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NATURAL GAS PROPERTIES EVALUATION FOR PIPE FLOW SIMULATION

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Abstract. *The discoveries of the Pre-salt oilfields have driven the development of new technologies to enable the production of the deepwater reservoirs located in regions far from the Brazilian coast. In this scenario, subsea pipelines play an important role. They are a simple and economically feasible way for the transportation of oil and gas. Analyses of the steady and transient flow inside the pipes should be addressed in the design, considering the variation of the fluid properties. In this context, a pipe flow simulator project has been developed to attend petroleum industry. This program considers gas flow analyses. In this case, the fluid compressibility factor (Z-factor) and the viscosity are important fluid properties. The Z-factor corrects the ideal gas equation of state to achieve the real gas behavior. The viscosity of the fluid is an important parameter for the friction factor determination. These two properties are function of the pressure, temperature and gas composition. For the petroleum industry application, Z-factor and viscosity must be determined considering the presence of contaminants in the gas, such as hydrogen sulfide and carbon dioxide. Several models can be found in literature. Some of these models were implemented and compared with experimental results of the literature in order to assess which model is best suited for the application under development. Different combinations of the pseudo-reduced parameters models and the Z-factor models were analyzed. In selection of the most appropriate methods for calculating the fluid properties, the aspects considered were accuracy, computational effort and applicability of the model. Absolute errors of approximately 2% were found by comparison of the best combinations with experimental data.*

Keywords: *petroleum, z-factor, viscosity, gas properties, simulator.*

1. INTRODUCTION

The pre-salt reserves are at water depths of about 2 km and distances of 200-300 km from the coast. In this scenario, the oil must flow through pipes, which can be complex risers systems or simple submarine pipelines. In both cases, due to the length of the pipes and the low water temperature, the influence of temperature on the behavior of the fluid is enhanced. Thus, the evaluation of the properties of the fluid flow is crucial for optimizing the design and operation of the lines, increasing the safety and reducing the costs of construction and operation.

Due to the great depths of these fields, a subsea separator has been developed (Melo, *et al*, 2007; Shiguemoto, *et al*, 2011). This equipment separates liquid and gas phase of the petroleum to be transported in separate pipelines. The advantages are the increased lifetime of the pumping system, reduction of the friction factor between fluid and pipe, weight reduction on the platform and increase of floor space that can build viable smaller platforms.

In this context NISO (Non-ISOthermal transient flow) Project is running, funded by CNPq, where an application to simulate one phase flow in pipes is being developed. The main objective of the paper is to evaluate the numerical models to determine the properties of gases, which consists of the Z-factor and viscosity. As a software application, the requirements of the models are high precision, low computational processing time and broad scope of application.

The Z-factor models have been developed through computational methods for over half a century (Poettmann & Carpenter, 1952). The mathematical models can be compared to the Standing & Katz abacus (1941), as shown by Fattah (1995) and experimental data as presented by Londono et al (2005). All models evaluated describe the Z-factor as a function of pseudo-reduced pressure and temperature.

Pseudo-reduced properties are defined by the ratio of the property (pressure or temperature) of a fluid and its respective pseudo-critical property (pseudo-critical pressure or temperature). As the pseudo-critical properties are a function of the chemical composition of the fluid, the Z-factor is therefore a function of pressure, temperature and gas

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composition. In this work, some pseudo-reduced properties models and then Z-factor models will be described and evaluated.

For pure substances, the critical properties are obtained experimentally. However, for mixtures, mathematical models are used due to the complexity and costs associated to these experiments. Then, models have been used for calculate the pseudo-critical properties.

Kay (1936) demonstrated by experiments that hydrocarbons with similar molecular structure, like ethylene and isopentane, assume the same behavior in the reduced pressure and temperature curves. Rosa (2006) attributed to Kay (1936) a method of calculating the critical properties by averaging the properties of the components weighted by mole fraction. Stewart et al (1959) developed a nonlinear model based on the molar fraction of the components. Satter & Campbell (1968) evaluated four models for calculating critical properties of mixtures based on the mole fraction of the components, with and without contaminants, and the method of Stewart et al (1959) was the one that had the best performance.

Fattah (1997) analyzed thirteen linear models that describe the critical properties of a mixture as a function of the specific gravity. Also, a new linear model created was presented. Models based on the specific gravity allow the determination of the pseudo-reduced properties when the composition is unknown (Kay, 1936). In addition, the cost of measuring specific gravity is lower than the cost of the composition measurement.

Londono et al (2005) used data with approximately eight thousand points to develop a model that characterizes the critical pressure and temperature of a mixture in function of the squared specific gravity. The models were developed to reduce the error of the Z-factor models developed by Dranchuck & Abou-Kassem (1975) and Nishiumi & Saito (1975). The authors claim that the mean absolute error of the Z-factor in relation to the experimental data are 3.06% and 2.55%, respectively.

Rosa (2006) refers to three Z-factor models that are often used: an explicit model, developed by Brill & Beggs (1974) and two implicit models, one established by Dranchuck & Abou-Kassem (1975) and another arranged by Hall & Yarborough (1973). Fattah (1995) compared eight Z-factor models with the Standing & Katz (1941) abacus and described a table of recommended range of application for each model. Among the compared models, Dranchuck et al (1974), Dranchuck & Abu-Kassem (1975) and Hall & Yarborough (1973) were the models that present smaller errors and have better performance over the evaluated range.

As in the case of the Z-factor, different models have been studied and developed to determine the viscosity of the petroleum fluids. Comparisons with experimental data have demonstrated that each model presents different limitations due to the assumptions adopted. A brief discussion about some of this models can be seen further.

Herning & Zipperer (1936) proposed a model to calculate the viscosity of a gas mixture as a function of the average of each component viscosity weighted by the product of the molar fraction and the square root of the molecular weight of each component. Comparisons with experimental results to evaluate the accuracy of this model were not found.

Wilke (1950) developed a method for mixtures based on the kinetic theory, which is function of concentration, molecular weight, diffusion coefficient and density. The author proposed a simplified model for binary mixtures that is function of the viscosity, concentration and molecular weight of each component. A model based on data from thirteen binary mixtures was compared with experimental data and presented an average error of 1.9%.

Dean & Stiel (1958) have proposed a model that is function of the molar mass of the mixture, viscosity of each component, pseudo-reduced temperature and pressure and the Z-factor. This model was developed for hydrocarbons mixtures and comparisons with 1396 points of experimental binary mixture had shown an average error of 3.73%. Dean & Stiel (1958) compared their model with Wilke's model (Wilke, 1950) and observed that their model had the poorest results for almost all tested mixtures.

Bicher & Katz (1943) performed experiments with mixtures of methane and propane and based on these data elaborated abacus of mixtures viscosity as a function of temperature, pressure and molecular weight. The authors claim that the experimental precision is 3.2%.

Carr et al (1954) compiled and compared the data of various authors, getting a procedure to obtain the viscosity of hydrocarbon mixtures in the presence of contaminants. They used the Kay's correlation (Kay, 1936) to determine the pseudo-reduced properties, which was associated with a correction factor of viscosity named viscosity ratio to determine the viscosity at pressure of interest. Three natural gas mixtures' data were used to generate this abacus: one with high content of ethane (25.3%), one with high concentration of nitrogen (15.8%) and one with low-ethane (3.6 %). The concentration of methane in those mixtures was 73.4%, 73.1% and 95.6%, respectively. Other components were present in the mixtures. The viscosity at atmospheric pressure was obtained by Bicher & Katz's (1943) abacus, including correction due to the presence of nitrogen, carbon dioxide and sulfide hydrogen. Carr et al (1954) methodology was compared with experimental data and presented an error of approximately 3%.

Dempsey (1965) developed a correlation to calculate the viscosity at atmospheric pressure depending on the specific gravity and temperature and formulated corrections for viscosity at the pressure of interest.

Standing (1977) developed an equation to calculate the viscosity at atmospheric pressure based on Carr et al (1954) abacus, including the correction of contaminants proposed by authors. The deviation of the equation with respect to the abacus data was 0.38%, according to the author. For different pressures, Standing (1977) recommended Dempsey's (1965) correlation to correct the viscosity at the pressure of interest.

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Lee et al (1966) measured the density and viscosity of four samples of hydrocarbon gases in a wide range of pressure and temperature. Lee et al (1966) model was compared against these data and a mean error of 2.7% was observed. The model calculates the viscosity as a function of density, temperature and molecular weight. For the cases when the density of the experimental data is unknown, they proposed some modifications to use the method of Kay (1936).

Jossi et al (1962) developed a model that relates the reduced density with the viscosity residual modulus. The authors used data from 14 pure substances, in which the hydrogen, ammonia and water behaved differently from other substances and different between them. The authors performed regression curves for the hydrogen, water, ammonia and all other substances analyzed (called normally behaving substance by the authors), which resulted in fourth degree polynomials. Furthermore, a simplified model was developed for normally behaving substance that have a limited range and less precision. Comparisons with experimental data were not presented in the work.

Londono et al (2005) conducted a study to evaluated Jossi et al (1962) and Lee et al (1966) viscosity models, and developed a new model. To calculate the density, the authors used Dranchuck & Abou-Kassem (1975) and Nishiumi & Saito (1975) Z-factor models and also proposed a new one. The study consisted of an error evaluation for each model through comparisons with approximately 4,900 data points obtained from pure substances and mixtures. The constants of Jossi et al (1962) and Lee et al (1966) models were also recalculated in order to reduce the error. The best performances were obtained for Lee et al (1966) viscosity model which presented an average absolute error of 2.29% and Nishiumi & Saito (1975) Z-factor model which shown an error of 0.732%.

This work aims to evaluate those published model and find the most suitable for the flow simulation software that is being developed. The desired characteristics for a proper model are: (1) low computational effort; (2) high accuracy; (3) wide range of application and (4) the input parameters should match with those that users have available.

2. METHODOLOGY

2.1 Z-factor model assessment methodology

The Brill & Beggs (1974) model uses explicit formulations, which presents low computational effort in comparison to implicit models. The Dranchuck & Abou-Kassem (1975) and Saito & Nishiumi (1975) models present similar precision and computational effort (Londono et al, 2005). However, the Nishiumi & Saito (1975) model requires the acentric factor as input and others specific experimental constants of each substance. Constants for some pure hydrocarbon substances can be found in McCain (1990), which consists of light hydrocarbon components and some contaminants, but cover only a small part of the components found in the petroleum. The Dranchuck & Abou-Kassem (1975) and Hall & Yarborough (1973) model have errors of the same order of magnitude as presented by Fattah (1995) and Rosa (2006).

Based on the literature review, it was decided to do not evaluate the Nishiumi & Saito (1975) model due to the requirement of specific input variables that depends on experimental data. Since, the Brill & Beggs (1974) model presents advantages in relation to other models because the explicit formulation, it was considered in the evaluation carried out in this work. Dranchuck & Abou-Kassem (1975) and Hall & Yarborough (1973) models are also included in this assessment in order to verify the performance between them and in relation to the explicit model.

The pseudo-critical properties models found in the literature review vary in relation to the complexity and input variables. The assessment presented in the literature do not allow identify which model is more suitable for our purpose, therefore the evaluations considered the main published models possible to be replicated and some recent models. Those models are Kay (1936), Stewart et al (1959), Fattah (1997) and Londono et al (2005).

The experimental data used to Z-factor models assessment and to validate the implementation of the model were obtained from the doctoral thesis of Satter (1963). Computational routines were written to check the implementations.

First, a qualitative evaluation of the Z-factor for the range of validity of each model was performed through comparisons of the calculated graph with Standing & Katz (1941) chart. The calculated graphical curves were obtained at the same reduced temperature and for step of reduced pressure increment of 0.1.

Second, quantitative appraisals was carried out by comparing point to point the Z-factor calculated by the models with the values extracted from the Standing & Katz (1941) chart. Five points of each reduced temperature curve is considered, which consists of the minimum Z-factor in this curve and the two points to the left of this value (lower reduced pressure) and two points to the right (higher reduced pressure).

Third, the pseudo-critical properties models and Z-factor models were combined originating twelve combinations. Each combination was compared to values for Z-factor measured by Satter (1963), which consists of five mixtures composition analyzed by seven pressure values and three temperatures, resulting in a total of one hundred and five measuring points of Z-factor under different conditions. The mixtures compositions are presented in Tab. 1. The average errors were grouped by model, temperature, pressure and mixture composition to conduct further analysis.

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Table 1. Mixtures composition from Satter's (1963).

Mixture	CH_4	C_2H_6	H_2S
1	0.871	0.064	0.065
2	0.831	0.071	0.098
3	0.836	0.117	0.047
4	0.800	0.107	0.093
5	0.713	0.090	0.197

2.2 Viscosity model assessment methodology

The viscosity model proposed by Herning & Zipperer (1936) requires knowledge of the viscosity of each component in the mixture, Wilke (1950) model requires knowledge of the thermal diffusivity coefficient, the Dean & Stiel (1958) model needs mole fraction of each component of the mixture and the viscosity of each component, and Jossi et al (1962) model requires the critical Z-factor, which involves the volume value or density measured at the critical point. These models were not evaluated in this work due to the required inputs, which are usually uncommon for the users. Therefore, the assessment considered the Standing (1977), Dempsey (1965) and Lee et al (1966) models because those models require input data usually known by the user. For Lee et al. (1966) model the Z-factor is required and was calculated using two of the models analyzed in this work which used Londono et al (2005) and Fattah (1997) models to calculate the critical properties. The others viscosity models requires the critical temperature and pressure which were calculated using Dempsey (1965), Londono et al. (2005) and Fattah (1997) models. All these resulted in eight combinations presented in Tab. 2. The results were compared with the experimental data obtained by Lee et al (1966), which consists of the measurement of the viscosity of four mixtures composition in function of the density for different temperature and pressure. The compositions of the mixtures are presented in Tab. 3.

Table 2. Viscosity models evaluated in this work.

#	Critial properties	Z-factor	Viscosity at 1 atm	Viscosity at high pressure
1	Dempsey (1965)	-	Dempsey (1965)	Dempsey (1965)
2	Londono et al (2005)	-	Dempsey (1965)	Dempsey (1965)
3	Fattah (1997)	-	Dempsey (1965)	Dempsey (1965)
4	Dempsey (1965)	-	Standing (1977)	Dempsey (1965)
5	Londono et al (2005)	-	Standing (1977)	Dempsey (1965)
6	Fattah (1997)	-	Standing (1977)	Dempsey (1965)
7	Londono et al (2005)	Dranchuck & Abou-Kassem (1975)	-	Lee et al (1966)
8	Fattah (1997)	Brill & Beggs (1974)	-	Lee et al (1966)

Table 3. Mixtures composition from Lee et al (1963).

Components	Mixture			
	1	2	3	4
N_2	0	1.40	4.80	0.55
CO_2	3.20	1.40	0.90	1.70
He	0	0.03	0.03	0
C1	86.30	71.70	80.70	91.50
C2	6.80	14.00	8.70	3.10
C3	2.40	8.30	2.90	1.40
nC4	0.48	1.90	1.70	0.50
iC4	0.43	0.77	0	0.67
C5	0.22	0.39	0.13	0.28
C6	0.10	0.09	0.06	0.26
C7+	0.04	0.01	0.03	0.08
Total	99.97	99.99	99.98	100.04

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3. RESULTS

3.1 Z-factor

3.1.1 Qualitative comparison with Standing & Katz (1941)

Table 4 presents the range utilized to generate the results shown in Fig 1. The reduced pressure (Pr) range was discretized with step of 0.1 while the reduced temperature (Tr) range was discretized with step of 0.1 until Tr <= 2.0 and step of 0.2 for higher Tr. It is observed in Fig. 1 that the models presented the same trend of plot presented by Standing & Katz (1941).

Table 4. Temperature and pressure range for graphical evaluation.

Model	Tr	Pr
Dranchuk & Abou-Kassem (1975)	1.1 to 3.0	0.2 to 8.0
Hall & Yarborough (1973)	1.1 to 3.0	0.2 to 8.0
Brill & Beggs (1974)	1.2 to 2.4	0.2 to 8.0

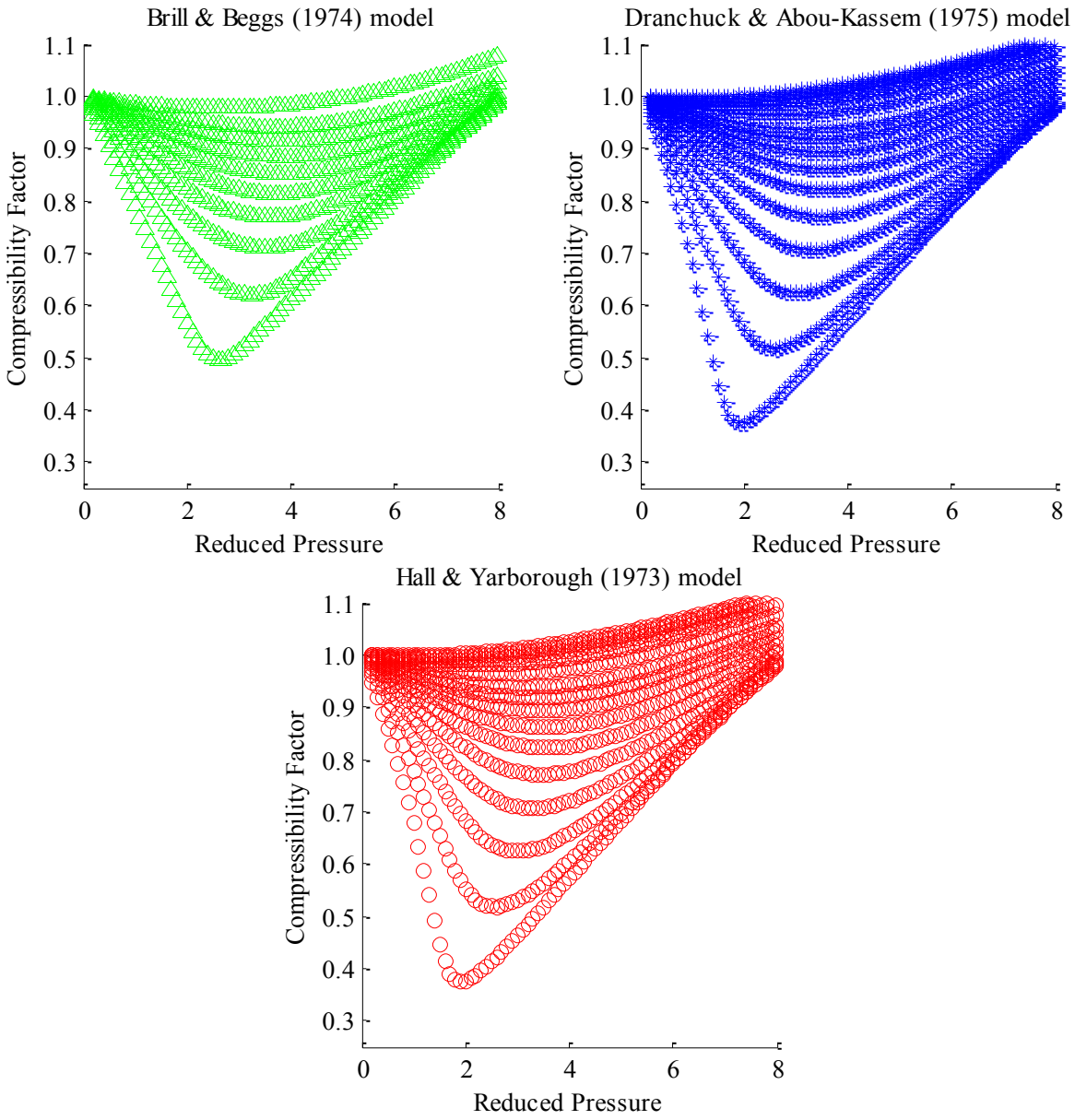

Figure 1. Graphical comparison of models.

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3.1.2 Quantitative comparison with Standing & Katz (1941)

The absolute mean errors were calculated considering as reference the data from Standing & Katz (1941). Due to model limitations the errors were calculated for two ranges of reduced temperature: in the first, all models are valid (Table 5); the second one comprises a range presented by Standing & Katz (1941), where Brill & Beggs (1974) model is not valid (Table 6).

Table 5. Errors of the models based on Standing & Katz (1941) chart from 1.2 to 2.4 pseudo-reduced temperature.

Model	Mean error [%]	Absolute mean error [%]
Dranchuk & Abou-Kassem (1975)	0.19	0.34
Hall & Yarborough (1973)	0.17	0.37
Brill & Beggs (1974)	0.17	1.05

Table 6. Errors of the models based on Standing & Katz (1941) chart from 1.05 to 3.0 pseudo-reduced temperature.

Model	Mean error [%]	Absolute mean error [%]
Dranchuk & Abou-Kassem (1975)	0.28	0.98
Hall & Yarborough (1973)	0.52	1.03
Brill & Beggs (1974)	-21.76	22.89

In the range where all models are valid (Table 5), the errors obtained are at the same order even with the difference that Brill & Beggs (1974) model are explicit while the others are implicit.

Table 6 presented errors calculated considering the range valid on Standing & Katz (1941). It is observed that models of Dranchuk & Abou-Kassem (1975) and Hall & Yarborough (1973) presented similar errors. Otherwise, model of Brill & Beggs (1974) presented higher errors, once the model is not valid for this reduced temperature range.

3.1.3 Quantitative comparison with Satter (1963)

The same three Z-factor models described before were compared with experimental data from Satter (1963). The mean error and the absolute mean error calculations are presented in Table 7. Each Z-factor model was combined with four different pseudo-critical property model. It is noted that the lowest error values were obtained for the scenario that combines the Brill & Beggs (1974) Z-factor model and Fattah (1997) pseudo-critical property model.

Table 7. Errors of the models based on data from Satter (1963).

Z-factor model	Pseudo-critical property model	Mean error	Absolute mean error
Brill & Beggs (1974)	Kay (1936)	-3.7 %	3.7 %
	Stewart et al (1959)	-3.1 %	3.1 %
	Londono (2005)	2.2 %	2.3 %
	Fattah (1997)	0.9 %	1.9 %
Hall & Yarborough (1973)	Kay (1936)	-3.3 %	3.3 %
	Stewart et al (1959)	-2.6 %	2.6 %
	Londono (2005)	3.4 %	3.4 %
	Fattah (1997)	1.8 %	2.4 %
Dranchuk & Abou-Kassem (1975)	Kay (1936)	-3.3 %	3.3 %
	Stewart et al (1959)	-2.7 %	2.7 %
	Londono (2005)	3.3 %	3.3 %
	Fattah (1997)	1.8 %	2.4 %

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Table 8. Reduced temperature calculated by analyzed models.

Mixture	Temperature	Reduced Temperature			
		Model			
		Kay (1936)	Stewart et al (1959)	Londono (2005)	Fattah (1997)
1	101.5	1.49	1.49	1.62	1.53
	130.9	1.56	1.57	1.70	1.61
	160.0	1.64	1.65	1.78	1.69
2	101.8	1.44	1.45	1.57	1.50
	131.7	1.52	1.53	1.65	1.58
	161.1	1.59	1.61	1.74	1.66
3	101.0	1.46	1.47	1.59	1.51
	129.7	1.54	1.54	1.67	1.59
	160.2	1.62	1.62	1.75	1.67
4	101.7	1.42	1.43	1.54	1.48
	130.6	1.49	1.50	1.62	1.56
	160.3	1.57	1.58	1.71	1.64
6	101.8	1.32	1.34	1.45	1.42
	130.5	1.38	1.41	1.52	1.49
	161.0	1.45	1.48	1.60	1.57

A statistical analysis were carried-out in order to determine the absolute mean error of each set of data obtained at the same reduced temperature and for the same mixture. The reduced temperature depends on the pseudo-critical model, therefore the reduced temperature values for each model are presented in Table 8.

In Fig. 2c it is observed the effect of mixture composition in the absolute mean error calculated for each model. The best performance was expected for the combined use of models presented by Londono et al (2005) and Dranchuk & Abou-Kassem (1975), once more mixture combinations are contained in their model's data formulation. Londono et al (2005) proposed new coefficients for the Dranchuk & Abou-Kassem (1975) model with the aim to reduce the error. They used approximately 5000 experimental data considering different concentrations of contaminants and achieved the goal. Figure 2a presents the comparison between each models combination. It can be observed by Fig. 2b a trend in decreasing the error as reduced temperature increases. Figure 2c presents the absolute mean error calculated with original coefficients of Dranchuk & Abou-Kassem (1975) while Fig. 2d presents results obtained with coefficients proposed by Londono et al (2005). Table 9 presents a comparison between the errors obtained considering the original coefficients of Dranchuk & Abou-Kassem (1975) and the modified coefficients proposed by Londono et al (2005). Opposed as expected, the absolute mean errors obtained with the original coefficients were lower than the errors obtained with modified coefficients. In this comparison it is noted that the combination of modified Dranchuk & Abou-Kassem (1975) coefficients and pseudo-critical properties models reduced the errors when compared with original Dranchuk & Abou-Kassem (1975) coefficients.

Table 9. Comparison between original and modified coefficient of DAK (1975) model.

Z-factor Model	Pseudo-critical properties model	Mean error [%]	Absolute mean error [%]
Original Dranchuk & Abou-Kassem (1975) coefficients	Kay (1936)	-3.28	3.28
	Stewart et al (1959)	-2.60	2.60
	Londono (2005)	3.36	3.36
	Fattah (1997)	1.80	2.36
Modified coefficients by Londono (2005)	Kay (1936)	-2.96	2.96
	Stewart et al (1959)	-2.28	2.28
	Londono (2005)	3.61	3.61
	Fattah (1997)	2.09	2.39

The absolute mean error were plotted against the reduced pressure in Fig. 2e. Each line represents a different model combination. It is observed that Fattah (1997) model has a trend in increasing the error with the increase of reduced pressure, while the other models has maximum error with reduced pressure near to 4 and trend to reduce de error with the increase of reduced pressure. This trend difference could be explained due to a linear model adopted by Fattah (1997) and a non-linear model adopted by other authors. Londono et al (2005) had shown that linear models does not represents precisely the critical properties variations and a quadratic model like the one used in his work and by other authors is recommended.

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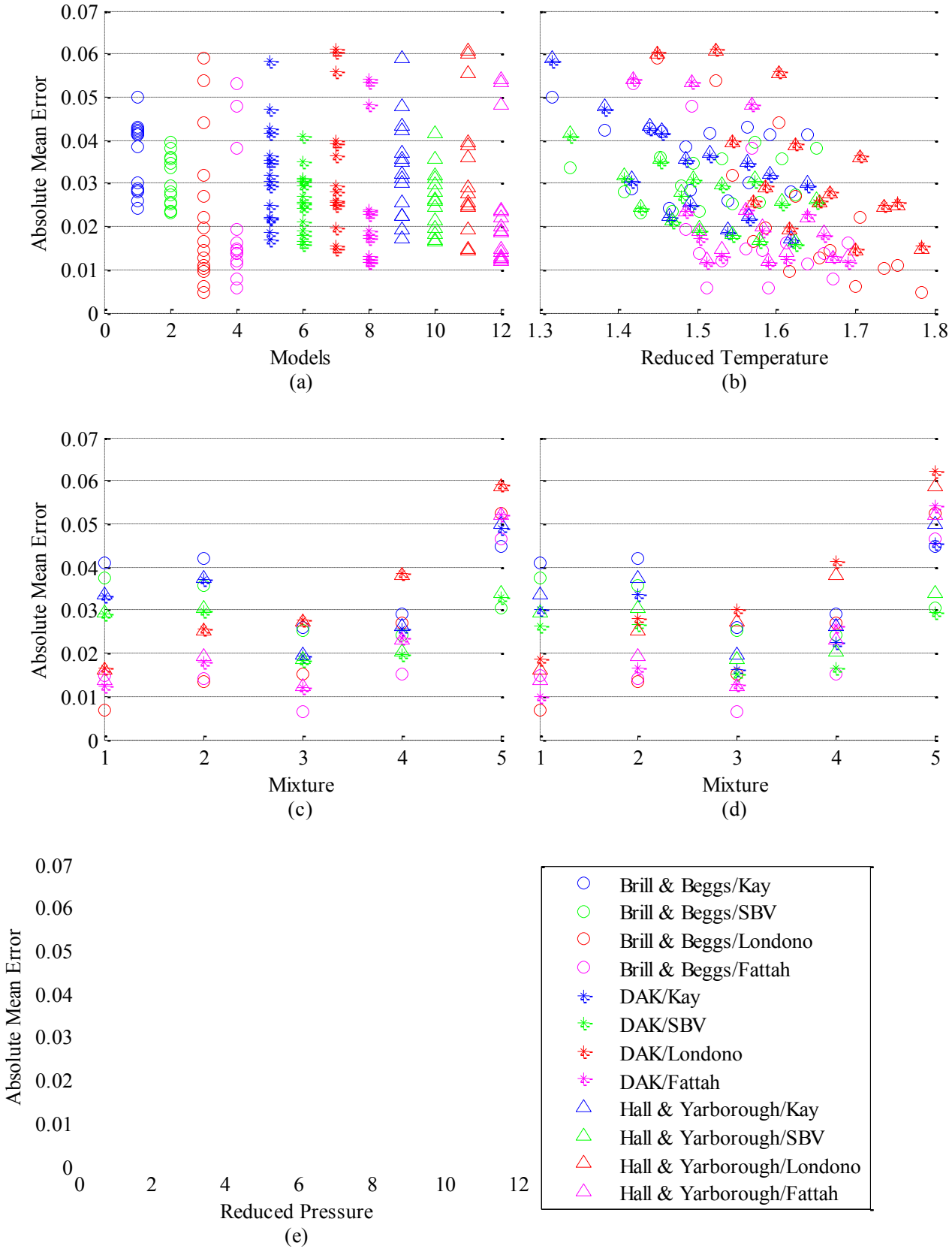

Figure 2. (a) Dispersion of AME (absolute mean error) of isotherms; (b) Tendency of AME of isotherms in function of reduced temperature; (c) AME of each mixture with original coefficients; (d) AME of each mixture with modified coefficients by Londono et al (2005); (e) Tendency of AME of isobaric in function of reduced pressure.

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3.1.4 Discussion

Graphical comparison between the results generated by the models and results of Standing & Katz (1941) have shown that the models has good agreement in the evaluated range. A quantitative comparison have shown that Dranchuk & Abou-Kassem (1975) and Hall & Yarborough (1973) models does not present significant difference when compared, and presented lower error than Brill & Beggs (1974) model.

Quantitative comparison using experimental data from Satter (1963) presented different results than expected. The Brill & Beggs (1974) model combined with Fattah (1997) model of critical properties presented the lowest absolute mean error from all tested evaluated. The combination of Dranchuk & Abou-Kassem (1975) and Londono et al (2005) models were obtained from the largest dataset compared to other models, so it was expected that this combination presents the best performance. From the comparisons performed from Dranchuk & Abou-Kassem (1975) using Satter (1963) data, it can be observed a divergence between these results and that from quantitative analysis using Standing & Katz (1941) data.

The divergences found in these comparisons needs a deeper analysis. Data are from distinct and independent sources. Standing & Katz (1941) abacus is considered the main reference in estimation of Z-factor and are obtained considering hydrocarbons with no contaminants. Dranchuk & Abou-Kassem (1975) model was tested for several dataset with an absolute mean error range from 0.3% to 61.9% depending on the presence of contaminants and the range. Londono et al (2005) recalculated optimized coefficients for Dranchuk & Abou-Kassem (1975) model and obtained absolute mean error of 3.06% for approximately 6000 points, including pure substances and mixtures. Also Londono's et al (2005) model obtained absolute mean error of 3.6% comparing with Satter (1963) data that has 105 mixture points of two hydrocarbons with a contaminant in five different concentrations. Therefore, it is observed that the error obtained in the model is in agreement with Dranchuk & Abou-Kassem (1975), however higher than found by Londono et al (2005). This divergence must be due to the specificity of the data set used (Satter, 1963), which has 1/60 times less points than the dataset uses by Londono et al (2005). Another fact that may have contributed to this discrepancy is the presence of contaminants in the data set used in this work (Satter, 1963) and the absence of contaminants in the data set used by Londono et al (2005).

Fattah (1995) found that the model of Brill & Beggs (1974) has a smaller range of applicability than the other models in this work, which is in agreement with the range used to perform the results presented in Tab. 6. In the evaluation with experimental data from Satter (1963), the model was used within the range suggested by Fattah (1995), which explains the good performance observed. Thus, the particular data set resulted in better performance of the model Brill & Beggs (1974).

However, the analysis is inconclusive for choosing a more generic model with less computational time and less error. The pseudo-reduced coordinate model developed by Fattah (1997) has shown better performance in the region tested, but error tends to increase with increasing of reduced pressure once Londono et al (2005) had already found that linear models do not represent properly the critical coordinates. Thus, it would be necessary to use a large data set to evaluate the performance and power of these models and name them as generic. This was accomplished by Londono et al (2005) for the Dranchuk & Abou-Kassem (1975) model, however, they did not test the model of Brill & Beggs (1974).

Considering that the aim of this work is the choice of a model for implementation in the software simulation that is being developed by the authors, it was decided to let the user choose between two options. The first option is the combination of Dranchuk & Abou-Kassem (1975) model with coefficients modified by Londono et al (2005) and its pseudo-critical coordinate model calculation because of its greater reliability due to the amount and diversity of experimental data used by the authors. Furthermore, the error obtained for this combination was 3.6%. The second option is the combination of Brill & Beggs (1974) Z-factor model and the pseudo-critical model proposed by Fattah (1997) due to higher speed of calculation and have obtained the best result of 1.9%, in relation to the Satter (1963) data. This second option is faster, but with higher risk and lower coverage. From the point of view of data input by the user, the models of Fattah (1997) and Londono et al (2005) is simpler, and the specific gravity can be measured or calculated if the molar fraction of each component is known.

3.2 Viscosity

The absolute mean error of each combination with the samples is presented in Tab. 10.

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Table 10. Absolute mean error [%] of each combination for each sample.

Combination	Sample				Mean [%]
	1	2	3	4	
1	6.4	4.1	8.6	7.3	6.6
2	8.5	5.9	9.3	12.5	9.1
3	6.7	4.7	8.7	7.9	7.0
4	6.2	4.6	6.9	6.8	6.1
5	8.2	6.3	7.5	12.1	8.5
6	6.4	5.1	7.0	7.3	6.5
7	1.3	1.7	2.4	2.5	2.0
8	1.0	2.5	2.4	2.3	2.1

The models proposed by Standing (1977) and Dempsey (1965) had similar performance, with a slight advantage to Standing (1977). The critical coordinate model proposed by Londono et al (2005) had the worst performance when associated with viscosity models of Standing (1977) and Dempsey (1965). The model of Lee et al (1966) associated with the Z-factor models proposed obtained the best results, and the Z-factor and pseudo-critical models had little influence on the result of this viscosity model. The absolute mean error obtained for the Lee et al (1966) model is smaller than the error reported by the author and smaller than the error found by Londono et al (2005).

As the findings of this study coincide with the trend reported in the literature, it was decided to choose the viscosity model of Lee et al (1966) to be implemented in the software simulator. Additionally, the input to this model is the density, temperature, pressure and molar mass, and if the density is not known, it can be calculated from the general gas law using one of the Z-factor models tested in this work.

3.3 Conclusions

This work evaluated different models to determine the Z-factor and the viscosity aiming to find a method that is better suited in a transient flow simulator. These objectives were partially achieved. Comparisons of the results obtained from the Z-factor and pseudo-critical models with experimental results demonstrated divergences. Thus, depending on the fluid composition one method presents advantages in relation to others. Therefore, the user will be able to choose one of two options, one is the best result founded in this work and another is the most reliable result in literature. The first option is explicit, so, it performs better than the other, which is implicit. Both models have same inputs that match with those that user have available. The Lee et al (1966) viscosity model was chosen because had the best performance with both options of Z-factor model.

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