CSCanada
Advances in Petroleum Exploration and Development
Vol. 17, No.1, 2019, pp. 71-78
DOI:10.3968/11003

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

Uncertainty in Fluid Flow Measurement: A Case Study of Flow Measurement Comparison Through PVC and Steel Pipes at Varying Temperatures for Liquid With Small Air Bubbles

N. Uwaezuoke[a],*; S. I. Onwukwe[a]; A. J. Ibegbu[b]

[a]Department of Petroleum Engineering, Federal University of Technology, P.M.B 1526, Owerri, Imo State, Nigeria.
[b]Department of Mechanical Engineering, Madonna University, #1 Madonna University Road, Akpugo Campus, Nigeria.
*Corresponding author.

Received 15 October 2018; accepted 8 February 2019
Published online 22 April 2019

Abstract
Using fresh water with small amount of air bubbles of size as small as a pencil dot, the existing flow meter in the flow system (hydraulics) was proved using the Sierra Ultrasonic meter (Innova-Sonic™ Model 210i) with measurement medium taken at ambient temperature of 30°C. The procedures for installation of the ultrasonic meter were followed and measurement taken with transducers mounted using V-method and N-method respectively, on a pipe size of 20mm. The V-method and N-method gave average flow rates of 0.02918cf/sec and 0.04402cf/sec respectively. The V-method resulted in a meter factor of 1.9610, while the N-method resulted in a meter factor of 3.2511. The V-method and N-method gave relative percentage error values of 49% and 69.2% respectively. The V-method proved to be suitable for the pipe size of 20mm used in the experiment, with standard deviation of 5.3339×10^{-4} and variance of 2.84505×10^{-7} compared to standard deviation of 6.8×10^{-3} and variance of 4.624×10^{-5} obtained from N-method. It is recommended that a meter factor of 1.9610 obtained from V-method be applied on the existing meter. The liquid flow rates at measurement medium temperatures of 50°C and 70°C were determined by the use of poly-vinyl chloride and steel pipes respectively. It was observed that fluid flow rate increased with increase in temperature, and flow rate determined with ultrasonic flowmeter depends on material type as flow through poly-vinyl chloride pipe was generally higher compared with steel pipe at the temperatures values considered.

Key words: Flow measurement; PVC pipe; Steel pipe; Temperature; Ultrasonic flowmeter

Uwaezuoke, N., Onwukwe, S. I., & Ibegbu, A. J. (2019). Uncertainty in Fluid Flow Measurement: A Case Study of Flow Measurement Comparison Through PVC and Steel Pipes at Varying Temperatures for Liquid With Small Air Bubbles . *Advances in Petroleum Exploration and Development*, *17*(1), 71-78. Available from: http://www.cscanada.net/index.php/aped/article/view/11003
DOI: http://dx.doi.org/10.3968/11003

INTRODUCTION
Flow meters are devices used for measuring or monitoring volumetric or mass flow rates of liquids and gases (i.e. bulk fluid movement) while they are transported through a pipe. They are regarded as process instruments with a reasonable degree of precision that are used to measure linear or non-linear flow of fluid at certain volumetric or mass flow rates through a pipeline. Due to constant desire for accuracy and optimal performance, different types of flow meters for both single phase and multiphase flow applications can now be obtained in the market easily. If the transport pipe is used to convey one phase fluid i.e. either liquid or gas, a single-phase meter is used. If the simultaneously transported fluid is a mixture or combination of two fluids which could be a single liquid or a mixture of liquids (e.g. oil and water) like liquid and gas, then it is a multi-phase flow which requires a multiphase flowmeter for measurement. The complexity of a flow meter and its designs/technologies keep updating as the nature of fluids change from single phase flow to multiphase flow. The key requirements for a flow meter are reliable measurement accuracy with negligible human intervention and evincing strength in design for operating in harsh environmental conditions.

Ultrasonic flow meters have a high accuracy in stationary flow conditions, and their maximum error does not exceed 2% or 3% at turbulent flow rate (Re>4000), and 5% at laminar (Re<2000) or transient (2000<Re<4000) flow rates (Berrebi et al., 2018). Problems inherent in ultrasonic flowmeter calculations exist. How to estimate the differential time of flight accurately has been highlighted as a problem in ultrasonic flow measurement (Ma et al., 2012). The Transit-time and Doppler-shift flow meters are common.

The location or metering point where the fluid is being measured in this work is a hydraulic bench loop. This is a very valuable and necessary apparatus that is used in experiments and tests in fluid mechanics and hydraulics because it provides continuous and controlled recirculating supply of water to other auxiliary modules that are used to demonstrate a particular aspect of hydraulic theories and principles such as impact of jets, Bernoulli's theorem, Reynold's number study, losses due to fiction in pipelines, flow over weirs etc. Computerized Data Acquisition models are also available. Research students in every branch of Engineering and Technology, Physics and Science use it to study characteristics of fluid flow. Accuracy concerns existed in its metering system, and needed to be investigated at various temperatures and pipe materials.

However, meter proving has been described as the means by which meters are calibrated to provide a "meter factor" that can be applied to the meter indicated volume that will result in a recorded volume that can be traced back to a regulated reference standard, and this is achieved by passing an identical volume of fluid through both the meter and the meter prover and then comparing the results (Harry, 2018). This procedure is achieved by comparing the measuring/service meter which is hydraulic bench meter in this case, with a certified master prover, which is an ultrasonic flow meter. The meter must be proved at stable atmospheric and fluid conditions such as pressure, temperature, density and flow rate; these conditions must be stabilized for a prolonged time before actual taking of readings for consistency and accuracy.

In this work, concern was only on single-phase flow measurement and use of ultrasonic flow meter for detection of flow uncertainty in liquid flow with small air bubbles. The existing flow meter was proved, and at varying temperatures, the flow rate of water with small air bubbles was determined with poly-vinyl chloride (PVC) and steel pipes.

1. LITERATURE REVIEW

The American Petroleum Institute (API) and other associations have established basic reference standards in flow measurement (Baker, 1990). The standards are followed during equipment installation and monitoring. Also, fluid flow through closed pipes can be measured by use of mass flow or volumetric flow rates (Morris, 2001). Flow meters are chosen based on temperature and pressure of the fluid and particular applications such as natural gas, compressed air measurement, gas mixing and blending applications, burner control, liquid measurement, steam flow measurement (Morris, 2001 & Sierra Instruments, 2018), and also accuracy (Lynnworth and Liu, 2006).

However, with wide-beam illumination transit time, ultrasound can be used to measure volume flow independent of the cross-sectional area of the vessel or tube (Drost, 1978). The two common ultrasonic meter path geometries are the chordal-path geometry and bounce-path geometry (Greg, 2018). The mean flow velocity could be obtained by the solution of a system of two linear equations (Lynnworth & Brown, 2001). These are Equations (1) and (2);

$$\bar{\upsilon}(t) = \frac{L}{2}\left(\frac{1}{\hat{T}_{dw}(t-T_s)} - \frac{1}{\hat{T}_{up}(t)}\right) = \frac{L}{2}\frac{\delta T}{\hat{T}_{up}(t)\hat{T}_{dw}(t-T_s)} \quad (1)$$

$$\delta T = \hat{T}_{up}(t) - \hat{T}_{dw}(t-T_s) \quad (2)$$

where $\bar{\delta}$ is the mean flow velocity of the fluid along the sound path, L is the distance between receiving and transmitting transducers, $\hat{T}_{dw}(t-T_s)$ and $\hat{T}_{p}(t)$ are the estimations of the downstream transit-time and the upstream transit-time respectively.

Some advantages and disadvantages of ultrasonic flow meters are presented in Table 1.

Particularly, ultrasonic flow meters are affected by the acoustic properties of the fluid and the impact could be as a result of the viscosity, density, suspended particles and temperature.

Other errors in ultrasonic flow measurement in liquids and gases are relative prediction error on the mean flow velocity and zero-crossing error given as Equation 3 and Equation 4 respectively;

$$E_s = \frac{\bar{\upsilon}_p(t-T_s) - \bar{\upsilon}_p(t)}{\bar{\upsilon}_p(t)} \quad (3)$$

$$E_z \cong \frac{C^2 \bar{\varepsilon}_H^0}{L\,\bar{\upsilon}_p^0}\frac{\left(\cos\left(2\pi * f_p\theta\right) - \cos\left(2\pi * f_p(\theta - T_s)\right)\right)}{\sin\left(2\pi * f_p\theta\right)}$$

(4)

where $\bar{\delta}_p(t)$ is the mean flow velocity at time t when pulsations are involved, T_s is the time delay, C is the speed of sound in water, and $2\pi f_i\theta$ is the phase of the flow pulsations.

Table 1
Advantages and Disadvantages of Ultrasonic Meters

	Advantages	Disadvantages
1	No flow calibration required	Not fully accepted by industry
2	High accuracy	Susceptible to pressure and reduction valve poise
3	Sophisticated self-diagnostic capability	
4	Large rangeability	
5	No additional pressure drop	
6	No moving parts	
7	No maintenance, low operational and installation costs	

Also, installation effects exist and transducer installation location has been identified as a major challenge (Ma, et al., 2012; Eric, 2018; Mahadeva et al., 2009). Transducer mounting methods such as V-method, N-method and Z-method are possible (Sierra Instruments, 2018). Similarly, pulsating flow and internal pipe wall roughness are other sources of error (Berrebi et al., 2018 & Xiaotang and Cegla, 2018). Disturbances also generate error in flow measurement (Carl and Jerker, 2000). Different types of poly-vinyl chloride (PVC) pipes with varying wall thicknesses with water flow have also been shown to have an effect on the flow (Bruna et al., 2018), due to varying material types. Irrespective of all these, ultrasonic flow meters are used as meter provers due to their high accuracy.

Also uncertainties in measurement have been an issue for a long period (Rodger et al., 1981). As a result, meter factors are used to correct errors in measurement. Technique for meter proving has been presented and meter factor is determined by dividing the prover meter (master meter) volume by the existing meter volume (Greg, 2018 & Harry, 2018). A summary of the publications and inventions of ultrasonic flowmeters from 1955 to 2005 have since been presented (Lynnworth and Liu, 2006).

2. MATERIALS AND METHOD

The aim is to determine the accuracy of an existing meter in hydraulic bench by the application of API standards and use of V-method and N-method of transducer placement. Subsequently, meter factors were calculated for both methods and the correct factor selected for application. At measurement medium temperatures of 50°C and 70°C, using different pipe materials, flow rates were also determined.

2.1 Materials

Hydraulic bench FME 00 (Volumetric Type):
Presented in Table 2 are the specifications for the hydraulic bench used to establish the fluid flow loop in the experiment.

Table 2
Specifications of the Hydraulic Bench

Dimension:	1130 x 730 x 1000 mm
Weight:	70 kg
Sump tank capacity:	165 litres
Small channel capacity:	8 litres
Centrifugal pump capacity:	0.37kW, 30 – 80 litres per minute
Measuring scale:	0 – 7 litres for small tank 0 – 40 litres for big tank

Ultrasonic Flowmeter
Innova-Sonic^{TM} Model 210i designed for liquid flow measurement only (tolerant of small air bubbles) was used for the flow measurement as the master meter. The main components are the transmitter and transducers. Table 3 is the options in terms of fluid type. The operating temperature range for the measuring medium of -40°C to 80°C was maintained. Similarly, the allowable transmitter operating temperature range of -10°C to 50°C was not exceeded, and was monitored with a sensor.

Table 3
Fluid Type Options

S/N	Fluid Type
a	Sea Water
b	Kerosene
c	Gasoline
d	Fuel Oil
e	Crude Oil
f	Propane
g	Butane (0oC)
h	Other
i	Diesel Oil
j	Castor Oil
k	Peanut Oil
l	Gasoline #90
m	Gasoline #93
n	Alcohol
o	Water (125oC)

Other materials used include:
- Stop watch
- PVC and steel pipes (20 mm diameter), both with the same internal diameter and internal pipe wall roughness
- Vernier caliper
- Temperature sensor (thermometer)
- Single-phase fluid (fresh water) with small air bubbles maintained at 30°C ambient temperature, 50°C and 70°C respectively
- Fluid flow period (20 min.) was assumed

2.2 Method

2.2.1 Transducer Mounting Methods

The two transducer mounting methods used for this experiment and the reasons for applying these methods are as follows:

• V-method: This is a standard method that is mainly used on small diameter pipes ranging from approximately 50mm to 400mm (Sierra Instruments, 2018) and it usually gives more accurate readings compared to other methods. Also, it is appropriate to use, but still requires proper installation of the transducers, contact on the pipe at the pipe's centerline and equal spacing on either side of the centerline.

• N-method: This is an uncommon method that is used on smaller diameter pipes while the sound waves traverse the fluid twice and bounce three times off the pipe walls but the accuracy of the measurement can be improved by extending the transit distance as appropriate.

Both methods were used at a preset flow rate of the bench that was kept constant for about 20 minutes so as to obtain a stable condition of flow of fluid through the test piece for accurate readings; also, the transducers were proper installed by firstly smearing the coupling compound on the surface of the test piece for actual contact of the transducers on the pipe at its centerline with equal and adequate spacing on either side of the centreline of the apparatus and test piece for accuracy.

The set ups for the different mounting methods are illustrated in Figure 1 and Figure 2, and the Z method was not used in the experiment.

Figure 1
A set -up of N-method in the hydraulic bench

Figure 2
A set-up of V-method in the hydraulic bench

2.2.2 Computational Methods

MATLAB was used in computing the numeric values of paired sample probability *t*-tests because of its speed of computation, automated capability and precise efficiency. The paired sample plots, tables and radar diagrams were also made using MATLAB and Microsoft Excel programs respectively.

2.2.3 Data Log for the V- and N-Methods

Flow rate of the hydraulic bench was determined using Equation 5;

$$Q = \frac{V}{T} \quad (5)$$

where Q = flow rate; V = volume; T = time

At a volume of a 10 litres interval, readings for the time were obtained using a stop watch which recorded 23.4, 22.9, 25.3, 24.5 and 22.6 seconds respectively for the V-method and 25.0, 25.8, 27.0, 25.2 and 27.4 seconds respectively for the N-method. Thus, the obtained time intervals at a constant volume of 10 litres were used to calculate the flow rates in Table 4 and Table 5. The average values were taken.

3. RESULTS AND DISCUSSION

The ultrasonic flow meter gave the readings of the velocity, strength quality for both the upstream and downstream in percentage. The meter factor was obtained by dividing the master meter (ultrasonic flow meter) by the sub meter in the (hydraulic bench).

Table 4
Comparison of the Flow Rates of the Meters Using the V-Method

V-Method								
Run number	Hydraulic bench		Ultrasonic meter		Strength quality			Volumetric error (%)
	T (sec)	Q (cf/sec)	Q (cf/sec)	V (f/s)	Upstream (%)	Downstream (%)	Quality	
1	23.4	0.0151	0.0291	8.892	60.1	61.6	69	48.1
2	22.9	0.0154	0.029	8.9699	60.1	61.6	69	46.9
3	25.3	0.0139	0.029	8.8026	60.1	61.6	72	52.1
4	24.5	0.0144	0.0296	8.8399	60.1	61.7	72	51.3
5	22.6	0.0156	0.0292	8.8413	60.2	61.6	76	46.6
	Average	0.01488	0.02918					49
		Meter factor	1.96102					

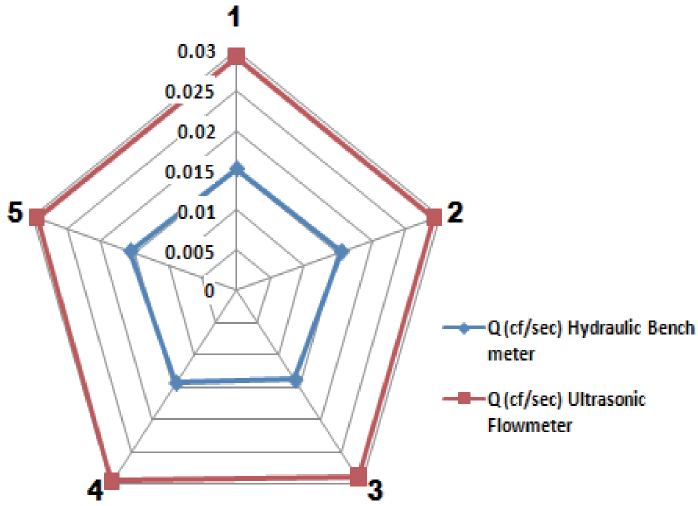

Figure 3
Flow rate using V-method for five runs

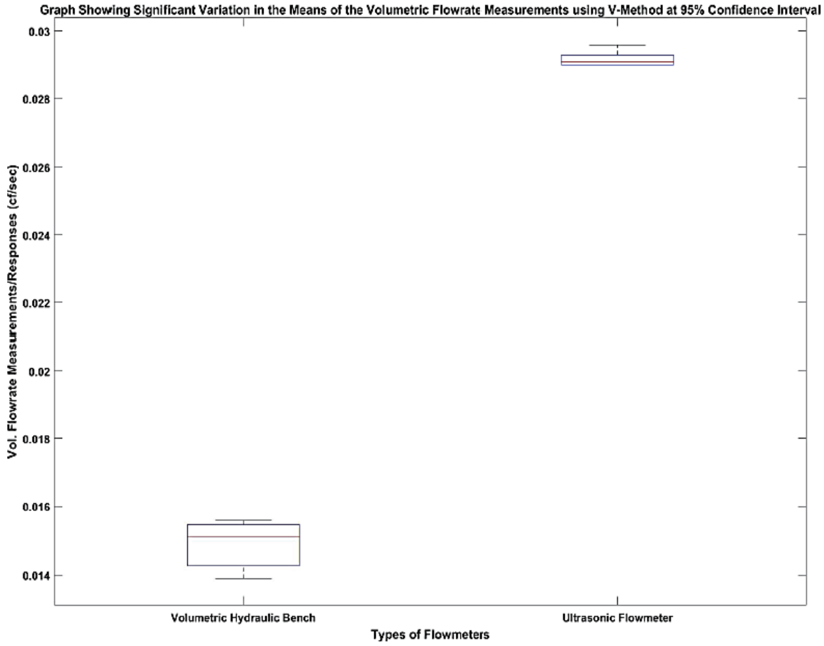

Figure 4
A paired sample flow rate for V-method probability *t*-test at 5% significance level

Table 5
Comparison of the Flow Rates of the Meters Using the N-Method

V-Method								
Run number	Hydraulic bench T (sec)	Hydraulic bench Q (cf/sec)	Ultrasonic meter Q (cf/sec)	Ultrasonic meter V (f/s)	Upstream (%)	Strength quality Downstream (%)	Quality	Volumetric error (%)
1	25.0	0.0141	0.0349	10.693	59.0	60.7	87	59.5
2	25.8	0.0137	0.0380	11.515	58.9	60.6	86	63.9
3	27.0	0.0130	0.0384	11.624	59.1	60.5	85	66.1
4	25.2	0.0140	0.0542	16.562	58.7	61.2	76	74.1
5	27.4	0.0129	0.0546	16.591	58.6	61.1	75	76.3
	Average	0.01354	0.04402					69.2
		Meter factor	3.251108					

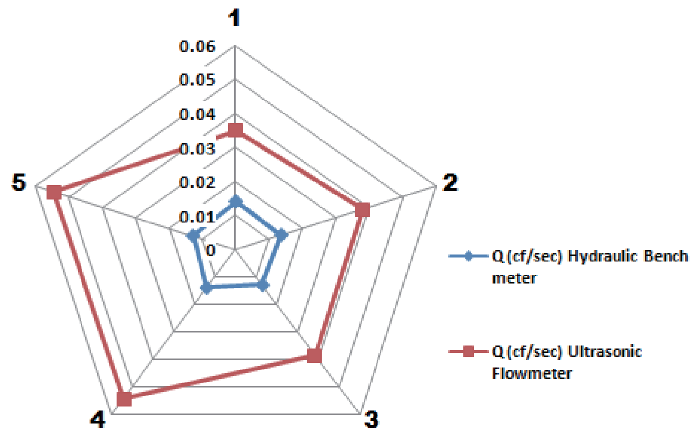

Figure 5
Flow rates using N-method for five runs

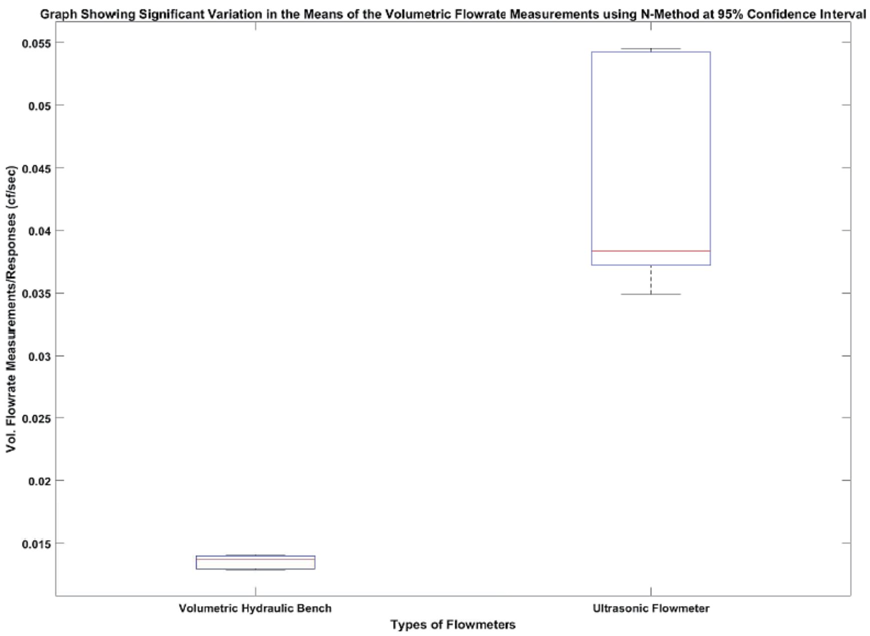

Figure 6
A paired sample flow rate for N-method probability *t*-test at 5% significance level

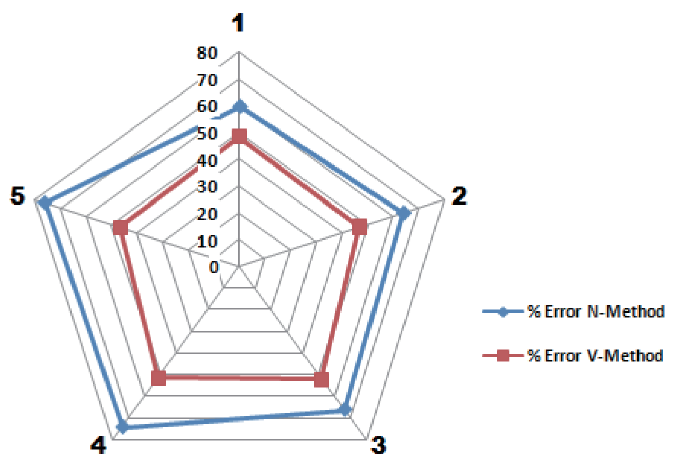

Figure 7
Relative percentage error of the N- and V-methods

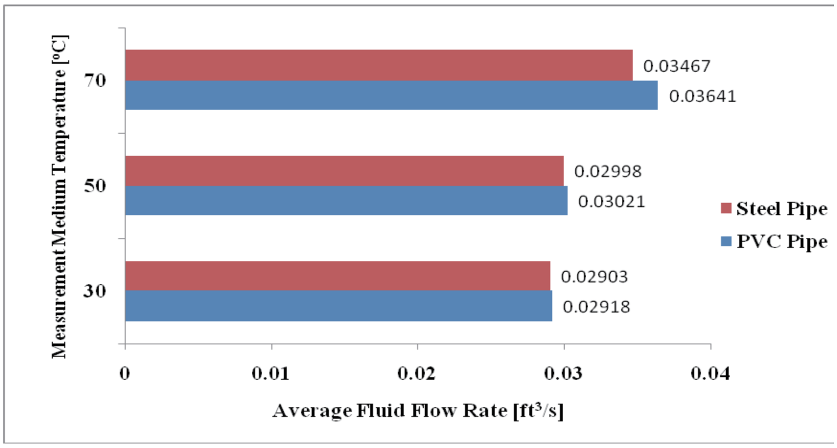

Figure 8
Measured average fluid flow rates in PVC and steel pipes with V-method

In this work, two transducer mounting methods which are the N and V methods were used for measuring the volumetric flow rate of water though hollow PVC and steel pipes of 1meter long and 20mm internal diameter respectively. The flow rate of the hydraulic bench which has the sub meter was kept constant as it recirculates through the test pipe that upon which was mounted the clamp-on ultrasonic flow meter which is the prover or master meter. The volumetric flow rate through the hydraulic bench was calculated using Equation 3 against that obtained instantaneously through the ultrasonic flow meter. Figure 3 to Figure 8 show the observations.

Figure 3 displays the variation of the volumetric flow rate between the hydraulic bench and ultrasonic meter using the V-method. The minimum and maximum values of volumetric flow rate of the bench are 0.0139 cf/sec and 0.0156 cf/sec respectively, with a total average of 0.01488 cf/sec while that of ultrasonic flow meter are 0.029 cf/sec and 0.0296 cf/sec with a total average of 0.02918 cf/sec.

The paired sample probability test, *t*-test; at 5% significance level as displayed by Figure 4, conducted on the hydraulic bench and ultrasonic flow meter against volumetric flow measurements using V-method showed that h = 1, which invariably rejects the null hypothesis at that significance level with probability, p, of observing the value as 1.0572×10^{-10} which is much more less than 0.05; and confidence interval limits of -0.0151 and -0.0135. The standard deviation was obtained as 5.3339×10^{-4} and variance as 2.84505×10^{-7} which is much more less than 3%.

Figure 5 displays the variation of the volumetric flow rate between the hydraulic bench and ultrasonic meter using the N-method. The minimum and maximum values of volume rate of the bench are 0.0129 cf/sec and 0.0141 cf/sec with a total average of 0.01354 cf/sec while that of ultrasonic flow meter are 0.0349 cf/sec and 0.0546 cf/sec with a total average of 0.04402 cf/sec.

The paired sample probability test, *t*-test; at 5% significance level as displayed by Figure 6, conducted on the hydraulic bench and ultrasonic flow meter against volumetric flow measurements using N-method showed that h = 1 which invariably rejects the null hypothesis at that significance level with probability p of observing the value as 1.0125×10^{-4} which is much more less than 0.05; and confidence interval limits of -0.0404 and -0.0206. The standard deviation was obtained as $6.8 \times 10^{-3}$and variance as 4.624×10^{-5} which is much more less than 3%.

Figure 7 represents the relative percentage error (between the ultrasonic meter and the existing meter) of the V-method against the N-method which shows that the N-method has percentage relative error values greater than the V-method values with average percentage relative errors of 69.2 and 49 respectively; the computed meter factors are also 1.96102 and 3.25111 respectively.

Hence; the V-method gives a more accurate and reliable reading comparatively using the pointers.

The readings in Figure 8 are average fluid flow rates and were taken using the V-method of transducer placement as was proved to be more reliable for the pipe sizes under consideration. Flow rate increased with increase in temperature for both the PVC and steel pipes. The flow rate values were higher for the PVC pipe compared to the steel pipe at all the temperature values used. The increase in flow rate with temperature could be as a result of the effect of temperature on the small air bubbles. The ultrasonic flow meter model used was designed to be tolerant of liquids with small air bubbles (Sierra Instruments, 2018).

CONCLUSION

The results of the *t*-tests signify the comparative acceptability and reliability of the V- and N-methods using its parameters, as recommended by equipment manufacturers. The relative percentage errors (Figure 7) and the computed meter factors also signify that the V-method is preferred to the N-method considering this scenario; average relative percentage error for the V-method is 49 with meter factor of 1.9610, while that of the N-method are 69.2 and 3.25 respectively; hence, a meter factor of 1.9610 should be applied on the volumetric flowrate measured using this hydraulic bench (sub meter) as estimated by the master meter (ultrasonic flow meter) for higher accuracy and reliable readings. Also, temperature and material type affect flow rate.

ACKNOWLEDGEMENT

Thanks to the Management of the University, for providing the Ultrasonic Flowmeter (Innova-Sonic™ Model 210i) in support of Research in Fluid Flow Measurement Technology.

REFERENCES

Baker, R. C. (1990). Fluid flow measurement. *Flow Measurement and Instrumentation, 1*(4), 241-243. https://doi.org/10.1016/0955-5986(90)90020-8

Berrebi, J., Martinsson, P. E., Willatzen, M., & Delsing, J. (2018, Jun. 5). *Ultrasonic flow metering errors due to pulsating flow*. Denmark: Accessed from DiVA portal. https://www.diva-portal.org/smash/get/diva2:989127/FULLTEXT01.pdf

Bruna, P., Torres, R.R., Adroaldo, D.R., & Marcia, P. (2018). Performance of ultrasonic flow meter in different Vinyl polychloride pipes. *IRRIGA, 23*, 87-95, https://doi.org/10.15809/irriga.2018v23n1p87-95.

Carl, C., & Jerker, D. (2000). Installation effects on an ultrasonic flow meter with implications for self diagnostics. *Flow measurement and instrumentation, 11,* 109-122.

Drost, C. J. (1978). *Vessel diameter-independent volume flow measurements using ultrasound (*17th, pp.299-302). Biomedical Symposium, San Diego.

Eric, K. (2018, Jul. 10). *Flow meter installation effects*. Houston, TX, USA: Accessed from American School of Gas Measurement Technology.

Greg, W. (2018, Nov. 8). *Fundamentals of meter provers and proving methods. Flow measurement devices*. Houston, TX, USA: Accessed from American School of Gas Measurement Technology.

Gu, X. T., & Cegla, F. (2019). The Effect of Internal Pipe Wall Roughness on the Accuracy of Clamp-On Ultrasonic Flowmeters. *IEEE Transactions on Instrumentation and Measurement, 68*(1), 65-72. 10.1109/TIM.2018.2834118.

Harry-James, J. H. (2018, Jun. 5). *Liquid meter proving technique*. Calgary, Canada: Press Release of iMEC Corporation.

Lynnworth, L., & Brown, A. (2001). Ultrasonic Flow meters. *Flow Measurement* (2nd ed.). Research Triangle Park: D. W. Spitzer, USA.

Lynnworth, L., & Liu, Y. (2006). Ultrasonic flowmeters: half-century progress report, 1955-2005. *Elsevier Ultrasonics, 44*(Supplement), e1371-e1378. https://doi.org/ 10.1016/j.ultras. 2006.05.046

Ma, L., Liu, J., & Wang, J. (2012). Study of the accuracy of ultrasonic flowmeters for liquid. *AASRI Procedia*, *3*, 14-20. https://doi.org/10.1016/j.aasri.2012.11.004

Mahadeva, D.V., Baker, R.C., & Woodhouse, J. (2009). Further studies of the accuracy of clamp-on transit-time ultrasonic flowmeters for liquids. *IEEE Transactions on Instrumentation and Measurement, 58*, 1602–1609. https://doi.org/10.1109/TIM.2009.2012954

Monterey, L. (2018, Jul. 5). Sierra instruments. *Use the right flow meter for your application*. CA, USA: Accessed from Sierra Instruments.

Morris, A. S. (2001). Flow measurement. *Measurement and Instrumentation Principles* (3th ed., pp.319-339). Butterworth Heinemann, Oxford. https://doi.org/10.1016/B978-075065081-6/50017-5

Rodger, B., Dowdell, R.E., & Wendt, R. E. (1981). Flow, Its measurement and control in science and industry (Vol.1, Part 2). Flow measuring devices. *Internationale Jahrestagung-Fraunhofer-Institut Fuer Treib-Und Explosivstoffe*

