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Equation of State

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Abstract

An equation of state (EOS) is a thermodynamic expression that relates pressure (P), temperature (T), and volume (V). This equation is used to describe the state of reservoir fluids at given conditions. The cubic equations of state (CEOS) such as Van der Waals, Redlich-Kwong, Soave, and Peng-Robinson are simple models that have been widely used in the oil industry. This chapter expressed literature for EOS that varies from simple expressions to multiple constant and convoluted types of equations. Many attempts have been made to describe the thermodynamic behavior of fluids to predict their physical properties at given conditions. So, several forms of the equation of state have been presented to the oil industry in order to calculate reservoir fluid properties. The heat exchanger is important in wildly fields as in aerospace, petrochemical industry, refrigeration, and other fields. The optimization design of the heat exchanger is a great significance to industry process to reduce production cost, realize energy conservation, and reduce energy consumption.

Keywords: EOS types, EOS importance, EOS history, cubic equation of state, heat transfer

1. Introduction

In the last six decades, petroleum engineers realized the importance of using EOS for PVT modeling in addition to the following [1]:

1. Predicting physical properties of the black oil in the laboratories is very expensive.
2. Difficulty to obtain a representative sample due to reservoir nature or operation issues.
3. Insufficient sample volume in order to obtain a complete analysis.
4. Error in lab analyses.
5. Samples are nonrepresentative (not monophasic sample, OBM contamination, etc.).
6. Lab report quality check.
7. Estimating the hydrocarbon reserves.

1.1 Classification of equation of state

There are different types of EOS which fall into three categories:

1.1.1 First class of EOS

These equations are basically cubic equation of state. The cubic equations of state such as the Van der Waals [2], Redlich and Kwong [3], Soave-Redlich-Kwong [4], and Peng-Robinson [5] equations give reasonable results for the thermodynamic behavior of real fluids.

1.1.2 Second class of EOS

These EOS are non-cubic in form. They are providing accurate results for both vapor and liquid phases. The Benedict et al. [6] equation is a good example for this class equation.

1.1.3 Third class of EOS

These are nonanalytical EOS that are highly constrained for some specific fluids [7]. Even though they are constrained, they are capable of expressing real fluid thermodynamic properties precisely.

Among all these EOS, the first-class EOS is more useful because it provides an analytical solution than the more complex and complicated non-cubic second type and nonanalytical third type that require time-consuming iterative calculations. In general, the overall performance in fluid properties prediction is somewhat better using the Soave-Redlich-Kwong (SRK) equation than using the Redlich-Kwong (RK) and Van der Waals EOS [8].

2. Development history of the equation of state

Several forms of EOS have been presented to the petroleum industry to estimate hydrocarbon reservoir fluid properties and sought to a better representation of the PVT relationship for fluids [9].

In 1662, Robert Boyle (Boyle's law) discovered that for a constant temperature, there is an inverse relationship between volume of gas and its pressure ($P \propto V^{-1}$). In 1780, Jacques Charles (Charles's Law) showed that the volume of gas is proportional to the absolute temperature at a constant pressure ($V \propto T$). In 1834, Clapeyron combined these two results into the ideal gas law, $PV = RT$ [10], assuming that the molecules are very far and have no attractive or repulsive forces between them and elastic collisions between these molecules. This equation is known as the ideal gas law and/or the general gas law. It is expressed mathematically as [11].

$$P V = n R T \quad (1)$$

where P: absolute pressure, psia; V: volume, ft³; T: absolute temperature, °R; R: the universal gas constant (10.73159 ft³ psia °R⁻¹ lb-mole⁻¹; n: number of moles of gas, lb-mole.

For gases at low pressures, the ideal gas law is a convenient satisfactory tool. The application of the ideal gas law at higher pressures may lead to errors up to 500%, compared to 2–3% at atmospheric pressure. Real gases behave differently than ideal

gases, the reason for this deviation is that the ideal gas law was derived under the assumption that the volume of molecules is very small and neither molecular attraction nor repulsion exists between them, and this is not the real case. In order to write an equation of state for a real gas, a correction factor has to be inserted into the ideal gas equation [12]:

$$P V = Z n R T \quad (2)$$

where Z: the correction factor which is known as the compressibility factor.

The equation has different names, such as the compressibility equation and/or the real gas equation [13]. A review of recent advances in the empirical cubic EOS field is presented next [11]. Van der Waals [2] is one of the earliest attempts to represent the behavior of real gases by an equation, where the two assumptions were made for the ideal gas EOS:

1. The gas molecule volume is very small compared to the volume of the container.
2. There are no attractive or repulsive forces between the gas molecules or the walls of the container.

Van der Waals attempted to eliminate these assumptions in the development of an empirical EOS for the real gases.

First assumption elimination: the gas molecules occupy a considerable fraction of the volume at higher pressures, and the volume of the molecules (b) is subtracted from the actual molar volume (V) to give the following expression:

$$p = \frac{RT}{v - b} \quad (3)$$

Second assumption elimination: he added corrective term (a), denoted by (a/V^2) , in order to account for the attractive forces between molecules.

Van der Waals introduced the following equation (Eq. (4)):

$$\left(p + \frac{a}{V_M^2} \right) (V_M - b) = RT \quad (4)$$

where a: attraction parameter; b: repulsion parameter.

The symbol “a” is considered a measure of the intermolecular attractive forces between the molecules. “b” is known as the co-volume and considered to reflect the volume of molecules [2]. The “a” and “b” values can be obtained from the critical properties of the fluid [14], where the repulsion pressure, $p_{\text{repulsion}}$, is represented by the term $RT/(V_m - b)$, and the attraction pressure, $p_{\text{attraction}}$, is described by a/V_m^2 . The Van der Waals equation of state despite its simplicity, while it provides a correct description and qualitative of the PVT substances behavior in the liquid and gaseous phases. Yet, it is not accurate enough to be suitable for design purposes. The equation of state approach for calculating physical properties and phase equilibrium proved to be a powerful tool, and much energy was devoted to the development of new and accurate equations of state [11]. Other researchers began attempts to improve Van der Waals equation of state for over 100 years. Usually a change of the molecular attraction term $(a/V_m M^2)$ was proposed. Clausius in 1880 [15] proposed that the molecular attraction term was inversely proportional to temperature [16]:

$$\left[P + \frac{a}{T(V_M + c)^2} \right] (V_M - b) = RT \quad (5)$$

The addition of a fourth constant (c) enabled better agreement with data. However, mathematical manipulations required in thermodynamic calculations were more difficult. So Berthelot in 1899 [17] removed the constant (c), resulting in the following equation:

$$\left(P + \frac{a}{TV_M^2} \right) (V_M - b) = RT \quad (6)$$

Dieterici in 1899 [18] handled the temperature dependence of the molecular attraction term in a different manner [6]:

$$\left[P \text{ EXP} \left(\frac{a}{V_M RT} \right) \right] (V_M - b) = RT \quad (7)$$

Lorentz in 1881 [19] addressed the molecular volume term [20]:

$$\left(P + \frac{a}{V_M^2} \right) \left(V_M - \frac{bV_M}{V_M + b} \right) = RT. \quad (8)$$

Wohl in 1927 [21] considered the effect of temperature on the molecular attraction term:

$$\left(P + \frac{a}{TV_M(V_M - b)} - \frac{c}{T^2V_M^3} \right) (VM - b) = RT \quad (9)$$

The constants a, b, and c in the equations above have different values for different substances. Several investigations proposed virial-type of EOS. Kammerlingh-Onnes in 1901 [22] proposed the virial equation of state as follows [23]:

$$PV_M = RT \left[1 + \frac{B}{V_M} + \frac{C}{V_M^2} + \dots \right] \quad (10)$$

where B and C are not constants which are functions of temperature and are called the second and third virial coefficients. Beattie and Bridgeman in 1927 published a five-constant equation that gives a satisfactory representation of volumetric properties except in the critical region [24]:

$$P = \frac{RT}{V_{M2}} \left(1 - \frac{c}{V_M T^3} \right) \left[V_M + B_o \left(1 - \frac{b}{V_M} \right) \right] - \frac{A_o(1-a/V_M)}{V_M} \quad (11)$$

Benedict et al. [6] suggested a multiparameter equation of state known as the Benedict-Webb-Rubin (BWR) equation [6]:

$$P = \frac{RT}{V_M} + \frac{B_o RT - A_o - C_o/T^2}{V_M^2} + \frac{bRT - a}{V_M^3} + \frac{a\alpha}{V_M^6} + \frac{c}{T^2 V_M^3} \left(1 + \frac{\gamma}{V_M^2} \right) \text{EXP} \left(\frac{-\gamma}{V_M^2} \right) \quad (12)$$

This equation may be considered a modification of the Beattie-Bridgeman equation of state where A_0 , B_0 , C_0 , a , b , c , α , and γ are eight adjustable parameters.

The BWR equation could treat critical components and was able to work in the critical area. However, the BWR equation suffers from some disadvantages [25]. Perhaps, the most important model for the modification of the Van der Waals equation of state is the Redlich-Kwong (RK) (1949) which is demonstrated by an adjustment of the Van der Waals's attraction term (a/V_m^2) and includes the system temperature explicitly. They could improve the prediction of the physical and volumetric properties of the vapor phase. In RK EOS, the attraction pressure term was replaced with a generalized temperature-dependent term (Eq. (13)) [3]:

$$\rho = \frac{RT}{V - b} - \frac{\alpha}{V(V + b)\sqrt{T}} \quad (13)$$

For pure substances, the equation parameters a and b are usually expressed as.

$$b = \Omega_b R T_c / P_c \quad (14)$$

$$a = \Omega_a R^2 T_c^{2.5} / P_c \quad (15)$$

where $\Omega_a = 0.42747$ and $\Omega_b = 0.08664$.

Replacing the molar volume (V) in Eq. (13) with (ZRT/P) and rearranging give.

$$Z^3 - Z^2 + (A - B - B^2) Z - AB = 0 \quad (16)$$

where

$$B = \frac{bp}{RT} \quad (17)$$

$$A = \frac{ap}{R^2 T^{2.5}} \quad (18)$$

Three real roots in the two-phase region are yielded. The largest root corresponds to the compressibility factor of the gas phase, Z_v , while the smallest positive root corresponded to that of the liquid, Z_L [11].

For mixtures, the equation parameters a and b are usually expressed as a_m and b_m for a hydrocarbon liquid mixture with a composition of x_i :

$$a_m = \left[\sum_{i=1}^n X_i \sqrt{a_i} \right]^2 \quad (19)$$

$$b_m = \sum_{i=1}^n [X_i b_i] \quad (20)$$

a_m and b_m for a hydrocarbon gas mixture with a composition of y_i :

$$\alpha_m = \left[\sum_{i=1}^n y_i \sqrt{a_i} \right]^2 \quad (21)$$

$$b_m = \sum_{i=1}^n [y_i b_i] \quad (22)$$

where n : number of components in the mixture; a_i : Redlich-Kwong a parameter for the i component; b_i : Redlich-Kwong b parameter for the i component; b_m :

parameter b for mixture; x_i : mole fraction of component i in the liquid phase; y_i : mole fraction of component i in the gas phase.

Replacing the molar volume (V) in Eq. (13) with (ZRT/P) and rearranging give.

$$Z^3 - Z^2 + (A - B - B^2) Z - AB = 0 \quad (23)$$

where

$$B = \frac{b_m P}{RT} \quad (24)$$

$$A = \frac{a_m P}{R^2 T^{2.5}} \quad (25)$$

Then the compressibility factor of the gas phase or the liquid can be calculated.

Joffe and Zudkevitch [26] showed that a substantial improvement in the representation of fugacity of gas mixtures could be obtained by treating interaction parameters as empirical parameters [26]. Spear et al. [27] also states that the RK equation of state could be used to calculate the vapor-liquid critical properties of binary mixtures [28]. Chueh and Prausnitz [29] showed that the RK equation can be adapted to predict both vapor and liquid properties. Spear et al. [28] gave seven examples of systems for which the vapor-liquid critical properties of hydrocarbon mixtures could be calculated by using the RK equation of state. Carnahan and Starling [30] used the Redlich-Kwong equation of state to calculate the gas-phase enthalpies for a variety of substances [30]. Their results showed that the Redlich-Kwong equation was a significant improvement over the Van der Waals equation. Other workers applied the Redlich-Kwong equation to the critical properties and the high-pressure phase equilibria of binary mixtures. The results showed that the accuracy of the Redlich-Kwong equation of state calculations for ternary systems was only slightly less than that for the constituent binaries [31].

The success of the Redlich-Kwong equation has been the impetus for many further empirical improvements. One of the milestones in developing of CEOS was reported by Soave [4]. His development in the evaluation of the parameter in the attraction pressure term for the RK equation is shown in (Eq. (22)). Soave replaced the term $(a/T^{0.5})$ in Eq. (22) with a more general temperature-dependent term, denoted by a $\alpha(T)$, to give

$$p = \frac{RT}{V-b} - \frac{a \alpha(T)}{V(V+b)} \quad (26)$$

where $\alpha(T)$ is a dimensionless factor. Soave used vapor pressures of pure components to introduce an expression for the temperature correction parameter $\alpha(T)$. At temperatures other than the critical temperature, the correction parameter $\alpha(T)$ was defined by the following equation:

$$\alpha(T) = \left[1 + m \left(1 - \sqrt{T_r} \right) \right]^2 \quad (27)$$

Soave correlated the parameter “ m ” with the centric factor (ω) to give.

$$m = 0.480 + 1.574\omega, - 0.176\omega^2 \quad (28)$$

where T_r : reduced temperature, °R; ω : a centric factor of the substance; T : system temperature, °R.

For pure substances the equation parameters a and b are usually expressed as.

$$b = \Omega_b R T_c / P_c \quad (29)$$

$$a = \Omega_a R^2 T_c^2 / P_c \quad (30)$$

In general, most EOS inputs are only the critical properties, and a centric factor of each components is shown in **Table 1**.

where Ω_a and Ω_b are the SRK dimensionless pure component parameters:

$$\Omega_a = 0.42747.$$

$$\Omega_b = 0.08664.$$

Replacing the molar volume (V) in the equation with (ZRT/p) and rearranging give the compressibility factor Z :

$$Z^3 - Z^2 + (A - B - B^2) Z - AB = 0 \quad (31)$$

where

$$B = \frac{b_m p}{RT} \quad (32)$$

$$A = \frac{a_m P}{(RT)^2} \quad (33)$$

For mixtures, the equation parameters a and b are usually expressed as a_m and b_m for a hydrocarbon liquid mixture with a composition of x_i :

$$a_m = \sum_i \sum_j \left[x_i x_j \sqrt{a_i a_j \alpha_i \alpha_j (1 - k_{ij})} \right] \quad (34)$$

$$b_m = \sum_i [X_i b_i] \quad (35)$$

The following is the calculation for a_m and b_m for a gas mixture with a composition of y_i :

$$a_m = \sum_i \sum_j \left[y_i y_j \sqrt{a_i a_j \alpha_i \alpha_j (1 - k_{ij})} \right] \quad (36)$$

$$b_m = \sum_i [y_i b_i] \quad (37)$$

A binary interaction parameter (BI), classically noted as k_{ij} , is usually involved in the “a” parameter expression to provide more flexibility to the EOS and designed to characterize any binary system formed by components i and j in the hydrocarbon mixture [32]. Vidal and Daubert [33], Graboski and Daubert [34], and Slot-Petersen [35] suggested that no BIs were required for hydrocarbon systems. However, with no hydrocarbons present, binary interaction parameters can improve the phase in volumetric behavior predictions of the mixture by the SRK EOS for compressibility factor calculations of the gas or the liquid phases [34, 36, 37]. The equilibrium ratio, K_i , that is, $K_i = y_i / x_i$, can be redefined in terms of the fugacity of component:

Compound	Formula	Molecular weight	Critical pressure (psia)	Critical temperature (°F)	Critical volume (ft ³ /lb)	Liquid specific gravity (water = 1)	Gas specific (air = 1)	Acentric factor
Methane	CH ₄	16.042	667.0	-116.66	0.0985	(0.3)	0.55400	0.0115
Ethane	C ₂ H ₆	30.069	706.6	89.92	0.0775	0.35643	1.03830	0.0994
Propane	C ₃ H ₈	44.096	615.5	205.92	0.0728	0.50738	1.52270	0.1529
Isobutane	C ₄ H ₁₀	58.122	527.9	274.41	0.0715	0.56295	2.00710	0.1865
<i>n</i> -Butane	C ₄ H ₁₀	58.122	550.9	305.55	0.0703	0.58408	2.00710	0.2003
Isopentane	C ₅ H ₁₂	72.149	490.4	369	0.0685	0.62460	2.49140	0.2284
<i>n</i> -Pentane	C ₅ H ₁₂	72.149	488.8	385.8	0.0676	0.63113	2.49140	0.2515
<i>n</i> -Hexane	C ₆ H ₁₄	86.175	436.9	453.3	0.0688	0.66404	2.97580	0.2993
<i>n</i> -Heptane	C ₇ H ₁₆	100.202	396.8	512.9	0.0682	0.68819	3.46020	0.3483
<i>n</i> -Octane	C ₈ H ₁₈	114.229	360.7	564.2	0.0673	0.70698	3.94450	0.3977
<i>n</i> -Nonane	C ₉ H ₂₀	128.255	330.7	610.8	0.693	0.72186	4.42890	0.4421
<i>n</i> -Decane	C ₁₀ H ₂₂	142.282	304.6	652.2	0.0703	0.73406	4.91330	0.4875
Carbon monoxide	CO	28.01	506.7	-220.63	0.0527	0.79265	0.96720	0.0510
Carbon dioxide	CO ₂	44.01	1070.0	87.76	0.0343	0.82203	1.51970	0.2239
Hydrogen sulfide	H ₂ S	34.082	1306.5	212.81	0.0462	0.80269	1.17690	0.1010
Air	—	28.9586	551.9	-220.97	0.0458	0.87603	1.00000	—
Hydrogen	H ₂	2.0159	190.7	-399.9	0.5319	0.07087	0.06961	-0.2140
Oxygen	O ₂	31.9988	731.4	-181.43	0.0367	1.14230	1.10500	0.0222
Nitrogen	N ₂	28.0135	492.5	-232.53	0.0511	0.80687	0.96740	0.0372
Water	H ₂ O	18.0153	3200.1	705.1	0.04975	1.00000	0.62210	0.3443

Table 1.
Physical properties of each components.

$$K_i = \frac{\left[\frac{f_i^L}{(X_i P)} \right]}{\left[\frac{f_i^V}{(y_i P)} \right]} = \frac{\Phi_i^L}{\Phi_i^V} \quad (38)$$

where f_i^V = fugacity of component “i” in the gas phase; f_i^L = fugacity of component “i” in the liquid phase; Φ_i^V = fugacity coefficient of component “i” in the vapor phase; Φ_i^L = fugacity coefficient of component “i” in the liquid phase.

Soave proposed the following expression for the fugacity coefficient of component i in the liquid phase:

$$\ln \left(\frac{f_i^L}{X_i P} \right) = \ln (\Phi_i^L) = \frac{b_i(Z^L - 1)}{b_m} \ln (Z^L - B) - \left(\frac{A}{P} \right) \left[\frac{2\psi_i}{a_m} - \frac{b_i}{b_m} \right] \ln \left[1 + \frac{B}{Z^L} \right] \quad (39)$$

where

$$\psi_j = \sum_j \left[x_j \sqrt{a_i a_j \alpha_i \alpha_j (1 - k_{ij})} \right] \quad (40)$$

$$a_m = \sum_i \sum_j \left[x_i x_j \sqrt{a_i a_j \alpha_i \alpha_j (1 - k_{ij})} \right] \quad (41)$$

Fugacity coefficient of component i in the gas phase:

$$\ln (\phi_j) = \frac{b_i(Z^i - 1)}{b_m} - \ln (Z^i - B) - \left(\frac{A}{B} \right) \left[\frac{2\psi_i}{a_m} - \frac{b_i}{b_m} \right] \ln \left[1 + \frac{B}{Z^i} \right] \quad (42)$$

where:

$$\psi_j = \sum_j \left[y_j \sqrt{a_i a_j \alpha_i \alpha_j (1 - k_{ij})} \right] \quad (43)$$

$$a_m = \sum_i \sum_j \left[y_i y_j \sqrt{a_i a_j \alpha_i \alpha_j (1 - k_{ij})} \right] \quad (44)$$

3. Heat exchanger

Heat exchanger is an energy (heat) exchange equipment, where it transfers the heat from a working medium to another working medium. Knowing heat exchanger is important in widely fields as in aerospace, petrochemical industry, refrigeration, and other fields. The optimization design of the heat exchanger is a great significance to industry process to reduce production cost, realize energy conservation, and reduce energy consumption [38]. The development technique for different types of the heat exchanger has been reviewed by many researchers. The development method can be by two ways: passive method and active method. The passive method is to generate swirling flow and disturb the thermal boundary layer by installing vortex generator or tabulators such as baffle, rib, winglet, wing, etc.

The active method is to add the external power to increase efficiency and heat transfer rate such as vibration. So the use of the active method must consider both benefit of the system and additional power cost [39].

3.1 Optimization techniques of heat exchanger

The optimization techniques of heat exchanger can be shown at three different stages as the following [40]:

1. Identification of the lowest initial cost of a heat exchanger design that meets the process specifications.
2. Identification of a heat exchanger design that will work most acceptably over the plant lifetime.
3. Identification of the minimum total cost of the process by choosing heat exchangers system and auxiliary components that will make the best plant process specifications.

3.2 Criteria of the ideal heat exchanger

The dissimilarities of optimization techniques levels can be understood if we list the required criteria of the ideal heat exchanger as follows [41]:

1. The heat exchangers should be flexible enough to meet specifications process such as normal fouling transients and seasonal and diurnal changes in service stream temperatures.
2. Special requirements as weight, length, or inventory standards are important for heat exchangers especially in retrofit applications.
3. The heat exchanger must endure operation under standard and foreseeable operating conditions, maintain the mechanical stresses of manufacturing transport, and minimize the effects of fouling and corrosion.
4. The heat exchanger must be maintainable, cleaning, repair or replacement and its components as gaskets and tubes with minimum downtime.
5. The exchanger must achieve process specifications, i.e., achieve any changes in the thermal conditions by allowable pressure drops.
6. There are other requirements, such as experience, capability of operating, maintenance personnel, and manufacturing time.
7. The exchanger should cost as little as possible.

4. Fluid flow and heat transfer mechanism

The heat transfer and fluid flow mechanism in porous media is important in engineering and industrial fields such as petroleum and chemical engineering [42]. This mechanism occurs for many studies such as in microchannels and nanofluids.

Example 1: In case of study characteristics of fluid flow and heat transfer in the (100) silicon microchannel heat sink, the heat convection capabilities in the phase changes as well as in a single-phase flow and the mechanism of bubble nucleation. In the heat transfer characteristics, the results illustrate that changing in the phase process in the microchannels reduces environment working temperature and absorbs the heat. Six different microchannel geometries are selected for the heat transfer experiment as shown in **Table 2**.

Figure 1 shows that the decreasing wall temperature phenomenon during the phase change is the same as Peng and Wang [43].

On the aspect of fluid flow characteristics, the effects of the viscosity and friction coefficient of the fluid in the microchannels are much significant than the macros. Where the specifications of the sink are registered in **Table 2**, Chip 1–4 are prepared for fluid flow experiment. The friction factor is decreasing with the power of Reynolds number as shown in **Figure 2** [44].

1. Nanoparticle types and concentration in the base fluids
2. Changing in thermophysical properties such as viscosity, surface tension, thermal conductivity, density, and heat capacity
3. The operation condition especially the mass and heat fluxes
4. The modification of wettability and capillary wicking force surface roughness

During the last 2 years, there were some review papers which outlined the subject of boiling heat transfer using nanofluids as a new category in thermal fluids.

Chip name	Width (μm) W_c	Depth (μm) H_c	Hydraulic diameter (μm)	Number of channels
Chip 1	400	260	221	10
Chip 2	300	130	150	13
Chip 3	250	184	134	15
Chip 4	200	148	109	19
Chip 5	150	113	83	25
Chip 6	100	78	57	38

Table 2.
 Specification of the sink.

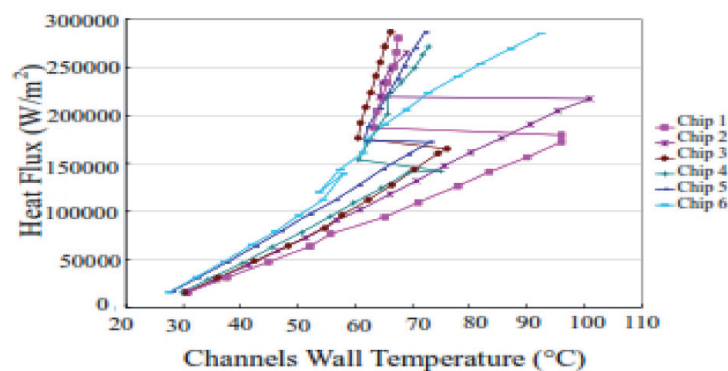


Figure 1.
 The heat flux and channel wall temperature.

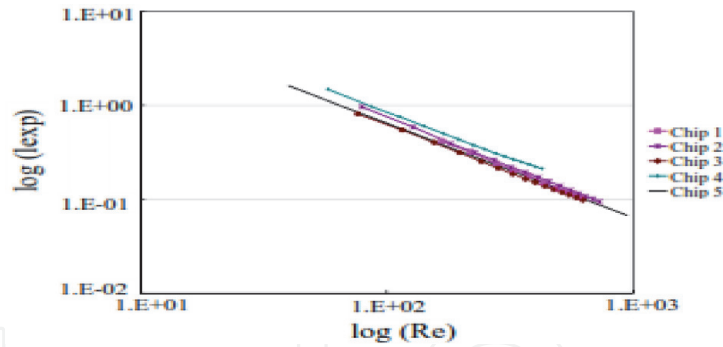


Figure 2.

Exponential relations between the friction factor and the Reynolds number. Example 1: in the case of study characteristics of fluid flow and heat transfer, nanofluid is widely utilized in numerous industrial applications such as boiler tubes, evaporators, and cooling of reactors in a nuclear power plant. The main parameters that directly influence on the heat transfer performance are listed as follows [45].

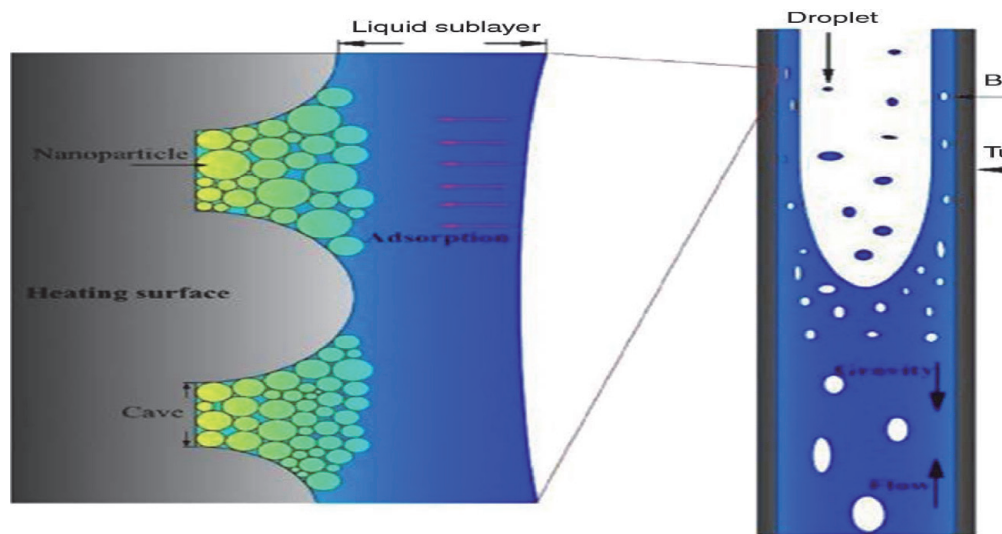


Figure 3.

Illustration of the mechanism of flow boiling CHF using nanofluid introduced.

Available results reported that the effect of nanoparticles on the flow boiling HTC is conflicting, but the CHF could enhance on 50%. During the boiling process, parameters such as flow pattern and pressure drop were affected by the deposition of nanoparticles [46]. Authors concluded that using nanofluids might intensify the boiling HT and CHF, depending on many parameters related to additives, nanoparticles, geometry concentration, and fluid properties [47].

Their work shows how the nanofluids can achieve high heat flux with small temperature differences throughout the boiling process, which modify the critical heat flux [48]. All article reviewers said that nanofluids is a complicated phenomenon and it is not fully understood from mechanism of boiling heat transfer and two-phase flow. Collected studies show enhancement in CHF, and its improvement could achieve more than 50% [49]. HTC behavior could increase or decrease during flow boiling and pool, and it depends on several parameters related to surface texture on thermophysical properties [50]. Wang et al. shows the mechanism of depositing nanoparticles on the heating surface and creating the porous layer as shown in **Figure 3**. The results show that the CHF of flow boiling is enhanced up to 18% as compared to conventional fluid. This enhancement increases with increasing some parameters, for example, the pressure system and the channel diameter [45].

Example 2: in the case of study fluid flow and heat transfer characteristics using nanofluid in a single-phase turbulent flow by using helically corrugated tubes, pitch-to-diameter ratio ($P/DH = 0.18, 0.22$ and 0.27) and rib-height-to-diameter

ratio ($e/DH = 0.02, 0.04$ and 0.06) of helically corrugated tubes on the heat transfer enhancement, isothermal friction, and thermal performance factor in a concentric tube heat exchanger are examined. Results illustrate that the thermal performance of the corrugated tube and heat transfer are increased as compared to those of the smooth tube. The rate increase in heat transfer rate is between 123 and 232%, depending on the rib height/pitch ratios and Reynolds number. The friction factor (average) of the corrugated tube is between 1.46 and 1.93 over the smooth tube [51].

Abbreviations

EOS	equation of state
BWR	Benedict-Webb-Rubin
RK	Redlich-Kwong
SRK	Soave-Redlich-Kwong
CEOS	cubic equations of state
MSRKE	modified Soave-Redlich-Kwong equation of state
p	system pressure, psia
P_c	critical pressure, psia
P_r	reduced pressure, psia
p_i	initial pressure, psia
T	system temperature, °F
T_c	critical temperature, °R
T_r	reduced temperature, °R
T_i	initial temperature, °F
a	equation of state attraction parameter
b	equation of state repulsion parameter
B	second virial coefficient
C	third virial coefficient
a, b, c, A_0, B_0, C_0	constant in Benedict-Webb-Rubin equation
a, b, c, A_0, B_0	constant in Beattie and Bridgeman equation of state
f_i^v	fugacity of component i in the gas phase
f_j^l	fugacity of component j in the liquid phase
ϕ_i^v	fugacity coefficient of component i in the vapor phase
ϕ_i^l	fugacity coefficient of component i in the liquid phase
x	mole fraction of gas phase
y	mole fraction of liquid phase
k	equilibrium ratio for the component
K_{ij}	interaction coefficient parameter
A, B	parameter in Soave-Redlich-Kwong equation of state
a_T	temperature-dependent coefficient in Soave-Redlich-Kwong equation of state
a_c	constant coefficient in Soave-Redlich-Kwong equation of state
a_{Ti}	temperature-dependent coefficient of component i
m	parameter in Soave-Redlich-Kwong equation of state
Z	compressibility factor
Z_i	the mole fraction of component in the mixture
Z_L	compressibility factor of the liquid phase
Z_v	compressibility factor of the gas phase
ω	a centric factor of the substance
n_l	number of moles in liquid phase
n_v	number of moles in gas phase

n_t	total number of moles of mixture
F_l	one mole liquid of total fraction
F_v	one mole vapor of total fraction
X_i	mole fraction in the liquid phase
y_i	mole fraction in the vapor phase
γ	constant in Benedict-Webb-Rubin equation of state

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