A STUDY OF HELICAL COILED TUBULAR

REACTORS IN LAMINAR FLOW

By

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PREFACE

        The purpose of this project was to study the
performance of a helically coiled reactor and compare its
performance to straight tube plug flow and laminar flow
reactors. The hydrolysis of crystal violet dye with sodium
hydroxide is the reaction that was used in this study.

        To compare the three reactor types, it is necessary to
know the kinetics of the reaction. The reaction is carried
out with an excess of sodium hydroxide; therefore, the
reaction is a pseudo-first order reaction. Batch reactions
were performed to determine the temperature dependence of
the rate constant:

$$k = 3.4x10^{10} \exp(-6570/T).$$

At 25 °C, the rate constant is 9.1 l/(mol·min).

        A 2 inch coil, a 4 inch coil, and a laminar flow
reactor were used in the flow experiments. For the laminar
flow reactor, the experimental conversions agreed very well
with theoretical values. For the coils, the values followed
the same trend as the theoretical curve, but did not match
the theoretical values well. It was found that the size of
the coil does not effect conversion, and this conclusion is
supported by theory. Finally, the equations for pressure
drop in a coil were found to be valid.

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NOMENCLATURE

A	absorbance, dimensionless
c	concentration, mol/l
C	ratio of coiled friction factor to straight tube friction factor, f_c/f_s, dimensionless
C_v	flow coefficient
D	diameter of tube, ft
E	residence time distribution function, dimensionless
E_1	exponential integral, dimensionless
f	friction factor, dimensionless
g_c	gravitational constant, $32.2\dfrac{\text{lb}_m\text{ft}}{\text{lb}_f\text{s}^2}$
k	rate constant, 1/mol/min
k'	pseudo first order rate constant, min^{-1}
l	path length, cm
L	length of tube, ft
N_{Dn}	Dean Number, $N_{Re}\left(\dfrac{r_t}{R_c}\right)^{1/2}$, dimensionless
N_{Re}	Reynolds Number, $\dfrac{D\rho\bar{v}}{\mu}$, dimensionless
Q	volumetric flow rate, GPM
r_t	tube radius, ft
R_c	coil radius, ft

SG	specific gravity of a fluid
t	time, min
T	temperature, K
% T	percent transmittance
v	volumetric flow rate, ml/min
$\bar{v}$	velocity, ft/min
X	conversion, dimensionless

GREEK LETTERS

ΔP	pressure drop, lb_f/ft^2
ε	molar absorbance coefficient, 1/mol/cm
ρ	density, lb_m/ft^3
τ	residence time, min
θ	reduced time, t/τ, dimensionless

SUBSCRIPTS

A	crystal violet dye
B	sodium hydroxide
c	coiled tube
O	initial
s	straight tube

CHAPTER I

INTRODUCTION

The purpose of this project is to study the performance
of a helical coiled tubular reactor in laminar flow and
compare its performance to straight tube plug flow and
laminar flow reactors. The hydrolysis of crystal violet dye
with sodium hydroxide is the reaction that will be used in
this study.

A helical coiled system induces secondary flows,
reduces axial dispersion, and increases pressure drop when
compared to a straight tube of equal length. The effect of
helical coils on reactor performance is not clearly
understood; however, the performance of a helical coiled
reactor falls in between that of a plug flow reactor and a
laminar flow reactor.

The results of this work will facilitate the design of
helical coiled reactors. Reactant conversion and pressure
drop in a helical coil can be calculated using the governing
equations, if the size of the reactor and the kinetics of
the reaction are known. Finally, this work will provide a
plan for the implementation of a reactor experiment in
undergraduate laboratories.

This project will study the kinetics of the reaction, the use of residence time distributions to predict conversion, and the reliability of the available pressure drop correlations. A computer data acquisition system has been assembled to aid in the taking and analyzing of the data.

Chapter II covers the theory of helical coils including the topics of secondary flow, pressure drop, axial dispersion, and residence time distributions. Chapter III discusses the kinetics of the crystal violet dye/sodium hydroxide reaction. It also includes the setup and results of batch experiments. In Chapter IV, the computer data acquisition system is discussed in detail, including discussion of hardware, software, setup, and implementation. Chapter V describes the experimental system and the procedure used in all flow experiments. Chapter VI presents a discussion of the results of the experiments, and Chapter VII is the conclusions that can be drawn from the results. Finally, Chapter VIII is the recommendations for further experimentation.

CHAPTER II

THEORY

Secondary Flow

When a fluid flows through a helical coil, a secondary
flow perpendicular to the main flow is produced. Secondary
flows are induced by the curvature of the tube which imparts
centrifugal forces on the fluid. Dean (1927) first studied
flow through helical coils and calculated the profiles of
the secondary flow, examples of which are shown in Figure 1.
These velocity profiles are only valid when $N_{Dn} < 1$, where
the Dean number is defined as

$$N_{Dn} = N_{Re}(r_t / R_c)^{1/2} . \qquad (1)$$

Later investigators calculated profiles for $N_{Dn} < 1,000$. At
Dean numbers of approximately 300, the secondary velocity
profiles become asymmetric as shown by Austin and Seader
(1973). An example of these asymmetric profiles is given in
Figure 2.

Further information on the amount of secondary flow in
a helical coil can be obtained from the critical Reynolds
number. The critical Reynolds number is the point at which

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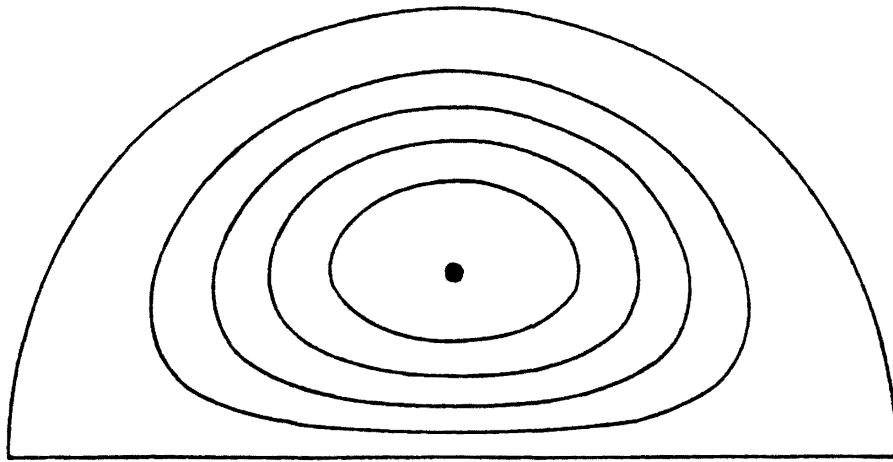
Figure 1. Secondary Velocity Profiles for a Coiled Tube,
$N_{Dn} = 1$ (from Austin and Seader, 1973)
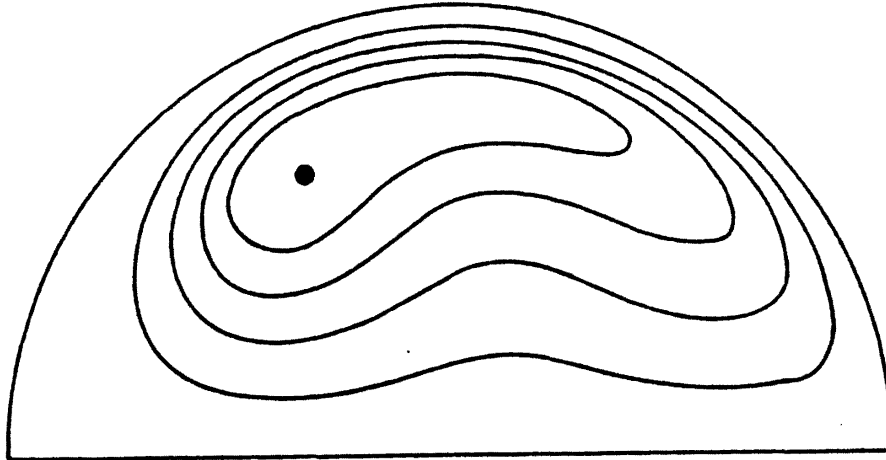
Figure 2. Secondary Velocity Profiles for a Coiled Tube,
$N_{Dn} = 401.3$ (from Austin and Seader, 1973)

turbulence first occurs in the system. For a straight tube this point is generally accepted as $(N_{Re})_{Critical}$ = 2,100. For coiled tubes the critical Reynolds number increases as the curvature ratio (r_t/R_c) increases. For turbulence to occur the inertial forces of the fluid must overcome the other forces in the system, such as viscous forces and centrifugal forces. Since a helical coil increases centrifugal forces, the value of the critical Reynolds number can be significantly higher. Srinivasan et al. (1970) give the following equation for the critical Reynolds number in helical coils:

$$(N_{Re})_{Critical} = 2100 \, [1 + 12 \, (r_t/R_c)^{1/2}] . \qquad (2)$$

Pressure Drop

The pressure drop through a helical coil was higher than that of a straight tube. This led to equations describing the pressure drop in a helical coil. The equation for pressure drop through a straight tube in laminar flow is given by the Hagen-Poiseuille equation (McCabe et al., 1985):

$$\Delta P_s = \frac{2 f_s L \rho \bar{v}^2}{g_c D} \qquad (3)$$

$$\text{where} \qquad f_s = \frac{16}{N_{Re}} . \qquad (4)$$

Most investigators expanded on this by multiplying by a correction factor, C, defined as the friction factor in helical flow divided by the friction factor in straight flow. White (1929) proposed the following equation:

$$\Delta P_c = \frac{2Cf_s L \rho \bar{v}^2}{g_c D} \tag{5}$$

where
$$\frac{1}{C} = \{1 - [1 - (11.6/N_{Dn})^{0.45}]^{1/0.45}\} . \tag{6}$$

This equation is applicable for $11.6 < N_{Dn} < 2,000$. It also assumes that the tube forming the coil is of circular cross-section. Koutsky and Adler (1964) expanded the applicability of the above equation by defining C for tubes of elliptical cross-section. Figure 3 is a graph of C as a function of the Dean number and the ellipticity.

One disadvantage of the White and Koutsky/Adler correlations is that they are only valid for $N_{Re} < 2,100$, because the definition of f_s is only valid for this range. Therefore, Srinivasan et al. (1970) proposed the following equations for pressure drop which are valid for the following curvature ratios, $0.0097 < r_t/R_c < 0.135$. The first equation is

$$\Delta P_c = \frac{2f_c L \rho \bar{v}^2}{g_c D} . \tag{7}$$

For laminar flow, f_c is defined as
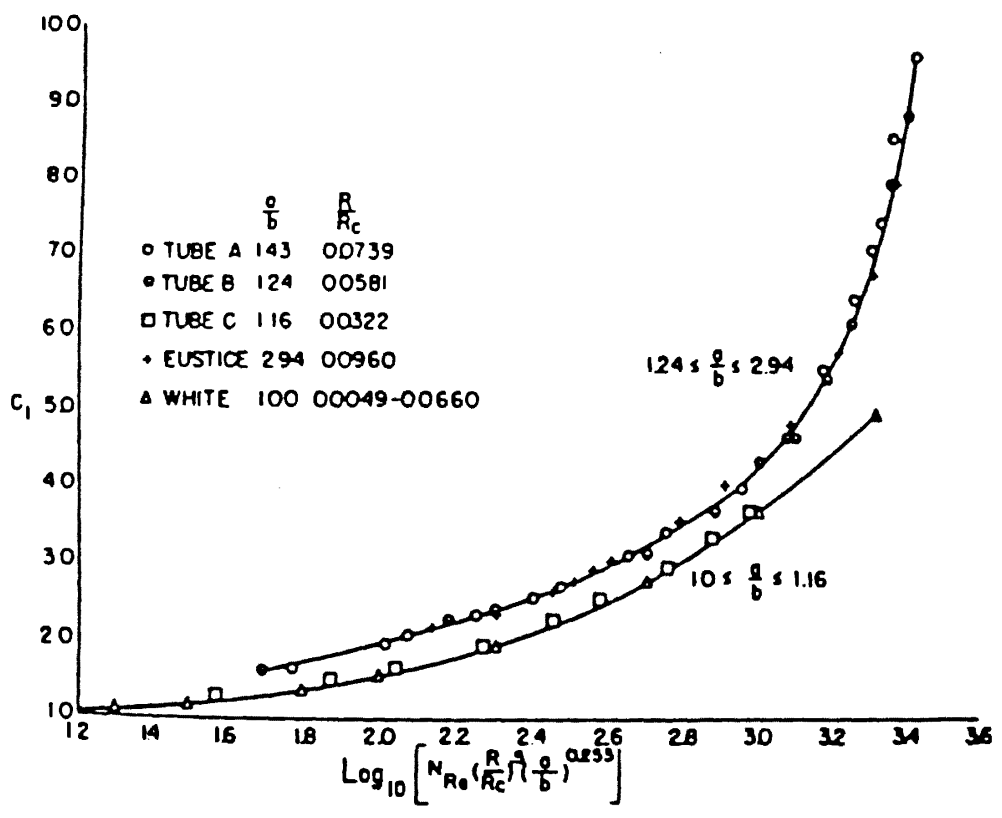
Figure 3. Pressure Drop Characteristics of Helical Coils in
Laminar Flow   (from Koutsky and Adler, 1964)

$$f_c = \frac{7.7(r_t / R_c)^{1/2}}{N_{Dn}^{0.725}} \tag{8}$$

for $30 < N_{Dn} < 300$.

For transition flow $(2,100 < N_{Re} < 10,000)$, f_c is defined as

$$f_c = \frac{1.8(r_t / R_c)^{1/2}}{N_{Dn}^{1/2}} \tag{9}$$

for $300 < N_{Dn} < (N_{Dn})_{Critical}$, where $(N_{Dn})_{Critical}$ is defined as

$$(N_{Dn})_{Critical} = (N_{Re})_{Critical} (r_t/R_c)^{1/2} . \tag{10}$$

Axial Dispersion

One of the characteristics of a helical coil is that axial dispersion is minimized. Axial dispersion can be thought of as the extent to which a tracer sample injected at t = 0 will exit the reactor with the same residence time. For plug flow, there is no axial dispersion. In laminar flow, the particles of fluid are separated due to the parabolic velocity profile. In helical flow, the secondary flows cause each particle of fluid to experience different velocities as it flows down the tube thus reducing the degree to which a tracer sample would disperse. Axial dispersion can also be thought of in terms of the residence time distribution as described in the next section (Koutsky and Adler, 1964).

Residence Time Distribution

The residence time is the amount of time that a particle of fluid spends in a reactor. The normal way of expressing the distribution of residence times in a reactor is through E(t), the exit age distribution function. E(t) is the age distribution of the exiting stream of the reactor. The residence time distribution is an indication of the degree of mixing in the system. RTD's can be found experimentally through pulse and step tests or theoretically if information is known about the flow patterns in the system (Fogler, 1986). Most often, RTD's are expressed as non-dimensional quantities, and this is called the reduced RTD.

Ruthven (1971) developed a theoretical expression for the reduced RTD of a helical coil using the velocity profiles presented by Dean. His result for the RTD is as follows

$$E(\theta) = 0 \qquad 0 < \theta < 0.613 \qquad (11)$$

$$\text{and} \quad E(\theta) = \frac{0.705}{\theta^{3.81}} \qquad \theta > 0.613. \qquad (12)$$

Nauman (1977) corrected some mathematical errors made in the derivation of Eqs. 11 and 12 and presented the following expression which more accurately describes the system:

$$E(\theta) = 0 \qquad\qquad 0 < \theta < 0.61293 \qquad (13)$$

$$\text{and} \quad E(\theta) = \frac{0.5709}{\theta^{3.84}} + \frac{0.1449}{\theta^3} \qquad \theta > 0.61293. \qquad (14)$$

These expressions differ from the reduced RTD for a straight tube in ideal laminar which is given by Ruthven as

$$E(\theta) = 0 \qquad 0 < \theta < 0.5 \qquad (15)$$

$$\text{and} \quad E(\theta) = \frac{1}{2\theta^3} \qquad \theta > 0.5 . \qquad (16)$$

The difference is due to the secondary flows in the helical coil (Ruthven, 1971).

The RTD expressions can be related to concentrations and conversion by the following:

$$\frac{c}{c_o} = \int_0^\infty \frac{c'(\theta)}{c_o'} E(\theta) d\theta \qquad (17)$$

where for a first order reaction

$$\frac{c'(\theta)}{c_o'} = e^{-k\tau\theta} . \qquad (18)$$

Now, the conversion, X, is

$$X = 1 - \frac{c}{c_o} = 1 - \int_0^\infty \frac{c'(\theta)}{c_o'} E(\theta) d\theta . \qquad (19)$$

For a straight tube, the integral can be found in tables as

$$X = 1 - e^{-k\tau\theta} \left[1 - \frac{k\tau}{2} \right] + \left[\frac{k\tau}{2} \right]^2 E_1 \left(\frac{k\tau}{2} \right) \qquad (20)$$

where E_1 is the exponential integral defined by Gradshetyn and Ryzhik (1980) as,

$$E_1 = \int_v^\infty \frac{e^{-v}}{v} dv . \qquad (21)$$

Integration of the helical coil RTD can be done numerically using the trapezoidal rule for different values of the

product $k\tau$. Conversion for plug flow is given by Levenspiel (1972) as

$$X = 1 - e^{-k\tau}. \tag{22}$$

Figure 4 shows a comparison of the conversion of a straight tube, a helical coil, and a plug flow reactor for a first order reaction. Appendix A contains tables of the exponential integral and the results of the numerical integration of the helical coil RTD.
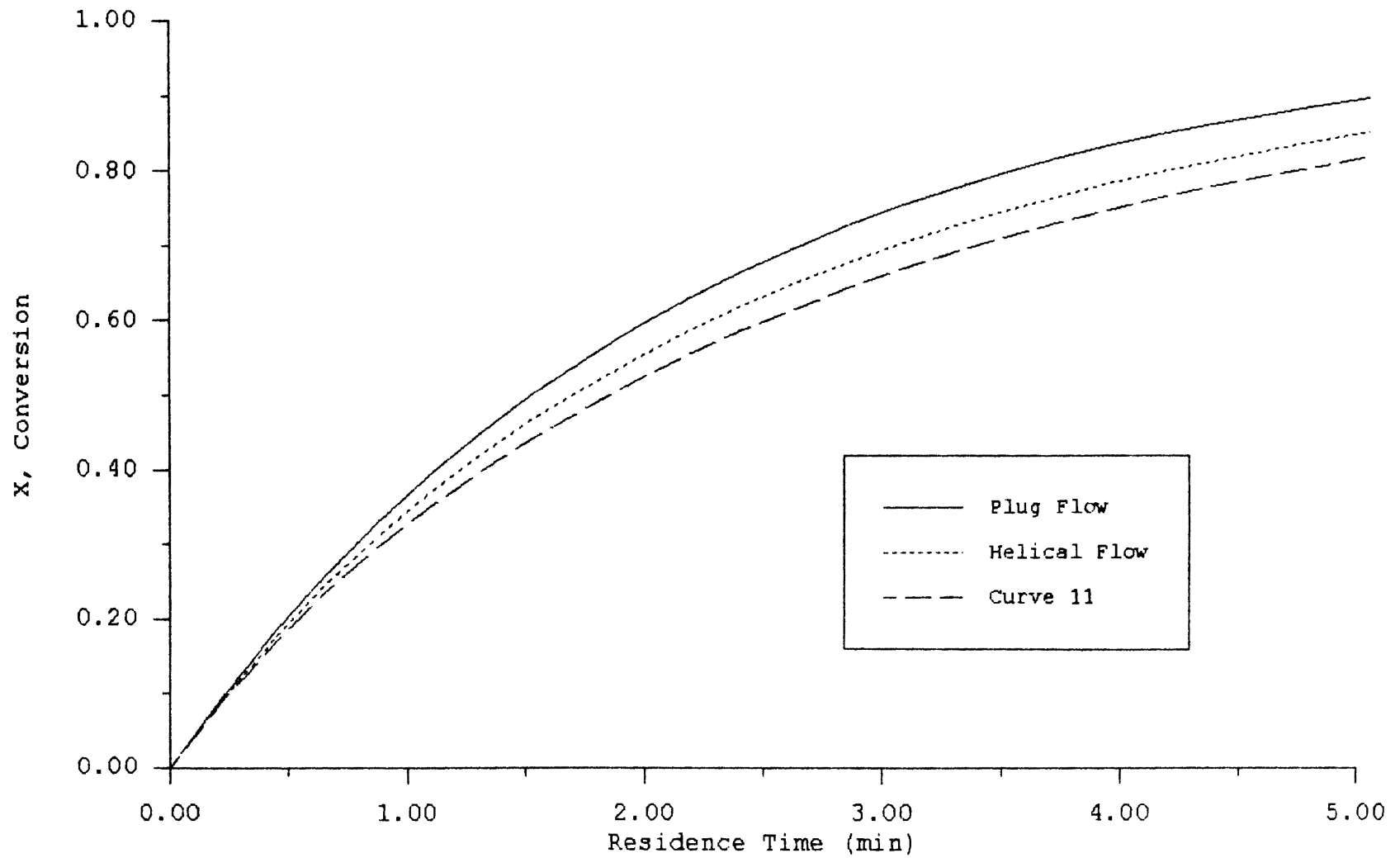
Figure 4: Comparison of Ideal Laminar, Helical, and Plug Flow Reactors

CHAPTER III

KINETICS OF THE BATCH REACTION

The hydrolysis of crystal violet dye with sodium
hydroxide has been used for many years in teaching
laboratories. There are several reasons for this. First,
the reaction can be done at very low concentrations (10^{-5}
Molar for the dye and 10^{-2} Molar for the NaOH). When sodium
hydroxide reacts with crystal violet dye, a clear product is
formed; therefore, the reaction can be followed by the
change in color of the solution using a spectrometer. This
reaction has been studied by several investigators, but none
have provided a definitive statement on the kinetics of the
reaction. Instead, they provide only a rate constant at
their particular temperature of interest. In this chapter,
the temperature dependence of the reaction will be studied.
The setup of the batch reaction system will also be
discussed.

Setup of the Batch Reactor

Several possible configurations of the batch reactor
were used to determine which provided the best results. In

all, sixty batch experiments were performed. The first
system, in which four experiments were performed, was a
beaker of solution mixed by a magnetic stirring rod. This
system did not provide consistent results because of the
time required to transfer the reacting solution to the
spectrometer cuvette. The second system was the reacting
solution in the cuvette which was left in the spectrometer
during the reaction. Twenty-eight experiments of this type
were performed. Since the reactants are in over a thousand
to one ratio, the assumption of well mixed holds even though
no actual "mixing" is taking place. The results of this
system were better than that of the beaker system, but were
not used because the temperature inside the spectrometer
fluctuated. The final system was a cuvette that was taken
out of the spectrometer and either placed in the ambient air
or in a temperature controlled water bath. This method
produced the most consistent results and is the method that
will be discussed in the remainder of this chapter.

Experimental Procedure

The experiments were conducted in one of two manners.
In both cases, 0.08 Molar NaOH and 2.4×10^{-5} Molar dye were
used. The first procedure is for experiments done at room
temperature. Equal volumes of dye and NaOH solution were
mixed together in a beaker. This mixture was then

transferred to a cuvette and placed in the spectrometer.
The initial transmittance reading was taken, and a stopwatch
was started. The cuvette was then removed from the
spectrometer and placed in a test tube rack. At one minute
intervals, the cuvette was placed in the spectrometer and a
transmittance reading was taken. Immediately after taking
the reading, the cuvette was placed back in the test tube
rack. This continued until the transmittance reached 80 to
90 %. The method for experiments done at temperatures other
than room temperature were very similar. The differences
were that the initial dye and NaOH solutions were heated to
the desired temperature and that the cuvettes were placed in
the water bath rather than in the test tube rack.

Analysis of Data

For each experiment, the percent transmittance was
converted to absorbance by the following equation:

$$A = -\log(\% T/100) . \qquad (23)$$

Absorbance and concentration have a linear relation as shown
by the Beer-Lambert Law (Atkins, 1986):

$$C = \frac{A}{\varepsilon l} \qquad (24)$$

where ε is the molar absorbance coefficient and l is the
path length of the sample.

The reaction of crystal violet dye with NaOH is first order with respect to both reactants (Corsaro, 1964). The rate law for this reaction is

$$-r_A = kC_A C_B .$$
<div align="right">(25)</div>

where A represents the dye and B represents NaOH. However, the great excess of NaOH over dye (over 1,000:1) makes this reaction pseudo-first order, and the rate law reduces to

$$r_A = -k'C_A$$
<div align="right">(26)</div>

where $\quad k' = kC_B .$
<div align="right">(27)</div>

Combining Eq. 26 with the design equation for a batch reactor and integrating the result obtains (Fogler, 1986)

$$\ln(C_{AO} / C_A) = k't .$$
<div align="right">(28)</div>

Substituting Eqs. 24 into 28 and simplifying, the following equation is obtained

$$\ln(A_O / A) = k't .$$
<div align="right">(29)</div>

By plotting $\ln(A_0/A)$ versus time, the pseudo-first order rate constant, k', can be found by determining the slope of the resulting straight line with an intercept of zero. The actual rate constant, k, is found by dividing k' by C_{B0}.

The temperature dependence of rate constants often fits the Arrhenius equation, which is

$$k = k_0 \exp(-E / RT) .$$
<div align="right">(30)</div>

Eq. 29 can be rearranged to give the equation of a straight line:

$$\ln(k) = \ln(k_0) - E/RT. \qquad (31)$$

. By plotting the natural log of the rate constant versus the inverse of the temperature, the pre-exponential factor, k_0, and the activation energy can be found from the resulting straight line. The slope of this line is the activation energy divided by R, the ideal gas constant. The y intercept is the natural log of the pre-exponential factor.

Results

Twenty-eight experiments were performed to determine the temperature dependence of the reaction. Fourteen experiments were performed at 24 °C. The range of the rate constant for these experiments is from 7.7 to 8.9 l/(mol·min) with an average of 8.5 l/(mol·min). Six experiments were performed at 30 °C with a range of 12.4 to 13.8 l/(mol·min) and an average of 13.1 l/(mol·min). Four experiments were done at 35 °C. The rate constants at 35 °C ranged from 18.2 to 18.7 l/(mol·min) with an average of 18.5 l/(mol·min). Finally, four experiments were done at 40 °C. The rate constant had a range of 25.2 to 27.7 l/(mol·min) and an average of 26.6 l/(mol·min). Table I summarizes the results of all twenty-eight experiments. In addition, Appendix B contains the data for each of the sixty experiments performed.

TABLE I

RESULTS OF BATCH KINETIC EXPERIMENTS

Run	T (°C)	k (l/mol/min)	Run	T (°C)	k (l/mol/min)
1	24	8.6	15	30	13.8
2	24	8.7	16	30	13.6
3	24	8.3	17	30	12.4
4	24	8.7	18	30	12.8
5	24	8.8	19	30	12.5
6	24	7.8	20	30	13.3
7	24	8.7	21	35	18.2
8	24	8.5	22	35	18.7
9	24	8.5	23	35	18.6
10	24	8.3	24	35	18.4
11	24	8.6	25	40	25.2
12	24	8.9	26	40	27.7
13	24	8.0	27	40	27.4
14	24	8.8	28	40	25.9

Next, a plot of the natural log of k versus the inverse of the temperature was made, and a least squares line was fit to the data. The result is Figure 5. The rate constant can now be given by the following equation:

$$k = 3.4 \times 10^{10} \exp(-6570/T) . \qquad (32)$$

At 25 °C, Eq. 32 gives a rate constant of 9.1 1/(mol·min). Egekeze (1988) determined the rate constant to be 7.33. Corsaro (1964) determined the rate constant to be 9.61. Finally, Hudgins and Cayrol (1981) give of a rate constant of 13.5. Hudgins and Cayrol do not provide any details of the method used to determine their rate constant. Corsaro described his methodology, but his results are from only two experiments. Egekeze tried to show a temperature dependence of the reaction, but based his expression on only four data points.
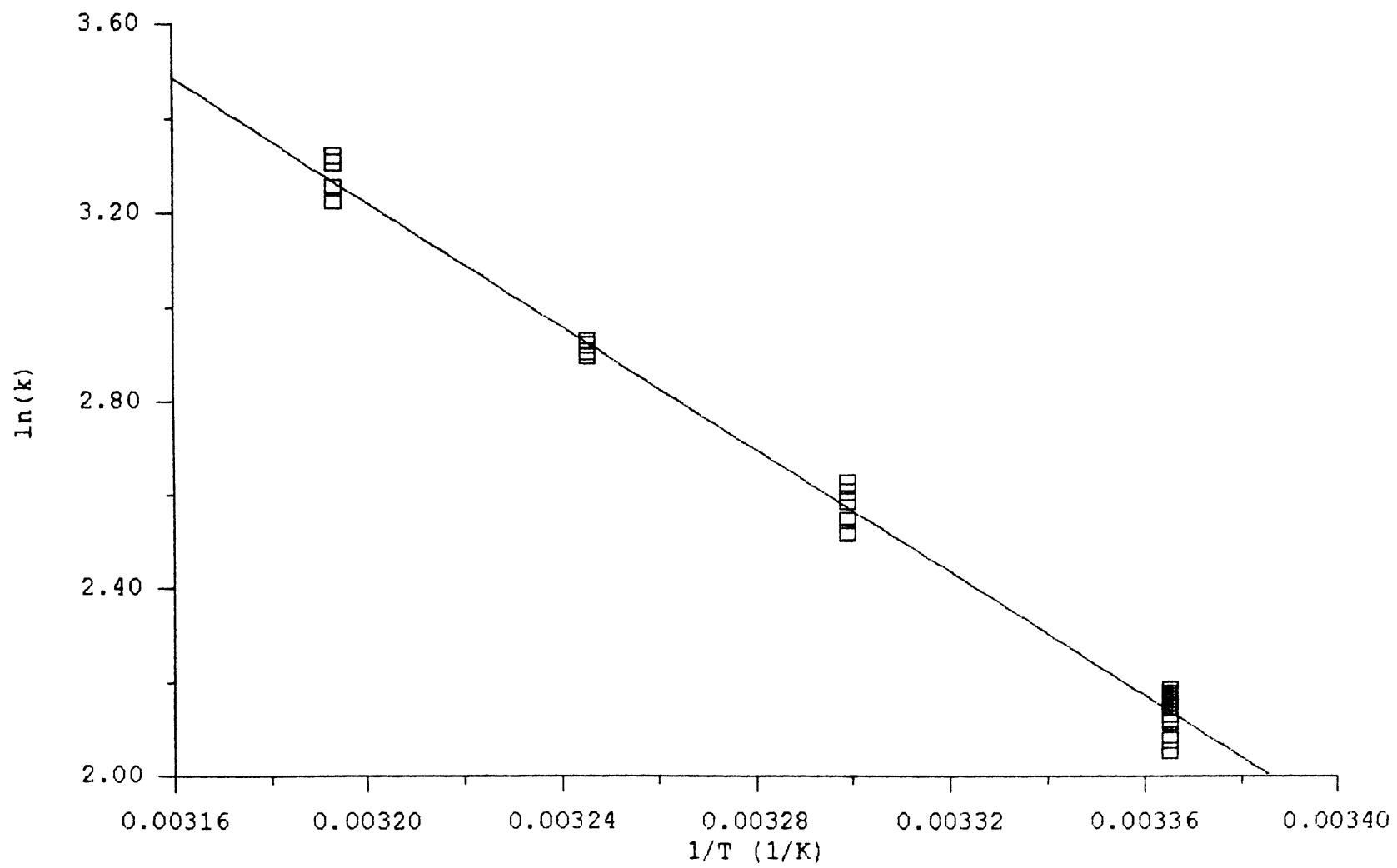
Figure 5: Temperature Relation of the Rate Constant

CHAPTER IV

COMPUTER DATA ACQUISITION

Four experimental variables are measured in the helical
coil experiment: absorbance, pressure drop, and flow rate.
The flow rates are measured using a rotameter, and the
pressure drop is measured using a mercury manometer.
However, the absorbance readings are taken using a computer
data acquisition system. This system consists of two
spectrometers with analog outputs, a data acquisition board,
data acquisition software, and a personal computer.
National Instruments hardware and software were chosen to be
used in this project. The data acquisition board is a LAB-
PC+ which is capable of handling ten analog DC inputs. The
software is LABVIEW for Windows. This program has a
graphical interface which makes setting up the system very
easy. In LABVIEW, the user sets up "virtual instruments"
and can display the information as gauges, strip charts,
digital displays, etc.

For this system, two strip charts are used. Both the
absorbance and the transmittance are displayed on strip
charts as well as on digital displays. The output of the

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data can be displayed in any manner that the user finds
suitable.

The voltage outputs from the two spectrometers are read
every second by the program. These values are then
converted into the appropriate units. The voltage output is
from zero to one volt; therefore, the percent transmittance
can be found by

$$\%T = 100V.$$ (33)

The equation for absorbance is

$$A = -\log(V).$$ (34)

Figure 6 shows the wiring diagram for this system.
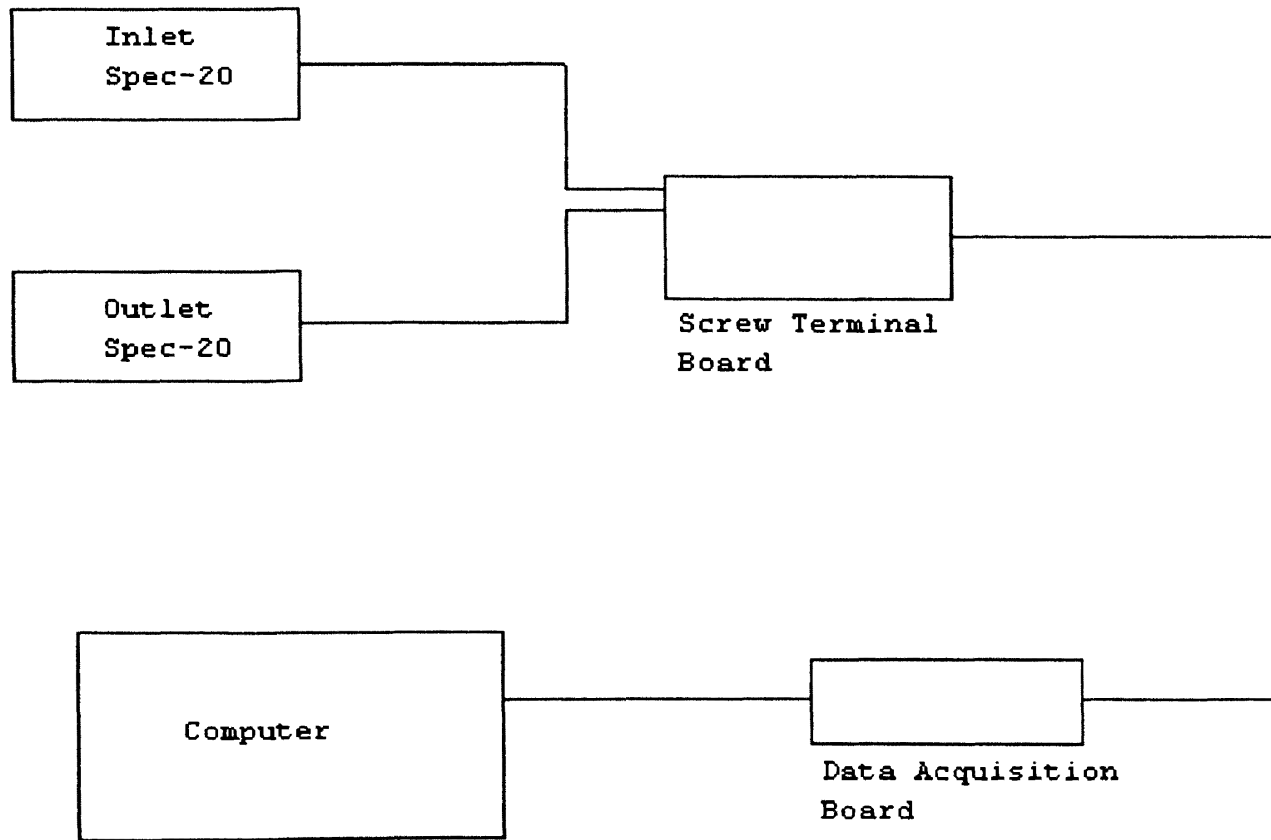
Figure 6. Wiring Diagram For Computer Data Acquisition System

CHAPTER V

EXPERIMENTAL SETUP AND PROCEDURE

The Experiment

The experiment is shown in Figure 7. Each section of
the tank holds approximately 70 1. The two pumps are 1/8
horsepower centrifugal pumps. The sodium hydroxide and dye
solutions are pumped from the tank through the rotameters
and to the reactor system. The rotameters measure flows up
to 770 ml/min each and are accurate to within 15.4 ml/min.

The reactor system consists of five parts: the inlet
and outlet spectrometers, the spectrometer cuvettes, the
pressure transducer, the reactor connections, and the
reactor. The fluid first enters the inlet spectrometer.
Both spectrometers are Spectronic 20's and have a
photometric readability of 0.2 % transmittance. The
instruments are interfaced with a computer as discussed in
the previous chapter. An integral part of the spectrometers
is the flow-through cuvettes that are used. A drawing of a
cuvette is in Figure 8. These cuvettes are a two piece
construction which enables them to be cleaned. When placed
in the spectrometer, it is necessary to shield them
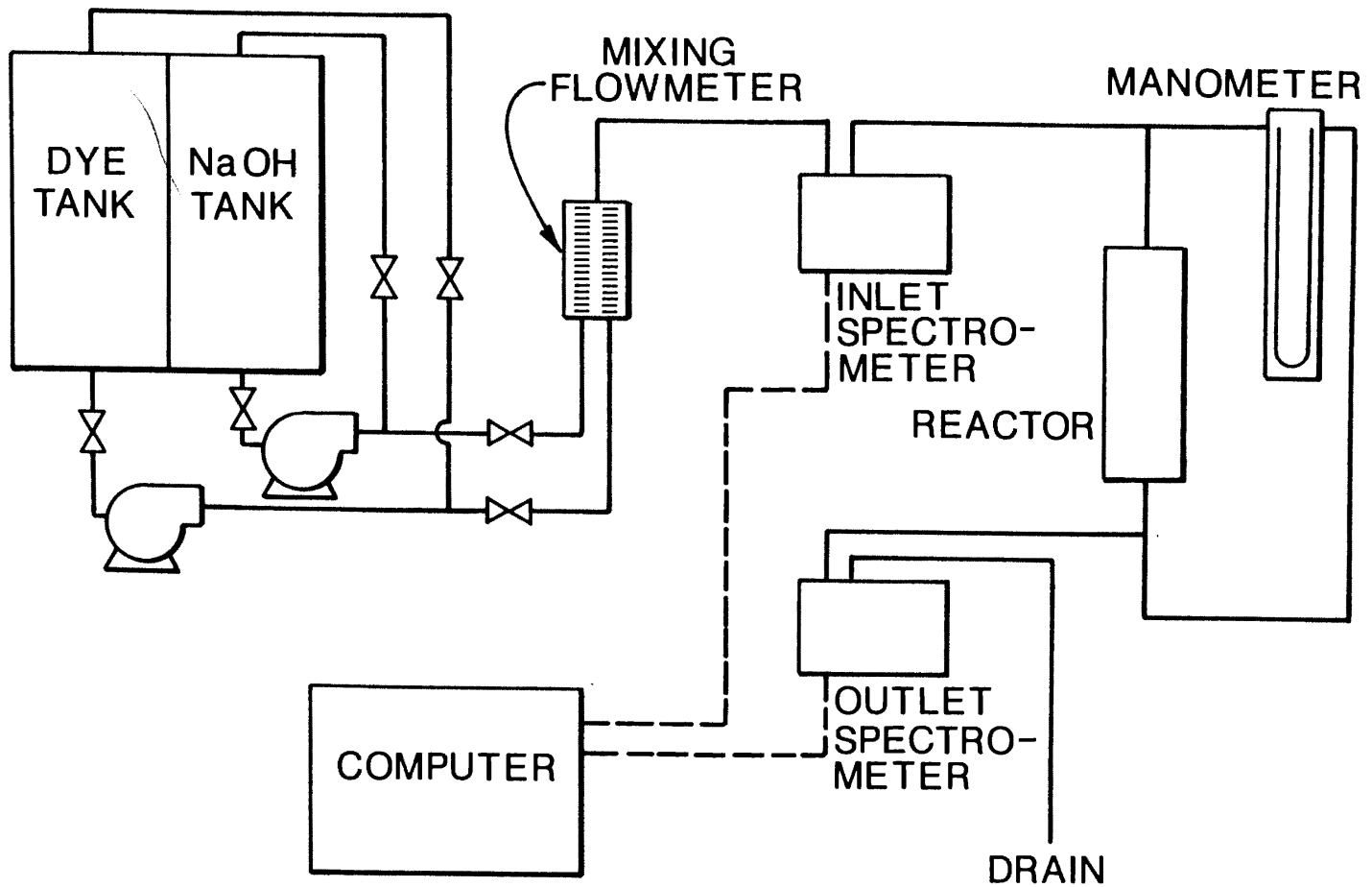
FIGURE 7. EXPERIMENTAL SETUP

$\frac{1^{\cdot}}{4}$ O.D.

FLOW
IN

FLOW
OUT

GLASS CAP

GLASS SEAL

SPECTRONIC 20
CUVETTE

$\frac{5^{\cdot}}{16}$ O.D.

$\frac{1^{\cdot}}{8}$ I.D.

$\frac{7^{\cdot}}{16}$
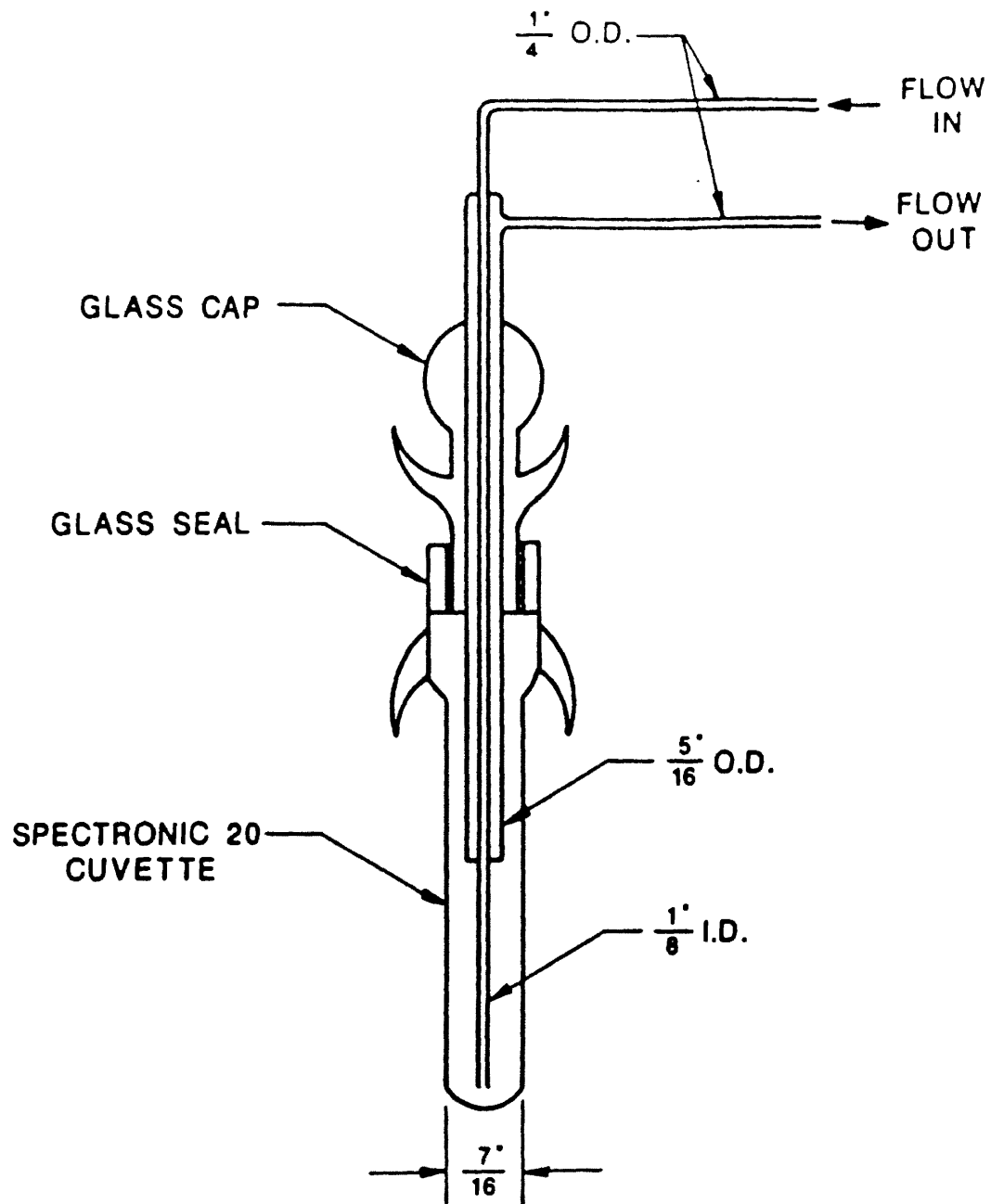
Figure 8. Drawing of Flow Through Cuvette
(from Egekeze, 1988)

from the ambient light. This has been done by using flexible foam pipe insulation and duct tape.

Next, the fluid flows to the inlet pressure tap and the mercury manometer. The pressure tap is located after the inlet spectrometer so that the measured pressure drop is only of the reactor and not of the reactor and the cuvettes.

There are three different reactor systems each having a 1/4 inch inside diameter. There are two coiled reactors that are 50 ft long. One reactor is coiled around a 2 inch Schedule 40 pipe and the other around a 4 inch pipe. There is also one straight tube reactor that is 48 ft long. These can be connected to the system through the use of quick connect fittings. These fittings allow the reactors to be changed easily and quickly. The fittings also seal when disconnected which makes changing reactors less messy. After flowing through the reactor, the fluid goes to the outlet pressure tap, through the outlet spectrometer, and to the drain.

Experimental Procedure

The experimental procedure for the conversion experiments is as follows:

1. Turn on the spectrometers and let them warm up for fifteen minutes.

2. Measure approximately 0.49 g of crystal violet dye and 160 g of sodium hydroxide. Mix the crystal violet dye and the sodium hydroxide with 50 l of

tap water in their holding tanks to produce nominal solutions of 2.4×10^{-5} M for the dye and 0.08 M for the NaOH.

3. Connect the desired reactor to the system.

4. After a 15 min warm up, calibrate the spectrometers by setting the reading to 0.0 with a blank and to 100 % with 0.08 M NaOH running through the cuvette.

5. Set the flows at the desired flow rate.

6. Wait four times the residence time and then take both inlet and outlet absorbance readings.

7. Repeat steps (4) and (5) starting at the highest flow and decreasing to the lowest until all runs are completed.

8. After all runs are completed, flush the system with tap water.

The procedure for the pressure drop experiments is

1. Fill one of the holding tanks with tap water.

2. Connect the desired reactor to the system.

3. Set the flow at the desired rate.

4. Wait 1 min for the pressure reading to stabilize and then record the pressure.

5. Repeat steps (4) and (5) for all other desired flows proceeding from the highest flow to the lowest flow.

CHAPTER VI

RESULTS AND DISCUSSION

Kinetic Results

Experiments were run using three different reactors: a 2 inch helical coil, a 4 inch helical coil, and a straight tube laminar flow reactor. Twenty-nine experiments were performed using the 2 inch reactor, twenty-six with the 4 inch coil, and nineteen with the laminar flow reactor. Appendix C contains the data from all of the experiments performed.

The purpose of the experiments is to validate the RTD given in Eqs. 13 and 14 by Nauman (1977). This is done by comparing the actual conversion obtained in a helical coil reactor with the theoretical value predicted by the RTD. The conversion in a reactor is given by the following equation

$$X = \frac{C_0 - C}{C_0} . \tag{35}$$

However, the relationship between absorbance and concentration is linear (Atkins, 1986), so combining Eq. 24 with Eq. 35 gives

$$X = \frac{A_o - A}{A_o}.$$ (35)

To compare the differences of the 2 and 4 inch reactors, it is necessary to know the characteristics of the reactor and the conditions of the experiments. The 2 inch reactor has a curvature ratio, r_c/R_t, of 0.090, while the 4 inch reactor has a ratio of 0.051. The Reynolds numbers for both experiments ranged from approximately 400 to 3,000, while the Dean number ranged from 100 to 800. The critical Reynolds number calculated by Eq. 2 for the 2 inch reactor is 9,600 and for the 4 inch reactor is 7,800; therefore, the flow in both of the helical coils is always in the laminar regime. Now, the experimental results will be discussed.

When the conversions of the 2 and 4 reactors are compared with the theoretical, as in Figure 9, the experimental points lie above the theoretical line. There could be two reasons for this; the RTD was not valid, or the experimental setup was lacking. The same trend is found when the laminar flow runs were plotted with the theoretical laminar conversions as in Figure 10. Since the characteristics of laminar flow reactors have been well studied, it was decided that the experimental system was not accurately measuring the conversion.

The experimental system was found to be deficient. Approximately four and three-quarter feet of tubing connects the cuvettes to the reactor; therefore, the measured
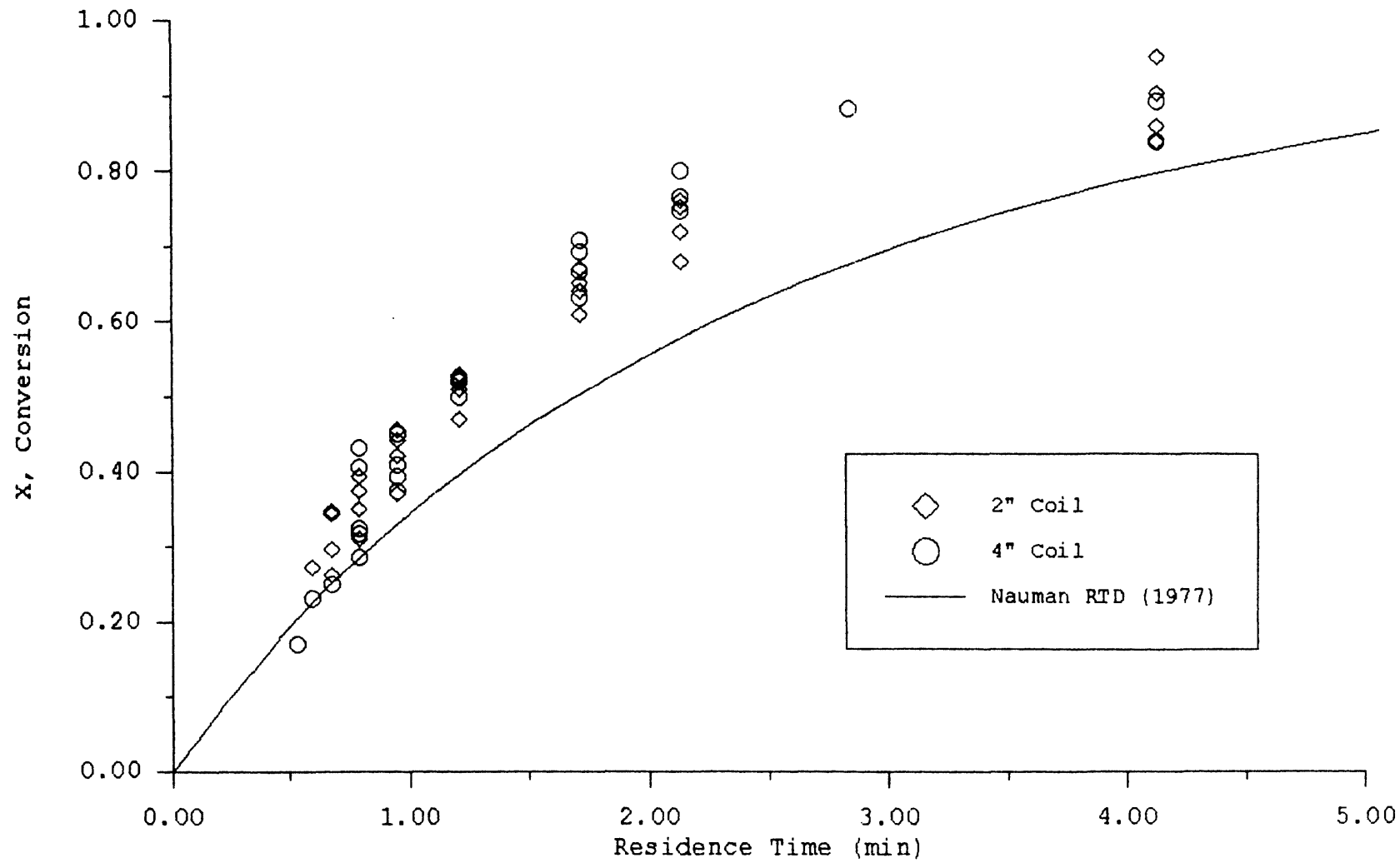
Figure 9: Comparison of Experimental Conversion with Theoretical
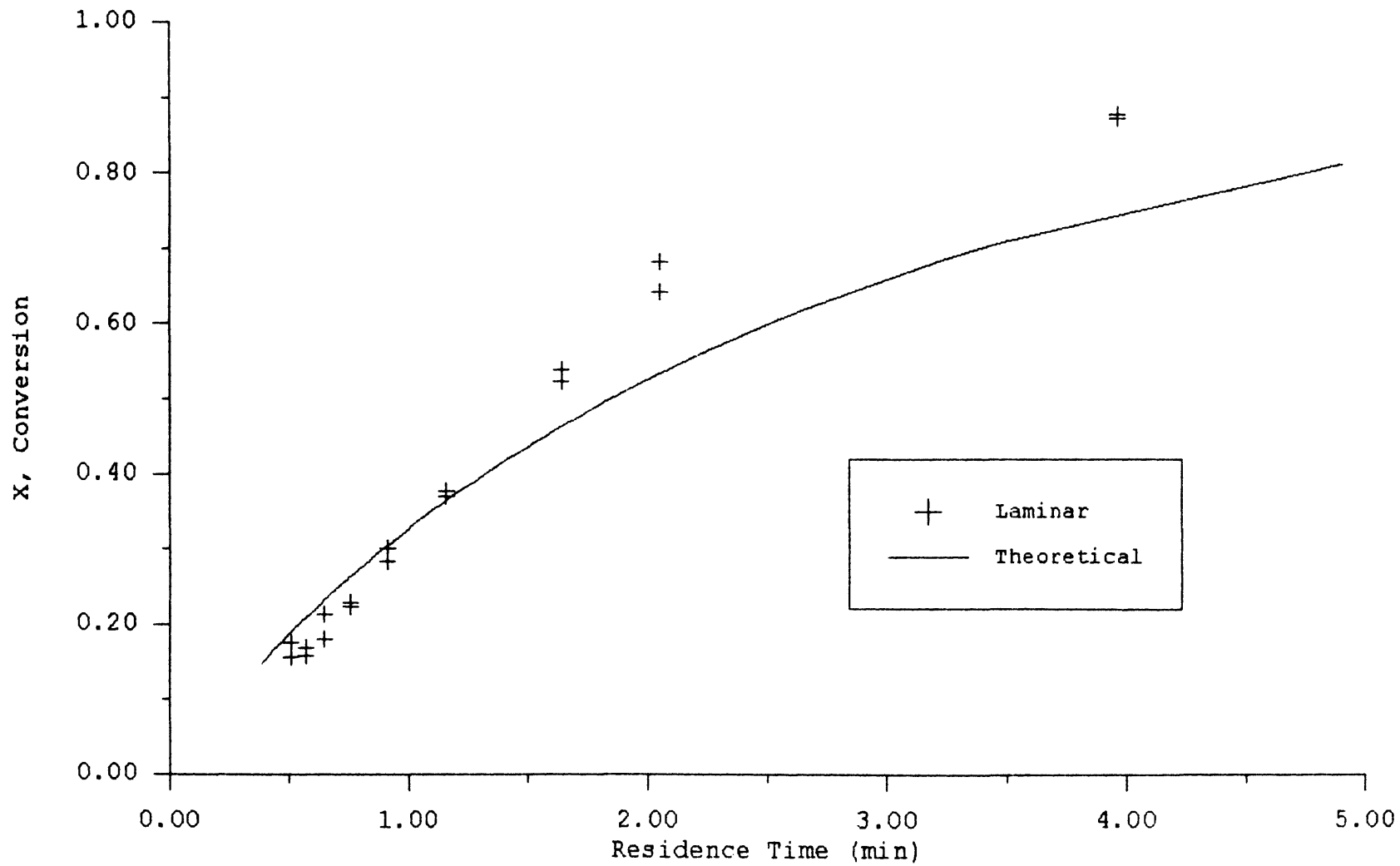
Figure 10: Comparison of Experimental Laminar Flow Conversion to Theoretical

conversion was the sum of the conversions of the reactor and the extra tubing. Since it was not possible to eliminate this length of tubing, the conversion that would be obtained in a laminar reactor of this length was calculated using Eq. 19 and subtracted from the measured conversion. The result would be the conversion obtained in the helical coil.

The corrected laminar conversions were plotted with the theoretical in Figure 11. The data now are more closely grouped to the line, confirming that the extra tubing was the cause of the larger measured conversions. The rest of the discussion of results will only include results that have been corrected for the extra tubing.

The results for the 2 and 4 inch reactors are now grouped close to the theoretical prediction. Figure 12 shows the conversion obtained in the 2 inch coil plotted with the theoretical conversions. Figure 13 shows the results of the experiments performed with the 4 inch reactor.

The RTD predicts that curvature ratio does not effect conversion, and this is confirmed in Figure 14. This figure shows both the 2 and 4 inch data together. The results of the two different reactors fall on top of each other, thus showing that there is no relation between conversion and curvature ratio for helical coils.

Since the data were still above the theoretical prediction, a propagation of errors analysis was done for both the conversion and the residence time. It was found
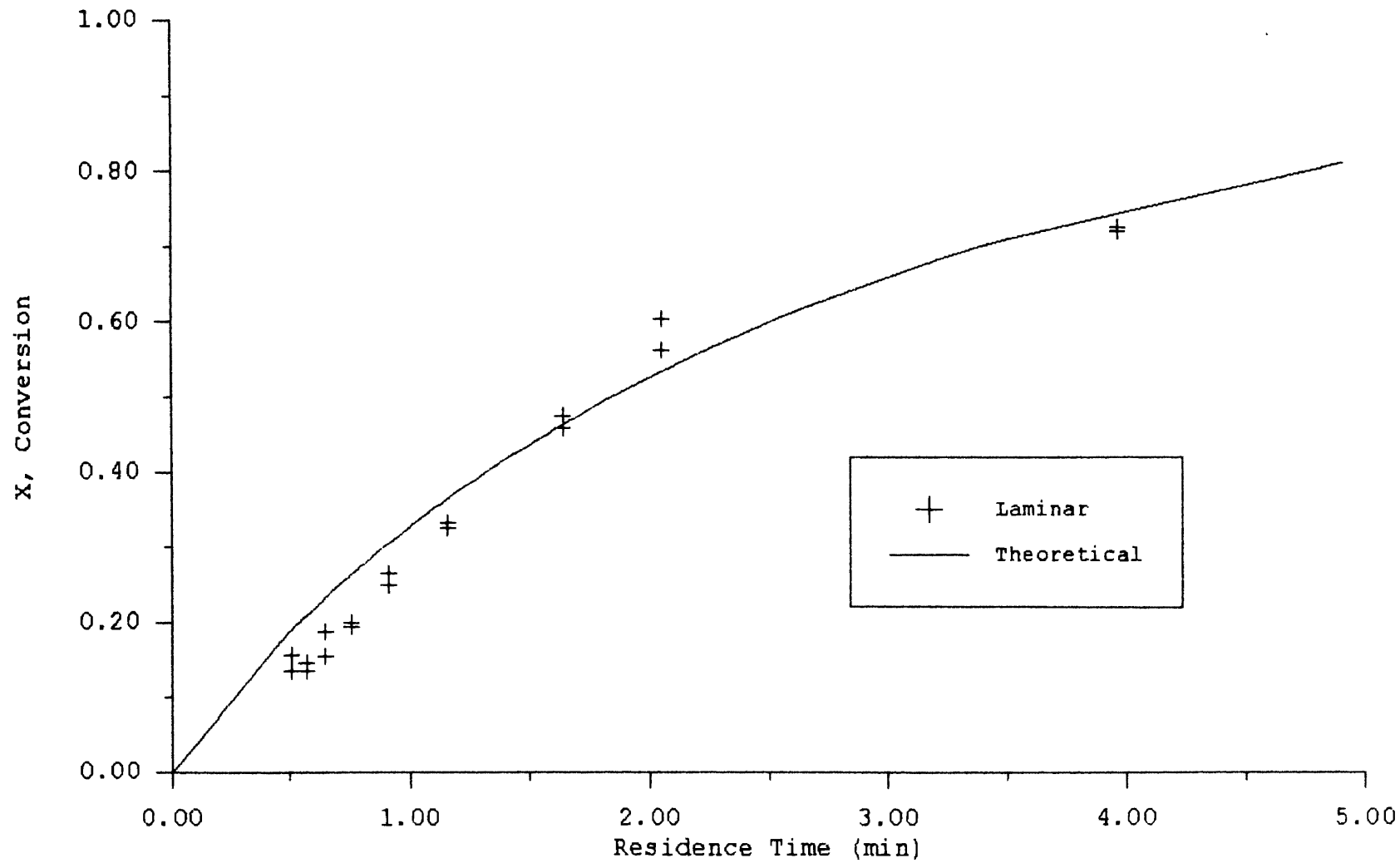
Figure 11: Comparison of Corrected Laminar Conversion to Theoretical
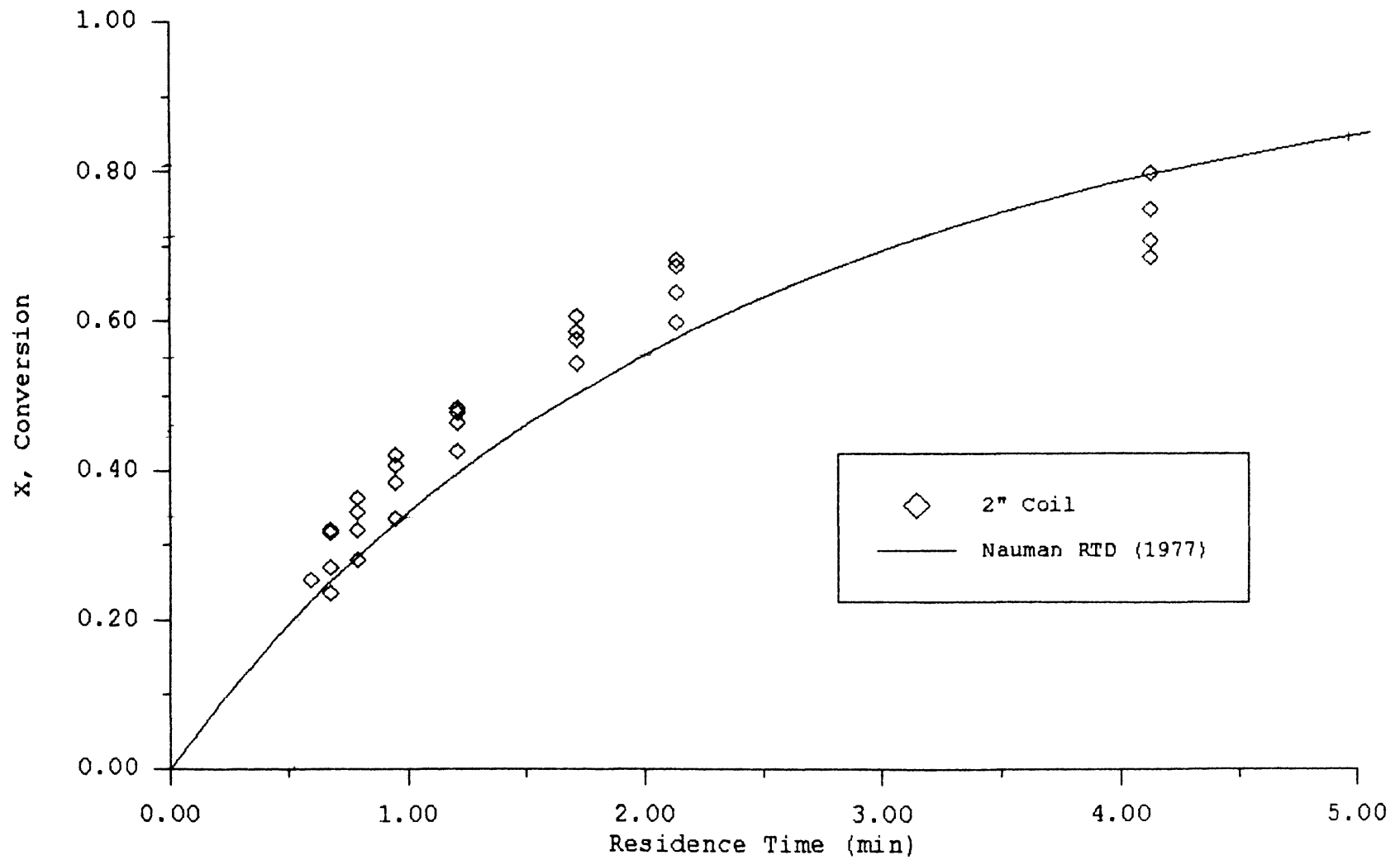
Figure 12: Comparison of 2 Inch Helical Coil Conversion to Theoretical
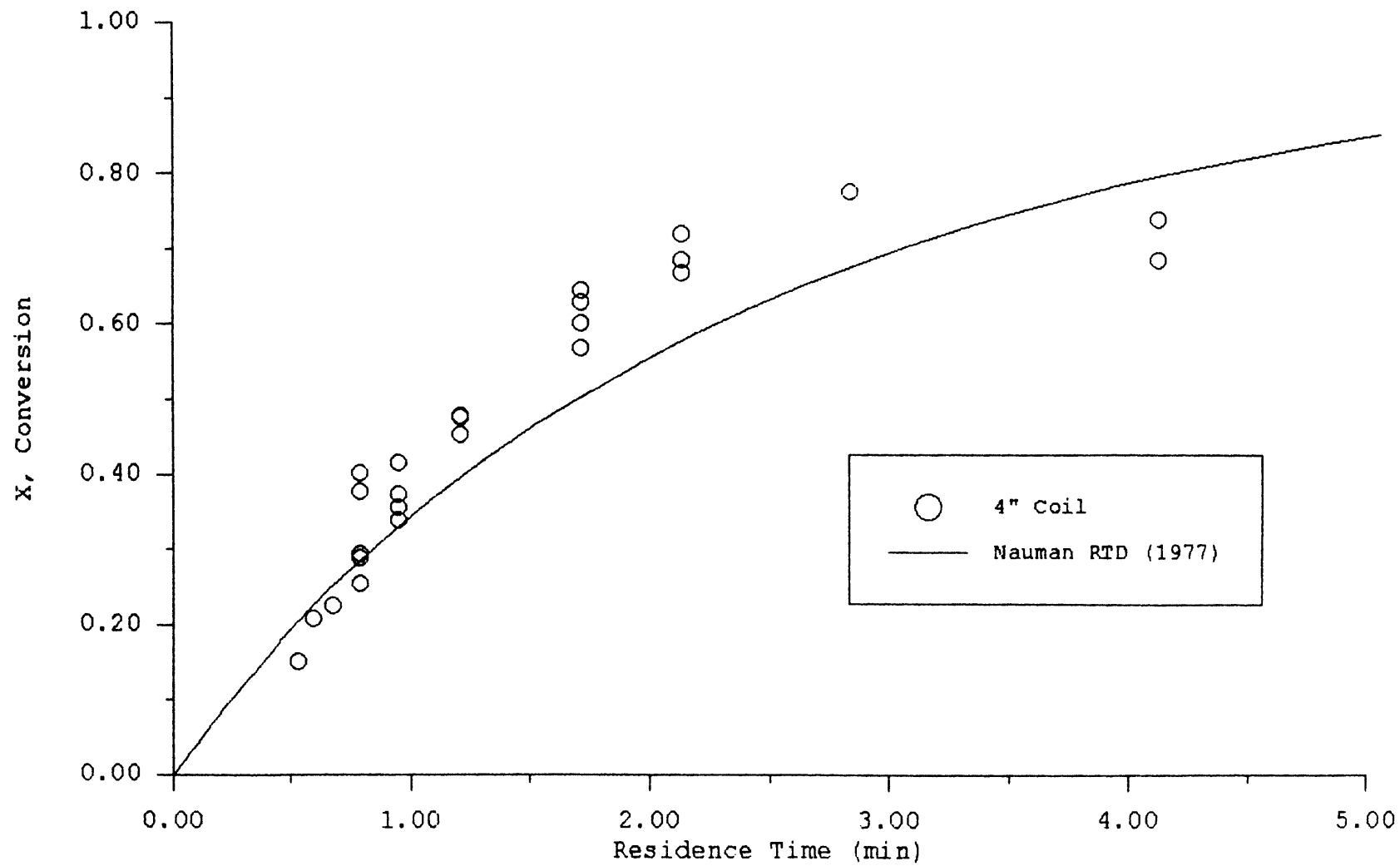
Figure 13: Comparison of 4 Inch Helical Coil Conversion to Theoretical
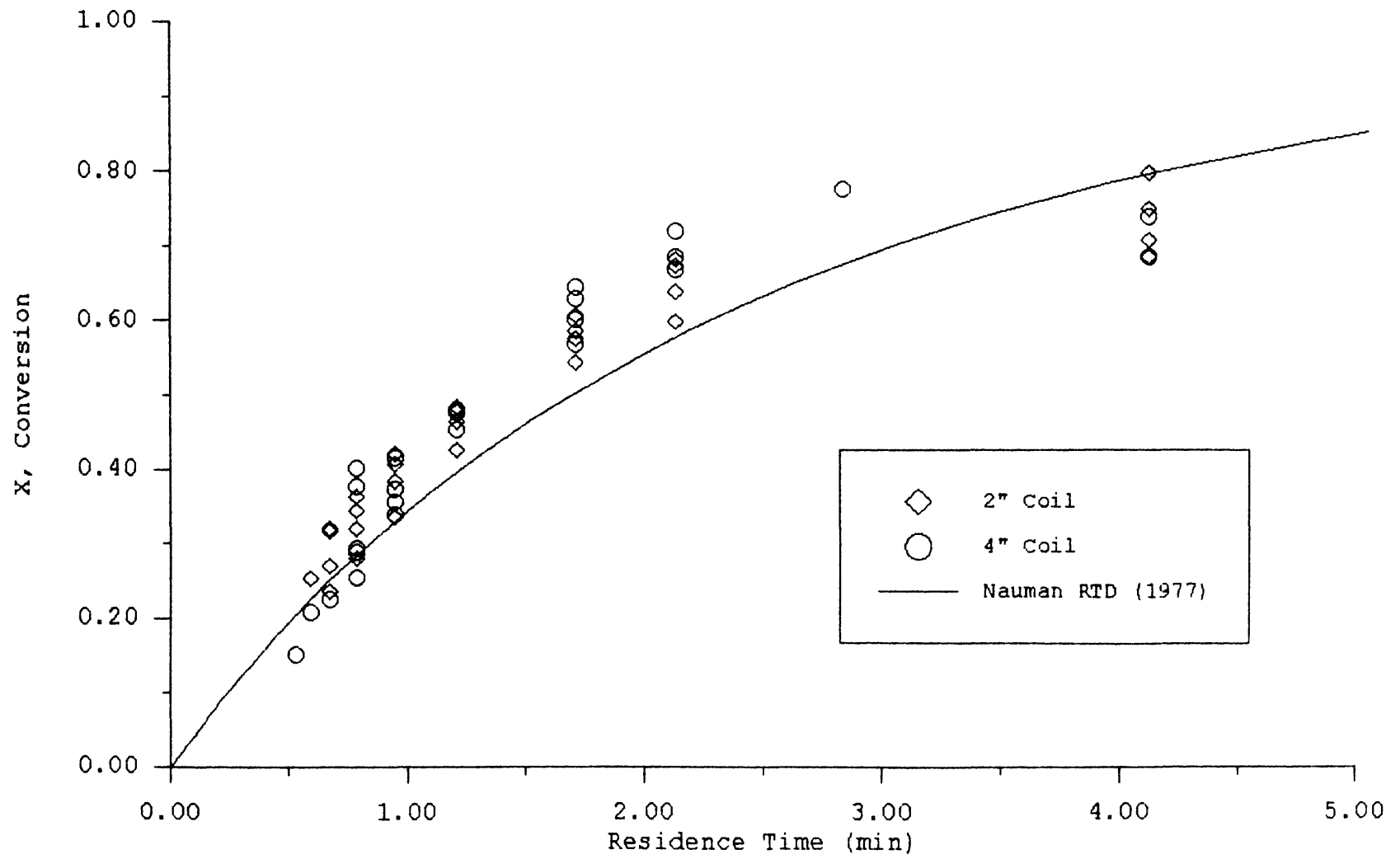
Figure 14: Comparison of the 2 and 4 Inch Helical Coils

that the majority of the error was in the residence time, τ. The residence time is the volume of the reactor divided by the volumetric flow rate. It was the measurement of the volumetric flow rate that contributed the most to the error. At low flow rates, high residence times, the error in the residence time was over 1 min. The error in the conversion was found to have a maximum deviation of 1 % conversion. The details of the error analysis are given in Appendix D. Figure 15 shows the 2 and 4 inch data with error bars. The span of these bars puts the data within reasonable limits of the theoretical values.

The experimental results also show that the helical coil conversion is higher than laminar flow conversion. In Figure 16, the results of the experiments with the laminar flow reactor are plotted with the results of the helical coil reactor. The trend of these points is that the measured laminar flow conversion is below both the measured and the theoretical helical coil conversions. As discussed in Chapter 2, helical coil conversion should be higher than laminar flow conversion.

When compared to previous work, the results of this study were found to fall much closer to the theoretical. In 1988, Egekeze performed the same experiments. Figures 17, 18, and 19 compare the results of the 2 inch reactors, the 4 inch reactors, and the laminar flow reactors, respectively. In Figure 17, the results match fairly well for the 2 inch reactor. However, in Figure 18, it can be seen that
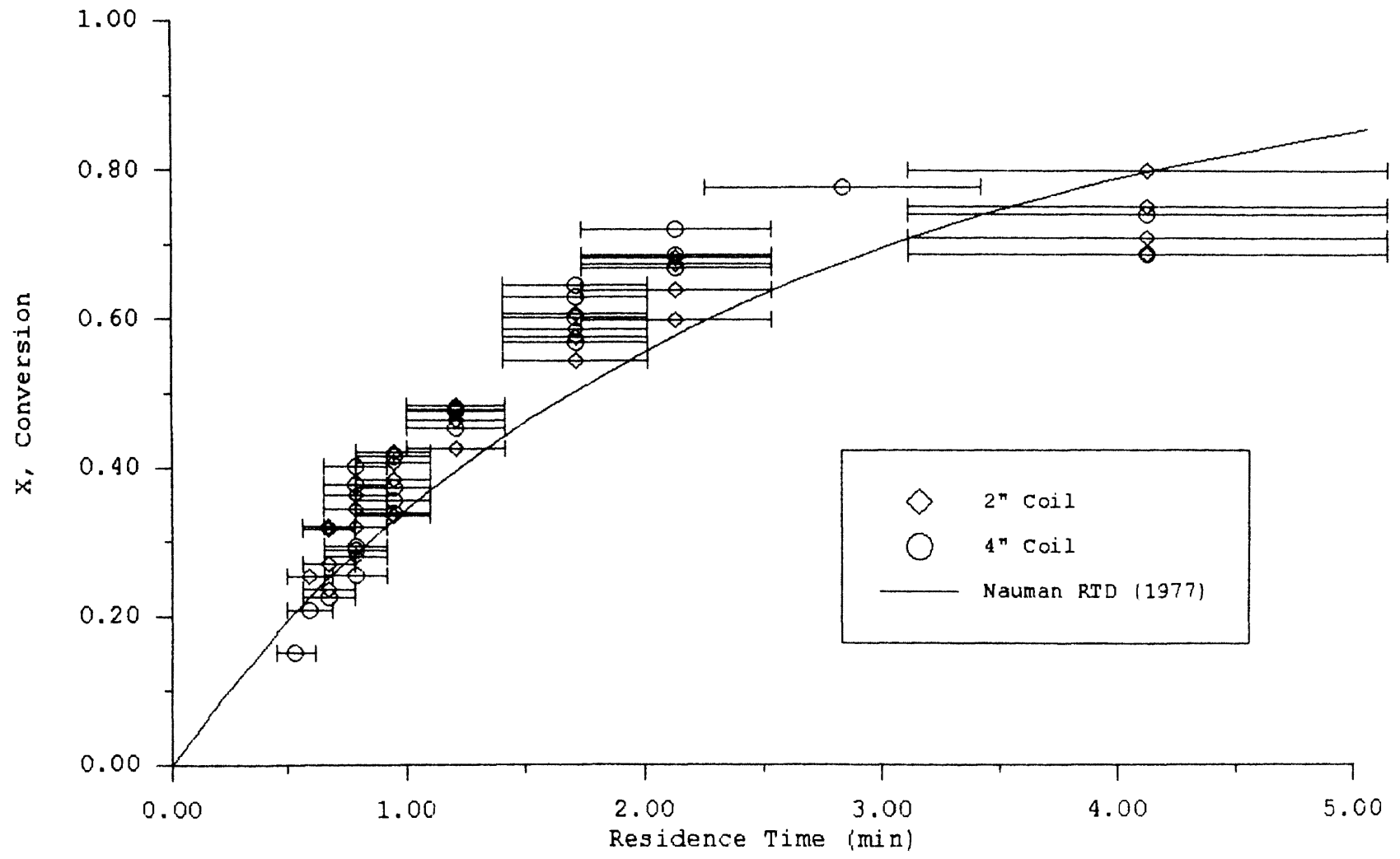
Figure 15: Comparison of Helical Coil Conversion to Theoretical
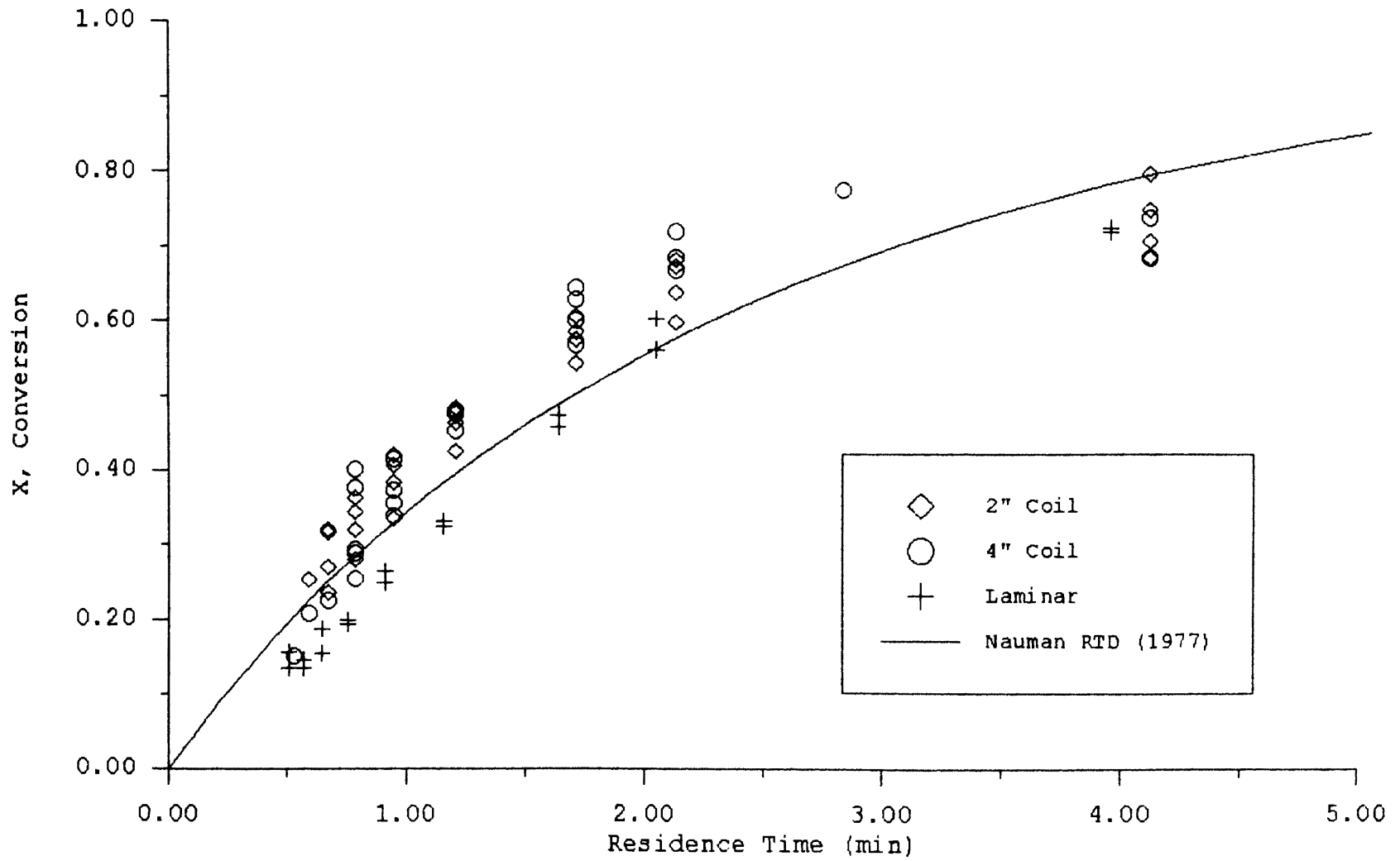
Figure 16: Comparison of the 2 Inch, 4 Inch, and Laminar Flow Reactors
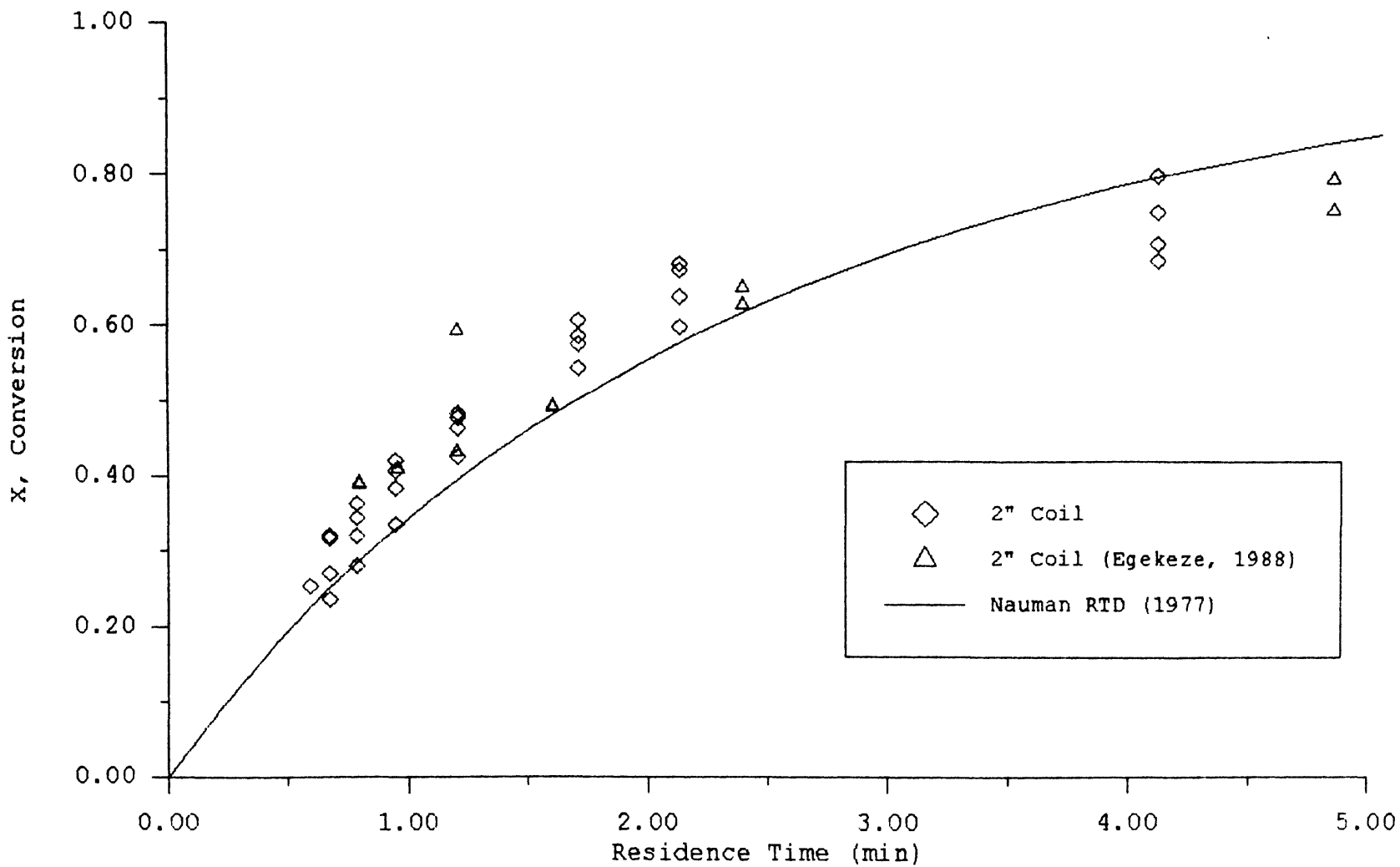
Figure 17: Comparison of 2 Inch Reactor Conversion with Previous Work
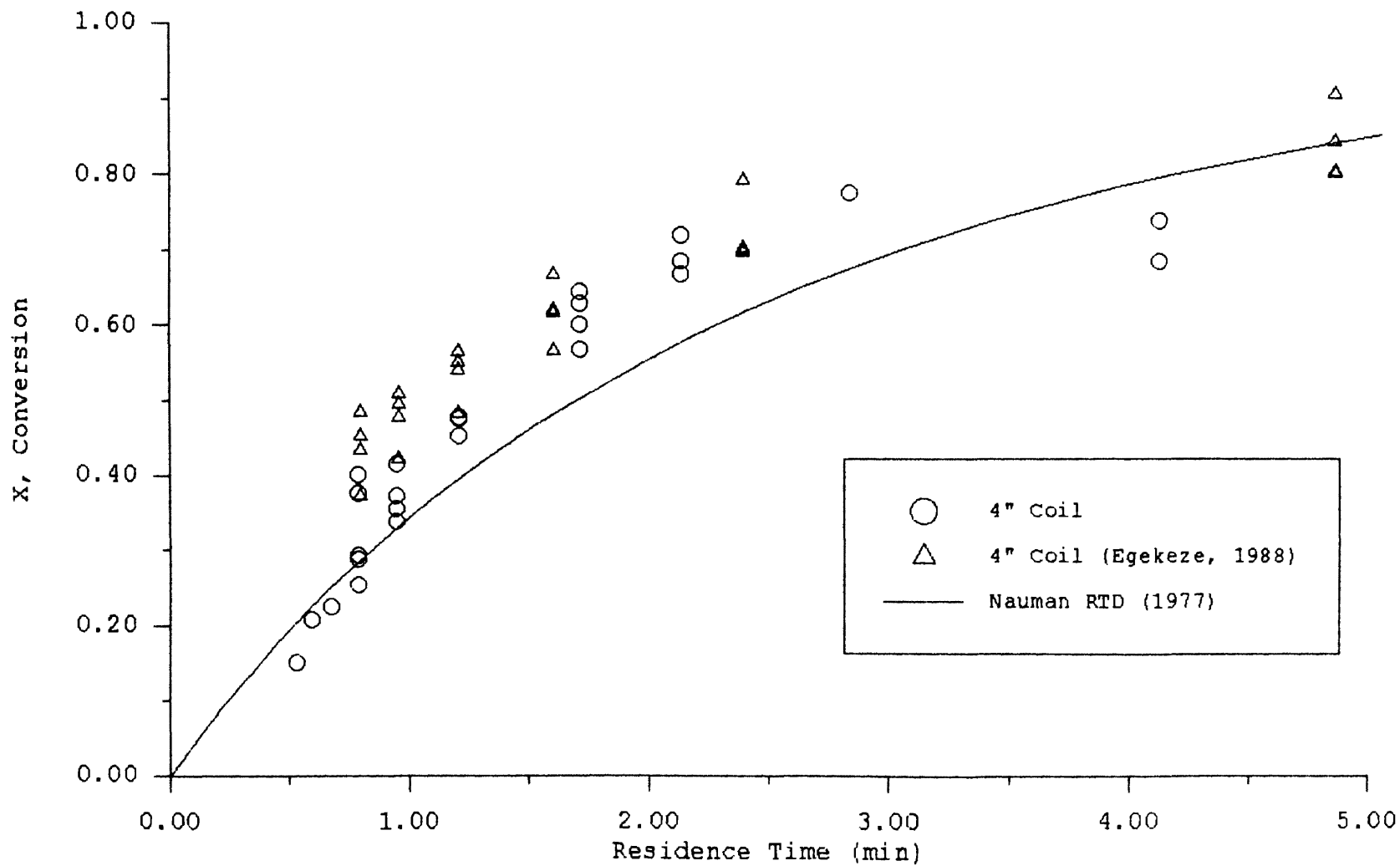
Figure 18: Comparison of 4 Inch Reactor Conversion with Previous Work
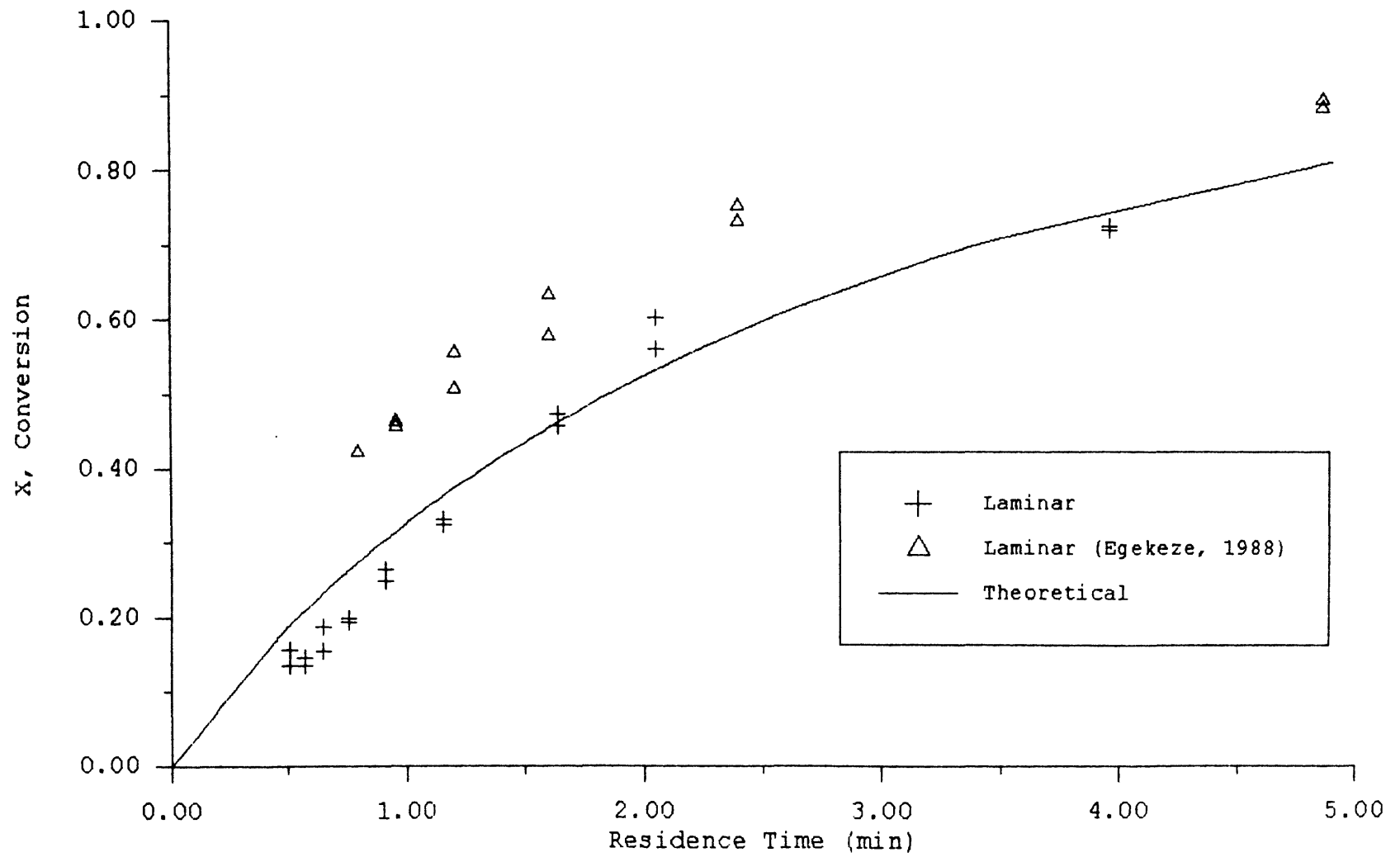
Figure 19: Comparison of Laminar Reactor Conversion with Previous Work

Egekeze's results tend to be slightly above the results of this study. This is even more clearly seen in Figure 19, where his laminar results are well above both the experimental and theoretical results.

Hydraulic Results

Pressure drop measurements were also taken on the three reactor systems. A total of one hundred-eighty experiments were done. The pressure drop that was measured was a combination of the pressure drop of the reactor and the pressure drop of the connections joining the reactor to the rest of the system. The pressure drop for a helical coil was given by Eqs. 7, 8, and 9. The pressure drop for a straight tube in laminar flow is given by Eqs. 3 and 4. Finally, the pressure drop of the connections is given by

$$\Delta P = \frac{Q^2 (SG)}{C_v^2} \tag{37}$$

The manufacturer of the fittings, Swagelok, provided the above equation and stated that the flow coefficient for each fitting was 0.2. The total estimated pressure will be the sum of the pressure drop across the reactor plus four times the pressure drop across one connection. These values have been compared to measured values to check the validity of the pressure models. The results of this comparison are shown in Table II. The difference between the experimental

TABLE II

PERCENT DEVIATIONS BETWEEN MEASURED AND
PREDICTED PRESSURE DROPS

v (ml/min)	2 Inch Deviation	4 Inch Deviation	Laminar Deviation
770	3.6	6.4	1.0
720	4.6	6.2	0.1
670	4.9	5.9	1.3
610	5.9	4.3	0.7
560	9.1	1.3	2.3
510	10.8	0.7	2.9
460	12.4	2.1	3.4
410	13.2	3.0	4.2
360	13.6	4.0	6.5
310	14.7	2.4	3.1
250	6.9	2.6	8.3
200	11.5	20.8	8.6
140	15.8	1.3	12.0
90	10.4	13.0	17.4
30	68.1	64.3	38.8

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and predicted pressure drops differed by less than fifteen percent at all but the lowest flow rates. At low flow rates the values differed by as much as sixty-eight percent.

Theory predicts that a 2 inch coil will have a higher pressure drop than a 4 inch coil which will have more pressure drop than a straight tube. This is shown in Figure 20. In the experiments, four pressure measurements were taken at fifteen different flow rates on each of the reactors. The average of the four readings was plotted in this figure. The data from all of the pressure experiments are given in Appendix C.
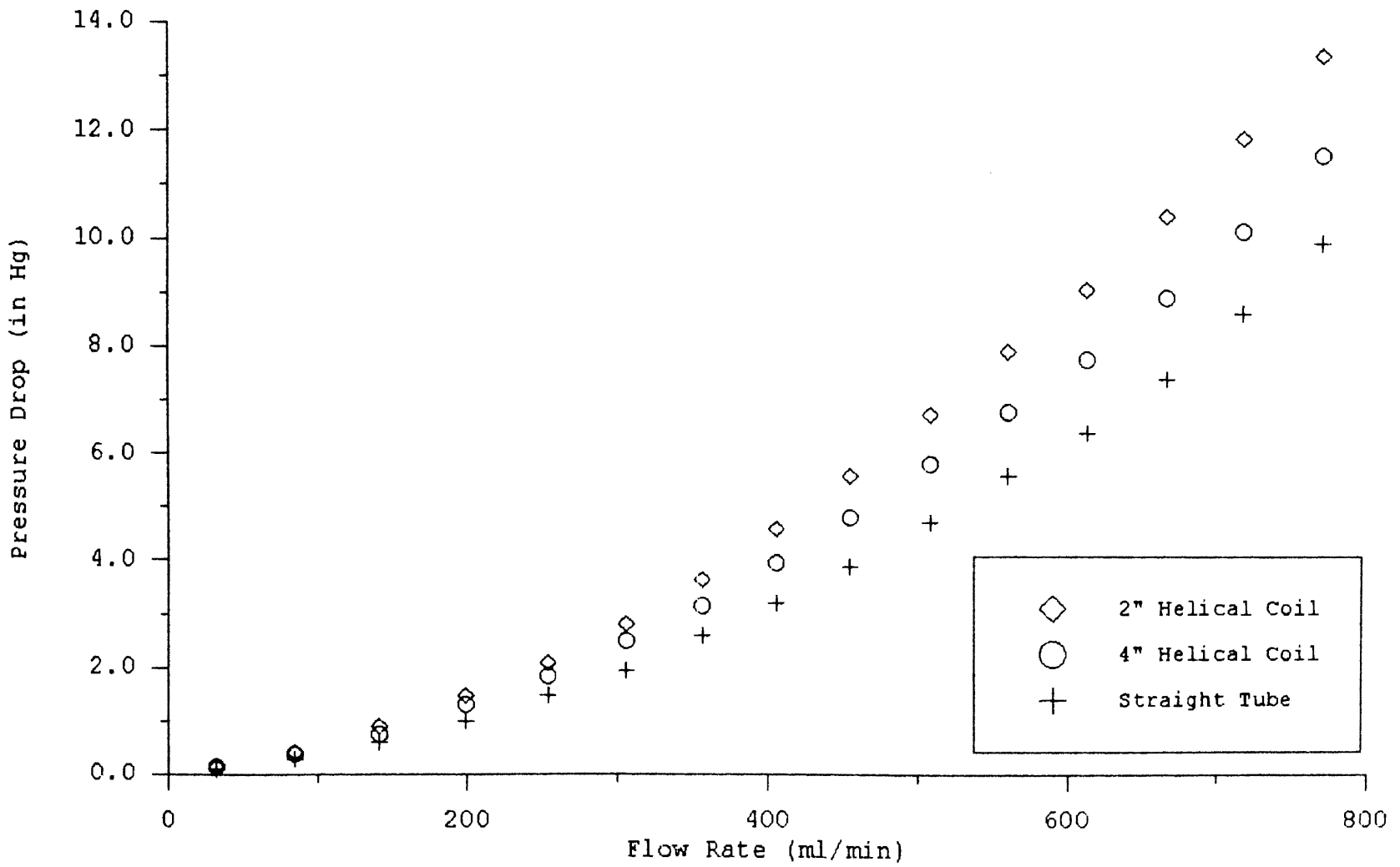
Figure 20: The Effect of Curvature Ratio on Pressure Drop

CHAPTER VII

CONCLUSIONS

The first conclusion is that the batch experiments were performed properly and that the Arrhenius relation that was found is valid. This is shown by Figure 11 in which the experimental laminar flow conversions fall almost directly on the theoretical line that is based upon the rate constant.

Second, the experimental system is viable, since the experimental and theoretical values match so closely in Figure 11. In the design of the system, it is important to keep the length of tubing connecting the reactor to the cuvettes as short as possible. However, by subtracting the conversion obtained in this tubing from the measured conversion, it is possible to obtain a good estimate of the reactor conversion.

Third, the single RTD for helical coils was confirmed, since the results of the 2 and 4 inch reactors fall very close together. The experimental results for the helical coil and the theoretical do not match as closely as the laminar results, but many of the experimental points fall within one standard deviation of the RTD based

conversion, and none fall more than two standard deviations from the line. Finally, the points tend to fall above the predictions; therefore, the conversion based upon the RTD developed by Nauman (1977) does appear to be a reasonable estimate for the conversion obtained in a helical coil. The experiments also upheld the belief that helical coil conversion falls between plug flow and laminar flow conversion.

The available correlations for pressure drop through a helical coil were shown to be valid. This was determined from the small percent differences of the predicted and measured pressure drops. The only point at which the correlations were not predictive was at low flows (less than 85 ml/min).

Finally, the computer data acquisition system provided a better way to take the data. By having the computer convert the percent transmittance readings to absorbance, it was possible to eliminate this manual calculation. The strip chart displays allow the user to visually see the process approaching steady state. This allows the experimenter to more accurately determine when the readings should be taken.

CHAPTER VIII

RECOMMENDATIONS

Three recommendations to improve this experiment can be offered. The first is to replace the flow meters and the pumps with improved equipment. By obtaining better measurements of the flow, the error in the residence time could be reduced dramatically. A peristaltic pump would provide a very accurate way of measuring the flow, eliminating the need for flow meters. In addition, the unit could be incorporated into the computer data acquisition system. This would allow the user to control the flow from the computer.

The range of experiments conducted could also be increased by buying new pumps. New pumps with greater flow capabilities and a higher outlet pressure would allow a turbulent flow reactor to be studied along with the helical coil and laminar flow reactors. Again, a peristaltic pump would be capable of producing the desired flows at moderate pressures.

The next recommendation is to purchase a pressure transducer. A pressure transducer could be incorporated

into the data acquisition system. This addition would allow the entire experiment to be run from the computer. It would also eliminate the mercury which is a known health hazard.

The final recommendation is to purchase new spectrometers that are designed for flow through cells. This would eliminate the foam shield that currently is used and would improve the quality of data being taken. Also, a commercially designed cuvette would have better optical qualities than the cuvettes that are currently being used.

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APPENDIX A

REACTOR CONVERSION INFORMATION

TABLE III

VALUES OF THE EXPONENTIAL INTEGRAL

$$E_1 = \int_v^\infty \frac{e^{-v}}{v} dv$$

x	E_1	x	E_1	x	E_1
0.00	∞	0.32	0.85834	0.64	0.41965
0.01	4.03790	0.33	0.83610	0.65	0.41152
0.02	3.35476	0.34	0.81475	0.66	0.40359
0.03	2.95912	0.35	0.79422	0.67	0.39585
0.04	2.68126	0.36	0.77446	0.68	0.38831
0.05	2.46790	0.37	0.75544	0.69	0.38095
0.06	2.29531	0.38	0.73711	0.70	0.37377
0.07	2.15084	0.39	0.71944	0.71	0.36676
0.08	2.02694	0.40	0.70238	0.72	0.35992
0.09	1.91874	0.41	0.68591	0.73	0.35324
0.10	1.82292	0.42	0.67000	0.74	0.34671
0.11	1.73711	0.43	0.65461	0.75	0.34034
0.12	1.65954	0.44	0.63973	0.76	0.33412
0.13	1.58890	0.45	0.62533	0.77	0.32803
0.14	1.52415	0.46	0.61139	0.78	0.32209
0.15	1.46446	0.47	0.59788	0.79	0.31628
0.16	1.40919	0.48	0.58478	0.80	0.31060
0.17	1.35778	0.49	0.57209	0.81	0.30504
0.18	1.30980	0.50	0.55977	0.82	0.29961
0.19	1.26486	0.51	0.54782	0.83	0.29430
0.20	1.22265	0.52	0.53622	0.84	0.28910
0.21	1.18290	0.53	0.52495	0.85	0.28402
0.22	1.14538	0.54	0.51400	0.86	0.27905
0.23	1.10988	0.55	0.50336	0.87	0.27418
0.24	1.07624	0.56	0.49302	0.88	0.26941
0.25	1.04428	0.57	0.48296	0.89	0.26475
0.26	1.01389	0.58	0.47317	0.90	0.26018
0.27	0.98493	0.59	0.46365	0.91	0.25571
0.28	0.95731	0.60	0.45438	0.92	0.25134
0.29	0.93092	0.61	0.44535	0.93	0.24705
0.30	0.90568	0.62	0.43656	0.94	0.24285
0.31	0.88151	0.63	0.42800	0.95	0.23874

TABLE III (Continued)

x	E_1	x	E_1	x	E_1
0.96	0.23471	3.80	0.00482	7.00	0.00012
0.97	0.23076	3.90	0.00427	7.10	0.00010
0.98	0.22689	4.00	0.00378	7.20	0.00009
0.99	0.22310	4.10	0.00335	7.30	0.00008
1.00	0.21938	4.20	0.00297	7.40	0.00007
1.10	0.18599	4.30	0.00263	7.50	0.00007
1.20	0.15841	4.40	0.00234	7.60	0.00006
1.30	0.13545	4.50	0.00207	7.70	0.00005
1.40	0.11622	4.60	0.00184	7.80	0.00005
1.50	0.10002	4.70	0.00164	7.90	0.00004
1.60	0.08631	4.80	0.00145	8.00	0.00004
1.70	0.07465	4.90	0.00129	8.10	0.00003
1.80	0.06471	5.00	0.00115	8.20	0.00003
1.90	0.05620	5.10	0.00102	8.30	0.00003
2.00	0.04890	5.20	0.00091	8.40	0.00002
2.10	0.04261	5.30	0.00081	8.50	0.00002
2.20	0.03719	5.40	0.00072	8.60	0.00002
2.30	0.03250	5.50	0.00064	8.70	0.00002
2.40	0.02844	5.60	0.00057	8.80	0.00002
2.50	0.02491	5.70	0.00051	8.90	0.00001
2.60	0.02185	5.80	0.00045	9.00	0.00001
2.70	0.01918	5.90	0.00040	9.10	0.00001
2.80	0.01686	6.00	0.00036	9.20	0.00001
2.90	0.01482	6.10	0.00032	9.30	0.00001
3.00	0.01305	6.20	0.00029	9.40	0.00001
3.10	0.01149	6.30	0.00026	9.50	0.00001
3.20	0.01013	6.40	0.00023	9.60	0.00001
3.30	0.00894	6.50	0.00020	9.70	0.00001
3.40	0.00789	6.60	0.00018	9.80	0.00001
3.50	0.00697	6.70	0.00016	9.90	0.00000
3.60	0.00616	6.80	0.00014	10.00	0.00000
3.70	0.00545	6.90	0.00013		

from Weast (1970)

TABLE IV

CALCULATED CONVERSIONS FOR LAMINAR FLOW,
PLUG FLOW, AND HELICAL COIL REACTORS

$k'\tau$	Laminar Reactor	Plug Flow Reactor	Helical Coil	$k'\tau$	Laminar Reactor	Plug Flow Reactor	Helical Coil
0.10	0.09	0.10	0.09	2.50	0.84	0.92	0.87
0.20	0.17	0.18	0.17	2.60	0.85	0.93	0.88
0.30	0.24	0.26	0.25	2.70	0.86	0.93	0.89
0.40	0.30	0.33	0.31	2.80	0.87	0.94	0.90
0.50	0.35	0.39	0.37	2.90	0.88	0.95	0.91
0.60	0.40	0.45	0.42	3.00	0.89	0.95	0.91
0.70	0.44	0.50	0.47	3.10	0.89	0.96	0.92
0.80	0.49	0.55	0.51	3.20	0.90	0.96	0.93
0.90	0.52	0.59	0.55	3.30	0.91	0.96	0.93
1.00	0.56	0.63	0.59	3.40	0.91	0.97	0.94
1.10	0.59	0.67	0.62	3.50	0.92	0.97	0.94
1.20	0.62	0.70	0.65	3.60	0.92	0.97	0.95
1.30	0.64	0.73	0.68	3.70	0.93	0.98	0.95
1.40	0.67	0.75	0.70	3.80	0.93	0.98	0.95
1.50	0.69	0.78	0.73	3.90	0.94	0.98	0.96
1.60	0.71	0.80	0.75	4.00	0.94	0.98	0.96
1.70	0.73	0.82	0.77	4.10	0.94	0.98	0.96
1.80	0.75	0.83	0.78	4.20	0.95	0.98	0.97
1.90	0.77	0.85	0.80	4.30	0.95	0.99	0.97
2.00	0.78	0.86	0.82	4.40	0.95	0.99	0.97
2.10	0.79	0.88	0.83	4.50	0.96	0.99	0.97
2.20	0.81	0.89	0.84	4.60	0.96	0.99	0.97
2.30	0.82	0.90	0.85	4.70	0.96	0.99	0.98
2.40	0.83	0.91	0.86				

APPENDIX B

RESULTS OF BATCH EXPERIMENTS

TABLE V

BATCH RESULTS USED IN ARRHENIUS PLOT

Run	$T(^\circ C)$	t(min)	% T	A	$\ln(A_o/A)$	k(1/mol/min)
1	24	0	8.0	1.10	0.00	8.6
		1	16.0	0.80	0.32	
		2	27.0	0.57	0.66	
		3	39.0	0.41	0.99	
		4	51.5	0.29	1.34	
		5	64.0	0.19	1.73	
		6	72.5	0.14	2.06	
		7	80.0	0.10	2.43	
2	24	0	9.0	1.05	0.00	8.7
		1	17.5	0.76	0.32	
		2	29.0	0.54	0.67	
		3	41.0	0.39	0.99	
		4	53.5	0.27	1.35	
		5	64.5	0.19	1.70	
		6	74.0	0.13	2.08	
		7	82.0	0.09	2.50	
3	24	0	10.0	1.00	0.00	8.3
		1	19.0	0.72	0.33	
		2	30.0	0.52	0.65	
		3	42.5	0.37	0.99	
		4	53.5	0.27	1.30	
		5	64.0	0.19	1.64	
		6	73.0	0.14	1.99	
		7	80.5	0.09	2.36	
4	24	0	10.0	1.00	0.00	8.7
		1	19.0	0.72	0.33	
		2	30.5	0.52	0.66	
		3	43.0	0.37	1.00	
		4	55.5	0.26	1.36	
		5	66.0	0.18	1.71	
		6	75.0	0.12	2.08	
		7	83.0	0.08	2.51	

TABLE V (Continued)

Run	T(°C)	t(min)	% T	A	$\ln(A_o/A)$	k(1/mol/min)
5	24	0	8.0	1.10	0.00	8.8
		1	16.5	0.78	0.34	
		2	27.5	0.56	0.67	
		3	40.0	0.40	1.01	
		4	53.0	0.28	1.38	
		5	64.5	0.19	1.75	
		6	73.5	0.13	2.10	
		7	82.0	0.09	2.54	
6	24	0	10.0	1.00	0.00	7.8
		1	18.5	0.73	0.31	
		2	28.0	0.55	0.59	
		3	39.5	0.40	0.91	
		4	51.0	0.29	1.23	
		5	61.0	0.21	1.54	
		6	70.5	0.15	1.89	
		7	78.0	0.11	2.23	
7	24	0	10.0	1.00	0.00	8.7
		1	18.5	0.73	0.31	
		2	30.5	0.52	0.66	
		3	42.0	0.38	0.98	
		4	55.0	0.26	1.35	
		5	66.0	0.18	1.71	
		6	75.5	0.12	2.10	
		7	83.5	0.08	2.55	
8	24	0	10.0	1.00	0.00	8.5
		1	18.5	0.73	0.31	
		2	29.0	0.54	0.62	
		3	41.5	0.38	0.96	
		4	53.5	0.27	1.30	
		5	64.5	0.19	1.66	
		6	74.0	0.13	2.03	
		7	82.0	0.09	2.45	

TABLE V (Continued)

Run	T(°C)	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
9	24	0	9.0	1.05	0.00	8.5
		1	18.0	0.74	0.34	
		2	28.0	0.55	0.64	
		3	40.0	0.40	0.97	
		4	52.0	0.28	1.30	
		5	63.5	0.20	1.67	
		6	73.0	0.14	2.03	
		7	81.0	0.09	2.44	
10	24	0	9.0	1.05	0.00	8.3
		1	17.5	0.76	0.32	
		2	28.0	0.55	0.64	
		3	40.0	0.40	0.97	
		4	52.5	0.28	1.32	
		5	63.5	0.20	1.67	
		6	72.0	0.14	1.99	
		7	80.0	0.10	2.38	
11	24	0	10.0	1.00	0.00	8.6
		1	19.0	0.72	0.33	
		2	30.5	0.52	0.66	
		3	42.5	0.37	0.99	
		4	55.0	0.26	1.35	
		5	66.0	0.18	1.71	
		6	74.5	0.13	2.06	
		7	82.0	0.09	2.45	
12	24	0	9.0	1.05	0.00	8.9
		1	19.0	0.72	0.37	
		2	30.0	0.52	0.69	
		3	43.0	0.37	1.05	
		4	55.5	0.26	1.41	
		5	66.0	0.18	1.76	
		6	75.0	0.12	2.12	
		7	82.5	0.08	2.53	

TABLE V (Continued)

Run	T(°C)	t(min)	% T	A	ln(A_0/A)	k(l/mol/min)
13	24	0	9.0	1.05	0.00	8.0
		1	17.0	0.77	0.31	
		2	27.5	0.56	0.62	
		3	39.0	0.41	0.94	
		4	51.0	0.29	1.27	
		5	61.5	0.21	1.60	
		6	70.5	0.15	1.93	
		7	77.5	0.11	2.25	
14	24	0	9.0	1.05	0.00	8.8
		1	18.0	0.74	0.34	
		2	30.0	0.52	0.69	
		3	42.5	0.37	1.03	
		4	55.0	0.26	1.39	
		5	65.5	0.18	1.74	
		6	74.5	0.13	2.10	
		7	82.0	0.09	2.50	
15	30	0	14.0	0.85	0.00	13.8
		1	30.5	0.52	0.50	
		2	49.0	0.31	1.01	
		3	66.0	0.18	1.55	
		4	84.0	0.08	2.42	
		5	88.0	0.06	2.73	
		6	93.0	0.03	3.30	
16	30	0	14.0	0.85	0.00	13.6
		1	29.0	0.54	0.46	
		2	48.5	0.31	1.00	
		3	64.0	0.19	1.48	
		4	78.0	0.11	2.07	
		5	87.5	0.06	2.69	
		6	94.0	0.03	3.46	

TABLE V (Continued)

Run	$T(°C)$	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
17	30	0	14.0	0.86	0.00	12.4
		1	28.5	0.55	0.45	
		2	46.0	0.34	0.93	
		3	62.5	0.20	1.43	
		4	76.0	0.12	1.97	
		5	85.0	0.07	2.49	
		6	91.0	0.04	3.04	
18	30	0	13.0	0.89	0.00	12.8
		1	28.0	0.55	0.47	
		2	46.0	0.34	0.97	
		3	62.5	0.20	1.47	
		4	76.0	0.12	2.01	
		5	85.5	0.07	2.57	
		6	91.5	0.04	3.13	
19	30	0	14.0	0.85	0.00	12.5
		2	46.5	0.33	0.94	
		4	75.5	0.12	1.95	
		6	91.0	0.04	3.04	
20	30	0	15.0	0.82	0.00	13.3
		2	47.0	0.33	0.92	
		4	77.0	0.11	1.98	
		6	93.5	0.03	3.34	
21	35	0	14.0	0.85	0.00	18.2
		1	35.0	0.46	0.63	
		2	61.0	0.21	1.38	
		3	81.5	0.09	2.26	
		4	93.0	0.03	3.30	
		5	99.0	0.004	5.28	
22	35	0	15.0	0.82	0.00	18.7
		1	39.0	0.41	0.70	
		2	64.5	0.19	1.46	
		3	82.5	0.08	2.29	

TABLE V (Continued)

Run	T(°C)	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
23	35	0	14.0	0.85	0.00	18.6
		1	36.5	0.44	0.67	
		2	62.5	0.20	1.43	
		3	82.0	0.09	2.29	
24	35	0	16.0	0.80	0.00	18.4
		1	38.5	0.41	0.65	
		2	64.5	0.19	1.43	
		3	82.5	0.08	2.25	
25	40	0	14.0	0.85	0.00	25.2
		1	45.0	0.35	0.90	
		2	76.0	0.12	1.97	
		3	91.5	0.04	3.10	
26	40	0	16.0	0.80	0.00	27.7
		1	48.5	0.31	0.93	
		2	79.5	0.10	2.08	
		3	94.5	0.02	3.48	
27	40	0	15.0	0.82	0.00	27.4
		1	47.5	0.32	0.94	
		2	78.5	0.11	2.06	
		3	94.0	0.03	3.42	
28	40	0	17.0	0.77	0.00	25.9
		1	48.5	0.31	0.90	
		2	79.0	0.10	2.02	
		3	93.0	0.03	3.20	

TABLE VI

RESULTS OF OTHER BATCH EXPERIMENTS

Run	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
1	0.0	74.5	0.13	0.00	11.1
	1.0	81.5	0.09	0.36	
	2.0	85.0	0.07	0.59	
	3.0	88.0	0.06	0.83	
	4.0	92.0	0.04	1.26	
	6.0	89.5	0.05	0.98	
	8.0	95.0	0.02	1.75	
2	0.0	71.0	0.15	0.00	4.8
	1.0	71.0	0.15	0.00	
	2.0	71.5	0.15	0.02	
	3.0	75.0	0.12	0.17	
	4.0	77.0	0.11	0.27	
	5.0	80.5	0.09	0.46	
	6.0	82.0	0.09	0.55	
	7.0	85.0	0.07	0.75	
	8.0	87.0	0.06	0.90	
3	0.0	0.8	2.12	0.00	5.4
	1.0	1.0	2.00	0.06	
	2.0	1.0	2.00	0.06	
	3.0	1.0	2.00	0.06	
	5.0	2..0	1.70	0.22	
	7.0	2.3	1.65	0.25	
	10.0	4.0	1.40	0.42	
	13.0	6.0	1.22	0.55	
	16.0	11.0	0.96	0.80	
	18.0	15.5	0.81	0.96	
	20.0	18.5	0.73	1.06	
	22.0	24.0	0.62	1.23	
	24.0	28.0	0.55	1.35	
	26.0	33.0	0.48	1.48	
	28.0	39.0	0.41	1.65	
	30.0	43.0	0.37	1.76	

TABLE VI (Continued)

Run	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
4	0.0	2.5	1.60	0.00	6.5
	2.0	4.5	1.35	0.17	
	4.0	7.5	1.12	0.35	
	6.0	11.0	0.96	0.51	
	8.0	17.0	0.77	0.73	
	10.0	24.0	0.62	0.95	
	12.0	29.5	0.53	1.11	
	14.0	36.0	0.44	1.28	
	16.0	43.0	0.37	1.48	
	18.0	49.5	0.31	1.66	
	20.0	55.0	0.2596	1.8198	
	22.0	57.5	0.2403	1.8970	
	24.0	65.0	0.1871	2.1475	
	26.0	70.0	0.1549	2.3363	
	28.0	71.0	0.1487	2.3768	
5	0.0	2.5	1.60	0.00	7.4
	2.0	5.0	1.30	0.21	
	4.0	8.5	1.07	0.40	
	6.0	14.0	0.85	0.63	
	8.0	21.0	0.68	0.86	
	10.0	29.0	0.54	1.09	
	12.0	38.0	0.42	1.34	
	14.0	47.0	0.33	1.59	
	16.0	55.0	0.26	1.82	
	18.0	63.0	0.21	2.08	
	20.0	69.0	0.16	2.30	
	22.0	74.5	0.13	2.53	
	24.0	79.5	0.10	2.78	

TABLE VI (Continued)

Run	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
6	0.0	5.0	1.30	0.00	8.0
	2.0	9.5	1.02	0.24	
	4.0	15.5	0.81	0.47	
	6.0	23.0	0.64	0.71	
	8.0	32.5	0.49	0.98	
	10.0	45.0	0.35	1.32	
	12.0	52.0	0.28	1.52	
	14.0	61.0	0.21	1.80	
	16.0	69.5	0.16	2.11	
	18.0	76.5	0.12	2.41	
	20.0	82.5	0.08	2.75	
7	0.0	5.0	1.30	0.00	8.4
	2.0	10.5	0.98	0.28	
	4.0	17.0	0.77	0.53	
	6.0	25.0	0.60	0.77	
	8.0	34.5	0.46	1.04	
	10.0	45.0	0.35	1.32	
	12.0	55.0	0.26	1.61	
	14.0	64.0	0.19	1.90	
	16.0	72.0	0.14	2.21	
	18.0	78.5	0.11	2.52	
	20.0	84.0	0.076	2.84	
8	0.0	5.5	1.26	0.00	8.7
	2.0	11.0	0.96	0.27	
	4.0	17.5	0.76	0.51	
	6.0	27.0	0.57	0.80	
	8.0	37.0	0.43	1.07	
	10.0	48.0	0.32	1.37	
	12.0	58.5	0.23	1.69	
	14.0	68.0	0.17	2.02	
	16.0	76.5	0.12	2.38	
	18.0	83.5	0.08	2.78	
	20.0	89.5	0.05	3.26	

TABLE VI (Continued)

Run	t (min)	% T	A	$\ln(A_o/A)$	k (1/mol/min)
9	0.0	6.0	1.22	0.00	10.0
	2.0	12.0	0.92	0.28	
	4.0	20.5	0.69	0.57	
	6.0	32.0	0.49	0.90	
	8.0	45.0	0.35	1.26	
	10.0	57.5	0.24	1.63	
	12.0	69.0	0.16	2.03	
	14.0	78.0	0.11	2.43	
	16.0	85.0	0.07	2.85	
	18.0	89.0	0.05	3.18	
	20.0	92.0	0.04	3.52	
10	0.0	8.0	1.10	0.00	9.5
	2.0	17.0	0.77	0.35	
	4.0	27.0	0.57	0.66	
	6.0	38.0	0.42	0.96	
	8.0	50.0	0.30	1.29	
	10.0	61.0	0.21	1.63	
	12.0	70.5	0.15	1.98	
	14.0	78.5	0.11	2.35	
	16.0	85.0	0.07	2.74	
	18.0	89.5	0.05	3.13	
	20.0	93.0	0.03	3.55	
11	0.0	8.0	1.10	0.00	9.2
	2.0	16.0	0.80	0.32	
	4.0	25.0	0.60	0.60	
	6.0	36.0	0.44	0.91	
	8.0	47.5	0.32	1.22	
	10.0	58.5	0.23	1.55	
	12.0	68.5	0.16	1.90	
	14.0	76.5	0.12	2.24	
	16.0	83.0	0.08	2.61	
	18.0	87.5	0.06	2.94	
	20.0	93.0	0.03	3.55	

TABLE VI (Continued)

Run	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
12	0.0	8.5	1.07	0.00	8.4
	2.0	16.0	0.80	0.30	
	4.0	25.0	0.60	0.58	
	6.0	35.0	0.46	0.85	
	8.0	46.0	0.34	1.16	
	10.0	57.0	0.24	1.48	
	12.0	66.0	0.18	1.78	
	14.0	74.0	0.13	2.10	
	16.0	81.0	0.09	2.46	
	18.0	86.0	0.07	2.79	
13	0.0	8.5	1.07	0.00	10.2
	2.0	17.0	0.77	0.33	
	4.0	28.0	0.55	0.66	
	6.0	41.0	0.39	1.02	
	8.0	54.0	0.27	1.39	
	10.0	65.5	0.18	1.76	
	12.0	75.5	0.12	2.17	
	14.0	83.0	0.08	2.58	
	16.0	89.0	0.05	3.05	
14	0.0	8.5	1.07	0.00	9.9
	2.0	17.0	0.77	0.33	
	4.0	27.0	0.57	0.63	
	6.0	40.0	0.40	0.99	
	8.0	53.0	0.28	1.36	
	10.0	65.0	0.19	1.74	
	12.0	74.5	0.13	2.13	
	14.0	82.0	0.09	2.52	
	16.0	87.5	0.06	2.92	

TABLE VI (Continued)

Run	t(min)	% T	A	ln(A_o/A)	k(l/mol/min)
15	0.0	8.0	1.10	0.00	8.3
	2.0	15.0	0.82	0.29	
	4.0	24.0	0.62	0.57	
	6.0	34.5	0.46	0.86	
	8.0	45.5	0.34	1.17	
	10.0	56.0	0.25	1.47	
	12.0	66.0	0.18	1.80	
	14.0	74.0	0.13	2.13	
16	0.0	9.5	1.02	0.00	9.5
	2.0	17.5	0.76	0.30	
	4.0	28.0	0.55	0.61	
	6.0	40.5	0.39	0.96	
	8.0	53.0	0.28	1.31	
	10.0	64.5	0.19	1.68	
	12.0	74.0	0.13	2.06	
	14.0	82.0	0.09	2.47	
17	0.0	10.5	0.98	0.00	9.0
	2.0	18.0	0.74	0.27	
	4.0	28.5	0.55	0.59	
	6.0	41.0	0.39	0.93	
	8.0	53.0	0.28	1.27	
	10.0	64.0	0.19	1.62	
	12.0	73.5	0.13	1.99	
18	0.0	9.0	1.05	0.00	10.1
	2.0	17.0	0.77	0.31	
	4.0	28.0	0.55	0.64	
	6.0	42.0	0.38	1.02	
	8.0	56.5	0.25	1.44	
	10.0	68.0	0.17	1.83	
	12.0	78.0	0.11	2.27	

TABLE VI (Continued)

Run	t(min)	% T	A	$\ln(A_0/A)$	k(l/mol/min)
19	0.0	10.0	1.00	0.00	9.2
	2.0	18.0	0.75	0.29	
	4.0	28.5	0.55	0.61	
	6.0	40.5	0.39	0.94	
	8.0	53.0	0.28	1.29	
	10.0	64.5	0.19	1.66	
	12.5	76.0	0.12	2.13	
20	0.0	11.0	0.96	0.00	9.2
	2.0	19.5	0.71	0.30	
	4.0	30.0	0.53	0.61	
	6.0	42.0	0.38	0.94	
	8.0	54.5	0.26	1.29	
	10.5	68.5	0.16	1.76	
	12.0	75.5	0.12	2.06	
21	0.0	9.5	1.02	0.00	10.4
	2.0	18.0	0.74	0.32	
	4.0	29.5	0.53	0.66	
	6.0	43.0	0.37	1.03	
	8.0	57.5	0.24	1.45	
	10.0	70.0	0.15	1.89	
	12.0	80.0	0.10	2.36	
22	0.0	9.0	1.05	0.00	9.2
	2.0	17.0	0.77	0.31	
	4.0	27.5	0.56	0.62	
	6.0	40.5	0.39	0.98	
	8.0	53.5	0.27	1.35	
	10.0	64.0	0.19	1.69	
	12.0	73.0	0.14	2.03	

TABLE VI (Continued)

Run	t(min)	% T	A	ln(A$_o$/A)	k(l/mol/min)
23	0.0	9.0	1.05	0.00	9.0
	2.0	16.5	0.78	0.29	
	4.0	27.0	0.57	0.61	
	6.0	38.5	0.41	0.93	
	8.0	51.0	0.29	1.27	
	10.0	62.5	0.20	1.63	
	12.0	72.0	0.14	1.99	
24	0.0	9.0	1.05	0.00	8.8
	2.0	17.0	0.77	0.31	
	4.0	26.0	0.59	0.58	
	6.0	38.0	0.42	0.91	
	8.0	50.0	0.30	1.25	
	10.0	61.5	0.21	1.60	
	12.0	71.0	0.15	1.95	
25	0.0	10.0	1.00	0.00	9.9
	2.0	18.5	0.73	0.31	
	4.0	30.0	0.52	0.65	
	6.0	43.0	0.37	1.00	
	8.0	56.5	0.25	1.39	
	10.0	68.0	0.17	1.79	
	12.0	78.0	0.11	2.23	
26	0.0	10.5	0.98	0.00	9.4
	2.0	19.0	0.72	0.31	
	4.0	30.0	0.52	0.63	
	6.0	42.5	0.37	0.97	
	8.0	55.0	0.26	1.33	
	10.0	66.0	0.18	1.69	
	12.0	75.5	0.12	2.08	

TABLE VI (Continued)

Run	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
27	0.0	6.0	1.22	0.00	9.4
	1.0	13.5	0.87	0.34	
	2.0	25.0	0.60	0.71	
	3.0	38.5	0.41	1.08	
	4.0	52.5	0.28	1.47	
	5.0	65.0	0.19	1.88	
	6.0	74.5	0.13	2.26	
	7.0	82.5	0.08	2.68	
28	0.0	6.0	1.22	0.00	9.2
	1.0	13.0	0.89	0.32	
	2.0	23.5	0.63	0.66	
	3.0	36.5	0.44	1.03	
	4.0	50.5	0.30	1.42	
	5.0	63.0	0.20	1.81	
	6.0	74.0	0.13	2.23	
	7.0	82.0	0.09	2.65	
29	0.0	6.0	1.22	0.00	8.4
	1.0	13.0	0.89	0.32	
	2.0	23.0	0.64	0.65	
	3.0	35.5	0.45	1.00	
	4.0	48.0	0.32	1.34	
	5.0	60.0	0.22	1.71	
	6.0	69.0	0.16	2.03	
	7.0	76.0	0.12	2.33	
30	0.0	7.0	1.15	0.00	9.7
	1.0	15.0	0.82	0.34	
	2.0	26.5	0.58	0.69	
	3.0	40.5	0.39	1.08	
	4.0	55.0	0.26	1.49	
	5.0	67.5	0.17	1.91	
	6.0	78.0	0.11	2.37	
	7.0	85.5	0.07	2.83	

TABLE VI (Continued)

Run	t(min)	% T	A	$\ln(A_o/A)$	k(l/mol/min)
31	0.0	6.0	1.22	0.00	9.2
	1.0	13.5	0.87	0.34	
	2.0	24.0	0.62	0.68	
	3.0	37.0	0.43	1.04	
	4.0	51.0	0.29	1.43	
	5.0	64.0	0.19	1.84	
	6.0	74.0	0.13	2.23	
	7.0	81.5	0.09	2.62	
32	0.0	6.0	1.22	0.00	8.6
	1.0	13.0	0.89	0.32	
	2.0	23.0	0.64	0.65	
	3.0	35.0	0.46	0.99	
	4.0	48.5	0.31	1.36	
	5.0	60.5	0.22	1.72	
	6.0	70.5	0.15	2.09	
	7.0	78.0	0.11	2.43	

APPENDIX C

RESULTS OF FLOW EXPERIMENTS

TABLE VII

RESULTS OF 2 INCH HELICAL COIL REACTOR

v (ml/min)	N_{Re}	τ (min)	A_o	A	X_{Meas}	X_{Corr}
810	2700	0.59	0.99	0.72	0.27	0.25
710	2400	0.68	0.98	0.69	0.30	0.27
710	2400	0.68	0.88	0.65	0.26	0.24
710	2400	0.68	1.01	0.66	0.35	0.32
710	2400	0.68	1.05	0.69	0.34	0.32
610	2000	0.79	0.97	0.63	0.35	0.32
610	2000	0.79	0.87	0.60	0.31	0.28
610	2000	0.79	1.04	0.63	0.39	0.37
610	2000	0.79	1.04	0.65	0.38	0.35
510	1700	0.95	0.95	0.55	0.42	0.39
510	1700	0.95	0.86	0.54	0.37	0.34
510	1700	0.95	1.03	0.56	0.46	0.42
510	1700	0.95	1.04	0.58	0.44	0.41
400	1300	1.21	0.94	0.46	0.51	0.47
400	1300	1.21	0.87	0.46	0.47	0.43
400	1300	1.21	1.00	0.47	0.53	0.49
400	1300	1.21	1.05	0.50	0.52	0.48
280	940	1.71	0.91	0.30	0.67	0.61
280	940	1.71	0.87	0.34	0.61	0.55
280	940	1.71	1.00	0.36	0.64	0.58
280	940	1.71	1.03	0.36	0.65	0.59
230	760	2.14	0.88	0.21	0.76	0.68
230	760	2.14	0.87	0.28	0.68	0.60
230	760	2.14	1.01	0.25	0.75	0.67
230	760	2.14	1.03	0.29	0.72	0.64
230	760	4.13	0.82	0.04	0.95	0.80
120	390	4.13	0.82	0.08	0.90	0.75
120	390	4.13	0.93	0.13	0.86	0.71
120	390	4.13	0.93	0.15	0.84	0.69

TABLE VIII

RESULTS OF 4 INCH HELICAL COIL REACTOR

v (ml/min)	N_{Re}	τ (min)	A_o	A	X_{Meas}	X_{Corr}
910	3000	0.53	0.88	0.73	0.17	0.15
810	2700	0.59	0.91	0.70	0.23	0.21
710	2400	0.68	0.88	0.66	0.25	0.23
610	2000	0.79	0.88	0.60	0.32	0.29
610	2000	0.79	0.84	0.60	0.29	0.26
610	2000	0.79	0.86	0.51	0.41	0.38
610	2000	0.79	0.81	0.46	0.43	0.40
610	2000	0.79	0.77	0.52	0.33	0.30
510	1700	0.95	0.88	0.52	0.41	0.37
510	1700	0.95	0.89	0.54	0.39	0.36
510	1700	0.95	0.82	0.45	0.45	0.42
510	1700	0.95	0.72	0.45	0.38	0.34
400	1300	1.21	0.86	0.43	0.50	0.46
400	1300	1.21	0.92	0.44	0.52	0.48
400	1300	1.21	0.82	0.39	0.52	0.48
400	1300	1.21	0.70	0.35	0.50	0.46
280	940	1.71	0.86	0.25	0.71	0.65
280	940	1.71	0.88	0.27	0.69	0.63
280	940	1.71	0.79	0.29	0.63	0.57
280	940	1.71	0.66	0.22	0.67	0.60
230	760	2.14	0.85	0.17	0.80	0.72
230	760	2.14	0.75	0.19	0.75	0.67
230	760	2.14	0.64	0.15	0.77	0.69
170	570	2.84	0.76	0.09	0.88	0.78
120	390	4.13	0.68	0.11	0.84	0.69
120	390	4.13	0.56	0.06	0.89	0.74

TABLE IX

RESULTS OF LAMINAR FLOW REACTOR

v (ml/min)	N_{Re}	τ (min)	A_o	A	X_{Meas}	X_{Corr}
910	3000	0.51	0.97	0.80	0.18	0.16
910	3000	0.51	0.90	0.76	0.16	0.14
810	2700	0.57	0.95	0.79	0.17	0.15
810	2700	0.57	0.89	0.75	0.16	0.14
710	2400	0.65	0.94	0.74	0.21	0.19
710	2400	0.65	0.89	0.73	0.18	0.16
610	2000	0.76	0.92	0.71	0.23	0.20
610	2000	0.76	0.89	0.69	0.23	0.20
510	1700	0.91	0.93	0.65	0.30	0.27
510	1700	0.91	0.88	0.63	0.28	0.25
400	1300	1.16	0.90	0.56	0.38	0.33
400	1300	1.16	0.86	0.54	0.37	0.33
280	940	1.64	0.89	0.41	0.54	0.48
280	940	1.64	0.84	0.40	0.52	0.46
230	760	2.05	0.82	0.26	0.68	0.60
230	760	2.05	0.81	0.29	0.64	0.56
120	390	3.96	0.79	0.10	0.87	0.72
120	390	3.96	0.74	0.09	0.88	0.73

TABLE X

RESULTS OF PRESSURE DROP EXPERIMENTS FOR
THE 2 INCH HELICAL COIL REACTOR

v	ΔP, Pressure Drop (PSI)					
(ml/min)	Run 1	Run 2	Run 3	Run 4	Average	Predicted
770	5.6	6.6	6.6	6.6	6.6	6.3
720	5.0	5.8	5.8	5.8	5.8	5.6
670	4.4	5.1	5.1	5.1	5.1	4.9
610	3.8	4.5	4.4	4.4	4.4	4.2
560	3.4	3.9	3.9	3.9	3.9	3.6
510	2.9	3.3	3.3	3.3	3.3	3.0
460	2.4	2.8	2.8	2.8	2.8	2.5
410	2.0	2.3	2.3	2.3	2.3	2.0
360	1.6	1.8	1.8	1.8	1.8	1.6
310	1.3	1.4	1.4	1.4	1.4	1.2
250	1.0	1.0	1.0	1.0	1.0	1.0
200	0.7	0.7	0.7	0.7	0.7	0.7
140	0.4	0.4	0.4	0.4	0.4	0.4
90	0.2	0.2	0.2	0.2	0.2	0.2
30	0.1	0.1	0.1	0.1	0.1	0.04

TABLE XI

RESULTS OF PRESSURE DROP EXPERIMENTS FOR
THE 4 INCH HELICAL COIL REACTOR

v (ml/min)	ΔP, Pressure Drop (PSI)					
	Run 1	Run 2	Run 3	Run 4	Average	Predicted
770	5.7	5.6	5.7	5.7	5.7	6.1
720	5.0	5.0	5.0	5.0	5.0	5.3
670	4.3	4.4	4.4	4.4	4.4	4.6
610	3.8	3.8	3.8	3.8	3.8	4.0
560	3.3	3.3	3.3	3.4	3.3	3.4
510	2.8	2.8	2.8	2.8	2.8	2.8
460	2.4	2.4	2.4	2.4	2.4	2.3
410	1.9	1.9	1.9	2.0	1.9	1.9
360	1.5	1.5	1.5	1.6	1.6	1.6
310	1.2	1.2	1.2	1.2	1.2	1.3
250	0.9	0.9	0.9	0.9	0.9	0.9
200	0.6	0.6	0.6	0.6	0.6	0.6
140	0.3	0.4	0.4	0.4	0.4	0.4
90	0.2	0.2	0.2	0.2	0.2	0.2
30	0.1	0.1	0.1	0.05	0.1	0.04

TABLE XII

RESULTS OF PRESSURE DROP EXPERIMENTS FOR
THE LAMINAR FLOW REACTOR

v (ml/min)	ΔP, Pressure Drop (PSI)					
	Run 1	Run 2	Run 3	Run 4	Average	Predicted
770	4.9	4.9	4.9	4.8	4.9	4.8
720	4.2	4.2	4.2	4.2	4.2	4.2
670	3.6	3.6	3.7	3.6	3.6	3.7
610	3.1	3.1	3.1	3.1	3.1	3.2
560	2.8	2.7	2.8	2.8	2.7	2.7
510	2.3	2.3	2.3	2.3	2.3	2.3
460	1.9	1.9	1.9	1.9	1.9	1.8
410	1.6	1.6	1.6	1.6	1.6	1.5
360	1.3	1.3	1.3	1.3	1.3	1.2
310	0.9	0.9	1.0	1.0	1.0	0.9
250	0.7	0.7	0.7	0.7	0.7	0.7
200	0.5	0.4	0.5	0.4	0.5	0.5
140	0.3	0.3	0.3	0.3	0.3	0.3
90	0.1	0.1	0.1	0.1	0.1	0.1
30	0.05	0.05	0.05	0.05	0.05	0.04

APPENDIX D

ERROR ANALYSIS

An error analysis was performed on the two main variables of the experiment, conversion and residence time. The analysis was based upon a propagation of errors in the measured quantities. This was done using the following equation

$$\sigma_Q^2 = \sum_{i=1}^{n} (\frac{\partial Q}{\partial x_i}\sigma_{x_i})^2 .$$

(37)

where Q is the quantity of interest, the x's are the measured values, and the σ's are the errors associated with the measurements. Eq. 37 was applied to the following equations:

$$X = 1 - \frac{A}{A_o} ,$$

(38)

$$A = -\log(\%T/100) ,$$

(39)

$$\tau = \frac{\pi r^2 L}{v} ,$$

(40)

$$\text{and} \quad v = v_A + v_B .$$

(41)

The result for Eq. 38 is as follows

$$\sigma_X = \frac{1}{A_o^2}\sqrt{A_o^2\sigma_A^2 + A^2\sigma_{A_o}^2} .$$

(42)

The error in A is expressed as

$$\sigma_A = \frac{\sigma_{\%T}}{\%T} .$$

(43)

Eq. 43 is substituted into Eq. 42 to obtain the final expression for the error in the conversion. When experimental values were substituted into the above

equations along with $\sigma_{\%T} = 0.2$, the calculated deviations were always less than 1 % conversion.

The error in the residence time can be expressed as

$$\sigma_\tau = \frac{\pi r}{v}\sqrt{4L^2r^2\sigma_r^2 + r^2\sigma_L^2 + \frac{L^2r^2}{v^2}\sigma_v^2} \qquad (44)$$

where $\qquad \sigma_v = \sqrt{\sigma_{v_A}^2 + \sigma_{v_B}^2}$. $\qquad (45)$

The values of the measured variables and the errors associated with these values are listed in Table XII. Table XIII shows the error in the residence time associated with each flow rate. The maximum error in the residence time is over 1 min. Since the error in conversion is a maximum of 0.01, the error in the residence time is the significant source of error in this experiment.

TABLE XIII

EXPERIMENTAL VALUES AND ASSOCIATED ERRORS

Variable	Value	Error
reactor length	50 ft	2 in
tube radius	0.25 in	0.01 in
total flow	120-810 ml/min	22 ml/min

TABLE XIV

ERRORS ASSOCIATED WITH RESIDENCE TIME

v (ml/min)	τ (min)	σ_τ (min)
120	4.13	1.01
170	2.84	0.58
230	2.14	0.40
280	1.71	0.30
400	1.21	0.21
510	0.95	0.16
610	0.79	0.13
710	0.68	0.11
810	0.59	0.10

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