Simulation of Invasive Ultrasonic Tomography for Three Phase Mixture

Abdulrahman Alfareh[1], M. H. F. Rahiman[1], M. T. M. Talib[1], Jaysuman Pusppanathan[2] and Juliza Jamaludin[3]
[1]*Tomography Imaging and Instrumentation Research Group, School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.*
[2]*Faculty of Biosciences & Medical Engineering, Universiti Teknologi Malaysia, 81310 Skudai Johor, Malaysia.*
[3]*Faculty of Engineering and Built Environment, Universiti Sains Islam Malaysia, 71800 Bandar Baru Nilai, Negeri Sembilan, Malaysia*
hafiz@unimap.edu.my

***Abstract*—Crude Oil Mixture has been a concern research area for many researchers and organization. Because of the importance of oil and its component, in order to separate and measure its components, which considered as black gold for 20th century till now. Non-invasive ultrasonic tomography has been applied to investigate and differentiate the verity of crude oil components have some limitations in terms of the wave penetration through the pipes and reflection of signals. Thus, the approach that has been proposed in this project is by using invasive ultrasonic tomography method to visualize the structure distribution and deliver some information such as mixture concentration and mass of flow components of different materials. Ultrasonic wave propagation with various frequencies of the transmission signal has been implemented in software platform (FEM), to evaluate the design and investigate the result. Therefore, the main consideration in designing of an ultrasonic system is the efficiency of the ultrasonic sensor and the frequency of propagated signals. The contribution in this project is developing a three-phase measurement for a mixture using invasive Ultrasonic technique to improve the accuracy of the system and implement Linear Back Projection Algorithm (LBPA). The conclusion of this paper has shown the capability of ultrasonic transducers of visualizing the internal distribution of multi-phase mixture.**

Index Terms*—Crude Oil Mixture; Propagated Signals Invasive; Ultrasonic Approach.

I. INTRODUCTION

The monitoring of the fluid in the pipeline of the oil industry has importance to measure the fluids produced from oil wells accurately for efficient oil exploitation and production [1]. Fluids are widely well-known in the oil industry, chemical plant, and other engineering fields. Which the efficiency and accuracy are essential factors of those systems [2]. Normally, oil fields exploitation produce a complex mixture of oil ,water ,gas and other fluids ,which made a difficult in measuring the multi-phase fluids. The normal technique is to separates each component individually, and measurement can be applied to each component using single phase measurement. Thus, the cost, time and efforts will be increased. Therefore, looking for another approach is highly recommended, which is capable of measuring the flow rate and extracting information such as mixture concentration and mass of flow components for each component, without separation. In this study, we are going to design a ring of ultrasonic sensors that use the basics of ultrasound sensor tomography in order to measure the distribution of concentration for the mixture in the pipelines, which is multi-phase flow measurement by using invasive ultrasonic approach. The previous researchers have been through this issue, where some projects have been done to implement a good solution for this problem. A few decades back, significant efforts have been done to design and develop multiphase flow meters. For instance, the National Engineering Laboratory, UK (NEL) has developed various MPF meters particularly in gas–oil-water flows for oil and gas industries. Nevertheless, most of those systems are applicable to deal with homogeneous fluids only, which considered as a limitation for the systems [3-18].

II. FUNDAMENTALS OF ULTRASONIC

Ultrasound is a branch of acoustics with soundwave above 20 KHz that utilize the mechanical pressure wave of above human hearing range. The basic principle of ultrasound is transmitting a sound wave signal and receive the reflection as shown in Figure 1.

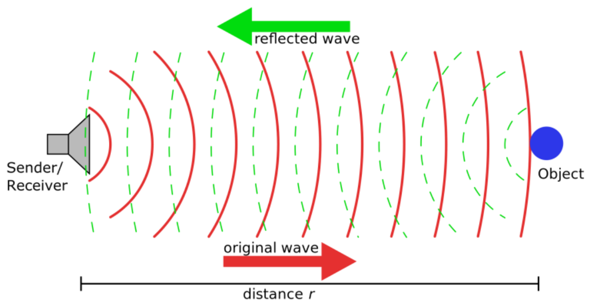


Figure1: Basic of ultrasound

Generally, there are three distinguish modes commonly used in ultrasound application, in order to collect signal data. First is transmission mode, where the signal is transmitted as a fan-shaped beam by the transducer and received by the opposite one [19,20]. The second type is reflection mode. The main goal of reflection signal is to reconstruct a cross-sectional image, showing a particular parameter and propriety of material under the testing process by using the collected data from the reflected signal. Some parameters must be taken in account when dealing with the nonhomogeneous and multiphase mixture, such as detection of discontinuity which known as a material interface that can be assessed by amplitude and the time of flight of the reflected signal. Interface or interaction point between materials occurred whenever there are non-homogeneities. Where each material has different impedance and sound velocity [6-17]. By other words, the reflection occurs in the boundary, because of both yields high acoustic impedance, the technique of reflection mode is highly recommended to use highly sensitive transducer in designing an ultrasonic system to be able to measure the backscattering signal at high signal-to-noise ratios accurately [4-11]. Finally, diffraction or refraction mode of the signal at a discrete or continuous interface. Ultrasonic has the ability to propagate longitudinal waves, share waves, surface waves and plate waves. Longitudinal waves (compressional) are capable of propagation through fluids in an equilibrium state according to [5].

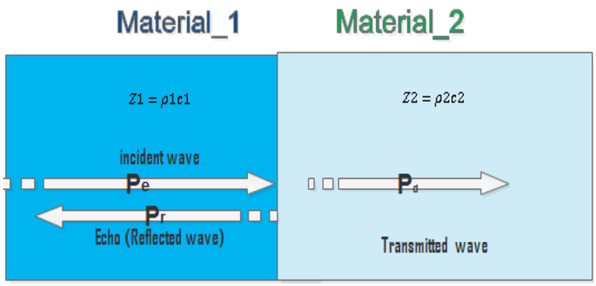


Figure 2: Signal propagation and material interface

To investigate the signal propagation of ultrasonic waves in multiphase mixture. The impedance and velocity properties of the material are an essential part of the signal behavior during penetration through the materials and interfacing different materials [21-23].

$$\text{Reflection coefficient, } \boldsymbol{R} = \frac{P_r}{P_e} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (1)$$

$$\text{Transmission coefficient, } \boldsymbol{D} = \frac{Pd}{Pe} = \frac{2Z_2}{Z_2 + Z_1} \quad (2)$$

$$Z = \rho\, c \quad (3)$$

where: Z_1 = Impedance of first material
Z_2 = Impedance of second material
ρ = Material density
c = Speed of sound
P_e = Incident wave
P_r = Reflected wave
P_d = Transmitted wave sound pressure

A significant parameter is vitally considered in designing ultrasonic system, which is choosing an appropriate ultrasonic sensor with suitable specifications to meet the objectives of the application.

III. System Design

Essentially, process tomography technique has several categories depends on the core of the systems which is clearly the sensor array.

A. *Structure*

As a sample of the tomographic system structure can be divided into three parts, sensor array, data acquisition and measurement system and image reconstruction algorithm as shown in Figure 3. Inflow measurement, the sensor array is normally used as transducers to transmit and receive signals from the system, which is mounted around the pipe or the column for data acquisition propose. The measurement system is dependently upon the core of the system and type of desired data [9-12]. Finally, the image reconstruction algorithms to visualize and represent the collected data.

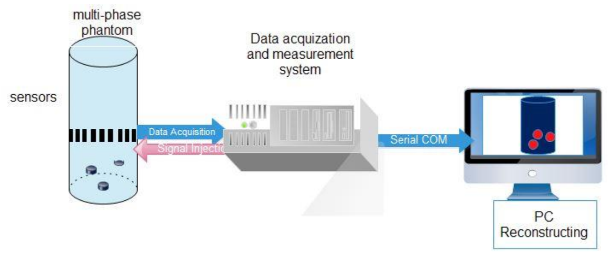


Figure 3: Structure of the system

B. *Prototype*

The system that has been proposed in this design has sixteen ultrasonic transducers are mounted around the pipe intensively as a ring. The 16 sensors are placement with a diameter of 60 mm as shown in Figure 4.

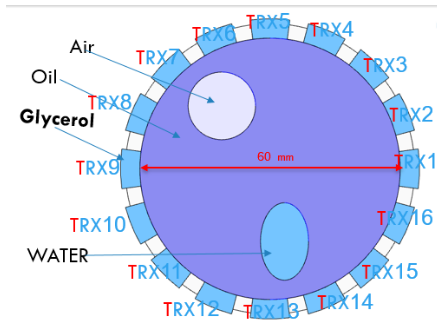


Figure 4: Prototype design

The mathematical specification calculation of the model as below.

$$\text{Circumference} = \mathbf{2\pi r} \;=2*30*\boldsymbol{\pi}=188.5 \text{ mm} \quad (4)$$

$$\text{Degree of rotation is } \frac{360}{16} = 22.5 \text{ degree} \quad (5)$$

$$\text{Angle sector} = (\mathbf{22.5\pi/180})\mathbf{r} = 11.78 \text{ mm} \quad (6)$$

C. *Materials Properties*

The boundaries interfacing of acoustic impedance is an important factor, in terms of reflection and transmission of signals between two materials. The transmitted signal from the transducer penetrates through the different materials layers. Where reflection is excessive when the propagating signal from high acoustic impedance to low acoustic impedance. Besides, this study will consider the transmission mode technique and invasive ultrasonic method [24]. The material properties of the targeted media to be imaged and visualized, where the image could be acquired is listed in Appendix A.

Table 1
Material Properties

Material	Speed of Sound	Density
Water	1500 [m/s]	1000 [kg/m^3]
Oil (Crude Oil)	1200 [kg/m^3]	800 [kg/m^3]
High-strength alloy steel	5920 [kg/m^3]	7850 [kg/m^3]
Glycerol	2730 [m/s]	1190 [kg/m^3]
Air	340 [m/s]	1 [kg/m^3]

By referring to the Equations (1) and (2), the reflection coefficient and transmission coefficient can be calculated to approximately the amount of the signal that can be transmitted and penetrated the interfacing between two materials, which in this project, there are three cases of interfacing as follow.

Case1:

$$R(\text{Glycerol/oil}) = \frac{800\left[\frac{kg}{m^3}\right] - 1190[kg/m\text{^}3]}{800\left[\frac{kg}{m^3}\right] + 1190[\frac{kg}{m^3}]} * 100 = -19.597\%$$

Case 2:

$$R(\text{oil/ water}) = \frac{1000\left[\frac{kg}{m^3}\right] - 800[kg/m\text{^}3]}{1000\left[\frac{kg}{m^3}\right] + 800[kg/m\text{^}3]} = 11.11\%$$

Case 3:

$$R(\text{oil/Gas}) = \frac{800\left[\frac{kg}{m^3}\right] - 340[kg/m\text{^}3]}{800\left[\frac{kg}{m^3}\right] + 340[\frac{kg}{m^3}]} = 40.35\ \%$$

where: R (oil/Gas) = Reflection coefficient between oil and gas
R(oil/ water) = Reflection coefficient between oil and water
R(Glycerol/oil) = Reflection coefficient between Glycerol and oil

As can be noted the reflection of sound waves is totally depends on interfacing impedance of interacted materials which is the density of material multiplied by the speed of sound. The scattered waves from oil to air is the lowest, which means (40.35%) of sound waves have been reflected, where the percentage of the reflection is very high compared to the percentage of reflection between oil and water.

IV. Result and Discussion

The ultrasonic tomography system of the multiphase mixture for visualizing internal impedance that proposed in this paper has been proved using a simulation of final element method (FEM)[5-10]. The transmission mode and linear back projection algorithm have been used in order to reconstruct the image clearly and approximately as the real Phantom [40-19]. Transmission mode has the concept of transmitting the pressure signal from the transmitter and other transducers act as receivers as shown in Figure 5.

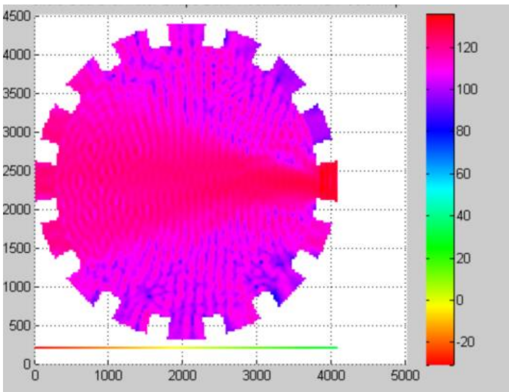


Figure 5: Continuous sound wave approach for 500 KHz

The continuous sound wave approach has been utilized in designing and evaluation the system to clearly investigate and analysis the internal interaction and distribution of the mixture component. As shown in Figure 5, where the transducer No 1 is transmitting a continuous sound wave with 500 KHz signal and other transducers are receiving. The frequency is an impact factor when dealing with ultrasonic solutions in fluids. Thus, transmitted signals by the transducers play a great role when it comes to accuracy depends on the media properties [25,26]. Normally, liquids have sonic velocity for approximation 1mm $\mathbf{us}^{-1}$. Therefore, transducer with greater frequency more than 1 MHz has the ability to resolve objects less than 1mm [27].

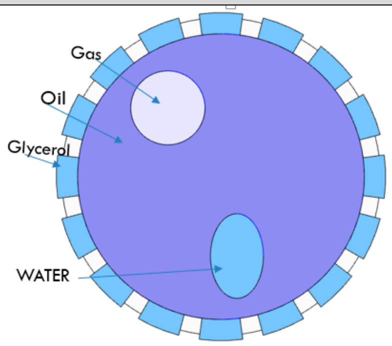
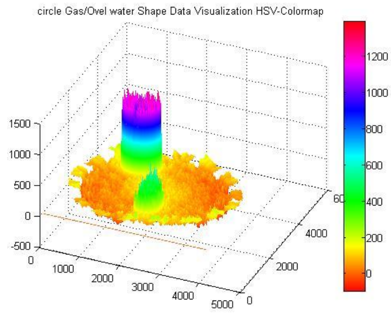
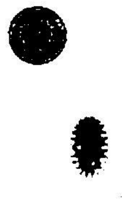
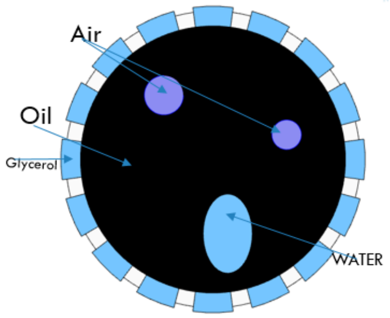
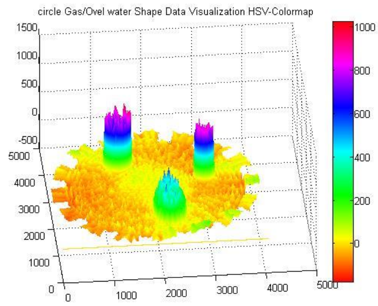
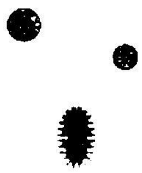
Linear back projection algorithm in Equation (7) proved its capability, accuracy and contribution in ultrasonic system tomography to visualize the multiphase components [28-41].

$$VLBP(x,y) = \sum_{Tx=1}^{n} \sum_{Rx=1}^{n} STx,R * MTx,Rx(x,y) \qquad (7)$$

where: VLBP(x,y) = Voltage distribution
STx,Rx = Sensor loss voltage
MTx, Rx = Sensitivity maps

The sensitivity map that shown as 3D in figure, is a matrix of 128x128 pixels where data has been collected and the coding of the linear back projection algorithm was used to reconstruct the image as shown in the appendix A. the 3D image in Appendix A has shown the different between three components, where the oil is the lowest level as background of the system , and two phantoms of different material (water and gas) have been adding to simulate three-phase mixture. Two cases have been carried out in this study. First is case No 1, where the oil is the lowest level as background the phantom and water is shown as an oval and gas is presented as a circle in the phantom No 1. Moreover, the height of the shapes that represent materials depends on the density of that materials and speed of sound (acoustic impedance). As a result, the height of the shapes in 3D is inversely proportional to acoustic impedance. Second, phantom No 2 shows the two gas columns and oval that represent water, it could be noted to two gas columns has the same height and water has less than that because of the higher density. Therefore, using ultrasonic tomography for the multiphase mixture is an effective technique for monitoring and visualizing the internal distribution of three-phase mixture.

APPENDIX A

	Phonam	LBP 3D image	Thresholding
1			
2			

ACKNOWLEDGMENT

The authors are grateful for the funding from the Ministry of Higher Education Malaysia under FRGS Grant (FRGS/1/2015/WAB07/UNIMAP/02/1).

REFERENCES

[1] L. Giannone, T. Eich, J. C. Fuchs, M. Ravindran, Q. Ruan, L. Wenzel, M. Cerna, and S. Concezzi, “Data acquisition and real-time bolometer tomography using LabVIEW RT,” Fusion Eng. Des., vol. 86, no. 6–8, pp. 1129–1132, 2011.

[2] F. Simonetti, P. B. Nagy, A. Brath, C. L. Willey, G. Instanes, A. O. Pedersen, and E. Mechanics, “Paper No. 5750,” no. 5750, pp. 1–13.

[3] I. Lock, S. Mei, I. Ismail, and A. Shafquet, “Real-time monitoring and measurement of wax deposition in pipelines via non-invasive electrical capacitance tomography,” Meas. Sci. Technol., vol. 25403, p. 25403.

[4] M. Hafiz, F. Rahiman, R. A. Rahim, M. Hezri, F. Rahiman, and M. Tajjudin, “Ultrasonic Transmission-Mode Tomography Imaging for Liquid / Gas Two-Phase Flow Ultrasonic Transmission-Mode Tomography Imaging for Liquid / Gas Two-Phase Flow,” no. January 2007, 2016.

[5] P. Huthwaite, “Improving accuracy through density correction in guided wave tomography Subject Areas :,” 2016.

[6] D. Andrews, C. F. Barn, H. Ware, and C. Cb, “Modelling of Ultrasonic Transducers and Ultrasonic Wave Propagation for Commercial Applications using Finite Elements with Experimental Visualization of Waves for Validation .”

[7] L. Borcea, “Electrical impedance tomography,” vol. 18, 2002.

[8] J. Kwon, S. Choi, and S. M. Song, “Implementation and evaluation of the ultrasonic TOF tomography for the NDT of concrete structures.”

[9] O. Kazeem, O. Taiwo, A. Kazeem, and D. Mondiu, “Determination Of Some Physical Properties Of Castor (Ricirus Communis) Oil,” vol. 1508, no. 3, pp. 1503–1508, 2014.

[10] R. White and C. Acoustics, “W - domain,” vol. 3, 2012.

[11] D. Andrews, “Modelling Ultrasonic Transducers Application examples.”

[12] “Modeling of Ultrasonic Wave Propagation,” p. 2014, 2014.

[13] J. Abbaszadeh, H. A. Rahim, R. A. Rahim, S. Sarafi, M. N. Ayob, and M. Faramarzi, “Sensors and Actuators A : Physical Design procedure of ultrasonic tomography system with steel pipe conveyor,” Sensors Actuators A. Phys., vol. 203, pp. 215–224, 2013.

[14] Y. A. Wahab, R. A. Rahim, M. Hafiz, F. Rahiman, H. A. Rahim, S. R. Aw, N. Shima, and M. Fadzil, “Jurnal Teknologi A Review of Process Tomography Application in Inspection System,” vol. 3, pp. 35–39, 2014.

[15] M. H. F. Rahiman, L. T. Siow, R. A. Rahim, Z. Zakaria, and V. Ang, “Initial Study of a Wire Mesh Tomography Sensor for Liquid / Gas Component Investigation,” vol. 10, 2015.

[16] H. Leemreize, J. D. Almer, S. R. Stock, and H. Birkedal, “Three-dimensional distribution of polymorphs and magnesium in a calcified underwater attachment system by diffraction tomography,” 2013.

[17] Q. Su, C. Tan, and F. Dong, “Measurement of Phase Fraction in Oil-Water Two - Phase Flow Using Ultrasound Attenuation Method,” pp. 1890–1895, 2015.

[18] W. Deng, J. Lee, and H. Lee, “Kinematics Simulation and Control of a New 2 DOF Parallel Mechanism Based on Matlab / SimMechanics,” pp. 233–236, 2009.

[19] H. J. Vinegar, S. L. Wellington, J. Harold, and S. L. Wellington, “Tomographic imaging of threephase flow experiments Tomographic imaging of three .. phase flow experiments,” vol. 96, no. 1987, 2010.

[20] J. Abbaszadeh, H. Binti, A. Rahim, R. Bin, A. Rahim, and S. Sarafi, “Frequency analysis of ultrasonic wave propagation on metal pipe in ultrasonic tomography system,” 2014.

[21] R. A. Rahim, M. H. F. Rahiman, and M. N. M. Taib, “Non-Invasive Ultrasonic Tomography : Liquid / Gas Flow Visualization,” pp. 243–247.

[22] M. H. F. Rahiman, R. A. Rahim, H. A. Rahim, R. G. Green, Z. Zakaria, E. J. Mohamad, and S. Z. M. Muji, “Sensors and Actuators A : Physical An evaluation of single plane ultrasonic tomography sensor to reconstruct three-dimensional profiles in chemical bubble column,” *Sensors Actuators A. Phys.*, vol. 246, pp. 18–27, 2016.

[23] M. Hafiz, F. Rahiman, R. A. Rahim, M. Hezri, F. Rahiman, and M. Tajjudin, “Ultrasonic Transmission-Mode Tomography Imaging for Liquid / Gas Two-Phase Flow,” vol. 6, no. 6, pp. 1706–1715, 2006.

[24] Z. Wei and L. K. Weavers, “Ultrasonics Sonochemistry Combining COMSOL modeling with acoustic pressure maps to design,” Ultrason. Sonochem., vol. 31, pp. 490–498, 2016.

[25] K. Wu, M. Kobayashi, Z. Sun, C. Jen, P. Sammut, J. Bird, B. Galeote, and N. Mrad, “Engine Oil Condition Monitoring Using High Temperature Integrated Ultrasonic Transducers,” pp. 1–7, 2011.

[26] D. Kurniadi and A. Trisnobudi, “ detection and monitoring the multi-phase flow using ultrasonic wave velocity tomogrphy ,” no. 2, pp. 2–7.

[27] M. Wilt, S. Gould, and P. Services, Applications of tomography in the oil-gas industry e Part 2 23. 2015.

[28] M. S. Beck, “Process Tomography Principles , techniques and applications ”,2005.

[29] M. Barmatz, “Acoustic radiation potential on a sphere in plane , cylindrical , and spherical standing wave fields a),” vol. 77, no. March, pp. 928–945, 1985.

[30] Y. Jin and A. Eydgahi, “Monitoring of Distributed Pipeline Systems by Wireless Sensor Networks,” 2008.
[31] S.-M. H. and C. P. L. E J Fordham, R T Ramos†, A Holmes, S Simonian‡, “Multi-phase-fluid discrimination with local fibre-optical probes : III . Three-phase flows,” vol. 1347.
[32] R. Thorn, G. A. Johansen, and E. A. Hammer, “Three-Phase Flow Measurement in the Offshore Oil Industry Is There a Place for Process Tomography ” pp. 228–235, 1999.
[33] N. Nordin, M. Idroas, Z. Zakaria, and M. N. Ibrahim, “Design and Fabrication of Ultrasonic Tomographic Instrumentation System for Inspecting Flaw on Pipeline,” *Procedia Manuf.*, vol. 2, no. February, pp. 313–318, 2015.
[34] I. Ismail, J. C. Gamio, S. F. A. Bukhari, and W. Q. Yang, “Tomography for multi-phase flow measurement in the oil industry,” vol. 16, pp. 145–155, 2005.
[35] Q. Wang, H. Wang, Z. Cui, and C. Yang, “Reconstruction of electrical impedance tomography (EIT) images based on the expectation maximum (EM) method,” *ISA Trans.*, vol. 51, no. 6, pp. 808–820, 2012.
[36] Z. Wei, “Scale-up Design of Ultrasound Irradiator for Advanced Oxidation Process (AOP) Using COMSOL Simulation,” pp. 1–6.
[37] F. Authors, “Ultrasonic tomography imaging simulation of two-phase homogeneous flow,” 2012.
[38] M. Hafiz, F. Rahiman, R. Abdul, R. Universiti, H. Abdul, R. Universiti, M. Universiti, and T. Hussein, “Ultrasonic tomography - image reconstruction algorithms,” no. January, 2012.
[39] A. J. Devaney, P. N. T. Wells, M. S. Beck, R. A. Williams, D. I. Crecraft, and P. N. T. Wells, “Process tomography using ultrasonic sensors.”
[40] E. Systems, “Development of a multiphase flow meter by means of multiple ultrasonic velocity profile measurements,” pp. 61–64.
[41] A. A. Almabrok, A. M. Aliyu, L. Lao, and H. Yeung, “International Journal of Multiphase Flow Gas / liquid flow behaviours in a downward section of large diameter vertical serpentine pipes,” *Int. J. Multiph. Flow*, vol. 78, pp. 25–43, 2016.

.