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EMPIRICAL CORRELATION ANALYSIS APPLIED TO SOUND SPEED OF CRUDE OILS

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Abstract. *Performing measurements on physicochemical properties of crude oil has proven to be a hard task, since petroleum is composed by a complex mixture of hydrocarbons, besides the possibility of property variation between oils even from the same well. Therefore, the search for methods to simplify measurements and calculations of crude oils properties needs to be studied, for example sound speed. In this context, this paper uses a high accurate instrument to analyze both density and sound speed. However, due to intrinsic limitations of employing this technology in the field, the use of empirical correlations can be useful to evaluate sound speed in a wide range of pressure and temperature. By calculating the API gravity of the oil, using experimental density data, it is possible to evaluate the use of empirical correlations to estimate the sound speed of crude oils when comparing the calculated values to measured values. Results shows that sound speed can be predicted with a maximum relative deviation of 0.2% in a temperature range between 20ºC and 50ºC at the local pressure of 0.1 MPa. Additionally, design of experiments analysis presents minimal interaction between temperature and API, resulting in similar sound speed behavior between oil samples.*

Keywords: *Crude oil, Petroleum, Sound speed, Empirical correlation, Design of experiments.*

1. INTRODUCTION

Knowledge of thermodynamic properties is of great importance to understand the behavior of a fluid and, therefore, is indispensable in the petroleum industry when it comes to production process. However, crude oil is a complex mixture of hydrocarbons, generally in a liquid state, that can also include, in lesser quantity, other components like sulfur, oxygen, nitrogen, metals and other elements. Such wide variation in composition can alter properties and refining behavior of the oil, these variations are not only from a reservoir to another but can also be depth dependent within the same well (Speight, 2015).

On the other hand, speed of sound is a thermodynamic property which may serve as an indicator associated to related properties, providing useful information about the nature of the fluid. In petroleum fluids it is shown that acoustic measurements data can be used to determine the bubble point of the fluid when performing measurements at different pressures (Wang, 1989; Ball et. al, 2001). For heavy oils it is also shown that at low temperatures sound speed can be used to determine the start of the glass phase or the quasi-solid state, where the viscosity rapidly increases alongside with an exponential increase of the sound velocity of the fluid (Han et. al, 2008). On the field side, sound speed can be used as a method for diagnosis of ultrasonic flow meters, since it is a sub-product of the measurement process, being the flow velocity the main product (Franco et. al, 2019).

It is possible to estimate speed of sound using equations of state (EOS), as shown from various literatures sources about petroleum fluids (Riazi and Hameeda, 2014; Berryman, 1992; Ye et. al, 1992). However, when it comes to crude oil, the knowledge a priori of other properties of the oil is needed, such as molecular weight, viscosity, heat capacitance and thermal expansivity, and sometimes it turns out to be a difficult task to accurately measure these properties beforehand. Additionally, some simple methods applied to estimate those properties in light oil may not be appropriate to be used in heavy oils (Batzle et.al, 2006). Therefore, empirical correlations may be elaborated to determine the speed of sound for crude oils. Batzle and Wang (1992) propose a equation for sound speed prediction as a function of temperature, pressure and density. The great advantage of the said correlations is to turn possible to correlate the sound speed with the API gravity of the oil, which is one of the most known way to define a petroleum fluid in the industry.

This work study sound speed of crude oils using experimental readings from a high accuracy densimeter and sound speed analyzer. Readings are compared with an empirical correlation developed by Batzle and Wang (1992) and to a proposed linear regression analysis of the oil samples. Furthermore, design of experiments (DOE) approach is used in order to investigate the effect of API gravity and temperature on sound speed behavior.

2. METHODOLOGY

In this study, three samples of crude oil from Brazilian coast fields are analyzed, identified as A, B and C. Mixing and sample preparation were executed according to ASTM D5854 (2019**)**, pre characterization process followed the description of Sad et al. (2019). The density and sound speed measurements were performed using an high accuracy density and sound speed meter, model Anton Paar DSA 5000M. This instrument is able to simultaneously measure density and sound speed with high accuracy. The equipment is also able to operate in a wide range of temperature, from 0 ºC to 100 ºC, and its variation is controlled with a deviation of 0.005 ºC. For density and sound speed measurements, the instrument is able to operate from 0 to 3 g/cm³ and 1000 to 2000 m/s, respectively.

For this work, the instrument operated with subsequent measurements from 20 to 50 ºC, with a step of 2 ºC, resulting in 16 datasets to analyze for each sample. Since the equipment does not control the pressure, it is kept at the local environment pressure of approximately 0.1 MPa. The experiment is then performed a second time, under the same conditions, in order to obtain data for a statistical analysis.

2.1 Density x API Gravity

For density measurements, the analyzer utilizes the U-shaped oscillating tube method and possess a system for the electronic excitation. This method of density determination is in compliance with ASTM D5002 (2019), ASTM D1250 (2019) and ISO 12185 (1996**)**. The method consists in measuring the oscillation of the tube, which changes with temperature and density of the filled sample. By monitoring the pattern of oscillation, the density can be measured after mathematical conversions. Viscosity related errors is corrected by measuring the damping of the tube's oscillation. Measurement present repeatability of 0.001 kg/m³.

With the density data acquired, the API gravity of the oil can be determined. The API gravity is an important scale developed by the American Petroleum Institute to classify crude oil and petroleum liquids as light, medium or heavy, which is inversely proportional to density (Riazi, 2005). API gravity is defined as:

$$API = \frac{(141.5)}{\rho} - 131.5 \tag{1}$$

Where ρ is the dimensionless specific gravity and its defined as the ratio between the density of one substance to the density of a reference substance, in the case of API gravity, the reference is pure water at 288.7 K (15.5 ºC).

In Brazil, the "Agência Nacional de Petróleo, Gás Natural e Biocombustíveis" (ANP) is the official regulatory agency for laws and classifications for petroleum fluids. Ordinance ANP No. 9 (2000) is used as reference for the API classification. The ANP classification ranges from 10 to 22 API degrees for heavy oil, 22 to 31 API degrees for medium oil and values greater than 31 API degree are classified as light oil.

2.2 Sound Speed

The speed of sound is measured by DSA 5000M concomitant to the filled sample used to measure the density. The method consists in measuring the transit time by a sound wave, emitted by a transmitter inside the measuring cell, and monitoring the signal of the received sound wave. Considering the precise knowledge of distance between the receiver and transmitter, sound speed can be calculated, taking into consideration the correction factors associated to the electronic components and signal processor. Since sound speed presents a high dependence with temperature, the instrument also controls the temperature precisely, applying the same method used to measure density.

This article compares experimental data to the empirical correlation for sound speed of petroleum developed by Batzle and Wang (1992). Then, it is proposed a linear regression obtained from sound speed measurements of oil samples from Brazilian coast. The correlation proposed by Batzle and Wang (1992) was obtained after analyzing the data results of nine different types of crude oils in a wide range of API gravity. It was observed that sound speed possesses a relation of linearity for both temperature and pressure, the R-squared values were higher than 0.98 for the majority of the oils. Therefore, the authors developed a correlation through linear regression that correlates oil density, temperature and pressure to obtain the sound speed. The empirical correlation is defined, in terms of API gravity, as:

$$V = (15450)(77.1 + API)^{-1/2} - (3.7)T + (4.64)P + (0.0115)(0.36API^{1/2} - 1)TP \tag{2}$$

Where V [m/s] is the sound speed, T [ºC] the temperature and P [psi] the fluid pressure, which for this work is the local pressure.

It is observed that sound speed decreases with increasing temperature, and increases with pressure. Since the instrument does not control pressure, this effect is not observed in this paper, although it is known that pressure affects sound speed. Recently, Loranger (2018) studied pressure effect in sound speed and observed that it takes a significant change in the pressure value to change the sound speed, a change of 1 MPa in pressure would result in an increase of 4 m/s in sound speed. However, temperature analysis shows that the speed of sound changes at higher rates with the change of temperature, the reason may lie in the fact that the inter-atomic distance increases with temperature because of thermal expansion which in turn decreases the velocity (George et. al, 2013).

2.3 Design of experiments

For any type of experiment, the related influential variables will have an independent effect on the final response. However, variables in an experiment may also interact with each other, producing different types of effects on the response of the experiment. As stated by Montgomery (2014), varying all variables at the same time in order to optimize an experiment will yield better results in understanding how the response works instead of fixing a variable and optimizing another. This method of analysis, called design of experiments, is a statistical approach to understand the effects of the involved parameters and how they interact, identifying the significance of the controlled variables of the experiment and if they are statistically relevant for the model.

In the present work, understanding how API (density) and temperature affects sound speed is of interest. Furthermore, analysis of how these variables interact with each other, and its consequences on the linear regression model, is also studied. Following that, a factorial design of two levels is implemented.

Factorial designs of two levels can be represented as 2^k experiment, where k represents the number of factors involved. For this study, the factors are API and temperature.

Table 1. Matrix of a 2^2 Factorial design

Run	API	Temperature
1	-	-
2	+	-
3	-	+
4	+	+

The replicate of the experiment is used for Pareto chart analysis and ANOVA, where the significance of the variables is displayed by means of p-value. Therefore, a confidence level of 95% is used, which means that variables, and interactions, with p-values greater than 0.05 are not significant for the model.

3. RESULTS AND DISCUSSION

3.1 API Gravity

The acquired experimental density data is used to estimate API gravity of the oil samples and its value at the reference temperature through conversion by linear regression. This conversion is possible since the density data shows a high R-squared value of 0.99. Table 2 shows the results for the API gravity calculation and the density measurement result at 20 ºC.

Table 2. Experimental results for the API gravity and density at 20 ºC of the samples.

Sample code	API Gravity (º)	Density (kg/m³)	ANP Classification
A	24.7	901.1	Medium oil
B	25.5	897.5	Medium oil
C	18.4	939.7	Heavy oil

Following Ordinance ANP No. 9 (2000), the samples tested are classified as two medium oils (A and B) and a heavy oil (C).

3.2 Sound speed measurement

Speed of sound readings present linear correlation with temperature variation, considering all the data points acquired. Results present R-squared values higher than 0.99. Figure 1 shows the readings for sound speed measurement, as a function of temperature at pressure of 0.1 MPa. Performing a linear regression for each sample, it is observed that the highest residual represents a deviation of 0.14% or 2.08 m/s when compared to the measured velocity, in oil C at 20 ºC.

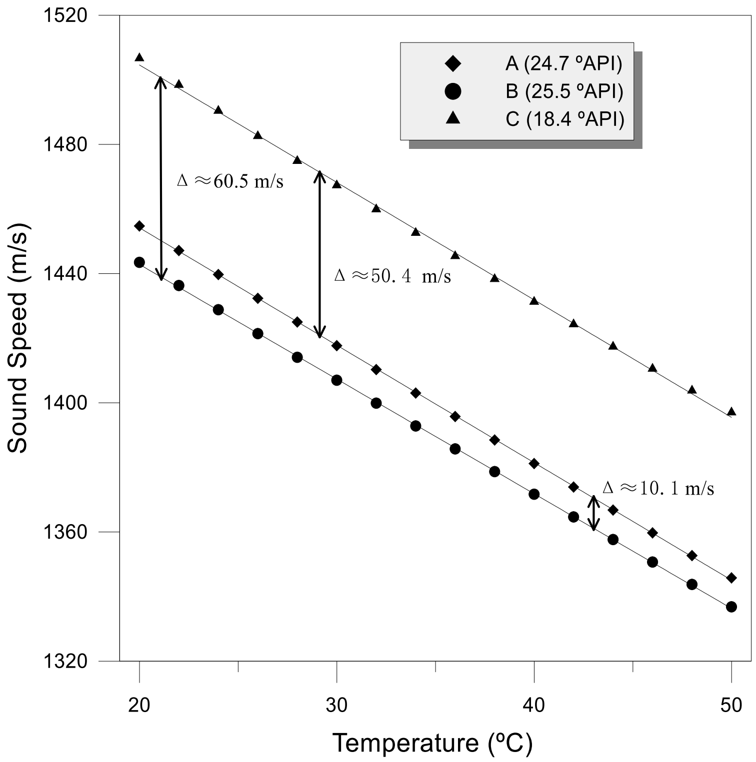


Figure 1: Experimental readings for sound speed measurement at a temperature range from 20 ºC to 50 ºC for oil samples A, B and C obtained by the DSA 5000M.

It is noticed from Fig.1 that the speed of sound is related to the density of the sample, as observed in the sound speed measurements a higher density (or lower API) results in a higher sound speed. In other words, heavier oils present higher sound speeds than lighter oils. As can be seen by Fig.1, the sample oil C has the highest sound velocity, while oils A and B present lower sound velocities. In addition, the latter pair presents a small difference in API gravity when compared to oil C which is followed by a small difference in the sound velocity for both oils, as well.

Through graph analysis in combination to linear regression, its noted that the decrease in speed of sound is similar for all the three tested samples, speed of sound decreases by approximately 3.6 m/s in average for each 1 ºC increment in the oil sample. It is also noticed that the difference in sound speed between oils samples analyzed tends to be uniform through the temperature range. The values 60.5 m/s (between sample B and C), 50.4 m/s (between sample A and C) and 10.1 m/s (between samples A and B) are an average of the data points, with absolute deviation around 0.7 m/s and the relative deviation around 0.06%.

The linear regressions made for each oil result in the following slope of the curves: -3.64 for oil C, -3.64 for oil A and -3.56 for oil B. The slopes are very similar, although the difference of 2.2% when comparing the slope of oil B with the other oils. In addition, considering the range of temperature analyzed and the differences in Fig. 1, it is possible to say that the sound speed behavior present minimal, or even no change, with temperature variation, regardless the composition and origin of the crude oil.

Following that, a new empirical model can be developed to estimate sound speed in the tested API and temperature range for the Brazilian coast fields oils, using experimental data results from the tested samples. This can be done after verifying the linearity between API gravity and sound speed. The developed linear regression presents a coefficient of determination R^2 of 0.99. The highest residual represents a deviation of -0.14% or -2.04 m/s when compared to the measured sound speed, in oil A. The slope of the curve obtained by the regression is -8.6, which represents a decrease of 8.6 m/s per one unit of API gravity increase or, a decrease of 0.56% in the sound velocity per unit of API gravity increase.

Therefore, a new model is proposed using linear regression, with a confidence level of 95%, resulting in:

$$V = (0.008)(API)T - (8.54)API - (3.78)T + (1734.6) \tag{3}$$

The proposed equation estimates sound speed utilizing only API gravity, which uses density data, and temperature, in ºC, as input parameters.

3.3 Comparison with empirical correlations

Due to the high linearity between sound speed and temperature, linear regression correlations can be used as a method of estimation for sound speed. Using the empirical correlation developed by Batzle and Wang (1992), who analyzed the behavior of the sound speed with temperature and pressure variation, and the proposed Eq. (3), it is possible to evaluate the speed of sound estimation by empirical methods. Figure 2 shows the results of the estimations, in the y-axis the measurement value is displayed, while in the x-axis the empirical correlation values are noted. Therefore, drawing a 45º line from the origin we can evaluate the proximity of the data points obtained with the measurement of the crude oil by the DSA 5000M.

In graph A, from Fig. 2, a dashed line is shown, representing an error of 0.5%. So, values between the 45º line and the dashed line means an error less than 0.5% when compared to measured values. Table 3 shows the magnitude of the deviation observed by the comparison with the empirical correlations. Relative deviation is calculated as:

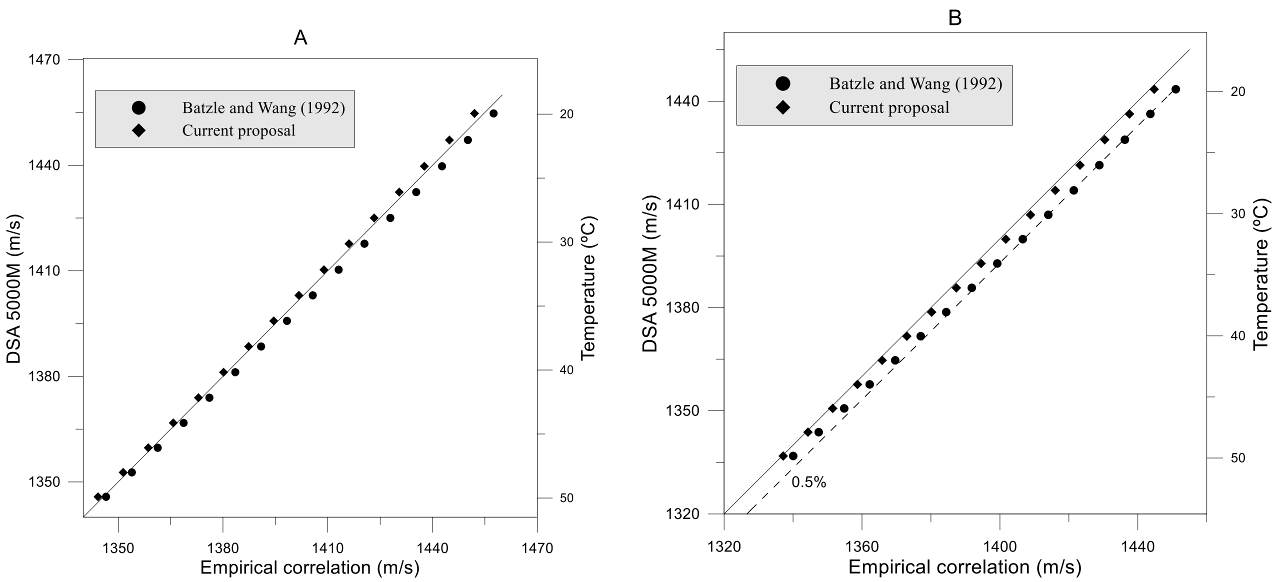
$$Deviation = \frac{V_m - V_e}{V_m} \times 100 \qquad (4)$$

Where V_m is the measured sound speed and V_e the estimated sound speed by empirical correlation models.

When analyzing the results from Eq. (1), oil B presents the largest deviation out of the three oils samples, while the other oils had maximum errors of 0.21% (oil A) and 0.2% (oil C). It is also noticed that the current proposal of empirical correlation, derived from the tested oil samples from Brazilian coast, presents a better estimation of sound speed under the measurement range, a maximum deviation of -0.19% is observed. In addition, since two of the three samples used to develop Eq. (3) are medium oils, the largest deviation observed is from the heavy oil, which is still a satisfactory result.

Table 3. Maximum deviation observed for each oil by comparing the measurement from the DSA 5000M with the empirical correlation developed by Batzle and Wang and the current proposal.

Sample code	Maximum deviation			
	Batzle and Wang (1992)		Current proposal	
	(%)	(m/s)	(%)	(m/s)
A	0.21	3.0	-0.19	-2.7
B	0.52	7.6	0.14	2.0
C	0.20	2.9	-0.12	-1.8



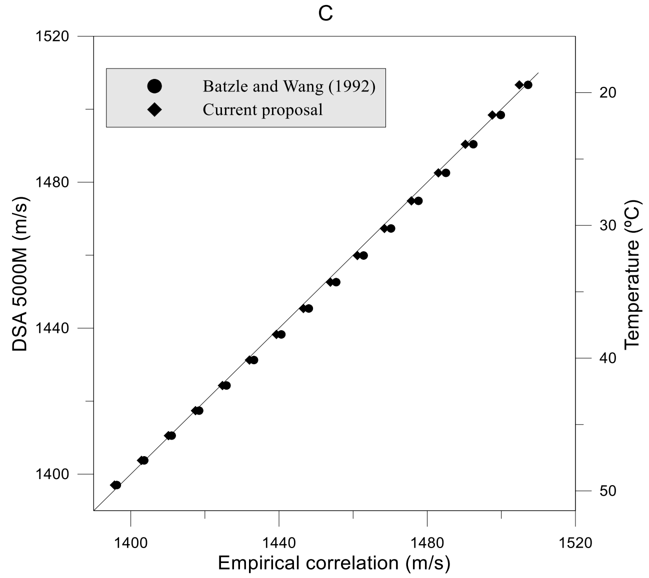


Figure 2: Comparison between measurement of sound speed by the DSA 5000M and the empirical correlations: current proposal and Batzle and Wang (1992) applied to oil samples A, B and C.

To better understand the deviation behavior, the graphs in Fig. 3 shows the correlation residuals. It is noted that with the increase of API gravity the error tends to increase, which results in the overestimation of sound speed by the correlations for lighter oils. This is probably due to the decrease in speed of sound in light oils, which tends to have more dissolved gases in its composition and smaller hydrocarbon chains.

Temperature also present an effect in the comparison, with the increment of temperature it is observed that the correlation tends to underestimate the results, proceeding to exhibit a linear behavior. This behavior can be related to the fact that the increase in temperature leads to the loss of light compounds in lighter oils, which can modify sound speed behavior.

The decrease in API gravity results in the proximity with the measurement result. Additionally, the residual curve tends to be parabolic, which is the resulting format of a residual graph from a linear regression.

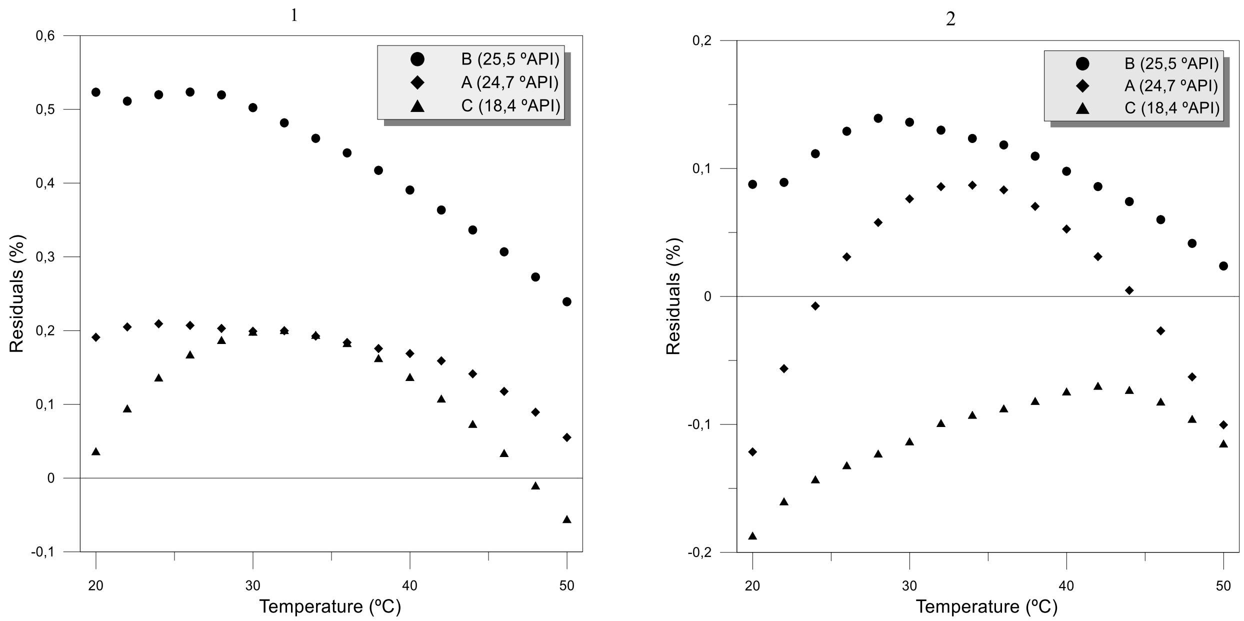


Figure 3: Residuals form the comparison between experimental measurement and the empirical correlations: (1) Batzle and Wang (1992) and (2) current proposal, applied to oil samples A, B and C.

In graph 1, from Fig.3, it is also observed that the crude oil B exhibits a higher deviation when compared to the others. This is probably related to a higher concentration of paraffin components (alkanes-saturated), common occurrence in lighter oils (Lyons and Plisga, 2004), and other related elements that can probably alter the values of sound speed, since lighter components will tend to have a lower speed of sound value due to the lower density. Even so, the correlation still predicts the property under a deviation of 0.52% in the analyzed temperature range.

For better evaluation of the developed model performance in sound speed prediction, it is made a comparison between the proposed correlation using Eq. (3) and the equation proposed by Batzle and Wang (1992), through Eq. (1), for sound speed of crude oil at pressure of 1 MPa. For this analysis, the data obtained by Batzle and Wang (1992) and Loranger (2018) are used as simulation parameters. Table 4 presents the comparison results.

The new developed model, as Eq. (3), is a better predictor for heavy and medium oils, with the highest deviation being 1.2%, for a 7 ºAPI oil at 39 ºC, against an error of 1.9% using Eq. (1). However, when comparing results with light oil measurements, the developed model starts to highly deviate, with an error of 5.4% for a 57 ºAPI oil at 23 ºC. This can be related to the lack of light oil measurement data and also suggests a different type of sound speed behavior in lighter oils due to a higher presence of lower density components.

Table 4. Comparison between empirical correlation models and measured data from literature.

Measured data from Batzle and Wang (1992) and Loranger (2018)			Deviation (%)	
API (º)	Temperature (ºC)	Sound Speed (m/s)	Batzle and Wang (1992)	Current Proposal
7	23	1583	1,1	0,4
7	39	1511	1,9	1,0
12	23	1528	1,5	1,3
12	40	1465	1,6	1,3
28	15	1434	1,2	0,6
34	25	1363	0,8	-0,5
34	41	1293	1,6	0,5
57	23	1237	1,0	-5,4
57	45	1157	0,9	-5,2

3.4 Factorial analysis and ANOVA

For investigation on how the variables, and its interaction affects sound speed, the 2^2 factorial design is performed and Tab. 5 presents the matrix of experiments with the values for the levels after acquiring measurement data, the second column of sound speed data represents the replicate results for this analysis. Therefore, a total of 8 runs is performed for factorial analysis and ANOVA.

Table 5. Matrix of experiments for the 2^2 factorial design

Temperature (ºC)	API (º)	Test 1 Sound Speed (m/s)	Test 2 Sound Speed (m/s)
20	18.4	1507	1508
50	18.4	1396	1399
20	25.5	1443	1444
50	25.5	1336	1338

Table 6 presents the results for ANOVA and Fig. 4a presents the Pareto chart for standardized effects. All the calculations are performed using Minitab statistical software.

By analyzing Tab. 6 and Fig. 4.(a), it is noticed that temperature and API have significant effects on the results of sound speed, with p-values less than $\alpha = 0.05$, where α represents the significance level. On the other hand, the interaction between those parameters present p-value of 0.128, and can be considered not statistically significant.

Figure 4.(b) shows the behavior of variable interactions. The curves are approximately parallel with each other, presenting a difference of 2.7%, which represents the small interaction effect between the variables.

Further analysis on variable interaction shows that, opposite to variable individual effects, the interaction tends to increase the sound speed. From Fig.1, in Section 3.2, the measured data shows that the decrease in sound speed tends to be uniform for crude oils. Applying the DOE analysis combined with linear regression model shows that the low interaction between API and temperature results in an uniform tendency. That is, removing the interaction coefficient from the developed model, in Eq. (3), results in sound speed difference between oils becoming constant through the temperature range.

Table 6. Variable effects and ANOVA results for p-value.

Term	Effect	Coefficient	F-Value	P-Value
Temperature	-108.41	-54.2	15322	0
API	-61.9	-31	4999	0
Temperature x API	1.7	0.8	3.7	0.128

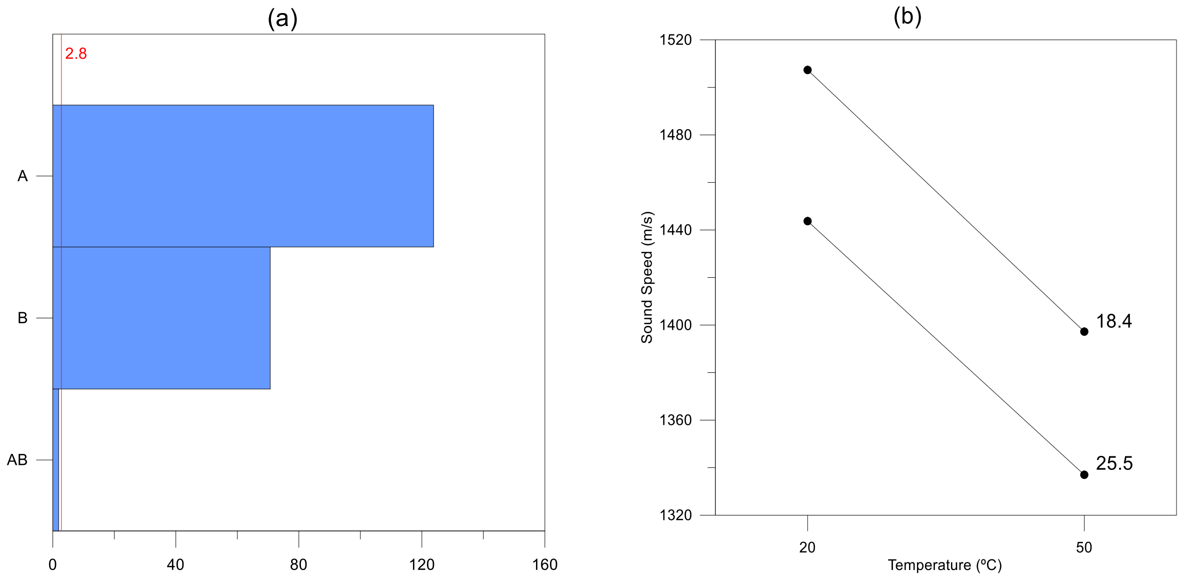


Figure 4: (a) Pareto chart for standardized effects and (b) two-factor interaction plot for sound speed.

4. CONCLUSIONS

Sound speed and density of crude oil decreases linearly with temperature, considering the temperature range of 20 ºC to 50 ºC used in this work. From the examined data, density or API gravity of an oil is a dominant factor in sound speed analysis, heavier oils will have a higher sound velocity, regardless the composition and origin of the crude.

The oils under test in this work had no noticeable phase transition and are kept at constant pressure, being a limiter for the obtained results. Therefore, considering the temperature range and pressure used in this study, the empirical correlation developed by Batzle and Wang (1992) proved to be a high accurate method of sound speed estimation for crude oils with deviations below the 0.5% mark for all samples tested. However, considering temperature and API range analyzed, the error obtained in the comparison presented a tendency to underestimate the temperature effect and overestimate the decrease in density or increase in API gravity.

On the other hand, due to the high linearity between sound speed, temperature and density experimentally observed, it is proposed a new correlation to better represent the speed of sound for the Brazilian coast fields oil samples. The linear regression proposed decreased sound speed deviation in the tested range, with the highest deviation being 0.19% when compared to experimental results.

Besides, since crude oil presents a volatile and complex composition, performing concomitant measurement of density and sound speed improves the quality of the results, as can be seen by the proposed empirical correlation model in this study. Therefore, although Eq. (1) is a generic equation to describe sound speed at different temperatures and pressures, the proposed empirical correlation presents better results for medium and heavy oils, due to the tested oils used to develop the correlation being in the same API range. Furthermore, comparison with literature values of sound speed shows that the application of empirical correlations for sound speed in crude oils should be used within a determined range, especially for oils with high API, where composition and behavior start to highly deviate from medium and heavy oils.

Using DOE analysis contributed to study the effect of interaction between variables and how it impacts the model. In present case, the interaction of API and temperature is minimal, or statistically negligible, which results in the fact that speed of sound presents a tendency to decrease in the same proportion, as observed by measured data and linear regression model coefficient analysis.

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