

# A Study of Multiphase Flow Imaging Using Ultrasonic Tomography

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## ABSTRACT

This study was conducted to investigate the multiphase flow regime in the pipelines using ultrasonic tomography technique. Multiphase flow occurs when two or more phases are flows along a closed or open pipe. The phases involved in this study are solid, liquid and gas flow which combination of these materials was tested in vertical condition. Ultrasonic tomography technique was use to solve this problem and the transmission mode was implemented. In the tomography system, number of projections will contribute to the image reconstruction result. Hence, more projection data captured tends to enhance the tomogram. In order to overcome this issue, 16 ultrasonic transceivers were used rather than separated transmitter receiver technique. These 16 transceivers will generate data equals to 32 separate transmitter-receiver sensor. It means that by using transceivers more data can be obtained because more space can be saved. Non-invasive sensor arrangements applied to this system and supported with electronic measurement circuits and a data acquisition system, data for image reconstruction were generated. At the image reconstruction part, 'Linear Back Projection' (LBP) algorithm has been applied. The results obtained are useful for the monitoring of multiphase flow.

**Keywords:** Ultrasonic Tomography, Image reconstruction, Sensitivity map

## 1. Introduction

Multiphase flow is encountered in many chemical and process engineering applications. Managing systems involving two or more phases is common in areas from the processing of fuels and chemicals to the production of food, pharmaceuticals, and specialty materials. In the petroleum industry for example, the problem of multiphase flow mixtures has been of interest since the early 1980s. Since then, considerable research has been conducted into the development of a multiphase flow systems suitable for use in an industrial environment [1].

The conventional approach is to separate the mixture into individual components and then measure those separately. There are some problems with the required three phase separators; their bulk, high installation cost and considerable maintenance. Therefore, it is highly attractive to have relatively simple multiphase flow systems which are capable of measuring flow of each component directly without separation [2].

Furthermore, a monitoring system that can be applied non-invasively is vital in multiphase flow system. The monitoring system should be able to provide the information about the composition of the multiphase system. Thus, tomography is the most beneficial technology that can be applied to solve the problem. Ultrasonic tomography imaging can provide images of a cross section of pipe or vessel and thus, information about the fluids inside the pipe or vessel can be extracted by analysing the image obtained.

The quality of reconstructed image depends on the number of measurements done. The higher the numbers of measurements will normally increase the spatial resolution of the system and this will enhance the quality of

reconstructed image [3]. This research presents new technique in ultrasonic tomography by using ultrasonic transceiver instead of separate transmitter receiver approach. Common separate transmitter-receiver method are widely use in the ultrasonic tomography research. This method required large space in order to place around the pipeline or vessel. This is because the needs of having pair of the sensors which is transmitter and receiver. While the transceiver has an advantage of dual functioning since each transceiver have capability of become transmitter and receiver with the help of switching circuit. Therefore, the number of transceivers mounted around the measurement pipe or vessel can give up to double measurements compare to common technique.

## 2. Ultrasonic Tomography

The ultrasonic tomography is one of the non-invasive techniques that can be used in the industry for monitoring the flow composition, non destructive testing and extensively in medical imaging [4]. The method involves in using ultrasonic techniques is through transmitting and receiving sensors that are axially spaced along the flow stream.

An ultrasonic tomography system is based upon interaction between the incident ultrasonic waves and the object to be imaged [24]. Whenever there is an interface between one substance and another, the ultrasonic wave is strongly reflected [17] and this type of tomography technique has the advantage of imaging two components flow and gives the opportunity of providing the quantitative and real time data on chemical media within a full scale industrial process [24].

## 3. Recent Research on Ultrasonic Tomography in Flow Application

Since its introduction and development in the last two decades, more detailed and advance research on ultrasonic tomography in flow application have been explored and developed by many researchers worldwide. Gai *et al.* (1989) [5] has presented a paper on flow imaging using ultrasonic time-resolved transmission mode tomography. The paper considers some problems encountered in flow imaging and describe an algorithm using transmission mode ultrasound on a solid/liquid and liquid/gas flow. The algorithm takes the pulse's arrival at a specific time as its image reconstruction data and is viewed as a modified backprojection method.

Chen *et al.* (1996) [6] from Cranfield University (UK) has presented a paper on ultrasonic tomographic technique for gas/liquid and solid particle flow measurement. An ultrasonic tomographic system and image reconstruction algorithm based on measurements of scattered waves is described.

Xu and Xu (1997) [7] from Tianjin University (China) have developed an ultrasonic facility for tomographic imaging of gas/liquid two-phase flow based on the binary logic operation and a method of "time-of-propagation along straight path". They established the principle and construction of the facility and their primary emphasize was on the evaluation of its performance in flow regime identification and cross-sectional void fraction measurement.

Warsito *et al.* (1999) [8] from Shizuoka University (Japan) has carried out a research on the cross-sectional distributions of gas and solid holdups in slurry bubble column using ultrasonic computed tomography. They utilize the transmission mode method in the experiment. The energy attenuation and the velocity changes were sense by the system in the experimental vessel due to gas and solid hold-ups and the image were reconstruct using Filtered Back Projection algorithm.

Peter Hauptman *et al.* (2002) [9] from University Magdeburg (German) have work out a paper work on the ultrasonic sensors application in the process industry in which the advantages, disadvantages, commercial example, possibilities and limitations of ultrasonic process sensors are discussed. Since 2004, Ruzairi and M. Hafiz *et al.* had carried a research on the development of ultrasonic tomography in imaging the liquid/gas two phase flows. Transmission mode approach been implemented for sensing the flow. Till today, they have come out with many paper works on it.

Ng Wei Yap *et al.* (2005) [10] from Universiti Teknologi Malaysia has done an iimplementation of the ultrasonic tomography to determine the composition of the water and oil flow. The transmission method of ultrasonic tomography is implemented in the project as the ultrasonic waves can propagate through both the medium of water and oil. He utilizes the non-invasive methods that do not disturb the internal flow of the pipeline. The velocity of ultrasonic waves varies in water, oil and different composition of water and oil. The composition of water and oil can be determined from the measurement of this propagation time. Sixteen pairs of ultrasonic sensor mounted non-invasively around the periphery of an acrylic pipe.

Cowell *et al.* (2006) [11] from University of Leeds (UK) has review a paper on the ultrasonic signal characteristics in the presence of highly reflecting solid/liquid interfaces. The paper was split into three sections which first it review on the basic physical effects that occur when ultrasound waves pass from one material to another. Those principles were then applied and illustrated using a metal wall and surrounded by water in the second section. Last section was on the simulations to illustrate the response.

Supardan *et al.* (2007) [12] has presented a paper on the investigation of gas holdup distribution in a two phase bubble column using ultrasonic computed tomography. In the study, time averaged of gas holdup distributions were

investigated in a 16cm diameter bubble column for two phase dispersed system of air-water and air-glycerol solution by implementing the transmission mode method.

Jaysuman (2009) [13] conducted a research to measure two phase liquid – gas flow regime by using a dual functionality ultrasonic transducer. Comparing to the common separated transmitter – receiver ultrasonic pairs transducer, using dual functionality ultrasonic transceiver is capable to produce same measurement results hence further improvised and contributes to the hardware design improvement and system accuracy. Due to the disadvantages and the limitations of the separated ultrasonic transmitter – receiver pair, the research presents a non-invasive of ultrasonic tomography system using ultrasonic transceiver as an alternative approach. By using 8 units of ultrasonic transceivers, the electronic measurement circuits, the data acquisition system and suitable image reconstruction algorithms, the measurement of a liquid/gas flow was realized. The system is capable of visualizing the internal characteristics of liquid and gas flow and provides the concentration profile for the corresponding liquid and gas flow.

## 4. Ultrasonic Tomography Modeling

Process tomography can be used to obtain both qualitative and quantitative data needed in modelling a multi fluid flow system [14]. The modelling is carried out to predict the spatial and temporal behaviour of a process and it becomes more significant as the inherent complexity of a process increases [15]

### 4.1 Ultrasonic Wave at Boundaries

Varieties of interactions are possible at the interface between two mediums. The attenuation of amplitude of the incident acoustic wave due to the object or field of interest may be detected. Variation in the speed of sound in an inhomogeneous material may also be measured. The variation of both amplitude and phase of the scattered field cause by a physical inhomogeneous field may be sense.

In process tomography, the difficult part is the identification of interfaces between different materials. Process tomography using ultrasonic sensing will rely upon detectable interactions both in a homogeneous transmission medium and from interfaces, for example gas hold-ups (gas bubbles) in a liquid flow. Several interactions that are possible are [4]:

- Attenuation of the amplitude of the incident acoustic waves due to the absorption and scattering effects caused by the object or field of interest.
- Variation of speed of sound in an inhomogeneous medium.
- Variation of both amplitude and phase of the scattered field caused by a physical inhomogeneous field.

A useful descriptor of the interaction of ultrasound with a material is its acoustic impedance (the complex ratio of sound pressure to particle velocity), which is analogous to electrical impedance [16]. The acoustic impedance ( $Z$ ) is described as:

$$Z = \rho c \quad (1)$$

where  $Z$  is the acoustic impedance ( $\text{kg/m}^2\text{s}$ ),  $\rho$  is the density of the medium ( $\text{kg/m}^3$ ) and  $c$  is the sound velocity in the medium ( $\text{m/s}$ )

The difference of acoustic impedance at the interface will control the amount of energy reflected. Conversely, if the impedances are similar, most of the energy will be transmitted [17]. In this research, the couplant was used to match the acoustic impedance of the transducer with experimental column. However, in this research the ultrasonic energy losses between the transducer/couplant/experimental column are assumed zero.

The behaviour of the ultrasonic wave at the surface and interface between two mediums can be describe in terms of power reflection coefficient ( $R$ ) and power transmission coefficient ( $T$ ) as in equation 2.5 and equation 2.6 respectively.

$$R = \left(\frac{P_r}{P_i}\right)^2 = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \quad (2)$$

$$T = \left(\frac{P_t}{P_i}\right)^2 = \left(\frac{2Z_2}{Z_2 + Z_1}\right)^2 \quad (3)$$

where  $P_r$  is reflected sound pressure,  $P_t$  is transmitted sound pressure and  $P_i$  is incident sound pressure

From the equation it shows that the larger difference of acoustic impedance of the two medium, the greater amount of wave will be reflected. So, the more energy reflected, the lesser reading will be at the receiver. Thus, the sensed interaction data may be used as source data for imaging purpose. The following sections will describe the investigations of ultrasonic wave propagation for several situations involved in this research.

#### 4.2 Ultrasonic Wave Propagation from Liquid to Gas

Figure 1 shows ultrasonic wave propagation from water to gas medium. It is given that acoustic impedance (at room temperature) of liquid which correspond to water,  $Z_1 = 1.5 \times 10^6 \text{ kg/m}^2\text{s}$  and gas correspond to air,  $Z_2 = 430 \text{ kg/m}^2\text{s}$ . The calculation for percentage reflected wave at the liquid (water)/ gas (air) interface is presented as follows:

$$\begin{aligned} R(\text{water/gas}) &= \left( \frac{430 - 1.5 \times 10^6}{430 + 1.5 \times 10^6} \right)^2 \times 100\% & (4) \\ &= -0.9994 \times 100\% \\ &= 99.94\% \end{aligned}$$

$$\begin{aligned} T(\text{water/gas}) &= \left( \frac{2 \times 430}{430 + 1.5 \times 10^6} \right)^2 \times 100\% & (5) \\ &= 0.0006 \times 100\% \\ &= 0.06\% \end{aligned}$$

The negative sign indicates the reversal of the phase relative to the incident wave. From the calculation in (4) and (5), clearly shows that almost all the wave is reflected at the interface of liquid and gas. It proved that due to the large mismatch of acoustic impedance between liquid and gas, only 0.06% of the transmitted ultrasonic wave could penetrate the boundary of liquid gas. The penetration is too little hence automatically generate large sensor loss value. Therefore, transmitted ultrasonic wave is detectable if the transmission along the path is free from gasses. However, the transmitted wave is totally reflected and it is not detectable if the transmission path having the gas obstacles [17].

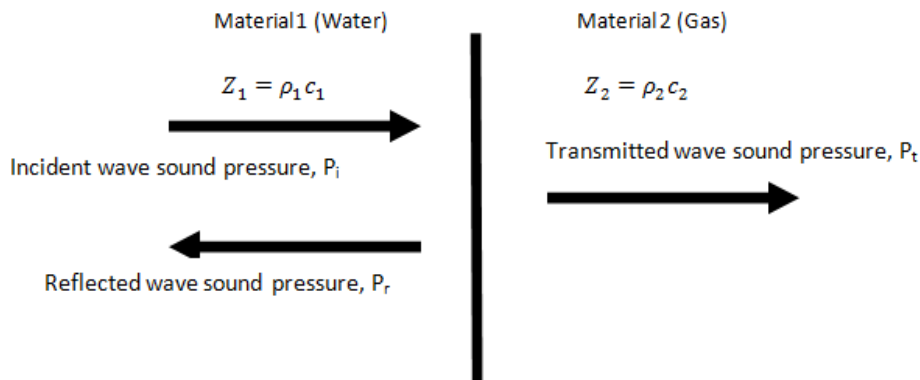


Figure 1. Ultrasonic wave propagation from water to gas medium

#### 4.3 Ultrasonic Wave Propagation from Liquid to Cement

Figure 2 shows ultrasonic wave propagation from water to cement (solid). Given acoustic impedance of water is  $1.5 \times 10^6 \text{ kg/m}^2\text{s}$  and cement is  $5 \times 10^6 \text{ kg/m}^2\text{s}$ . The following calculation shows the reflection coefficient and transmission coefficient at water-cement boundary.

$$\begin{aligned} R\left(\frac{\text{water}}{\text{cement}}\right) &= \left( \frac{5 \times 10^6 - 1.5 \times 10^6}{5 \times 10^6 + 1.5 \times 10^6} \right)^2 \times 100\% & (6) \\ &= 0.54 \times 100\% = 54\% \end{aligned}$$

$$\begin{aligned} T(\text{water/cement}) &= 100\% - 54\% & (7) \\ &= 46\% \end{aligned}$$

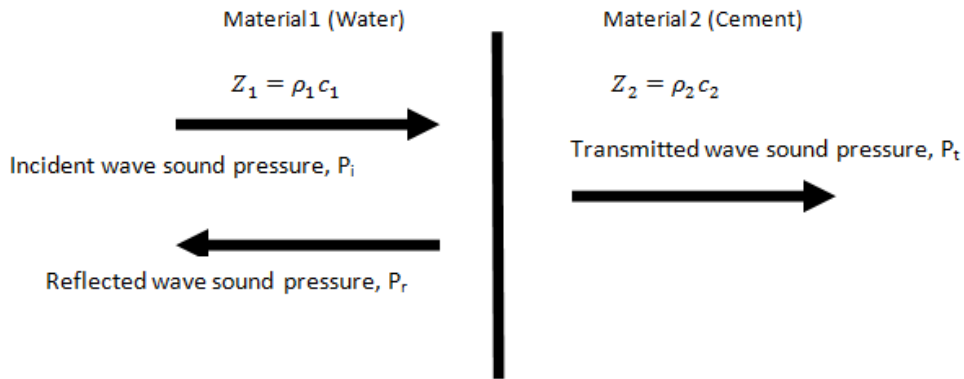


Figure 2. Ultrasonic wave propagation from water to cement (solid)

#### 4.4 Ultrasonic Wave Propagation from Liquid to Wood

Figure 3 shows ultrasonic wave propagation from water to wood (solid). Known acoustic impedance of water is  $1.5 \times 10^6 \text{ kg/m}^2\text{s}$  and wood is  $0.15 \times 10^6 \text{ kg/m}^2\text{s}$ . By using similar equation, the percentage of reflection wave and transmitting wave are calculated.

$$R(\text{water/wood}) = \left( \frac{0.15 \times 10^6 - 1.5 \times 10^6}{0.15 \times 10^6 + 1.5 \times 10^6} \right)^2 \times 100\% \quad (8)$$

$$= -0.8175 \times 100\%$$

$$= -81.75\%$$

$$T(\text{water/wood}) = 100\% - 81.75\% \quad (9)$$

$$= 18.25\%$$

From the calculation results, wood are reflecting more waves compared to cement. Only 18.25% wave will transmit through the wood while 46% through the cement. Thus there will be a difference in the sensor loss value.

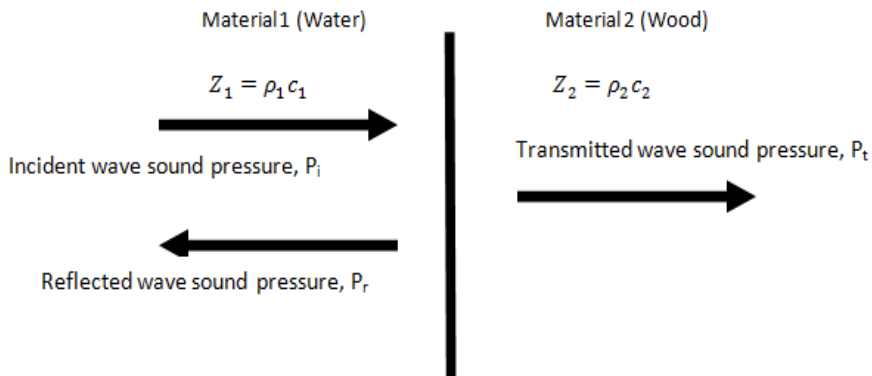


Figure 3. Ultrasonic wave propagation from water to wood (solid)

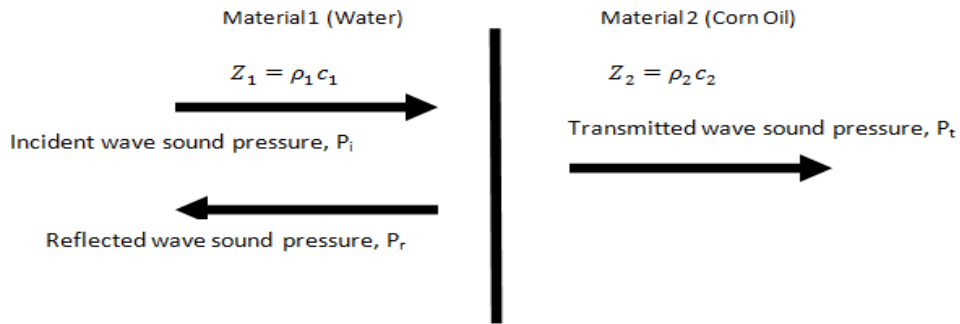
#### 4.5 Ultrasonic Wave Propagation from Liquid to Corn oil

Figure 4 shows ultrasonic wave propagation from water to corn oil (liquid). The result state that only 2.73% of ultrasonic wave that will reflected at the water/oil interface. Almost all of the wave could go through the corn oil.

$$R(\text{water/cornoil}) = \left( \frac{1.42 \times 10^6 - 1.5 \times 10^6}{1.42 \times 10^6 + 1.5 \times 10^6} \right)^2 \times 100\% \quad (10)$$

$$= 2.73 \times 100\%$$

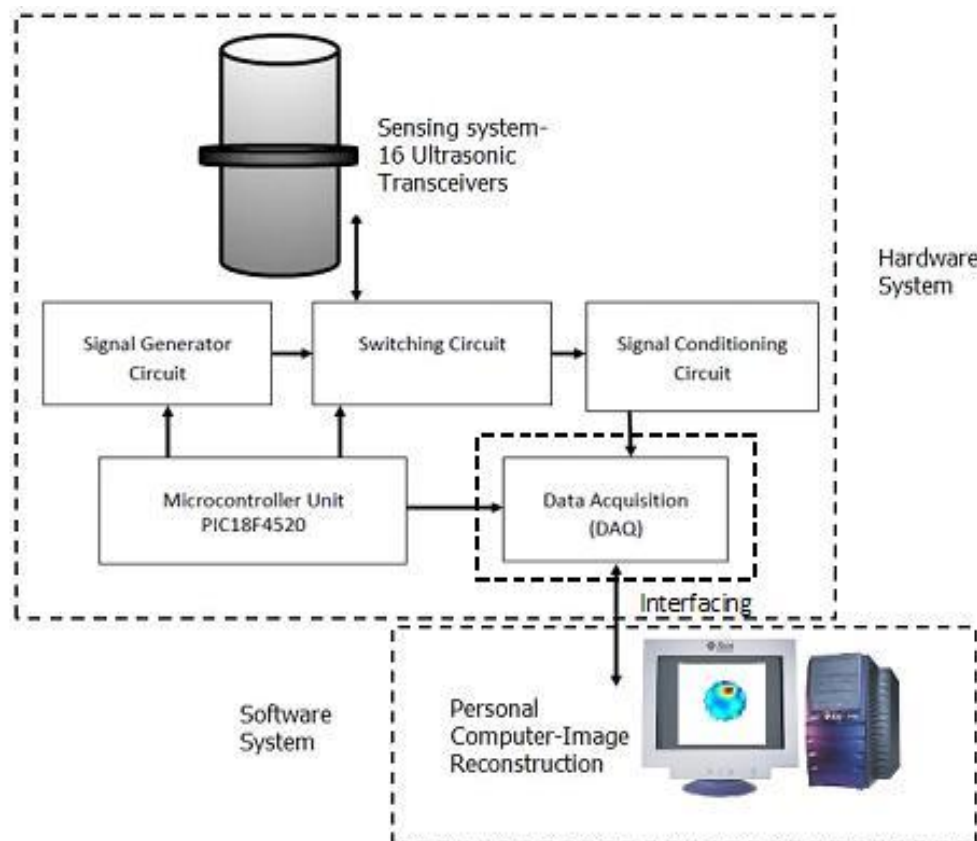
$$\begin{aligned}
 &= - 2.73\% \\
 T(\text{water/cornoil}) &= 100\% - 2.73\% \\
 &= 97.27\%
 \end{aligned}
 \tag{11}$$



**Figure 4.** Ultrasonic wave propagation from water to corn oil (liquid)

### 5. Hardware Development

In process tomography system, hardware is the important part to build besides the software part. It is important as this part will acquire the data for image reconstruction. This part is fundamental to the success or failure of an acoustic imaging system. Therefore, given the object to be imaged and the specifications to be achieved, the design of front-end of an acoustic imaging system should be regarded as a first priority [5]. The hardware part is divided into two major parts which is sensing unit and the electronic circuitry to acquire the data needed for image reconstruction. Figure 5 shows the block diagram of ultrasonic tomography system.



**Figure 5.** Ultrasonic Tomography Systems

### 6. Data Acquisition

Data acquisition systems typically convert analog signals or waveforms into digital values for processing. The data captured will then store in txt file and will be analyses for further development in image reconstruction. In this research, the NI-USB 6218 data acquisition device from National Instruments is used. This device is connected via Universal Serial Bus (USB) to a computer. To work along with this device, LabVIEW (short for Laboratory Virtual Instrumentation Engineering Workbench) from National Instruments is used. The reason for this software being use is because of its simplicity and it uses dataflow programming language which makes it easy to use and time saving. The data flow block diagram is shown in below Figure 6 while Figure 7 shows the front control panel program of the DAQ.

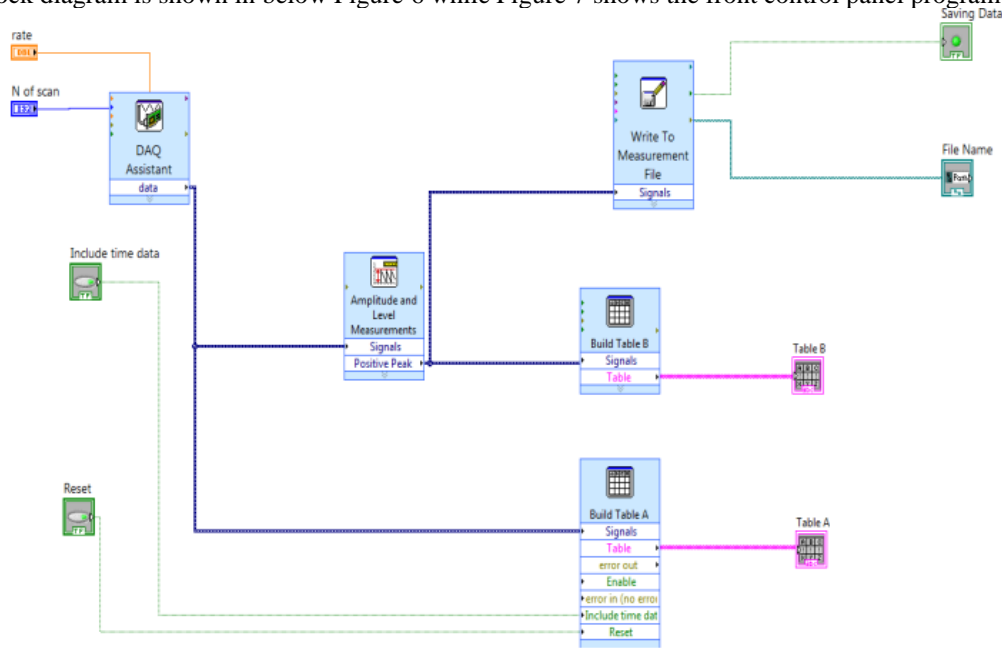


Figure 6: NI-USB Block Diagram Program in LabVIEW

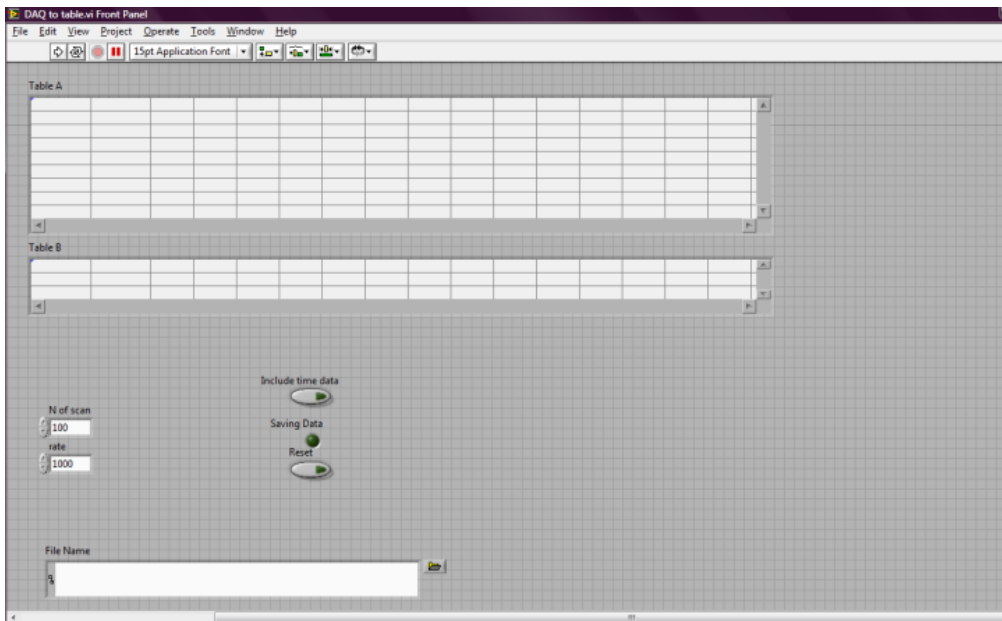
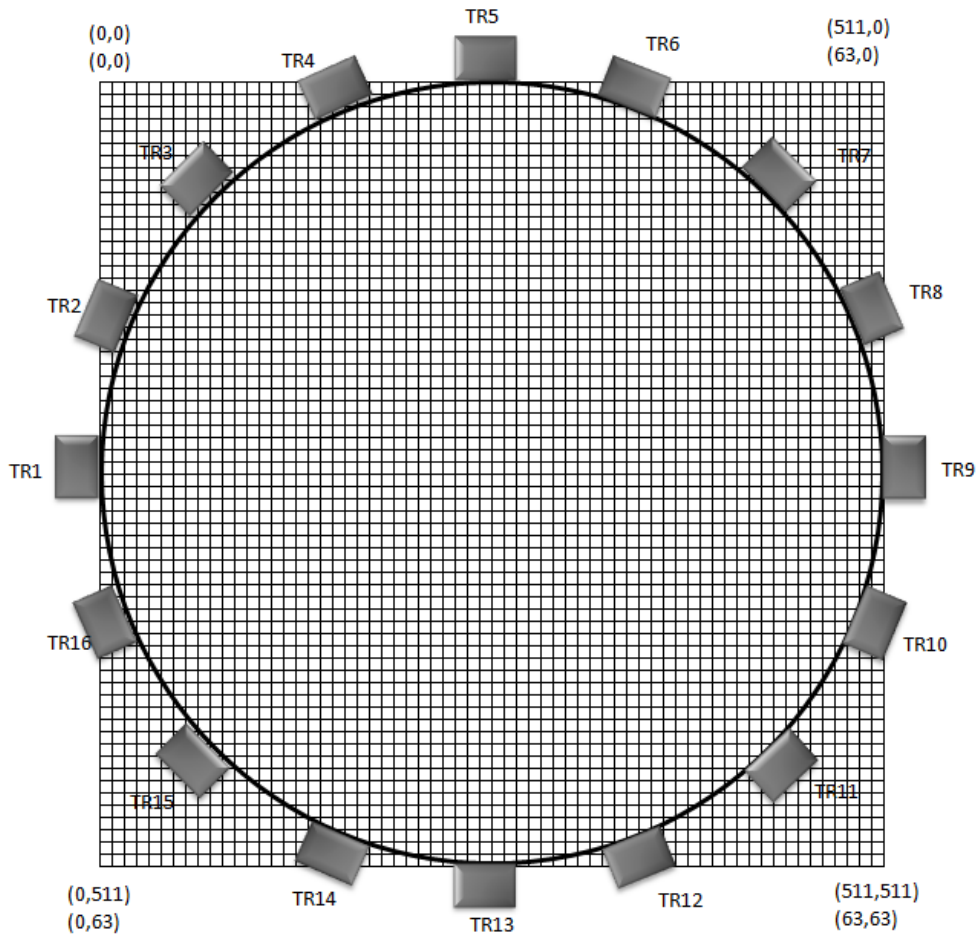


Figure 7. NI-USB Control Panel Program in LabVIEW

### 7. Image Reconstruction

There are many types of image reconstruction algorithm that can be applied depends on the requirement. Some examples of image reconstruction algorithm such as Linear Back Projection algorithm (LBP), Hybrid Binary

Reconstruction algorithm (HBR), Finite Element Method (FEM), and Hybrid Reconstruction Algorithm (HRA). In this research, Linear Back Projection Algorithm has been applied.



**Figure 8:** Image Plane Model for 64x64 Pixels Transceiver Tomogram

In order to derive this algorithm, the forward problems need to be solved first. The forward problem determines the theoretical output of each of the sensors when the sensing area is considered to be two dimensional [18]. The cross section of the pipe is mapped onto 64 by 64 rectangular arrays consisting of 4096 pixels as shown in Figure 8. The forward problem can be solved by using the analytical solution of sensitivity maps which produces the sensitivity matrices [19]. Every transceiver that acts as transmitters are virtually excited and every pixel on the path will be counted.

## 8. Sensitivity Map

Sensitivity map is a plotted of the sensitivity distribution. The sensitivity distribution can be determined by calculating the ultrasonic energy attenuation at position of each receiver due to obstruction in the object space [20]. The image plane model in Figure 7 and Figure 8 is developed by using 512x512 pixels. Then this size is reduced to 64x64 pixels by grouping the 512x512 pixels into 8x8 pixels each. To generate a series of sensitivity map, custom created software of Visual Basic 6.0 had been used. The projection of each transmitter to the receiver is represented by the virtual projection developed by using the Visual Basic program.

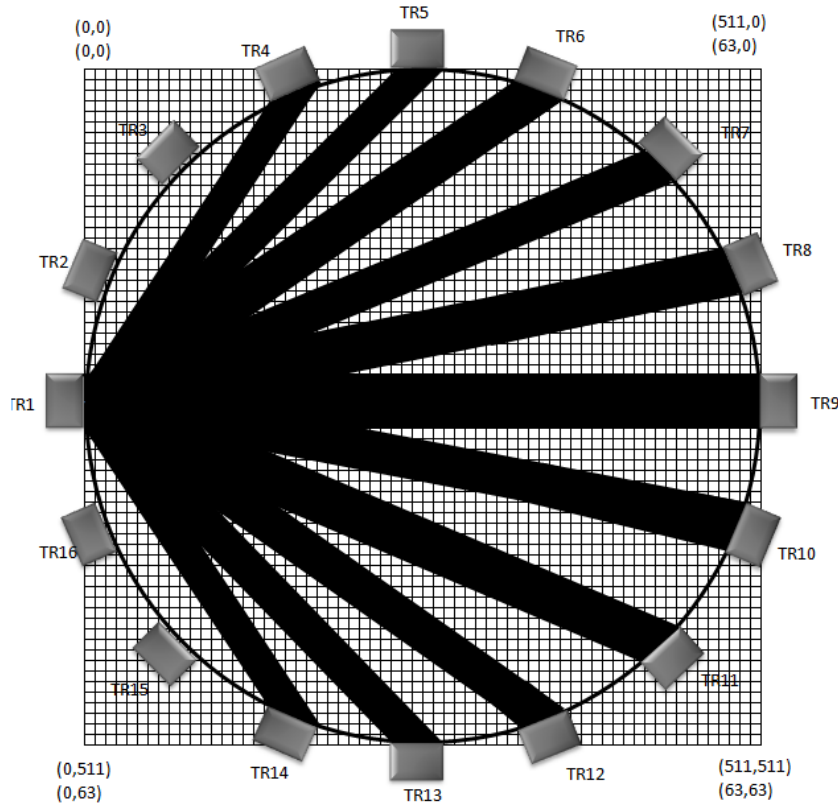


Figure 9. Projection for channel 1

The virtual projection that lay on the projection path was coloured black. The computer graphic memory is used to retrieve the small pixels (512 x 512 pixels) colour occupied by the projection using the function provided by *Windows API* function call library. Any small pixels occupied by projection (blacked) is counted and summed into the corresponding major pixels (64 x 64 pixels). The result for the projection of Figure 9 was then formed into a matrix and the details of the sensitivity map.

### 9. Linear Back Projection Algorithm (LBPA)

In Linear Back Projection Algorithm (LBPA), the concentration profile is generated by combining the projection data from each sensor with its computed sensitivity maps [21]. This method is computationally straight forward to implement besides low computation cost and is popular method for image reconstruction. The measurements obtained at each projected data are the attenuated sensor values due to object space in the image plane. These sensor values are then back projected by multiply with the corresponding normalized sensitivity maps by using below formula [22]:

$$V_{LBP}(x, y) = \sum_{Tx=1}^{16} \sum_{Rx=1}^{16} S_{Tx,Rx} x \bar{M}_{Tx,Rx}(x, y) \quad (12)$$

where

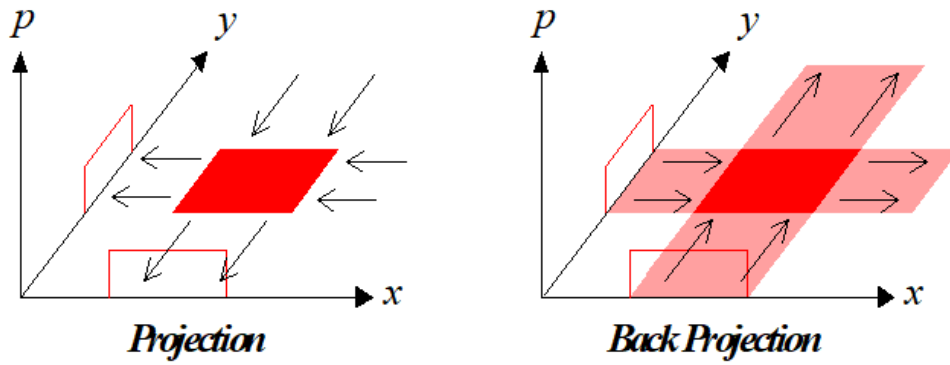
$V_{LBP}(x, y)$  = Voltage distribution obtained using LBPA

$S_{Tx,Rx}$  = Sensor loss voltage of transmitter (Tx) and receiver (Rx)

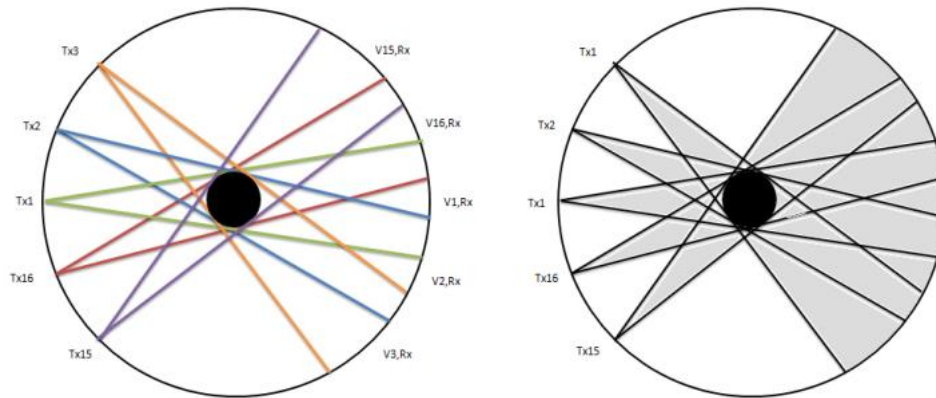
$\bar{M}_{Tx,Rx}(x, y)$  = Normalized sensitivity maps

The back projection algorithm is functioning to reconstruct the cross-sectional image plane from the projection data. It takes a pixel-based approach that basically consists of summing up the contribution of single measurements to the pixel values in the measurement plane [23]. In this method, a large number of ultrasonic transducers is necessary to obtain a good spatial resolution.

The measurements obtained at the receiver are the attenuated sensor value due to object space in the image plane. These sensor values are then back projected by multiplying with the corresponding normalized sensitivity maps. The back projected data values are smeared back across the unknown density function (image) and overlapped to each other to increase the projection data density. The processes of back projection are illustrated in Figure 10 and Figure 11.



**Figure 10.** Linear Back Projection Technique



**Figure 11.** The fan-shaped beam back projection

## 10. Experiments, Results and Analysis

The experiments were done in the pipe vessel. All the test was carried out vertically using various test material. In this section, the image reconstruction for several experimental results will be presented and discuss further.

### 10.1 System Calibration

In developing a measurement system, a calibration of the instrumentation is important in order to assign the standard or reference value for the system. Failure of doing calibration may bring the risk of taking false data. Decisions to be made based on such data can potentially be incorrect.

### 10.2 Full Flow Model

The calibration for this system was done in condition of full flow. During full flow, the pipe will totally fill with liquid. The liquid provides low acoustic impedance, hence the signal from transmitter could penetrate the pipe wall and travel to the receiver through the water. The value captured will be use as reference value for other experiment.

As the beam angle for each transceiver is  $125^\circ$ , there are only eleven transceivers within the boundary. The two transceivers beside the transmitter are outside the boundary, so total of four will not receive the projected signal. These signals will be used for the image reconstruction later. Figure 12 and figure 13 shows the full flow projections and reconstructed image for full flow.

The other values captured by the other four outsiders will not be counted as they are values due to the Lamb wave. Lamb wave generated due to the complex vibration effects. The Lamb wave is a wave that propagates and travels within the pipe boundary [22]

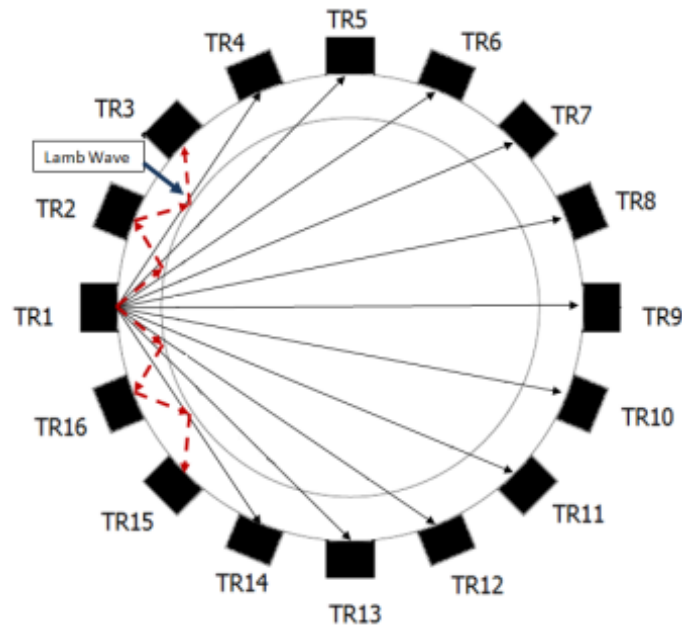


Figure 12. Full flow projections for Transceiver 1

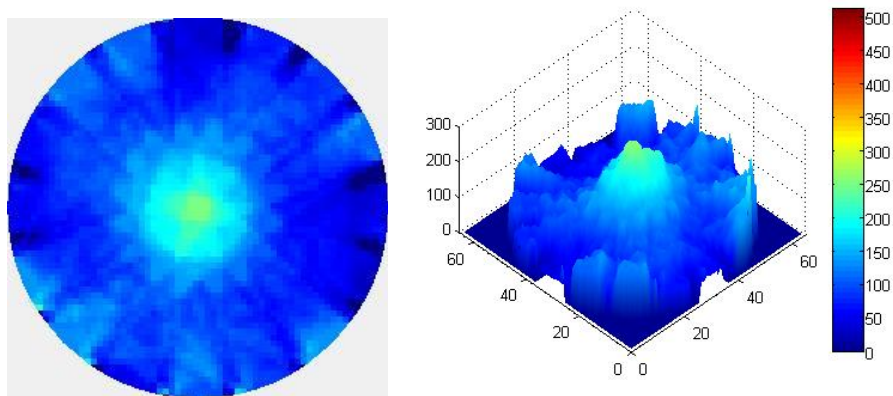


Figure 13. Reconstructed image for full flow

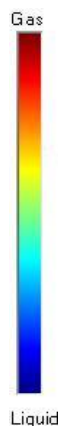
### 10.3 The Experimental Design

The experiment conducted for multiphase purpose was conducted by using several materials. Each material has different acoustic impedance value, as shown in Table 1, which is very useful for ultrasonic tomography system. The test materials and its acoustic impedance value are shown in table below. Two categories which are two phase flow and three phase flow experiment were conducted.

**Table 1.** Acoustic impedance for test materials

Material	Acoustic Impedance, Z (kg/m <sup>2</sup> s)
Water (Liquid)	1.5x10 <sup>6</sup>
Gas (Air)	430
Corn oil (Liquid)	1.42
Wood (Solid)	0.15x10 <sup>6</sup>
Cement (Solid)	5x10 <sup>6</sup>

The tomogram drawings were accomplished using Visual Basic 6 software. The test profile image includes together for every experiment so the comparison could be shown and discuss. The colour levels created for representing the liquid and air concentration in the tomogram is shown in Figure 14.



**Figure 14.** Colour bar representing concentration profile

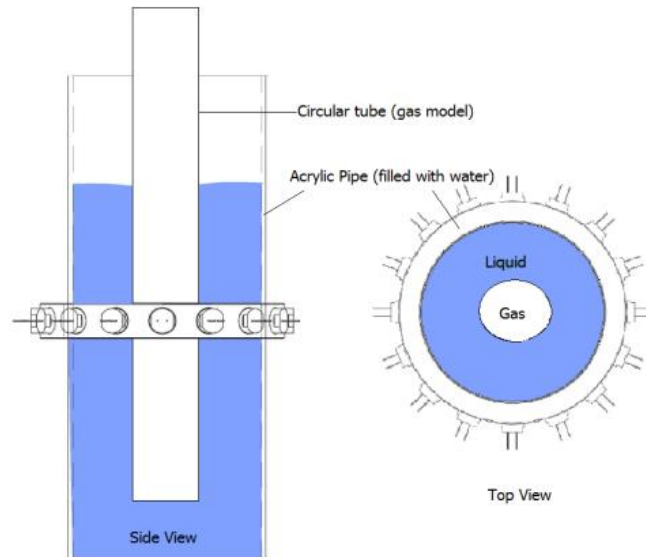
In order to evaluate the image reconstructed, simulations were carried out before the experiment. The similar size and type of material was used to be placed at the respective position in the sensing area of the developed hardware system. The difference image between the original and reconstructed images gives the quantitative and qualitative measurements that compare the quality of the reconstructed image with the original. All results presents in following section.

**10.4 Two Phase Flow Experiment**

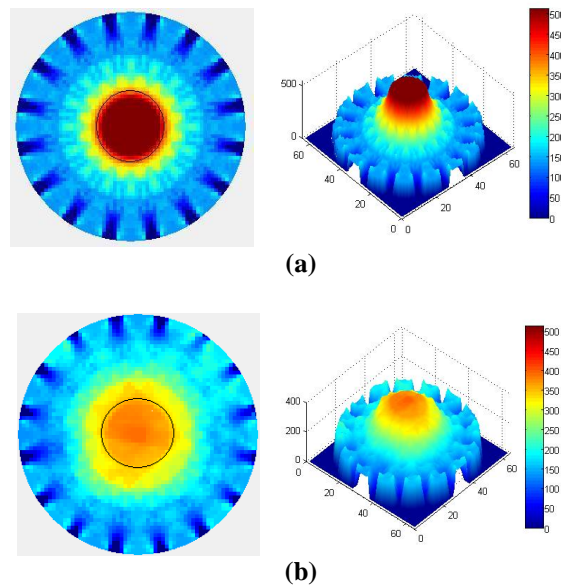
Two phase flow means that, there are two types of components or materials inside the pipe vessel. The two-phase flow systems consider were mixtures of liquids with gas, liquid mixed with solid and also liquid-liquid flow.

**10.5 Annular flow**

Annular flow is the situation when an empty circular tube (gas model) was put in the middle of the pipe and the gap between the tube and pipe was filled up with liquid (distilled water). In this experiment, 35mm hollow pipes were place in the middle of the vessel. This can be illustrated as Figure 15. Figure 16 shows comparison of reconstructed images between test profile and experiment for annular flow.



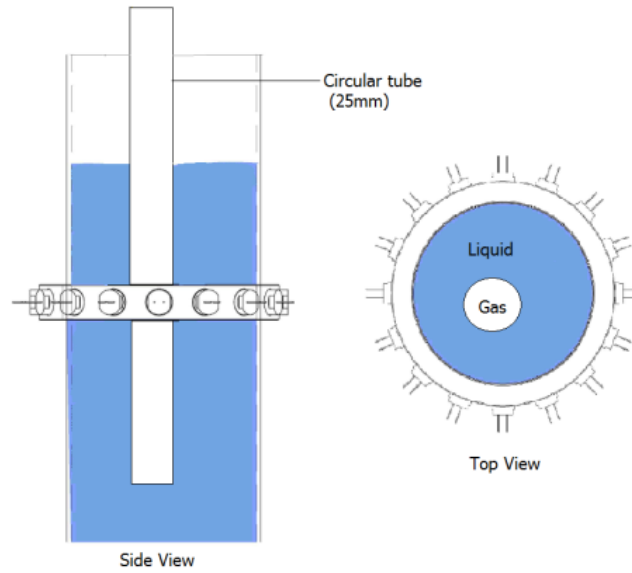
**Figure 15.** Experiment vessel setup for annular flow (30mm)



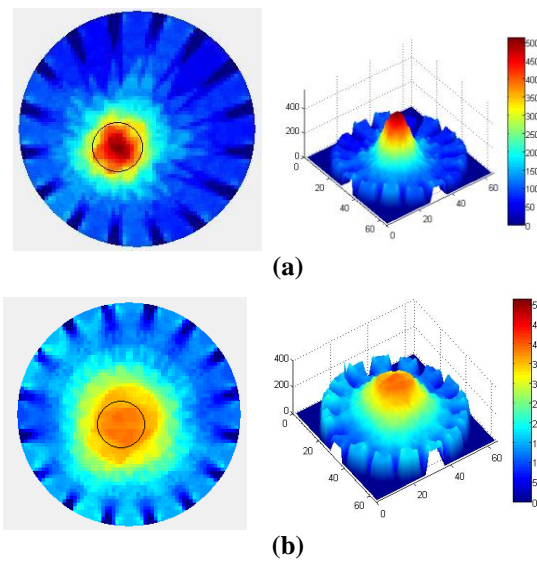
**Figure 16.** Comparison of reconstructed images between (a) test profile and (b) experiment for annular flow

### 10.6 Single Gas Hold Up

Similar as previous part, this experiment were done to investigate the two phase flow of liquid-gas. Smaller tubes of 25mm, which present gas phase, were placed inside the pipe but in a different location. Tomogram produce can be seen in Figure 17 and Figure 18.



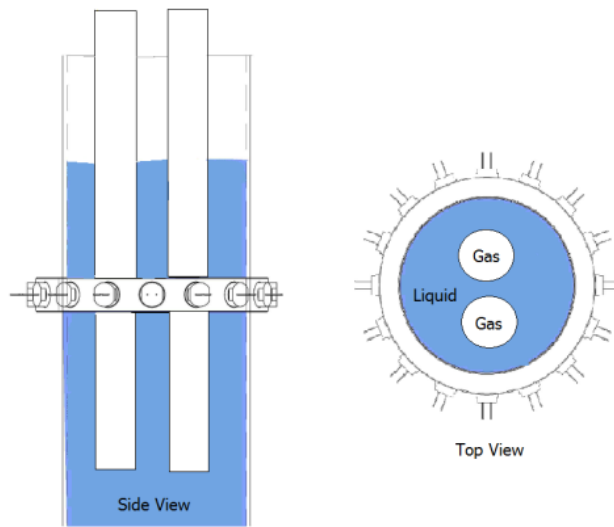
**Figure 17.** Experiment vessel setup for single gas hold up (25mm)



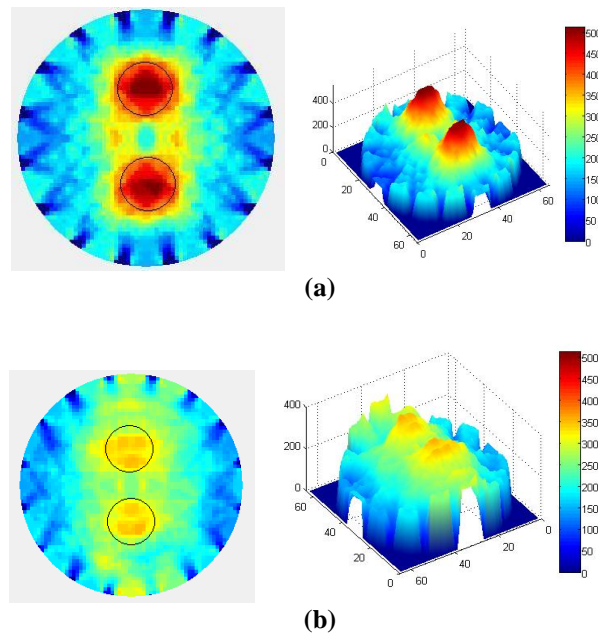
**Figure 18.** Comparison of reconstructed images between (a) test profile and (b) experiment single gas hold up

### 10.7 Dual Gas Hold Up

In this experiment, two air hold up analysis were carried out. Two circular tubes of 25 mm were inserted in the vessel. The achieve result shown in Figure 19 and Figure 20.



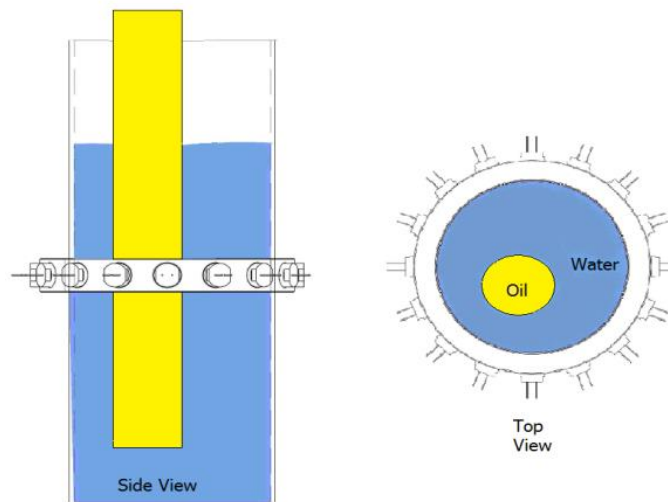
**Figure 19.** Experiment vessel setup for dual gas hold up (20mm)



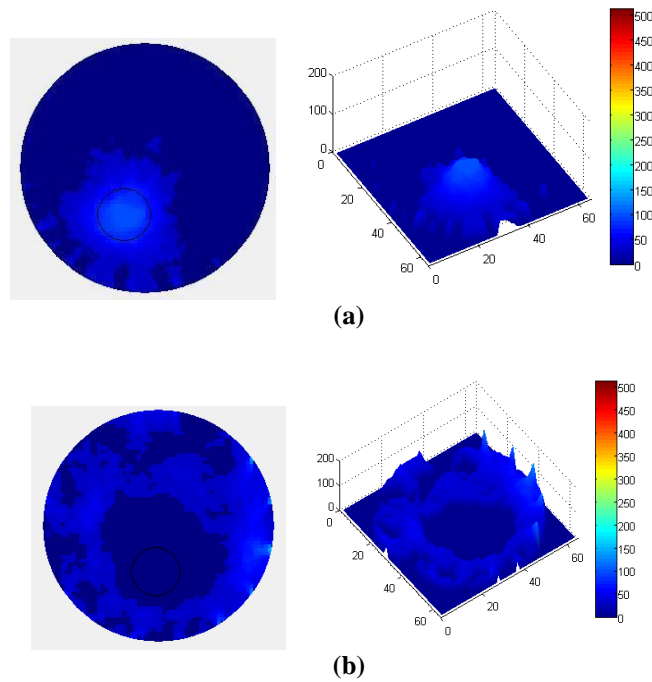
**Figure 20.** Comparison of reconstructed images between (a) test profile and (b) measured system for dual gas hold up

### 10.8 Water and Oil

In order to investigate two phase of liquid-liquid material, corn oil was use as test material. The oils were filled in the plastic tube and place vertically inside the pipe. It can be illustrated in Figure 21. The image reconstruction is shown in Figure 22.



**Figure 21.** Experiment vessel setup for water - oil flow (25mm)



**Figure 22.** Comparison of reconstructed images between (a) test profile and (b) measured system for oil - water flow.

### 10.9 Water and Cement

Cement which has  $5 \times 10^6$  kg/m<sup>2</sup>s of acoustic impedance were being tested for state of liquid-solid. A 25mm of cement in cylinder tube were located as in Figure 23 and Figure 24.

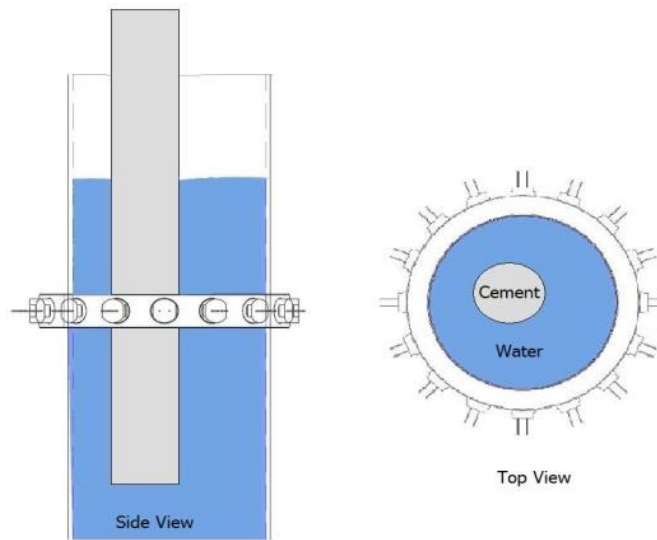


Figure 23. Experiment vessel setup for water - cement flow (35mm)

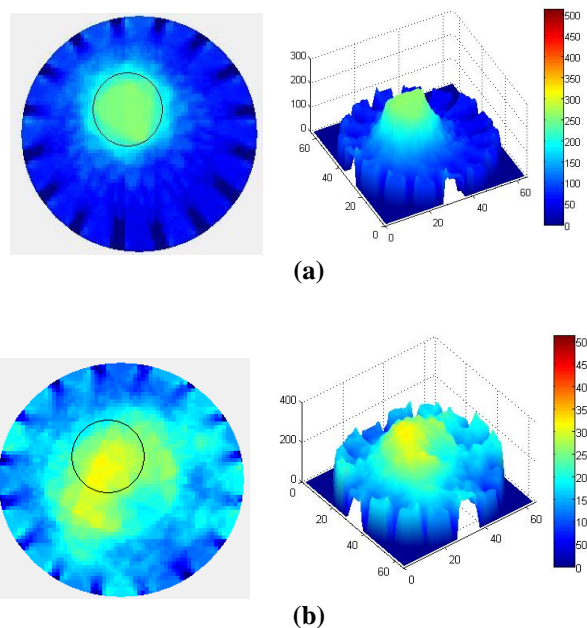


Figure 24. Comparison of reconstructed images between (a) test profile and (b) measured system for cement-water flow

### 10.10 Water and Wood

The other test material for solid is wood which have  $0.15 \times 10^6 \text{ kg/m}^2\text{s}$  of acoustic impedance. The value of acoustic impedance of wood are less than cement, thus a comparison could be done. A wood of 28mm long and 18mm width were used. Figure 25 shows the experimental setup for water-wood flow. Figure 26 shows comparison of reconstructed images between (a) test profile and (b) measured system for wood - water

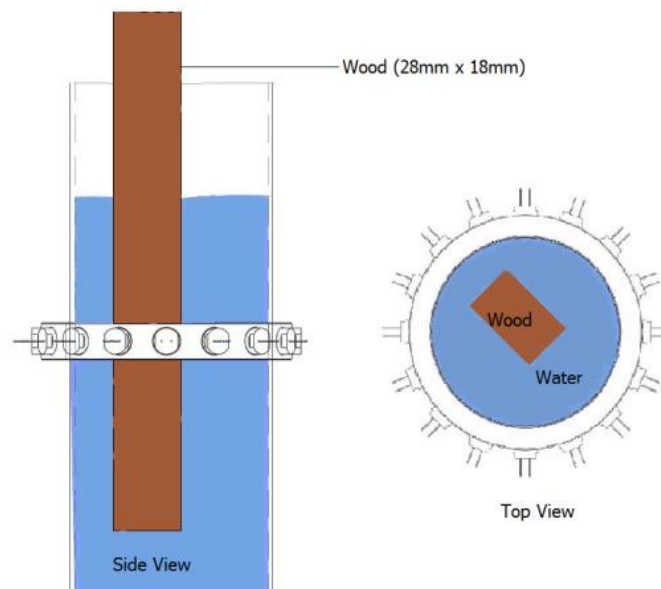


Figure 25. Experiment vessel setup for water - wood flow (28mmx18mm)

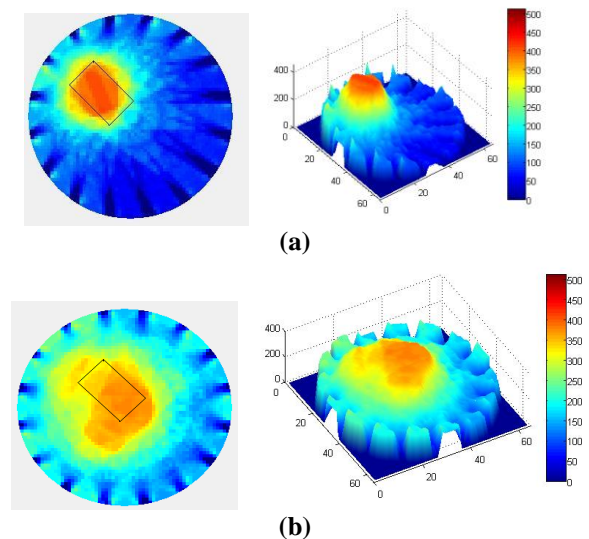
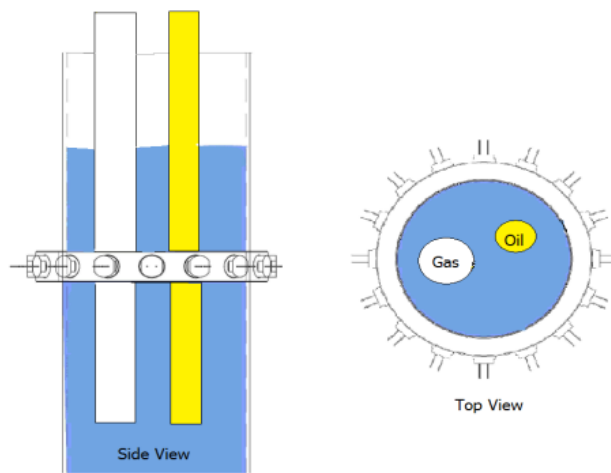


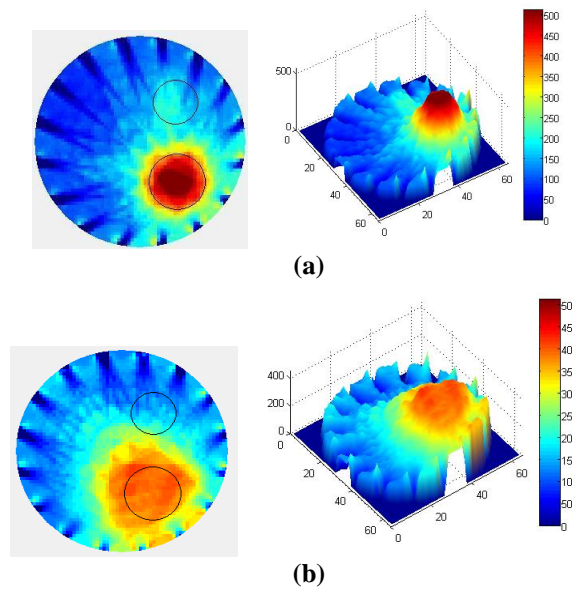
Figure 26. Comparison of reconstructed images between (a) test profile and (b) measured system for wood - water

### 10.11 Three Phase Flow Experiment

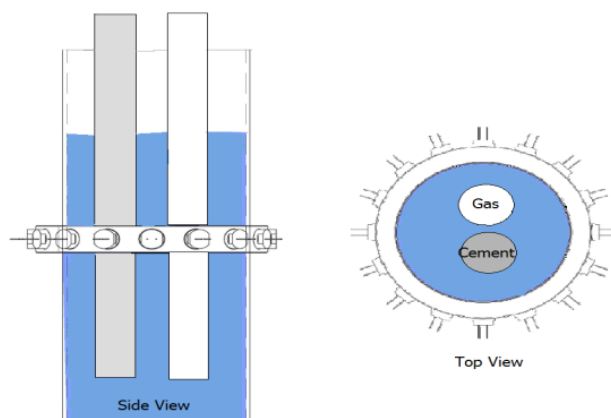
The three phase flow measurement means that there are three materials inside the vessel to be identify. This experiment conducted to identify the location and material inside the pipe. Two states of experiment were done which is liquid-liquid-gas and liquid-gas-solid. The test materials used are similar with previous testing. The experimentations are as follows:



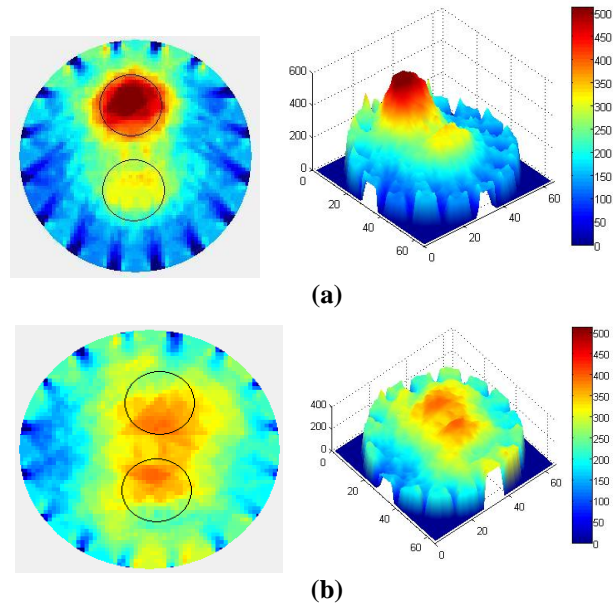
**Figure 27.** Experiment vessel setup for water, air (30mm) and oil flow (25mm)



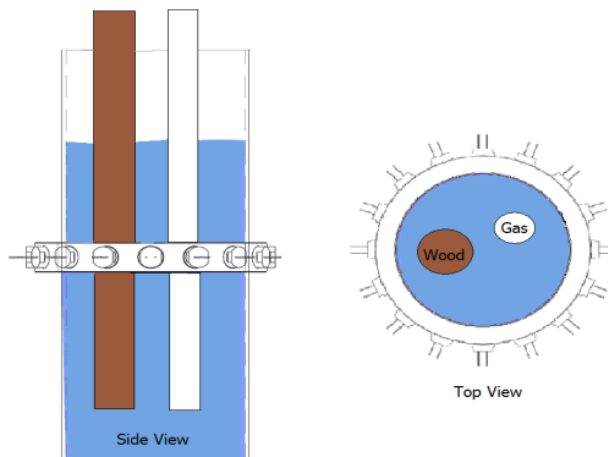
**Figure 28.** Comparison of reconstructed images between (a) test profile and (b) measured system for oil-air-water flow



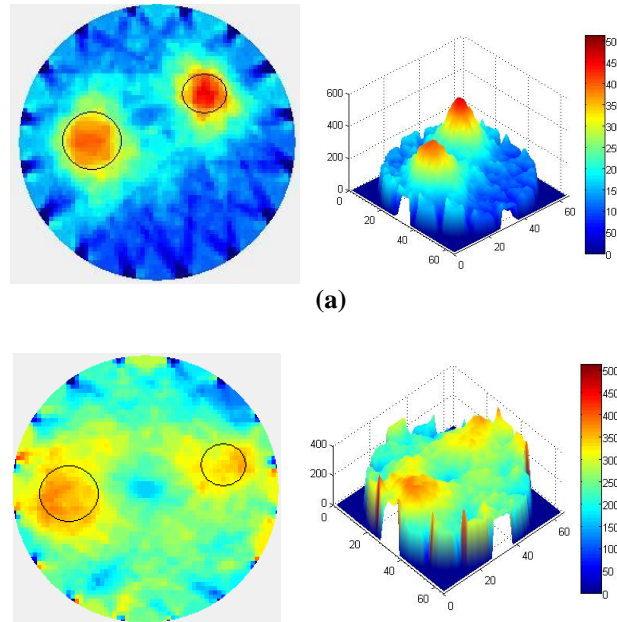
**Figure 29:** Experiment vessel setup for water, air (30mm) and cement flow (30mm)



**Figure 30.** Comparison of reconstructed images between (a) test profile and (b) measured system for cement-air-water flow



**Figure 31.** Experiment vessel setup for water, wood (25mm) and air flow (19mm)



**Figure 32.** Comparison of reconstructed images between (a) test profile and (b) measured system for wood-air- water flow

### 11. Discussions

In general, for the two phase flow results, the existence of difference object in the vessel could be trace and distinguishable. This is because of the dissimilarity of acoustic impedance between the two medium. The higher the difference the more obvious it becomes. For instance, the images of liquid-gas flow are almost the same with the test profile. It is cause by the high acoustic impedance mismatch between water and air. As explained earlier, about 99.94% of the transmit wave are reflected at the boundary of water-air hence create high value of sensor loss at the receiver.

Among the three liquid-gas images, the annular flow gives the best image in terms of size and shape. This is due to the location of the other two object are not in the middle of the pipe. It depends on the projection angle and intensity distribution at each point. Table 2 shows the area of real, theory and experiment for the liquid-gas flow. The errors of theory and experiment area are calculated.

**Table 2:** Difference of area between real theory and experiment

Flow	Real (mm <sup>2</sup> )	Theory (mm <sup>2</sup> )	Experiment(mm <sup>2</sup> )	Error
Annular flow	706.9	663.71	829	E <sub>T</sub> =6.1% E <sub>E</sub> =17.3%
Single gas flow	490.9	450.13	663.7	E <sub>T</sub> =8.31% E <sub>E</sub> =35.2%
Dual gas flow	314.2	303.72	330.71	E <sub>T</sub> =3.34% E <sub>E</sub> =5.25%

The error of the theory are because of the fault while determine the area when perform the modelling. While for the experiment error, it becomes higher because of the smeared image. The back projection technique results in blurring the object image. Nevertheless, the small error value shows that this technique could detect gas-liquid flow as well as predicting the size of the gas flow.

For water-oil flow, the densities of corn oil are almost the same with water. It clarifies the fact that only 2.73% of the waves are reflected which means this method is not suitable for imaging oil water flow. In the case of liquid-solid flow, cement with  $5 \times 10^6$  kg/m<sup>2</sup>s of acoustic impedance show blurry image rather than wood with  $0.15 \times 10^6$  kg/m<sup>2</sup>s. The images successfully differentiate the two different materials although the exact shape could not be constructed.

For three phase flow results, it shows that this technique could detect the location of object other than liquid phase. However, it could not differentiate the type of the object itself. In water-oil-air flow, only the gas phase clearly appeared while corn oil is not stand out. As discussed earlier, the percentage of transmit wave are high so the sensor loss are low thus did not give much differences of the density. As shown above, the presence of air-cement and air-wood could be detected. Nevertheless, the intensity of those two objects is almost same, but still the size is dissimilar. It is due to the transmit wave are cross each other hence effect the sensor loss value received by opposite receiver.

Obviously, all the reconstructed images turn out to blur the object. This is due to the process of back projection. The back projected data values that smeared back across the unknown density function and overlapped to each other

lead to the formation of smearing effect. Another reason that causes dissimilarity of the experiment image and modeling image are the sensitivity of the transceiver itself. The fault of sensor fabrication affects also the quality of the image. Not all of the sensor could transmit or receive with corresponding value. Besides that, the number of projection will also affect the image quality as LBP algorithm depends on projection number to increase the intensity of the object.

## 12. Conclusions

A non-invasive of multiphase flow imaging using transceiver method has been developed and implemented successfully. Sixteen transceivers have been successfully implemented non-invasively in this research. The fabrication including designing the sensor jig and mounting using suitable coupling mater. The software for image reconstruction has successfully created using Visual Basic 6.0 software. The algorithm for sensitivity map has also created in this software. The program could also display the image through GUI and store the concentration profile value in the matrix form

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