ON THE USE OF SOUND SPEED FOR EVALUATION OF THE PERFORMANCE OF LIQUID ULTRASONIC FLOW METER IN ZERO FLOW CONDITIONS

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Received: Sept 10, 2022
Revised: Sept 15, 2022
Accepted: Setp 18, 2022

ABSTRACT

At present, ultrasonic flow meters have become well known in custody transfer applications in the petroleum industry. Since facilities for calibration of these meters are costly and limited, methods for performance verification in zero flow conditions have been developed. However, for liquid measurement, a method of zero flow verification is not available yet. In this context, this study presents a new method for zero flow test in liquid ultrasonic flow meters, using ahighly accurate instrument as a reference for sound speed. The aim is to evaluate the performance, of a multipath liquid ultrasonic flow meter under different pressures and temperatures, by comparing the calculated sound speed with the result from the reference instrument. Additionally, transit time measurement is also verified in order to account for systematic errors. The experiments were conducted with two test fluids: water and mineral oil, with a maximum deviation of 0.25%during comparison. On the other hand, performing a transit time analysis indicates the presence of systematic errors, meaning that transit times can be adjusted in order to improve the performance of the flow meter. Furthermore, a factorial design is performed to investigate the effect of pressure and temperature, indicating a minimal pressure effect on sound speed when compared to the temperature effect.

Keywords: sound speed, ultrasonic flow meter, flow measurement, design of experiments, factorial design

INTRODUCTION

In the last decades, liquid ultrasonic flow meters (LUFM) have become more and more in process industry applications. As practical application of LUFM, one can exemplify Petrochemical applications, in which fiscal flow metering are required to report to regulatory agencies. Other important and strict application of LUFM is in custody transfer, when fluids are exchanged between different parties. In this case, high precision flow measurement is required, since payment is done through the amount of transferred fluid (Dupuis, 2014). Furthermore, LUFM are also used in pipeline leakage detection, where besides the main characteristic of high precision, the flow meter uses other available parameters to perform diagnosis in order to identify disruptions. Such conditions include stratification, valve obstructions and zero flow condition measurement (Soddy, 2017). The increase of application of ultrasonic flow meters reflects the advances in microprocessor technology, transducers, electronics and data analysis, resulting in high accurate flow meters with large measurement ranges, with an inherent non-intrusive design (Kalivoda, 2012).

On the other hand, since LUFM are applied in fiscal metering operations, they need to be periodically calibrated. In Brazil, flow measurement of hydrocarbon fluids is governed by "Agência Nacional do Petróleo" (ANP) in collaboration with the National Institute of Metrology (INMETRO). This regulation defines operation conditions, calibration frequency, uncertainty class and limits of errors (ANP/INMETRO, 2013).

However, most ultrasonic flow meters are calibrated in certificated laboratories, where generally the calibration conditions differ from operation conditions. Even if flow rate, temperature and pressure are the same, it is very rare to perform calibration with the same fluid. In previous work, Hogendoorn et al. (2011) presented parameters that affect flow metering and, hence, LUFM performance. According to the authors, the most influential parameters are: changes in temperature and pressure, pipeline configuration and external factors, such as multiphase flow and non-newtonian fluids. On the other hand, as shown in the work of Hogendoorn et al. (2011), one of the main characteristics of LUFM is the long time stable performance over years without calibration.

At present, calibration facilities for ultrasonic flow meters (UFM) are costly and limited. Therefore, methods for performance evaluation have been developed, such as the dry calibration procedure for zero-flow verification. However, up to now it is only used in flare UFM, being well established and in agreement with the Brazilian regulatory agency as well as American Gas Association (AGA, 2002). Since sound speed is a thermodynamic property, it can be predicted through equations of state, once fluid composition and thermodynamic state are well known. Thus, the dry calibration method consists in monitoring the sound speed result in a UFM operating in zero flow conditions, in comparison to an equation of state result (De Boer and Lansing, 1997; Franco et al., 2019).

In this context, this study aims to develop a new methodology for evaluation of liquid ultrasonic flow meters in zero- flow conditions, similarly to the dry calibration procedure for flare gas UFM. Therefore, a 5-path ultrasonic flow meter is experimentally examined at different temperatures and pressures, with two test fluids: tap water and mineral oil. For sound speed comparison, results are compared with readings from a highly accurate reference sound speed analyser. Finally, design of experiments (DOE) approach is performed in order to investigate pressure and temperature effect, as well as their contribution, to the sound speed result.

METHODOLOGY

Zero flow condition

The principle of an ultrasonic flow meter is based on the transit time measurement, which is emitted and received by ultrasonic transducers, as illustrated in Fig. 1.

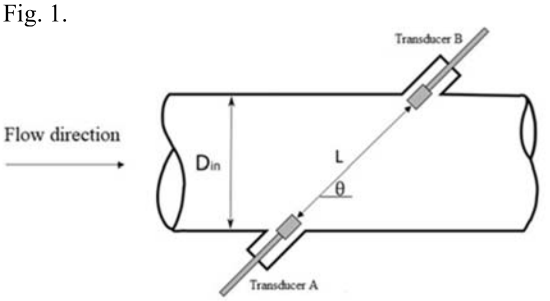

Figure 1. Basic arrangement of a single-path ultrasonic flow meter.

The expressions that correlates the geometric parameters (D and θ) with transit time measurement, results in two equations and two unknown variables linear system. In this case, these variables are referred as flow velocity V [m/s], given by Eq. (1), and sound speed c [m/s], given by Eq. (2).

$$V = \frac{D}{\sin(2\theta)}\left(\frac{t_{BA} - t_{AB}}{t_{BA}.t_{AB}}\right) \tag{1}$$

$$c = \frac{D}{2.\sin(\theta)}\left(\frac{t_{BA} + t_{AB}}{t_{BA}.t_{AB}}\right) \tag{2}$$

Where L [m] represents the acoustic path, D [m] is the pipeline diameter and θ [º] is the angle between acoustic path and flow direction.

The measured ultrasonic pulses travel times t_{AB} [s] and t_{BA} [s] are also denominated as downstream and upstream transit time, respectively. In normal operation, when there is a moving fluid flow in the pipe, the transit times t_{AB} and t_{BA} are different. The velocity of the ultrasonic pulse travelling downstream is accelerated by flow velocity. On the other hand, flow velocity decreases the upstream transit time. However, on a zero flow condition test, upstream and downstream travel times should be the same, since there is no fluid flow to affect the propagation of ultrasonic pulse. Following Eq. (1) and Eq. (2), flow velocity equals zero since transit times are equal, and sound speed can still be calculated as a function of geometrical parameters and transit time, even with zero flow.

As mentioned, sound speed is a thermodynamic property, hence only dependent on fluid condition and composition. Therefore, knowing the pressure and temperature, as well as the fluid composition, a comparison of sound speed results can be made. Besides the evaluation of thermodynamic state in the performance of sound speed measurement, it is also interesting to evaluate systematic errors in UFM. Transit times are composed of different time delays. For example, delay due to (a) processing, (b) acoustic effects, (c) corrections during calibration process and (d) cables and impedance (Lunde et al., 2003). Moreover, the identification of systematic errors improves traceability, which is a key factor in measurement accuracy, since measurement uncertainty consists of random and systematic errors (Tawackolian et al., 2013).

Test fluids and reference instrument

In this paper, two liquids are selected for tests with the 5-path ultrasonic flow meter: tap water and mineral oil. Both fluids are submitted to density and sound speed measurement, prior to the LUFM measurement, by a digital densimeter and sound speed analyser (Anton Paar DSA5000M) in order to obtain reference sound speed for comparison with the LUFM results. The instrument is able to measure both properties, density and sound speed, using the same filled sample. For density measurements, it uses an U-shaped oscillating tube method combined with a system for electronic excitation. By monitoring the pattern of oscillation, density can be measured after mathematical conversions. For sound speed measurement, the equipment uses the transit time principle, presenting an emitter and a receiver, to measure the transit time. Once the distance between transducers are precisely known, sound speed is calculated. The instrument is able to operate with a temperature range from 0 to 100 ºC, with an uncertainty of 0.005 ºC. However, only temperature can be controlled, consequently, reference values for sound speed comparison are kept at the local pressure of 0.1 MPa. For establishment of reference values in this study, the instrument operates with subsequent measurements from 20 to 50 ºC with a step of 2 ºC, resulting in 16 datasets for analysis.

The 5-path LUFM in this study is an operational flow meter for custody transfer of crude oils. Therefore, since mineral oil is a derived product from crude oil, it presents similar sound speed behaviour when compared to crude oil, as shown in previous work (Lima et al., 2020). Another advantage is related to characterization and traceability, properties that are easier to evaluate in a refined product, as mineral oil. On the other hand, crude oil is a complex mixture of hydrocarbons and other components, and its composition can vary even inside the same well (Speight, 2015). In a previous work, Lima et al. (2020) evaluated sound speed in crude oils, by comparing these results with previously characterized fluids. Results shows that mineral oil presents similar behavior of linearity with temperature as observed in crude oil.

Experimental description

The examined LUFM is composed of three main components, responsible for reading the signal from the transducers until calculating the results of flow velocity and sound speed. The steps for data conversion are as follows the UFS-V (sensor), responsible for fluid storage and contains the five pairs of transducers, sends the measurement to the UFC-V (converter), which converts transducers signals into transit time and other related signals. Finally, the data is sent to the UFP-V (processor), which is responsible for calculating flow velocity and sound speed.

However, considering the main objective of performing sound speed verification at different pressure and temperature, additional instruments are coupled to the experimental setup. These are represented in Fig. 2

For pressure and temperature control, a hydrostatic pump and a thermostatic bath are integrated in the measuring system, respectively. For this experiment, the pump operates from 0 to 10 bar, with steps of 5 bar, resulting in three levels. For the thermostatic bath, temperature range vary from 20 to 60 ºC with steps of 20 ºC, in order to also obtain three levels. However, due to intrinsic limitations, the bath is able to only operate with water and, consequently, temperature control is performed for water tests only.

An industrial computer (item 8 in Fig. (2)) is applied to acquire all data acquisition, which includes not only the LUFM but also a temperature sensor and pressure sensor. Data acquisition is done with 0.1 Hz. So, for each measuring point, a minimum of 60 readings (approximately 10 minutes) is defined. Basically, sound speed is considered as the mean.

Following that, the matrix of design of experiments for a three level and two factor (3^2) factorial design is describedin Tab. 1. result from the data sample for LUFM measurements

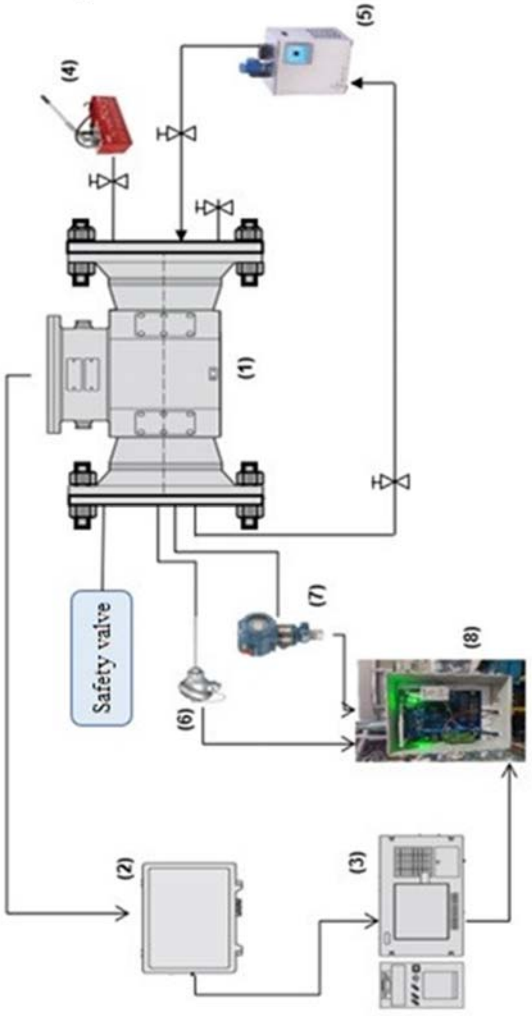

Figure 2: Experimental setup: (1) sensor, (2) converter, (3) processor, (4) hydrostatic pump, (5) thermostatic bath, (6) temperature transmitter, (7) pressure transmitter and (8) data acquisition device, 2Stools IC.

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This method consists in evaluating how the controllable factors, in this case pressure and temperature, affect a system response, in this case sound speed readings of a LUFM. Additionally, the use of analysis of variance, can describe statistical significance by means of p-value and Pareto chart (Montgomery and Runger, 2010). Therefore, the proposed experiment is performed a second time, under the specified conditions, in order to obtain replicates for statistical analysis.

Since temperature is not controlled by the thermostatic bath during mineral oil tests, data for temperature levels is collected at local temperature, which changes through the day.

Table 1: Matrix for a 3^2 factorial design.

Run	Pressure	Temperature
1	P1	T1
2	P1	T2
3	P1	T3
4	P2	T1
5	P2	T2
6	P2	T3
7	P3	T1
8	P3	T2
9	P3	T3

Since temperature is not controlled by the thermostatic bath during mineral oil tests, data for temperature levels is collected at local temperature, which changes through the day.

RESULTS AND DISCUSSION

Sound speed measurement

Since for this study the sound speed result is the average value from a period of ten minutes of data acquisition, the standard deviation of these readings is analyzed in order to assess meter repeatability. Sound speed readings present an average standard deviation of 0.3 m/s for water tests and 0.05 m/s for mineral oil tests. Basically, the LUFM presents better repeatability operating in mineral oil rather than water. However, when comparing measurement data with the sound speed analyzer, mineral oil has a higher sound speed deviation. The comparison at 1 bar is illustrated in Fig. (3) and Fig. (4), for water and mineral oil, respectively.

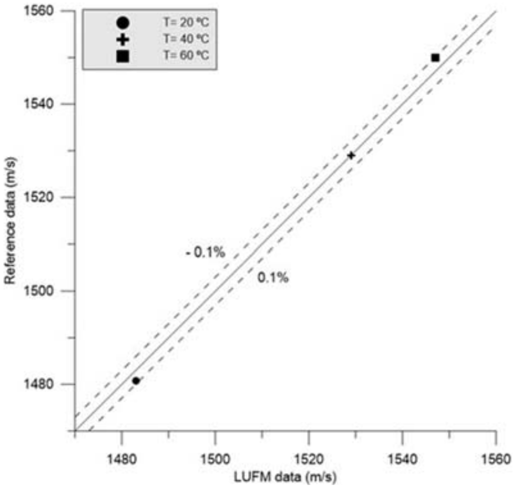

Figure 3: Comparison between LUFM and reference meter at 1 bar for water tests.

Results from Fig. (3) and Fig. (4) are illustrated alongside a y = x function, which represents a perfect correlation between LUFM and reference sound speed analyzer.

One can notice that, water presents higher agreement with the perfect correlation when compared to mineral oil. It is found that, for water, the measured deviation is within a narrow band of ± 0.1%, whereas mineral oil presents a highest deviation of 0.25% and thus a larger deviation band. This result can be related to fluid composition, since mineral oil is a derived product from petroleum, it is composed of a complex mixture of hydrocarbons and other products added during refinement process. Therefore, LUFM accuracy also depends on fluid composition.

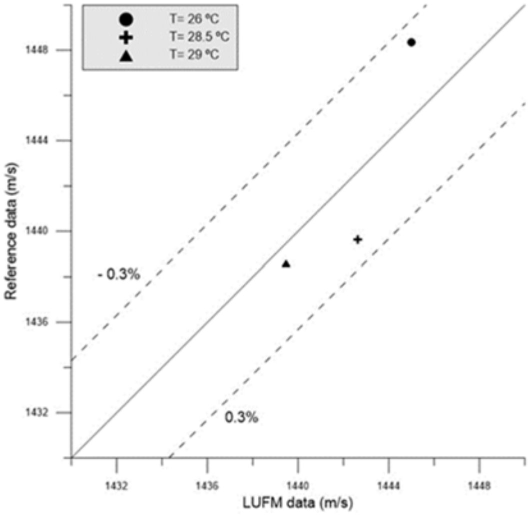

Figure 4: Comparison between LUFM and sound speed analyzer at 1 bar for mineral oil tests.

Later, pressure and temperature are evaluated at three different levels for both fluids. Results are presented in Fig. (5) and Fig. (6), for water and mineral oil, respectively. Notice that both pressure and temperature have influence on sound speed result. Moreover, similarly to temperature, the linearity between pressure and sound speed is high, with R-squared higher than 0.99. However, it is noted that pressure increase results in sound speed increase, whereas an increase in temperature results in the decrease of sound speed.

As can be seen in Fig. (5), there is a modification of pressure effect on sound speed measurement by UFM at the highest temperatures for water, where sound speed starts to show an almost uniform behavior with pressure change. At 60 ºC sound speed starts to slightly decrease. From 5 bar to 10 bar there is a decrease of 0.1 m/s, whereas at 20 ºC there is an increase of 2 m/s from the same interval. This interaction between temperature and pressure can be associated to the behavior of water sound speed in high temperatures, where it starts to deviate from the linearity present at lower temperatures.

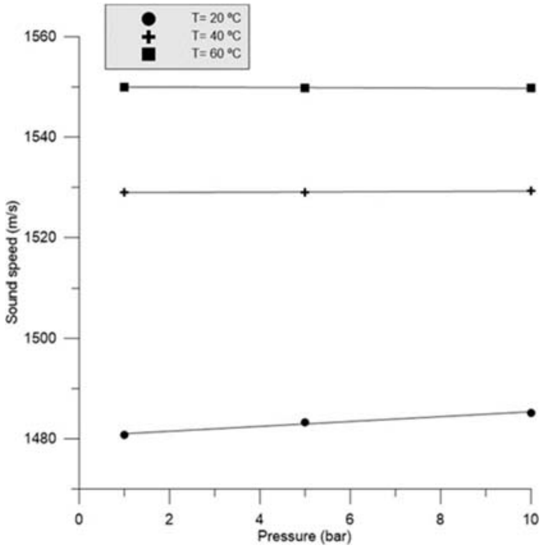

Figure 5: LUFM experimental readings for water at different pressure and temperature conditions.

As can be seen in Fig. (5), there is a modification of pressure effect on sound speed measurement by UFM at the highest temperatures for water, where sound speed starts to show an almost uniform behavior with pressure change. At 60 ºC sound speed starts to slightly decrease. From 5 bar to 10 bar there is a decrease of 0.1 m/s, whereas at 20 ºC there is an increase of 2 m/s from the same interval. This interaction between temperature and pressure can be associated to the behavior of water sound speed in high temperatures, where it starts to deviate from the linearity present at lower temperatures.

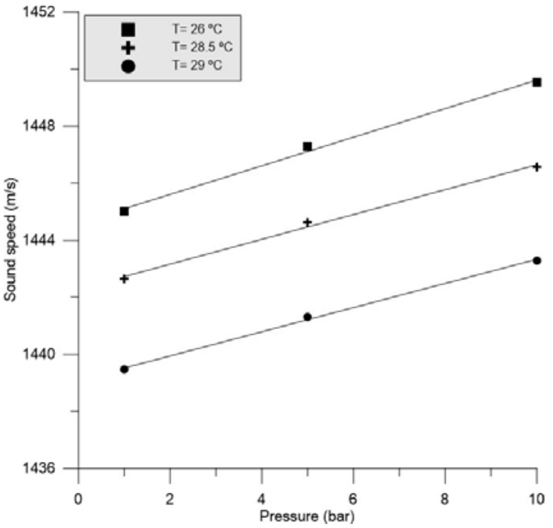

Figure 6: LUFM sound speed readings for mineral oil at different pressure and temperature conditions.

The measured transit time ($TT_{measured}$) is also evaluated and compared to an ideal transit time (TT_{ideal}), which is calculated by Eq. 2 using the measured sound speed and the known geometric parameters. The expression for the comparison is represented by Eq. 3 and the results are presented in Tab. 2 and Tab. 3, for mineral oil and water, respectively.

$$\mathrm{TT}_{\mathrm{difference}} = \frac{\mathrm{TT}_{\mathrm{measured}} - \mathrm{TT}_{\mathrm{ideal}}}{\mathrm{TT}_{\mathrm{ideal}}}.100 \qquad (3)$$

Table 2: Comparison between ideal and measured transit time for mineral oil readings in all LUFM channels.

	Channel 1	**Channel 2**	**Channel 3**	**Channel 4**	**Channel 5**
1 bar	-0.404	-0.017	-0.083	-0.014	-0.218
5 bar	-0.412	-0.022	-0.085	-0.016	-0.221
10 bar	-0.411	-0.023	-0.084	-0.015	-0.219
Mean	-0.409	-0.021	-0.084	-0.015	-0.219
Std. deviation	0.004	0.003	0.001	0.001	0.002

Table 3: Comparison between ideal and measured transit time for water readings in all LUFM channels.

	Channel 1	**Channel 2**	**Channel 3**	**Channel 4**	**Channel 5**
1 bar	-0.46	-0.07	-0.13	-0.07	-0.26
5 bar	-0.43	-0.05	-0.12	-0.05	-0.25
10 bar	-0.37	0.01	-0.05	0.02	-0.19
Mean	-0.43	-0.05	-0.11	-0.04	-0.24
Std. deviation	0.03	0.03	0.03	0.03	0.03

Table 2 presents comparison results for mineral oil tests in each pressure level. As mentioned, standard deviation for mineral oil readings are lower than water readings in Tab. 3. This fact can be related to transducer characteristics. Ultrasound signal is sensitive to propagation medium and, since the LUFM is applied for petroleum metering, repeatability is better for fluids with similar composition, in this case mineral oil.

Further analysis in transit time comparison indicates presence of systematic behavior. That is, each channel tends to present similar deviation, regardless of fluid composition. Channel 1 has the largest deviation, while channels 2 and 4 have the smallest. Therefore, since sound speed measurement for a multipath UFM is considered as the mean result from each channel, adjustments in channel 1 can improve the meter accuracy.

Sound speed measurement

Factorial analysis for water tests

To evaluate pressure and temperature effect on sound speed result, a 32 factorial design is performed with water readings. Results are presented in Fig. (7).

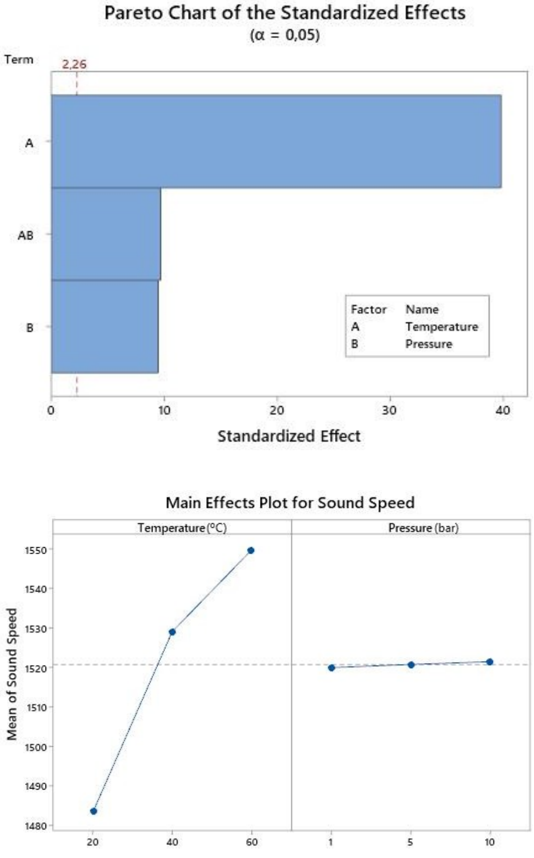

Figure 7: Factorial analysis results for water.

Performing an analysis on Pareto chart results in conjunction with main effects plot, it is found that temperature has a significantly higher effect on sound speed than pressure. Even so, pressure still is statistically significant to the model, since all parameters presented a p-value lower than 0.05, which represents a confidence interval of 95%. The main effects illustrated in Fig. (7) shows the change in sound speed curvature with temperature, which is noticed at the intermediate level of 40 ºC, indicating that sound speed increases at a slower rate than it increases at lower temperatures in case of UFM operating in water.

Factorial analysis for mineral oil tests

Since temperature is not controlled during mineral oil experiments, only two temperature levels are applied for analysis. Moreover, because it is a local temperature, the selected temperature interval is smaller than the one achieved for water. The 22 factorial design results for mineral oil are presented in Fig. (8).

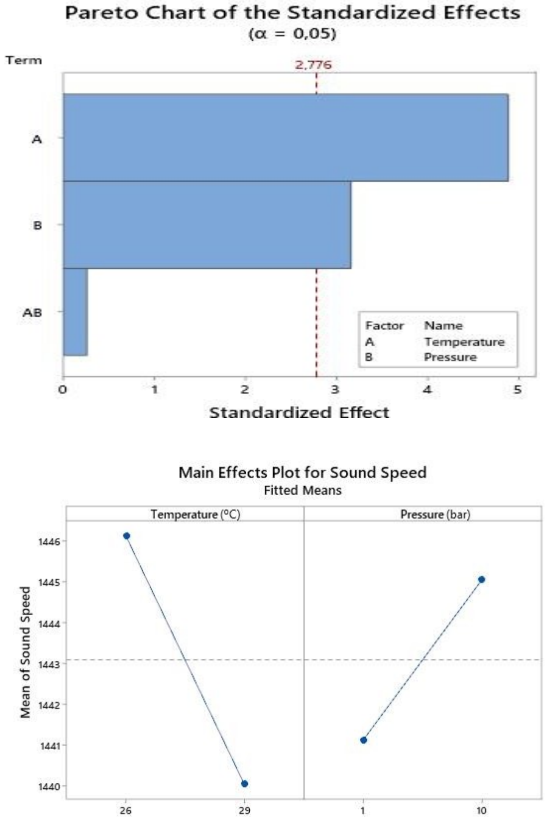

Figure 8: Factorial analysis results for mineral oil.

Similarly, to water analysis, temperature also presents higher effect on sound speed than pressure, even at a significantly lower temperature interval of 3 ºC. Moreover, temperature and pressure interaction, represented by AB, is not statistically significant and could be discarded during a linear regression model. This fact can also be assessed by verifying p-value result, which is 0.806 for AB and, therefore, higher than 0.05. Furthermore, by analyzing the main effects plot, differently from temperature, pressure increase tends to increase sound speed. On the other hand, temperature increase results in the decrease of sound speed.

CONCLUSIONS

This study presented an initial development of a new methodology to evaluate LUFM performance, by analyzing the sound speed measured by the flow meter and compare those results with a fluid characterization from a reference meter. The difficulty and inaccuracy in elaborating equations of state for different types of fluids can be avoided, since petroleum and its derived products can highly deviate in composition, establishing an equation of state becomes complex.

The investigated flow meter has shown a maximum deviation of sound speed of 0.25% when compared with reference. Furthermore, maximum deviation occurs with UFM operating in mineral oil. On the other hand, UFM shows better repeatability with mineral oil. Additionally, since mineral oil is a derived product, it is observed similar sound speed behavior of the UFM with the sound speed of crude oils. This indicates that, the dry calibration method using fluids with similar composition to petroleum is more precise in order to assess UFM accuracy. Therefore, even if the tests with water presented a narrower deviation band, shown in Fig. (3), it presents different sound speed behavior, as shown in the factorial analysis and standard deviation analysis.

Systematic errors can also be accounted along the experiment. By monitoring transit times measured in comparison with a reference value, deviations between channel readings were evaluated, indicating that adjustments can be made in order to improve self-channels accuracy. Moreover, the presence of systematic errors points to need of traceability in transit time readings, in order to monitor changes that can lead to meter inaccuracy.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Petrobras, “Agência Nacional do Petróleo, Gás Natural e Biocombustíveis” – ANP, FINEP and “ToSolve Engenharia e Tecnologia” for the financial support for this research.

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