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Experimental Characterization of Process Pressure Variations on The Accuracy and Performance of Liquid Ultrasonic Flow Meters

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***Abstract* — This paper investigated the influence of process pressure variations on the accuracy and performance of ultrasonic flow meters. Process measurement technology provides a tool for optimizing production processes and dosing operations. Accurate measurement is key and primary to profitability in the business of supply and purchase of liquids like petroleum, gas and chemical products. Three 6" size ultrasonic flow meters were mounted on a skid and used to carry out the experiment parallel in connections each other to take flows from a common header, measure and discharge their individual flows into a common discharge header. The three meters were designate 1, 2 and 3 respectively. Meters 1 and 2 being service meters while Meter 3 is the calibrated master meter. The experiment was carried ten times to increase reliability of results. Experimental data were collected and analyzed using computational formulae technique. Results showed that; Meter 1 had an optimum process pressure of 12.38 and 9.43 bar with respect to flow rate and meter factor respectively as performance indicator. While Meter 2 had an optimum process pressure of 12.4 and 12.41 bar with respect to flow rate and meter factor respectively as performance indicator. Findings indicated significant relationship between process pressure, flow rate and meter factor using ultrasonic flow meter. The outcome of this study will be a useful guide to users of ultrasonic flow meters to maintain optimum process pressures of each meter during fluid supply.**

Keywords— Measurement, Optimizing, Dosing, Header, Discharge.

I. INTRODUCTION

Accurately measuring the rate of fluid flow within a system as a whole or in part is crucial for many industrial processes today and essential in gases and liquids handling which are an integral part of the process, compressed air, water or process steam supply that are fundamental to plant operation [1, 2].

Measurement technology provides a tool for optimizing production processes and dosing operations [3]. In addition to pressure and temperature, the flow rate is one of the most important measured variables in flow measurement [4]. The quantitative determination of amount, volume, and flow rate allows production processes to be optimized through control and regulation [5]. There are several measuring techniques for flow measurement, which include; differential pressure flowmeters using orifice plate or venturi tube, v-cone, variable area Flowmeters, rotameter, positive displacement flowmeters, turbine flowmeters, coriolis meters, ultrasonic meters, magnetic flowmeters, magnetic resonance flowmeters and host of others. Each of these flow meters has its strengths and weakness [6, 7].

Ultrasonic flow meters are widely used in various industries for precise flow rate measurements of liquids and gases [8]. The principle of operation of an Ultrasonic Meter is based on the time taken for a sound wave (called a "chord path") to pass across the meter in both directions [9]. Transmitter (Tx) becomes receiver (Rx) and receiver becomes transmitter [9]. The common terminology for the technique is 'time of flight' ultrasonic meter [10]. The meter uses

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diagonally arranged multiple chord paths. When no flow is present the time taken for the sound wave to cross the meter will be the same in both directions (upstream Tx to downstream Rx, then, by change of function, from downstream Tx to upstream Rx) [11]. The velocity of sound for the process fluid may be established this way [11].

Ultrasonic contrapropagation methods have been used to measure the flow of natural gas since the 1970s, flare gases since the 1980s, and smokestack gases in continuous emissions monitoring since the 1990s [10].

Contrapropagation means sound waves are timed in a direction with the flow and later or simultaneously, against the flow [12]. At low Mach number, << 1, the time difference is directly proportional to the flow velocity V PATH along the path. Even at Mach 0.1 the time difference is very nearly proportional to the velocity along the path [13]. In any event, by timing upstream and downstream, the correct velocity can be computed along the path [14].

Ultrasonic flow meters are widely used in various industries for precise flow rate measurements of liquids and gases [15, 16]. However, there is limited research on how variations in process pressure affect the accuracy and calibration of ultrasonic flow meters. Understanding this relationship is essential for optimizing flow measurement accuracy in different operating conditions and it is the need to close this knowledge gap that necessitated this research. This research topic aims to provide valuable insights into the practical challenges of using ultrasonic flow meters under varying process pressures, potentially leading to improved measurement accuracy and reliability in industrial applications of ultrasonic flow measurement. The research objectives of this paper are to: (1) To assess how changes in process pressure impact the accuracy of ultrasonic flow meters in real-world industrial settings; (2) To determine the extent to which process pressure affects the meter factor (calibration) of ultrasonic flow meters; and (3) To develop practical recommendations for compensating for process pressure variations in ultrasonic flow meter measurements.

II. MATERIALS

The materials used are: Three 6” size ultrasonic flow meters; water; metering skid; pen; field note; flow computer and flow execrate spirit.

A. System Description

The receiver and transmitter are placed in V-configuration inside the meter housing. The sensors are the primary measuring elements. The signal converter/transducer transforms ultrasonic signals to flow that can be interpreted by flow computer. The 6’’ ultrasonic meters are connected to 6’’ pipes using bolted flanges. Graphite gasket is inserted in between the meter flange and pipe flange to seal it up and ensure air tightness of the connection.

B. Experimental Method

Proving of one duty meter is done at a time by comparing volume measure by the duty meter to the volume measured by calibrated master meter which must be within 0.05% tolerance.

The study was carried out applying a six steps methodology as follows.

Step 1: Three 6” size ultrasonic flow meters were connected in parallel mounted on a metering to take flows from a common header, measure and discharge their individual flows into a common discharge header as well.

Step 2: Two of these ultrasonic flow meters were designated as duty meters (Meters 1 and 2) while the third meter was designated as the calibrated master. The three meters are exactly the same in design and construction. However, the only difference between the master and duty meters is that; the master meter calibrated yearly at certified laboratory/facility so as to ensure transfer of international measurement reference standards. While the certified master meter was used to transfer internal measurement standards to the duty meter in a process called proving or quassi calibration.

Step 3: A bypass loop system line was connected from each of the two duty meters to the master. The by-pass loop was fitted with gate valve to control flow into the bypass line.

Step 4: The discharge outlet of the three meters were connected to a common discharge header. The discharge header was connected to a storage tank via pipe network. All the inlet and outlet valves were open. Whereas the bypass valves were closed.

Step 5: Prior to the experiment, leak test was carried out on the entire pipe network to ensure that the integrity of the pipes, joints, valves, flanges and other related associated accessories.

Step 6: The pump was put on to push the fluid through the ultrasonic flow meters that are mounted on the pipeline while the process pressure was increased steadily until upper limit of the design pressure of the system was attained. The corresponding fluid flow rate was measured and recorded while corresponding meter factors were determined by calculation in each case. This experiment was carried ten times so as to achieve more reliable results. The test rig (experimental set up) is illustrated in Fig. 1.

III. DATA COLLECTION

The primary data for this study were obtained through the fluid flow experiment, while the secondary data was determined from the primary data using computation method.

A. Data Analysis

A1. Governing equations The Formulae a used for analysis of data of this research are:

$$\text{Meter Factor} = \frac{\text{Actual volume}}{\text{Indicated volume}} \quad (1)$$

$$\text{Meter Factor} = \frac{\text{Prover volume}}{\text{Meter indicated volume}} \quad (2)$$

$$\text{Flow rate} = \frac{\text{Volume flow}}{\text{Time taken}} \quad (3)$$

Flow rate is measured in cubic meter per hour or bbl per hour
Note that $1m^3$/hr = about 6.2898 bbl/hr.
Meter Factor is a ratio of two volume without unit.

A2. Equation that governs the operation of the ultrasonic flow meter

There is a basic equation that governs the operation of ultrasonic flow meters. Ultrasonic flow meters use ultrasonic waves to measure the velocity of a fluid flowing through a pipe. The basic equation is derived from the principle of the Doppler effect or the time-of-flight measurement of ultrasonic waves.

For a Doppler ultrasonic flow meter, which measures the frequency shift of ultrasonic waves reflected off the flowing fluid particles, the basic equation is:

$$f_d = 2f_o \frac{v}{c} \cos(\theta) \quad (4)$$

, where

- ❖ f_d is the Doppler-shifted frequency,
- ❖ f_o is the emitted frequency of the ultrasonic wave,
- ❖ v is the fluid velocity,
- ❖ c is the speed of sound in the fluid, and
- ❖ θ is the angle between the direction of fluid flow and the direction of the ultrasonic beam.

For a transit-time ultrasonic flow meter, which measures the time it takes for an ultrasonic wave to travel upstream and downstream in the flowing fluid, the basic equation is:

$$v = \frac{2d}{\Delta t} \quad (5)$$

, where

- ❖ v is the fluid velocity,
- ❖ d is the distance between the upstream and downstream transducers,
- ❖ Δt is the time difference between the upstream and downstream travel times.

These equations serve as the foundation for the operation of ultrasonic flow meters, allowing them to estimate the fluid velocity and subsequently calculate the flow rate. Remember that specific implementations and variations of ultrasonic flow meters may incorporate additional factors or corrections to enhance accuracy.

A3. Error analysis of an ultrasonic flow meter

The error analysis of an ultrasonic flow meter involves assessing the various sources of uncertainties and inaccuracies in the measurements. While there isn't a single universal equation for error analysis, as it depends on the specific type and model of the ultrasonic flow meter, the overall error (E) in flow rate measurement can be expressed as the sum of individual error contributions:

$$E = E_{signal} + E_{alignment} + E_{temperature} + E_{pressure} + E_{wall} + E_{transducer} \quad (6)$$

General categories of error components ultrasonic flow meters include:

1. Signal-Related Error (signal) E_{signal}: This includes errors related to signal attenuation, absorption, reflections, and interference. It can be influenced by factors like the quality of transducers, signal processing algorithms, and the presence of impurities in the fluid.
2. Alignment Error (alignment) $E_{alignment}$: Misalignment of transducers can introduce errors in transit-time measurements. This error can be affected by factors such as the installation angle and the accuracy of the alignment process.
3. Temperature-Related Error (temperature) $E_{temperature}$: Changes in fluid temperature can affect the speed of sound, introducing errors in velocity and flow rate measurements. Some ultrasonic flow meters incorporate temperature compensation algorithms to mitigate this effect.
4. Pressure-Related Error (pressure) $E_{pressure}$: Variations in fluid pressure can impact the compressibility of the fluid and the speed of sound, contributing to errors in velocity measurements. Pressure compensation may be applied to address this.
5. Pipe Wall Effects (wall) E_{wall}: Coating, deposits, or irregularities on the pipe wall can interfere with ultrasonic signals, introducing errors. Signal processing techniques and proper installation can help minimize this type of error.
6. Transducer Performance (transducer) $E_{transducer}$: Changes in transducer characteristics over time can lead to inaccuracies. Regular calibration and maintenance are essential to monitor and correct for these changes.

It's important to note that the specific equations for each error component will depend on the design and features of the particular ultrasonic flow meter being used. Manufacturers typically provide detailed documentation and guidelines for error analysis, including correction factors and compensation methods.

For a more precise error analysis, referring to the user manual or technical documentation of the specific ultrasonic flow meter model is crucial. This documentation typically outlines the factors affecting accuracy and provides insights into how each error component is quantified and managed. The technical information/specification of meters used for the study are presented in Table I.

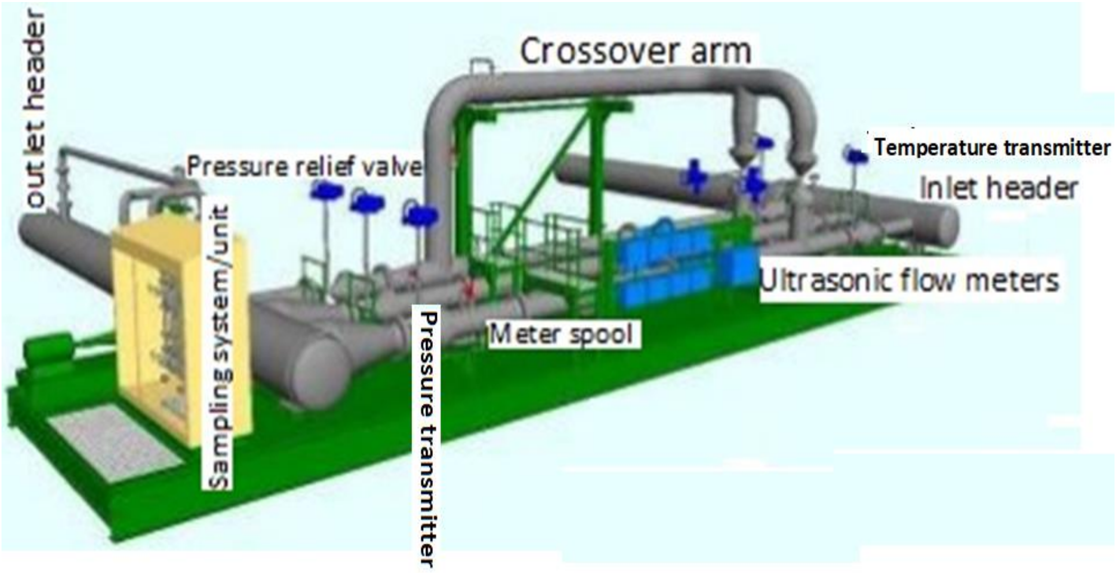

Fig. 1. The test rig (Ultrasonic Flow Metering Skid).

Table I. Technical specification of meters.

Component / Process condition	Specification
Meter size	6”
Sensor (Ultrasonic flow sensor UFC)	The ALTOSONIC-V flowmeter consists of a flow sensor and a signal converter.
Measuring principle (type)	Ultrasonic transit time
Signal converter (Intrinsically safe signal converter circuits). The remote signal converter is placed in a flameproof box, horizontally installed.	V = 6.51V, I = 208 mA, C = 22 µF
Viscosity range	High viscosity version: 0.1...1500 cP
Pressure range	ASME 150...600
Power supply	DC: 24 VDC +10%/-15% or AC: 100...240 VAC, 50/60 Hz
Power consumption	DC: 28 W (with optional heater: 203 W) or AC: 35 W
Transducer signals	Intrinsically safe flow sensor circuits: Vmax/Ui = 18 V, Imax/Ii = 210 mA, Ci = 100 nF, Li = 700 µH, Pi = 1 W
Temperature measurement	PT100 signal (Vmax/Ui = 10 V, Imax/Ii = 25 mA, Pi = 250 mW, Li = 10 µH, Ci = 1 nF)
Pressure range	ASME 150...600

IV. RESULTS AND DISCUSSION

Results of analysis of collected research data are presented using tables and figures/graphs as follows. Three 6” size, five path ultrasonic flow meter was used for the experiment. Each of the meter is fitted with both primary and secondary instruments to measure process parameters like; process temperature, process pressure, density and viscosity respectively which are used for compensation and calculation of final volume supplied.

From analysed data presented in Table II, Figures 2 and 3, at 12.38 bar (process pressure) Meter 1 had maximum flow rate of 28121.25 bbl/hr and lowest flow rate of 22660 bbl/hr at 9.43 bar. The technical and economic implications of this is that it makes more economic sense to supply fluid at 12.38 bar so as to reduce operation time, cost on energy and wages for employees. In this regard, 12.38 bar is the optimum process pressure for Meter 1 with respect to flow rate as performance indicator. This is similar to the results recorded by Davey, and Charlie (2023) in [9].

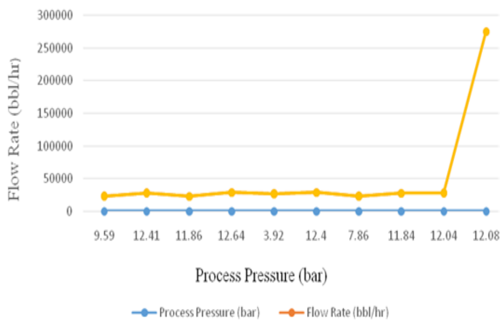

Fig. 2. Meter 1 Flow rate vs process pressure.

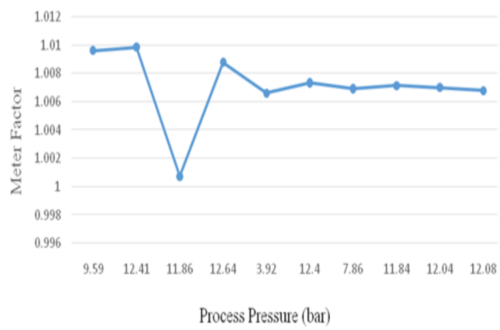

Fig. 3. Meter 1 Meter factor vs process pressure.

Furthermore, Meter 1 produced highest meter factor of 1.01076 at process pressure of 9.43 bar which is the optimum process pressure for Meter 1 with respect to meter factor as performance indicator. While the same meter had its lowest meter factor of 1.00293 at 11.94 bar. The implication of this is that it makes more economic/business sense to supply fluid at 9.43 bar than 11.94 bar using Meter 1 and meter factor as performance indicator. This is because the final indicated volume is obtained by multiplying gross volume by meter factor which is used for billing. Hence the higher the meter factor produced, the better it is for the supplier of fluid products. This is also in tandem with the views of Davey, and Charlie (2023) in [9]. It is therefore advisable that users of ultrasonic flow meters should determine the optimum process pressure and apply same during all fluid supply operations while keeping to best practice and highest traceability of internationally accepted measurement standard.

Table II. Meter 1 process pressure parameters.

Test S/N	Process Pressure (bar)	Flow Rate (bbl/hr)	Meter Factor	Temperature (℃)
TEST 1	9.43	22660.00	1.01076	14.4
TEST 2	3.695	25727.50	1.01001	12.2
TEST 3	11.94	22404.36	1.00293	13.1
TEST 4	12.54	27863.75	1.00581	12.3
TEST 5	3.86	27127.50	1.00625	10.3
TEST 6	12.38	28121.25	1.00496	12.6
TEST 7	8.72	23682.50	1.00724	11.7
TEST 8	11.75	26921.25	1.00648	10.7
TEST 9	12.04	27279.36	1.00673	13.8
TEST 10	12.07	27083.12	1.00707	13.2

Similarly, from Table III, Figures 4 and 5, it could be observed at 12.4 bar (process pressure) Meter 2 had maximum flow rate of 28639.38 bbl/hr and lowest flow rate of 22816.86 bbl/hr at 11.86 bar. The technical and economic implications of this is that it makes more economic sense to supply fluid at 12.4 bar so as to reduce operation time, cost on energy and wages for employees. In this regard, 12.4 bar is the optimum process pressure for Meter 2 with respect to flow rate as performance indicator (Sudtana *et al.* 2019) in [10]. This supports maximum profitability which is good for business.

Result obtained from Meter 1 is similar to that from study on the influence of the velocity profile on the accuracy of ultrasonic flow meters (Doppler and Transit-Time type) measurements which was carried out by Synowiec, *et al.*, in [17]. Measurements carried out on long straight sections where the velocity profile changes with an increase in the Reynolds number, as well as behind typical disturbing elements: bends, double bends, constrictions or valves [18]. Modern development of technical culture and measurement technique forces making measurements as accurately as possible due to the fact that measurement information is used for various purposes [19].

Table III. Meter 2 process pressure parameters.

Test S/N	Process Pressure (bar)	Flow Rate (bbl/hr)	Meter Factor	Temperature (℃)
TEST 1	9.59	23221.9	1.00961	12.4
TEST 2	12.41	27863.13	1.00985	11.6
TEST 3	11.86	22816.86	1.00075	10.1
TEST 4	12.64	28410	1.00880	13.3
TEST 5	3.92	26888.75	1.00661	12.3
TEST 6	12.4	28639.38	1.00734	12.6
TEST 7	7.86	22983.13	1.00694	14.8
TEST 8	11.84	27394.38	1.00715	11.7
TEST 9	12.04	27783.13	1.00701	12.5
TEST 10	12.08	27918.80	1.00679	11.2

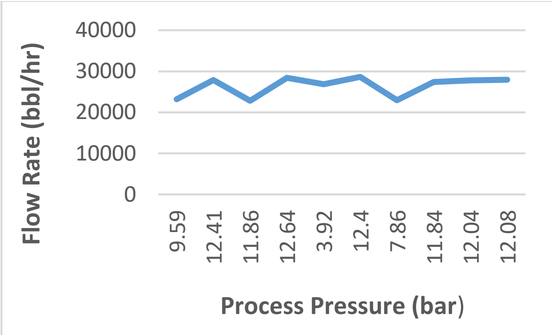

Fig. 4. Meter 2 flow rate vs process pressure.

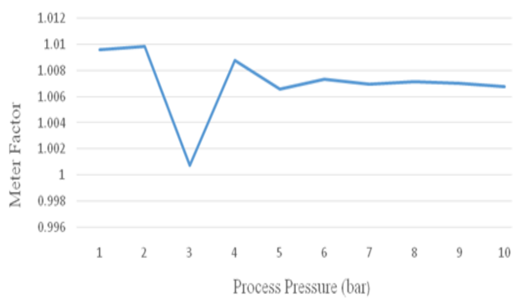

Fig. 5. Meter 2 meter factor vs process pressure.

Meanwhile, Meter 2 produced highest meter factor of 1.00985 at process pressure of 12.41 bar which is the optimum process pressure for Meter 2 with respect to meter factor as performance indicator. While the same meter had its lowest meter factor of 1.00075 at 11.86 bar. The implication of this is that it makes more economic/business sense to supply fluid at 12.41 bar than 11.86 bar using Meter 2 and meter factor as performance indicator. This supported by (Sudtana *et al.* 2019) in [10].

V. CONCLUSION

The final indicated volume or total station volume was obtained by the addition of flows through the two duty meters but excluding the flows through the master meter which was only used to prove or validate flows the duty meters in each of the ten-test carried out. However, from analysis carried out it was observed that both meters produced low meter factor at low process pressure.

Findings show some level of relationship between process pressure, flow rate and meter factor using ultrasonic flow meter. The significance of this is that for every process pressure, there is a resulting flow rate and meter factors. Therefore, the user of these meters should always keep to the optimum process pressure regime of each meter so as to save money on running cost and make more money. The user of ultrasonic meters will also have to strike a balance between higher flow rate (reduced operation time, reduced wage cost and reduced energy expenses) and higher meter factor which translates into higher volume and more profits for the business while keeping to best practice and highest traceability of internationally accepted measurement standard.

Recommendations to users of ultrasonic flow meter:

1. The user should Select the right ultrasonic flow meter for the application taking into consideration the flow rate range, accuracy requirements, and process conditions, including the expected range of process pressure.
2. Ensure installation of ultrasonic flow meter according to the manufacturer's instructions. This includes installing the flow meter in a straight section of pipe and away from sources of turbulence, vibration, and noise.
3. Calibrate the ultrasonic flow meter regularly. This is especially important if the process pressure is variable.
4. Monitor the ultrasonic flow meter readings for changes. If the readings change significantly, it may be a sign that the meter factor has changed due to a change in process pressure.
5. Use a pulse damper to reduce the pulsation of the flow. This will help to improve the accuracy of the ultrasonic flow meter readings.
6. Use a pressure sensor to measure the process pressure. This information can be used to correct the meter factor of the ultrasonic flow meter using a software algorithm.
7. Always use a redundant (master meter) ultrasonic flow meter to verify the readings of the primary flow meter. This is especially important in applications where the accuracy of the flow measurement is critical.
8. Consider temperature compensation in addition to pressure compensation, as changes in temperature can also affect ultrasonic flow meter performance.
9. Keep the ultrasonic flow meter well-maintained. Regularly check for any damage or wear on transducers, cables, and other components, as these can affect performance under varying pressures.
10. The user should ensure the respective optimum process pressures of each meter is known and adhered to during fluid supply operations.

Recommendations for meter manufacturers:

1. Develop new calibration methods that are more accurate under varying process conditions.
2. Develop new ultrasonic flow meter designs that are less sensitive to process pressure changes.
3. Develop new algorithms for correcting the meter factor of ultrasonic flow meters under varying process conditions.

NOMENCLATURE

Symbols	*Interpretation*
m³/hr	*cubic meter per hour*
bbl/hr	*barrel per hour*

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AUTHORSHIP CONTRIBUTIONS

This research work is entirely that of the author.

DATA AVAILABILITY STATEMENT

The author confirms that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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