), Legends are the same as indicated in Figure 2.3)

the calculation of the second interaction parameter, ν_{21}:

$$\nu_{21} = \nu_{12}\left(\frac{\nu_2}{\nu_1}\right)^{1/3} \qquad (2.32)$$

The above equation allows the calculation of the McAllister parameter, ν_{21}, from the value of ν_{12} obtained earlier from equation (2.31). Their results showed an absolute average deviation in the range of 0.02 % to 1 % in predicting the kinematic viscosities of binary *n*-alkane mixtures using the above technique compared to those calculated by the correlative McAllister model.

As stated earlier by McAllister (1960), one should apply the four-body collision model if the ratio between the molecular radii of the molecules in a binary mixture exceeded 1.5. On that basis, Asfour *et al.* (1991) suggested a technique analogous to the one reported for three-body interaction model to calculate the McAllister three adjustable parameters mentioned earlier as follows:

$$\frac{\nu_{1122}}{\left(\nu_1^2 \nu_2^2\right)^{1/4}} = 1 + 0.03\frac{\left(N_2 - N_1\right)^2}{\left(N_1^2 N_2^2\right)^{1/4}} \qquad (2.33)$$

$$\nu_{1112} = \nu_{1122}\left(\frac{\nu_1}{\nu_2}\right)^{1/4} \qquad (2.34)$$

$$\nu_{2221} = \nu_{1122}\left(\frac{\nu_2}{\nu_1}\right)^{1/4} \qquad (2.35)$$

Again, experimental data different than those used in developing the above equations were used to validate the Asfour *et al*. (1991) proposed technique. The results showed good agreement with published experimental data.

Nhaesi and Asfour (1998) extended the Asfour *et al*. (1991) technique to regular binary mixtures. As a substitute for the number of carbon atoms in *n*-alkanes, they suggested the use of the *effective carbon number* (*ECN*) concept in case of regular systems. Nhaesi and Asfour (1998) reported a semi-log plot of the kinematic viscosities of pure *n*-alkanes (C_5-C_{18}) measured at 308.15 K *versus* the number of carbon atoms in each molecule. The straight line relation obtained is shown in Figure 2.5 which is represented by the following equation

$$\ell n\, \nu = -1.943 + 0.193\,(ECN) \tag{2.36}$$

where, ν is the kinematic viscosity of the pure component at 308.15 K in cSt. Nhaesi (1998) has reported values of the *ECN*s of some compounds calculated with the help of equation (2.36).

The reported *ECN* values enabled Nhaesi and Asfour (1998) to develop a technique for regular binary systems similar to equation (2.31) reported earlier for *n*-alkane systems. The first binary adjustable parameter, ν_{12}, for the case of regular compounds may be calculated from

$$\frac{\nu_{12}}{\left(\nu_1^2 \nu_2\right)^{1/3}} = 0.8735 + 0.0715\,\frac{\left(ECN_2 - ECN_1\right)^2}{\left(ECN_1^2\, ECN_2\right)^{1/3}} \tag{2.37}$$

Equation (2.32) can still be used to calculate the second adjustable parameter, ν_{21}.

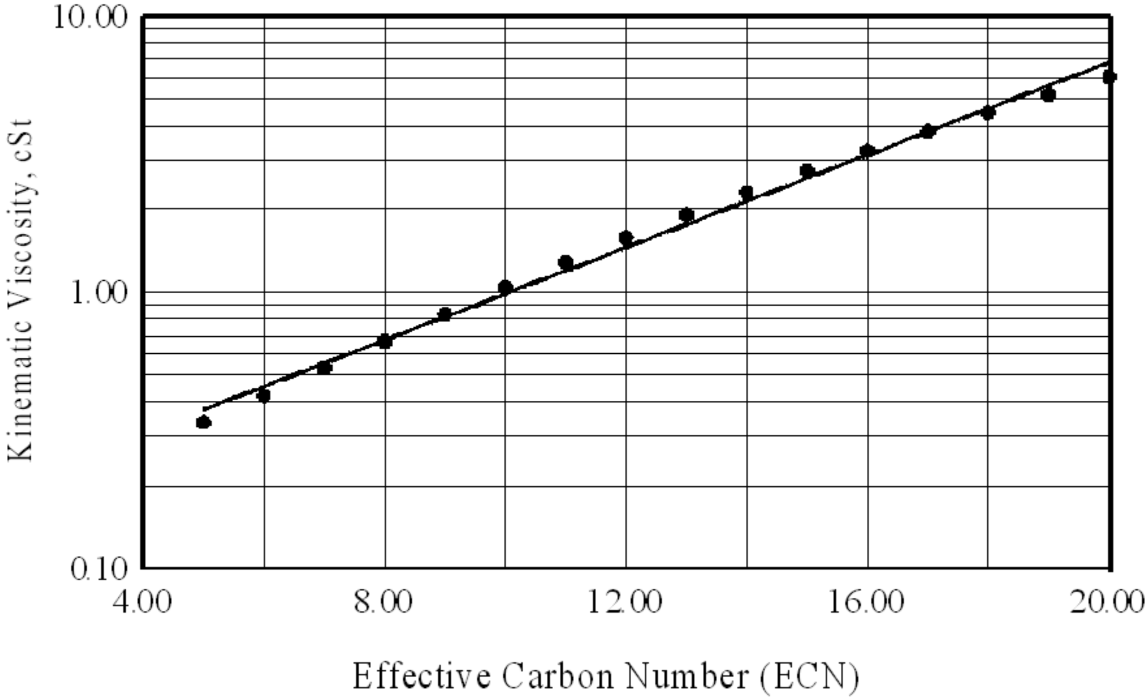

Figure 2.5: Experimental Values of Kinematic Viscosities of *n*-alkane Systems at 308.15 K Versus Effective Carbon Number (Nhaesi and Asfour 1998).

B. Ternary systems

Chandramouli and Laddha (1963) and Kalidas and Ladhha (1964) extended the McAllister three-body model to ternary mixtures. Figure 2.6 represents the different types of molecular interactions accompanied with the assumption of a three-body interaction model. They obtained the following equation:

$$\begin{aligned}
\ell n\nu = {} & x_1^3\ell n\nu_1 + x_2^3\ell n\nu_2 + x_3^3\ell n\nu_3 + 3x_1^2x_2\ell n\nu_{12} + 3x_1^2x_3\ell n\nu_{13} \\
& + 3x_2^2x_1\ell n\nu_{21} + 3x_2^2x_3\ell n\nu_{23} + 3x_3^2x_1\ell n\nu_{31} + 3x_3^2x_2\ell n\nu_{32} \\
& + 6x_1x_2x_3\ell n\nu_{123} - \ell n(x_1M_1 + x_2M_2 + x_3M_3) + x_1^3\ell nM_1 \\
& + x_2^3\ell nM_2 + x_3^3\ell nM_3 + 3x_1^2x_2\ell n\left[\frac{(2M_1+M_2)}{3}\right] \\
& + 3x_1^2x_3\ell n\left[\frac{(2M_1+M_3)}{3}\right] + 3x_2^2x_1\ell n\left[\frac{(2M_2+M_1)}{3}\right] \\
& + 3x_2^2x_3\ell n\left[\frac{(2M_2+M_3)}{3}\right] + 3x_3^2x_1\ell n\left[\frac{(2M_3+M_1)}{3}\right] \\
& + 3x_3^2x_2\ell n\left[\frac{(2M_3+M_2)}{3}\right] + 6x_1x_2x_3\ell n\left(\frac{M_1+M_2+M_3}{3}\right)
\end{aligned} \qquad (2.38)$$

Again, Nhaesi and Asfour (2000b) followed the same procedure described in the previous section to calculate the McAllister's adjustable parameters. They plotted the dimensionless lumped parameter, $\nu_{123}/(\nu_1\ \nu_2\ \nu_3)^{1/3}$ against $1/T$, they obtained horizontal lines at all tested temperatures which confirmed their earlier findings. Furthermore, a

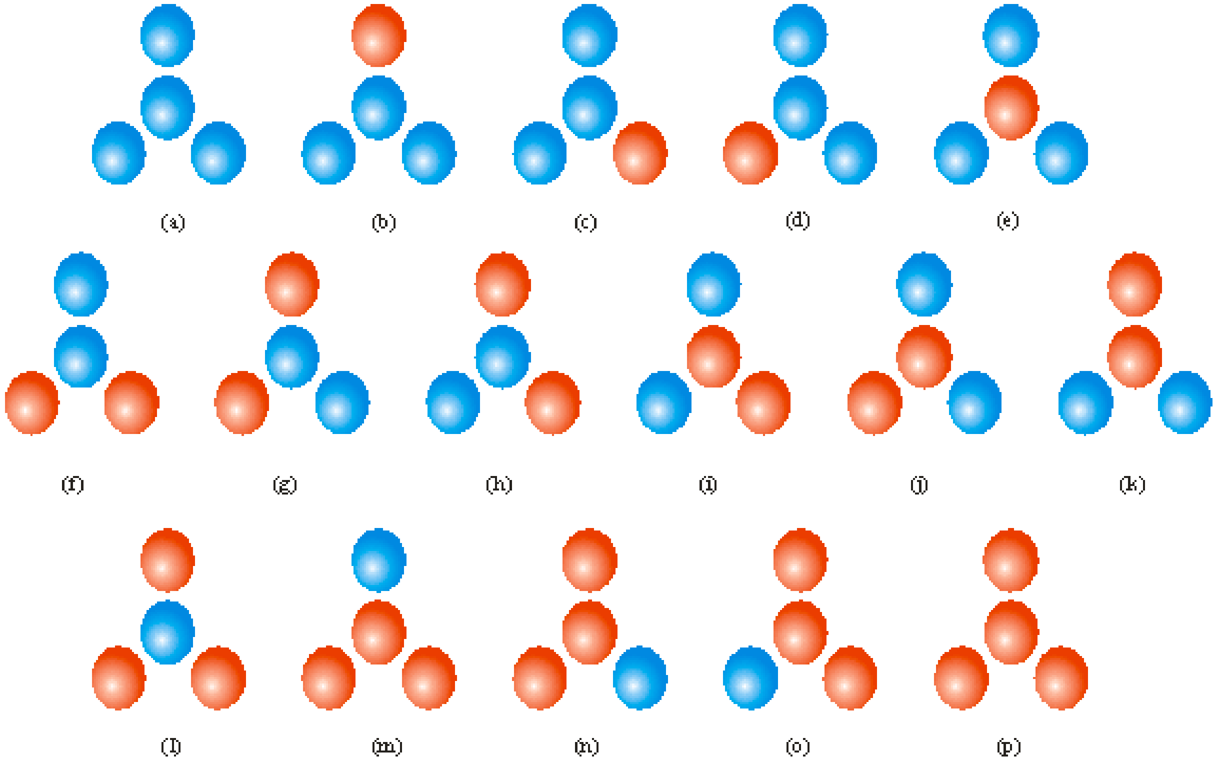

Figure 2.6: Different Types of Molecular Interactions Encountered with Ternary Systems (Three-Body Interaction Model, Kalidas *et al.* (1964))

straight line was obtained when they plotted $\nu_{123}/(\nu_1\ \nu_2\ \nu_3)^{1/3}$ versus $(N_3-N_1)^2/N_2$, where N_1, N_2, and N_3 are the carbon numbers of components 1, 2, and 3, respectively.

Using the least-square technique they were able to get the equation of the straight line as follows:

$$\frac{\nu_{123}}{(\nu_1\nu_2\nu_3)^{1/3}} = 0.9637 + 0.0313\frac{(N_3 - N_1)^2}{N_2} \tag{2.39}$$

The above equation can be used to predict the ternary interaction parameter if the kinematic viscosities of pure components and their number of carbon atoms are known. In case of regular solutions the numbers of carbon atoms in equation (2.39) are replaced by the effective carbon numbers.

C. Multi-component systems

Dizechi and Marschall (1982) introduced the first modification to the generalized McAllister three-body equation. Their modified equation included two constants; *C* and *Z* suggested earlier by Goletz and Tassios (1977) to account for the dependence of the adjustable parameters on temperature. They suggested the following equation

$$\begin{aligned} \ell n\, \nu_m = {} & \frac{1}{t + C_{avg}} \sum_{i=1}^{n} (t + C_i)\, x_i^3\ \ell n(\nu_i M_i) + \\ & \frac{3}{t + C_{avg}} \sum_{\substack{i=1 \\ i \neq j}}^{n} \sum_{j=1}^{n} (t + C_{ij})\, x_i^2\ x_j \ell n(\nu_{ij} M_{ij}) \\ & \frac{1}{t + C_{avg}} \sum_{\substack{i=1 \\ i \neq j \neq k}}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} (t + C_{ijk})\, x_i\ x_j x_k\ \ell n\ (\nu_{ijk} M_{ijk}) - \ell n(M_{avg}) \end{aligned} \tag{2.40}$$

where

$$M_{avg} = \sum_{i}^{n} x_i M_i \tag{2.41}$$

$$M_{ij} = (2M_i + M_j)/3 \tag{2.42}$$

$$M_{ijk} = (M_i + M_j + M_k)/3 \tag{2.43}$$

$$C_i = 239 + Z\, t_{b,i} \tag{2.44}$$

$$C_{avg} = \sum_{i}^{n} x_i C_i \tag{2.45}$$

$$C_{ij} = (2C_i + C_j)/3 \tag{2.46}$$

$$C_{ijk} = (C_i + C_j + C_k)/3 \tag{2.47}$$

Dizechi (1980) reported in a study an optimizing technique for the determination of the value of *Z*. He found that *Z* is a weak function of temperature therefore, only one value may be considered sufficient.

Dizechi and Marschall (1982) tested their model using data on eight binary and four ternary polar liquid mixtures at various temperatures. The results of the comparison between their model and the original McAllister equation showed improvements in the prediction of viscosity of the mixtures.

Soliman (1987) continued the earlier work of Dizechi and Marschall (1982) and attempted to reduce the number of adjustable parameters and to improve the capabilities of the McAllister equation. He made some modifications to the original McAllister equation and introduced only one constant, *B*, as follows:

$$\ell n\,\nu_m = \sum_{i=1}^{n} x_i^3\,\ell n\,\nu_i + 3\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} x_i\,x_j\,\ell n\,\nu_{ij} +$$

$$\frac{\displaystyle\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left(x_i + x_j\right)^3 B_{ij}\,x_i\,x_j}{\left[\left(\dfrac{M_i}{M_j}\right)^2 x_i + x_j\right]} + 6\sum_{i=1}^{n-2}\sum_{j=i+1}^{n-1}\sum_{k=j+2}^{n} x_i\,x_j\,x_k\,\ell n\,\nu_{ijk} \tag{2.48}$$

For the above two modifications, equations (2.40) and (2.48), all the adjustable parameters and the constants are to be determined from fitting experimental viscosity data using the least square technique.

Soliman and Marschall (1990) reported a comparison on eight binary, five ternary, and one quaternary liquid mixture containing strongly polar liquids including water. As a result of the comparison made in their study amongest the three models, the original McAllister equation, equation (2.40), and equation (2.48), Soliman's (1987) equation, equation (2.48), performed better than the other two equations.

Although the two previous modifications to the original McAllister equation for multi-component liquid mixtures showed a remarkable improvement in the liquid mixture viscosities, it still did not change the correlative nature of the original McAllister model. Extensivee databases are needed to calculate the introduced constants besides the adjustable parameters which are not readily available in all cases.

Nhaesi and Asfour (2000b) were able to develop a generalized form of McAllister's three-body equation for multi-component liquid mixtures.

They suggested that the activation energy for *n*-component liquid systems can be represented by the following general equation:

$$\Delta G_m = \sum_{i=1}^{n} x_i^3 \Delta G_i + 3 \sum_{i=1}^{n} \sum_{j=1}^{n} x_i^2 x_j \ \Delta G_{ij} + \\ 6 \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} x_i x_j x_k \ \Delta G_{ijk} \tag{2.49}$$

Taking into consideration that the free energies of activation for kinematic viscosities are additive. They also assumed the following:

$$\Delta G_{iji} = \Delta G_{iij} = \Delta G_{ij} \tag{2.50}$$

$$\Delta G_{jij} = \Delta G_{ijj} = \Delta G_{ji} \tag{2.51}$$

The kinematic viscosities for pure component, binary interaction, ternary interaction, or a mixture may be expressed in the form of Arrhenius-type equation as follows:

$$\nu_i = \frac{hN_0}{M_i} e^{(\Delta G_i / RT)} \tag{2.52}$$

$$\nu_{ij} = \frac{hN_0}{M_{ij}} e^{(\Delta G_{ij} / RT)} \tag{2.53}$$

$$\nu_{ijk} = \frac{hN_0}{M_{ijk}} e^{(\Delta G_{ijk} / RT)} \tag{2.54}$$

$$\nu_m = \frac{hN_0}{M_{avg}} e^{(\Delta G_m / RT)} \tag{2.55}$$

where,

$$M_{ij} = (2M_i + M_j)/3 \tag{2.56}$$

$$M_{ijk} = (M_i + M_j + M_k)/3 \tag{2.57}$$

$$M_{avg} = \sum_{i}^{n} x_i M_i \tag{2.58}$$

The logarithms of equations (2.52) to (2.55) were taken then substituted into equation (2.49) in order to eliminate free energies of activation. The final form of the generalized three-body interaction model for *n*-components was obtained after rearrangement as follows:

$$\ell n\,\nu_m = \sum_{i=1}^{n} x_i^3\,\ell n\left(\nu_i M_i\right) + 3\sum_{\substack{i=1\\ i\neq j}}^{n}\ \sum_{j=1}^{n} x_i^2 x_j\,\ell n\left(\nu_{ij} M_{ij}\right)$$

$$6\sum_{\substack{i=1\\ i\prec j\prec k}}^{n}\ \sum_{j=1}^{n}\ \sum_{k=1}^{n} x_i^2 x_j x_k\ \ell n\left(\nu_{ijk} M_{ijk}\right) - \ell n\left(M_{avg}\right) \tag{2.59}$$

Only two types of interactions, on the bais of a three-body interaction, are considered; *viz*., the binary interaction parameter, ν_{ij}, and the ternary interaction parameter, ν_{ijk}. If the values of these parameters along with the properties of pure components are known, the kinematic viscosity of the mixture can be calculated from equation (2.59).

Nhaesi and Asfour (2000b) also indicated that the number of binary and ternary interaction parameters, N_2 and N_3, depends on the number of components involved in the mixture. N_2 and N_3 can be calculated from the following equations:

$$N_2 = \frac{n!}{(n-2)!} \tag{2.60}$$

$$N_3 = \frac{n!}{3!\,(n-3)!} \tag{2.61}$$

where n is the number of pure components in the mixture. The foregoing techniques reported by Asfour *et al*. (1991) and Nhaesi and Asfour (1998) and (2000b) effectively converted the McAllister model from a correlative model into a predictive one. They also broadened its applicability without the need for a large experimental database. Their technique showed very promising results when applied to different types of liquid mixtures with dramatically reduced Absolute average deviations, (*AAD*s), compared to other models available in the literature.

Nhaesi (1998) and Nhaesi and Asfour (2000a) employed "*the pseudo-binary mixture model",* first reported by Wu (1992), Wu and Asfour (1992), and Wu *et al.* (1998), to the McAllister model for multi-component systems. The *pseudo-binary* model simply treats the multi-component mixture as a binary mixture of pure component 1 and a *pseudo* component 2', which is actually a mixture of components 2,3,4,…*n*. Nhaesi (1998) and Nhaesi and Asfour (2000a), the following equations were employed:

$$\frac{\nu_{12'}}{\left(\nu_1^2 \nu_{2'}\right)^{1/3}} = 1 + 0.044 \frac{\left[(ECN)_{2'} - (ECN)_1\right]^2}{\left[(ECN)_1^2 (ECN)_{2'}\right]^{1/3}} \tag{2.62}$$

$$\nu_{2'1} = \nu_{12'} \left(\frac{\nu_{2'}}{\nu_1}\right)^{1/3} \tag{2.63}$$

where ν_1 and $(ECN)_1$ are the kinematic viscosity and effective carbon number of pure component 1. $\nu_{2'}$ and $(ECN)_{2'}$ are the kinematic viscosities and effective carbon numbers of the *pseudo-binary* component 2'.

Again, only two interaction parameters appear in the above equations; *viz.*, $\nu_{12'}$ and $\nu_{2'1}$ for the *pseudo-binary* mixture 12'. Nhaesi (1998) and Nhaesi and Asfour (2000a) suggested the following series of the simple mixing rules for the calculation of the properties of the *pseudo-binary* component 2',

$$\ell n\, \nu_{2'} = \sum_{i=2}^{n} x_i\, \ell n\, \nu_i \tag{2.64}$$

$$(ECN)_{2'} = \sum_{i=2}^{n} \times_i \, (ECN)_i \tag{2.65}$$

$$\ell n\, M_{2'} = \sum_{i=2}^{n} \times_i \, \ell n M_i \tag{2.66}$$

It should be pointed out here that equation (2.65) is used for the calculation of the *ECN* of the *pseudo-binary* mixture using the *ECN*s constituting the regular mixture of interest. Also, the mole fraction, $\times_i$, that appears in the above equations is calculated from the following formula as suggested by Nhaesi (1998) in his study,

$$\times_i = \frac{x_i}{\sum_{i=2}^{n} x_i} \tag{2.67}$$

whereas the small x_i in the numerator of the above equation represents the mole fraction of component *i* in the original mixture, i.e., 1,2,…,*n*. Their results showed better viscosity prediction than the original McAllister model for both *n*-alkanes and regular solutions.

2.4.2 Models based on the principle of corresponding states

The corresponding states principle was originally proposed by van der Waals. According to that principle all fluids would have approximately the same compressibility factor, and all deviate from ideal-gas behavior to about the same degree. On that basis, the van der Waals equation of state can be written for all fluids in a reduced form.

According to that principle, two parameters are to be expressed in a dimensionless form; i.e., reduced temperature and reduced molar volume,

$$T_r = \frac{T}{T_c} \qquad\qquad V_r = \frac{V}{V_c} \tag{2.68}$$

where *r* and *c* denote the reduced and the critical property, respectively.

Experimental results showed that the above two-parameter corresponding states equation has limited applicability to some noble gases and nearly spherical molecules as described by Ely and Marrucho in their review (2000). In order to expand the equation's applicability to wider range of fluids, the principle expressed the reduced compressibility factor, Z_r of a target fluid in terms of a universal function of the above two reduced parameters,

$$Z_r^{(j)}(T_r, V_r) = Z_r^{(0)}(T_r, V_r) \tag{2.69}$$

where the compressibility factor, $Z=PV/RT$

$$(\eta\xi) = (\eta\xi)^{0} \tag{2.70}$$

where

$$\xi = V_c^{2/3} T_c^{-1/2} M^{-1/2} \tag{2.71}$$

j and *0* denote target and spherical reference fluid, respectively.

Pitzer *et al.* (1955) expanded equation (2.69) by Taylor expansion of an acentric factor to the following form:

$$Z = Z^{(0)} + \omega Z^{(1)} \tag{2.72}$$

$Z^{(0)}$: Compressibility of a simple fluid with zero acentric factor.

$Z^{(1)}$: Complicated deviation function.

ω : Acentric factor to account for departure from spherical symmetry.

Later on, Letsou and Stiel (1973) have extended equation (2.70) to viscosities of liquids in the form:

$$\ln(\eta\xi) = \ln(\eta\xi)^{(0)} + \omega \ln(\eta\xi)^{(1)} \tag{2.73}$$

Then equation (2.72) has been written by Lee and kesler (1975) as the three parameter corresponding states:

$$Z = Z^{(0)} + \frac{\omega}{\omega^{(r)}}\left[Z^{(r)} - Z^{(0)}\right] \tag{2.74}$$

$Z^{(r)}$: Represents the compressibility of a reference fluid with $\omega>0$

The problem with their model is still the presence of spherical reference fluid (at ω=0) which requires frequent interpolations/extrapolations when describing real systems.

Teja and Rice (1980), Teja and Sandler (1980), and Teja *et al.* (1985) utilized the corresponding states principle to conclude that very accurate thermodynamic properties can be predicted if the reference fluids are chosen so that they are similar to pure component of interest or to the key component of interest in case of mixtures. Their proposed general form of the corresponding states, equation (2.74), is known as "Generalized Corresponding States Principle" GCSP and is given by,

$$Z = Z^{(r_1)} + \frac{\omega - \omega^{(r_1)}}{\omega^{(r_2)} - \omega^{(r_1)}}\left[Z^{(r_2)} - Z^{(r_1)}\right] \tag{2.75}$$

The superscripts r_1 and r_2 refer to two nonspherical reference fluids.

In an analogous manner, Teja and Rice (1981) extended equation (2.73) to viscosities as follows:

$$\ell n(\eta\xi) = \ell n(\eta\xi)^{(r_1)} + \frac{\omega - \omega^{(r_1)}}{\omega^{(r_2)} - \omega^{(r_1)}}\left[\ell n(\eta\xi)^{(r_2)} - \ell n(\eta\xi)^{(r_1)}\right] \tag{2.76}$$

In order to extend the above equation to mixtures, Teja and Rice (1981) suggested the use of the van der Walls' one fluid model to replace T_c, V_c, ω, and M of pure fluids by the *pseudo-critical* properties.

T_{cm}, V_{cm}, ω_m, and M_m of a hypothetical equivalent substance as for polar mixtures

$$T_{cm}V_{cm} = \sum_{i}\sum_{j} x_i x_j T_{cij} V_{cij} \tag{2.77}$$

$$V_{cm} = \sum_{i}\sum_{j} x_i x_j V_{cij} \tag{2.78}$$

$$\omega_m = \sum_{i} x_i \omega_i \tag{2.79}$$

$$M_m = \sum_i x_i M_i \qquad (2.80)$$

$$Z_{cm} = \sum_i x_i Z_{ci} \qquad (2.81)$$

For non-polar mixtures, they used the mixing rules suggested by Reid and Belenyessy (1960) and Teja (1978) as follows:

$$T_{cij} V_{cij} = \psi_{ij} \left(T_{cii} V_{cii} T_{cjj} V_{cjj} \right)^{1/2} \qquad i \neq j \qquad (2.81)$$

$$V_{cij} = \frac{\left(V_{cii}^{1/3} + V_{cjj}^{1/3} \right)^3}{8} \qquad (2.82)$$

where ψ_{ij} is a binary interaction parameter that is independent of temperature and has to be calculated from experimental data.

Teja and Rice (1981) stated that this parameter is sufficient to characterize each binary mixture if the appropriate reference fluid has been chosen.

Teja and Rice (1981) also suggested using the Andrade equation (1930) to correlate the properties of the reference fluids as a function of the reduced temperature,

$$\ell n \left(\xi \right) = A + B\, T_R^{-1} \qquad (2.83)$$

The constants *A* and *B* of the above equation can be calculated by fitting pure components properties data using the least-squares technique.

It should be pointed out here that this model is applicable best for the cases of fluids of critical volume ratios of less than 3.5. Larger error values are to be expected for polar mixtures or fluids with larger critical volume ratios.

The Teja and Rice (1981) GCSP model can be used either as a predictive technique, if the binary interaction parameter is to set to unity, or as a correlative technique if $\psi_{ij} \neq 1$; in the latter case viscosity data are required.

The main disadvantage of the Teja and Rice (1981) technique is the difficulty of choosing the reference fluids especially for multi-component systems. This will lead to significantly different results.

Papaloannou *et al.* (1991) in their study indicated that "the Teja and Rice model (1981) is applicable to aqueous binary mixtures but not suitable for aqueous ternary mixtures if one-fluid type mixing rule was incorporated".

Realizing the above problem, Wu and Asfour (1992) successfully introduced a modification to the GCSP proposed by Teja and Rice (1981). This was achieved by treating any multi-component mixture as a *pseudo-binary* mixture consisting of pure component 1 and *pseudo*-pure component 2′. The latter is actually a mixture of components 2, 3… n in the system. The two reference fluids, r_1 and r_2 in that case would be simply component 1 and component 2′, respectively. This resulted in a unique *pseudo* interaction parameter, $\xi_{12'}$

Wu and Asfour (1992) were able to calculate the reduced properties of component 2′ by using the following polynomials:

$$\varpi^{r2} = \sum_i A_i \, \overline{N}^i \tag{2.84}$$

$$T_{c,r2} = \sum_i B_i \, \overline{N}^i \tag{2.85}$$

$$P_{c,r2} = \sum_i C_i \, \overline{N}^i \tag{2.86}$$

$$\ell n\left(\eta\varepsilon\right)^{r2} = \sum_i D_i \, \overline{N}^i \tag{2.87}$$

$$\overline{N} = \sum_i x_i \, N_i \tag{2.88}$$

where A_i, B_i, and C_i are the equation parameters to be determined by least-squares fitting, and

$\overline{N}$: the average chain length for *pseudo*-component.

D_i : is a temperature dependent parameter and has to be calculated at different temperatures.

Furthermore, Wu (1992) suggested in her study the following correlation to calculate the value of *pseudo-binary* interaction parameter for *n*-alkanes:

$$\xi^{*}_{12'} = 0.8367 + 0.0328\left(N_2 - N_1\right) + 0.0426\left(N_3 - N_2\right) \tag{2.89}$$

where N is the number of carbon atoms of the component in the *n*-alkane ternary mixture.

Wu *et al.* (1998) tested the above modified generalized corresponding states principle using experimental data on five quaternary and one quinary *n*-alkane systems. Results showed significant improvement in viscosity prediction over the original model. Wu and Asfour (1992) and Wu *et al.* (1998) called their method; the modified generalized corresponding states principle, (MGCSP).

For regular solutions, on the other hand, Nhaesi and Asfour (2000a) extended the MGCSP originally proposed for *n*-alkanes to multi-component regular systems. They replaced the number of carbon atoms appearing in equation (2.89) by the effective carbon number calculated from equation (2.36). The results of testing the modified model using regular ternary, quaternary, and quinary systems at different temperature levels were good compared to the original GCSP.

Nhaesi and Asfour (2000a) incorporated the *pseudo-binary* model into their generalized McAllister model for multi-component systems (Nhaesi and Asfour 2000b). Their objective was to reduce the complexity of the calculations involved in the cases of multi-component systems by converting such multi-component systems into "*pseudo-binary*" systems. The results they reported, while they were better than other models were not as good as those obtained by using the generalized McAllister's model for multi-component systems. However, that represented a simpler and more convenient way for calculating the viscosities of multi-component systems. In other words, predictive capability was partly scarified for the sake of convenience!

Ely and Hanley (1981a) *extended* the corresponding states principle to enhance a method that was earlier proposed by Hanley (1976). Their method states that the viscosity of a fluid or a mixture at a temperature T is equal to the viscosity of a hypothetical pure fluid which is then related to the viscosity of a reference fluid at a corresponding state point. Thus,

$$\eta_{mix}(\rho, T, x_i) = \eta_0(\rho_0, T_0)F_\eta \tag{2.90}$$

and

$$F_\eta = \left(\frac{M_i}{M_0}\right)^{1/2} f_i^{1/2} h_i^{-2/3} \tag{2.91}$$

where the subscripts 0, i refer to the reference fluid and the mixture of interest, respectively. M is the molecular weight, and T_0, and ρ_0 are the state points and are defined as,

$$T_0 = T / f_i \qquad \text{and} \qquad \rho_0 = \rho h_i \tag{2.92}$$

where f_i and h_i are the equivalent substance reducing ratios which were defined as :

$$f_i = \left(\frac{T_{c,i}}{T_{c,0}}\right)\theta_i(T_{r,i}, \rho_{r,i}, \omega_i) \tag{2.93}$$

$$h_i = \left(\frac{\rho_{c,0}}{\rho_{c,i}}\right)\phi_i(T_{r,i}, \rho_{r,i}, \omega_i) \tag{2.94}$$

θ_i and ϕ_i are the shape factors and are functions of the reduced temperature, T_r, and reduced density, ρ_r. ω is the acentric factor, and the subscript c denotes the critical point.

Ely and Hanley (1981a) utilized their ECSP (Extended Corresponding States Principle) to develop a computer program known as TRAPP (Transport Properties Prediction). They tested it using a database of 35 pure hydrocarbons and 26 binary mixtures with methane as the reference fluid. Their predicted results resulted in *AAD*s within 5 % to 10 % for pure components and about 7.0 % for mixtures. The main restrictions of their method were the size ratio between the molecules constituting the mixture and the non-correspondence in choosing the reference fluid which greatly affected the results.

Although the TRAPP method developed by Ely and Hanley (1981a) was applicable for straight chain non-polar hydrocarbons, Baltatu *et al.* (1996) have further extended the TRAPP method to predict the viscosity of heavy crude oil fractions. They introduced a new correction factor to account for the disturbances in the behavior of crude oil fractions at high densities as well as an improved scheme for shape factor calculation. The viscosity was predicted with *AAD*s of about 17 %. Subsequently, Lee and Wei (1993) introduced the concept of three-reference-fluid corresponding states approach. They applied their approach to both aqueous and non-aqueous solutions. Using oxygen, octane and water as the three reference fluids, Lee and Wei (1993) tested their approach using data on 16 aqueous and 52 non-aqueous solutions. Their *AAD*s were found to be 5.23 % and 3.96 %, respectively.

Queimada *et al*. (2003) introduced a new corresponding states model to predict the viscosity of long chain *n*-alkanes. Their model was based on the GCSP proposed by Teja and Rice (1981), equation (2.76). Their viscosity prediction results for the pure *n*-alkane series showed an *AAD* value of 3.15 %. The authors expected better results to be obtained in the case of viscosity prediction of mixtures but with performing large interpolations/extrapolations.

Recently, Queimada *et al*. (2006) have applied their model to predict the viscosity, density, and surface tension of five petroleum distillation cuts from crudes of different sources. Their method showed very good density and surface tension estimation whereas, there were small deviations in the case of viscosity. Queimada *et al*. (2006) concluded in their study that the suggested model may be used for real and synthetic nonpolar mixtures with *n*-alkane contents above 10 %.

2.4.3 Models based on the group contribution method

The group-contribution concept was first suggested by Langmuir (1925). He was the first one to use the group contribution for the prediction of thermodynamic properties of liquid mixtures.

The group-contribution approach is mainly based on the additivity assumption of the contribution of the different chemical groups constituting a compound, i.e., the physical property of a compound is a result of the summation of the contribution of all chemical groups constituting that compound. Moreover, the contribution made by one chemical group is independent of the contribution of other groups. Consequently, this enables the prediction of the physical properties of systems with no available experimental data. The main advantage of the group-contribution approach is that the behavior of large numbers of components in a mixture can be represented by smaller numbers of the chemical groups constituting the mixture. This is because the number of chemical groups involved in the mixture is much smaller than the number of components.

Many researchers took advantage of this concept in their work for the estimation of different thermodynamic or physical properties of mixtures. Examples of those workers are: Redlich *et al.* (1959), Pierotti *et al.* (1959), and Derr and Papadopoulos (1959) for the estimation of the heat of mixing, and Wilson and Deal (1962) for the correlation of activity coefficients. The latter approach was extended by Derr and Deal (1969) in a method they termed the "*analytical solution of groups*" (ASOG) method.

Abrams and Prausnitz (1975) proposed an activity coefficient model based on the extension of the *quasi-chemical* theory of liquid mixtures known as UNIQUAC. The significant work based on the group-contribution concept was achieved by Fredenslund *et al.* (1975) when combined with the UNIQUAC model to predict the activity coefficients of non-ideal liquid mixtures. Thus resulting in the well known UNIFAC model (UNIQUAC Functional-group Activity Coefficients).

Wu (1986) successfully employed the group contribution approach to predict the liquid mixtures viscosities. He divided the free energies of activations into two parts; the first part is the summation of the molar activation energies of the pure components. The second part is an excess free energy due to mixing. WU (1986) used the UNIFAC model to determine the excess Gibbs free energy (the second part) combined with the regression of experimental viscosity data for the determination of the group interaction parameters. He tested his model using data on more than 80 binary mixtures containing different polar and non-polar compounds and obtained good results.

Chevalier *et al.* (1988) utilized both Eyring's equation and the UNIFAC model to develop the following equation for the kinematic viscosity of liquid mixtures, v_{m} (widely known as UNIFAC-VISCO),

$$\ell n\left(\nu_m M_m\right) = \sum_{i=1}^{n} x_i \; \ell n\left(\nu_i M_i\right) + \frac{\Delta G^{*,ex}}{RT} \tag{2.95}$$

where the molecular weight of the mixture, M_m, can be determined from the following simple mixing rule,

$$M_m = \sum x_i \; M_i \tag{2.96}$$

In their model, they assumed that the excess molar free energy of activation for flow, $\Delta G^{\neq ex}$, that represents the deviation from ideality may be taken as the summation of two terms as follows:

$$\Delta G^{*ex} = \Delta G^{*ex,c} + \Delta G^{*ex,r} \tag{2.97}$$

The first term, $\Delta G^{*ex,c}$, is the combinatorial part that represents the differences in shape and size of the molecules in the mixture. While the second term, $\Delta G^{*ex,r}$, is the residual part which is due to energy interaction between the functional groups contained in the molecules constituting that mixture. Moreover, they also reported the following equation:

$$\Delta G^{*ex} = RT \sum x_i \; \ell n \gamma_i^{\neq} \tag{2.98}$$

where the activity coefficient is also a function of two activity coefficients; one related to the combinatorial part, $\gamma_i^{\neq,c}$, and the second is related to the residual part, $\gamma_i^{\neq,r}$. For details of calculations of both parts, one can refer to the original paper.

In addition to calculating the group interaction parameter, they introduced a method of simplifying each branched or cyclic molecule by breaking it down into a sum of functional groups. But this on the other hand neglected isomers.

Chevalier *et al.* (1988) compared their proposed model with Wu's model (1986). Their average absolute deviations for 105 binary systems were slightly lower than those reported by Wu (1986) at only one temperature, *viz*., 298.15 K.

Gaston-Bonhomme *et al.* (1994) continued the study performed by Chevalier *et al.* (1988) to further discuss the temperature dependence of the interaction parameters which was not taken into consideration in their first study. They were not able to accomplish better results for the viscosity prediction considering the temperature effect. Therefore, they suggested ignoring the temperature effect on the interaction parameters for the mixtures as soon as the error in viscosity remains acceptable.

Cao *et al.* (1992) developed what they called the *statistical thermodynamic model* and used it to correlate the viscosities of both pure compounds (314 pure compounds) and binary mixtures (215 binary mixtures from different types of solutions). Following that, they used the results to predict the viscosities of multi-component liquid mixtures (14 ternary and one quaternary liquid mixture). Their model was theoretically based on Eyring's absolute rate theory combined with the local composition concept.

Cao *et al*. (1992) reported the following equation for the prediction of the kinematic viscosity of liquid mixtures, *v*:

$$\ell n(\nu M) = \sum_{i=1}^{n} x_i \, \ell n(\nu_i M_i) - \sum_{i=1}^{n} q_i n_i x_i \sum_{j=1}^{n} \theta_{ji} \ell n \, \tau_{ji} \tag{2.99}$$

where v_{i} and M_{i} are the kinematic viscosity and the molecular weight of pure component i, respectively. q_i is the area parameter of molecule i and is calculated from the surface area of the UNIFAC group. The details of such calculations are described by Hansen *et al.* (1991). The molecular fraction of component i, x_i, in the liquid mixture can be calculated from,

$$x_i = \frac{N_i}{\sum_{j=1}^{n} N_j} \tag{2.100}$$

θ_{ji} is the local composition and τ_{ji} is the interaction parameter that has to be determined from fitting experimental kinematic viscosity data into the model, equation (2.99). The last pure component parameter n_i is determined from correlating experimental viscosity data as a function of temperature as follows:

$$\ell n \left(n_i \right) = \sum_{j=0} A_j T^j \tag{2.101}$$

Cao *et al.* (1992) tested their model using data on 15 multi-component liquid mixtures. Their results showed an overall absolute average deviation of 2.90 % compared to 5.70 % when Wu’s model (1986) was tested. An important feature of the Cao *et al.* (1992) model is the capability of their equation to correlate viscosity data even if the data were at different temperatures. But this does not change the correlative nature of the equation at its first stage of application.

Subsequently, Cao *et al.* (1993a) introduced the molecular size into their model to develop a new model “*viscosity-thermodynamics*” model or UNIMOD. They thought it would be better to correlate thermodynamic properties (activity coefficients) to transport properties (viscosity) due to the availability of experimental thermodynamic data. In their statistical model they were able to successfully correlate activity coefficients and viscosities of liquid mixtures. For the prediction of kinematic viscosity of a liquid mixture, their equation was reported as,

$$\ell n\left(\nu M\right)=\sum_{i=1}^{n}\phi_i\,\ell n\left(\nu_i M_i\right)+2\sum_{i=1}^{n}\phi_i\,\ell n\left(\frac{x_i}{\phi_i}\right)-\sum_{i=1}^{n}\frac{q_i n_i\,\phi_i}{r_i}\sum_{j=1}^{n}\theta_{ji}\,\ell n\left(\tau_{ji}\right) \tag{2.102}$$

All the terms were defined as before in their previous work. Additionally, r_i is the number of segments in a molecule *i* and ϕ_i is the average segment fraction of component *i*. Using the same parameters, another equation was reported for the activity coefficient. The overall absolute average deviation for 1991 viscosity data of 134 binary systems was found to be 2.77 %.

In a subsequent paper, Cao *et al.* (1993b) proposed their group-contribution model for the prediction of both the viscosities and the activity coefficients of liquid mixtures. Their earlier UNIMOD model was combined with the group-contribution concept to produce what they called “GC-UNIMOD”. Depending only on experimental vapor-liquid equilibrium data, viscosity of liquid mixtures can be predicted with no need for viscosity data.

Cao *et al.* (1993b) have divided the viscosity equation of their UNIMOD model into two parts; a combinatorial part, ξ^{C}_{i}, to account for the combinatorial contribution of component *i* to the viscosity of the mixture, and a residual part, ξ^{R}_{i}, to account for the residual contribution of component *i* to the viscosity of the mixture. Here, the combinatorial part corresponds exactly to the combinatorial part of the UNIMOD for viscosity. It contains only the properties of pure components. While the residual part that contains the interaction parameter between different components is expressed in terms of group-contribution as,

$$\xi_i = \sum_{\text{all groups k}} \nu_k^{(i)} \left(\Xi_{ki} - \Xi_{ki}^{(i)} \right) \tag{2.103}$$

where, $\nu_k^{(i)}$ is the number of group *k* in molecule *i*, Ξ_{ki} is the group residual viscosity of group *k* for component *i* in the mixture, and $\Xi_{ki}^{(i)}$ is the group residual viscosity of group *k* for component *i* in the solution- of-group of pure component *i*.

The GC-UNIMOD for kinematic viscosity including the above mentioned two parts may be then introduced as,

$$\ell n\left(viscosity\right) = \sum_{i=1}^{n} \left(\xi_i^c + \xi_i^R \right) \tag{2.104}$$

where,

$$\xi_i^c = \phi_i \, \ell n \left(\nu_i \, \frac{M_i}{M} \right) + 2\,\phi_i \, \ell n \left(\frac{x_i}{\phi_i} \right) \tag{2.105}$$

and,

$$\xi_i^R = -\frac{q_i n_i \, \phi_i}{r_i} \sum_{j=1}^{n} \phi_{ji} \, \ell n \left(\psi_{ji} \right) \tag{2.106}$$

Combining the above equations together, the GC-UNIMOD expression for kinematic viscosity of liquid mixtures is given by,

$$\ell n\left(\nu\right)=\sum_{i=1}^{n}\left[\begin{array}{l}\phi_i\ \ell n\left(\nu_i\ \dfrac{M_i}{M}\right)+2\,\phi_i\ \ell n\left(\dfrac{x_i}{\phi_i}\right)\\ +\displaystyle\sum_{all\ groups\ k}\nu_k^{(i)}\left[\Xi_{ki}-\Xi_{ki}^{(i)}\right]\end{array}\right] \qquad (2.107)$$

$$\Xi_{mi}=-\frac{Q_m}{R_m}\,N_{ki}^{vis}\,\phi_i\sum_{all\ groups\ k}\theta_{km}\ \ell n\left(\Psi_{km}\right) \qquad (2.108)$$

where N_{ki}^{vis} is defined as the viscosity parameter of group *k* in component *i* and may be calculated from the following equation:

$$N_{ki}^{vis}=Q_k\left(\frac{q_i-r_i}{2}-\frac{1-r_i}{z}\right) \qquad (2.109)$$

and q_i, and r_i are area parameters and number of segments of molecule, *i* respectively. Their values are determined by the following equations:

$$q_i=\sum_{all\ groups\ k}\nu_k^{(i)}Q_k \qquad (2.110)$$

$$r_i=\sum_{all\ groups\ k}\nu_k^{(i)}R_k \qquad (2.111)$$

The surface area parameter, Q_k and the volume parameter, R_k are calculated from van der Waals group surface area, A_{wk}, and volume, V_{wk}, as in the UNIFAC, as follows:

$$Q_k = \frac{A_{wk}}{2.5 \times 10^9} \tag{2.112}$$

and

$$R_k = \frac{V_{wk}}{15.17} \tag{2.113}$$

A group of researchers, Martins *et al.* (2000 and 2001) utilized the UNIQUAC method accompanied with Eyring's theory to correlate both the absolute and kinematic viscosities of mixtures within the temperature range of (283.15 to 328.15) K and at a pressure of 0.1 MPa. In their first study, they used their proposed model to predict the viscosities of about 350 different types of binary mixtures with an overall *AAD* (%) of 1.2. In their second study, they extended the model to treat multi-component liquid mixtures. Their overall *AAD* (%) of 2.95 was obtained for 48 ternary and 3 quaternary non-electrolyte liquid systems.

Generally speaking, the group contribution approach may be considered one of the best predictive techniques since no experimental data about mixtures are required in order to predict the viscosity.

It should be pointed out here that there is no evidence that the contribution of the same chemical group in different compounds remains the same.

2.4.4 Models based on local composition

Wei and Rowely in their series of publications (1984a, 1984b, and 1985) have introduced their local composition model for the prediction of shear viscosity of liquid mixtures. The model is similar to the model reported earlier by Rowley (1982 and 1983) for the prediction of thermal conductivity. The model is also well known as the “*non-random two liquid model*” (NRTL). The reported model has no adjustable parameters and uses only equilibrium thermodynamic data.

The local composition model can be written in terms of volume fraction, ϕ_i, for multi-component systems as,

$$\eta = \frac{exp(\xi)}{V} \tag{2.114}$$

$$\xi = \sum_i \phi_i \xi_i^0 + \sum_i \phi_i \left[\frac{\sum_j \phi_j G_{ji} (\xi_{ji} - \xi_i^0)}{\sum_j \phi_i G_{ji}} \right] - \frac{\sigma H^E}{RT} \tag{2.115}$$

with the assumption that

$$\xi_{ji} = \xi_{ij} = \frac{\sum_i (\phi_i^* \phi_{ii}^* \xi_i^0)}{\sum_j (\phi_j^* \phi_{jj}^*)} \tag{2.116}$$

where for a pair of interactions *i* and *j*, one has

$$G_{ji} = exp\left(\frac{-\alpha\, A_{ji}}{RT}\right) \qquad i \neq j \tag{2.117}$$

$$\phi_j^* = \frac{1}{(1+\Gamma_{ji})} \tag{2.118}$$

$$\phi_{ii}^* = \frac{1}{\left(1+\frac{\phi_j^* G_{ji}}{\phi_i^*}\right)} \tag{2.119}$$

and

$$\Gamma_{ji} = (V_i / V_j)(G_{ji} / G_{ij})^{1/2}\, exp\left[\frac{(\xi_j^0 - \xi_i^0)}{2}\right] \tag{2.120}$$

where ξ_i^0 is the pure component *i* value and is determined from,

$$\xi_i^0 = \ell n\,(\eta_i V_i) \tag{2.121}$$

In the above model, α, A_{ij}, and A_{ji} are the NRTL model parameters for each binary system. They can be determined either directly from the literature data or by fitting vapor-liquid or liquid-liquid equilibrium data to the NRTL equation. The molar volume, *V*, for pure components or for liquid mixtures were determined using their own density data.

Wei and Rowely (1984a) tested their model using experimental data on 24 binary systems of different solution types at 298.15 K. Their results for shear viscosity prediction agreed with the experimental viscosity data within an average absolute deviation of 5 % over the entire composition range. Excess enthalpy data, H^E, were obtained from Christensen *et al.* (1982). The value of the factor σ that appears in equation (2.115) was taken to be 0.25 throughout their work.

For ternary systems, Wei and Rowely (1984b) used 20 different ternary systems for testing their NRTL model at the same temperature of 298.15 K. The same steps followed earlier by those authors were also followed for their calculation of the shear viscosities of the different ternary systems except for the case of calculating the excess enthalpies of ternary systems. Because no direct data could be obtained, the raw data were curve fitted to the following equation:

$$H^E = \sum_i x_i \frac{\sum_j H_{ji} G'_{ji} x_j}{\sum_k H_{ki} x_k} \qquad (2.122)$$

$$G'_{ji} = exp\left[\frac{-\left(H_{ji} - T\,S_{ji}\right)}{RT}\right] \qquad (2.123)$$

where H_{ji} and S_{ji} are binary adjustable parameters. Results of the comparison between values of shear viscosities calculated by their model and the corresponding experimental data available from the literature showed an average absolute deviation of 6.4 %.

In a subsequent study, Wei and Rowely (1985) continued their studies for predicting the shear viscosities of multi-component non-aqueous solutions. For 47 binary systems, the absolute average deviation was reported as 1.1 % and as 0.8 % for 7 ternary systems which were tested when compared with experimental data available from the literature as well as for data obtained in their laboratory.

The Wei and Rowely (1985) NRTL model gave good results. It has the advantages of not containing any adjustable parameters in the case of binary mixtures. For the case of ternary systems, it contains only two binary adjustable parameters. The tests reported by those authors were limited since they were carried out at only one temperature; *viz*., 298.15 K. As such, the temperature dependence of the model has not yet been tested.

2.4.5 Models based on molecular thermodynamic

The first serious attempt to develop those kinds of models was introduced by Patel and Teja (1982). They developed a cubic equation of state (EOS) that can predict many volumetric properties of fluids and fluid mixtures. They introduced two parameters; F and ζ_c , to Soave's equation (1972) and to the Peng and Robinson equation (1976) to characterize each fluid. It has been applied to non-polar as well as polar liquids. In addition, they extended their method so that it could be used to treat different binary mixtures. The Patel-Teja equation of state was capable of predicting vapor-liquid equilibrium data to within acceptable accuracy.

Lee *et al.* (1998) utilized the Patel-Teja equation of state with zero binary interaction constant to calculate density and excess Gibbs free energy of liquid mixtures. They were able to satisfactorily correlate the viscosity of a wide variety of aqueous and non-aqueous systems. Only limited mixture viscosity data were required besides the kinematic viscosity values of pure components at the temperature of interest. Testing their new modification on aqueous and non-aqueous binary and ternary systems led to reasonable viscosity results.

The Patel and Teja (1982) equation of state is given by:

$$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)+c(V-b)} \tag{2.124}$$

where

$$a(T) = a_c \alpha(T) \tag{2.125}$$

$$b = \frac{\Omega_b R T_c}{P_c} \tag{2.126}$$

$$c = (1-3\zeta_c)\frac{RT_c}{P_c} \tag{2.127}$$

and

$$\alpha(T) = \left[1 + F\left(1 - T_r^{0.5}\right)\right]^2 \tag{2.128}$$

$$a_c = \left[3\zeta_c^2 + 3(1-2\zeta_c)\Omega_b + \Omega_b^2 + 1 - 3\zeta_c\right]\frac{R^2 T_c^2}{P_c} \tag{2.129}$$

where Ω_b represents the positive real root of the following equation:

$$\Omega_b^3 + (2 - 3\zeta_c)\Omega_b^2 + 3\zeta_c^2\Omega_b - \zeta_c^3 = 0 \tag{2.130}$$

The two fluid characteristic parameters indicated earlier, F and ζ_c, were either taken from the literature or determined by fitting experimental vapor pressures and density data to the EOS.

For the mixtures, Lee *et al.* (1998) defined the equation constants *a*, *b*, and *c* as follows:

$$a_m = \sum_{i=1}^{c}\sum_{j=1}^{c} x_i\, x_j\, (1 - k_{aij})(a_i a_j)^{0.5} \tag{2.131}$$

$$b_m = \sum_{i=1}^{c} x_i b_i \tag{2.132}$$

and

$$c_m = \sum_{i=1}^{c} x_i c_i \tag{2.133}$$

The binary interaction parameter contained in equation (2.131), k_{aij}, was set to zero in the Lee *et al.* (1998) study.

Utilizing Eyring's viscosity equation, Lee *et al.* (1998) assumed that the excess activation free energy of flow, $G^{\neq ex}$, can be calculated with the help of the following equation:

$$G^{\neq ex} = -\sigma\, G^{ex} \tag{2.134}$$

where G^{ex} is the excess Gibbs free energy of solution (which was calculated from the Patel-Teja equation of state with zero binary interaction parameter) and σ is a proportionality factor. Lee *et al.* (1998) used the proportionality factor as a constant for non-aqueous systems (as per the Wei and Rowley (1985) assumption) and it was considered as a linear composition-dependent (LCD) function for aqueous systems. Lee *et al.* (1998) model is also known as the Eyring-Patel-Teja Model.

Guo *et al.* (1997) developed a new generalized model for predicting the viscosities of pure hydrocarbons as well as hydrocarbon mixtures. Their new general model was based on the similarity between P-v-T and P-μ-T relationships of both Patel-Teja and Peng-Robinson cubic equations of state. Their model showed significant improvements to viscosity prediction as compared to other EOS based models.

Lee *et al.* (1999) pointed out in their study to drawbacks in the Lee *et al.* Eyring-Patel-Teja model (1998) previously discussed. The first drawback is that the proportionality factor, σ, cannot be taken as a constant because it varies with composition for aqueous solutions. The second drawback is the appearance of an additional ternary interaction parameter with any ternary system. They attributed those drawbacks to two factors; *viz.*, the assumption of the linear composition-dependent (LCD) function and the zero value of the binary interaction parameter.

In order to improve the Eyring-Patel-Teja model, Lee *et al.* (1999), suggested the calculation of the excess activation free energy of flow, $G^{\neq ex}$, from the available functionality of the excess Gibbs free energy of solution, G^{ex} in terms of fugacity coefficients as

$$G^{ex} = RT\sum_{i=1}^{n_c} x_i \left(\ell n\phi_i - \ell n\phi_i^0\right) \tag{2.135}$$

where ϕ is the fugacity coefficient.

Two different mixing rules were applied in the Lee *et al*. (1999) study to determine the values of the Patel-Teja constants; a_m, b_m, and c_m.

Utilizing the one-parameter van der Waals one-fluid mixing rule, the model correlates the viscosities of 60 non-aqueous binary mixtures with an overall *AAD* (%) of 2.1. When the two-parameter Redlich-Kister type mixing rule was applied to 15 aqueous binary mixtures, an overall *AAD* (%) of 4.5 was obtained.

Lee *et al.* (1999) modified the Eyring-Patel-Teja model. Thus, it became capable of predicting viscosities for different types of both binary and ternary solutions even at elevated pressures with reasonably good accuracy.

Lee and Lee (2001) studied the viscosities of 31 different types of binary mixtures by applying four EOS based models. The application of the different types of EOS with the incorporation of different mixing rules was also employed in their study. Moreover, they discussed the effect of determining the interaction parameters using either excess volumes of mixing or using the densities of the binary system data on the prediction of viscosity. They concluded as a result of their study that the accuracy of viscosity prediction was highly dependent on the source of binary interaction parameters. They found that the *AAD* was lower than 1 % for the case of binary interaction parameters calculated with the help of the excess volumes of mixing. On the hand, the *AAD*s were below 3 % if the interaction parameters were calculated using mixture densities. Their explanation to such an observation was that the dependence on the EOS to give accurate volume estimation is very high in case of mixture density calculations. Alternatively, this dependence is very much reduced in the case of excess volumes of mixing because of the fact that pure volumes are always subtracted from mixing volumes.

Lin *et al.* (2007) continued the work of Lee and Lee (2001) on 65 different binary mixtures. Lin *et al.* (2007) attempted to study the effect of EOS, mixing rule, and interaction parameter on viscosity estimation. They utilized equations of state with different mixing rules to determine the constants a_m, b_m, and c_m. The results were compared and different conclusions than those reached by Lee and Lee (2001) were reached. Lin *et al.* (2007) did not provide clear explanations for the conflicting conclusions that were reported.

Recently, many researchers have utilized equations of state in combination with the Eyring theory to predict the viscosity of different types of solutions at different conditions of temperatures and pressures. Examples of those studies are; the study performed by Salinas *et al.* (2003) on some binary non-ideal mixtures at elevated pressures, the work reported by Weirong and Lempe (2006) in their study of 67 binary and 18 ternary mixtures, and the Tochigi *et al.* (2007) study on the prediction of the viscosities of binary mixtures at high pressures.

2.5 Empirical Equations for Viscosity of Liquid Mixtures

2.5.1 The Allan and Teja correlation

The Allan and Teja correlation (1991) may be considered as one of the most famous and reliable empirical correlation for viscosity calculation. The reported Antoine-type equation for viscosity of liquid mixtures is as follows:

$$\ell n(\eta) = A\left[-\frac{1}{B}+\frac{1}{T+C}\right] \tag{2.136}$$

where η is the absolute viscosity of the mixture in cp, T is the absolute temperature in K, and A, B, and C are equation parameters dependent on the number of carbon atoms in the components. Allan and Teja (1991) reported the following equations for the calculation of the equation parameters A, B, and C,

$$A = 145.73 + 99.01n + 0.83n^2 - 0.125n^3 \tag{2.137}$$

$$B = 30.48 + 34.04n - 1.23n^2 + 0.017n^3 \tag{2.138}$$

$$C = -3.07 - 1.99n \tag{2.139}$$

where n is the number of carbon atoms of n-alkanes. Allan and Teja (1991) presented a new method in which the viscosity of hydrocarbon mixtures can be predicted on the basis of data on n-alkanes. Equations (2.137) to (2.139) are simple three constant equations in only one parameter, n, to represent the properties of n-alkanes from ethane through eicosane. They indicated that in order to calculate the viscosity of a hydrocarbon mixture, both the composition and the effective carbon number of each component must be known. The hydrocarbon mixture then was treated as a single component with an *ECN* calculated from the following simple mixing rule:

$$ECN_m = \sum x_i \, ECN_i \qquad (2.140)$$

Allan and Teja (1991) tested their proposed equation on 11 hydrocarbon mixtures and compared their results with the TRAPP method. Their overall absolute average deviation for all mixtures was found to be 5.8 % compared with 9.53 % calculated using the TRAPP model.

2.5.2 The Heric and Brewer model

Heric and Brewer (1967) have proposed the following equation for the calculation of the kinematic viscosity of binary mixtures, ν_{m},

$$\ell n \, \nu_m = \sum_{i=1}^{n} x_i \, \ell n \, \nu_i + \sum_{i=1}^{n} x_i \, \ell n \, M_i - \ell n \sum_{i=1}^{n} x_i \, M_i + \delta_{i \ldots n} \qquad (2.141)$$

where M is the molecular weight, x is the mole fraction, the subscript i denotes pure component i, and $\delta_{i \ldots n}$ is defined by the following equation:

$$\delta_{i \ldots n} = \sum_{\substack{i=1 \\ i \prec j}}^{n} x_i \, x_j \left[A_{ij} + B_{ij} \left(x_i - x_j \right) + C_{ij} \left(x_i - x_j \right)^2 + \ldots \right] \qquad (2.142)$$

Fitting experimental data to the above equation leads to the determination of the values of the adjustable parameters A, B, and C. Note that the subscript j denotes the second pure component in the binary mixture. Testing the above model with data from 14 binary non-electrolyte systems at only one temperature; *viz.*, 298.15 K led to a standard errors of 0.07 % to 0.41 %. For ternary mixtures, Heric and Brewer (1969) expanded their binary model to the following form:

$$\delta_{123} = \sum_{\substack{i=1 \\ i \prec j}}^{3} x_i x_j \left[A_{ij} + B_{ij}\left(x_i - x_j\right) + C_{ij}\left(x_i - x_j\right)^2 + \ldots\right] \\ + x_1 x_2 x_3 \left(A_{123} + B_{123} x_1 + C_{123} x_2\right) \tag{2.143}$$

and

$$\delta_{123} = \sum_{\substack{i=1 \\ i \prec j}}^{3} x_i x_j \left[A'_{ij} + B'_{ij} x_i + C'_{ij} x_i^2 + \ldots\right] \\ + x_1 x_2 x_3 \left(A'_{123} + B'_{123} x_1 + C'_{123} x_2\right) \tag{2.144}$$

Heric and Brewer (1969) tested their extended model using experimental data on 11 ternary non-electrolyte mixtures. They found the standard error for kinematic viscosity calculation to be 0.28 % to 0.5 %. The large number of adjustable parameters required needed by that model to achieve accuracy is obviously a major draw back.

2.5.3 The Grunberg-Nissan equation

Grunberg and Nissan (1949) proposed their parabolic type equation for correlating the viscosity of mixtures with only one adjustable parameter,

$$\ell n\, \eta_m = \sum_{i=1}^{n} x_i \ell n\left(\eta_i\right) + \sum_{i \prec j}\sum x_i\, x_j G_{ij} \tag{2.145}$$

where G_{ij} is the only interaction parameter in the equation. The binary form of the equation can be reached if G_{ij} is set to zero. Irving (1977) reported that the difficulty of generalizing the Grunberg's equation arises from the dependence of this interaction parameter on the type of system and sometimes on the temperature. Moreover, it does not deal with aqueous solutions.

Nhaesi and Asfour (2000a) applied "*the pseudo-binary concept*" to the Grunberg-Nissan equation. They suggested rewriting the above equation as follows:

$$\ell n\eta_m = \sum_{i=1}^{n} x_i \, \ell n\eta_i + x_1 (1 - x_1) G_{12'} \qquad (2.146)$$

where $2^{'}$ refers to the *pseudo*-component 2 (components 2,3,…*n*) as described earlier. They tested their model using viscosity data on both regular multi-component liquid systems and *n*-alkane systems. They concluded from a comparison between their proposed model and the original Grunberg and Nissan equation (1949) that; although their proposed model showed higher *AAD* values than the original Grunberg and Nissan equation. However, they recommended the use of the proposed *pseudo-binary* form of the Grunberg and Nissan model because it requires less calculation time and is less complex than the original equation.

2.6 The Artificial Neural Networks (ANNs) Based Models

2.6.1 General

Artificial neural networks (ANNs) are fast computing techniques that are capable of solving very complicated problems. The concept of neural networks was first introduced in late 1800s as an analogue to the human brain. The networks are composed of artificial neurons connected to perform the desired function. This is done by learning the relationships through repeated presentation of data, then generalizing to new unseen data.

The ANNs have many advantages over classical computational techniques; *viz*., (i) they are capable of successfully representing highly non-linear relationships between dependant and independent variables, (ii) they are very fast in terms of data processing and learning ability, and (iii) they are characterized with their fault tolerance. On the other hand, the major drawback of the ANNs is their “black box” nature, i. e., the details of what is actually going inside the network itself remains unknown, (Lippmann 1987).

The basic processing element of an ANN is the neuron. The first attempt to model a single neuron was suggested by McCulloch and Pitts (1943). Later, Rosenblatt (1958) came up with his “*perceptron*” model as a simplest form of a neural network.

Although there are many types of neural networks, the basic principles behind their design are almost the same. The basic processing element, the neuron, receives input signals then processes them through certain function (activation function) and reveals an output signal. Each neuron is connected to at least another one neuron, and each connection has an associated weight. The neuron output signal is a function of the weighted sum of the inputs. The problem of finding the value of these weights is called *learning or training* of a network. Training the network is providing it with a set of random data selected from the input space. The network then has to learn the input/output relationship by adjusting the weights in such a way that the difference between the real output and the desired output is as minimum as possible. This type of learning process is known as supervised learning, (Haykin 1994).

There are two main types of activation functions; *viz*., (i) *the threshold function,* and (ii) *the sigmoid function.* The latter type may be considered the most common form of activation functions. This sigmoid function could be either a logistic function in the form [Haykin (2008)]:

$$f(x)=\frac{1}{1+exp(-ax)} \tag{2.148}$$

Or a hyperbolic tangent function in the form,

$$f(x)=tanh(ax) \tag{2.149}$$

2.6.2 Neural network architectures

Haykin (2008) identified the following three different classes of network architectures:

A. Single-layer feed-forward networks: this network structure consists of an input layer and an output layer, an example of this structure is shown in Figure 2.7a.
B. Multi-layer feed-forward networks: this structure is characterized by the presence of one or more hidden layers. The presence of such hidden layers enables greater processing power and system flexibility. Those layers are called “hidden” because their neurons cannot be viewed from the input or the output layers. This architecture is shown in Figure 2.7 b. It should be indicated here that the flow of the data is in one direction from the input to the output in the above two structures.

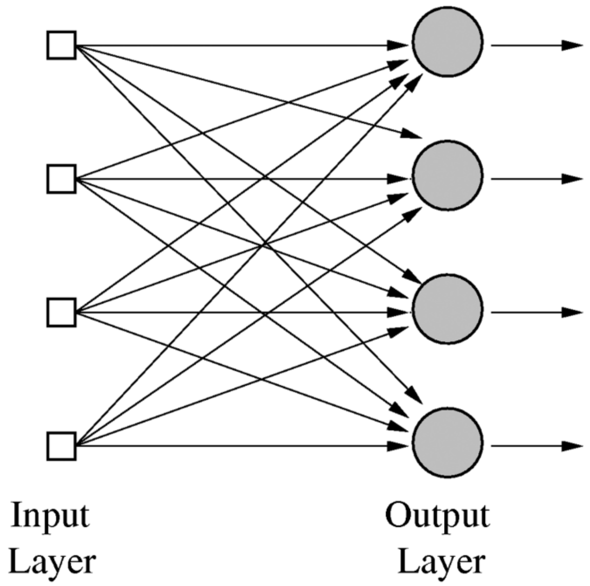

Figure 2.7a: Single-Layer Feed-Forward Network

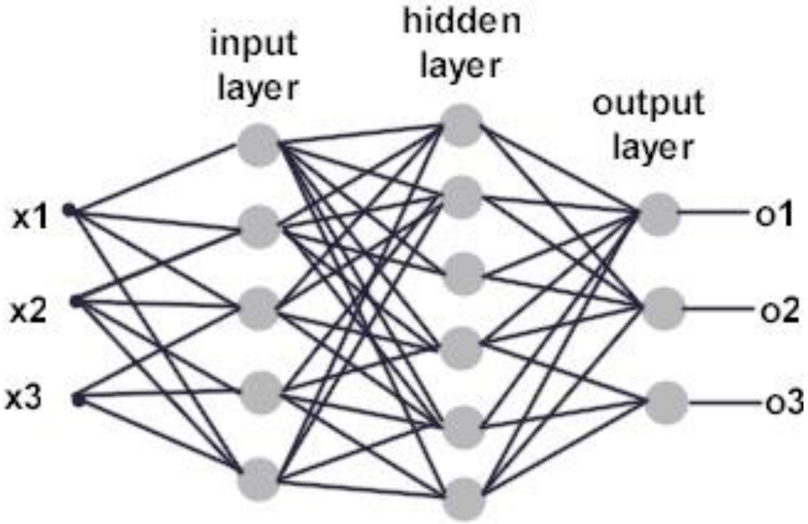

Figure 2.7b: Multi-Layer Feed-Forward Network with One Hidden Layer

C. Recurrent networks: this structure is characterized by the presence of at least one feed-back loop. This network could be single layer or multiple layers as shown in Figure 2.8.

There are general steps involved in the design of any network. These steps are; training, testing, validation, and generalization. A brief description of each step is in order.

(i) *Training:* The training step may be considered the most important step during the design of a network. This is in order for the network to properly understand and learn the relationships between the dependant and independent variables. Learning could either be supervised (may be called as learning with a teacher) or learning without a teacher. The supervised learning is when one feeds the network with a set of input-output examples and it is required to calculate the error signal: the difference between the actual and the desired responses. One of the most popular algorithms is the *back-propagation* algorithm. Learning without a teacher is subdivided by Haykin (2008) into: (i) reinforcement learning, and (ii) unsupervised learning.

(ii) *Testing:* This term refers to using a set of data in order to find the best network configuration. Testing may be employed during training step to monitor the error and find the optimal number of training iterations or epochs. It also can be used to figure out the optimal number of hidden neurons, (Priddy and Keller 2005).

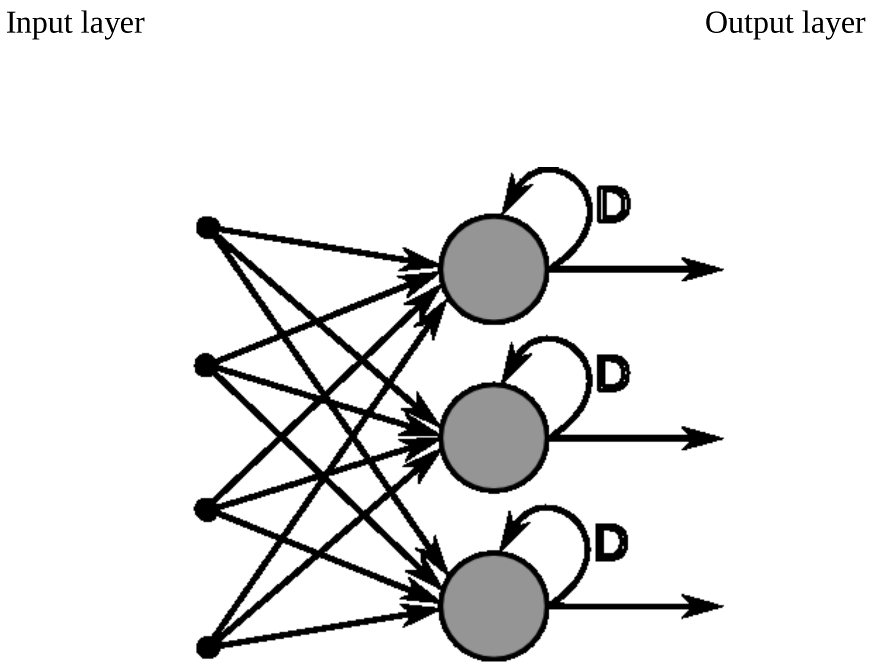

Figure 2.8: Single Layer Recurrent Network

(iii) *Validation:* This particular step is not as essential as other design steps, i. e., it may be chosen to be performed or not. The purpose of this step is to determine the optimum point to stop training, (Priddy and Keller 2005).

(iv) *Generalization:* Once the network is well trained, it is ready for production. The generalization term refers to the measure of the performance of a network when fed with data that were never seen before even if these data are slightly different than those used before for training or testing.

2.6.3 Back-propagation training algorithm

Back-propagation is the most popular supervised technique in training feed forward multilayer networks. Back-propagation requires the activation function used by each neuron to be differentiable. The technique is performed on two phases (Wythoff 1993 and Haykin 2008). The first phase is the *forward phase*; it involves introducing the input(s) to the network along with assumed initial values of the weights and the desired output value. The input signal then will propagate through the network layer by layer in the forward direction until an output value is obtained. The second phase is the *backward phase*; in this phase an error signal is calculated at the end of the network by comparing the network output from the previous phase to the desired output that was given to the network. Then the error signal will then propagate in the backward direction layer by layer while applying an adjustment to the weights. This procedure is repeated until reaching certain allowable error value or number of epochs. Figures 2.9a and 2.9b indicates a schematic of the two phases involved in the back-propagation algorithm.

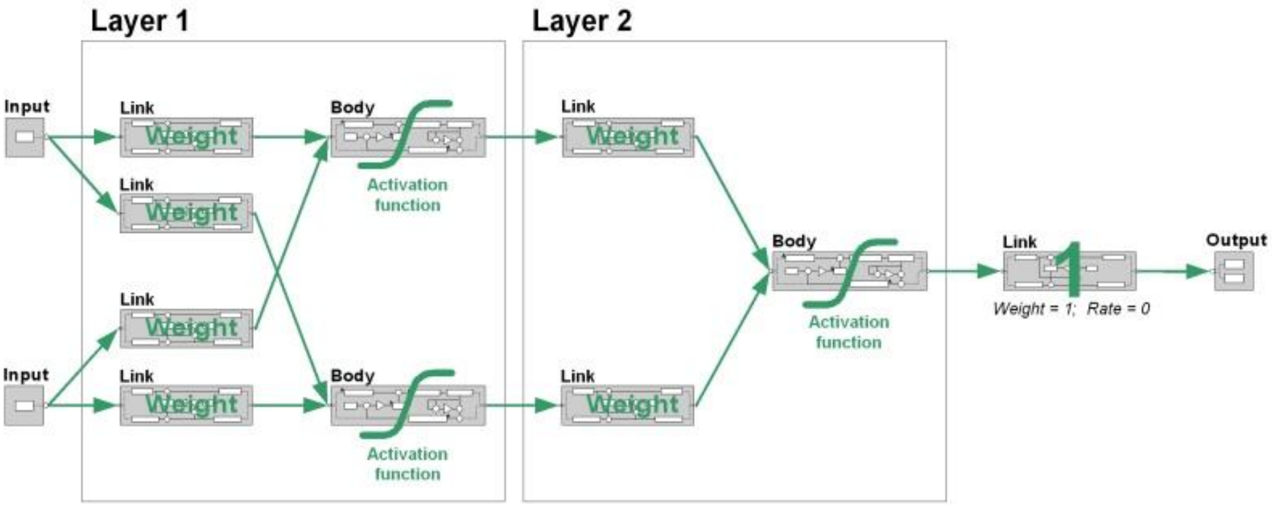

Figure 2.9a: A schematic Diagram Showing the Forward Phase in the Back-propagation Neural Network.

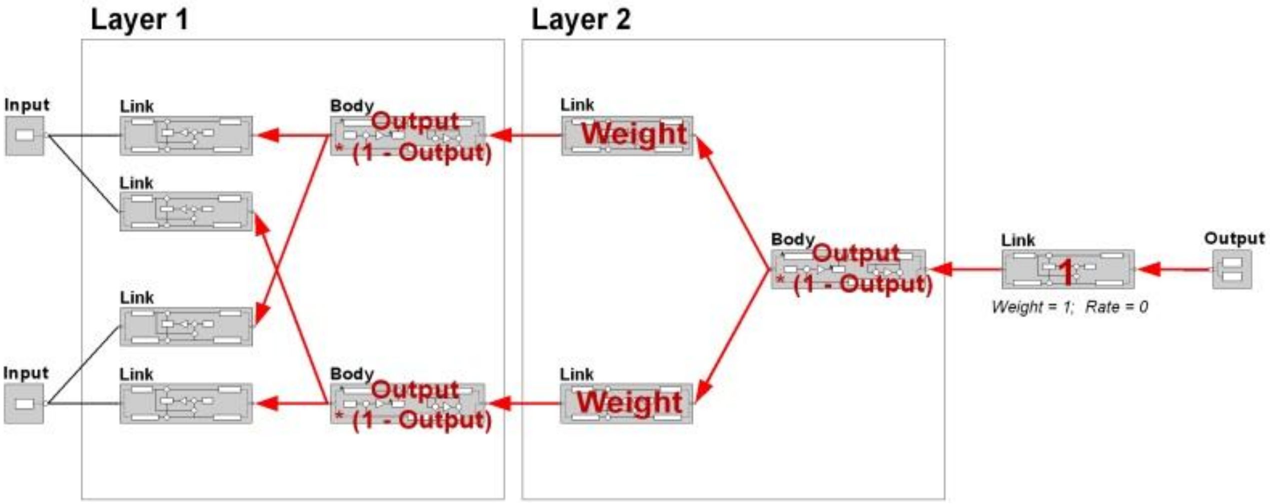

Figure 2.9b: A schematic Diagram Showing the Backward Phase in the Back-propagation Neural Network.

2.6.4 Application of the neural networks in the prediction of the physical properties of pure components and liquid mixtures

In the present section some of the work that was reported in the literature on the use of the ANNs for the prediction of the different properties of pure components and liquid mixtures and the relevant results obtained are reviewed.

Lee and Chen (1993) developed two group-contribution-based ANNs to some thermodynamic properties of different hydrocarbons. The same authors indicated in their study that the networks have been tested on 29 substances that were not used before in the training phase. Overall absolute average deviation values (*AAD*s) of 6.9 %, 7.7 %, and 7.1 % were obtained for the prediction of the normal boiling points, the critical temperatures, and the critical volumes, respectively. Whereas, relatively high error values of 14.1 % and 14.9 % were reported for the critical pressures and the acentric factors. Nashawi and Elgibaly (1999) developed an ANN to estimate the absolute viscosity of organic compounds having different structures. They tried five different networks by changing the input variables. The selected network that gave the lowest error value of 13.03 % had the lowest number of input variables. These results were obtained on the basis of 35 data points that were not used in the training of the networks. Nashawi and Elgibaly (1999) indicated in their conclusions to the fact that the developed network can easily be integrated to liquid mixtures at different temperature levels without any further explanation.

Suzuki *et al.* (2001) conducted a study on the prediction of pure component viscosities. A large database containing a variety of organic compounds was utilized in the training, testing and validation of the networks. Two networks with different structures were developed; one based on the compound temperature dependence and the other one did not take the temperature dependence into account. The results obtained in the Suzuki *et al*. (2001) study indicated the possibility of developing a network that is capable of reliably estimating liquid viscosities over a wide range of temperatures for compounds with different chemical structures.

The recent research work by Murata *et al*. (2004) dealt with the prediction of the viscosity of liquids and liquid mixtures depending only on the chemical structures. The three layer neural network developed in their study enabled the prediction of the viscosity of a wide selection of hydrocarbons over a temperature range approximately from the melting point to the bubble point. The average and the maximum deviations reported in their study of viscosity prediction were 9.5 and 14.3 %, respectively. Murata *et al*. (2004) indicated that the prediction of viscosity using the NN was only for the case of pure components. For binary mixtures, they proposed a predictive method using ASOG-VISCO group interaction parameters.

For liquid mixtures on the other hand, fewer studies were reported. Lee *et al*. (1994) developed three different ANNs for predicting the density and absolute viscosity of multi-component polar liquid mixtures in the temperature range of 303.15 through 323.15 K. The three networks were capable of predicting the densities of both binary and ternary aqueous solutions to within ± 1 %. For the case of viscosity, the prediction was comparable to the corresponding states model by Lee and Wei (1993). Testing the networks was performed on binary and ternary mixtures as the availability of experimental data on multi-component liquid mixtures was limited. Lee *et al*. (1994)

reported in their study that the prediction of viscosity is much more complicated than the prediction of the density.

Finally, Mehlman *et al*. (1998) developed three separate neural networks to predict, the density, viscosity, and refractive index of multi-component liquid solvents (up to four components). The networks were trained on binary data with mole fractions of pure components involved in each mixture as inputs. The temperature was not included as an input to the networks unlike the study of Lee *et al*. (1994). The results of the study showed an overall *AAD* (%) of less than 1 % in the case of density and refractive index for all examined systems, whereas the *AAD* (%) ranged from 1 % to 15 % in the case of viscosity prediction. Mehlman *et al*. (1998) explanation for such a relatively large error values in case of viscosity predictions is the presence of highly non-liner viscosity surface which made it more difficult to predict. The study also referred to that the predictive capability of the networks showed a strong dependence of the network on the solvent system without providing the reasons for such dependence.

CHAPTER 3

EXPERIMENTAL EQUIPMENT AND PROCEDURES

3.1 General

The purpose of the present chapter is to describe the materials used to prepare the different solutions and the experimental equipment used to measure the densities and viscosities of all pure components as well as the corresponding mixtures involved in the present study. Furthermore, the chapter deals with detailed explanation of the procedures and the steps taken to carry out the experiments.

3.2 Materials

The pure components used in composing the systems involved in the present study were purchased from Sigma-Aldrich Chemical Company. These components are: benzene, toluene, ethylbenzene, heptane, and cyclooctane.

Two sets of compounds were used in the equipment calibration. The first set was used in the density meter calibration. These were: p-xylene and undecane which were supplied by Aldrich Chemical Company, and 1-hexanol and 1-heptanol which were supplied by Fluka Chimika Company. The second set used in the calibration of the viscometers included four standard fluids namely; N0.4, N0.8, N1.0, and N2.0 which were purchased from Cannon Instruments Company.

The manufacture’s stated purities of the chemicals used for calibrating the density meter were 99+%. Further analysis of all pure chemicals was performed in our laboratory to confirm the stated purities. An HP5890 Gas Chromatograph was used for that purpose. It is equipped with an FID and an HP1 (cross-linked methyl silicon gum) column of the dimensions; 30 m × 0.53 mm × 2.65 μm (length × diameter × film thickness). The column is covered by US Patent # 4,293,415. The results of the chromatographic analysis showed that the purities of all chemicals exceeded their corresponding stated values. All chemicals are used as it is with out further purification. Table 3.1 reports all the pure components along with their supplier, their stated and checked purities.

It should be pointed out here that, double-distilled water was used in the density meter calibration in addition to the other chemicals. The double-distilled water was prepared in our laboratory and kept in sealed glass vials until used.

3.3 <u>Preparation of Solutions</u>

The investigated solutions were prepared gravimetrically following the procedure suggested by Asfour (1979). In that procedure, 30 mL glass vials were first washed with a special detergent solution purchased from Fisher Scientific, rinsed with de-ionized water and then acetone. The vials then were placed in an oven to dry at 130 °C. The vials, after drying, were stored in desiccators until used.

The vials were fitted with Tuf-bond, Teflon/silicone, discs and aluminum seals to minimize evaporation losses that may lead to composition changes. The glass vials, the Tuf-bond, Teflon/silicone, discs, and the aluminum seals were all supplied by Chromatographic Specialties Ltd.

Table 3.1: Specifications of the Chemicals used in the Present Study

Supplier	**Compound**	**Specification mol%**	**GC analysis, mass %**
Aldrich Chemical Company	Benzene	99+%	99.95
	Toluene	99+%	99.04
	Ethylbenzene	99+%	99.43
	Heptane	99+%	99.53
	Cyclooctane	99+%	99.64
	p-Xylene	99+%	99.24
	Undecane	99+%	99.94
Fluka-Chemika	1-Hexanol	≥ 99% (GC)	99.12
	1-Heptanol	≥ 99% (GC)	99.82

During the preparation of each mixture, a glass vial was first weighed empty and its weight was recorded. Then the pure components were injected in the glass vials starting with the lower vapor pressure component. The weight of the glass vial containing the components was recorded after each injection. The injection was performed using a 0.01 L hypodermic syringes fitted with size G23 and G24 needles. All syringes, needles, and beakers were washed and dried as described before.

All individual pure components were weighed on a Mettler HK 160 balance with a precision of $\pm 1\times 10^{-7}$ kg.

All prepared solution mixtures were kept in the refrigerator until used.

3.4 **Density Measurement**

3.4.1 **Equipment**

An Anton Paar type density meter was employed in the present study for measuring the densities of the pure components and all prepared mixtures. A pictorial view of the density meter is shown in Figure 3.1. It consists of a processing unit, DMA 60, and a remote measuring cell (into which the samples are injected), DMA 602 (that contains a hollow U-shape oscillator tube). The instrument is working under the principle of measuring the change of the natural frequency of the oscillator tube as it is filled with different fluids. At each temperature, when a sample is introduced into the U-shaped sample tube (oscillator), a change in the mass of the oscillator is caused. This results in a change of the frequency of the oscillator.

Figure 3.1: Pictorial View of the Precision Density Meter

The period of oscillation of the tube is displayed to 6 decimal places. The temperature of the sample contained in the oscillator tube is controlled by an N4B Haake circulator fitted with an IPTS-68 platinum temperature sensor. De-ionized water is used as the circulating fluid inside the water bath; its temperature is displayed digitally. The density meter temperatures were always checked by an Omega electronic thermometer with a resolution of ± 0.005 °C fitted with a calibrated ITS-90 platinum temperature sensor. The accuracy of the Omega electronic thermometer is ± 0.01 °C.

The density meter set-up is also connected to a refrigeration unit for the purpose of taking measurements below the ambient laboratory temperature.

Density is a strong function of temperature. Asfour (1979) recommended placing the DMA 60/DMA 602 density meter system into a temperature controlled wooden chamber in which the temperature fluctuations were kept to within ± 0.5 °C. This would lead to better stability in density meter readings. The density meter employed in the present study covers the range of densities of 0.5 to 2 kg/L with a precision of $\pm 1.5\times 10^{-6}$ kg/L.

3.4.2 Procedures

Before sample injection, the U-shape sample tube has to be washed with ethanol many times then dried by means of the air pump installed in the DMA 602 unit until constant readings are displayed. Samples were withdrawn from the glass vials using 0.002 L hypodermic syringe fitted with a thin G24 needle. After removing the needle, the sample was injected carefully into the measuring tube. The sample had to be injected very slowly to prevent the formation of any air bubbles in the injected sample which would result in erroneous readings. Following injection, the sample is left for, a 20 -30 min time interval in order to reach thermal equilibrium.

After equilibrium is reached, 10 consecutive readings were recorded. The ten consecutive readings should only differ by one or two digits, as a maximum, in the six decimal place. The average reading is then calculated and reported. The procedure was repeated for each sample at the four investigated temperatures. The density meter readings are reported in Appendix A.

3.4.3 Density meter equation

The density meter supplier suggested the following three-parameter equation which relates the frequency of oscillation of the U-shaped tube and the density:

$$\rho = \frac{A\tau^2}{1 - B\tau^2} - C \tag{3.1}$$

Compounds with accurately known density values at the temperatures of interest indicated earlier, were employed in calibrating the density meter. The densities of the compounds used for the calibration and the corresponding density meter readings are fitted to equation (3.1) using the least-squares technique. This results in the determination of the values of the constants *A*, *B*, and *C* at each temperature level.

Density meter calibration information and results as well as the values of the parameters *A*, *B*, and *C* are reported in Chapter 4.

3.5 <u>Viscosity Measurement</u>

3.5.1 <u>Equipment</u>

Cannon-Ubbelohde capillary type viscometers supplied by Cannon Instrument Company were employed in the present study for the measurement of kinematic viscosities. The viscometer shown in Figure 3.2 has many advantages as described earlier by Asfour (1979). Different sizes of viscometers were used in order to cover the viscosity range of interest.

Four viscometers of size 25, namely; 25B349, 25B350, 25B365, and 25B366, were employed for measuring kinematic viscosities of solutions having viscosities in the range 0.5 through 2 cSt. Four other viscometers of size 50, namely; 50B183, 50B159, 50B830, and 50B831, were employed for measuring the kinematic viscosities of solutions having viscosities in the range 0.8 to 4 cSt. The uncertainty in viscosity measurement was about ± 0.1 %.

During viscosity measurement, the viscometers were placed in a CT-1000 constant temperature bath purchased from Cannon Instrument Company. A pictorial view of the CT-1000 holding the viscometers is shown in Figure 3.3. This temperature bath is capable of keeping the temperature fluctuations to within ± 0.005 °C. Again, the Omega digital thermometer was used for continuous monitoring of the bath temperature.

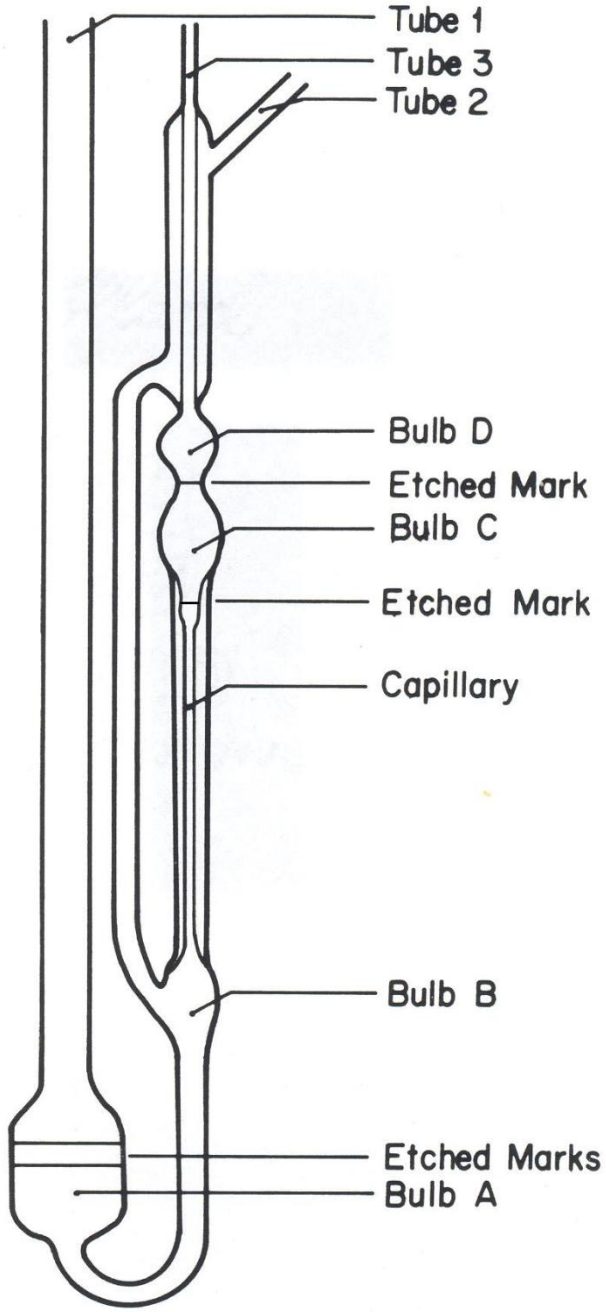

Figure 3.2: The Cannon-Ubbelohde Viscometer

3.5.2 Procedures

The capillary glass viscometer was cleaned by washing them thoroughly with the special surfactant purchased from Fisher Scientific, rinsed thoroughly with de-ionized water, then with acetone. They were then dried in an oven at 130° C for about 10 to 15 minutes maximum before they were used.

The viscometers placed vertically in the water bath supported by a plastic holder. Samples were then poured carefully into the viscometers until the liquid level is between the two etched marks in bulb A as shown in Figure 3.2. After adjusting the temperature, the samples are allowed to reach thermal equilibrium for about 20 minutes.

Viscosity measurements were taken by closing the opening of tube 2 by one finger and applying suction to the opening of tube 3 using a pipette suction bulb which draws the liquid up into bulbs C and D (this had to be done carefully to prevent entrapping of air bubbles) until the liquid level reached the middle of bulb D. The, suction is then removed from tube 3 and the finger is removed from tube 2. The liquid will start to move down; the stop watch was clicked when the liquid meniscus reached the upper etched mark of bulb C and clicked again when the level of the liquid reached the lower etched mark of the same bulb.

This is known as the efflux time. A highly accurate digital set of stop watches was used for measuring the efflux time. To minimize human errors, three efflux time readings that agreed to within ± 0.1 % were recorded. The average value of those readings was calculated and reported.

Figure 3.3: Pictorial View of the Constant Temperature Bath

3.5.3 Viscosity equation

The measured efflux time is related to the kinematic viscosity through the following equation proposed by the manufacturer:

$$\nu = C\,t - \frac{E}{t^{n}} \qquad (3.2)$$

where ν is the kinematic viscosity , t is the efflux time of the sample measured in seconds (the average value of the three readings is used). In the present study viscometers with trumpt-shaped ends were employed, hence the value of n is set equal to 2.

Again, the least-square fitting technique was used to determine the values of the constants C and E contained in equation (3.2). The standard calibration fluids indicated earlier in Section 3.2 were used to determine the values of the constants C and E.

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 General

The quinary system investigated in the present study; *viz.*, benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4) + cyclooctane (5) is selected as a regular type solution with differences in the structure and shape of the constituents of the system. In addition, the kinemtic viscosities and densities of all its corresponding quaternary, ternary, and binary sub-systems were measured over the entire composition range and at 293.15 K, 298.15 K, 308.15 K, and 313.15 K. Table 4.1 presents all the systems investigated in the present study. The raw data on all the systems studied at all the temperature levels are reported in Appendix A.

Density and viscosity data over the entire composition range and at different temperatures for a variety of systems are available in the literature. Much fewer ternary system data are also available in the literature. Data on quaternary systems are very scarce in the literature. Our laboratory is the only laboratory in the world that has been reporting density and viscosity-composition data for quinary systems. Such data represent valuable contributions to the literature for their own value as well as for use in developing and testing new viscosity predictive models.

Table 4.1: List of Systems Investigated in the Present Study

a) Quinary System

Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5)

b) Quaternary Systems

1 Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4).
2 Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4).
3 Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).
4 Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).
5 Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4).

c) Ternary Systems

1 Benzene (1) + Toluene (2) + Heptane (3).
2 Benzene (1) + Ethylbenzene (2) + Heptane (3).
3 Toluene (1) + Ethylbenzene (2) + Heptane (3).
4 Benzene (1) + Toluene (2) + Ethylbenzene (3).
5 Benzene (1) + Toluene (2) + Cyclooctane (3).
6 Toluene (1) + Ethylbenzene (2) + Cyclooctane (3).
7 Benzene (1) + Ethylbenzene (2) + Cyclooctane (3).
8 Benzene (1) + Heptane (2) + Cyclooctane (3).
9 Toluene (1) + Heptane (2) + Cyclooctane (3).
10 Ethylbenzene (1) + Heptane (2) + Cyclooctane (3).

d) Binary Systems

1 Benzene (1) + Toluene (2).
2 Toluene (1) + Ethylbenzene (2).
3 Toluene (1) + Heptane (2).
4 Ethylbenzene (1) + Heptane (2).
5 Benzene (1) + Ethylbenzene (2).
6 Benzene (1) + Heptane (2).
7 Benzene (1) + Cyclooctane (2).
8 Toluene (1) + Cyclooctane (2).
9 Ethylbenzene (1) + Cyclooctane (2).
10 Heptane(1) + Cyclooctane(2)

4.2 Density Meter Calibration Data

Calibration of the density meter was performed according to the procedures described earlier in Chapter 3. Calibration was performed at the four temperatures. The literature density values of the fluids used for the calibration and the corresponding density meter readings are reported in Table 4.2. Those reported data were fitted into the density meter equation to calculate the equation constants at each temperature. Values of the constants and standard deviation of the fit are also reported in Table 4.2.

Complete error analysis for the density measurements are reported in Appendix B.

4.3 Viscometers Calibration Data

A set of eight Cannon-Ubbelohde viscometers were employed in the present study. The viscometers were calibrated at the four temperatures of interest in the present study. The standard calibration fluids covering the kinematic viscosity range of the components employed in the present study along with their measured efflux time, equation parameters, standard deviation of the fit are reported in Table 4.3. The procedure explained earlier in Chapter 3 was followed.

Detailed error Analysis for viscosity measurements are also reported in Appendix B.

Table 4.2: Density Meter Calibration Data

Substance	Temperature = 293.15 K		Source
	Density, kg/L	Density meter reading, sec	
p-Xylene	0.861	0.732298	Timmermans 1950
D D water	0.998234	0.75699	Perry, 1997
Undecane	0.7402	0.709843	TRC Tables 1988
N0.8	0.8667	0.733234	Cannon Instr. Co.
1-Hexanol	0.8198	0.724529	TRC Tables 1988
1-Heptanol	0.8223	0.725184	TRC Tables 1988

Parameters of the Density Meter (Equation 3.1)

A = 4.068113

B = -0.0824188

C = 1.227824

Standard Deviation of Fit (kg/L) = 3.6×10^{-4}

Substance	Temperature = 298.15 K		Source
	Density, kg/L	Density meter reading, sec	
p-Xylene	0.85666	0.731261	Timmermans 1950
D D water	0.99707	0.756531	Perry, 1997
Undecane	0.7365	0.70891	TRC Tables 1988
N0.8	0.8624	0.732208	Cannon Instr. Co.
1-Hexanol	0.8162	0.72363	TRC Tables 1988
1-Heptanol	0.8186	0.724295	TRC Tables 1988

Parameters of the density meter (Equation 3.1)

A = 3.959453

B = -0.05530668

C = 1.199485

Standard Deviation of Fit (kg/L) = 3.9×10^{-4}

Table 4.2 (Cont'd.): Density Meter Calibration Data

Substance	Temperature = 308.15 K		Source
	Density, kg/L	Density meter reading, sec	
p-Xylene	0.8478	0.729192	Timmermans 1950
D D water	0.994061	0.755504	Perry, 1997
Undecane	0.7291	0.707054	TRC Tables 1988
N0.8	0.8538	0.730165	Cannon Instr. Co.
1-Hexanol	0.8080	0.721838	TRC Tables 1988
1-Heptanol	0.8117	0.722523	TRC Tables 1988

<u>Parameters of the density meter (Equation 3.1)</u>

A = 3.808087

B = -0.01681595

C = 1.158852

Standard Deviation of Fit (kg/L) = 2.2×10^{-4}

Substance	Temperature = 313.15 K		Source
	Density, kg/L	Density meter reading, sec	
p-Xylene	0.8436	0.728157	Timmermans 1950
D D water	0.9922497	0.754908	Perry, 1997
Undecane	0.7255	0.706123	TRC Tables 1988
N0.8	0.8494	0.729128	Cannon Instr. Co.
1-Hexanol	0.8054	0.720918	TRC Tables 1988
1-Heptanol	0.8077	0.72163	TRC Tables 1988

<u>Parameters of the density meter (Equation 3.1)</u>

A = 3.811508

B = -0.01729367

C = 1.158681

Standard Deviation of Fit (kg/L) = 4.7×10^{-4}

Table 4.3: Viscometers Calibration Data

T = 293.15 K

Viscometer	Viscosity Standard	Efflux Time (s)	Standard Viscosity $\times 10^6$ (m^2/s)	Parameters		Standard Deviation $\times 10^9$ (m^2/s)
				$C \times 10^9$ (m/s^2)	$E \times 10^6$ ($m^2.s$)	
25 (B349)	N 0.4	273.75	0.4822	0.001768	110.30	0.6
	N 0.8	427.9	0.7568			
	N 1.0	719.83	1.272			
25 (B350)	N 0.4	276.76	0.4822	0.001748	160.30	0.7
	N 0.8	433.97	0.7568			
	N 1.0	727.36	1.272			
25 (B365)	N 0.4	264.91	0.4822	0.001852	641.50	1.5
	N 0.8	411.91	0.7568			
	N 1.0	687.05	1.272			
25 (B366)	N 0.4	255.71	0.4822	0.001913	540.40	2.7
	N 0.8	399.51	0.7568			
	N 1.0	664.67	1.272			
50 (B158)	N 0.8	176.01	0.7568	0.004363	316.60	1.6
	N 1.0	291.86	1.272			
	N 2.0	664.65	2.898			
50 (B3159)	N 0.8	193.92	0.7568	0.003957	373.60	1.1
	N 1.0	321.95	1.272			
	N 2.0	732.73	2.898			
50 (B830)	N 0.8	178.61	0.7568	0.004248	5.550	3.3
	N 1.0	298.23	1.272			
	N 2.0	682.65	2.898			
50 (B831)	N 0.8	187.69	0.7568	0.004099	413.30	1.5
	N 1.0	310.79	1.272			
	N 2.0	707.41	2.898			

Table 4.3 (Cont'd.): Viscometers Calibration Data

T = 298.15 K

Viscometer	Viscosity Standard	Efflux Time (s)	Standard Viscosity $\times 10^6$ (m^2/s)	Parameters		Standard Deviation $\times 10^9$ (m^2/s)
				$C \times 10^9$ (m/s^2)	$E \times 10^6$ ($m^2.s$)	
25 (B349)	N 0.4	262.95	0.4617	0.001764	121.40	0.05
	N 0.8	405.50	0.7152			
	N 1.0	672.29	1.185			
25 (B350)	N 0.4	265.90	0.4617	0.001744	149.90	0.01
	N 0.8	410.68	0.7152			
	N 1.0	679.57	1.185			
25 (B365)	N 0.4	253.72	0.4617	0.001836	371.01	0.32
	N 0.8	393.43	0.7152			
	N 1.0	644.67	1.185			
25 (B366)	N 0.4	245.12	0.4617	0.0019003	278.40	0.1
	N 0.8	378.18	0.7152			
	N 1.0	623.58	1.185			
50 (B158)	N 0.8	167.10	0.7152	0.00435108	351.30	0.13
	N 1.0	273.90	1.185			
	N 2.0	602.66	2.622			
50 (B3159)	N 0.8	183.33	0.7152	0.0039421	262.11	0.06
	N 1.0	301.55	1.185			
	N 2.0	665.20	2.622			
50 (B830)	N 0.8	169.29	0.7152	0.0042433	55.094	0.2
	N 1.0	278.57	1.185			
	N 2.0	618.24	2.622			
50 (B831)	N 0.8	176.03	0.7152	0.004089	133.40	0.05
	N 1.0	290.00	1.185			
	N 2.0	641.39	2.622			

Table 4.3 (Cont'd.): Viscometers Calibration Data

T = 308.15 K

Viscometer	Viscosity Standard	Efflux Time (s)	Standard Viscosity $\times 10^6$ (m^2/s)	Parameters		Standard Viscosity $\times 10^6$ (m^2/s)
				$C \times 10^9$ (m/s^2)	E ×106 ($m^2.s$)	
25 (B349)	N 0.4	241.66	0.4248	0.001762	38.17	0.04
	N 0.8	364.71	0.6428			
	N 1.0	590.07	1.039			
25 (B350)	N 0.4	245.02	0.4248	0.001735	-19.34	0.12
	N 0.8	369.30	0.6428			
	N 1.0	599.26	1.039			
25 (B365)	N 0.4	233.41	0.4248	0.0018324	178.89	0.07
	N 0.8	352.15	0.6428			
	N 1.0	567.04	1.039			
25 (B366)	N 0.4	217.04	0.4248	0.001889	-631.70	0.3
	N 0.8	339.87	0.6428			
	N 1.0	547.87	1.039			
50 (B158)	N 0.8	149.94	0.6428	0.004338	191.80	0.16
	N 1.0	240.86	1.039			
	N 2.0	503.88	2.186			
50 (B3159)	N 0.8	165.12	0.6428	0.003938	229.70	0.19
	N 1.0	265.41	1.039			
	N 2.0	555.05	2.186			
50 (B830)	N 0.8	152.11	0.6428	0.0042435	42.24	0.16
	N 1.0	244.45	1.039			
	N 2.0	515.39	2.186			
50 (B831)	N 0.8	160.07	0.6428	0.004092	284.70	0.19
	N 1.0	254.31	1.039			
	N 2.0	534.76	2.186			

Table 4.3 (Cont'd.): Viscometers Calibration Data

T = 313.15 K

Viscometer	Viscosity Standard	Efflux Time (s)	Standard Viscosity $\times 10^6$ (m^2/s)	Parameters		Standard Viscosity $\times 10^6$ (m^2/s)
				$C \times 10^9$ (m/s^2)	$E \times 10^6$ ($m^2.s$)	
25 (B349)	N 0.4	232.45	0.4085	0.001763	63.58	0.005
	N 0.8	346.86	0.6109			
	N 1.0	555.30	0.9785			
25 (B350)	N 0.4	235.49	0.4085	0.001737	27.06	0.005
	N 0.8	351.81	0.6109			
	N 1.0	563.44	0.9785			
25 (B365)	N 0.4	224.49	0.4085	0.001832	162.50	0.09
	N 0.8	335.01	0.6109			
	N 1.0	534.12	0.9785			
25 (B366)	N 0.4	217.04	0.4085	0.001897	167.12	0.04
	N 0.8	323.16	0.6109			
	N 1.0	515.88	0.9785			
50 (B158)	N 0.8	142.77	0.6109	0.004337	181.16	0.11
	N 1.0	226.84	0.9785			
	N 2.0	463.52	2.010			
50 (B3159)	N 0.8	157.27	0.6109	0.003937	204.93	0.016
	N 1.0	249.47	0.9785			
	N 2.0	510.78	2.010			
50 (B830)	N 0.8	145.04	0.6109	0.004244	73.153	0.21
	N 1.0	230.10	0.9785			
	N 2.0	473.96	2.010			
50 (B831)	N 0.8	150.64	0.6109	0.004093	123.34	0.04
	N 1.0	239.42	0.9785			
	N 2.0	491.26	2.010			

4.4 Density-Composition Data

Ten consecutive density meter readings were taken with differences in the last two digits and an average value was taken in each case and recorded. The raw density-composition data are reported in Appendix A. The average value was then substituted in equation (3.1) in order to calculate the density of the solution. This procedure was repeated for the quinary system and all corresponding quaternary, ternary, and binary sub-systems. Tables 4.4 through 4.29 report density-composition data for all investigated systems at the different temperatures.

4.5 Kinematic Viscosity-Composition Data

The kinematic-viscosity composition data were collected over the entire composition range for all systems. Results are reported in Tables 4.4 through 4.29. The average value of three efflux time readings was used in the calculation of the kinematic viscosities. In addition, kinematic viscosities along with density values were utilized to determine the corresponding absolute viscosity for each system.

Table 4.4: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quinary System; Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Mole Fraction, x_4	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K						
1.0000	0.0000	0.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.0000	0.0000	0.8671	0.6837	0.5928
0.0000	0.0000	1.0000	0.0000	0.8671	0.7773	0.6740
0.0000	0.0000	0.0000	1.0000	0.6839	0.6008	0.4109
0.0000	0.0000	0.0000	0.0000	0.8362	2.9960	2.5052
0.1751	0.2765	0.2601	0.1261	0.8318	0.7733	0.6433
0.3967	0.1239	0.2677	0.0894	0.8421	0.7593	0.6394
0.2472	0.1496	0.2656	0.2867	0.8013	0.6639	0.5320
0.2945	0.2512	0.1300	0.1952	0.8171	0.7172	0.5860
0.1354	0.3236	0.2145	0.3025	0.7990	0.6413	0.5124

Table 4.4 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quinary System; Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Mole Fraction, x_4	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K						
1.0000	0.0000	0.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.0000	0.0000	0.8624	0.6439	0.5552
0.0000	0.0000	1.0000	0.0000	0.8628	0.7321	0.6316
0.0000	0.0000	0.0000	1.0000	0.6798	0.5726	0.3892
0.0000	0.0000	0.0000	0.0000	0.8320	2.6786	2.2285
0.1751	0.2765	0.2601	0.1261	0.8273	0.7268	0.6013
0.3967	0.1239	0.2677	0.0894	0.8374	0.7149	0.5987
0.2472	0.1496	0.2656	0.2867	0.7967	0.6280	0.5003
0.2945	0.2512	0.1300	0.1952	0.8125	0.6767	0.5498
0.1354	0.3236	0.2145	0.3025	0.7944	0.6082	0.4832

Table 4.4 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quinary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5)

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Mole Fraction, x_4	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K						
1.0000	0.0000	0.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.0000	0.0000	0.8528	0.5792	0.4940
0.0000	0.0000	1.0000	0.0000	0.8537	0.6621	0.5652
0.0000	0.0000	0.0000	1.0000	0.6713	0.5209	0.3497
0.0000	0.0000	0.0000	0.0000	0.8236	2.1887	1.8026
0.1751	0.2765	0.2601	0.1261	0.8181	0.6561	0.5368
0.3967	0.1239	0.2677	0.0894	0.8279	0.6406	0.5303
0.2472	0.1496	0.2656	0.2867	0.7875	0.5669	0.4464
0.2945	0.2512	0.1300	0.1952	0.8031	0.6142	0.4933
0.1354	0.3236	0.2145	0.3025	0.7852	0.5519	0.4333

Table 4.4 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quinary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Mole Fraction, x_4	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K						
1.0000	0.0000	0.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.0000	0.0000	0.8483	0.5512	0.4676
0.0000	0.0000	1.0000	0.0000	0.8495	0.6231	0.5294
0.0000	0.0000	0.0000	1.0000	0.6671	0.4990	0.3329
0.0000	0.0000	0.0000	0.0000	0.8197	1.9958	1.6360
0.1751	0.2765	0.2601	0.1261	0.8137	0.6205	0.5049
0.3967	0.1239	0.2677	0.0894	0.8452	0.6083	0.5141
0.2472	0.1496	0.2656	0.2867	0.7831	0.5408	0.4235
0.2945	0.2512	0.1300	0.1952	0.7987	0.5799	0.4632
0.1354	0.3236	0.2145	0.3025	0.7808	0.5268	0.4113

Table 4.5: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K					
1.0000	0.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.0000	0.8671	0.6837	0.5928
0.0000	0.0000	1.0000	0.8671	0.7773	0.6740
0.0000	0.0000	0.0000	0.8362	2.9960	2.5052
0.1305	0.3223	0.2704	0.8792	0.9039	0.7730
0.1697	0.3713	0.3259	0.8552	0.7857	0.6771
0.2558	0.2331	0.1754	0.8618	0.9593	0.8187
0.3179	0.2695	0.2717	0.8534	0.8027	0.6922
0.1267	0.3705	0.2633	0.8624	0.8623	0.7387
0.2712	0.1615	0.3319	0.8567	0.8802	0.7550

Table 4.5 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K					
1.0000	0.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.0000	0.8624	0.6439	0.5552
0.0000	0.0000	1.0000	0.8628	0.7321	0.6316
0.0000	0.0000	0.0000	0.8320	2.6786	2.2285
0.1305	0.3223	0.2704	0.8507	0.8492	0.7224
0.1697	0.3713	0.3259	0.8572	0.7452	0.6388
0.2558	0.2331	0.1754	0.8488	0.8983	0.7625
0.3179	0.2695	0.2717	0.8577	0.7552	0.6478
0.1267	0.3705	0.2633	0.8522	0.8121	0.6920
0.2712	0.1615	0.3319	0.8532	0.8257	0.7045

Table 4.5 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System; Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K					
1.0000	0.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.0000	0.8528	0.5792	0.4940
0.0000	0.0000	1.0000	0.8537	0.6621	0.5652
0.0000	0.0000	0.0000	0.8236	2.1887	1.8026
0.1305	0.3223	0.2704	0.8416	0.7562	0.6364
0.1697	0.3713	0.3259	0.8478	0.6701	0.5681
0.2558	0.2331	0.1754	0.8397	0.7925	0.6655
0.3179	0.2695	0.2717	0.8482	0.6751	0.5726
0.1267	0.3705	0.2633	0.8429	0.7267	0.6125
0.2712	0.1615	0.3319	0.8440	0.7315	0.6174

Table 4.5 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, × 10^6 (m^2/s)	Absolute Viscosity, η, × 10^3(Pa.s)
Temperature, T = 313.15 K					
1.0000	0.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.0000	0.8483	0.5512	0.4676
0.0000	0.0000	1.0000	0.8495	0.6231	0.5294
0.0000	0.0000	0.0000	0.8197	1.9958	1.6360
0.1305	0.3223	0.2704	0.8374	0.7148	0.5985
0.1697	0.3713	0.3259	0.8434	0.6364	0.5367
0.2558	0.2331	0.1754	0.8354	0.7497	0.6263
0.3179	0.2695	0.2717	0.8437	0.6372	0.5376
0.1267	0.3705	0.2633	0.8386	0.6891	0.5779
0.2712	0.1615	0.3319	0.8396	0.6935	0.5822

Table 4.6: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K					
1.0000	0.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.0000	0.8671	0.6837	0.5928
0.0000	0.0000	1.0000	0.8671	0.7773	0.6740
0.0000	0.0000	0.0000	0.6839	0.6008	0.4109
0.1368	0.3144	0.2583	0.8022	0.6361	0.5103
0.1931	0.3718	0.3029	0.8368	0.6739	0.5639
0.2915	0.2175	0.1558	0.7911	0.6167	0.4878
0.3284	0.2622	0.2680	0.8346	0.6686	0.5581
0.1549	0.3507	0.2556	0.8130	0.6440	0.5236
0.1991	0.1632	0.3634	0.8063	0.6466	0.5213

Table 4.6 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K					
1.0000	0.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.0000	0.8624	0.6439	0.5552
0.0000	0.0000	1.0000	0.8628	0.7321	0.6316
0.0000	0.0000	0.0000	0.6798	0.5726	0.3892
0.1368	0.3144	0.2583	0.7976	0.6021	0.4803
0.1931	0.3718	0.3029	0.8321	0.6360	0.5292
0.2915	0.2175	0.1558	0.7864	0.5841	0.4594
0.3284	0.2622	0.2680	0.8299	0.6307	0.5234
0.1549	0.3507	0.2556	0.8083	0.6150	0.4971
0.1991	0.1632	0.3634	0.8017	0.6123	0.4909

Table 4.6 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K					
1.0000	0.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.0000	0.8528	0.5792	0.4940
0.0000	0.0000	1.0000	0.8537	0.6621	0.5652
0.0000	0.0000	0.0000	0.6713	0.5209	0.3497
0.1368	0.3144	0.2583	0.7883	0.5537	0.4365
0.1931	0.3718	0.3029	0.8226	0.5740	0.4722
0.2915	0.2175	0.1558	0.7770	0.5290	0.4110
0.3284	0.2622	0.2680	0.8203	0.5750	0.4717
0.1549	0.3507	0.2556	0.7990	0.5535	0.4422
0.1991	0.1632	0.3634	0.7924	0.5535	0.4386

Table 4.6 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K					
1.0000	0.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.0000	0.8483	0.5512	0.4676
0.0000	0.0000	1.0000	0.8495	0.6231	0.5294
0.0000	0.0000	0.0000	0.6671	0.4990	0.3329
0.1368	0.3144	0.2583	0.7840	0.5214	0.4088
0.1931	0.3718	0.3029	0.8181	0.5471	0.4476
0.2915	0.2175	0.1558	0.7725	0.5053	0.3903
0.3284	0.2622	0.2680	0.8157	0.5414	0.4416
0.1549	0.3507	0.2556	0.7945	0.5280	0.4195
0.1991	0.1632	0.3634	0.7880	0.5288	0.4167

Table 4.7: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K					
1.0000	0.0000	0.0000	0.8671	0.6837	0.5928
0.0000	1.0000	0.0000	0.8671	0.7773	0.6740
0.0000	0.0000	1.0000	0.6839	0.6008	0.4109
0.0000	0.0000	0.0000	0.8362	2.9960	2.5052
0.1448	0.3462	0.2180	0.8108	0.8660	0.7022
0.1970	0.4056	0.2576	0.8073	0.7307	0.5899
0.2901	0.2383	0.1379	0.8243	0.9081	0.7485
0.3428	0.2812	0.2290	0.8116	0.7380	0.5989
0.1459	0.3981	0.2181	0.8125	0.8131	0.6606
0.2969	0.1703	0.2757	0.7994	0.8058	0.6441

Table 4.7 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System; Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K					
1.0000	0.0000	0.0000	0.8624	0.6439	0.5552
0.0000	1.0000	0.0000	0.8628	0.7321	0.6316
0.0000	0.0000	1.0000	0.6798	0.5726	0.3892
0.0000	0.0000	0.0000	0.8320	2.6786	2.2285
0.1448	0.3462	0.2180	0.8065	0.8160	0.6581
0.1970	0.4056	0.2576	0.8029	0.6983	0.5606
0.2901	0.2383	0.1379	0.8199	0.8554	0.7014
0.3428	0.2812	0.2290	0.8072	0.6985	0.5638
0.1459	0.3981	0.2181	0.8081	0.7725	0.6243
0.2969	0.1703	0.2757	0.7950	0.7595	0.6038

Table 4.7 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K					
1.0000	0.0000	0.0000	0.8528	0.5792	0.4940
0.0000	1.0000	0.0000	0.8537	0.6621	0.5652
0.0000	0.0000	1.0000	0.6713	0.5209	0.3497
0.0000	0.0000	0.0000	0.8236	2.1887	1.8026
0.1448	0.3462	0.2180	0.7978	0.7316	0.5836
0.1970	0.4056	0.2576	0.7939	0.6336	0.5030
0.2901	0.2383	0.1379	0.8110	0.7583	0.6149
0.3428	0.2812	0.2290	0.7982	0.6338	0.5059
0.1459	0.3981	0.2181	0.7993	0.6966	0.5568
0.2969	0.1703	0.2757	0.7862	0.6797	0.5344

Table 4.7 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, × 10^6 (m^2/s)	Absolute Viscosity, η, × 10^3(Pa.s)
Temperature, T = 313.15 K					
1.0000	0.0000	0.0000	0.8483	0.5512	0.4676
0.0000	1.0000	0.0000	0.8495	0.6231	0.5294
0.0000	0.0000	1.0000	0.6671	0.4990	0.3329
0.0000	0.0000	0.0000	0.8197	1.9958	1.6360
0.1448	0.3462	0.2180	0.7937	0.6924	0.5495
0.1970	0.4056	0.2576	0.7898	0.6033	0.4765
0.2901	0.2383	0.1379	0.8069	0.7201	0.5811
0.3428	0.2812	0.2290	0.7939	0.6008	0.4769
0.1459	0.3981	0.2181	0.7952	0.6629	0.5271
0.2969	0.1703	0.2757	0.7820	0.6471	0.5060

Table 4.8: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K					
1.0000	0.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.0000	0.8671	0.7773	0.6740
0.0000	0.0000	1.0000	0.6839	0.6008	0.4109
0.0000	0.0000	0.0000	0.8362	2.9960	2.5052
0.1387	0.3377	0.2186	0.8100	0.8837	0.7158
0.1816	0.3964	0.2742	0.8032	0.7334	0.5890
0.2966	0.2257	0.1294	0.8255	0.9405	0.7763
0.3306	0.2852	0.2292	0.8104	0.7471	0.6055
0.1425	0.3949	0.2127	0.8129	0.8270	0.6723
0.2984	0.1696	0.2736	0.7983	0.8134	0.6493

Table 4.8 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K					
1.0000	0.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.0000	0.8628	0.7321	0.6316
0.0000	0.0000	1.0000	0.6798	0.5726	0.3892
0.0000	0.0000	0.0000	0.8320	2.6786	2.2285
0.1387	0.3377	0.2186	0.8057	0.8319	0.6702
0.1816	0.3964	0.2742	0.7987	0.7007	0.5597
0.2966	0.2257	0.1294	0.8210	0.8827	0.7247
0.3306	0.2852	0.2292	0.8059	0.7044	0.5677
0.1425	0.3949	0.2127	0.8085	0.7855	0.6351
0.2984	0.1696	0.2736	0.7938	0.7658	0.6079

Table 4.8 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K					
1.0000	0.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.0000	0.8537	0.6621	0.5652
0.0000	0.0000	1.0000	0.6713	0.5209	0.3497
0.0000	0.0000	0.0000	0.8236	2.1887	1.8026
0.1387	0.3377	0.2186	0.7968	0.7442	0.5930
0.1816	0.3964	0.2742	0.7897	0.6348	0.5013
0.2966	0.2257	0.1294	0.8120	0.7804	0.6337
0.3306	0.2852	0.2292	0.7966	0.6381	0.5083
0.1425	0.3949	0.2127	0.7996	0.7034	0.5624
0.2984	0.1696	0.2736	0.7848	0.6816	0.5349

Table 4.8 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K					
1.0000	0.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.0000	0.8495	0.6231	0.5294
0.0000	0.0000	1.0000	0.6713	0.5209	0.3329
0.0000	0.0000	0.0000	0.8236	2.1887	1.6360
0.1387	0.3377	0.2186	0.7927	0.7040	0.5581
0.1816	0.3964	0.2742	0.7855	0.6044	0.4747
0.2966	0.2257	0.1294	0.8077	0.7391	0.5970
0.3306	0.2852	0.2292	0.7923	0.6028	0.4776
0.1425	0.3949	0.2127	0.7954	0.6707	0.5334
0.2984	0.1696	0.2736	0.7805	0.6481	0.5059

Table 4.9: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K					
1.0000	0.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.0000	0.8671	0.6837	0.5928
0.0000	0.0000	1.0000	0.6839	0.6008	0.4109
0.0000	0.0000	0.0000	0.8362	2.9960	2.5052
0.1408	0.3722	0.2076	0.8095	0.8181	0.6622
0.1753	0.4422	0.2485	0.8048	0.6838	0.5503
0.2873	0.2516	0.1269	0.8248	0.8941	0.7374
0.3185	0.3148	0.2193	0.8101	0.7097	0.5749
0.1406	0.4183	0.2021	0.8119	0.7710	0.6260
0.2916	0.1913	0.2667	0.7981	0.7844	0.6260

Table 4.9 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K					
1.0000	0.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.0000	0.8624	0.6439	0.5552
0.0000	0.0000	1.0000	0.6798	0.5726	0.3892
0.0000	0.0000	0.0000	0.8320	2.6786	2.2285
0.1408	0.3722	0.2076	0.8050	0.7708	0.6205
0.1753	0.4422	0.2485	0.8003	0.6548	0.5241
0.2873	0.2516	0.1269	0.8203	0.8392	0.6884
0.3185	0.3148	0.2193	0.8055	0.6707	0.5403
0.1406	0.4183	0.2021	0.8074	0.7341	0.5927
0.2916	0.1913	0.2667	0.7936	0.7386	0.5861

Table 4.9 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, × 10^6 (m^2/s)	Absolute Viscosity, η, × 10^3(Pa.s)
Temperature, T = 308.15 K					
1.0000	0.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.0000	0.8528	0.5792	0.4940
0.0000	0.0000	1.0000	0.6713	0.5209	0.3497
0.0000	0.0000	0.0000	0.8236	2.1887	1.8026
0.1408	0.3722	0.2076	0.7959	0.6935	0.5519
0.1753	0.4422	0.2485	0.7909	0.5940	0.4698
0.2873	0.2516	0.1269	0.8111	0.7432	0.6028
0.3185	0.3148	0.2193	0.7961	0.6091	0.4849
0.1406	0.4183	0.2021	0.7982	0.6614	0.5279
0.2916	0.1913	0.2667	0.7844	0.6591	0.5170

Table 4.9 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Quaternary System: Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction, x_1	Mole Fraction, x_2	Mole Fraction, x_3	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K					
1.0000	0.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.0000	0.8483	0.5512	0.4676
0.0000	0.0000	1.0000	0.6671	0.4990	0.3329
0.0000	0.0000	0.0000	0.8197	1.9958	1.6360
0.1408	0.3722	0.2076	0.7917	0.6553	0.5188
0.1753	0.4422	0.2485	0.7866	0.5659	0.4452
0.2873	0.2516	0.1269	0.8068	0.7042	0.5682
0.3185	0.3148	0.2193	0.7916	0.5741	0.4545
0.1406	0.4183	0.2021	0.7939	0.6289	0.4993
0.2916	0.1913	0.2667	0.7801	0.6270	0.4891

Table 4.10: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.8671	0.6837	0.5928
0.0000	0.0000	0.6839	0.6008	0.4109
0.0989	0.0834	0.7071	0.5911	0.4180
0.1532	0.1514	0.7250	0.5857	0.4246
0.2063	0.2347	0.7472	0.5861	0.4379
0.3398	0.2879	0.7812	0.5967	0.4661
0.3221	0.3851	0.7981	0.6089	0.4860
0.3825	0.3410	0.8014	0.6102	0.4890
0.4063	0.2513	0.7868	0.6001	0.4722
0.5069	0.0782	0.7707	0.5885	0.4536

Table 4.10 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
		Temperature, T = 298.15 K		
1.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.8624	0.6439	0.5552
0.0000	0.0000	0.6798	0.5726	0.3892
0.0989	0.0834	0.7028	0.5608	0.3941
0.1532	0.1514	0.7206	0.5568	0.4012
0.2063	0.2347	0.7426	0.5565	0.4133
0.3398	0.2879	0.7765	0.5660	0.4395
0.3221	0.3851	0.7934	0.5754	0.4565
0.3825	0.3410	0.7966	0.5783	0.4607
0.4063	0.2513	0.7821	0.5685	0.4446
0.5069	0.0782	0.7660	0.5584	0.4277

Table 4.10 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.8528	0.5792	0.4940
0.0000	0.0000	0.6713	0.5209	0.3497
0.0989	0.0834	0.6940	0.5122	0.3555
0.1532	0.1514	0.7116	0.5170	0.3679
0.2063	0.2347	0.7334	0.5074	0.3722
0.3398	0.2879	0.7670	0.5133	0.3937
0.3221	0.3851	0.7838	0.4975	0.3899
0.3825	0.3410	0.7869	0.4887	0.3846
0.4063	0.2513	0.7725	0.5351	0.4134
0.5069	0.0782	0.7564	0.5583	0.4223

Table 4.10 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.8483	0.5512	0.4676
0.0000	0.0000	0.6671	0.4990	0.3329
0.0989	0.0834	0.6898	0.4899	0.3379
0.1532	0.1514	0.7073	0.4861	0.3438
0.2063	0.2347	0.7291	0.4854	0.3539
0.3398	0.2879	0.7624	0.4904	0.3739
0.3221	0.3851	0.7792	0.4745	0.3698
0.3825	0.3410	0.7824	0.4655	0.3642
0.4063	0.2513	0.7680	0.5110	0.3924
0.5069	0.0782	0.7519	0.5275	0.3966

Table 4.11: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.8671	0.7773	0.6740
0.0000	0.0000	0.6839	0.6008	0.4109
0.1209	0.0800	0.7086	0.5968	0.4229
0.1834	0.1670	0.7349	0.6006	0.4414
0.2498	0.2489	0.7608	0.6120	0.4656
0.4188	0.2610	0.7946	0.6283	0.4992
0.3772	0.3683	0.8098	0.6512	0.5273
0.4268	0.3268	0.8110	0.6456	0.5236
0.4814	0.2310	0.8008	0.6310	0.5053
0.5461	0.0273	0.7682	0.5874	0.4513

Table 4.11 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.8628	0.7321	0.6316
0.0000	0.0000	0.6798	0.5726	0.3892
0.1209	0.0800	0.7043	0.5657	0.3984
0.1834	0.1670	0.7305	0.5704	0.4167
0.2498	0.2489	0.7563	0.5806	0.4391
0.4188	0.2610	0.7899	0.5952	0.4702
0.3772	0.3683	0.8052	0.6153	0.4954
0.4268	0.3268	0.8063	0.6126	0.4939
0.4814	0.2310	0.7961	0.5975	0.4756
0.5461	0.0273	0.7635	0.5581	0.4261

Table 4.11 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.8537	0.6621	0.5652
0.0000	0.0000	0.6713	0.5209	0.3497
0.1209	0.0800	0.6956	0.5165	0.3593
0.1834	0.1670	0.7215	0.5277	0.3808
0.2498	0.2489	0.7472	0.5284	0.3948
0.4188	0.2610	0.7804	0.5382	0.4200
0.3772	0.3683	0.7957	0.5291	0.4211
0.4268	0.3268	0.7968	0.5165	0.4115
0.4814	0.2310	0.7865	0.5608	0.4411
0.5461	0.0273	0.7540	0.5583	0.4209

Table 4.11 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.8495	0.6231	0.5294
0.0000	0.0000	0.6671	0.4990	0.3329
0.1209	0.0800	0.6914	0.4946	0.3420
0.1834	0.1670	0.7173	0.4965	0.3561
0.2498	0.2489	0.7429	0.5053	0.3753
0.4188	0.2610	0.7759	0.5139	0.3987
0.3772	0.3683	0.7913	0.5052	0.3997
0.4268	0.3268	0.7923	0.4920	0.3898
0.4814	0.2310	0.7820	0.5354	0.4186
0.5461	0.0273	0.7494	0.5264	0.3945

Table 4.12: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8671	0.6837	0.5928
0.0000	1.0000	0.8671	0.7773	0.6740
0.0000	0.0000	0.6839	0.6008	0.4109
0.0969	0.1009	0.7134	0.6035	0.4305
0.1470	0.2087	0.7393	0.6098	0.4508
0.2006	0.3034	0.7652	0.6228	0.4766
0.3447	0.3230	0.7953	0.6376	0.5070
0.3001	0.4285	0.8083	0.6587	0.5325
0.3679	0.3695	0.8095	0.6530	0.5286
0.4052	0.3033	0.8032	0.6415	0.5153
0.4850	0.1012	0.7774	0.6077	0.4725

Table 4.12 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8624	0.6439	0.5552
0.0000	1.0000	0.8628	0.7321	0.6316
0.0000	0.0000	0.6798	0.5726	0.3892
0.0969	0.1009	0.7091	0.5718	0.4055
0.1470	0.2087	0.7350	0.5788	0.4254
0.2006	0.3034	0.7608	0.5912	0.4498
0.3447	0.3230	0.7909	0.6048	0.4783
0.3001	0.4285	0.8038	0.6224	0.5003
0.3679	0.3695	0.8050	0.6186	0.4980
0.4052	0.3033	0.7987	0.6086	0.4861
0.4850	0.1012	0.7729	0.5771	0.4461

Table 4.12 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, v, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
		Temperature, T = 308.15 K		
1.0000	0.0000	0.8528	0.5792	0.4940
0.0000	1.0000	0.8537	0.6621	0.5652
0.0000	0.0000	0.6713	0.5209	0.3497
0.0969	0.1009	0.7004	0.5218	0.3655
0.1470	0.2087	0.7261	0.5360	0.3892
0.2006	0.3034	0.7519	0.5385	0.4049
0.3447	0.3230	0.7818	0.5479	0.4283
0.3001	0.4285	0.7946	0.5368	0.4265
0.3679	0.3695	0.7958	0.5224	0.4157
0.4052	0.3033	0.7895	0.5722	0.4518
0.4850	0.1012	0.7638	0.5772	0.4409

Table 4.12 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8483	0.5512	0.4676
0.0000	1.0000	0.8495	0.6231	0.5294
0.0000	0.0000	0.6671	0.4990	0.3329
0.0969	0.1009	0.6962	0.4995	0.3477
0.1470	0.2087	0.7219	0.5055	0.3649
0.2006	0.3034	0.7476	0.5150	0.3850
0.3447	0.3230	0.7775	0.5242	0.4076
0.3001	0.4285	0.7904	0.5128	0.4053
0.3679	0.3695	0.7915	0.4989	0.3949
0.4052	0.3033	0.7851	0.5477	0.4300
0.4850	0.1012	0.7595	0.5465	0.4151

Table 4.13: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.8671	0.6837	0.5928
0.0000	0.0000	0.8671	0.7773	0.6740
0.0919	0.0941	0.8678	0.7674	0.6660
0.1498	0.2059	0.8682	0.7520	0.6529
0.2085	0.2984	0.8688	0.7364	0.6398
0.3286	0.3323	0.8699	0.7253	0.6309
0.3028	0.4438	0.8697	0.7196	0.6258
0.3545	0.3964	0.8701	0.7205	0.6269
0.4040	0.2960	0.8705	0.7253	0.6314
0.5086	0.0974	0.8715	0.7369	0.6422

Table 4.13 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.8624	0.6439	0.5552
0.0000	0.0000	0.8628	0.7321	0.6316
0.0919	0.0941	0.8633	0.7202	0.6218
0.1498	0.2059	0.8636	0.7063	0.6100
0.2085	0.2984	0.8641	0.6937	0.5995
0.3286	0.3323	0.8651	0.6822	0.5902
0.3028	0.4438	0.8649	0.6742	0.5831
0.3545	0.3964	0.8653	0.6765	0.5854
0.4040	0.2960	0.8657	0.6812	0.5897
0.5086	0.0974	0.8666	0.6926	0.6002

Table 4.13 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.8528	0.5792	0.4940
0.0000	0.0000	0.8537	0.6621	0.5652
0.0919	0.0941	0.8540	0.6468	0.5524
0.1498	0.2059	0.8542	0.6394	0.5462
0.2085	0.2984	0.8546	0.6226	0.5320
0.3286	0.3323	0.8554	0.6094	0.5212
0.3028	0.4438	0.8551	0.5735	0.4904
0.3545	0.3964	0.8555	0.5649	0.4833
0.4040	0.2960	0.8559	0.6331	0.5418
0.5086	0.0974	0.8567	0.6765	0.5796

Table 4.13 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Ethylbenzene (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.8483	0.5512	0.4676
0.0000	0.0000	0.8495	0.6231	0.5294
0.0919	0.0941	0.8497	0.6140	0.5217
0.1498	0.2059	0.8498	0.6024	0.5120
0.2085	0.2984	0.8501	0.5912	0.5026
0.3286	0.3323	0.8508	0.5788	0.4924
0.3028	0.4438	0.8505	0.5427	0.4616
0.3545	0.3964	0.8508	0.5341	0.4544
0.4040	0.2960	0.8512	0.5995	0.5103
0.5086	0.0974	0.8521	0.6369	0.5427

Table 4.14: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.8671	0.6837	0.5928
0.0000	0.0000	0.8362	2.9960	2.5052
0.0972	0.0950	0.8391	1.9545	1.6400
0.1552	0.2047	0.8429	1.4298	1.2052
0.2053	0.2990	0.8470	1.1412	0.9666
0.3355	0.3319	0.8535	0.9419	0.8039
0.3139	0.4263	0.8563	0.8709	0.7458
0.3549	0.3968	0.8572	0.8629	0.7397
0.4084	0.3084	0.8560	0.8906	0.7624
0.5097	0.1052	0.8527	1.0316	0.8796

Table 4.14 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.8624	0.6439	0.5552
0.0000	0.0000	0.8320	2.6786	2.2285
0.0972	0.0950	0.8348	1.7814	1.4871
0.1552	0.2047	0.8385	1.3210	1.1076
0.2053	0.2990	0.8426	1.0622	0.8950
0.3355	0.3319	0.8489	0.8807	0.7476
0.3139	0.4263	0.8517	0.8129	0.6923
0.3549	0.3968	0.8525	0.8096	0.6902
0.4084	0.3084	0.8513	0.8385	0.7138
0.5097	0.1052	0.8480	0.9611	0.8150

Table 4.14 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
		Temperature, T = 308.15 K		
1.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.8528	0.5792	0.4940
0.0000	0.0000	0.8236	2.1887	1.8026
0.0972	0.0950	0.8262	1.5058	1.2441
0.1552	0.2047	0.8297	1.1431	0.9484
0.2053	0.2990	0.8336	0.9374	0.7814
0.3355	0.3319	0.8396	0.7784	0.6535
0.3139	0.4263	0.8422	0.6842	0.5763
0.3549	0.3968	0.8430	0.6690	0.5640
0.4084	0.3084	0.8418	0.7692	0.6475
0.5097	0.1052	0.8385	0.9182	0.7700

Table 4.14 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Toluene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.8483	0.5512	0.4676
0.0000	0.0000	0.8197	1.9958	1.6360
0.0972	0.0950	0.8222	1.3944	1.1465
0.1552	0.2047	0.8256	1.0712	0.8843
0.2053	0.2990	0.8294	0.8822	0.7317
0.3355	0.3319	0.8351	0.7360	0.6146
0.3139	0.4263	0.8378	0.6489	0.5437
0.3549	0.3968	0.8385	0.6315	0.5295
0.4084	0.3084	0.8373	0.7293	0.6107
0.5097	0.1052	0.8341	0.8651	0.7215

Table 4.15: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8671	0.6837	0.5928
0.0000	1.0000	0.8671	0.7773	0.6740
0.0000	0.0000	0.8362	2.9960	2.5052
0.1107	0.1093	0.8396	1.8077	1.5179
0.1580	0.1923	0.8428	1.4368	1.2110
0.1978	0.3146	0.8477	1.1395	0.9660
0.3472	0.3245	0.8529	0.9500	0.8103
0.2991	0.4492	0.8562	0.8934	0.7649
0.3549	0.3920	0.8559	0.8888	0.7607
0.3974	0.2961	0.8536	0.9162	0.7821
0.5026	0.1010	0.8498	0.9950	0.8456

Table 4.15 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8624	0.6439	0.5552
0.0000	1.0000	0.8628	0.7321	0.6316
0.0000	0.0000	0.8320	2.6786	2.2285
0.1107	0.1093	0.8354	1.6564	1.3838
0.1580	0.1923	0.8385	1.3291	1.1145
0.1978	0.3146	0.8433	1.0668	0.8996
0.3472	0.3245	0.8485	0.8914	0.7563
0.2991	0.4492	0.8518	0.8368	0.7128
0.3549	0.3920	0.8515	0.8354	0.7114
0.3974	0.2961	0.8492	0.8648	0.7344
0.5026	0.1010	0.8454	0.9322	0.7880

Table 4.15 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.0000	0.8528	0.5792	0.4940
0.0000	1.0000	0.8537	0.6621	0.5652
0.0000	0.0000	0.8236	2.1887	1.8026
0.1107	0.1093	0.8269	1.4078	1.1641
0.1580	0.1923	0.8300	1.1482	0.9529
0.1978	0.3146	0.8346	0.9433	0.7872
0.3472	0.3245	0.8396	0.7906	0.6638
0.2991	0.4492	0.8428	0.7098	0.5982
0.3549	0.3920	0.8425	0.6915	0.5826
0.3974	0.2961	0.8402	0.8039	0.6754
0.5026	0.1010	0.8365	0.8994	0.7523

Table 4.15 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8483	0.5512	0.4940
0.0000	1.0000	0.8495	0.6231	0.5294
0.0000	0.0000	0.8197	1.9958	1.6360
0.1107	0.1093	0.8230	1.3086	1.0769
0.1580	0.1923	0.8260	1.0779	0.8903
0.1978	0.3146	0.8305	0.8890	0.7384
0.3472	0.3245	0.8354	0.7488	0.6256
0.2991	0.4492	0.8386	0.6737	0.5649
0.3549	0.3920	0.8382	0.6562	0.5500
0.3974	0.2961	0.8361	0.7612	0.6364
0.5026	0.1010	0.8323	0.8494	0.7069

Table 4.16: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.8671	0.7773	0.6740
0.0000	0.0000	0.8362	2.9960	2.5052
0.0949	0.8146	0.8636	0.8168	0.7054
0.1418	0.6760	0.8599	0.8679	0.7464
0.2010	0.5301	0.8565	0.9206	0.7885
0.3210	0.3802	0.8557	0.9473	0.8106
0.3104	0.2777	0.8513	1.0773	0.9171
0.3630	0.2829	0.8537	1.0082	0.8607
0.4081	0.3205	0.8572	0.9148	0.7841
0.4789	0.4280	0.8661	0.7944	0.6880

Table 4.16 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, v, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.8628	0.7321	0.6316
0.0000	0.0000	0.8320	2.6786	2.2285
0.0949	0.8146	0.8592	0.7649	0.6572
0.1418	0.6760	0.8555	0.8156	0.6978
0.2010	0.5301	0.8520	0.8678	0.7394
0.3210	0.3802	0.8512	0.8880	0.7559
0.3104	0.2777	0.8468	1.0032	0.8496
0.3630	0.2829	0.8492	0.9414	0.7994
0.4081	0.3205	0.8526	0.8610	0.7341
0.4789	0.4280	0.8614	0.7456	0.6422

Table 4.16 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.8537	0.6621	0.5652
0.0000	0.0000	0.8236	2.1887	1.8026
0.0949	0.8146	0.8501	0.6888	0.5856
0.1418	0.6760	0.8464	0.7327	0.6201
0.2010	0.5301	0.8430	0.7753	0.6536
0.3210	0.3802	0.8420	0.7850	0.6609
0.3104	0.2777	0.8378	0.8347	0.6993
0.3630	0.2829	0.8399	0.7713	0.6478
0.4081	0.3205	0.8433	0.7958	0.6711
0.4789	0.4280	0.8517	0.7255	0.6179

Table 4.16 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.8495	0.6231	0.5294
0.0000	0.0000	0.8197	1.9958	1.6360
0.0949	0.8146	0.8458	0.6538	0.5530
0.1418	0.6760	0.8421	0.6972	0.5871
0.2010	0.5301	0.8387	0.7345	0.6160
0.3210	0.3802	0.8377	0.7431	0.6225
0.3104	0.2777	0.8335	0.7873	0.6563
0.3630	0.2829	0.8356	0.7282	0.6085
0.4081	0.3205	0.8389	0.7530	0.6317
0.4789	0.4280	0.8471	0.6851	0.5804

Table 4.17: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8792	0.7433	0.6535
0.0000	1.0000	0.6839	0.6008	0.4109
0.0000	0.0000	0.8362	2.9960	2.5052
0.1082	0.1048	0.8202	1.8127	1.4867
0.1636	0.1907	0.8066	1.3770	1.1107
0.2157	0.2928	0.7900	1.0571	0.8351
0.3626	0.3283	0.7847	0.8350	0.6552
0.3365	0.4215	0.7691	0.8050	0.6191
0.3585	0.3936	0.7733	0.7670	0.5931
0.4118	0.2773	0.7942	0.8348	0.6630
0.4929	0.0911	0.8306	1.0254	0.8517

Table 4.17 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8738	0.6926	0.6052
0.0000	1.0000	0.6798	0.5726	0.3892
0.0000	0.0000	0.8320	2.6786	2.2285
0.1082	0.1048	0.8160	1.6593	1.3540
0.1636	0.1907	0.8024	1.2743	1.0225
0.2157	0.2928	0.7857	0.9912	0.7788
0.3626	0.3283	0.7803	0.7858	0.6132
0.3365	0.4215	0.7646	0.7128	0.5450
0.3585	0.3936	0.7688	0.7247	0.5572
0.4118	0.2773	0.7898	0.7907	0.6244
0.4929	0.0911	0.8261	0.9568	0.7904

Table 4.17 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.0000	0.8629	0.6110	0.5272
0.0000	1.0000	0.6713	0.5209	0.3497
0.0000	0.0000	0.8236	2.1887	1.8026
0.1082	0.1048	0.8074	1.4071	1.1362
0.1636	0.1907	0.7938	1.1018	0.8746
0.2157	0.2928	0.7770	0.8786	0.6826
0.3626	0.3283	0.7712	0.6985	0.5387
0.3365	0.4215	0.7556	0.6110	0.4617
0.3585	0.3936	0.7597	0.6052	0.4598
0.4118	0.2773	0.7806	0.7365	0.5749
0.4929	0.0911	0.8168	0.9143	0.7468

Table 4.17 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Benzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, v, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8577	0.5762	0.4942
0.0000	1.0000	0.6671	0.4990	0.3329
0.0000	0.0000	0.8197	1.9958	1.6360
0.1082	0.1048	0.8035	1.3064	1.0497
0.1636	0.1907	0.7898	1.0356	0.8179
0.2157	0.2928	0.7729	0.8294	0.6410
0.3626	0.3283	0.7670	0.6634	0.5088
0.3365	0.4215	0.7513	0.5801	0.4358
0.3585	0.3936	0.7554	0.5758	0.4350
0.4118	0.2773	0.7763	0.6956	0.5400
0.4929	0.0911	0.8124	0.8634	0.7014

Table 4. 18: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8671	0.6837	0.5928
0.0000	1.0000	0.6839	0.6008	0.4109
0.0000	0.0000	0.8362	2.9960	2.5052
0.1047	0.1038	0.8200	1.7868	1.4652
0.1470	0.1954	0.8059	1.3737	1.1070
0.2113	0.3070	0.7888	1.0260	0.8093
0.3271	0.3228	0.7876	0.8705	0.6856
0.3053	0.4420	0.7681	0.7686	0.5904
0.3623	0.3772	0.7792	0.7799	0.6077
0.3904	0.3128	0.7902	0.8079	0.6384
0.4892	0.1012	0.8281	0.9677	0.8013

Table 4.18 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8624	0.6439	0.5552
0.0000	1.0000	0.6798	0.5726	0.3892
0.0000	0.0000	0.8320	2.6786	2.2285
0.1047	0.1038	0.8159	1.6386	1.3369
0.1470	0.1954	0.8017	1.2718	1.0196
0.2113	0.3070	0.7845	0.9649	0.7570
0.3271	0.3228	0.7833	0.8910	0.6415
0.3053	0.4420	0.7638	0.7244	0.5533
0.3623	0.3772	0.7748	0.7378	0.5717
0.3904	0.3128	0.7858	0.7678	0.6033
0.4892	0.1012	0.8237	0.9074	0.7474

Table 4.18 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.0000	0.8528	0.5792	0.4940
0.0000	1.0000	0.6713	0.5209	0.3497
0.0000	0.0000	0.8236	2.1887	1.8026
0.1047	0.1038	0.8074	1.3932	1.1249
0.1470	0.1954	0.7932	1.1068	0.8779
0.2113	0.3070	0.7759	0.8593	0.6667
0.3271	0.3228	0.7746	0.7306	0.5659
0.3053	0.4420	0.7550	0.6195	0.4677
0.3623	0.3772	0.7653	0.6157	0.4712
0.3904	0.3128	0.7770	0.7181	0.5579
0.4892	0.1012	0.8148	0.8749	0.7129

Table 4.18 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Toluene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8483	0.5512	0.4676
0.0000	1.0000	0.6671	0.4990	0.3329
0.0000	0.0000	0.8197	1.9958	1.6360
0.1047	0.1038	0.8035	1.2947	1.0403
0.1470	0.1954	0.7893	1.0400	0.8208
0.2113	0.3070	0.7719	0.8123	0.6270
0.3271	0.3228	0.7704	0.6937	0.5345
0.3053	0.4420	0.7509	0.5910	0.4438
0.3623	0.3772	0.7619	0.7625	0.5809
0.3904	0.3128	0.7728	0.6827	0.5276
0.4892	0.1012	0.8107	0.8294	0.6724

Table 4.19: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Ethylbenzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.0000	0.8671	0.7773	0.6740
0.0000	1.0000	0.6839	0.6008	0.4109
0.0000	0.0000	0.8362	2.9960	2.5052
0.0940	0.1048	0.8203	1.8186	1.4917
0.1397	0.2211	0.8029	1.3422	1.0776
0.1997	0.3239	0.7881	1.0400	0.8197
0.3323	0.3387	0.7888	0.8845	0.6976
0.2977	0.4478	0.7712	0.8027	0.6191
0.3474	0.4015	0.7792	0.8070	0.6289
0.3983	0.3009	0.7965	0.8579	0.6833
0.4974	0.1066	0.8304	1.0117	0.8400

Table 4.19 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Ethylbenzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.0000	0.8628	0.7321	0.6316
0.0000	1.0000	0.6798	0.5726	0.3892
0.0000	0.0000	0.8320	2.6786	2.2285
0.0940	0.1048	0.8161	1.6678	1.3611
0.1397	0.2211	0.7988	1.2449	0.9944
0.1997	0.3239	0.7840	0.9778	0.7666
0.3323	0.3387	0.7845	0.8329	0.6534
0.2977	0.4478	0.7669	0.7569	0.5805
0.3474	0.4015	0.7749	0.7634	0.5916
0.3983	0.3009	0.7922	0.8134	0.6444
0.4974	0.1066	0.8261	0.9502	0.7849

Table 4.19 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Ethylbenzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.0000	0.8537	0.6621	0.5652
0.0000	1.0000	0.6713	0.5209	0.3497
0.0000	0.0000	0.8236	2.1887	1.8026
0.0940	0.1048	0.8077	1.4133	1.1415
0.1397	0.2211	0.7903	1.0807	0.8540
0.1997	0.3239	0.7755	0.8703	0.6749
0.3323	0.3387	0.7759	0.7425	0.5761
0.2977	0.4478	0.7583	0.6475	0.4909
0.3474	0.4015	0.7663	0.6373	0.4884
0.3983	0.3009	0.7836	0.7603	0.5958
0.4974	0.1066	0.8174	0.9116	0.7452

Table 4.19 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Ternary System: Ethylbenzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction, x_1	Mole Fraction, x_2	Density, ρ (kg/L)	Kinematic Viscosity, v, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.0000	0.8495	0.6231	0.5294
0.0000	1.0000	0.6671	0.4990	0.3329
0.0000	0.0000	0.8197	1.9958	1.6360
0.0940	0.1048	0.8038	1.3144	1.0565
0.1397	0.2211	0.7864	1.0168	0.7996
0.1997	0.3239	0.7715	0.8227	0.6347
0.3323	0.3387	0.7718	0.7048	0.5440
0.2977	0.4478	0.7542	0.6170	0.4653
0.3474	0.4015	0.7622	0.6071	0.4628
0.3983	0.3009	0.7795	0.7235	0.5639
0.4974	0.1066	0.8134	0.8645	0.7032

Table 4.20: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Toluene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.8792	0.0000	0.7433	0.6535
0.0000	0.8671	0.0000	0.6837	0.5928
0.0403	0.8674	0.0132	0.6860	0.5950
0.1393	0.8682	0.0434	0.6834	0.5933
0.2551	0.8692	0.0639	0.6887	0.5986
0.3116	0.8697	0.0785	0.6902	0.6003
0.3863	0.8706	0.0762	0.6914	0.6019
0.5033	0.8718	0.0950	0.6996	0.6099
0.6139	0.8732	0.0887	0.7113	0.6211
0.7301	0.8748	0.0763	0.7174	0.6276
0.8551	0.8767	0.0484	0.7300	0.5976

Table 4.20 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Toluene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.8738	0.0000	0.6926	0.6052
0.0000	0.8624	0.0000	0.6439	0.5552
0.0403	0.8626	0.0124	0.6445	0.5560
0.1393	0.8634	0.0404	0.6443	0.5563
0.2551	0.8644	0.0591	0.6488	0.5608
0.3116	0.8649	0.0750	0.6535	0.5652
0.3863	0.8656	0.0752	0.6514	0.5380
0.5033	0.8668	0.0916	0.6576	0.5700
0.6139	0.8681	0.0867	0.6650	0.6031
0.7301	0.8696	0.0721	0.6701	0.5827
0.8551	0.8714	0.0452	0.6790	0.5917

Table 4.20 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Toluene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.8629	0.0000	0.6110	0.5272
0.0000	0.8528	0.0000	0.5792	0.4940
0.0403	0.8531	0.0151	0.5794	0.4943
0.1393	0.8537	0.0458	0.5854	0.4998
0.2551	0.8545	0.0673	0.5814	0.4968
0.3116	0.8550	0.0786	0.5811	0.4968
0.3863	0.8557	0.0778	0.5817	0.4977
0.5033	0.8566	0.0948	0.5872	0.5030
0.6139	0.8578	0.0909	0.5920	0.5078
0.7301	0.8591	0.0777	0.6013	0.5166
0.8551	0.8608	0.0487	0.6072	0.5227

Table 4.20 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Toluene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.8577	0.0000	0.5762	0.4942
0.0000	0.8483	0.0000	0.5512	0.4676
0.0403	0.8486	0.0089	0.5515	0.4680
0.1393	0.8491	0.0410	0.5512	0.4681
0.2551	0.8499	0.0599	0.5522	0.4693
0.3116	0.8503	0.0754	0.5516	0.4690
0.3863	0.8509	0.0738	0.5529	0.4705
0.5033	0.8518	0.0916	0.5573	0.4747
0.6139	0.8529	0.0874	0.5610	0.4785
0.7301	0.8541	0.0756	0.5635	0.4813
0.8551	0.8557	0.0443	0.5691	0.4870

Table 4.21: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Toluene (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.8671	0.0000	0.6837	0.5928
0.0000	0.8671	0.0000	0.7773	0.6740
0.0424	0.8672	-0.0216	0.7743	0.6715
0.1280	0.8673	-0.0313	0.7676	0.6658
0.2164	0.8673	-0.0316	0.7553	0.6550
0.2928	0.8673	-0.0334	0.7477	0.6485
0.3930	0.8673	-0.0266	0.7456	0.6467
0.4922	0.8673	-0.0330	0.7356	0.6380
0.5716	0.8673	-0.0297	0.7235	0.6275
0.7107	0.8673	-0.0267	0.7094	0.6153
0.8425	0.8672	-0.0178	0.6985	0.6057

Table 4.21 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Toluene (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.8624	0.0000	0.6439	0.5552
0.0000	0.8628	0.0000	0.7321	0.6316
0.0424	0.8627	0.0018	0.7289	0.6289
0.1280	0.8628	-0.0115	0.7233	0.6241
0.2164	0.8628	-0.0129	0.7144	0.6163
0.2928	0.8628	-0.0191	0.7063	0.6094
0.3930	0.8627	-0.0145	0.7004	0.6043
0.4922	0.8628	-0.0234	0.6917	0.5967
0.5716	0.8627	-0.0186	0.6831	0.5893
0.7107	0.8627	-0.0215	0.6699	0.5779
0.8425	0.8625	-0.0126	0.6585	0.5680

Table 4.21 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Toluene (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.8528	0.0000	0.5792	0.4940
0.0000	0.8537	0.0000	0.6621	0.5652
0.0424	0.8537	0.0027	0.6544	0.5587
0.1280	0.8537	-0.0065	0.6545	0.5587
0.2164	0.8536	-0.0085	0.6409	0.5471
0.2928	0.8536	-0.0116	0.6336	0.5408
0.3930	0.8535	-0.0101	0.6302	0.5379
0.4922	0.8534	-0.0156	0.6268	0.5349
0.5716	0.8534	-0.0141	0.6144	0.5243
0.7107	0.8532	-0.0136	0.6006	0.5125
0.8425	0.8530	-0.0056	0.5988	0.5108

Table 4.21 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Toluene (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, × 10^6 (m^2/s)	Absolute Viscosity, η, × 10^3(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.8483	0.0000	0.5512	0.4755
0.0000	0.8495	0.0000	0.6231	0.5294
0.0424	0.8495	-0.0036	0.6246	0.5306
0.1280	0.8494	-0.0105	0.6181	0.5250
0.2164	0.8493	-0.0121	0.6105	0.5185
0.2928	0.8493	-0.0161	0.6033	0.5124
0.3930	0.8492	-0.0153	0.5990	0.5186
0.4922	0.8491	-0.0186	0.5914	0.5022
0.5716	0.8490	-0.0218	0.5852	0.4968
0.7107	0.8488	-0.0173	0.5712	0.4853
0.8425	0.8486	-0.0103	0.5634	0.4781

Table 4.22: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Toluene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.6839	0.0000	0.6008	0.4109
0.0000	0.8671	0.0000	0.6837	0.5928
0.0901	0.8451	0.0038	0.6533	0.5521
0.1949	0.8210	0.0398	0.6272	0.5149
0.2903	0.8005	0.0827	0.6119	0.4898
0.3959	0.7796	0.0922	0.5991	0.4670
0.4836	0.7632	0.1112	0.5951	0.4542
0.5809	0.7462	0.1150	0.5891	0.4396
0.6809	0.7299	0.0908	0.5888	0.4298
0.7920	0.7129	0.0779	0.5903	0.4208
0.8884	0.6990	0.0448	0.5944	0.4155

Table 4.22 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Toluene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.6798	0.0000	0.5726	0.3892
0.0000	0.8624	0.0000	0.6439	0.5552
0.0901	0.8404	0.0029	0.6166	0.5182
0.1949	0.8163	0.0411	0.5941	0.4850
0.2903	0.7959	0.0874	0.5808	0.4622
0.3959	0.7751	0.0952	0.5694	0.4413
0.4836	0.7587	0.1149	0.5641	0.4280
0.5809	0.7418	0.1196	0.5602	0.4155
0.6809	0.7255	0.0967	0.5606	0.4067
0.7920	0.7085	0.0851	0.5609	0.3974
0.8884	0.6948	0.0466	0.5658	0.3931

Table 4.22 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Toluene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.6713	0.0000	0.5209	0.3497
0.0000	0.8528	0.0000	0.5792	0.4940
0.0901	0.8309	0.0080	0.5573	0.4631
0.1949	0.8070	0.0517	0.5460	0.4406
0.2903	0.7866	0.1014	0.5275	0.4150
0.3959	0.7659	0.1019	0.5179	0.3967
0.4836	0.7496	0.1308	0.5151	0.3861
0.5809	0.7328	0.1309	0.5201	0.3811
0.6809	0.7166	0.1121	0.5116	0.3666
0.7920	0.6998	0.0971	0.5108	0.3575
0.8884	0.6861	0.0573	0.5254	0.3605

Table 4.22 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Toluene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.6671	0.0000	0.4990	0.3329
0.0000	0.8483	0.0000	0.5512	0.4676
0.0901	0.8265	-0.0009	0.5313	0.4392
0.1949	0.8026	0.0442	0.5145	0.4129
0.2903	0.7822	0.0964	0.5042	0.3944
0.3959	0.7616	0.0946	0.4950	0.3770
0.4836	0.7454	0.1231	0.4922	0.3668
0.5809	0.7286	0.1213	0.4888	0.3562
0.6809	0.7125	0.1023	0.4896	0.3488
0.7920	0.6956	0.0921	0.4903	0.3410
0.8884	0.6820	0.0537	0.4937	0.3367

Table 4.23: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.6839	0.0000	0.6008	0.4109
0.0000	0.8671	0.0000	0.7773	0.6740
0.1034	0.845	-0.0206	0.7389	0.6244
0.2048	0.8241	-0.0201	0.7045	0.5806
0.2931	0.8064	-0.0060	0.6754	0.5447
0.3754	0.7905	-0.0045	0.6576	0.5199
0.4880	0.7695	-0.0022	0.6431	0.4949
0.5929	0.7508	-0.0165	0.6277	0.4713
0.6899	0.7339	0.0065	0.6173	0.4531
0.8051	0.7148	0.0029	0.6069	0.4338
0.8979	0.6999	-0.0066	0.6045	0.4231

Table 4.23 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.6798	0.0000	0.5726	0.3892
0.0000	0.8628	0.0000	0.7321	0.6316
0.1034	0.8405	0.0005	0.6958	0.5849
0.2048	0.8196	-0.0007	0.6654	0.5454
0.2931	0.8020	0.0114	0.6425	0.5153
0.3754	0.7861	0.0077	0.6257	0.4919
0.4880	0.7651	0.0117	0.6088	0.4658
0.5929	0.7465	-0.0060	0.5953	0.4443
0.6899	0.7296	0.0148	0.587	0.4283
0.8051	0.7105	0.0050	0.5783	0.4109
0.8979	0.6956	-0.0031	0.5751	0.4001

Table 4.23 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, × 10^6 (m^2/s)	Absolute Viscosity, η, × 10^3(Pa.s)
		Temperature, T = 308.15 K		
1.0000	0.6713	0.0000	0.5209	0.3497
0.0000	0.8537	0.0000	0.6621	0.5652
0.1034	0.8315	0.0012	0.6274	0.5217
0.2048	0.8106	0.0002	0.6075	0.4925
0.2931	0.7930	0.0139	0.5832	0.4625
0.3754	0.7772	0.0140	0.5662	0.4400
0.4880	0.7563	0.0150	0.5547	0.4195
0.5929	0.7377	-0.0070	0.5504	0.4061
0.6899	0.7209	0.0184	0.5353	0.3859
0.8051	0.7018	0.0115	0.5257	0.3690
0.8979	0.6871	-0.0083	0.5326	0.3659

Table 4.23 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.6671	0.0000	0.4990	0.3329
0.0000	0.8495	0.0000	0.6231	0.5294
0.1034	0.8274	-0.0143	0.5977	0.4945
0.2048	0.8065	-0.0111	0.5742	0.4631
0.2931	0.7888	0.0092	0.5569	0.4393
0.3754	0.7730	0.0037	0.5420	0.4190
0.4880	0.7522	-0.0056	0.5299	0.3986
0.5929	0.7336	-0.0224	0.5189	0.3807
0.6899	0.7167	0.0073	0.5119	0.3669
0.8051	0.6977	0.0020	0.5039	0.3516
0.8979	0.6830	-0.0151	0.5015	0.3425

Table 4.24: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, × 10^6 (m^2/s)	Absolute Viscosity, η, × 10^3(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.8792	0.0000	0.7433	0.6535
0.0000	0.8671	0.0000	0.7773	0.6740
0.0877	0.8677	0.0213	0.7759	0.6732
0.1855	0.8684	0.0505	0.7682	0.6671
0.2950	0.8693	0.0815	0.7585	0.6594
0.4137	0.8704	0.1039	0.7512	0.6538
0.4980	0.8712	0.1201	0.7515	0.6547
0.5965	0.8724	0.1182	0.7458	0.6506
0.7108	0.8739	0.1109	0.7404	0.6470
0.7904	0.8752	0.0901	0.7381	0.6459
0.8983	0.8771	0.0557	0.7413	0.6502

Table 4.24 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.8738	0.0000	0.6926	0.6052
0.0000	0.8628	0.0000	0.7321	0.6316
0.0877	0.8632	0.0383	0.7281	0.6285
0.1855	0.8639	0.0647	0.7218	0.6236
0.2950	0.8646	0.0923	0.7145	0.6178
0.4137	0.8656	0.1108	0.7064	0.6115
0.4980	0.8664	0.1235	0.7030	0.6090
0.5965	0.8675	0.1219	0.6985	0.6059
0.7108	0.8689	0.1081	0.6944	0.6034
0.7904	0.8701	0.0877	0.6909	0.6012
0.8983	0.8718	0.0536	0.6913	0.6027

Table 4.24 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.8629	0.0000	0.6110	0.5272
0.0000	0.8537	0.0000	0.6621	0.5652
0.0877	0.8541	0.0347	0.6538	0.5584
0.1855	0.8546	0.0634	0.6509	0.5563
0.2950	0.8552	0.0896	0.6399	0.5472
0.4137	0.8560	0.1102	0.6299	0.5392
0.4980	0.8566	0.1187	0.6282	0.5382
0.5965	0.8575	0.1183	0.6276	0.5382
0.7108	0.8587	0.1028	0.6181	0.5308
0.7904	0.8597	0.0841	0.6122	0.5263
0.8983	0.8612	0.0472	0.6165	0.5309

Table 4.24 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Ethylbenzene (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.8577	0.0000	0.5762	0.4942
0.0000	0.8495	0.0000	0.6231	0.5294
0.0877	0.8498	0.0282	0.6215	0.5282
0.1855	0.8502	0.0578	0.6156	0.5234
0.2950	0.8508	0.0822	0.6079	0.5172
0.4137	0.8515	0.1050	0.5985	0.5096
0.4980	0.8521	0.1098	0.5962	0.5080
0.5965	0.8528	0.1138	0.5909	0.5039
0.7108	0.8539	0.0969	0.5850	0.4996
0.7904	0.8548	0.0765	0.5796	0.4954
0.8983	0.8562	0.0448	0.5781	0.4949

Table 4.25: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Heptane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.8792	0.0000	0.7433	0.6535
0.0000	0.6839	0.0000	0.6008	0.4109
0.1099	0.6965	0.2160	0.5943	0.4139
0.2052	0.7085	0.3674	0.5857	0.4150
0.2896	0.7201	0.4653	0.5813	0.4185
0.4212	0.7403	0.5655	0.5777	0.4277
0.5078	0.7550	0.6406	0.5827	0.4400
0.6087	0.7745	0.6133	0.5904	0.4572
0.7263	0.8004	0.5187	0.6108	0.4889
0.7936	0.8171	0.4293	0.6272	0.5125
0.8987	0.8463	0.2594	0.6734	0.5699

Table 4.25 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Heptane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.8738	0.0000	0.6926	0.6052
0.0000	0.6798	0.0000	0.5726	0.3892
0.1099	0.6922	0.2155	0.5633	0.3899
0.2052	0.7041	0.3639	0.5569	0.3921
0.2896	0.7156	0.4689	0.5525	0.3954
0.4212	0.7357	0.5729	0.5500	0.4047
0.5078	0.7503	0.6467	0.5523	0.4144
0.6087	0.7697	0.6202	0.5598	0.4309
0.7263	0.7955	0.5231	0.5774	0.4593
0.7936	0.8121	0.4296	0.5930	0.4816
0.8987	0.8411	0.2572	0.6313	0.5310

Table 4.25 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Heptane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.8629	0.0000	0.6110	0.5272
0.0000	0.6713	0.0000	0.5209	0.3497
0.1099	0.6836	0.2162	0.5147	0.3518
0.2052	0.6953	0.3813	0.5167	0.3593
0.2896	0.7066	0.4870	0.5041	0.3562
0.4212	0.7265	0.5912	0.4999	0.3632
0.5078	0.7409	0.6685	0.5026	0.3724
0.6087	0.7600	0.6383	0.5165	0.3925
0.7263	0.7855	0.5371	0.5213	0.4094
0.7936	0.8019	0.4395	0.5315	0.4262
0.8987	0.8306	0.2576	0.5699	0.4734

Table 4.25 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Heptane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.8577	0.0000	0.5762	0.4942
0.0000	0.6671	0.0000	0.4990	0.3329
0.1099	0.6794	0.2181	0.4919	0.3342
0.2052	0.6911	0.3765	0.4856	0.3356
0.2896	0.7024	0.4815	0.4822	0.3387
0.4212	0.7221	0.5908	0.4777	0.3450
0.5078	0.7364	0.6646	0.4798	0.3534
0.6087	0.7554	0.6347	0.4854	0.3667
0.7263	0.7808	0.5326	0.4968	0.3879
0.7936	0.7971	0.4357	0.5057	0.4031
0.8987	0.8256	0.2571	0.5339	0.4408

Table 4.26: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.8792	0.0000	0.7433	0.6535
0.0000	0.8362	0.0000	2.9960	2.5052
0.1004	0.8377	0.2259	2.4237	2.0303
0.1826	0.8393	0.3578	2.0491	1.7198
0.3035	0.8422	0.5136	1.6286	1.3717
0.4080	0.8454	0.5853	1.3804	1.1670
0.5122	0.8491	0.6194	1.2054	1.0235
0.5243	0.8496	0.6118	1.1855	1.0072
0.6891	0.8573	0.5407	0.9620	0.8247
0.7904	0.8632	0.4257	0.8716	0.7523
0.9001	0.8708	0.2428	0.7963	0.6934

Table 4.26 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.8738	0.0000	0.6926	0.6052
0.0000	0.8320	0.0000	2.6786	2.2285
0.1004	0.8334	0.2207	2.1970	1.8311
0.1826	0.8351	0.3507	1.8720	1.5632
0.3035	0.8378	0.5061	1.5002	1.2569
0.4080	0.8409	0.5779	1.2750	1.0722
0.5122	0.8445	0.6115	1.1155	0.9421
0.5243	0.8450	0.6057	1.0968	0.9269
0.6891	0.8524	0.5370	0.8976	0.7651
0.7904	0.8582	0.4212	0.8145	0.6990
0.9001	0.8656	0.2396	0.7437	0.6438

Table 4.26 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.8629	0.0000	0.6110	0.5272
0.0000	0.8236	0.0000	2.1887	1.8026
0.1004	0.8249	0.2174	1.8105	1.4936
0.1826	0.8264	0.3505	1.5663	1.2944
0.3035	0.8290	0.5001	1.2935	1.0723
0.4080	0.8319	0.5755	1.1086	0.9222
0.5122	0.8352	0.6071	0.9680	0.8085
0.5243	0.8357	0.6037	0.9528	0.7963
0.6891	0.8427	0.5389	0.7912	0.6667
0.7904	0.8481	0.4248	0.7125	0.6042
0.9001	0.8551	0.2412	0.6609	0.5651

Table 4.26 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Benzene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.8577	0.0000	0.5762	0.4942
0.0000	0.8197	0.0000	1.9958	1.6360
0.1004	0.8210	0.2104	1.6660	1.3678
0.1826	0.8224	0.3450	1.4511	1.1934
0.3035	0.8249	0.4951	1.2038	0.9930
0.4080	0.8276	0.5706	1.0379	0.8590
0.5122	0.8309	0.6005	0.9083	0.7548
0.5243	0.8314	0.5977	0.8946	0.7437
0.6891	0.8381	0.5315	0.7486	0.6274
0.7904	0.8433	0.4214	0.6732	0.5677
0.9001	0.8501	0.2405	0.6191	0.5263

Table 4.27: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Toluene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.8671	0.0000	0.6837	0.5928
0.0000	0.8362	0.0000	2.9960	2.5052
0.0997	0.8372	0.2260	2.3334	1.9536
0.1951	0.8387	0.3684	1.8864	1.5822
0.3032	0.8409	0.4779	1.5191	1.2774
0.3904	0.8430	0.5219	1.3159	1.1093
0.4868	0.8457	0.5342	1.1547	0.9765
0.5898	0.8489	0.5197	1.0078	0.8555
0.6919	0.8527	0.4373	0.8839	0.7537
0.8003	0.8572	0.3226	0.7997	0.6855
0.8880	0.8612	0.2051	0.7429	0.6398

Table 4.27 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Toluene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.8624	0.0000	0.6439	0.5552
0.0000	0.8320	0.0000	2.6786	2.2285
0.0997	0.8330	0.2235	2.1135	1.7606
0.1951	0.8346	0.3600	1.7246	1.4393
0.3032	0.8366	0.4738	1.4033	1.1741
0.3904	0.8387	0.5199	1.2235	1.0261
0.4868	0.8413	0.5318	1.0737	0.9033
0.5898	0.8445	0.5167	0.9431	0.7964
0.6919	0.8482	0.4349	0.8339	0.7073
0.8003	0.8527	0.3201	0.7526	0.6417
0.8880	0.8566	0.2051	0.6997	0.5993

Table 4.27 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Toluene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.8528	0.0000	0.5792	0.4940
0.0000	0.8236	0.0000	2.1887	1.8026
0.0997	0.8246	0.2194	1.7496	1.4427
0.1951	0.8260	0.3620	1.4501	1.1978
0.3032	0.8281	0.4683	1.2108	1.0026
0.3904	0.8300	0.5180	1.0539	0.8748
0.4868	0.8325	0.5311	0.9409	0.7834
0.5898	0.8356	0.5184	0.8354	0.6981
0.6919	0.8392	0.4396	0.7467	0.6266
0.8003	0.8434	0.3265	0.6726	0.5673
0.8880	0.8473	0.2070	0.6328	0.5361

Table 4.27 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Toluene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.8483	0.0000	0.5512	0.4676
0.0000	0.8197	0.0000	1.9958	1.6360
0.0997	0.8207	0.2168	1.6152	1.3256
0.1951	0.8221	0.3582	1.3531	1.1124
0.3032	0.8241	0.4643	1.1325	0.9333
0.3904	0.8260	0.5129	0.9931	0.8203
0.4868	0.8285	0.5239	0.8461	0.7010
0.5898	0.8314	0.5077	0.7913	0.6579
0.6919	0.8349	0.4358	0.7080	0.5912
0.8003	0.8391	0.3244	0.6392	0.5364
0.8880	0.8429	0.2006	0.5971	0.5033

Table 4.28: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Ethylbenzene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.8671	0.0007	0.7773	0.6740
0.0000	0.8362	0.0000	2.9960	2.5052
0.0907	0.8375	0.1500	2.3904	2.0019
0.2033	0.8398	0.2399	1.8685	1.5691
0.3072	0.8423	0.2878	1.5398	1.2969
0.3701	0.8440	0.2898	1.4035	1.1846
0.4761	0.8471	0.2850	1.2295	1.0415
0.5798	0.8505	0.2548	1.0918	0.9286
0.7008	0.8549	0.1878	0.9605	0.8211
0.7922	0.8584	0.1360	0.8970	0.7700
0.8908	0.8624	0.0628	0.8341	0.7194

Table 4.28 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Ethylbenzene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.8628	0.0000	0.7321	0.6316
0.0000	0.8320	0.0000	2.6786	2.2285
0.0907	0.8333	0.2032	2.1642	1.8034
0.2033	0.8356	0.3460	1.7103	1.4291
0.3072	0.8380	0.4391	1.4246	1.1939
0.3701	0.8398	0.4568	1.3015	1.0929
0.4761	0.8428	0.4751	1.1438	0.9640
0.5798	0.8462	0.4488	1.0215	0.8644
0.7008	0.8505	0.3613	0.9024	0.7675
0.7922	0.8540	0.2828	0.8407	0.7179
0.8908	0.8580	0.1612	0.7858	0.6742

Table 4.28 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Ethylbenzene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, × 10^6 (m^2/s)	Absolute Viscosity, η, × 10^3(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.8537	0.0007	0.6621	0.5652
0.0000	0.8236	0.0000	2.1887	1.8026
0.0907	0.8248	0.2082	1.8032	1.4874
0.2033	0.8271	0.3520	1.4581	1.2061
0.3072	0.8295	0.4400	1.2315	1.0215
0.3701	0.8312	0.4581	1.1348	0.9433
0.4761	0.8342	0.4764	1.0032	0.8369
0.5798	0.8375	0.4460	0.9036	0.7568
0.7008	0.8417	0.3685	0.8003	0.6736
0.7922	0.8451	0.2898	0.7515	0.6351
0.8908	0.8490	0.1699	0.7017	0.5958

Table 4.28 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Ethylbenzene (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.8495	0.0000	0.6231	0.5294
0.0000	0.8197	0.0000	1.9958	1.6360
0.0907	0.8209	0.2066	1.6513	1.3556
0.2033	0.8232	0.3488	1.3490	1.1104
0.3072	0.8256	0.4374	1.1601	0.9578
0.3701	0.8272	0.4618	1.0596	0.8765
0.4761	0.8302	0.4718	0.9437	0.7835
0.5798	0.8334	0.4464	0.8506	0.7089
0.7008	0.8376	0.3667	0.7645	0.6403
0.7922	0.8409	0.2885	0.7110	0.5979
0.8908	0.8448	0.1756	0.6664	0.5629

Table 4.29: Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 293.15 K				
1.0000	0.6839	0.0000	0.6008	0.4109
0.0000	0.8362	0.0000	2.9960	2.5052
0.0938	0.8202	0.0874	2.3012	1.8874
0.1897	0.8055	-0.0547	1.8372	1.4799
0.2896	0.7900	-0.1170	1.4780	1.1676
0.3979	0.7733	-0.1621	1.2261	0.9481
0.4949	0.7587	-0.2202	1.0760	0.8163
0.5964	0.7434	-0.2363	0.9354	0.6954
0.6919	0.7293	-0.2496	0.8206	0.5985
0.7795	0.7163	-0.2078	0.7530	0.5394
0.8934	0.6996	-0.1342	0.6706	0.4691

Table 4.29 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 298.15 K				
1.0000	0.6798	0.0000	0.5726	0.3892
0.0000	0.8320	0.0000	2.6786	2.2285
0.0938	0.8160	0.0823	2.0868	1.7028
0.1897	0.8014	-0.0688	1.6701	1.3384
0.2896	0.7858	-0.1321	1.3682	1.0752
0.3979	0.7691	-0.1810	1.1436	0.8796
0.4949	0.7545	-0.2400	1.0042	0.7577
0.5964	0.7393	-0.2525	0.8786	0.6495
0.6919	0.7252	-0.2662	0.7788	0.5648
0.7795	0.7121	-0.2188	0.7103	0.5059
0.8934	0.6954	-0.1371	0.6346	0.4413

Table 4.29 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, × 10^6 (m^2/s)	Absolute Viscosity, η, × 10^3(Pa.s)
Temperature, T = 308.15 K				
1.0000	0.6713	0.0000	0.5209	0.3497
0.0000	0.8236	0.0000	2.1887	1.8026
0.0938	0.8077	0.0707	1.7396	1.4050
0.1897	0.7930	-0.0923	1.4187	1.1251
0.2896	0.7775	-0.1610	1.1893	0.9246
0.3979	0.7608	-0.2134	1.0007	0.7613
0.4949	0.7461	-0.2706	0.8857	0.6608
0.5964	0.7309	-0.2881	0.7832	0.5725
0.6919	0.7167	-0.2932	0.7015	0.5028
0.7795	0.7036	-0.2354	6377	0.4487
0.8934	0.6869	-0.1455	0.5826	0.4002

Table 4.29 (Cont'd.): Density, Kinematic Viscosity, and Absolute Viscosity-Composition Data for the Binary System: Heptane (1) + Cyclooctane (2).

Mole Fraction, x_1	Density, ρ (kg/L)	V^E (L/kmol)	Kinematic Viscosity, ν, $\times 10^6$ (m^2/s)	Absolute Viscosity, η, $\times 10^3$(Pa.s)
Temperature, T = 313.15 K				
1.0000	0.6671	0.0000	0.4990	0.3329
0.0000	0.8197	0.0000	1.9958	1.6360
0.0938	0.8038	0.0634	1.6025	1.2880
0.1897	0.7891	-0.1011	1.3229	1.0439
0.2896	0.7736	-0.1861	1.1124	0.8605
0.3979	0.7568	-0.2369	0.9417	0.7127
0.4949	0.7422	-0.3008	0.8363	0.6207
0.5964	0.7269	-0.3149	0.7414	0.5389
0.6919	0.7127	-0.3092	0.6670	0.4754
0.7795	0.6997	-0.2610	0.6083	0.4256
0.8934	0.6828	-0.1477	0.5499	0.3754

CHAPTER 5

DISCUSSION

5.1 General

Reliable viscosity-composition data for different types of liquid mixtures at different temperatures are needed from both theoretical and practical standpoints. From a theoretical standpoint, viscosity-composition data are needed for the development and validation of mathematical models for predicting the dependence of viscosities on composition. In the absence of reliable predictive models, viscosity-composition data are needed, from a practical standpoint, for design purposes. For those reasons, our laboratory started a program since the mid 1980s which aims at measuring and reporting the required data.

The models employed for predicting the viscosities of liquid mixtures can be classified into semi-theoretical and empirical models. Three models that fall into the first category are: (i) the predictive version of the McAllister's three-body model, (ii) a generalized corresponding states principle (GCSP), and (iii) a group contribution approach (GC-UNIMOD) were tested. Two models belonging to the empirical models; namely, (i) The Allan and Teja correlation, and (ii) A multi-layer artificial neural network (ANN) were tested and their predictive capabilities were compared with the semi-theoretical models indicated earlier.

In the present chapter, the measured densities and kinematic viscosities of pure components were compared with the corresponding literature values. In addition, the data gathered in the present study were utilized for the critical testing of the predictive capabilities of different viscosity models selected. Results of the testing and comparison are reported. In addition, a section on the description of the design and methodology of the ANN that was developed in the present study will follow at the end of the present chapter.

5.2 Accuracy and Precision of Pure Component Properties

The reproducibility of the experimental results is affected by the following factors: (i) the precision of the instruments used in measurements, (ii) the accuracy of the physical properties of the standard fluids used in the calibration of these instruments, and (iii) the purty of the chemicals employed.

For the density measurements, the DMA 60 density meter used combined with the DMA 602 remote cell for measuring the densities of pure components yields very precise measurements. As described earlier in details in Chapter 3, determining the density of any component depends on measuring the period of oscillation of the U-shaped tube filled with the liquid sample. The oscillation period is displayed digitally on six-digit readout panel; ten consecutive readings were taken and the average value is reported and then substituted into equation (3.1) to calculate the corresponding density. The maximum estimated error in the case of density was found to be 6.2×10^{-5} kg/L, (*cf.* Appendix B for the error analysis estimation).

For the case of the viscosity measurements, the use of the Cannon-Ubbelohde viscometers having many advantages over the other viscometer types provided highly accurate viscosity measurements. The reproducibility of the efflux time was always within ± 0.1%. In addition, the use of an RTD digital thermometer helped in keeping the temperature fluctuations to within ± 0.01 °C. This contributed to the reliability of the experimental measurements. Please refer to Appendix B for the maximum estimated error for each viscometer type used in the present study.

The densities and kinematic viscosities of the pure components were measured at four temperatures: 293.15 K, 298.15 K, 308.15 K, and 313.15 K. The reported data of the densities and viscosities were utilized for the calculation of the absolute viscosities at all temperatures. A comparison between the measured properties and the corresponding literature values is reported in Table 5.1.

It is clear from the data reported in Table 5.1 that the measured experimental values of the properties of pure components are in excellent agreement with those reported in the literature.

It should be pointed out here that the insignificant differences between the experimental results of the present study and those published in the literature may be attributed to two reasons; *viz*., (i) the pure components used in the present study were of purities that exceeded 99 % and that had been confirmed by the present author using GC analysis as explained earlier in Chapter 3. The purities of the compounds whose properties were reported in the literature, have not been readily available, (ii) in the present study, high precision measuring instruments were used for the measurement of the different properties. In addition, temperature fluctuations were strictly kept to within

± 0.01 K during all measurements, as densities and viscosities are strong functions of temperature. Literature sources do not include such fine details. For the above indicated reasons, the present author believes that the reported values of densities and viscosities are superior to the corresponding literature ones in terms of accuracy.

5.3 Testing the Predictive Capabilities of Some Viscosity Models

The experimental data for the quinary system: benzene, toluene, ethylbenzene, heptane, and cyclooctane, and all its corresponding binary, ternary, and quaternary sub-systems reported earlier in Chapter 4 were employed in testing some viscosity models available from the literature. The models that were tested are: (i) the predictive version of the McAllister three-body model, (ii) a generalized corresponding states principles (GCSP), (iii) the GC-UNIMOD, (iv) the Allan and Teja correlation, and (v) an artificial neural network based model, developed and designed specifically for the case considered in the present work. A computer program developed earlier by Nhaesi (1998) was used for the current model testing calculations except for the neural network. Public domain software, Joone 1.2.1, was employed for training, testing and generalizing the developed neural network. The predictive values of the kinematic viscosity for all studied systems at the investigated temperatures were then compared to the corresponding experimental values.

A statistical measure for calculating the deviation between the experimental and predicted (calculated) values is known as the percent absolute average deviation *AAD* (%) and is defined by,

Table 5.1: Physical Properties of Pure Components at 293.15 K.

Compound	Density, kg/L		Kinematic Viscosity × 10^6 m^2/s		Absolute Viscosity × 10^3 Pa.s	
	Experimental Value	Literature Value	Experimental Value	Literature Value	Experimental Value	Literature Value
Benzene	0.8792	0.8790 [1]	0.7433	0.7357 [1]	0.6540	0.6468 [1]
Toluene	0.8671	0.8668 [1]	0.6837	0.6747 [1]	0.5930	0.5848 [1]
Ethylbenzene	0.8672	0.8669 [1]	0.7773	0.7800 [1]	0.6740	0.6763 [1]
Heptane	0.6839	0.6838 [1]	0.6008	0.6096 [1]	0.4110	0.4169 [1]
Cyclooctane	0.8362	0.8359 [2]	2.9960	3.0339 [2]	2.5050	2.5360 [2]

[1] TRC Tables (1988)

[2] Tranzado *et al*. (2002)

[3] Timmermans (1950)

[4] Ritzoulis *et al*. (1986)

[5] Puri and Raju (1970)

[6] Nayak *et al*. (2001)

[7] Ewing *et al*. (1970)

Table 5.1 (Cont'd.): Physical Properties of Pure Components at 298.15 K.

Compound	Density, kg/L		Kinematic Viscosity × 10^6 m^2/s		Absolute Viscosity × 10^3 Pa.s	
	Experimental Value	Literature Value	Experimental Value	Literature Value	Experimental Value	Literature Value
Benzene	0.8738	0.8737 [1]	0.6926	0.6878 [1]	0.6050	0.6010 [1]
Toluene	0.8624	0.8622 [1]	0.6439	0.6378 [1]	0.5550	0.5500 [1]
Ethylbenzene	0.8628	0.8626 [1]	0.7321	0.7367 [1]	0.6320	0.6354 [1]
Heptane	0.6798	0.6795 [1]	0.5726	0.5821 [1]	0.3890	0.3955 [1]
Cyclooctane	0.8319	0.8318 [2]	2.6786	---	2.229	---

Table 5.1 (Cont'd.): Physical Properties of Pure Components at 308.15 K.

Compound	Density, kg/L		Kinematic Viscosity × 10^6 m^2/s		Absolute Viscosity × 10^3 Pa.s	
	Experimental Value	Literature Value	Experimental Value	Literature Value	Experimental Value	Literature Value
Benzene	0.8629	0.8629 [3]	0.6110	0.6066 [1]	0.5270	0.5236 [1]
Toluene	0.8528	0.8527 [4]	0.5792	0.5741 [1]	0.4930	0.4898 [1]
Ethylbenzene	0.8537	0.8548 [5]	0.6621	0.6614 [1]	0.5620	0.5645 [1]
Heptane	0.6714	0.6705 [6]	0.5209	0.5336 [1]	0.3500	0.3581 [1]
Cyclooctane	0.8236	0.8238 [7]	2.1887	--	1.8020	---

Table 5.1 (Cont'd.): Physical Properties of Pure Components at 313.15 K.

Compound	Density, kg/L		Kinematic Viscosity × 10^6 m^2/s		Absolute Viscosity × 10^3 Pa.s	
	Experimental Value	Literature Value	Experimental Value	Literature Value	Experimental Value	Literature Value
Benzene	0.8577	0.8575 [1]	0.5762	0.5722 [1]	0.4940	0.4908 [1]
Toluene	0.8483	0.8482 [1]	0.5512	0.5465 [1]	0.4670	0.4636 [1]
Ethylbenzene	0.8495	0.8494 [1]	0.6231	0.6286 [1]	0.5290	0.5338 [1]
Heptane	0.6671	0.6665 [1]	0.4990	0.5122 [1]	0.3330	0.3416 [1]
Cyclooctane	0.8197	0.8195 [2]	1.9958	2.0195 [2]	1.6340	---

$$AAD\,(\%) = \frac{1}{m}\left[\sum_{i}^{m}\frac{\left|\nu_i^{exp} - \nu_i^{pred}\right|}{\nu_i^{exp}}\right]\times 100 \tag{5.1}$$

where *m* is the number of experimental points, ν_i^{exp} and ν_i^{pred} are the experimental and the predicted kinematic viscosities of the pure component or the mixture, respectively.

In addition, the maximum deviation of the predicted kinematic viscosity values, (*MAX*), is calculated as a percentage using the following equation:

$$MAX\,(\%) = max\left[\frac{\left|\nu_i^{exp} - \nu_i^{pred}\right|}{\nu_i^{exp}}\right]\times 100 \tag{5.2}$$

The results of testing the different models are reported in Tables 5.3 through 5.9, Tables 5.11 through 5.14, and Tables 5.16 through 5.31. The testing results for each model are introduced in a separate sub-section and the overall comparison is given at the end. It should be noted here that the testing results of the cyclooctane-containing-systems are reported separately from non-cyclooctane- containing systems. This enables one to discern the effect of cyclooctane-containing systems on the predictive capability of the different models.

5.3.1 **The predictive version of the McAllister three-body interaction model**

As explained earlier in detail in Chapter 2, Asfour *et al.* (1991) successfully converted the McAllister three-body interaction model from a correlative model into a predictive one. The McAllister's three-body model for binary mixtures is given by,

$$\begin{aligned}\ell n\nu &= x_1^3\ell n\nu_1 + 3x_1^2x_2\ell n\nu_{12} + 3x_1x_2^2\ell n\nu_{21} + x_2^3\ell n\nu_2\\ &- \ell n\left[x_1 + \frac{x_2M_2}{M_1}\right] + 3x_1^2\ell n\left[\frac{(2 + M_2/M_1)}{3}\right]\\ &+ 3x_1x_2^2\ell n\left[\frac{(1 + 2M_2/M_1)}{3}\right] + x_2^3\ell n\left[M_2/M_1\right]\end{aligned} \tag{5.3}$$

Asfour's *et al.* (1991) suggested the following method for determining the binary interaction parameters:

(i) *For binary n-alkane mixtures*

$$\frac{\nu_{12}}{(\nu_1^2\nu_2)^{1/3}} = 1 + 0.044\frac{(N_2 - N_1)^2}{(N_1^2N_2)^{1/3}} \tag{5.4}$$

(ii) *For binary regular solutions*

$$\frac{\nu_{12}}{(\nu_1^2\nu_2)^{1/3}} = 0.8735 + 0.0715\frac{(ECN_2 - ECN_1)^2}{(ECN_1^2ECN_2)^{1/3}} \tag{5.5}$$

The second binary interaction parameter for the above two cases is calculated by,

$$\nu_{21} = \nu_{12}\left(\frac{\nu_2}{\nu_1}\right)^{1/3} \tag{5.6}$$

For ternary systems, the following expression was reported for McAllister's three-body interaction model (*cf.* Chapter 2 for the details)

$$\begin{aligned}\ell n\nu = {} & x_1^3\ell n\nu_1 + x_2^3\ell n\nu_2 + x_3^3\ell n\nu_3 + 3x_1^2x_2\ell n\nu_{12} + 3x_1^2x_3\ell n\nu_{13} \\ & + 3x_2^2x_1\ell n\nu_{21} + 3x_2^2x_3\ell n\nu_{23} + 3x_3^2x_1\ell n\nu_{31} + 3x_3^2x_2\ell n\nu_{32} \\ & + 6x_1x_2x_3\ell n\nu_{123} - \ell n(x_1M_1 + x_2M_2 + x_3M_3) + x_1^3\ell nM_1 \\ & + x_2^3\ell nM_2 + x_3^3\ell nM_3 + 3x_1^2x_2\ell n\left[\frac{(2M_1 + M_2)}{3}\right] \\ & + 3x_1^2x_3\ell n\left[\frac{(2M_1 + M_3)}{3}\right] + 3x_2^2x_1\ell n\left[\frac{(2M_2 + M_1)}{3}\right] \\ & + 3x_2^2x_3\ell n\left[\frac{(2M_2 + M_3)}{3}\right] + 3x_3^2x_1\ell n\left[\frac{(2M_3 + M_1)}{3}\right] \\ & + 3x_3^2x_2\ell n\left[\frac{(2M_3 + M_2)}{3}\right] + 6x_1x_2x_3\ell n\left(\frac{M_1 + M_2 + M_3}{3}\right)\end{aligned} \tag{5.7}$$

Nhaesi and Asfour (2000b) reported the following equation for calculating the ternary interaction parameter:

$$\frac{\nu_{123}}{(\nu_1\nu_2\nu_3)^{1/3}} = 0.9637 + 0.0313\frac{(N_3 - N_1)^2}{N_2} \tag{5.8}$$

where *N* is the number of carbon atoms for the case of *n*-alkanes or the *ECN* for the case of regular solutions.

The generalized form of the McAllister three-body interaction model for multi-component liquid mixture viscosity as reported by Nhaesi and Asfour (2000b) is as follows:

$$\begin{aligned}\ell n\nu_m = {} & \sum_{i=1}^{n} x_i^3\ell n(\nu_iM_i) + 3\sum_{\substack{i=1 \\ i\neq j}}^{n}\sum_{j=1}^{n} x_i^2x_j\ell n(\nu_{ij}M_{ij}) \\ & 6\sum_{\substack{i=1 \\ i\prec j\prec k}}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} x_i^2x_jx_k\ \ell n(\nu_{ijk}M_{ijk}) - \ell n(M_{avg})\end{aligned} \tag{5.9}$$

For calculating the kinematic viscosity of any liquid mixture at any composition, the selection of the appropriate equation to apply depends on the number of components and the type of liquids constituting the system under investigation. In order to calculate the values of the interaction parameters for *n*-alkane systems, equations (5.4), (5.6), and (5.8) are used, whereas for the case of regular solutions, equations (5.5), (5.6), and (5.8) are employed.

For the case of regular solutions, the effective carbon number (*ECN*) is used instead of the number of carbon atoms. The effective carbon number is calculated, as suggested by Nhaesi and Asfour (1998), with the help of the following equation:

$$\ell n \nu = -1.943 + 0.193\,(ECN) \tag{5.10}$$

Knowing the kinematic viscosity of the pure component of interest at 308.15 K, one should be able to substitute it into equation (5.10) in order to calculate the *ECN* value for that particular component. Table 5.2 reports the *ECN*s of the pure component of the quinary system involved in the present study.

Results of the predictive capabilities of the McAllister model using the experimental data reported in Chapter 4 are shown in Tables 5.3 through 5.9. For the purpose of analyzing the results in terms of *AAD* (%) and *MAX* (%), systems that contained cyclooctane were separated from other systems. Ten binary sub-systems were examined at four temperatures; *viz*., 293.15 K, 298.15 K, 308.15 K, and 313.15 K. For systems that do not contain cyclooctane, the results showed an overall *AAD* (%) of 1.29 for six systems with a maximum deviation of 7.68 % reported for the benzene (1) + toluene (2) system at 293.15 K. For the remaining four cyclooctane containing systems,

Table 5.2: Effective Carbon Numbers of the Pure Components as Calculated From Equation (5.10).

Pure Component	*ECN*
Benzene	7.47
Toluene	7.19
Ethylbenzene	7.92
Heptane	7.00
Cyclooctane	14.126

an overall *AAD* (%) of 24.87 was obtained which is relatively too high as compared to the value reported earlier for the non-cyclooctane-containing systems.

It should be pointed out here that some binary systems gave higher error values than expected when treated as regular solutions, i. e. when equation (5.5) was applied. These systems are; benzene (1) + toluene (2), benzene (1) + ethylbenzene (2), and toluene (1) + ethylbenzene (2). Application of equation (5.4) instead of equation (5.5) as suggested by Al Gherwi *et al.* (2006) in their study, i. e. treating these systems as *n*-alkanes gave much better results and reduced the error. Their explanation to such a phenomenon was that the interaction between the side chain groups (*n*-alkane chemical groups) is predominant and the overall *AAD* (%) of 24.87 was obtained which is relatively too high as compared to the value reported earlier for the non-cyclooctane-containing systems.

It should be pointed out here that some binary systems gave higher error values than expected when treated as regular solutions, i. e. when equation (5.5) was applied. These systems are: benzene (1) + toluene (2), benzene (1) + ethylbenzene (2), and toluene (1) + ethylbenzene (2). Application of equation (5.4) instead of equation (5.5) as suggested by Al Gherwi *et al.* (2006) in their study, i. e. treating these systems as *n*-alkanes gave much better results and reduced the error. Their explanation to such a phenomenon was that the interaction between the side chain groups (*n*-alkane chemical groups) is predominant and the benzene rings contained in these components tend to off-set each others. Moreover, it was found that equation (5.10) tends to overpredict the *ECN* of cyclooctane. An overpredicted value of 14.126 was calculated from equation (5.10) and then used in the calculation of the first adjustable parameter, v_{12}, from equation (5.5). The value of the first adjustable parameter is in turn when substituted into the McAllister, equation (5.3), gave relatively high error values. This confirms the same findings that were reported before by Al-Gherwi *et al.* (2006), El-Hadad (2004), and Cai (2004) when another cyclic compound; *viz.*, cyclohexane was used. Al-Gherwi *et al.* (2006) suggested that 75 % of that value led to improved results. In the present study, an *ECN* value of 10.595 that represents 75 % of the value calculated before from equation (5.10) was employed in the McAllister model. Dramatically reduced error values were obtained, as shown in Table 5.3. An overall *AAD* (%) of 11.67 using an *ECN* value of 10.595 as compared to 24.87 % when an *ECN* value of 14.126 was employed. The latter *ECN* value is the value that was obtained from equation (5.10), whereas the former *ECN* value represents 75% of the value calculated with the help of equation (5.10), as was suggested earlier by Al-Gherwi *et al*. (2006). The maximum deviation was reported for the heptane (1) + cyclooctane (2) system at 293.15 K. The maximum deviations were (51.51 and 27.80) % for the two *ECN* values, respectively. Similarly, the same calculation procedure was employed for the cases of the ternary and quaternary sub-systems at the same temperature levels.

For the case of the four ternary systems that do not contain cyclooctane, the overall *AAD* (%) was found to be 1.83 and the *MAX* (%) was found to be 12.52. The remaining six cyclooctane-containing systems gave an overall *AAD* (%) of 23.00 and a *MAX* (%) of 51.82 (for the case of *ECN* = 14.126). For the case of an *ECN* value of 10.595, an *AAD* of 11.16 % and a *MAX* (%) of 27.72 were obtained. It should be pointed out here that only one ternary system: benzene (1) + toluene (2) + ethylbenzene (3), was treated as a *n*-alkane mixture instead of a regular solution for the reasons stated earlier herein.

Table 5.3: Results of Testing the Predictive Version of McAllister's Three-body Interaction Model for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2)	293.15	1.64	7.68
	298.15	1.47	6.49
	308.15	0.62	1.57
	313.15	0.70	1.34
Toluene (1) + Ethylbenzene (2)	293.15	0.23	0.75
	298.15	0.21	0.51
	308.15	0.44	1.15
	313.15	0.41	0.75
Heptane (1) + Toluene (2)	293.15	1.31	2.63
	298.15	1.47	2.90
	308.15	2.38	5.14
	313.15	2.07	3.67
Heptane (1) + Ethylbenzene (2)	293.15	1.65	3.06
	298.15	1.77	3.00
	308.15	2.22	4.79
	313.15	2.41	4.04
Benzene (1) + Ethylbenzene (2)	293.15	0.73	1.40
	298.15	0.61	1.17
	308.15	0.57	1.38
	313.15	0.33	0.81
Benzene (1) + Heptane (2)	293.15	2.69	6.05
	298.15	2.18	5.01
	308.15	1.48	4.01
	313.15	1.33	3.43
Overall *AAD* (%)		1.29	

Table 5.3 (Cont'd.): Results of Testing the Predictive Version of the McAllister's Three-Body Interaction Model for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane: (Cyclooctane Containing Systems).

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Cyclooctane (2)	293.15	23.95	40.47
	298.15	22.59	38.30
	308.15	20.96	35.50
	313.15	20.01	33.95
Toluene (1) + Cyclooctane (2)	293.15	28.62	48.39
	298.15	27.15	45.69
	308.15	25.24	43.41
	313.15	24.76	47.38
Ethylbenzene (1) + Cyclooctane (2)	293.15	25.89	43.95
	298.15	24.53	41.47
	308.15	23.53	39.55
	313.15	22.07	37.32
Heptane (1) + Cyclooctane (2)	293.15	29.32	51.51
	298.15	28.20	48.97
	308.15	25.92	45.18
	313.15	25.10	43.46
Overall *AAD* (%)		24.87	

Table 5.4: Effect of Cyclooctane Effective Carbon Number (*ECN*) Change on the Predictive Capability of McAllister Model for Binary Systems.

		Cyclooctane (*ECN* = 14.126)		Cyclooctane (*ECN* = 10.595)	
System	T (K)	*AAD* (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) + Cyclooctane (2)	293.15	23.95	40.47	10.77	18.43
	298.15	22.59	38.30	9.58	16.58
	308.15	20.96	35.50	7.95	13.21
	313.15	20.01	33.95	7.14	11.90
Toluene (1) + Cyclooctane (2)	293.15	28.62	48.39	14.80	25.33
	298.15	27.15	45.69	13.52	22.98
	308.15	25.24	43.41	11.88	21.12
	313.15	24.76	47.38	11.45	23.44
Ethylbenzene (1) + Cyclooctane (2)	293.15	25.89	43.94	13.35	23.43
	298.15	24.53	41.47	12.16	21.31
	308.15	23.53	39.95	10.61	18.03
	313.15	22.07	37.32	9.35	16.62
Heptane (1) + Cyclooctane (2)	293.15	29.32	51.51	15.43	27.80
	298.15	28.20	48.97	14.47	25.66
	308.15	25.92	45.18	12.48	22.46
	313.15	25.10	43.46	11.78	21.01
Overall *AAD* (%)		24.87		11.67	

Table 5.5: Results of Testing the Predictive Version of the McAllister's three-body Interaction Model for the **Ternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Heptane (3)	293.15	1.03	4.05
	298.15	0.73	3.22
	308.15	2.46	7.61
	313.15	2.33	7.12
Benzene (1) + Ethylbenzene (2) + Heptane (3)	293.15	0.89	4.72
	298.15	0.68	3.72
	308.15	2.31	7.26
	313.15	2.22	6.63
Toluene (1) + Ethylbenzene (2) + Heptane (3)	293.15	2.03	3.68
	298.15	2.13	3.81
	308.15	4.15	12.52
	313.15	3.20	11.08
Benzene(1) + Toluene (2) + Ethylbenzene (3)	293.15	0.28	1.11
	298.15	0.19	0.77
	308.15	2.32	7.91
	313.15	2.40	7.75
Overall *AAD* (%)		1.83	

Table 5.5 (Cont'd.): Results of Testing the Predictive Version of the McAllister's Three-Body Interaction Model for the **<u>Ternary</u>** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane: (Cyclooctane Containing Systems).

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Cyclooctane (3)	293.15	24.27	44.76
	298.15	22.93	42.44
	308.15	20.91	37.88
	313.15	19.94	36.25
Toluene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	25.12	43.86
	298.15	23.72	41.10
	308.15	21.83	37.91
	313.15	20.62	35.68
Benzene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	16.49	36.25
	298.15	15.45	34.43
	308.15	15.41	39.06
	313.15	14.35	37.05
Benzene (1) + Heptane (2) + Cyclooctane (3)	293.15	28.74	50.90
	298.15	27.82	47.92
	308.15	25.30	43.05
	313.15	24.20	41.21
Toluene (1) + Heptane (2) + Cyclooctane (3)	293.15	30.02	51.82
	298.15	27.44	48.82
	308.15	26.10	44.01
	313.15	22.14	42.32
Ethylbenzene (1) + Heptane(2) + Cyclooctane (3)	293.15	27.73	49.26
	298.15	26.25	46.42
	308.15	24.31	42.58
	313.15	22.95	40.32
Overall *AAD* (%)		23.00	

Table 5.6: Effect of Cyclooctane Effective Carbon Number (*ECN*) Change on the Predictive Capability of McAllister Model for Ternary Systems.

		Cyclooctane (*ECN* = 14.126)		Cyclooctane (*ECN* = 10.595)	
System	T (K)	*AAD* (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Cyclooctane (3)	293.15	24.27	44.76	11.69	22.62
	298.15	22.93	42.44	10.63	20.65
	308.15	20.91	37.88	8.92	16.78
	313.15	19.94	36.25	8.07	15.40
Toluene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	25.12	43.86	12.78	23.38
	298.15	23.72	41.10	11.56	21.44
	308.15	19.79	35.80	8.17	17.09
	313.15	20.62	35.68	8.91	17.00
Benzene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	16.49	36.25	7.64	17.75
	298.15	15.45	34.43	6.83	16.18
	308.15	15.41	39.06	7.43	20.44
	313.15	14.35	37.05	6.49	18.81
Benzene (1) + Heptane (2) + Cyclooctane (3)	293.15	28.74	50.90	15.39	27.42
	298.15	27.82	47.92	14.62	24.90
	308.15	25.30	43.05	12.48	23.31
	313.15	24.20	41.21	11.52	21.96
Ethylbenzene (1) + Heptane(2) + Cyclooctane (3)	293.15	30.02	51.82	16.02	27.72
	298.15	27.44	48.82	13.81	24.90
	308.15	26.10	44.01	12.69	22.12
	313.15	22.14	42.32	10.48	19.73
Ethylbenzene(1)-Heptane(2)–Cyclooctane(3)	293.15	27.73	49.26	15.04	26.70
	298.15	26.25	46.42	13.74	24.65
	308.15	24.31	42.58	12.10	21.86
	313.15	22.95	40.32	10.91	19.92
Overall *AAD* (%)		23.00		11.16	

Table 5.7: Results of Testing the Predictive Version of the McAllister's three-body Interaction Model for the **Quaternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) Ethylbenzene (3) + Heptane (4)	293.15	1.09	3.81
	298.15	1.30	4.06
	308.15	1.65	4.50
	313.15	1.75	4.98
Overall *AAD* (%)		1.45	

Table 5.7 (Cont'd.): Results of Testing the Predictive Version of the McAllister's three-body Interaction Model for the **<u>Quaternary</u>** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4)	293.15	12.83	32.88
	298.15	11.89	30.98
	308.15	10.81	28.79
	313.15	10.12	27.16
Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4)	293.15	16.18	36.67
	298.15	15.09	34.50
	308.15	13.76	32.56
	313.15	13.00	30.72
Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4)	293.15	17.03	37.29
	298.15	16.02	35.06
	308.15	14.53	32.48
	313.15	13.66	30.59
Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4)	293.15	17.92	38.65
	298.15	16.65	36.50
	308.15	14.87	33.72
	313.15	14.33	32.15
Overall *AAD* (%)		14.44	

Table 5.8: Effect of Cyclooctane Effective Carbon Number (*ECN*) Change on the Predictive Capability of McAllister's Model for Quaternary Systems.

		Cyclooctane (*ECN* = 14.126)		Cyclooctane (*ECN* = 10.595)	
System	T (K)	*AAD* (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) +	293.15	12.83	32.88	6.09	16.74
Toluene (2) +	298.15	11.89	30.98	5.23	15.07
Ethylbenzene (3) +	308.15	10.81	28.79	4.26	13.14
Cyclooctane (4)	313.15	10.12	27.16	3.64	11.71
Toluene (1) +	293.15	16.18	36.67	8.83	19.77
Ethylbenzene (2) +	298.15	15.09	34.50	7.84	17.87
Heptane (3) +	308.15	13.76	32.56	6.64	16.17
Cyclooctane (4)	313.15	13.00	30.72	5.96	14.56
Benzene (1) +	293.15	17.03	37.29	9.72	20.29
Ethylbenzene (2) +	298.15	16.02	35.06	8.62	18.34
Heptane (3) +	308.15	14.53	32.48	7.28	16.08
Cyclooctane (4)	313.15	13.66	30.59	6.49	14.42
Benzene (1) +	293.15	17.92	38.65	11.79	22.62
Toluene (2) +	298.15	16.65	36.50	10.63	20.65
Heptane (3) +	308.15	14.87	33.72	7.42	16.74
Cyclooctane (4)	313.15	14.33	32.15	6.95	15.38
Overall *AAD* (%)		14.44		7.47	

Table 5.9: Results of Testing the Predictive Version of the McAllister's three-body Interaction Model for the **Quinary** System: benzene + toluene + ethylbenzene + heptane + cyclooctane and the Effect of Cyclooctane Effective Carbon Number (*ECN*) Change.

		Cyclooctane (*ECN* = 14.126)		Cyclooctane (*ECN* = 10.595)	
System	T (K)	*AAD* (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5)	293.15	5.61	17.28	3.12	9.85
	298.15	5.19	16.49	2.72	8.83
	308.15	4.35	14.22	1.94	6.30
	313.15	4.06	13.72	1.77	6.18
Overall *AAD* (%)		4.80		2.39	

For the quaternary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4), an overall *AAD* (%) of 1.45 was obtained with *MAX* (%) reported at 313.15 K of 4.98. The remaining four cyclooctane-containing systems gave an overall *AAD* (%) of 14.44 (for the case of *ECN* = 14.126) and 7.47 % for the case of *ECN* = 10.595. The *MAX* (%) for the two cases was 38.65 and 22.62, respectively.

Finally, results for testing the predictive capability of the modified McAllister three-body model for the quinary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4) + cyclooctane (5), gave an overall *AAD* (%) of 4.80 using the *ECN* of cyclooctane which is 14.13. The overall *AAD* (%) was reduced to 2.39 when an *ECN* value of 10.595 was employed. The *MAX* (%) was reported at 293.15 K and was found to be 17.28 and 9.85 in the two cases, respectively.

It is clear from the above results that the predictive version of the McAllister's three-body model is a powerful tool for predicting the viscosity of multi-component liquid mixtures. For the case of the systems that do not contain cyclooctane, the highest overall *AAD* (%) found was 1.83, which indicates an excellent predictive capability.

For the case of the cyclooctane-containing systems, highly unexcepected error values were obtained compared to the non-cyclooctane containing systems. After using 75 % of the value of the *ECN* calculated by equation (5.10), as described earlier, the maximum value of overall *AAD* (%) obtained was 11.67. That might be attributed to the molecular diameter ratio between cyclooctane and the second component in the same system. Similar results were reported by Howard and McAllister (1958) in their study of the acetone-water system. Howard and McAllister (1958) indicated that more interactions should be taken into consideration when dealing with binary mixtures having molecular radii ratio of more than 1.5.

5.3.2 The generalized corresponding states principle (GCSP)

The GCSP was developed by Teja and Rice (1981) for multi-component liquid mixtures. The GCSP was discussed earlier in Chapter 2. The experimental data that were reported in Chapter 4 were used in testing the GCSP. The application of the GCSP requires the knowledge of the critical properties of the components involved in the mixture. For that purpose, the critical properties of the different components were taken from Poling *et al.* (2001). Table 5.10 reports the critical properties of pure components of the quinary system: benzene + toluene + ethylbenzene + heptane + cyclooctane.

It should be pointed out here that there is no certain criterion described for the selection of the reference fluid. While this is not a concern in the case of binary systems, it becomes a problem as the number of components increases in the multi-component mixtures.

In case of the ternary, quaternary, and quinary systems involved in the present study, all the possible combinations for the reference fluids have been performed. The results reported herein are the ones that gave the lowest percentage *AAD*s.

Tables 5.11 through 5.14 show the results for testing the predictive capability of the GCSP model for the quinary system: benzene + toluene + ethylbenzene + heptane + cyclooctane and all its corresponding binary, ternary, and quaternary sub-systems at the four investigated temperatures.

Table 5.10: Physical and Critical Properties of Pure Components of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane*.

Pure Component	Molecular Weight	Critical Temperature, (K)	Critical Pressure, (bar)	Acentric Factor
Benzene	78.114	562.20	48.90	0.212
Toluene	92.140	591.80	41.00	0.263
Ethylbenzene	106.170	617.20	36.00	0.302
Heptane	100.205	540.30	27.40	0.349
Cyclooctane	112.210	647.20	35.60	0.236

- The Properties of Gases and Liquids, Reid *et al.* 1987.

Table 5.11: Results of Testing the Predictive Capability of the GCSP Model for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2)	293.15	2.10	7.78
	298.15	1.87	6.62
	308.15	0.84	1.71
	313.15	0.89	1.50
Toluene (1) + Ethylbenzene (2)	293.15	0.27	0.71
	298.15	0.22	0.47
	308.15	0.44	1.10
	313.15	0.48	0.72
Heptane (1) + Toluene (2)	293.15	6.30	8.76
	298.15	6.11	8.32
	308.15	4.94	7.64
	313.15	5.34	7.47
Heptane (1) + Ethylbenzene (2)	293.15	5.00	7.23
	298.15	4.87	6.65
	308.15	4.28	6.76
	313.15	4.04	5.74
Benzene (1) + Ethylbenzene (2)	293.15	1.42	2.12
	298.15	1.33	1.88
	308.15	1.27	2.18
	313.15	0.86	1.45
Benzene (1) + Heptane (2)	293.15	11.89	16.75
	298.15	11.36	15.86
	308.15	9.60	13.49
	313.15	9.76	13.39
Overall *AAD* (%)		3.98	

Table 5.11 (Cont'd.): Results of Testing the Predictive Capability of the GCSP Model for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane, (cyclooctane containing systems).

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Cyclooctane (2)	293.15	18.87	26.07
	298.15	17.11	24.00
	308.15	15.10	20.68
	313.15	14.00	19.21
Toluene (1) + Cyclooctane (2)	293.15	24.15	33.42
	298.15	22.37	30.75
	308.15	20.01	28.46
	313.15	19.36	31.22
Ethylbenzene (1) + Cyclooctane (2)	293.15	21.97	30.94
	298.15	20.42	28.67
	308.15	18.37	25.13
	313.15	16.74	23.62
Heptane (1) + Cyclooctane (2)	293.15	18.63	27.48
	298.15	17.49	25.40
	308.15	15.11	22.25
	313.15	14.26	20.84
Overall *AAD* (%)		18.37	

Table 5.12: Results of Testing the Predictive Capability of the GCSP Model for the **Ternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Heptane (3)	293.15	10.70	19.05
	298.15	10.20	18.63
	308.15	8.46	17.73
	313.15	8.40	16.85
Benzene (1) + Ethylbenzene (2) + Heptane (3)	293.15	5.63	16.80
	298.15	5.25	15.58
	308.15	3.74	8.70
	313.15	3.72	8.38
Toluene (1) + Ethylbenzene (2) + Heptane (3)	293.15	1.84	6.87
	298.15	1.75	6.19
	308.15	2.15	5.89
	313.15	2.12	5.04
Benzene(1) + Toluene (2) + Ethylbenzene (3)	293.15	4.09	6.82
	298.15	3.92	6.01
	308.15	5.32	13.36
	313.15	4.80	12.55
Overall *AAD* (%)		5.13	

Table 5.12 (Cont'd.): Results of Testing the Predictive Capability of the GCSP Model for the **Ternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane, (cyclooctane containing systems).

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Cyclooctane (3)	293.15	25.39	63.23
	298.15	24.94	62.18
	308.15	23.66	60.42
	313.15	23.25	59.46
Toluene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	29.98	63.82
	298.15	29.58	62.84
	308.15	28.79	60.81
	313.15	28.48	59.71
Benzene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	15.55	28.85
	298.15	15.61	28.53
	308.15	15.44	23.56
	313.15	15.88	23.67
Benzene (1) + Heptane (2) + Cyclooctane (3)	293.15	29.51	61.04
	298.15	28.77	60.16
	308.15	28.09	58.33
	313.15	27.91	57.56
Toluene (1) + Heptane (2) + Cyclooctane (3)	293.15	29.70	59.85
	298.15	30.19	58.85
	308.15	28.21	56.56
	313.15	30.51	55.57
Ethylbenzene (1) + Heptane(2) + Cyclooctane (3)	293.15	12.69	38.91
	298.15	12.66	37.94
	308.15	12.99	34.04
	313.15	13.39	34.37
Overall *AAD* (%)		23.38	

Table 5.13: Results of Testing the Predictive Capability of the GCSP Model for the **Quaternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4)	293.15	2.04	7.66
	298.15	1.98	6.79
	308.15	2.50	5.19
	313.15	2.31	5.43
Overall *AAD* (%)		2.21	

Table 5.13 (Cont'd.): Results of Testing the Predictive Capability of the GCSP Model for the **Quaternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4)	293.15	11.01	26.12
	298.15	11.42	25.94
	308.15	11.29	24.98
	313.15	11.77	24.76
Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4)	293.15	9.14	20.06
	298.15	8.95	20.07
	308.15	8.33	18.76
	313.15	8.37	18.88
Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4)	293.15	8.38	19.39
	298.15	7.73	17.95
	308.15	8.70	16.39
	313.15	7.93	17.82
Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4)	293.15	9.52	20.21
	298.15	9.51	20.15
	308.15	9.38	19.27
	313.15	9.00	19.09
Overall *AAD* (%)		9.40	

Table 5.14: Results of Testing the Predictive Capability of the GCSP Model for the **Quinary** System: benzene + toluene + ethylbenzene + heptane + cyclooctane

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5)	293.15	5.87	11.29
	298.15	5.83	10.93
	308.15	6.11	10.92
	313.15	6.20	10.19
Overall *AAD* (%)		6.00	

The binary sub-systems results show an overall *AAD* (%) of about 3.98 for six systems that do not contain cyclooctane with *MAX* (%) of 16.75 at 293.15 K. The *AAD* (%) is about 18.37 for the remaining four cyclooctane-containing systems and the *MAX* (%) is 33.42 reported at 293.15 K.

For the case of the four ternary sub-systems which do not contain cyclooctane, the overall *AAD* (%) was found to be 5.13 and was 23.38 for six cyclooctane-containing systems. The *MAX* (%) was reported at 293.15 in both cases and was found to be 19.05 and 63.82, respectively.

Testing the predictive capability of the GCSP model for the quaternary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4), gave an overall *AAD* (%) of 2.21 and a *MAX* (%) of 7.66. The remaining four quaternary cyclooctane-containing systems gave an overall *AAD* (%) of 9.40 and a *MAX* (%) of 26.12. The maximum deviations were reported at 293.15 K in both cases.

The results of testing the predictive capability of the GCSP model for the quinary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4) + cyclooctane, gave an overall *AAD* (%) of about 6.00 and a *MAX* (%) of 11.29 reported at 293.15 K.

One can observe from the results shown in the tables 5.11 through 5.14 that the predictive capability of the GCSP model may be considered relatively good especially for systems that do not contain cyclooctane. The highest value of the overall *AAD* (%) was found to be 5.13 for those systems. Results of all cyclooctane-containing systems were found to be consistent with those obtained from testing the McAllister’s model presented in the previous section. High error values were observed for those systems. The highest overall *AAD* (%) for the cyclooctane-containing systems was 23.4. The maximum deviation was generally found to be 63.82 % which is relatively high for the ternary system toluene (1) + ethylbenzene (2) + cyclooctane (3) at 293.15 K.

It should be pointed out here that the selection of the reference fluids strongly influences the value of errors obtained when the GCSP is used. There is no clear rule for the selection of the reference fluids that results in the lowest possible error. Wu (1992), Wu and Asfour (1992) and Wu *et al*. (1998) recognized that problem and discussed it in detail. Wu and Asfour (1992) proposed a *pseudo-binary* model that they incorporated into the GCSP that resulted in the Modified Generalized Corresponding States Principle (MGCSP) which helped to alleviate that problem. According to the MGCSP, a multi-component system is treated as a "*pseudo-binary*" mixture, thus the influence of the reference fluid selection on the final results is alleviated.

5.3.3 The GC-UNIMOD Model

The statistical thermodynamics-based model, GC-UNIMOD, developed by Cao *et al.* (1992) consists of two parts; *viz.*, the combinatorial part and the residual part as presented earlier in detail in Chapter 2. It was first applied for determining the vapour-liquid-equilibrium, VLE, data and later on was extended to the prediction of the viscosity of multi-component liquid mixtures.

In his study, Nhaesi (1998) reported that the effect of the residual part on the predictive capability is insignificant. Same conclusions were reported by Al-Gherwi (2005), El-Hadad (2004), and Cai (2004) in their study of viscosity of multi-component liquid mixtures.

Table 5.15: The contribution of the Different Chemical Groups Involved in the Pure Components of the Quinary System; benzene + toluene + ethylbenzene + heptane + cyclooctane for the GC-UNIMOD Method[*]

	Chemical Group					
Pure Components	Number of Occurrences	CH_3	CH_2	ACH	$ACCH_3$	$ACCH_2$
Benzene		0	0	6	0	0
Toluene		0	0	5	1	0
Ethylbenzene		1	0	5	0	1
Heptane		2	5	0	0	0
Cyclooctane		0	8	0	0	0

[*] The Properties of Gases and Liquids, Bruce E. Poling *et al.* 5th Edition,Chapter 8 (2001).

In the present study, the GC-UNIMOD model was tested using the experimental data reported earlier in Chapter 4 on the different systems investigated in the present study. Two cases were considered in the calculations; first, taking the residual part into account, second, setting the residual part to zero. The *AAD*s (%) and *MAX* (%) are calculated and reported in both cases.

Table 5.15 shows the contribution of the different chemical groups constituting the pure components involved in the present study. This was suggested by Poling *et al.* (2001) and these contributions are the same as used before by Cao *et al*. (1993b) in their work on the UNIFAC method.

The results of testing the GC-UNIMOD are reported in Tables 5.16 through 5.19. For the binary sub-systems of the quinary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4) + cyclooctane (5), the overall *AAD* (%) was found to be 2.21 for the six systems that do not contain cyclooctane while taking the residual part into account ($R \neq 0$) in the calculations. When the residual part was set to zero, (R=0), the overall *AAD* (%) was found to be 2.39 The *MAX* (%) for the case of the binary non-cyclooctane containing systems was found to be 8.93 when $R = 0$ for the binary system benzene (1) + heptane (2) at 293.15 K.

For the case of the four binary cyclooctane-containing systems, it was found that the overall *AAD* (%) was 23.83 when $R \neq 0$. Whereas, the *AAD* (%) was found to be 23.80 when the residual part was set equal to zero in the calculations; i.e., R=0. The *MAX* (%) reported as 41.67 for toluene (1) + cyclooctane system when $R \neq 0$ at 293.15 K.

Testing the predictive capability of the GC-UNIMOD model for the ternary systems, where cyclooctane was not one of the constituents, led to an overall *AAD* (%) of 4.49 when *R*≠0 and a *AAD* (%) value of 4.55 was obtained when *R*=0. The *MAX* (%) was reported for this group as 13.14 for the benzene (1) + toluene (2) + heptane (3) system when the residual part was set equal to zero at a temperature of 308.15 K. For the remaining ternary systems that contained cyclooctane as a component, the overall *AAD* (%) was 27.16 when *R*≠0 and 26.69 if *R*=0. It was found that the ternary system benzene (1) + toluene (2) + cyclooctane (3) showed a *MAX* (%) of 43.42 when *R*≠0.

For the quaternary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4), the overall *AAD* (%) was found to be 4.35 considering the residual part and was 4.5 when the residual part is neglected. This quaternary system showed a *MAX* (%) of 6.87 at 293.15 K with *R*≠0.

For the other quaternary cyclooctane-containing systems, the overall *AAD* (%) is 23.55 when *R*≠0 and is 23.11 when *R*=0. The quaternary system: benzene (1) + toluene (2) + heptane (3) + cyclooctane showed the max deviation of 37.42 % at 293.15 K when *R*≠0.

Finally, for the quinary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4) + cyclooctane (5), the results of testing the predictive capability of the GC-UNIMOD for this system taking the residual part into consideration resulted in an overall *AAD* (%) of 13.71, and 13.53 when the residual part is set equal to zero. The quinary system showed a maximum deviation of 20.24 % at 293.15 K when *R*≠0.

It can be concluded from the results of employing the viscosity-composition data for testing the predictive capability of the GC-UNIMOD method with and without taking the residual part into consideration that including the residual part has insignificant effect on the predictive capability of the method

In light of the above results one can conclude that the GC-UNIMOD exhibited a good predictive capability for systems that do not contain cyclooctane. This again confirms the earlier finding in the case of other models.

5.3.4 The Allan and Teja correlation

The Allan and Teja correlation (1991) was discussed in detail earlier in Chapter 2. The viscosity of a hydrocarbon mixture at a given temperature can be determined using that correlation with the help of equation (2.136). Allan and Teja (1991) reported three equations; *viz*., (2.137) through (2.139) for calculating the values of the three constants A, B, and C. The values of these constants depend on the effective carbon number of the mixture in question.

Using a simple mixing rule, Allan and Teja (1991) were able to find the value of the *ECN* of the mixture knowing the individual *ECN*s of all pure components involved in that mixture along with the composition. (*cf.* equation (2.140)).

In the present study, the Allan and Teja correlation was tested using the viscosity data reported in Chapter 4 for the quinary regular system: benzene (1) + toluene (2) +

Table 5.16: Results of Testing the Predictive Capability of the GC-UNIMOD Model for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	$(R \neq 0)$		$(R = 0)$	
		AAD (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2)	293.15	1.54	6.10	1.38	7.16
	298.15	1.78	5.18	1.36	5.65
	308.15	0.88	1.81	0.51	0.87
	313.15	0.77	1.51	0.35	0.68
Toluene (1) + Ethylbenzene (2)	293.15	1.09	1.67	0.27	0.70
	298.15	0.94	1.32	0.22	0.45
	308.15	1.13	1.90	0.54	1.10
	313.15	0.58	1.14	0.48	0.73
Heptane (1) + Toluene (2)	293.15	3.34	4.57	4.27	5.98
	298.15	3.17	4.19	4.11	5.60
	308.15	2.31	3.57	3.09	4.98
	313.15	2.48	3.44	3.43	4.85
Heptane (1) + Ethylbenzene (2)	293.15	2.80	4.32	4.04	5.97
	298.15	2.67	3.76	3.91	5.39
	308.15	2.31	3.96	3.39	5.58
	313.15	1.91	2.94	3.13	4.55
Benzene (1) + Ethylbenzene (2)	293.15	0.38	0.91	0.33	0.64
	298.15	0.44	0.73	0.22	0.48
	308.15	0.52	1.32	0.44	0.78
	313.15	0.83	1.26	0.37	0.74
Benzene (1) + Heptane (2)	293.15	6.23	8.84	6.30	8.93
	298.15	5.87	8.20	5.93	8.29
	308.15	4.40	6.68	4.46	6.77
	313.15	4.65	6.30	4.72	6.39
Overall *AAD* (%)		2.21		2.39	

Table 5.16 (Cont'd.): Results of Testing the Predictive Capability of the GC-UNIMOD Model for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane (cyclooctane containing systems).

System	Temperature,	($R \neq 0$)		($R = 0$)	
	K	*AAD* (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) + Cyclooctane (2)	293.15	30.08	40.92	29.80	40.52
	298.15	27.88	38.41	27.61	38.03
	308.15	24.62	34.17	24.36	33.81
	313.15	23.07	32.04	22.82	31.69
Toluene (1) + Cyclooctane (2)	293.15	30.51	41.67	35.76	40.54
	298.15	28.36	38.65	27.50	37.45
	308.15	25.37	35.39	24.56	34.37
	313.15	24.47	38.67	23.69	37.53
Ethylbenzene (1) + Cyclooctane (2)	293.15	26.09	36.30	25.49	35.53
	298.15	24.29	24.29	23.72	32.96
	308.15	21.84	29.65	21.29	28.90
	313.15	20.04	27.88	19.51	27.21
Heptane (1) + Cyclooctane (2)	293.15	21.12	30.91	21.12	30.91
	298.15	19.85	28.63	19.85	28.63
	308.15	17.28	25.22	17.28	25.22
	313.15	16.36	23.68	16.36	23.68
Overall *AAD* (%)		23.83		23.80	

Table 5.17: Results of Testing the Predictive Capability of the GC-UNIMOD Model for the **Ternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	($R \neq 0$)		($R = 0$)	
		AAD (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Heptane (3)	293.15	6.16	8.35	6.32	8.48
	298.15	5.87	7.77	6.02	7.89
	308.15	5.42	12.96	5.54	13.14
	313.15	5.38	12.81	5.50	12.99
Benzene (1) + Ethylbenzene (2) + Heptane (3)	293.15	6.23	8.91	6.34	9.01
	298.15	5.86	8.16	5.98	8.25
	308.15	5.59	12.86	5.68	12.98
	313.15	5.18	12.19	5.26	12.31
Toluene (1) + Ethylbenzene (2) + Heptane (3)	293.15	4.50	5.57	4.69	5.83
	298.15	4.40	5.29	4.59	5.54
	308.15	5.01	11.67	5.14	11.86
	313.15	4.68	11.04	4.77	11.22
Benzene(1) + Toluene (2) + Ethylbenzene (3)	293.15	0.38	0.73	0.31	0.62
	298.15	0.39	0.56	0.21	0.35
	308.15	3.47	8.54	3.24	8.11
	313.15	3.26	8.40	3.22	7.96
Overall *AAD* (%)		4.49		4.55	

Table 5.17 (Cont'd.): Results of Testing the Predictive Capability of the GC-UNIMOD Model for the **Ternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane (cyclooctane containing systems).

System	Temperature, K	($R \neq 0$) *AAD* (%)	($R \neq 0$) *MAX* (%)	($R = 0$) *AAD* (%)	($R = 0$) *MAX* (%)
Benzene (1) + Toluene (2) + Cyclooctane (3)	293.15	35.15	43.42	34.40	39.58
	298.15	32.75	40.46	32.03	36.86
	308.15	29.02	34.81	28.34	33.94
	313.15	27.26	33.15	26.60	32.42
Toluene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	31.98	38.62	31.11	37.07
	298.15	29.73	35.62	28.90	34.48
	308.15	26.60	31.08	25.82	30.32
	313.15	24.71	29.19	23.95	28.46
Benzene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	24.97	36.56	24.49	35.92
	298.15	23.23	34.27	22.76	33.66
	308.15	21.17	38.64	20.73	38.05
	313.15	19.34	36.37	18.91	35.80
Benzene (1) + Heptane (2) + Cyclooctane (3)	293.15	32.57	41.99	32.42	41.68
	298.15	31.14	39.09	31.00	38.79
	308.15	27.37	33.10	27.24	32.99
	313.15	25.74	31.55	25.61	31.44
Toluene (1) + Heptane (2) + Cyclooctane (3)	293.15	31.74	39.46	31.27	38.47
	298.15	28.21	36.82	27.76	35.86
	308.15	26.07	31.89	25.64	31.49
	313.15	20.72	27.29	20.32	26.92
Ethylbenzene (1) + Heptane (2) + Cyclooctane (3)	293.15	28.97	34.36	28.66	32.64
	298.15	26.92	31.65	26.62	30.24
	308.15	24.20	29.45	23.92	29.20
	313.15	22.38	27.73	22.11	27.49
Overall *AAD* (%)		27.16		26.69	

Table 5.18: Results of Testing the Predictive Capability of the GC-UNIMOD Model for the **Quaternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	($R \neq 0$)		($R = 0$)	
		AAD (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) Ethylbenzene (3) + Heptane (4)	293.15	5.05	6.69	5.21	6.87
	298.15	4.64	6.36	4.79	6.54
	308.15	3.92	5.78	4.07	5.95
	313.15	3.80	5.27	3.94	5.43
Overall *AAD* (%)		4.35		4.50	

Table 5.18 (Cont'd.): Results of Testing the Predictive Capability of the GC-UNIMOD Model for the **Quaternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane (cyclooctane containing systems).

System	Temperature,	($R \neq 0$)		($R = 0$)	
	K	*AAD* (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) +	293.15	25.29	34.95	24.64	34.13
Toluene (2) +	298.15	23.35	32.53	22.72	31.74
Ethylbenzene (3) +	308.15	20.94	29.46	20.35	28.71
Cyclooctane (4)	313.15	19.50	27.44	18.93	26.72
Toluene (1) +	293.15	25.43	32.49	24.97	31.77
Ethylbenzene (2) +	298.15	23.45	30.10	23.00	29.40
Heptane (3) +	308.15	20.91	27.64	20.49	26.98
Cyclooctane (4)	313.15	19.54	25.64	19.13	25.01
Benzene (1) +	293.15	27.28	34.87	27.01	34.50
Ethylbenzene (2) +	298.15	25.14	32.38	24.87	32.03
Heptane (3) +	308.15	22.38	29.27	22.13	28.93
Cyclooctane (4)	313.15	20.83	27.16	20.59	26.84
Benzene (1) +	293.15	29.41	37.42	28.95	36.79
Toluene (2) +	298.15	27.07	34.88	26.62	34.28
Heptane (3) +	308.15	23.66	31.33	23.24	30.76
Cyclooctane (4)	313.15	22.62	29.51	22.18	28.92
Overall *AAD* (%)		23.55		23.11	

Table 5.19: Results of Testing the Predictive Capability of the GC-UNIMOD Model for the **Quinary** System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	($R \neq 0$)		($R = 0$)	
		AAD (%)	*MAX* (%)	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5)	293.15	15.46	20.24	15.27	19.89
	298.15	14.56	19.28	14.37	18.94
	308.15	12.74	16.65	12.56	16.34
	313.15	12.07	16.00	11.90	15.69
Overall *AAD* (%)		13.71		13.53	

Table 5.20: Results of Testing the Predictive Capability of the Allan and Teja Correlation for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2)	293.15	25.06	27.33
	298.15	24.52	27.66
	308.15	23.29	24.07
	313.15	22.49	23.52
Toluene (1) + Ethylbenzene (2)	293.15	23.15	25.61
	298.15	22.65	24.85
	308.15	22.25	24.35
	313.15	21.80	23.52
Heptane (1) + Toluene (2)	293.15	8.44	25.61
	298.15	8.21	24.85
	308.15	8.22	23.91
	313.15	7.92	23.52
Heptane (1) + Ethylbenzene (2)	293.15	6.98	21.02
	298.15	6.86	20.68
	308.15	7.10	20.81
	313.15	6.97	19.87
Benzene (1) + Ethylbenzene (2)	293.15	23.44	27.33
	298.15	22.55	25.87
	308.15	21.57	23.64
	313.15	20.88	22.61
Benzene (1) + Heptane (2)	293.15	7.03	27.33
	298.15	6.77	25.87
	308.15	6.39	22.64
	313.15	6.19	22.49
Overall *AAD* (%)		15.03	

Table 5.20 (Cont'd.): Results of Testing the Predictive Capability of the Allan and Teja Correlation for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane, (cyclooctane containing systems).

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Cyclooctane (2)	293.15	9.61	27.20
	298.15	9.41	25.75
	308.15	9.03	23.64
	313.15	8.65	22.61
Toluene (1) + Cyclooctane (2)	293.15	11.88	25.61
	298.15	11.59	24.85
	308.15	11.37	23.91
	313.15	11.30	23.52
Ethylbenzene (1) + Cyclooctane (2)	293.15	12.67	21.12
	298.15	12.34	20.59
	308.15	11.63	20.61
	313.15	11.16	19.67
Heptane (1) + Cyclooctane (2)	293.15	19.50	33.61
	298.15	19.22	32.74
	308.15	18.16	31.10
	313.15	17.75	30.16
Overall *AAD* (%)		12.83	

ethylbenzene (3) + heptane (4) + cyclooctane (5), and all its corresponding quaternary, ternary, and binary sub-systems at different temperature levels. Results of the testing are listed in Tables 5.20 through 5.23.

For the binary sub-systems reported in Table 5.20, the overall *AAD* (%) was relatively high; *viz*., about 15 and the maximum deviation was reported as 27.66 % for the benzene (1) + toluene (2) system at 298.15 K. For cyclooctane-containing binary sub-systems, the overall *AAD* (%) was found to be slightly lower; i.e., 12.83 and the heptane (1) + cyclooctane (2) system showed the highest deviation of 33.61 % at 293.15 K.

Results of evaluating the predictive capability of the Allan and Teja correlation for ternary systems which do not contain cyclooctane and for the cyclooctane-containing systems are presented in Table 5.21. It can be seen from that table overall *AAD*s (%) of 11.66 and 13.41 for those systems, respectively. The *MAX* (%) deviations were found to be 28.04 and 33.37 for the above two groups, respectively.

For the quaternary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4), the overall *AAD* (%) was found to be 13.86. This quaternary system exhibited a maximum deviation at 293.15 K of 27.33 %. For the case of the remaining cyclooctane-containing systems reported in Table 5.21, an overall *AAD* (%) of 10.20 was found. For the cyclooctane-containing systems, three quaternary systems exhibited the same *MAX* (%) of 27.33 at the same temperature of 293.15 K. These systems were; benzene (1) + toluene (2) + ethylbenzene (3) + cyclooctane (4), benzene (1) + toluene (2) + heptane (3) + cyclooctane (4), and benzene (1) + ethylbenzene (2) + heptane (3) + cyclooctane (4).

Table 5.21: Results of Testing the Predictive Capability of the Allan and Teja Correlation for the **Ternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Heptane (3)	293.15	7.91	27.33
	298.15	7.55	25.87
	308.15	7.14	23.91
	313.15	6.92	23.52
Benzene (1) + Ethylbenzene (2) + Heptane (3)	293.15	7.77	27.33
	298.15	7.53	25.87
	308.15	7.25	23.64
	313.15	6.99	22.61
Toluene (1) + Ethylbenzene (2) + Heptane (3)	293.15	9.54	25.61
	298.15	9.30	24.85
	308.15	9.38	23.91
	313.15	9.08	23.52
Benzene(1) + Toluene (2) + Ethylbenzene (3)	293.15	23.78	27.33
	298.15	22.97	25.87
	308.15	22.08	28.04
	313.15	21.39	27.05
Overall *AAD* (%)		11.66	

Table 5.21 (Cont'd.): Results of Testing the Predictive Capability of the Allan and Teja Correlation for the **Ternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane, (cyclooctane containing systems).

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Cyclooctane (3)	293.15	10.02	27.33
	298.15	9.66	25.87
	308.15	9.51	23.91
	313.15	9.21	23.52
Toluene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	11.09	25.61
	298.15	10.61	24.85
	308.15	9.48	23.91
	313.15	9.55	23.52
Benzene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	9.91	27.33
	298.15	9.37	25.87
	308.15	11.00	23.64
	313.15	10.60	22.61
Benzene (1) + Heptane (2) + Cyclooctane (3)	293.15	17.08	28.23
	298.15	17.17	27.27
	308.15	16.41	25.92
	313.15	15.88	25.35
Toluene (1) + Heptane (2) + Cyclooctane (3)	293.15	17.38	28.20
	298.15	15.87	26.96
	308.15	15.81	24.70
	313.15	19.30	33.37
Ethylbenzene (1) + Heptane(2) + Cyclooctane (3)	293.15	17.93	29.65
	298.15	17.21	28.34
	308.15	16.31	27.18
	313.15	15.50	26.00
Overall *AAD* (%)		13.41	

Table 5.22: Results of Testing the Predictive Capability of the Allan and Teja Correlation for the **Quaternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) Ethylbenzene (3) + Heptane (4)	293.15	14.51	27.33
	298.15	14.06	25.87
	308.15	13.71	23.91
	313.15	13.17	23.52
Overall *AAD* (%)		13.86	

Table 5.22 (Cont'd.): Results of Testing the Predictive Capability of the Allan and Teja Correlation for the **Quaternary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4)	293.15	11.00	27.33
	298.15	10.55	25.87
	308.15	9.96	23.91
	313.15	9.57	23.52
Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4)	293.15	10.68	25.61
	298.15	9.95	24.85
	308.15	9.11	23.91
	313.15	8.60	23.52
Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4)	293.15	11.99	27.33
	298.15	11.24	25.87
	308.15	10.32	23.64
	313.15	9.78	22.61
Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4)	293.15	11.23	27.33
	298.15	10.50	25.87
	308.15	9.52	23.91
	313.15	9.22	23.52
Overall *AAD* (%)		10.20	

Table 5.23 shows an overall *AAD* (%) of 9.45 for the quinary system benzene (1) + toluene (2) + ethylbenzene (3) + heptane (4) + cyclooctane (5) and a *MAX* (%) of 27.33 at 293.15 K.

Generally speaking, the Allan and Teja correlation is considered a method with the least predictive capability of all the models tested in the present study.

5.3.5 **The artificial neural network based model**

Artificial neural networks (ANNs) have become a powerful tool for many chemical applications. The wide applicability of ANNs arises from their flexibility and ability to model non-linear relations without prior knowledge of the nature of these relations. In the present work, the application of ANNs to the prediction of the viscosities of multi-component liquid regular systems is considered.

5.3.5.1 **ANN methodology**

The ANN developed in the present study for the prediction of the kinematic viscosity of the regular quinary system and all its corresponding quaternary, ternary, and binary sub-systems will be briefly described.

The general structure of a multilayer network was selected on the basis of the highly non-linear relationship between kinematic viscosity and composition. One hidden layer was considered enough to describe this relationship. Figure 5.1 shows the general architecture of the developed neural network. One linear input layer with six neurons correspond to the six inputs fully connected to one non-linear hidden layer with four neurons and finally one linear output layer with one neuron corresponding to the predicted kinematic viscosity of the binary mixture.

Table 5.23: Results of Testing the Predictive Capability of the Allan and Teja Correlation for the **Quinary** System: benzene + toluene + ethylbenzene + heptane + cyclooctane.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5)	293.15	10.13	27.33
	298.15	9.56	25.87
	308.15	9.16	23.91
	313.15	8.95	23.52
Overall *AAD* (%)		9.45	

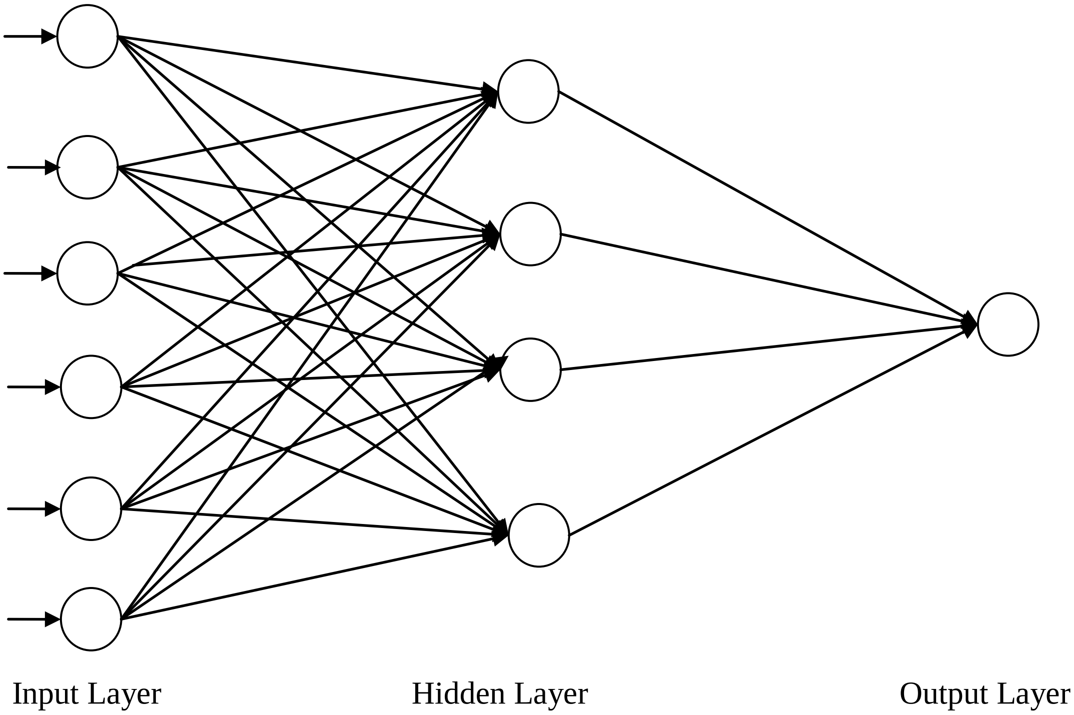

Figure 5.1: The Architecture of One Modular Network for a Binary System

A search procedure was implemented to identify the optimum number of neurons in the hidden layer as well as the type of the transfer function that gives the lowest possible root mean square error. The best performance was accomplished with a sigmoid transfer function of the logistic type and four neurons in the hidden layer.

The network was then trained using *half* of the binary data points gathered in the present study. The concept of the *modular* networks was utilized for the design of the current network. A *modular* network is characterized by a series of independent networks. Each independent network acts as a module and receives separate inputs to perform some sub-tasks for the general final task of the whole network. For example, in the current work, the binary trained network serves as a module for the ternary network. The output from the binary network together with the remaining component in the ternary systems acts as inputs to the ternary network and so on. A block diagram indicating an example of one modular network is shown in Figure 5.2.

The data for training were prepared using spread sheets. At the beginning of the design process, one network was developed to deal with all types of systems involved in the present study. Relatively high error values were observed. This led to separating the cyclooctane-containing-systems from systems that did not contain cyclooctane. This is the same procedure that was followed before in analyzing the results obtained from testing the other examined models as described earlier in the present chapter.

In order to reduce such high relatively error values, two networks were developed; the first one dealt with systems that did not contain cyclooctane and the second one was for the cyclooctane-containing systems.

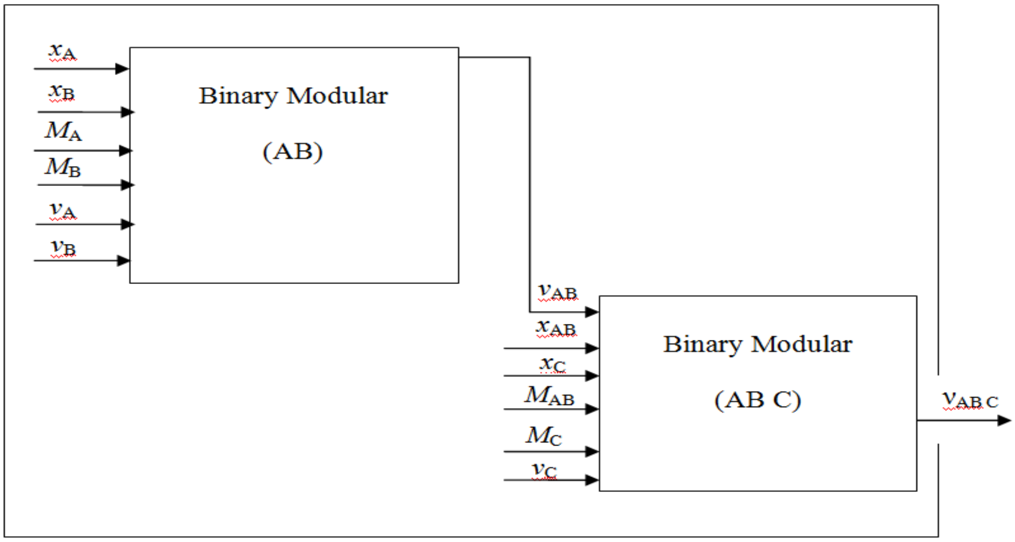

Figure 5.2: A Block Diagram for the Ternary Modular Network

Both networks had the same structure but, of course, they had different weights.

During the training phase, the inputs to the networks were: (i) the mole fractions of components 1 and 2 of the binary mixture, (ii) the kinematic viscosities of the pure components, (iii) the molecular weights of the pure components, and (iv) the temperature. Back propagation algorithm was employed in the training process. In order to calculate the error, the network was provided with a set of experimentally measured kinematic viscosity values so that the root mean square error in each case can be calculated by comparing the predicted value (*ideal*) with the corresponding measured value (*actual*) in each case. The following equation was used to calculate the error:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=0}^{n}\left(\nu_i^{actual} - \nu_i^{ideal}\right)^2} \qquad (5.10)$$

For the purpose of comparison with results obtained from other models, the corresponding *AAD* (%) was calculated in each case along with the overall values for all systems.

The software used during the training and testing is called “Joone 2.0.0 version” available from the public domain from www.Joone.org. The software is characterized by its simplicity and its user friendly interface.

5.3.5.2 Network design and results

After the networks were well trained, they were tested using the remaining binary data that were not part of the training process. The errors were as good as 2.98 % and 1.02 % for the binary non-cyclooctane-containing and the cyclooctane-containing-systems, respectively. But the error was increasing as the number of components increased, *viz*, in the sub-sequent ternary, quaternary and quinary systems' tests. Results were confusing in some systems with no clear reasons. This result led the present author to remove the temperature as one of the inputs to the network. It was thought that the effect of temperature is accounted for twice; (i) as an input to the network, and (ii) independently in the pure component kinematic viscosity values (due to the dependence of kinematic viscosities on temperature).

Training was repeated with the new inputs (excluding temperature). The results of training the first network on systems that did not contain cyclooctane led to an overall *AAD* (%) of 3.12. Training the second network that was developed for the cyclooctane-containing systems gave an overall *AAD* (%) of 0.93.

Both networks were retested using the remaining binary data, that were not part of the training process. Results of testing both networks are reported in Tables 5.24 and 5.25. The results reported in Table 5.24 for the binary non-cyclooctane containing systems showed an overall *AAD* (%) of 3.38. The benzene (1) + heptane (2) binary system showed a maximum deviation of 11.19 %. For the binary cyclooctane-containing systems an overall *AAD* (%) of 1.12 was obtained, and the heptane (1) + cyclooctane (2) binary system showed a maximum deviation of 5.19 % at 293.15 K.

For ternary systems consisting of components A, B, and C, there are only three possible combinations: AB-C, AC-B, and BC-A. In the first combination for example, data of components A and B were supplied to the appropriate modular network (depending on whether the system contained cyclooctane or not) to predict the kinematic viscosity of AB, ν_{AB}, then the resulting kinematic viscosity along with the properties of

Table 5.24: Results of Testing the Artificial Neural Network Model for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; (non-cyclooctane containing systems).

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2)	293.15	1.47	3.42
	298.15	1.99	2.54
	308.15	2.65	3.82
	313.15	2.30	3.56
Toluene (1) + Ethylbenzene (2)	293.15	4.15	6.15
	298.15	5.87	7.35
	308.15	5.99	7.82
	313.15	7.33	8.92
Heptane (1) + Toluene (2)	293.15	0.71	2.20
	298.15	1.02	1.59
	308.15	2.28	3.05
	313.15	1.52	2.10
Heptane (1) + Ethylbenzene (2)	293.15	2.04	2.63
	298.15	0.79	1.11
	308.15	1.38	2.35
	313.15	2.20	3.28
Benzene (1) + Ethylbenzene (2)	293.15	1.65	2.54
	298.15	2.56	3.64
	308.15	3.07	4.29
	313.15	4.09	5.39
Benzene (1) + Heptane (2)	293.15	8.53	11.19
	298.15	7.85	9.12
	308.15	4.49	6.30
	313.15	5.27	5.95
Overall *AAD* (%)		3.38	

Table 5.25: Results of Testing the Artificial Neural Network Model for the **Binary** Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; (cyclooctane containing systems).

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Cyclooctane (2)	293.15	0.94	2.15
	298.15	1.19	2.20
	308.15	0.58	0.79
	313.15	0.81	1.80
Toluene (1) + Cyclooctane (2)	293.15	2.23	2.94
	298.15	1.06	2.51
	308.15	1.05	1.77
	313.15	1.49	2.29
Ethylbenzene (1) + Cyclooctane (2)	293.15	1.07	2.17
	298.15	0.57	1.00
	308.15	1.46	2.76
	313.15	1.35	1.67
Heptane (1) + Cyclooctane (2)	293.15	2.18	5.19
	298.15	0.68	1.01
	308.15	0.45	1.10
	313.15	0.48	1.19
Overall *AAD* (%)		1.12	

component C were supplied, again, to the proper *modular* network to predict the kinematic viscosity of the ternary mixture ABC and so on. The designation A, B, and C were used in this part instead of components 1, 2, and 3 employed earlier in order to avoid confusion that might be caused to the reader especially with the nomenclature employed in the binary modular network and the McAllister binary or ternary interaction parameters.

It should be pointed out here that, treating a ternary system as if it was composed of two binary systems, required some normalization manipulations. For the first binary system, AB, the mole fractions of components A and B were the normalized mole fractions, x_A', and x_B' as per the following equations:

$$x_A' = \frac{x_A}{x_A + x_B} \qquad \text{and,} \qquad x_B' = \frac{x_B}{x_A + x_B} \tag{5.11}$$

The molecular weight of this binary system AB was calculated using the mixing rule suggested by Nhaesi and Asfour (2000 a) as,

$$M_{AB} = exp\left[x_A' \ell n\, M_A + x_B' \ell n\, M_B\right] \tag{5.12}$$

The same procedure was followed for all ternary systems and for all the three combinations.

As the number of components increases, the possible combinations increase too. For quaternary systems there were nine different combinations and there were 17 possible combinations for quinary systems. Due to time limitations, it was very hard to try all the possible combinations especially when we have both cyclooctane-and non-cyclooctane-

Table 5.26: Results of Testing the Artificial Neural Network Model for the **<u>Ternary</u>** non-cyclooctane containing Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination 1: AB C.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Heptane (3)	293.15	3.26	8.47
	298.15	1.36	5.69
	308.15	2.84	6.25
	313.15	2.58	5.65
Benzene (1) + Ethylbenzene (2) + Heptane (3)	293.15	3.34	9.99
	298.15	1.40	6.81
	308.15	2.96	5.56
	313.15	2.83	6.40
Toluene (1) + Ethylbenzene (2) + Heptane (3)	293.15	4.71	6.06
	298.15	6.29	7.88
	308.15	7.58	14.14
	313.15	7.80	13.46
Benzene(1) + Toluene (2) + Ethylbenzene (3)	293.15	17.39	22.09
	298.15	18.14	22.09
	308.15	18.26	23.87
	313.15	17.41	22.91
Overall *AAD* (%)		7.38	

Table 5.26 (Cont'd.): Results of Testing the Artificial Neural Network Model for the **Ternary** (non-cyclooctane containing) Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination 2: AC B.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Heptane (3)	293.15	5.10	9.33
	298.15	3.35	7.02
	308.15	3.19	7.19
	313.15	3.41	7.39
Benzene (1) + Ethylbenzene (2) + Heptane (3)	293.15	6.92	12.83
	298.15	4.71	10.03
	308.15	3.45	8.07
	313.15	2.89	6.87
Toluene (1) + Ethylbenzene (2) + Heptane (3)	293.15	1.41	2.62
	298.15	1.41	2.59
	308.15	3.40	9.35
	313.15	3.56	9.20
Benzene(1) + Toluene (2) + Ethylbenzene (3)	293.15	16.00	20.15
	298.15	16.56	20.15
	308.15	16.49	22.25
	313.15	16.50	21.09
Overall *AAD* (%)		6.72	

Table 5.26 (Cont'd.)**:** Results of Testing the Artificial Neural Network Model for the **Ternary** (non-cyclooctane containing) Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination 3: BC A.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Heptane (3)	293.15	7.01	9.83
	298.15	5.06	7.40
	308.15	4.30	8.49
	313.15	4.48	8.43
Benzene (1) + Ethylbenzene (2) + Heptane (3)	293.15	6.09	11.55
	298.15	3.64	8.71
	308.15	3.04	5.23
	313.15	2.89	5.00
Toluene (1) + Ethylbenzene (2) + Heptane (3)	293.15	2.68	4.81
	298.15	4.10	6.56
	308.15	5.45	12.58
	313.15	5.72	11.95
Benzene(1) + Toluene (2) + Ethylbenzene (3)	293.15	4.63	5.84
	298.15	6.32	7.51
	308.15	7.51	15.79
	313.15	7.82	15.82
Overall *AAD* (%)		5.05	

containing systems; i.e., the number of combinations will be doubled.

Results reported in Table 5.26 indicate the different possible combinations for the ternary-non-cyclooctane containing systems with the *AAD* (%) and *MAX* (%) calculated for each system at each temperature. In addition, the overall *AAD* (%) is calculated for each case. No specific criterion was provided in the present study for the selection of the optimum combination. It was observed that the difference in the overall *AAD* (%) among the three combinations was within 1 %. This led the present author to take the average predicted viscosity for the three combinations and compare it with the experimental value in order to calculate the *AAD* (%) for each system. Table 5.27 shows the average viscosity for all three combinations. It should be pointed out here that the overall *AAD* (%) for this average was the considered the value to be compared with the other tested models which is equal to 6.18.

The same procedure was followed for the remaining ternary cyclooctane-containing systems. Results for the three different combinations are reported in Table 5.28.

It should be pointed out here that in case of the ternary cyclooctane-containing systems, the first combination gave the lowest overall *AAD* (%). In this case the difference in the overall *AAD* (%) among the three possible combinations may be attributed to the fact that the cyclic network was trained to always have cyclooctane as the second component in the system. The average value in the case will not be considered and the present author will only consider the combination with the lowest error for the case of comparison. For the combination AB C, the overall *AAD* (%) was found to be

Table 5.27: Results of Testing the Artificial Neural Network Model for the **Ternary** (non-cyclooctane containing) Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; average of the three combinations.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Heptane (3)	293.15	5.12	9.21
	298.15	3.25	6.71
	308.15	3.16	7.04
	313.15	3.38	7.15
Benzene (1) + Ethylbenzene (2) + Heptane (3)	293.15	5.45	11.46
	298.15	3.03	8.52
	308.15	2.51	5.65
	313.15	2.42	4.69
Toluene (1) + Ethylbenzene (2) + Heptane (3)	293.15	2.11	3.93
	298.15	3.70	5.68
	308.15	5.09	12.02
	313.15	5.53	11.54
Benzene(1) + Toluene (2) + Ethylbenzene (3)	293.15	12.67	15.06
	298.15	13.67	15.63
	308.15	14.04	20.64
	313.15	13.61	19.94
Overall *AAD* (%)		6.18	

Table 5.28: Results of Testing the Artificial Neural Network Model for the **Ternary** (cyclooctane containing) Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination 1: AB C.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Cyclooctane (3)	293.15	0.57	1.36
	298.15	0.58	1.55
	308.15	3.68	9.32
	313.15	3.71	9.42
Toluene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	1.86	2.90
	298.15	2.82	3.75
	308.15	4.11	9.93
	313.15	4.18	10.15
Benzene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	1.11	2.32
	298.15	54.53	69.72
	308.15	3.42	10.65
	313.15	3.59	11.36
Benzene (1) + Heptane (2) + Cyclooctane (3)	293.15	3.91	7.68
	298.15	3.20	6.70
	308.15	4.40	11.91
	313.15	4.26	11.40
Toluene (1) + Heptane (2) + Cyclooctane (3)	293.15	0.59	1.27
	298.15	1.98	9.27
	308.15	4.17	9.19
	313.15	5.57	18.07
Ethylbenzene (1) + Heptane(2) + Cyclooctane (3)	293.15	1.46	2.56
	298.15	0.67	1.13
	308.15	3.57	8.20
	313.15	3.83	9.12
Overall *AAD* (%)		5.07	

Table 5.28 (Cont'd.)**:** Results of Testing the Artificial Neural Network Model for the **Ternary** (cyclooctane containing) Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination 2: AC B**.**

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Cyclooctane (3)	293.15	12.07	43.43
	298.15	10.94	38.18
	308.15	11.34	28.21
	313.15	10.80	23.58
Toluene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	10.44	37.67
	298.15	9.32	32.48
	308.15	10.19	22.59
	313.15	9.60	18.31
Benzene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	6.25	20.48
	298.15	6.83	22.66
	308.15	10.96	24.36
	313.15	11.42	24.00
Benzene (1) + Heptane (2) + Cyclooctane (3)	293.15	13.49	34.38
	298.15	13.61	34.38
	308.15	14.69	24.08
	313.15	14.01	23.73
Toluene (1) + Heptane (2) + Cyclooctane (3)	293.15	13.44	38.73
	298.15	11.55	33.43
	308.15	13.97	23.37
	313.15	11.51	22.04
Ethylbenzene (1) + Heptane(2) + Cyclooctane (3)	293.15	13.05	39.78
	298.15	12.25	34.50
	308.15	14.25	24.11
	313.15	13.83	24.05
Overall *AAD* (%)		11.66	

Table 5.28 (Cont'd.)**:** Results of Testing the Artificial Neural Network Model for the **Ternary** (cyclooctane containing) Sub-Systems of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination 3: BC A.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Cyclooctane (3)	293.15	11.22	43.21
	298.15	9.68	38.05
	308.15	9.27	28.38
	313.15	7.99	23.93
Toluene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	10.21	38.84
	298.15	9.32	33.68
	308.15	9.42	33.78
	313.15	9.08	19.39
Benzene (1) + Ethylbenzene (2) + Cyclooctane (3)	293.15	3.43	7.08
	298.15	2.57	4.16
	308.15	5.06	13.11
	313.15	6.05	14.83
Benzene (1) + Heptane (2) + Cyclooctane (3)	293.15	11.95	33.70
	298.15	11.67	33.70
	308.15	11.03	24.08
	313.15	10.56	19.86
Toluene (1) + Heptane (2) + Cyclooctane (3)	293.15	11.66	38.07
	298.15	10.32	32.89
	308.15	10.71	23.18
	313.15	9.36	18.93
Ethylbenzene (1) + Heptane(2) + Cyclooctane (3)	293.15	10.46	37.80
	298.15	10.03	32.68
	308.15	9.63	22.80
	313.15	9.18	18.74
Overall *AAD* (%)		9.19	

5.07 and the ternary system Toluene (1) + Heptane (2) + Cyclooctane (3) showed the maximum deviation of 18.07 % at a temperature of 313.15 K.

For the quaternary systems, as indicated earlier, the number of possible combinations is nine for each case, i.e., cyclooctane-containing systems and non-cyclooctane-containing systems. Based on the conclusions reached earlier for the different ternary combinations, only three combinations out of nine were considered. They agreed within ± 1 %, which confirmed the earlier results. The average value cannot be reported here because all possible combinations were not tried. The combination; BC D A gave the lowest *AAD* (%) of 3.72 for the quaternary system that did not contain cyclooctane. Table 5.29 reports the *AAD* (%) and the maximum deviation for this combination at different temperatures.

For the remaining quaternary cyclooctane-containing systems, the best combination out of the three trials was AB CD. It gave an overall *AAD* (%) of 2.98. Results of this combination are reported in Table 5.30.

For the quinary system, only one combination was tried which was AB C D E. The overall error was 3.43 %. The results of the *AAD* (%) and the *MAX* (%) are reported in Table 5.31 for that combination at all temperatures. The maximum deviation of 6.39 % was reported for the quinary system at 313.15 K.

Table 5.29: Results of Testing the Artificial Neural Network Model for the **<u>Quaternary</u>** (non-cyclooctane containing) Sub-System of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination BC D A.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) Ethylbenzene (3) + Heptane (4)	293.15	1.71	3.66
	298.15	3.23	5.62
	308.15	5.01	7.90
	313.15	4.91	7.14
Overall *AAD* (%)		3.72	

Table 5.30: Results of Testing the Artificial Neural Network Model for the **Quaternary** (cyclooctane containing) Sub-System of the Quinary System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination AB CD.

System	Temperature, K	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4)	293.15	4.03	4.94
	298.15	4.99	6.06
	308.15	5.93	7.56
	313.15	6.64	8.04
Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4)	293.15	1.45	2.95
	298.15	1.74	3.94
	308.15	3.15	4.53
	313.15	4.57	5.68
Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4)	293.15	2.73	6.27
	298.15	1.61	3.87
	308.15	1.38	2.39
	313.15	1.94	3.48
Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4)	293.15	2.73	5.90
	298.15	1.33	2.87
	308.15	1.35	2.39
	313.15	2.07	2.62
Overall *AAD* (%)		2.98	

5.4 Summary of the Comparison Between the Predictive Capabilities of the Different Viscosity Models

Analysis of the results presented earlier in the present chapter is summarized in this section. The comparison of the predictive capabilities of the models tested depends on two factors; *viz.*, (i) the type of the system; i.e., binary, ternary,..etc., and (ii) whether the system contained *cyclooctane* as one of its components or not.

Figures 5.3 through 5.9 show the overall comparison of the tested models for the investigated systems at the temperatures 293.15 K, 298.15 K, 308.15 K, and 313.15 K over the entire composition range. A bar chart type was used to facilitate the comparison.

Starting with the binary sub-systems of the quinary system: benzene (1) + toluene (2) + ethylbenzene (3) + heptanes (4) + cyclooctane (5), Figure 5.3 shows binary sub-systems that do not contain cyclooctane. It is clear from that figure that the *predictive* version of the McAllister three-body model has the best predictive capability of all tested models. The Allan and Teja correlation, on the basis of Figure 5.3, shows the lowest predictive capability of all tested models.

For the case of the binary cyclooctane-containing sub-systems, as shown in Figure 5.4, the artificial neural network developed for cyclic compounds gave the lowest *AAD* (%) of 1.12. This error value is very low as compared to the error value obtained from testing the predictive version of the McAllister model which is 11.67 % (upon using 75 % of the value of *ECN* of cyclooctane calculated with the help of equation (5.10); i.e., *ECN*=10.595) which is relatively high if compared with the value obtained from binary sub-systems that didn’t contain cyclooctane. The figure also shows the highest *AAD (%)*

Table 5.31: Results of Testing the Artificial Neural Network Model for the **Quinary** System: benzene + toluene + ethylbenzene + heptane + cyclooctane; Combination AB C D E.

System	T (K)	*AAD* (%)	*MAX* (%)
Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5)	293.15	1.25	2.56
	298.15	2.54	4.27
	308.15	4.72	6.21
	313.15	5.21	6.39
Overall *AAD* (%)		3.43	

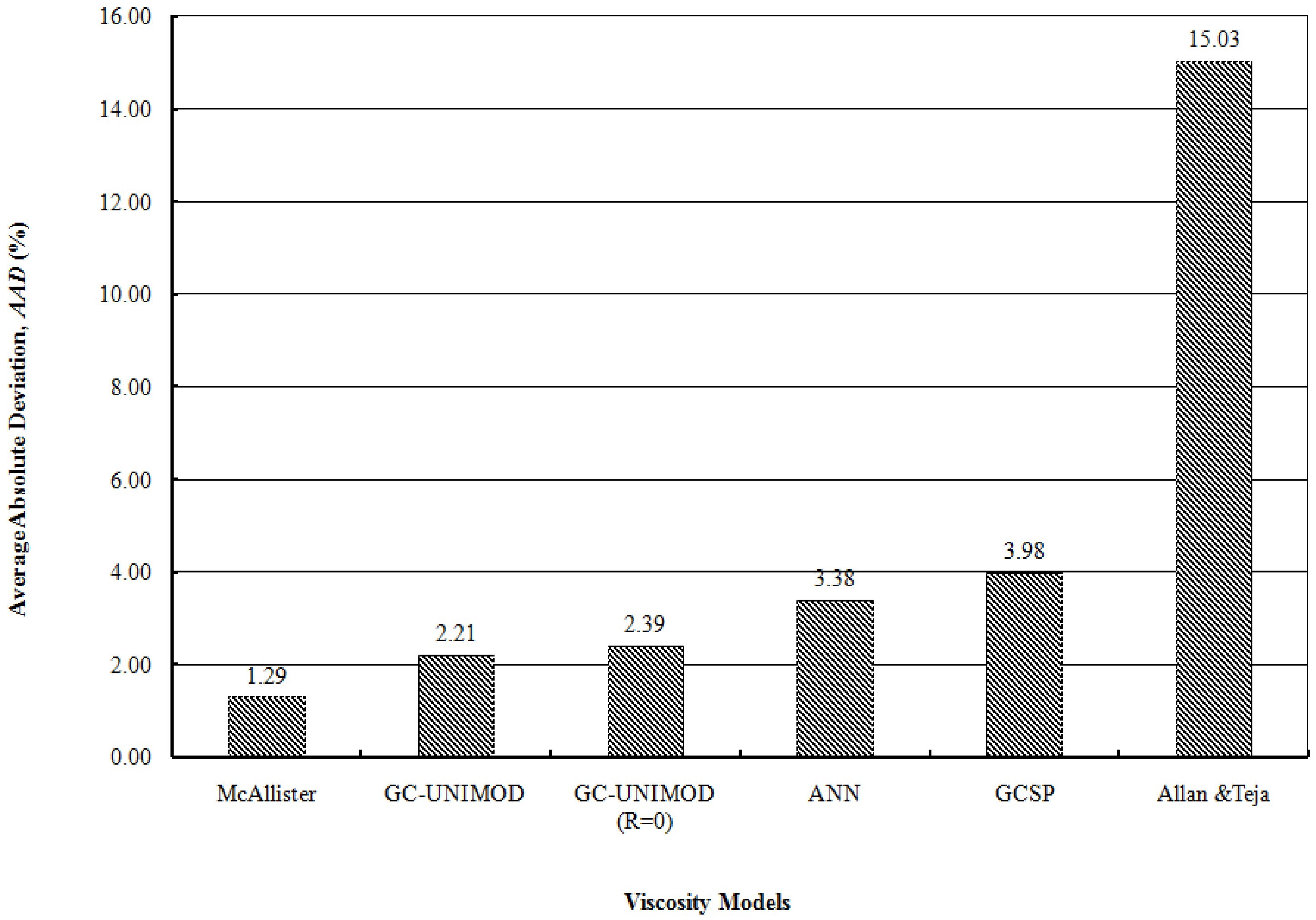

Figure 5.3: Predictive Capabilities of the Various Viscosity Models for Binary non-cyclooctane Containing Systems

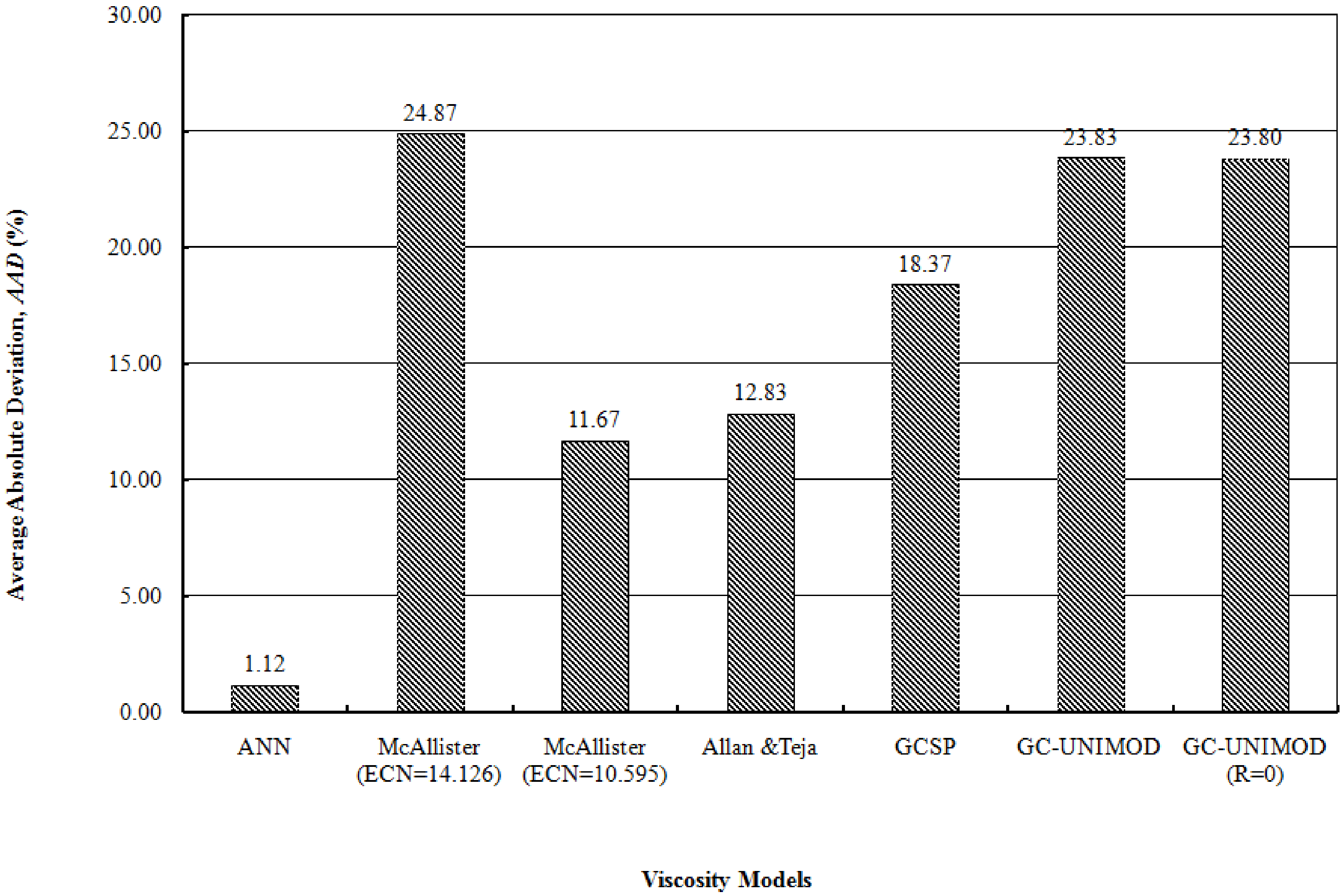

Figure 5.4: Predictive Capabilities of the Various Viscosity Models for Binary Cyclooctane Containing Systems.

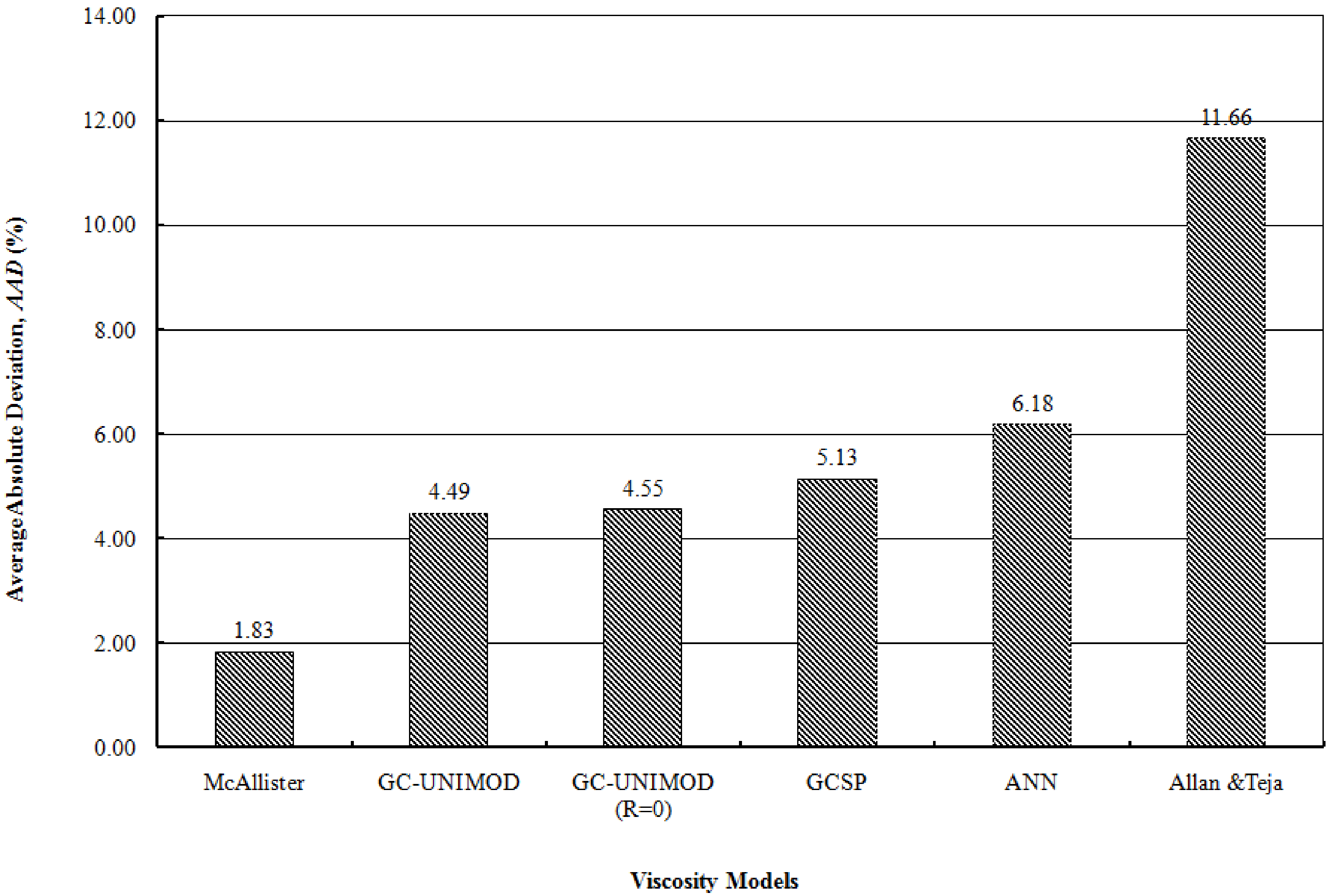

Figure 5.5: Predictive Capabilities of the Various Viscosity Models for Ternary non-cyclooctane Containing Systems.

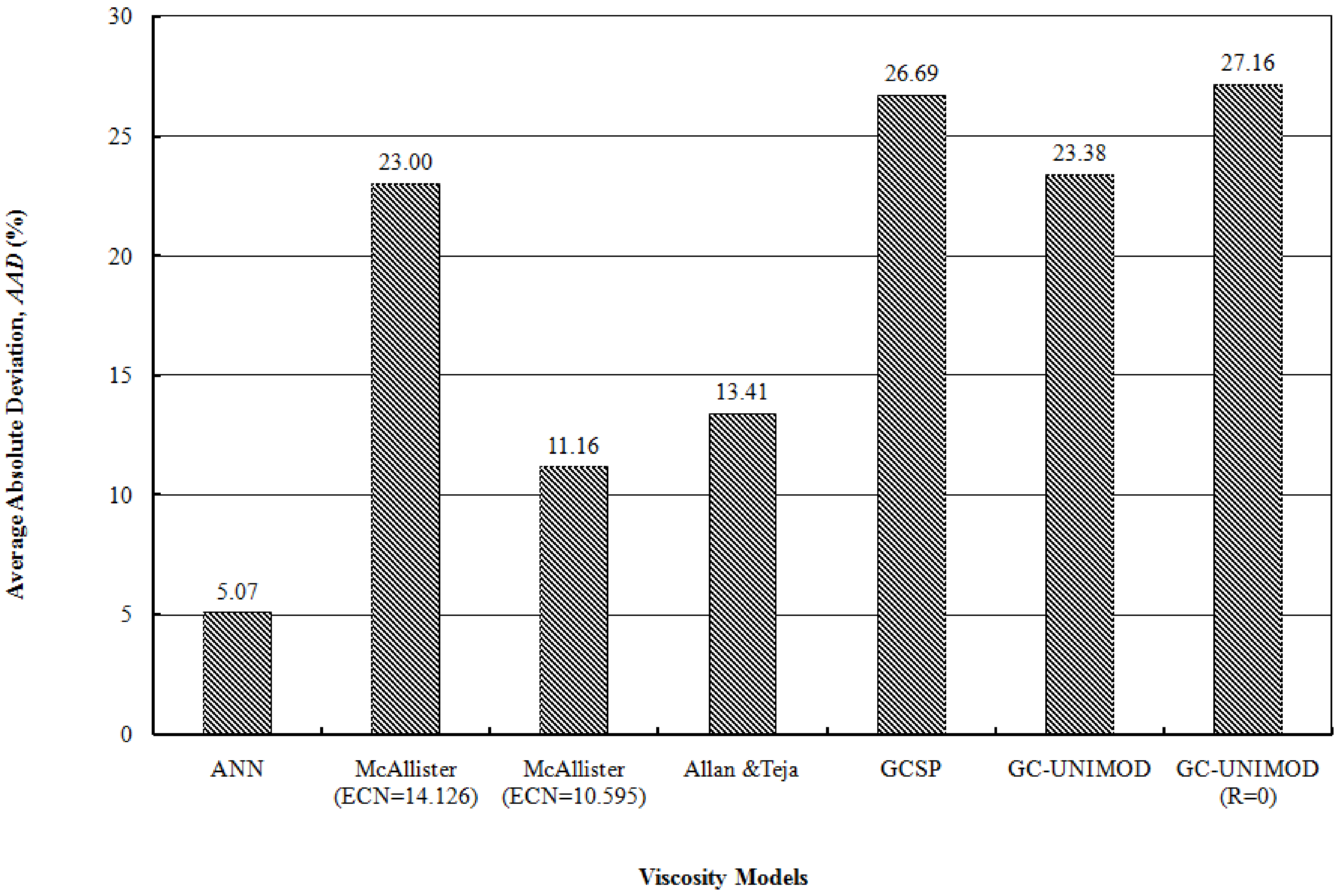

Figure 5.6: Predictive Capabilities of the Various Viscosity Models for Ternary Cyclooctane Containing Systems.

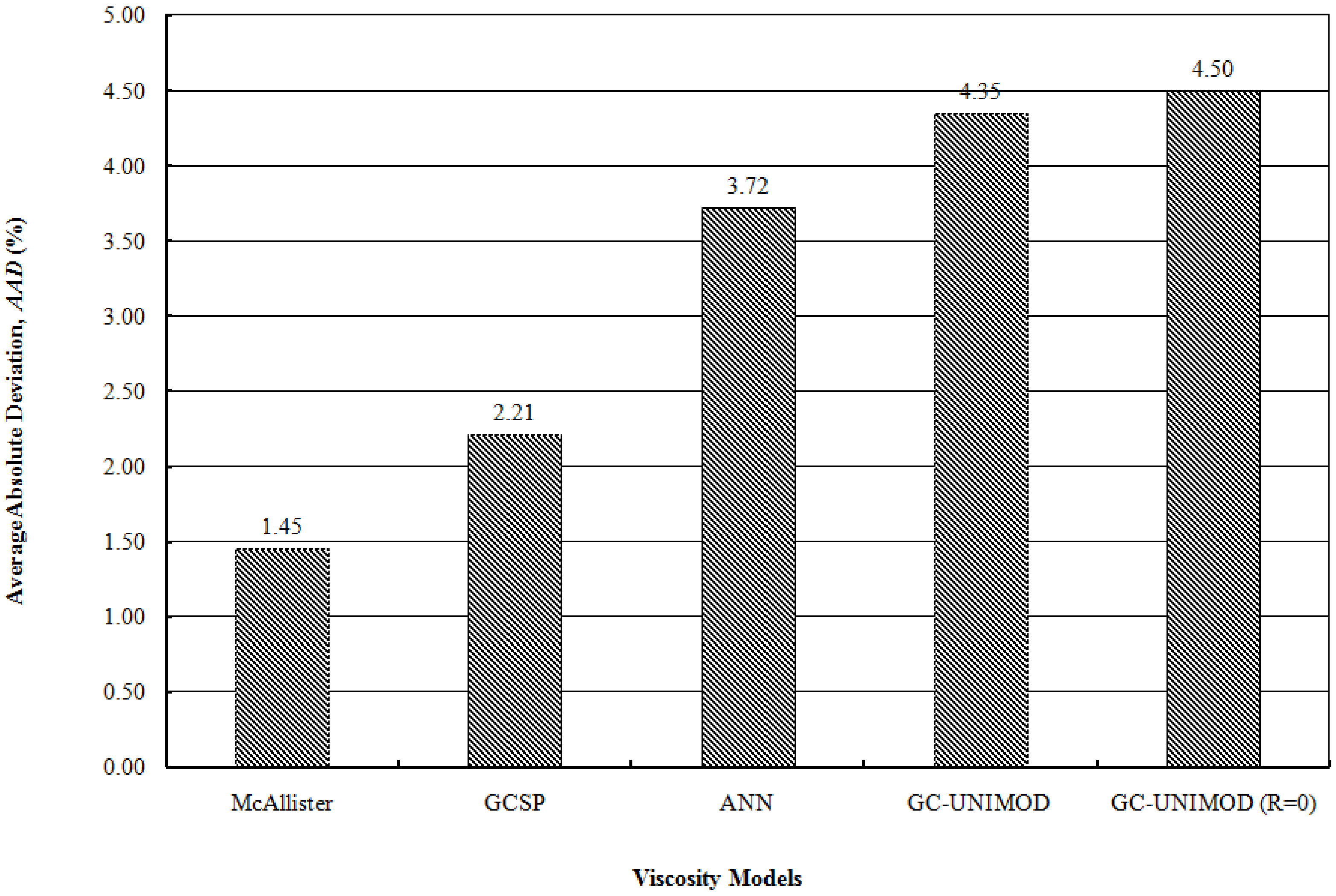

Figure 5.7: Predictive Capabilities of the Various Viscosity Models for Quaternary non-cyclooctane Containing Systems.

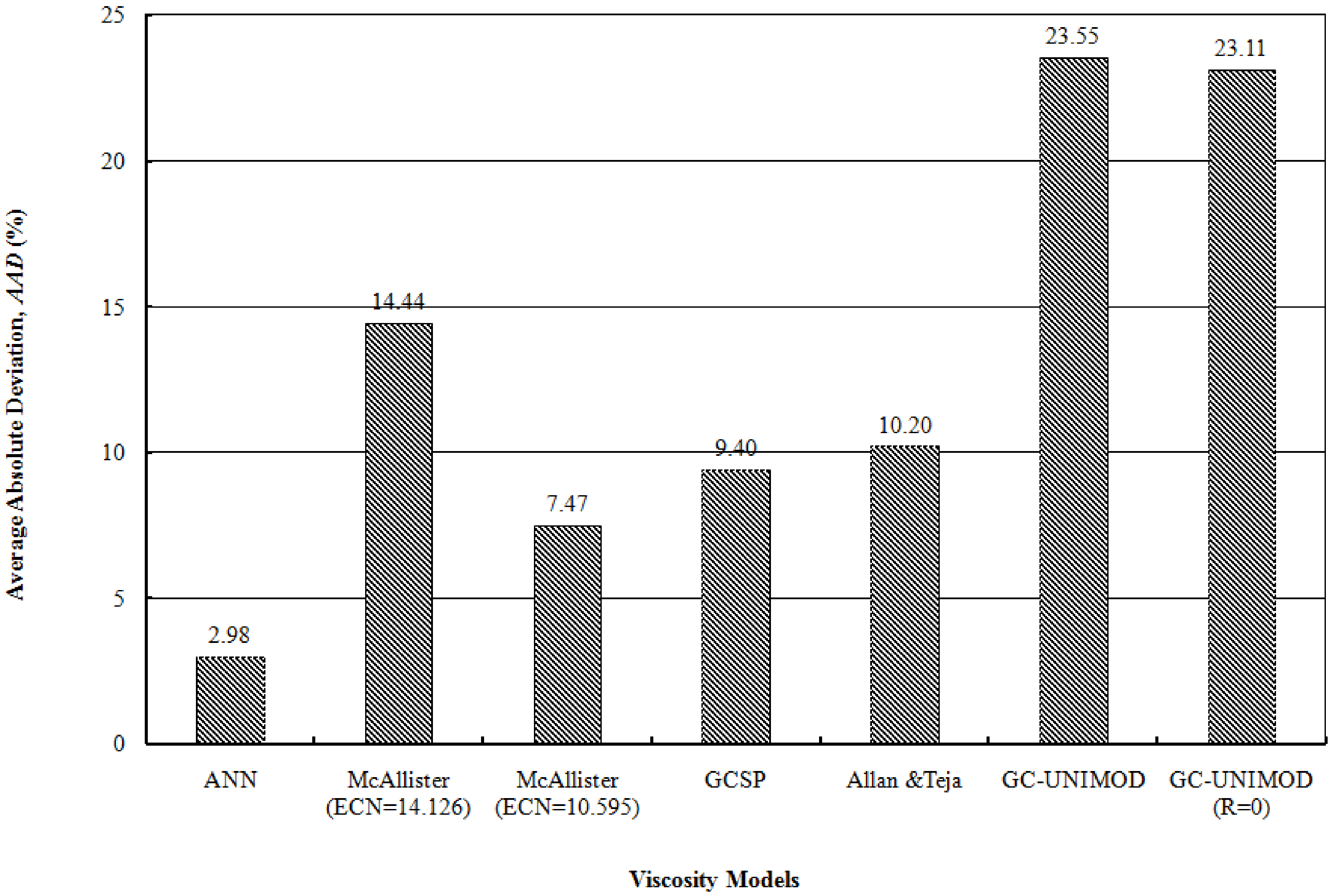

Figure 5.8: Predictive Capabilities of the Various Viscosity Models for Quaternary Cyclooctane Containing Systems.

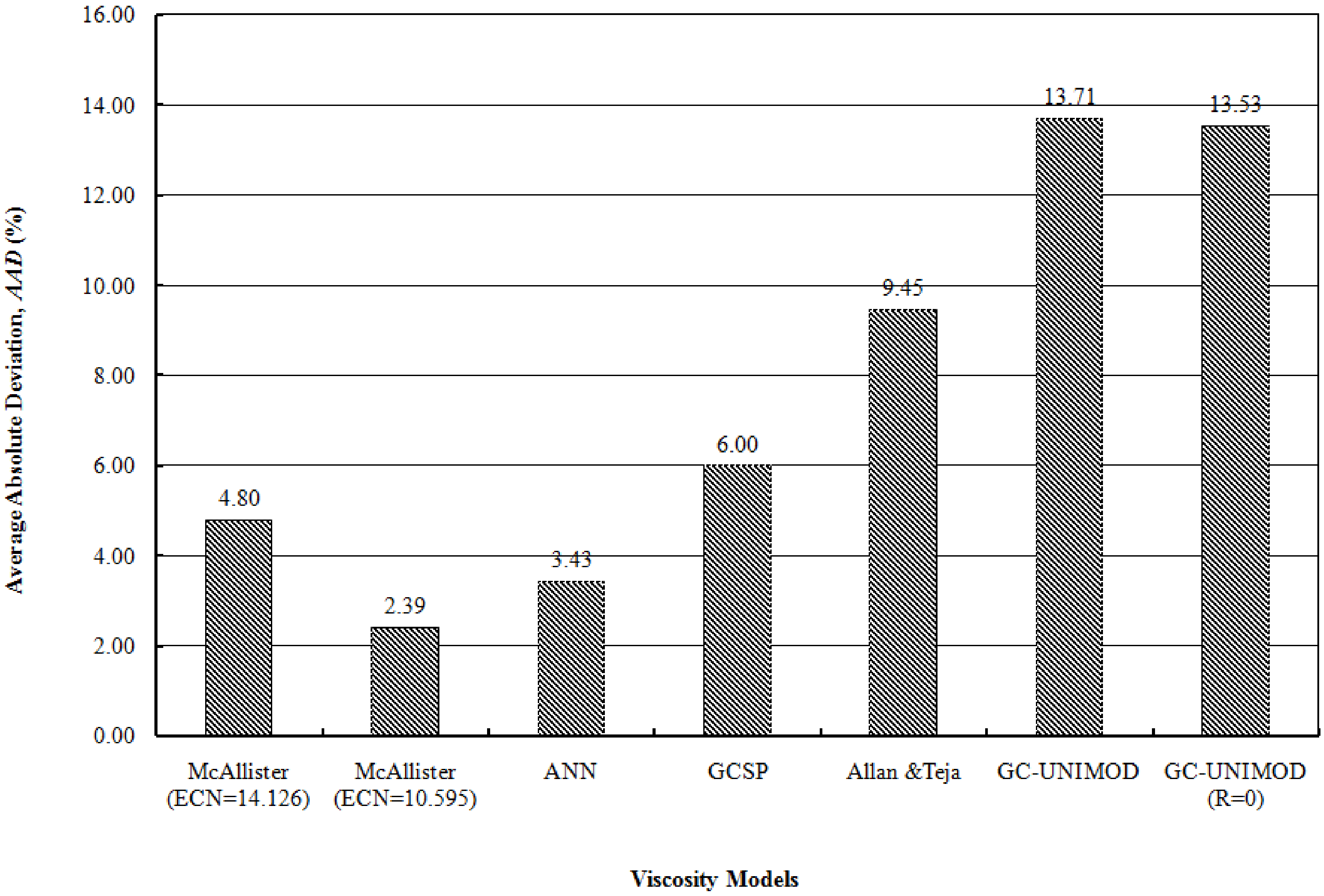

Figure 5.9: Predictive Capabilities of the Various Viscosity Models for Quaternary System; benzene + toluene + ethylbenzene + heptane + cyclooctane

found of 23.83 % for GC-UNIMOD method.

It should be pointed out here that the ANN gave results that are superior to other models, including the McAllister model in the case of the cyclooctane-containing systems. This is attributed to the fact that the ANN deals best with highly non-linear systems, which is the case for those cyclooctane-containing systems.

Figures 5.5 and 5.6 show the comparison results of the ternary sub-systems of the quinary system; benzene + toluene + ethylbenzene + heptane + cyclooctane, without and with cyclooctane as one of the components, respectively.

Again, the predictive version of the McAllister three-body model showed the lowest *AAD* (%) of 1.83, as shown in Figure 5.5, whereas the Allan and Teja correlation showing the worst viscosity predictive capability with a *AAD* (%) of 11.66.

For the case of the ternary-cyclooctane containing systems, Figure 5.6, indicates that the ANN showed the best predictive capability among the tested models with an overall *AAD* (%) of 5.07. The highest *AAD* (%) was found to be 27.16 for the case of the GC-UNIMOD.

For the case of the quaternary sub-systems, the predictive version of the McAllister three-body model gave the lowest *AAD* (%) of 1.45 confirming again its excellent predictive capability when compared with the remaining investigated models. This is clearly depicted in Figure 5.7. The highest *AAD* (%) was found to be 13.86 for the case of the Allan and Teja correlation.

For the cyclooctane-containing quaternary sub-systems, Figure 5.8 shows the lowest *AAD* (%) of 2.98 when the ANN was used. The highest *AAD* (%) value of 23.55 was obtained when the GC-UNIMOD was used.

Finally, testing the predictive capability of the different viscosity models using the data of the quinary regular system: benzene (1) + toluene (2) + ethylbenzene (3) + heptanes (4) + cyclooctane (5), confirmed the superior predictive capability of the predictive version of the McAllister three-body model. The lowest *AAD* (%) of 2.39 was obtained when an *ECN* value of 10.595 for cyclooctane was used. The result is shown in Figure 5.7. The GC-UNIMOD gave the highest *AAD* (%) of 13.71. In the case of the quinary system based on the previous results, one should expect the ANN to have the lowest error. This could not be confirmed in the current study because not all the possible combinations have been tested. The present author expects the ANN to be superior to other models in the case of the quinary system if all the combinations were tested. This has been confirmed before by the slightly different error results between the different combinations for the ternary and quaternary systems.

Generally speaking, the predictive version of the McAllister three-body model showed the best predictive capability when compared with all the other models investigated in the present study for the case of the non-cyclooctane containing systems. The developed ANN predicted the kinematic viscosities of the cyclooctane-containing-systems much better than all other tested models. This has been observed during training the network on the cyclooctane-containing-systems. The network learned the relation faster and easier than the non-cyclic network did with non-cyclooctane-containing systems.

The predictive capabilities of all tested models for all investigated systems are shown in the 3-D Figures 5.10 and 5.11. Figure 5.10 indicates the overall *AAD* (%) of the different tested models for all systems that did not contain cyclooctane, whereas, the overall *AAD* (%) of the cyclooctane-containing systems for all models are represented by Figure 5.11.

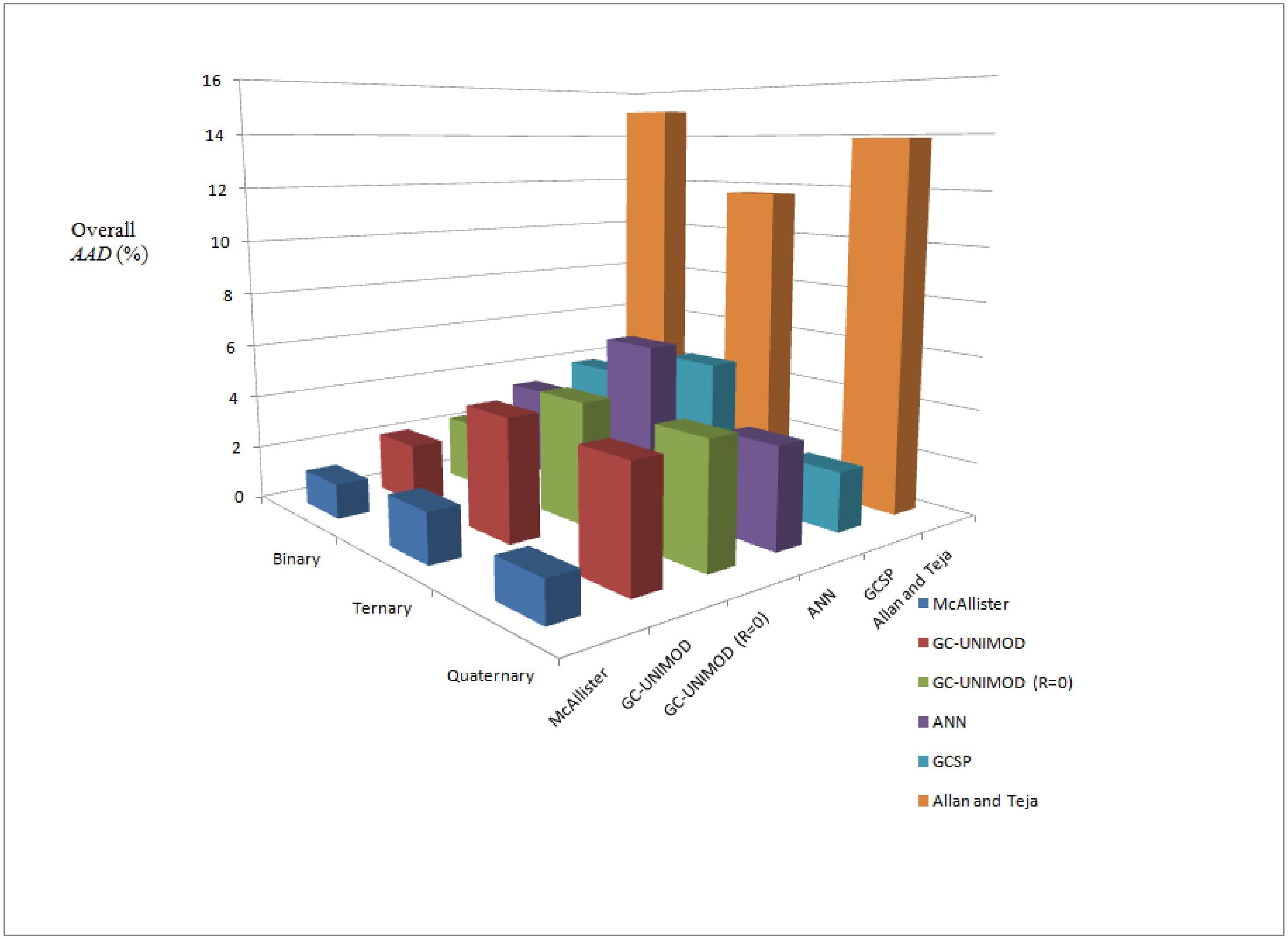

Figure 5.10: Predictive Capabilities of the Various Viscosity Models for non-cyclooctane Containing Systems.

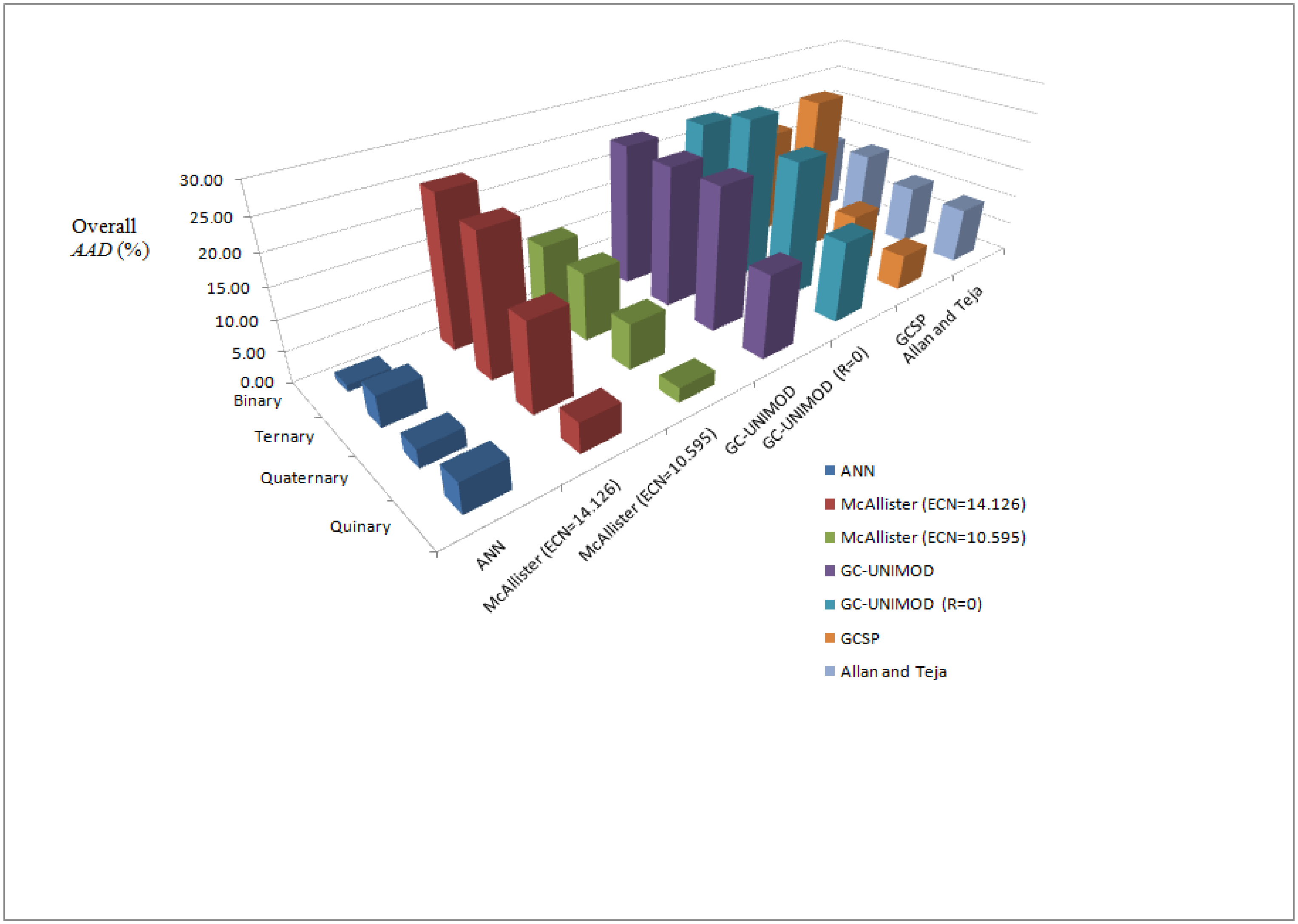

Figure 5.11: Predictive Capabilities of the Various Viscosity Models for Cyclooctane Containing Systems.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The densities and viscosities of one quinary, five quaternary, ten ternary, and ten binary regular liquid mixtures were measured and reported at four temperatures over the entire composition range. The multi-component viscosity and density composition data reported herein are considered valuable on their own since they represent new additions to the literature. The reported experimental data were utilized for further testing of the predictive capabilities of some well known viscosity models. Moreover, the binary data gathered in the present study were employed to develop an artificial neural network, that was used to predict the kinematic viscosities of remaining ternary, quaternary, and quinary systems investigated in the present study. Results from the artificial neural network were then reported and compared to the results obtained from testing the other models. During model testing calculations, cyclooctane containing systems were separated from other systems.

The following conclusions have been reached:

i) The densities and viscosities of the pure components constituting the investigated systems measured and reported in the present study were found to be in excellent agreement when compared with the corresponding literature values.

ii) A multi-layer artificial neural network with back propagation has been developed in the present study. The concept of the modular network was proposed in order to use binary data for the prediction of the kinematic viscosities of multi-component liquid systems.

iii) The developed artificial neural network was the best to predict the kinematic viscosities for all cyclooctane-containing systems with big difference in terms of the prediction error. The second best was the predictive version of the McAllister three-body model. The network trained on cyclooctane-containing binary mixtures was found to learn the viscosity-composition data easier and faster than did the non-cyclic network. This may be attributed to the neural network documented ability to successfully represent highly non-linear relationships.

iv) The modified version of the McAllister three-body model was found to have the best predictive capability of viscosities among all tested models for the case of systems that did not contain cyclooctane.

v) The equation employed for the calculation of the *ECN* of the regular solutions (Nhaesi and Asfour 1998) was found to overpredict the *ECN* of cyclooctane. Using 75 % of the overpredicted value as suggested by Al-Gerwi *et al*. (2006) led to dramatically reduced error values. This confirmed the earlier studies performed by El-Hadad (2004), Cai (2004), and Al-Gherwi (2006) in case of cyclohexane.

vi) Three binary systems and one ternary system contained the combination: benzene, toluene, and ethylbenzene gave higher error values when the first adjustable parameter, equation (2.37), was calculated by using the equation suggested for regular solutions. Applying the equation suggested for *n*-alkanes, equation (2.31), instead to calculate the McAllister's adjustable parameter much better results were obtained. This confirmed Al-Gerwi *et al*. (2006) earlier explanation that the benzene rings contained in these components tend to off-set each other and that the interactions only took place amongst the side chains.

vii) Testing the GC-UNIMOD showed the insignificant effect of including the residual part in the viscosity calculations.

6.2 Recommendations

The following recommendations are made for further studies:

i) Although the predictive version of the McAllister three-body model showed excellent predictive capability for the case of the non-cyclooctane-containing systems, more attention should be given to regular solutions containing cyclic compounds to compare their behavior with cyclooctane.

ii) There is an urgent need for the development of the generalized McAllister four-body interaction model. A four-body interaction model is expected to better predict the kinematic viscosities of systems that contain cyclic compounds with relatively large diameter molecules.

iii) The impressive results obtained from the application of the ANN for the case of the cyclooctane-containing-systems should be considered for further development and improvement of ANNs to treat different types of solutions as well as systems with more than five components.

iv) The predictive version of the McAllister model is recommended to be combined with the ANN in order to better represent the kinematic viscosity-composition relation for all types of multi-component systems. Prior knowledge of this relationship might facilitate the training of the network.

v) More research is required for reaching an optimum combination of the multi-component systems that can be provided to the modular neural network in order to reduce the time consuming trials.

NOMENCLATURE

a	group interaction energy parameter, constant
A	NRTL parameter
B	constant used generally as a parameter
C	constant used generally as a parameter
D	constant used generally as a parameter
E	constant used generally as a parameter
f_i	equivalent substance reducing ratio Eqn. (2.92)
F	characteristic parameter
G	NRTL non-randomness factor
Δ^*G	molar activation energy of viscous flow, J/mol
h	Plank’s constant
h_i	equivalent substance reducing ratio Eqn. (2.92)
H	enthalpy,
i	index number
j	index number
k	index number

K	Boltzman's constant
M	molecular weight
n	number of experimental points, number of interaction parameters, number of pure components in the mixture
N	Avogadro's number; number of carbon atoms
$\bar{N}$	average chain length for pseudo component
P	pressure, atm
Q	surface area parameter Eq. (2.110)
q	area parameter of molecule Eq. (2.109)
R	universal gas constant, volume parameter Eq. (2.111)
r	number of segment of molecule
S	adjustable parameter Eq. (2.123)
T	temperature, K
t	efflux time of the viscometer, s
V	liquid molar volume, m^3/mol
x	mole fraction
$\times$	mole fraction of the *pseudo-binary* component
Z	compressibility factor

Greek Symbols

η	absolute viscosity, Pa.s
θ	shape factor, Eq. (2.93), local composition Eq. (2.99)
λ	average distance between equilibrium positions in the direction of motion in Eyring's theory
λ_1, λ_2, λ_3	intermolecular distance involved in Eyring's theory
v	kinematic viscosity, m^2/s
v_{12}, v_{21}	binary interaction parameters in McAllister's three-body model
v_{123}	ternary interaction parameter in McAllister's three-body model
v_{1112}, v_{2221}, v_{1122}	different types of interaction parameters in McAllister's four-body model
ξ	interaction parameter in GCSP model
ρ	density, kg/L
σ	free energy mixing parameter in NRTL model, proportionality factor Eq. (2.134)
τ	shear stress Eq. (1.1), interaction parameter Eq. (2.99), density meter oscillation period, s Eq. (3.1)
Ξ	group residual viscosity Eq. (2.103)

Ω	positive real root of Eq. (2.130)
ω	Pitzer acentric factor
δ	Heric and Brewer model parameter Eq. (2.142)
γ	activity coefficient
α	NRTL model parameter Eq. (2.117)
ζ	reciprocal of fluid viscosity at critical temperature
ϕ	shape factor, Eq. (2.94), average segment fraction Eq. (2.102), volume fraction Eq. (2.115), fugacity coefficient Eq. (2.135)
ψ	interaction parameter in GCSP method Eq. (2.81)

Subscripts

1,2,3	refers to various components in the mixture
123	refers to interaction between three molecules
c	critical property
avg	average property
m	mixture property
cm	pseudo-critical property
r	reduced property

Superscripts

E	excess property
i	ideal property
i,j	refers to the ith and jth component in the mixture, respectively
ij	refers to the type i-j interaction in McAllister's model
ijk	refers to the type i-j-k interaction in McAllister's model
$^{\circ}$	refers to the spherical reference fluid
´	refers to the property of the pseudo mixture
j	refers to the target reference fluid
(r_1), (r_2)	refers to reference fluid numbers 1 and 2 respectively in the GCSP
(o)	refers to a property with a zero acentric value ($\omega=0$)
(r)	refers to a property with a non-zero acentric value ($\omega>0$)

Acronyms

AAD	average absolute deviation, usually expressed as %
ANN	Artificial Neural Network
ASOG	Analytical Solution of Group method

ECN	effective carbon number
ECSP	Extended Corresponding States Principle
EOS	Equation of State
GCSP	Generalized Corresponding States Principle
GC-UNIMOD	Group Contribution-Viscosity Thermodynamics Model
LCD	Linear Composition Dependent
MAX	maximum deviation, usually expressed as %
MGCSP	Modified Generalized Corresponding States Principle
NRTL	Nonrandom Two Liquids model
RMS	Root Mean Squared error
TRAPP	Transport Properties Prediction Program
UNIFAC	UNIQUAC Functional-group Activity Coefficients
UNIQUAC	Universal Quasi-Chemical model
VLE	vapor liquid equilibrium

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APPENDICES

Appendix A

Density and Kinematic Viscosity Raw Data

Table A.1: Raw Data for the Binary System Benzene (1) + Toluene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.0403	25 (B365)	0.733393	372.88	0.732296	352.68
0.1393	25 (B366)	0.733536	359.41	0.732432	340.33
0.2551	25 (B349)	0.733732	389.94	0.732618	368.30
0.3116	25 (B350)	0.733823	395.42	0.732701	375.33
0.3863	25 (B350)	0.733981	396.11	0.732846	357.06
0.5033	25 (B349)	0.734200	396.09	0.733054	373.30
0.6139	25 (B365)	0.734455	386.37	0.733293	379.78
0.7301	25 (B366)	0.734745	377.01	0.733571	353.78
0.8551	25 (B366)	0.735096	383.52	0.733903	358.45

Table A.1 (Cont'd.): Raw Data for the Binary System Benzene (1) + Toluene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.0403	25 (B365)	0.730111	317.16	0.729018	302.01
0.1393	25 (B366)	0.730223	306.35	0.729118	291.56
0.2551	25 (B349)	0.730380	330.16	0.729266	313.65
0.3116	25 (B350)	0.730457	334.82	0.729331	317.74
0.3863	25 (B350)	0.730586	335.17	0.729453	318.49
0.5033	25 (B349)	0.730766	333.47	0.729618	316.55
0.6139	25 (B365)	0.730975	324.00	0.729813	307.18
0.7301	25 (B366)	0.731219	314.93	0.730040	297.99
0.8551	25 (B366)	0.731518	318.15	0.730325	300.89

Table A.2: Raw Data for the Binary System Toluene (1) + Ethylbenzene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.0424	25 (B365)	0.733365	420.05	0.732315	398.30
0.1280	25 (B366)	0.733378	403.02	0.732326	381.63
0.2164	25 (B349)	0.733379	427.52	0.732322	405.38
0.2928	25 (B350)	0.733382	428.23	0.732325	405.51
0.3930	25 (B365)	0.733373	404.72	0.732312	382.87
0.4922	25 (B366)	0.733383	386.41	0.732317	365.08
0.5716	25 (B349)	0.733379	409.61	0.732305	387.71
0.7107	25 (B350)	0.733375	406.41	0.732299	384.67
0.8425	25 (B366)	0.733363	367.21	0.732276	347.72

Table A.2 (Cont'd.): Raw Data for the Binary System Toluene (1) + Ethylbenzene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.0424	25 (B365)	0.730227	357.90	0.729184	341.73
0.1280	25 (B366)	0.730226	343.64	0.729176	326.58
0.2164	25 (B349)	0.730215	363.89	0.729161	346.70
0.2928	25 (B350)	0.730208	365.10	0.729151	347.48
0.3930	25 (B365)	0.730190	344.73	0.729130	327.83
0.4922	25 (B366)	0.730182	328.70	0.729114	312.58
0.5716	25 (B349)	0.730167	348.89	0.729101	332.34
0.7107	25 (B350)	0.730142	346.10	0.729065	329.33
0.8425	25 (B366)	0.730108	313.58	0.729025	297.91

Table A.3: Raw Data for the Binary System Heptane (1) + Toluene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.0901	25 (B365)	0.729301	355.48	0.728216	337.62
0.1949	25 (B366)	0.724868	330.47	0.723789	314.13
0.2903	25 (B349)	0.721078	346.61	0.720001	329.88
0.3959	25 (B350)	0.717193	343.48	0.716125	327.30
0.4836	25 (B365)	0.714140	324.62	0.713076	309.37
0.5809	25 (B366)	0.710956	310.84	0.709895	296.44
0.6809	25 (B349)	0.707894	333.60	0.706835	318.46
0.7920	25 (B350)	0.704677	338.50	0.703621	322.42
0.8884	25 (B366)	0.702060	313.60	0.701012	299.38

Table A.3 (Cont'd.): Raw Data for the Binary System Heptane (1) + Toluene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.0901	25 (B365)	0.726047	305.18	0.724963	291.10
0.1949	25 (B366)	0.721625	284.94	0.720542	272.33
0.2903	25 (B349)	0.717845	299.63	0.716762	286.51
0.3959	25 (B350)	0.713987	298.39	0.712911	285.17
0.4836	25 (B365)	0.710936	282.31	0.709864	269.88
0.5809	25 (B366)	0.707768	270.74	0.706702	258.94
0.6809	25 (B349)	0.704711	290.59	0.703649	278.23
0.7920	25 (B350)	0.701508	294.31	0.700446	282.46
0.8884	25 (B366)	0.698904	273.68	0.697846	261.46

Table A.4: Raw Data for the Binary System Heptane (1) + Ethylbenzene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.1053	25 (B365)	0.729293	401.14	0.728247	380.38
0.2081	25 (B366)	0.725440	370.35	0.724394	351.35
0.2973	25 (B349)	0.722174	382.47	0.721129	364.75
0.3802	25 (B350)	0.719225	376.76	0.718184	359.43
0.4931	25 (B365)	0.715319	350.05	0.714274	333.41
0.5978	25 (B366)	0.711822	330.70	0.710778	314.72
0.6942	25 (B349)	0.708651	349.67	0.707607	333.37
0.8082	25 (B350)	0.705037	347.97	0.703996	332.36
0.8998	25 (B366)	0.702219	318.80	0.701175	304.22

Table A.4 (Cont'd.): Raw Data for the Binary System Heptane (1) + Ethylbenzene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.1053	25 (B365)	0.726161	343.19	0.725126	327.09
0.2081	25 (B366)	0.722307	318.29	0.721262	303.58
0.2973	25 (B349)	0.719039	331.18	0.717984	316.31
0.3802	25 (B350)	0.716089	326.24	0.715039	312.21
0.4931	25 (B365)	0.712181	303.75	0.711140	290.31
0.5978	25 (B366)	0.708688	287.34	0.707641	274.67
0.6942	25 (B349)	0.705513	304.03	0.704462	290.88
0.8082	25 (B350)	0.701899	302.87	0.700847	290.30
0.8998	25 (B366)	0.699087	277.59	0.698034	265.56

Table A.5: Raw Data for the Binary System Benzene (1) + Ethylbenzene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.0877	25 (B365)	0.733453	420.89	0.732401	397.84
0.1855	25 (B366)	0.733583	403.31	0.732518	380.87
0.2950	25 (B349)	0.733739	429.36	0.732660	405.47
0.4137	25 (B350)	0.733936	430.22	0.732842	405.56
0.4980	25 (B365)	0.734085	407.85	0.732979	384.25
0.5965	25 (B366)	0.734301	391.68	0.733175	368.67
0.7108	25 (B349)	0.734579	419.14	0.733437	394.11
0.7904	25 (B350)	0.734811	422.75	0.733650	396.73
0.8983	25 (B366)	0.735159	389.39	0.733970	364.88

Table A.5 (Cont'd.): Raw Data for the Binary System Benzene (1) + Ethylbenzene (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.0877	25 (B365)	0.730301	357.56	0.7292495	340.03
0.1855	25 (B366)	0.730391	341.74	0.7292495	325.27
0.2950	25 (B349)	0.730505	363.30	0.7292495	345.23
0.4137	25 (B350)	0.730648	362.99	0.7292495	344.73
0.4980	25 (B365)	0.730765	343.67	0.7292495	326.29
0.5965	25 (B366)	0.730926	329.15	0.7292495	312.33
0.7108	25 (B349)	0.731149	350.97	0.7292495	332.25
0.7904	25 (B350)	0.731328	352.76	0.7292495	333.82
0.8983	25 (B366)	0.731606	323.16	0.7292495	305.60

Table A.6: Raw Data for the Binary System Benzene (1) + Heptane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.1099	25 (B365)	0.701576	324.19	0.700524	308.92
0.2052	25 (B366)	0.703846	309.15	0.702789	294.74
0.2896	25 (B349)	0.706039	329.34	0.704967	313.90
0.4212	25 (B350)	0.709852	331.34	0.708761	316.22
0.5078	25 (B365)	0.712600	318.08	0.711498	302.99
0.6087	25 (B366)	0.716245	311.52	0.715124	296.28
0.7263	25 (B349)	0.721065	345.99	0.719923	327.99
0.7936	25 (B350)	0.724159	359.54	0.723005	340.75
0.8987	25 (B366)	0.729531	354.28	0.728351	333.54

Table A.6 (Cont'd.): Raw Data for the Binary System Benzene (1) + Heptane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.1099	25 (B365)	0.698416	282.12	0.697348	269.76
0.2052	25 (B366)	0.700650	268.91	0.699578	257.25
0.2896	25 (B349)	0.702811	286.34	0.701731	274.08
0.4212	25 (B350)	0.706573	288.01	0.705471	275.25
0.5078	25 (B365)	0.709283	275.57	0.708174	263.22
0.6087	25 (B366)	0.712881	268.77	0.711754	257.16
0.7263	25 (B349)	0.717637	296.08	0.716490	282.33
0.7936	25 (B350)	0.720694	306.21	0.719532	291.34
0.8987	25 (B366)	0.725996	297.92	0.724804	282.51

Table A.7: Raw Data for the Binary System Benzene (1) + Cyclooctane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.1004	50 (B158)	0.727944	555.75	0.726942	505.25
0.1826	50 (B159)	0.728249	518.18	0.727238	475.16
0.3035	50 (B831)	0.728779	397.96	0.727751	367.12
0.4080	50 (B830)	0.729361	324.97	0.728314	300.62
0.5122	50 (B158)	0.730041	277.23	0.728974	257.59
0.5243	50 (B159)	0.730140	300.63	0.729069	279.09
0.6891	50 (B831)	0.731542	236.49	0.730428	220.19
0.7904	50 (B830)	0.732622	205.21	0.731481	192.31
0.9001	50 (B158)	0.734012	187.49	0.732835	175.70

Table A.7 (Cont'd.): Raw Data for the Binary System Benzene (1) + Cyclooctane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.1004	50 (B158)	0.724946	988.17	0.723953	909.55
0.1826	50 (B159)	0.725216	828.68	0.724209	764.95
0.3035	50 (B831)	0.725699	734.15	0.724671	683.06
0.4080	50 (B830)	0.726221	638.96	0.725174	597.62
0.5122	50 (B158)	0.726843	528.60	0.725778	496.20
0.5243	50 (B159)	0.726929	503.07	0.725860	471.88
0.6891	50 (B831)	0.728205	449.13	0.727099	424.92
0.7904	50 (B830)	0.729199	410.59	0.728058	387.67
0.9001	50 (B158)	0.730484	347.09	0.729302	327.10

Table A.8: Raw Data for the Binary System Toluene (1) + Cyclooctane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.0997	50 (B158)	0.727861	535.08	0.726863	486.08
0.1951	50 (B159)	0.728142	477.15	0.727145	437.83
0.3032	50 (B831)	0.728537	371.33	0.727527	343.48
0.3904	50 (B830)	0.728924	309.80	0.727905	288.48
0.4868	50 (B158)	0.729416	265.69	0.728389	248.08
0.5898	50 (B159)	0.730003	256.13	0.728967	240.38
0.6919	50 (B831)	0.730706	217.77	0.729658	204.71
0.8003	50 (B830)	0.731530	188.29	0.730468	177.76
0.8880	50 (B158)	0.732265	174.92	0.731189	165.36

Table A.8 (Cont'd.): Raw Data for the Binary System Toluene (1) + Cyclooctane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.0997	50 (B158)	0.724882	954.91	0.7238911	881.82
0.1951	50 (B159)	0.725145	767.08	0.7238911	713.32
0.3032	50 (B831)	0.725520	687.24	0.7238911	642.64
0.3904	50 (B830)	0.725879	607.42	0.7238911	571.83
0.4868	50 (B158)	0.726345	513.87	0.7238911	484.44
0.5898	50 (B159)	0.726899	440.52	0.7238911	417.54
0.6919	50 (B831)	0.727563	423.88	0.7238911	401.95
0.8003	50 (B830)	0.728344	387.61	0.7238911	368.14
0.8880	50 (B158)	0.729047	331.94	0.7238911	315.58

Table A.9: Raw Data for the Binary System Ethylbenzene (1) + Cyclooctane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.0907	50 (B158)	0.727908	548.12	0.726911	497.72
0.2033	50 (B159)	0.728335	472.61	0.727340	434.20
0.3072	50 (B831)	0.728790	367.37	0.727787	348.67
0.3701	50 (B830)	0.729109	330.41	0.728107	306.85
0.4761	50 (B158)	0.729678	282.71	0.728668	264.04
0.5798	50 (B159)	0.730296	277.15	0.729281	260.12
0.7008	50 (B831)	0.731099	236.13	0.730079	221.36
0.7922	50 (B830)	0.731739	211.20	0.730710	198.46
0.8908	50 (B158)	0.732489	196.39	0.731450	185.56

Table A.9 (Cont'd.): Raw Data for the Binary System Ethylbenzene (1) + Cyclooctane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.0907	50 (B158)	0.724927	415.94	0.723938	901.51
0.2033	50 (B159)	0.725346	370.70	0.724354	711.12
0.3072	50 (B831)	0.725790	301.71	0.724793	658.32
0.3701	50 (B830)	0.726104	267.56	0.725095	610.07
0.4761	50 (B158)	0.726654	232.09	0.725649	515.48
0.5798	50 (B159)	0.727259	230.55	0.726242	448.75
0.7008	50 (B831)	0.728031	197.36	0.727007	433.95
0.7922	50 (B830)	0.728649	177.42	0.727619	409.46
0.8908	50 (B158)	0.729372	165.73	0.728325	351.91

Table A.10: Raw Data for the Binary System Heptane (1) + Cyclooctane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 293.15 K		Temperature = 298.15 K	
0.0938	50 (B158)	0.724721	527.69	0.723727	479.95
0.1897	50 (B159)	0.722007	464.73	0.721016	424.04
0.2896	50 (B831)	0.719124	361.36	0.718128	334.91
0.3979	50 (B830)	0.716019	288.66	0.715021	269.69
0.4949	50 (B158)	0.713294	247.79	0.712291	232.28
0.5964	50 (B159)	0.710439	238.06	0.709426	224.20
0.6919	50 (B831)	0.707785	202.65	0.706768	191.35
0.7795	50 (B830)	0.705330	177.30	0.704304	167.86
0.8934	50 (B158)	0.702167	157.92	0.701129	150.13

Table A.10 (Cont’d.): Raw Data for the Binary System Heptane (1) + Cyclooctane (2).

Mole Fraction x_1	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
		Temperature = 308.15 K		Temperature = 313.15 K	
0.0938	50 (B158)	0.721753	949.45	0.720763	874.89
0.1897	50 (B159)	0.719037	750.44	0.718038	697.40
0.2896	50 (B831)	0.716140	675.02	0.715148	631.25
0.3979	50 (B830)	0.713021	576.73	0.712017	542.21
0.4949	50 (B158)	0.710276	483.76	0.709270	456.95
0.5964	50 (B159)	0.707404	412.67	0.706387	391.30
0.6919	50 (B831)	0.704726	398.26	0.703693	378.70
0.7795	50 (B830)	0.702244	367.49	0.701216	350.34
0.8934	50 (B158)	0.699052	304.79	0.697999	290.35

Table A.11: Raw Data for the Ternary System Benzene (1) + Toluene (2) + Heptane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.0989	0.0834	25 (B365)	0.703594	322.50	0.702535	307.56
0.1532	0.1514	25 (B366)	0.706971	309.11	0.705901	294.68
0.2063	0.2347	25 (B349)	0.711134	332.07	0.710056	316.16
0.3398	0.2879	25 (B350)	0.717495	342.12	0.716396	325.35
0.3221	0.3851	25 (B365)	0.720641	331.94	0.719539	315.44
0.3825	0.3410	25 (B366)	0.721240	321.70	0.720135	305.90
0.4063	0.2513	25 (B349)	0.718546	339.98	0.717443	322.93
0.5069	0.0782	25 (B350)	0.715545	337.48	0.714433	321.02

Table A.11 (Cont'd.): Raw Data for the Ternary System Benzene (1) + Toluene (2) + Heptane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.0989	0.0834	25 (B365)	0.700412	280.74	0.699340	268.64
0.1532	0.1514	25 (B366)	0.703755	269.08	0.702674	257.51
0.2063	0.2347	25 (B349)	0.707883	288.25	0.706798	275.90
0.3398	0.2879	25 (B350)	0.714189	295.73	0.713067	282.55
0.3221	0.3851	25 (B365)	0.717320	286.58	0.716205	273.42
0.3825	0.3410	25 (B366)	0.717910	277.63	0.716792	264.61
0.4063	0.2513	25 (B349)	0.715220	293.16	0.714103	280.05
0.5069	0.0782	25 (B350)	0.712206	291.64	0.711082	279.15

Table A.12: Raw Data for the Ternary System Benzene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.1209	0.0800	25 (B365)	0.703879	325.53	0.702823	310.20
0.1834	0.1670	25 (B366)	0.708836	316.76	0.707776	301.76
0.2498	0.2489	25 (B349)	0.713692	346.65	0.712620	329.77
0.4188	0.2610	25 (B350)	0.719984	360.15	0.718891	342.04
0.3772	0.3683	25 (B365)	0.722812	354.36	0.721721	336.90
0.4268	0.3268	25 (B366)	0.723028	339.91	0.721930	323.77
0.4814	0.2310	25 (B349)	0.721137	357.40	0.720035	339.29
0.5461	0.0273	25 (B350)	0.715080	336.86	0.713972	320.83

Table A.12 (Cont'd.): Raw Data for the Ternary System Benzene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.1209	0.0800	25 (B365)	0.700708	283.10	0.699640	271.20
0.1834	0.1670	25 (B366)	0.705639	274.93	0.704562	262.95
0.2498	0.2489	25 (B349)	0.710471	300.14	0.709390	287.11
0.4188	0.2610	25 (B350)	0.716688	310.09	0.715590	296.04
0.3772	0.3683	25 (B365)	0.719541	304.86	0.718444	291.05
0.4268	0.3268	25 (B366)	0.719732	293.36	0.718628	279.59
0.4814	0.2310	25 (B349)	0.717824	307.08	0.716716	293.27
0.5461	0.0273	25 (B350)	0.711746	291.60	0.710624	278.56

Table A.13: Raw Data for the Ternary System Toluene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.0969	0.1009	25 (B365)	0.704778	329.05	0.703722	313.52
0.1470	0.2087	25 (B366)	0.709666	321.48	0.708615	306.12
0.2006	0.3034	25 (B349)	0.714521	352.76	0.713467	335.76
0.3447	0.3230	25 (B350)	0.720125	365.42	0.719068	347.50
0.3001	0.4285	25 (B365)	0.722519	358.38	0.721464	340.75
0.3679	0.3695	25 (B366)	0.722745	343.75	0.721682	326.92
0.4052	0.3033	25 (B349)	0.721581	363.34	0.720514	345.60
0.4850	0.1012	25 (B350)	0.716796	348.43	0.715731	331.71

Table A.13 (Cont'd.): Raw Data for the Ternary System Toluene (1) + Ethylbenzene (2) + Heptane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.0969	0.1009	25 (B365)	0.701623	285.95	0.700564	273.83
0.1470	0.2087	25 (B366)	0.706501	279.44	0.705438	267.63
0.2006	0.3034	25 (B349)	0.711352	305.85	0.710291	292.59
0.3447	0.3230	25 (B350)	0.716944	315.65	0.715880	301.97
0.3001	0.4285	25 (B365)	0.719339	309.27	0.718275	295.40
0.3679	0.3695	25 (B366)	0.719556	296.73	0.718490	283.53
0.4052	0.3033	25 (B349)	0.718386	313.28	0.717301	299.98
0.4850	0.1012	25 (B350)	0.713583	301.91	0.712513	289.09

Table A.14: Raw Data for the Ternary System Benzene (1) + Toluene (2) + Ethylbenzene (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.0919	0.0941	25 (B365)	0.733470	416.38	0.732409	393.60
0.1498	0.2059	25 (B366)	0.733548	394.89	0.732476	372.74
0.2085	0.2984	25 (B349)	0.733647	416.90	0.732562	393.72
0.3286	0.3323	25 (B350)	0.733848	415.45	0.732739	391.72
0.3028	0.4438	25 (B365)	0.733811	390.81	0.732702	368.68
0.3545	0.3964	25 (B366)	0.733896	378.59	0.732779	357.15
0.4040	0.2960	25 (B349)	0.733961	410.62	0.732848	386.63
0.5086	0.0974	25 (B350)	0.734140	422.09	0.733020	397.68

Table A.14 (Cont'd.): Raw Data for the Ternary System Benzene (1) + Toluene (2) + Ethylbenzene (3)

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.0919	0.0941	25 (B365)	0.730290	353.73	0.729225	335.94
0.1498	0.2059	25 (B366)	0.730326	335.53	0.729254	318.36
0.2085	0.2984	25 (B349)	0.730386	353.50	0.729296	335.78
0.3286	0.3323	25 (B350)	0.730531	351.13	0.729420	333.36
0.3028	0.4438	25 (B365)	0.730487	330.42	0.729373	312.62
0.3545	0.3964	25 (B366)	0.730551	320.82	0.729435	303.42
0.4040	0.2960	25 (B349)	0.730622	346.29	0.729502	328.10
0.5086	0.0974	25 (B350)	0.730785	355.48	0.729659	336.44

Table A.15: Raw Data for the Ternary System Benzene (1) + Toluene (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.0972	0.0950	50 (B158)	0.728199	448.34	0.727191	409.90
0.1552	0.2047	50 (B159)	0.728899	362.06	0.727873	335.68
0.2053	0.2990	50 (B831)	0.729665	279.70	0.728619	260.25
0.3355	0.3319	50 (B830)	0.730858	221.76	0.729782	207.85
0.3139	0.4263	50 (B158)	0.731369	201.41	0.730290	189.08
0.3549	0.3968	50 (B159)	0.731532	220.02	0.730440	206.92
0.4084	0.3084	50 (B831)	0.731310	219.37	0.730221	205.83
0.5097	0.1052	50 (B830)	0.730695	242.87	0.729609	226.74

Table A.15 (Cont'd.): Raw Data for the Ternary System Benzene (1) + Toluene (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.0972	0.0950	25 (B365)	0.725175	821.90	0.724173	761.36
0.1552	0.2047	25 (B366)	0.725825	604.20	0.724792	564.84
0.2053	0.2990	25 (B349)	0.726533	532.11	0.725490	500.69
0.3355	0.3319	25 (B350)	0.727635	448.61	0.726556	423.81
0.3139	0.4263	25 (B365)	0.728125	394.28	0.727040	373.74
0.3549	0.3968	25 (B366)	0.728262	379.86	0.727171	358.56
0.4084	0.3084	25 (B349)	0.728047	420.34	0.726955	398.68
0.5097	0.1052	25 (B350)	0.727447	484.66	0.726356	456.36

Table A.16: Raw Data for the Ternary System Toluene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.1107	0.1093	50 (B158)	0.728307	414.76	0.727305	381.24
0.1580	0.1923	50 (B159)	0.728886	363.83	0.727879	337.74
0.1978	0.3146	50 (B831)	0.729780	279.29	0.728760	261.38
0.3472	0.3245	50 (B830)	0.730745	223.67	0.729708	210.36
0.2991	0.4492	50 (B158)	0.731342	206.46	0.730304	194.45
0.3549	0.3920	50 (B159)	0.731294	226.45	0.730252	213.39
0.3974	0.2961	50 (B831)	0.730867	225.50	0.729828	212.22
0.5026	0.1010	50 (B830)	0.730177	234.27	0.729142	219.95

Table A.16 (Cont'd.): Raw Data for the Ternary System Toluene (1) + Ethylbenzene (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.1107	0.1093	25 (B365)	0.725309	768.44	0.724314	714.49
0.1580	0.1923	25 (B366)	0.725873	606.91	0.724870	568.36
0.1978	0.3146	25 (B349)	0.726724	535.41	0.725710	504.54
0.3472	0.3245	25 (B350)	0.727639	455.61	0.726605	431.21
0.2991	0.4492	25 (B365)	0.728223	409.06	0.727182	387.96
0.3549	0.3920	25 (B366)	0.728168	392.59	0.727124	372.56
0.3974	0.2961	25 (B349)	0.727757	439.21	0.726724	416.05
0.5026	0.1010	25 (B350)	0.727065	474.63	0.726030	448.09

Table A.17: Raw Data for the Ternary System Benzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.1082	0.1048	50 (B158)	0.724719	415.88	0.723718	381.91
0.1636	0.1907	50 (B159)	0.722220	348.76	0.721207	323.89
0.2157	0.2928	50 (B831)	0.719137	259.38	0.718109	242.95
0.3626	0.3283	50 (B830)	0.718156	196.60	0.717099	185.57
0.3365	0.4215	50 (B158)	0.715238	186.59	0.714172	166.72
0.3585	0.3936	50 (B159)	0.716019	196.28	0.714960	185.77
0.4118	0.2773	50 (B831)	0.719921	206.03	0.718861	194.23
0.4929	0.0911	50 (B830)	0.726648	241.14	0.725579	225.74

Table A.17 (Cont'd.): Raw Data for the Ternary System Benzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.1082	0.1048	25 (B365)	0.721713	768.08	0.720711	713.33
0.1636	0.1907	25 (B366)	0.719186	582.29	0.718171	546.08
0.2157	0.2928	25 (B349)	0.716050	498.71	0.715025	470.73
0.3626	0.3283	25 (B350)	0.714981	402.54	0.713914	382.05
0.3365	0.4215	25 (B365)	0.712046	352.09	0.710976	334.11
0.3585	0.3936	25 (B366)	0.712828	343.65	0.711752	327.05
0.4118	0.2773	25 (B349)	0.716726	402.52	0.715662	380.35
0.4929	0.0911	25 (B350)	0.723442	482.59	0.722366	455.46

Table A.18: Raw Data for the Ternary System Toluene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.1047	0.1038	50 (B158)	0.724695	409.96	0.723700	377.17
0.1470	0.1954	50 (B159)	0.722078	347.94	0.721080	323.26
0.2113	0.3070	50 (B831)	0.718911	251.90	0.717892	236.57
0.3271	0.3228	50 (B830)	0.718695	204.95	0.717664	193.35
0.3053	0.4420	50 (B158)	0.715056	178.45	0.714019	169.31
0.3623	0.3772	50 (B159)	0.717121	199.47	0.716085	189.02
0.3904	0.3128	50 (B831)	0.719162	199.64	0.718126	188.68
0.4892	0.1012	50 (B830)	0.726179	227.83	0.725147	214.13

Table A.18 (Cont'd.): Raw Data for the Ternary System Toluene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.1047	0.1038	25 (B365)	0.721710	760.48	0.720714	706.93
0.1470	0.1954	25 (B366)	0.719070	584.94	0.718069	548.42
0.2113	0.3070	25 (B349)	0.715859	487.75	0.714843	461.04
0.3271	0.3228	25 (B350)	0.715604	421.05	0.714561	399.51
0.3053	0.4420	25 (B365)	0.711939	356.99	0.710907	340.38
0.3623	0.3772	25 (B366)	0.713878	349.62	0.712958	432.79
0.3904	0.3128	25 (B349)	0.716054	392.50	0.715012	373.31
0.4892	0.1012	25 (B350)	0.723078	461.60	0.722048	437.59

Table A.19: Raw Data for the Ternary System Ethylbenzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 293.15 K		Temperature = 298.15 K	
0.0940	0.1048	50 (B158)	0.724737	417.24	0.723744	383.86
0.1397	0.2211	50 (B159)	0.721526	340.01	0.720532	316.47
0.1997	0.3239	50 (B831)	0.718788	255.28	0.717787	239.70
0.3323	0.3387	50 (B830)	0.718900	208.24	0.717883	196.62
0.2977	0.4478	50 (B158)	0.715631	186.08	0.714605	176.56
0.3474	0.4015	50 (B159)	0.717130	206.17	0.716104	195.39
0.3983	0.3009	50 (B831)	0.720334	211.55	0.719316	199.73
0.4974	0.1066	50 (B830)	0.726600	238.18	0.725591	224.18

Table A.19 (Cont'd.): Raw Data for the Ternary System Ethylbenzene (1) + Heptane (2) + Cyclooctane (3).

Mole Fraction x_1	Mole Fraction x_2	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
			Temperature = 308.15 K		Temperature = 313.15 K	
0.0940	0.1048	25 (B365)	0.721766	771.42	0.720770	717.70
0.1397	0.2211	25 (B366)	0.718531	571.05	0.717537	536.21
0.1997	0.3239	25 (B349)	0.715769	494.03	0.714755	466.94
0.3323	0.3387	25 (B350)	0.715850	427.87	0.714825	405.90
0.2977	0.4478	25 (B365)	0.712551	373.09	0.711516	355.33
0.3474	0.4015	25 (B366)	0.714063	361.86	0.713028	344.76
0.3983	0.3009	25 (B349)	0.717279	415.49	0.716254	395.49
0.4974	0.1066	25 (B350)	0.723560	481.14	0.722541	456.07

Table A.20: Raw Data for the Quaternary System Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4)

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 293.15 K		Temperature = 298.15 K	
0.1305	0.3223	0.2704	50 (B159)	0.731163	230.20	0.730115	216.83
0.1697	0.3713	0.3259	50 (B831)	0.732368	194.35	0.731296	183.23
0.2558	0.2331	0.1754	50 (B830)	0.730829	225.86	0.729765	211.99
0.3179	0.2695	0.2717	50 (B159)	0.732485	205.09	0.731395	193.36
0.1267	0.3705	0.2633	50 (B831)	0.731438	212.59	0.730379	199.42
0.2712	0.1615	0.3319	50 (B830)	0.731637	207.23	0.730567	194.94

Table A.20 (Cont'd.): Raw Data for the Quaternary System Benzene (1) + Toluene (2) + Ethylbenzene (3) + Cyclooctane (4)

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 308.15 K		Temperature = 313.15 K	
0.1305	0.3223	0.2704	25 (B366)	0.728012	398.22	0.726963	377.32
0.1697	0.3713	0.3259	25 (B349)	0.729152	380.43	0.728079	361.33
0.2558	0.2331	0.1754	25 (B350)	0.727653	456.72	0.726595	431.74
0.3179	0.2695	0.2717	25 (B366)	0.729219	354.73	0.728129	336.62
0.1267	0.3705	0.2633	25 (B349)	0.728255	412.54	0.727197	391.22
0.2712	0.1615	0.3319	25 (B350)	0.728444	421.57	0.727375	399.36

Table A.21: Raw Data for the Quaternary System Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4)

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 293.15 K		Temperature = 298.15 K	
0.1368	0.3144	0.2583	25 (B366)	0.721394	335.03	0.720320	318.31
0.1931	0.3718	0.3029	25 (B349)	0.727779	381.58	0.726689	361.09
0.2915	0.2175	0.1558	25 (B350)	0.719330	353.52	0.718242	335.69
0.3284	0.2622	0.2680	25 (B366)	0.727387	351.81	0.726286	333.23
0.1549	0.3507	0.2556	25 (B349)	0.723393	364.75	0.722307	349.18
0.1991	0.1632	0.3634	25 (B350)	0.722151	370.57	0.721078	351.79

Table A.21 (Cont'd.): Raw Data for the Quaternary System Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 308.15 K		Temperature = 313.15 K	
0.1368	0.3144	0.2583	25 (B366)	0.718166	289.10	0.717089	275.97
0.1931	0.3718	0.3029	25 (B349)	0.724519	325.97	0.723420	310.77
0.2915	0.2175	0.1558	25 (B350)	0.716055	304.76	0.714956	291.09
0.3284	0.2622	0.2680	25 (B366)	0.724083	300.70	0.722977	269.39
0.1549	0.3507	0.2556	25 (B349)	0.720141	314.33	0.719052	300.00
0.1991	0.1632	0.3634	25 (B350)	0.718918	318.94	0.717832	304.60

Table A.22: Raw Data for the Quaternary System Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 293.15 K		Temperature = 298.15 K	
0.1448	0.3462	0.2180	50 (B159)	0.722996	220.79	0.721970	208.53
0.1970	0.4056	0.2576	50 (B831)	0.722341	181.33	0.721300	171.87
0.2901	0.2383	0.1379	50 (B830)	0.725477	213.79	0.724444	201.91
0.3428	0.2812	0.2290	50 (B159)	0.723144	189.14	0.722094	179.25
0.1459	0.3981	0.2181	50 (B831)	0.723301	200.86	0.722268	189.83
0.2969	0.1703	0.2757	50 (B830)	0.720878	189.72	0.719841	179.39

Table A.22 (Cont'd.): Raw Data for the Quaternary System Toluene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 308.15 K		Temperature = 313.15 K	
0.1448	0.3462	0.2180	25 (B366)	0.719918	385.02	0.718888	365.56
0.1970	0.4056	0.2576	25 (B349)	0.719211	359.77	0.718164	342.62
0.2901	0.2383	0.1379	25 (B350)	0.722375	436.97	0.721347	414.69
0.3428	0.2812	0.2290	25 (B366)	0.719997	332.49	0.718928	317.49
0.1459	0.3981	0.2181	25 (B349)	0.720204	395.50	0.719167	376.34
0.2969	0.1703	0.2757	25 (B350)	0.717765	391.69	0.716722	372.67

Table A.23: Raw Data for the Quaternary System Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 293.15 K		Temperature = 298.15 K	
0.1387	0.3377	0.2186	50 (B159)	0.722849	225.19	0.721811	212.50
0.1816	0.3964	0.2742	50 (B831)	0.721582	181.96	0.720530	172.47
0.2966	0.2257	0.1294	50 (B830)	0.725699	221.42	0.724647	208.33
0.3306	0.2852	0.2292	50 (B159)	0.722920	191.39	0.721851	180.73
0.1425	0.3949	0.2127	50 (B831)	0.723373	204.17	0.722334	192.98
0.2984	0.1696	0.2736	50 (B830)	0.720677	191.52	0.719616	180.87

Table A.23 (Cont'd.): Raw Data for the Quaternary System Benzene (1) + Ethylbenzene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 308.15 K		Temperature = 313.15 K	
0.1387	0.3377	0.2186	25 (B366)	0.719748	391.81	0.718712	371.68
0.1816	0.3964	0.2742	25 (B349)	0.718429	360.43	0.717367	343.22
0.2966	0.2257	0.1294	25 (B350)	0.722550	449.76	0.721491	425.62
0.3306	0.2852	0.2292	25 (B366)	0.719707	334.84	0.718636	318.58
0.1425	0.3949	0.2127	25 (B349)	0.720254	399.35	0.719212	380.76
0.2984	0.1696	0.2736	25 (B350)	0.717510	392.78	0.716446	373.26

Table A.24: Raw Data for the Quaternary System Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 293.15 K		Temperature = 298.15 K	
0.1408	0.3722	0.2076	50 (B159)	0.722743	208.91	0.721689	197.25
0.1753	0.4422	0.2485	50 (B831)	0.721882	170.29	0.720811	161.40
0.2873	0.2516	0.1269	50 (B830)	0.725582	210.51	0.724517	198.11
0.3185	0.3148	0.2193	50 (B159)	0.722867	182.20	0.721785	172.38
0.1406	0.4183	0.2021	50 (B831)	0.723192	190.86	0.722132	180.52
0.2916	0.1913	0.2667	50 (B830)	0.720632	184.69	0.719567	174.49

Table A.24 (Cont'd.): Raw Data for the Quaternary System Benzene (1) + Toluene (2) + Heptane (3) + Cyclooctane (4).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
				Temperature = 308.15 K		Temperature = 313.15 K	
0.1408	0.3722	0.2076	25 (B366)	0.719581	364.59	0.718524	346.12
0.1753	0.4422	0.2485	25 (B349)	0.718650	337.31	0.717570	321.44
0.2873	0.2516	0.1269	25 (B350)	0.722391	428.28	0.721327	405.55
0.3185	0.3148	0.2193	25 (B366)	0.719602	319.17	0.718508	303.53
0.1406	0.4183	0.2021	25 (B349)	0.720009	375.52	0.718938	357.12
0.2916	0.1913	0.2667	25 (B350)	0.717433	379.83	0.716363	361.09

Table A.25: Raw Data for the Quinary System Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Mole Fraction x_4	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
					Temperature = 293.15 K		Temperature = 298.15 K	
0.1751	0.2765	0.2601	0.1261	25 (B366)	0.726863	405.97	0.725801	383.48
0.3967	0.1239	0.2677	0.0894	25 (B349)	0.728749	429.82	0.727661	405.70
0.2472	0.1496	0.2656	0.2867	25 (B350)	0.721227	380.45	0.720153	360.74
0.2945	0.2512	0.1300	0.1952	25 (B366)	0.724147	376.91	0.723069	357.27
0.1354	0.3236	0.2145	0.3025	25 (B349)	0.720807	363.22	0.719732	345.36

Table A.25 (Cont’d.): Raw Data for the Quinary System Benzene (1) + Toluene (2) + Ethylbenzene (3) + Heptane (4) + Cyclooctane (5).

Mole Fraction x_1	Mole Fraction x_2	Mole Fraction x_3	Mole Fraction x_4	Viscometer Number	Density Meter Reading	Efflux Time (s)	Density Meter Reading	Efflux Time (s)
					Temperature = 293.15 K		Temperature = 298.15 K	
0.1751	0.2765	0.2601	0.1261	25 (B366)	0.723677	344.53	0.722611	327.84
0.3967	0.1239	0.2677	0.0894	25 (B349)	0.725482	363.71	0.728393	345.43
0.2472	0.1496	0.2656	0.2867	25 (B350)	0.718004	326.63	0.716920	311.53
0.2945	0.2512	0.1300	0.1952	25 (B366)	0.720907	321.94	0.719816	306.57
0.1354	0.3236	0.2145	0.3025	25 (B349)	0.717576	313.44	0.716505	299.30

Appendix B

Estimated Experimental Errors

B.1 Density Measurements

The density of a compound, ρ, is related to the oscillation period, τ, of U-shaped tube of the density meter cell by a three parameter equation provided by the density meter supplier as follows:

$$\rho = \frac{A\tau^2}{1-B\tau^2} - C \tag{B.1}$$

The maximum error in the density measurements can be obtained as the change in the density with respect to the change in the oscillation period. Then, differentiating the above equation with respect to τ yields;

$$d\rho = \left[\frac{\left(1-B\tau^2\right)\left(2A\tau\right) - \left(A\tau^2\right)\left(-2B\tau\right)}{\left(1-B\tau^2\right)^2} \right] d\tau \tag{B.2}$$

The above equation can be rewritten as;

$$d\rho = \frac{2A\tau}{\left(1-B\tau^2\right)^2} d\tau \tag{B.3}$$

In the present study, the maximum fluctuation in the DMA 602 density meter readings was 1×10^{-5} seconds and the maximum value of the oscillation period, τ, observed during the measurements was 0.735159 at the temperature of 293.15 K. Substituting these values along with the corresponding A, B, and C values into equation (B.3), one obtains the maximum predicted error in density measurements as,

$$d\rho = \frac{2(3.959453)(0.735159)}{\left[1 + (-0.05530668)(0.735159)^2\right]^2} \times 10^{-5} = 6.2 \times 10^{-5}\ kg/L \tag{B.4}$$

B.2 Viscosity Measurements

The equation reported earlier in Chapter 3 for calculating the kinematic viscosity of a fluid is;

$$\nu = C\,t - \frac{E}{t^2} \tag{B.5}$$

As described earlier in Chapter 3, three measurements for the efflux time were taken for each sample that had to agree within ± 0.1 % and only the average value was reported. In order to obtain the maximum error in the measured kinematic viscosity, equation (B.5) is differentiated with respect to the efflux time, *t*, to give,

$$d\nu = \left(C - 2\frac{E}{t^3}\right) dt \tag{B.6}$$

It can be concluded from the above equation that the maximum value of the error in the kinematic viscosity depends on the constants *C* and *E* which are function of the viscometer type. That is to say, the maximum predicted error will have to be calculated for each viscometer used in the present study.

In order to obtain the maximum predicted error in the kinematic viscosity, *dv*, the time of the efflux's scatter, *dt*, may be taken as 0.1 % of the maximum value of the measured efflux time.

Table B.1. shows the maximum predicted error in the kinematic viscosity for each viscometer type.

Below, an example of the maximum error in the kinematic viscosity calculated for viscometer type 25 (B349)

$$d\nu = \left[0.001768 \times 10^{-9} + \frac{2 \times 110.30 \times 10^{-6}}{(532.11)^{3}} \right] \times 0.532 = 1.72 \times 10^{-12}\ m^{2} / s. \qquad \text{(B.7)}$$

Table B.1: Estimated Errors in Measuring Kinematic Viscosities for All Viscometer Types.

Viscometer number	Efflux time, *t*, (sec)	*dt*	*dv* ×10^{12} (m^2/s)
25 (B349)	532.11	0.532	1.72
25 (B350)	484.66	0.485	2.21
25 (B365)	821.90	0.822	3.42
25 (B366)	606.91	0.607	6.75
50 (B158)	988.17	0.988	4.96
50 (B159)	828.68	0.829	4.37
50 (B830)	638.96	0.639	5.84
50 (B831)	734.15	0.734	4.54

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