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A Simplified Calibration of Liquid Hold-Up and Film Thickness in Annular Flow in Horizontal Pipe

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Abstract: Annular flow is majorly encountered in petroleum industry, where gas and liquid are conveyed from gas wells or oil wells (dominated by gas) to the surface through the transport lines. A simplified annular flow bench calibration for liquid hold-up and film thickness in horizontal pipe was conducted using water/air in a 2-inch (50mm) Plexiglas pipe test tube with a length of 154mm. The calibration was achieved using five different acryl plastic rods inserts of 49mm, 48mm, 47mm, 46mm and 45mm with a length of 153mm respectively. The 2-inch (50mm) plexiglass test tube was installed with two pairs of conductivity ring sensors for liquid hold-up and the flush-mounted conductance probe sensor for liquid film thickness. The acts of measuring, recording and transmitting the data to a usable state were achieved using a digital data acquistion system (Labview). The conductivity ring sensors C1 and C2 results which were for the liquid hold-up in the calibration gave R-factors of 0.9962 and 0.9947 respectively, while the conductance probe sensor for the liquid film thickness presented an R-factor of 0.9949.

Keywords: Conductance, Sensors, Film Thickness, Acryl Rods, Annular Flow

1. Introduction

Annular flow in horizontal pipe is a complex flow of gas and liquid phase flowing at different velocity to the delivery end. Annular flow in pipes flow with gas phase as the dominant phase with liquid droplets being entrained while the liquid phase is sparsely distributed circumferentially across the walls of the pipe. It flow with high gas velocity at the core center of the pipe with much impact of gravity leaving the circumferential liquid film on the internal walls of the pipe which drains down to the bottom of the pipe, Osokogwu [18].

This means it flows with high gas velocity impact at the center of the pipe with gravity, leaving the circumferential liquid film on the internal walls of the pipe which drains to the bottom of the pipe as film thickness, Osokogwu [19]. According to Sergey et al [13], the liquid flows as a film along the pipe walls under gravity by high velocity gas stream at the core center of the pipe. The entrained liquid droplets with gas together, flows within the core of the pipe at high velocity and the entrained droplets travel at a velocity close to that of the gas, Shi [12]. Annular flow exhibits a slowly thick liquid film that moves at the bottom of the internal pipe walls than the gas phase, Shi [12]. The combined slow flow of the liquid at the bottom with the fast gas phase at the interface, aids to increase the pressure gradient and wall shear stress in annular flow. However, a thin liquid film exists at the curved surfaces and the upper walls while a thick liquid film exists at the bottom of the internal diameter of horizontal pipes, Osokogwu [19]. More so, the liquid which is non-uniformly distributed, flows circumferentially around the walls of the pipe. According to Setyawan et al [14], the asymmetry nature of annular flow in horizontal pipes is dependent on the mass flow rate of the liquid and gas. Liquid film thickness has been proven to be higher at the bottom of the pipe compared to the curved surface area and the upper walls of the pipe internally. This is because of the effects of gravity-induced drainage, which increases the liquid film thickness at the bottom of the pipe, [14, 15].

Also, McManus [10] investigated and reported on circumferential water film thickness in annular in pipes.

Anderson and Russel [2] likewise presented film thickness at the upper part of the walls of the pipe while Butterworth [3] experiments were on film thickness with respect to axial flow. More scholarly investigations of [4, 17, 9, 11] were also centered on liquid film thickness in annular flow in pipes.

Annular flow is mostly experienced in the oil and gas industry, power plants, chemical industries that uses: reactors, refrigerators, evaporators and heat exchangers in their operations. Based on its wide occurrence in the industries, several experimental studies have been published with more researches still on at different levels to proffer solutions to the emerging challenges in the industries. In achieving these studies, several calibrations using optical and electrical impedance techniques on annular flow were carried.

Among the few calibrations on liquid hold-up and film thickness in annular flow are: the application of surface-mounted conductance probes and its theory for liquid film thickness and wavy film of water measurements in two-phase flow which were conducted by Chao *et al.,*[5]. He presented an electrical conductance of probe as a function of film thickness with the aid of a theory developed. Also considered was liquid film thickness measurements on a non-conducting liquid as he did on conducting liquid. The application proved that resolution could be achieved both in parallel and perpendicular to the axis of the tube within a short-segmented probe distance with accuracy results in two-phase flow. Andreussi *et al*., [1] Reported calibration experiments on stratified, bubble and annular flow using (impedance method). In the experiments, three ring electrodes which were non-intrusive were flush-mounted to the walls of the pipe to measure the electrical impedance. The apparatus used comprises of an internal pipe 50mm with Plexiglas rods of different diameters to simulated annular flow condition in the calibration.

The works of Shi [12] were based on computer code three-field model (FIDAS-3DT) application for predicting liquid film thickness in horizontal annular two-phase sub channel flow. The liquid film thickness results were further validated with an experimental results of air/water flow conducted on a pipe with internal diameter of 32mm and 3.9m long. In conclusion, the model for film thickness in annular flow presented good results when compared with experimental results at steady and fully developed state.

For stratified and annular flow, Chao *et al*., [5] conducted calibration experiment using a conductance probe for measuring liquid fraction in gas-liquid flow. The test was categorized into section A and B. Section A was a big test apparatus of 70mm Plexiglas of internal diameter with a length of 480mm while section B was a small test apparatus of 14mm of internal diameter with a length of 70mm. More calibrations on bubble, stratified and annular flow using conductance ring sensors were conducted by Shi [12]. This was achieved using six conductance ring sensors that were flush-mounted on the internal walls of the calibration pipes to measure liquid fraction and axial velocity for bubble, stratified and annular flow.

Also, Fossa [7] carried out calibrations using conductance sensors with three electrodes set at adjacent and opposite directions. The calibration was conducted using a 40mm internal diameter pipe with a length of 5m. In the calibration experiments, stratified and annular flow conditions were considered. For annular flow, Fossa [7] used five acryl rods diameter pipes of 30mm, 33mm, 35mm, 37mm and 38mm. The acryl rods were inserted with their respective voltage output obtained and the void fraction noted as 0.56, 0.68, 0.76, 0.86 and 0.9 respectively. More so, extensive theoretical and experimental liquid hold-up analysis using gas-liquid flow in pipes/packed beds were carried out by Tso and Sugawara [16], using pairs of ring sensors. The aim was to determine cross-sectional liquid hold-up in stratified and annular flow distributions using Plexiglas cylindrical column with internal diameter of 14cm and 20cm long. At the end, they developed an analytical approach to annular flow distributions with respect to liquid hold-up.

The above calibrations and procedures were perfect in their unique ways. However, this study presents these annular flow calibrations for liquid hold-up and film thickness in a simplified approach with the pipe test tube design and the acryl rods shown in appendix.

Experimental Set-Up

A 2-inch (50mm) Plexiglas horizontal pipe test tube with a length of 154mm was used for annular flow bench calibration. The experimental pipe test tube set-up had two pairs of conductivity ring sensors of upstream and downstream as C1 and C2 respectively, installed at 70mm apart on the external surface of outer diameter of the pipe. Installed also, was a conductance probe sensor which was flush mounted in the internal diameter of the 2-inch pipe test tube. The conductance probe sensor has a central plate electrode of 10.25mm in diameter (inner conductor) and the outer circular plate of 1.80mm as outer conductor with a circular insulator of 2.40mm separating the two conductive plates as shown in figure 4.

Therefore, the conductivity ring sensor and the conductance probe sensor were connected directly with black coated flexible wires to the receiver as shown in figure 2. The receiver conveys the signals to the central processing unit were the signals were recorded in a Labview as the calibrations were being conducted.

The horizontal Plexiglas test tube was sealed at both ends with liquid drain holes of 6mm as shown in figure 2. The end cap (seals) were drilled at the center with a diameter of 25.02mm to a depth of 10mm. The essence was to enable the acryl rods to be fixed firmly at the center position of the 50mm test tube as part of the precautions for having a circumferential liquid film thickness across the pipe internal diameter. The drains were used for water passage: draining and introducing fresh water during the calibrations with a stopper as shown in the design (Appendix).

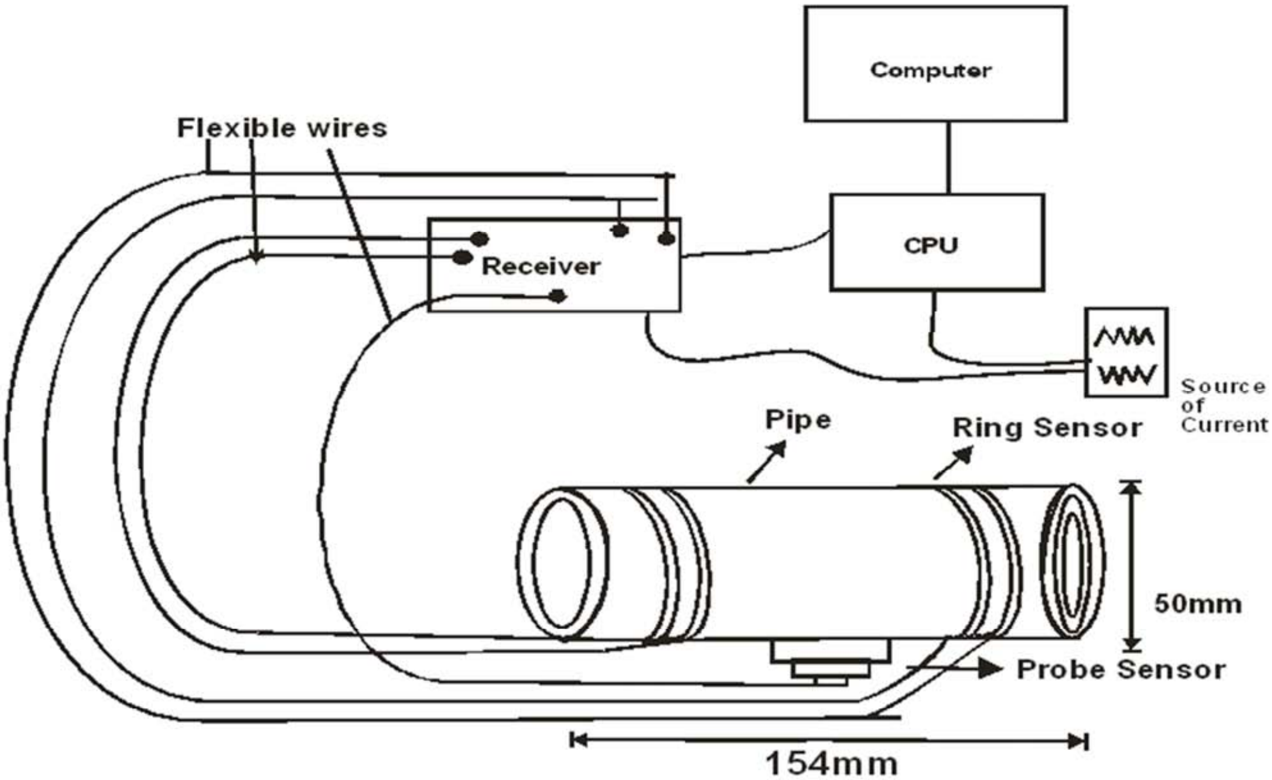

Figure 1. *Bench Calibration Set-up of Annular Flow.*

Figure 2. *Plexiglass Pipe Test Tube with Ring Sensors and Probe Sensor.*

Figure 3. *The different Acryl-Plastic Rods or Blocks used.*

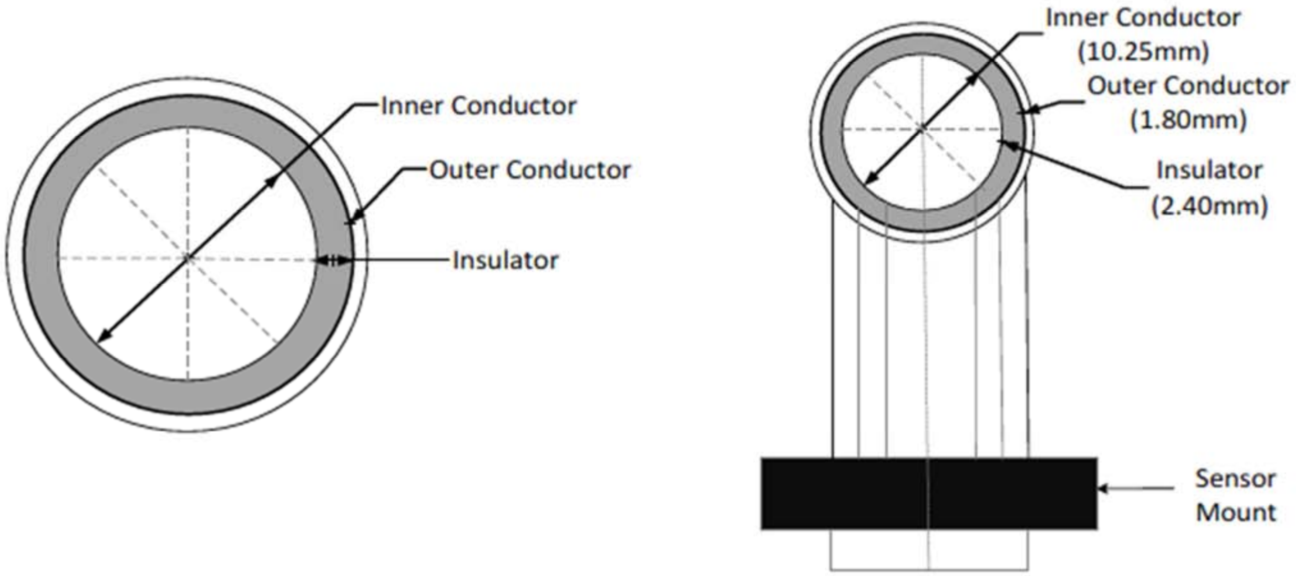

Figure 4. *A Sketch of Conductance Probe Sensors Used.*

2. Methodology

The annular flow calibration using horizontal pipe test tube was conducted with water of known volume with five different acryl rod inserts of 49mm, 48mm, 47mm, 46mm and 45mm with a length of 153mm respectively as shown in figure 3. The 50mm test tube was often filled up with volume of water weighed on each of the test conducted and the voltage values were recorded. On each of the acryl rod inserted, the space (annulus) between the acryl rod and the internal diameter of the 50mm test tube was always filled with water which was measured and the voltage recorded as presented in appendix 2. The entire voltage recorded from the different acryl rod inserts were normalized using the equation below;

$$G^* = \frac{G}{G_i}, \frac{V}{V_w}, or\ \frac{V_{signal} - V_{air}}{V_{water} - V_{air}} \quad (1)$$

Where V is the voltage of the reading at different liquid fractions, while V water, is the voltage of the full calibration pipe with water.

Conductance Probe Sensor

Conductance probe sensor was used for liquid film thickness in the calibration. The probe sensor has two electrodes, a central circular plate electrode of 10.25 mm in diameter (inner conductor) and the outer circular plate of 1.80 mm (outer conductor). The circular insulator of 2.40 mm is separated by two circular plates.

Conductivity Ring Sensors

This is used to obtain flow values by injecting electric current into the pipes through the outer pair of electrodes and measuring the corresponding electric potential drop in between each successive electrode Coney [6]. The conductivity sensors were used to measure the liquid hold-up. It measures a resistance based on amount of liquid fraction in the system or pipes and gives an output voltage as its readings.

Procedures For Liquid Hold-Up.

The following were the procedures and processes used in the calibration experiments:

Empty 50mm horizontal pipe test tube was also connected to source of current with the voltage recorded.

The 50mm horizontal pipe was filled with water without acryl rods and the voltage was recorded using the digital data acqusition system (Labview).

Each of the acryl plastic rods, inserted differently and the annulus between the 50mm (I.D) and the outer diameter of the acryl rod inserts, were filled with water and voltage values were recorded in Labview at sacn duration of 60s.

Also the the liquid fraction of each acryl rod inserts were weighed using weighing balance.

The bench calibration was repeated three times.

The voltage results recorded were normalized using equation 1.

A graph of normalized voltage against Liquid hold up was plotted with equations 1 as shown in figure 5.

The above equation of C1 and C2 were used to obtain the final liquid hold-up from the experimental data.

Procedure for Film Thickness using Conductance Probe Sensor.

The 50mm pipe was clamped to the base of the table to ensure that the water and the solid objects (acryl plastic rods) were stable.

The empty pipe of 154mm was recorded. Full pipe of 154mm with water was also recorded.

The solid objects (acryl plastic rods) were then inserted in these order, 49mm, 48mm, 47mm 46mm and 45mm and voltages were recorded.

The gap or space between the pipe of 50mm and the solid objects used (49mm, 48mm, 47mm, 46mm and 45mm), represents the *reference film thickness* in the bench calibrations.

The experiments with the solids (acryl plastic rods) were repeated 3times.

The output voltage was normalized using equation 1 and plotted against the reference film thickness as shown in Figure 6.

Conductivity Rings Calibration for Film Thickness

A bench calibration for liquid film thickness using conductivity ring sensors for annular flow was conducted also using a 50mm (I.D) with a length of 154mm. The calibrations for liquid film thickness were extended using conductivity ring sensors because of the wider coverage. The sensors could detect the circumferential liquid film thickness across the internal diameter of the pipe.

The 50mm horizontal pipe was filled with water without acryl plastic rods and the voltage values were recorded using the digital data acqusition system (Labview).

Each of the acryl plastic rods were inserted differently and the annulus between the 50mm (I.D) and the outer diameter of the acryl rod inserts, were filled with water and voltages were recorded in Labview at sacn duration of 60s.

Also the the liquid fraction of each acryl rod inserts which represents the reference film thicknesses were weighed.

The bench calibration was repeated three times.

The voltage results recorded were normalized using equation 1.

A graph of normalized voltage against reference film thickness was plotted as shown in figure 7.

The above equations of C1 and C2 are for the final film thickness from the experimental data.

3. Results/Discussion

The graphs of figures 5, 6 and 7 were the results of the recorded voltages which were transmitted to a usable state as data with the aid of digital data acquistion systems (Labview). Figure 5 presents the results of liquid fraction against normalized voltage from the conductivity ring sensors C1 and C2 which were further anylesed to obtain equations 1 and 2 respectively from both ring sensors.

$$C1=y=0.6601X - 0.0039 \ (R^2=0.9962) \tag{2}$$

$$C2=y=0.681X - 0.006 \ (R^2=0.9947) \tag{3}$$

The above equations (2 and 3) were required in determining the true values of liquid hold-up in a fully developed annular flow experiments of two-phase flow in horizontal pipe.

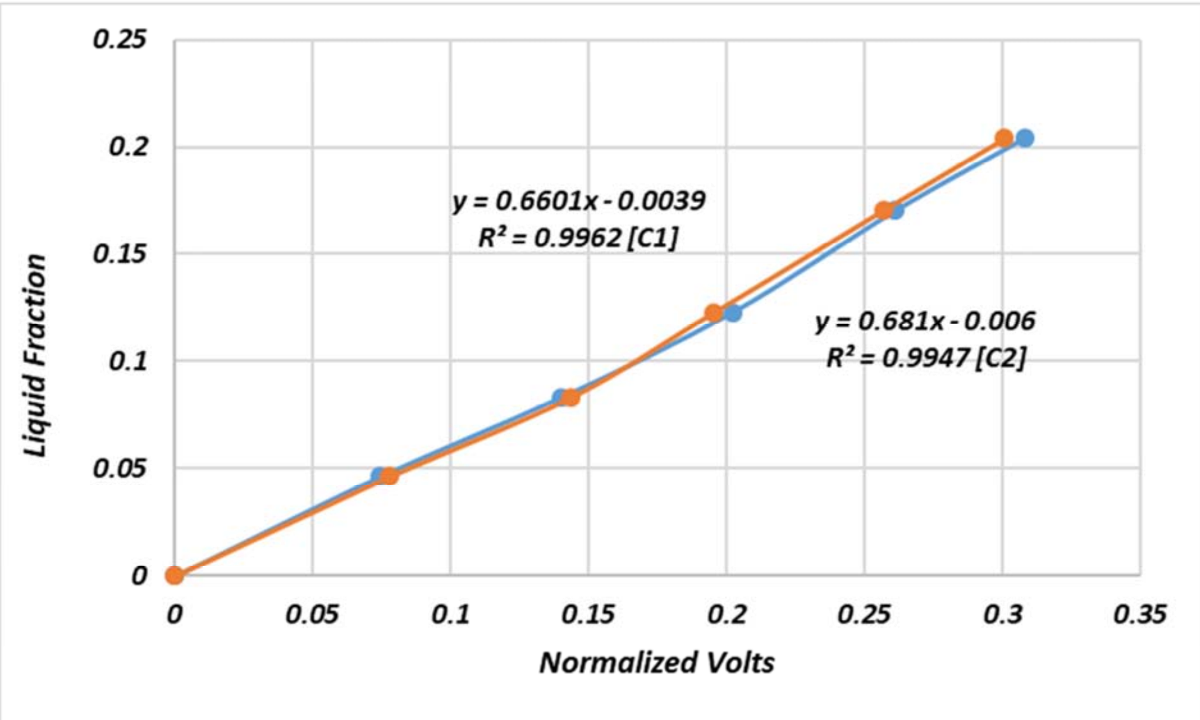

Figure 5. *Liquid Hold-Up Vs Normalized Voltages from Conductive Ring Sensors.*

The graph of figure 6 represents the normalized voltage values of the liquid from the conductance probe sensor against the reference film thickness. The reference film thickness is the annular (space) between the different acryl plastic rods inserted in the 50mm internal diameter pipe test tube. The graph presented a concave curve plot with a reference film thickness equation which could be further used to determine liquid film thickness from two-phase experiment in annular flow in horizontal pipe. The graph presents a reference film thickness equation 4 which could be used to determine the liquid film thickness in annular two-phase flow in horizontal pipe.

$$Y=-0.0253X^2 +0.2532X +0.016 \ (R^2=0.9949). \tag{4}$$

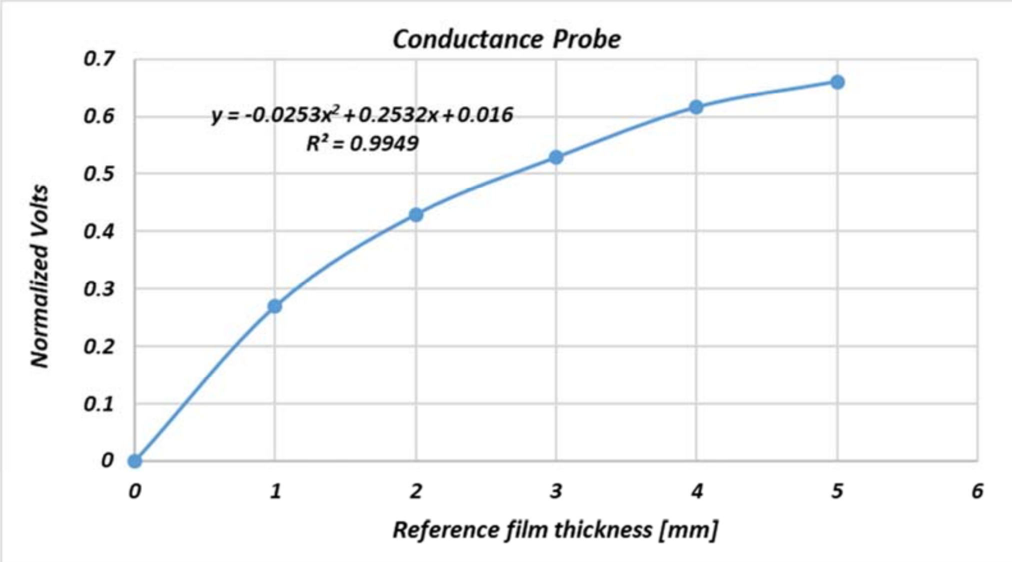

Figure 6. *Normalized Voltages Vs Reference Film Thickness from Probe Sensor.*

Liquid film thickness was further presented from the bench calibration experiments using conductivity ring sensors. Conductivity ring sensor covers the entire outer diameter of the 50mm test tube pipe hence could detect more liquid film thickness circumferentially in the internal diameter of the horizontal pipe. The graph of figure 7 which had the normalized voltages against the reference film thickness was from the bench calibration with conductivity ring sensors. The plot was not completely linear with the C1 and C2 equations (5 and 6) which could be further used in determining the true liquid film thickness in annular two-phase flow in horizontal pipes.

$$C1=0.0618X + 0.0098 \; (R^2=0.9951) \tag{5}$$

$$C2=0.0598X + 0.0129 \; (R^2=0.9925) \tag{6}$$

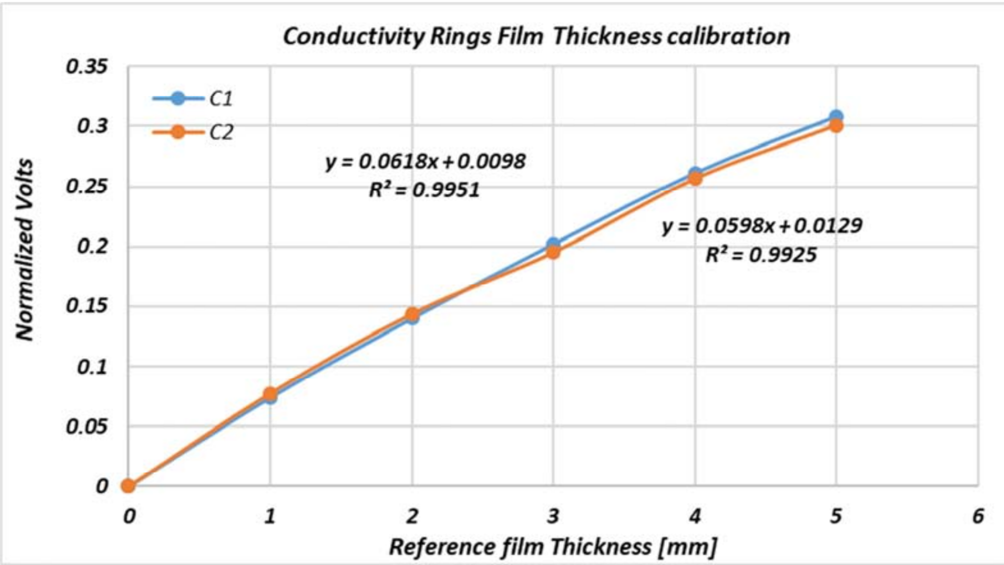

Figure 7. *Normalized Voltages Vs Reference Film Thickness Calibration from Ring Sensors.*

4. Conclusion

Annular flow bench calibrations for liquid hold-up and film thickness in horizontal pipe were achieved using conductivity ring and conductance probe sensors. From the calibrations, graphs of liquid hold-up, reference film thickness and corresponding equations 2 to 6 were presented. The equations which are vital from the experiments are used in determining the overall liquid hold-up and film thickness from two-phase experiments that conducted in the Laboratory. It was achieved by substituting the normalized voltage values of conductivity rings and conductance probe sensors respectively from two-phase flow experiments for annular in horizontal pipes into the respective equations 2 to 6 accordingly, to present the true liquid hold-up and film thickness in the study.

From the procedures expatiated above, annular flow calibration which is often seen as a difficult task could be easily developed in the laboratory with good results as illustrated in this study with the calibration set-up, apparatus designs as shown in appendix 1, procedures and the option of determining the liquid hold-up and film thickness using equations generated from your own calibrations.

Nomenclature

S=Sand Probe
C_1=Conductivity Ring Sensor (Upstream)
C_2=Conductivity Ring Sensor (Downstream)

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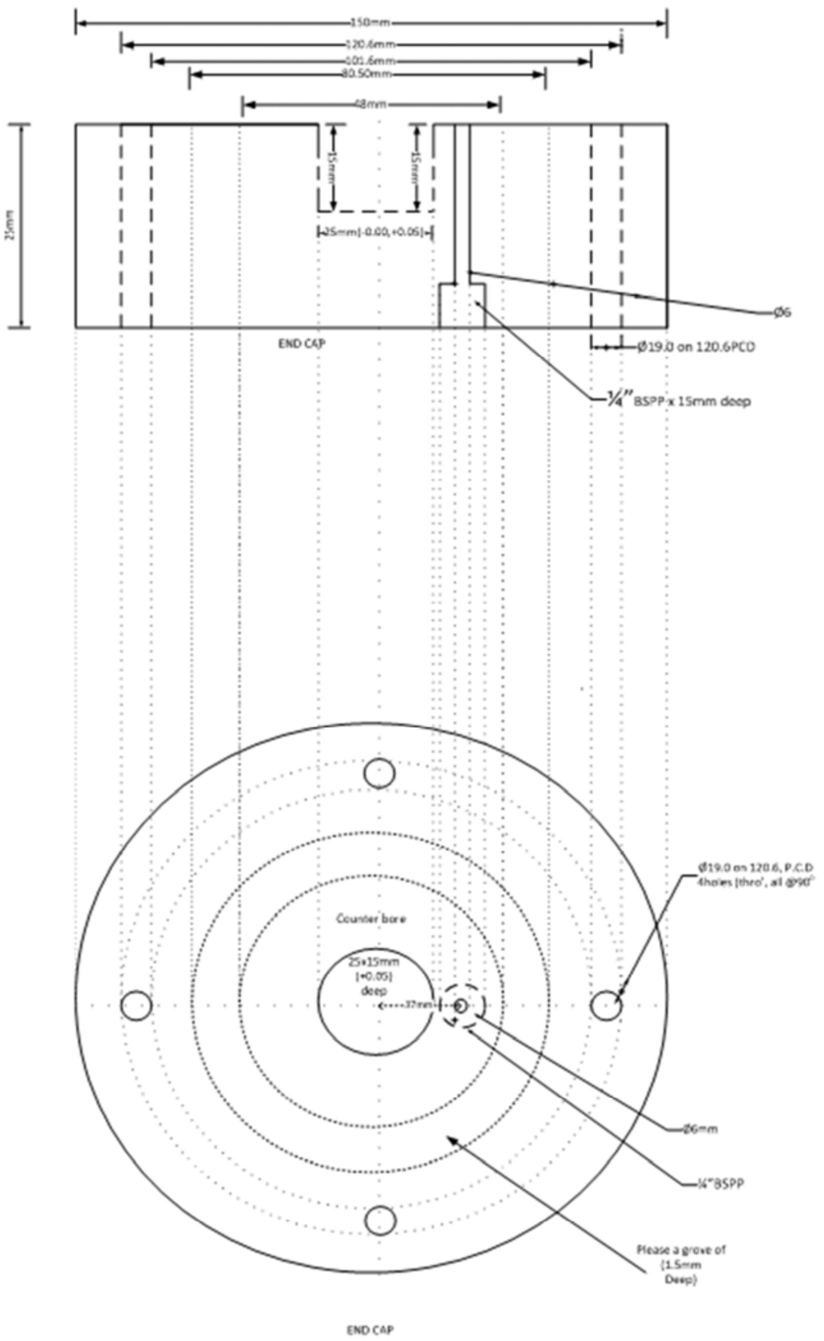
Appendix



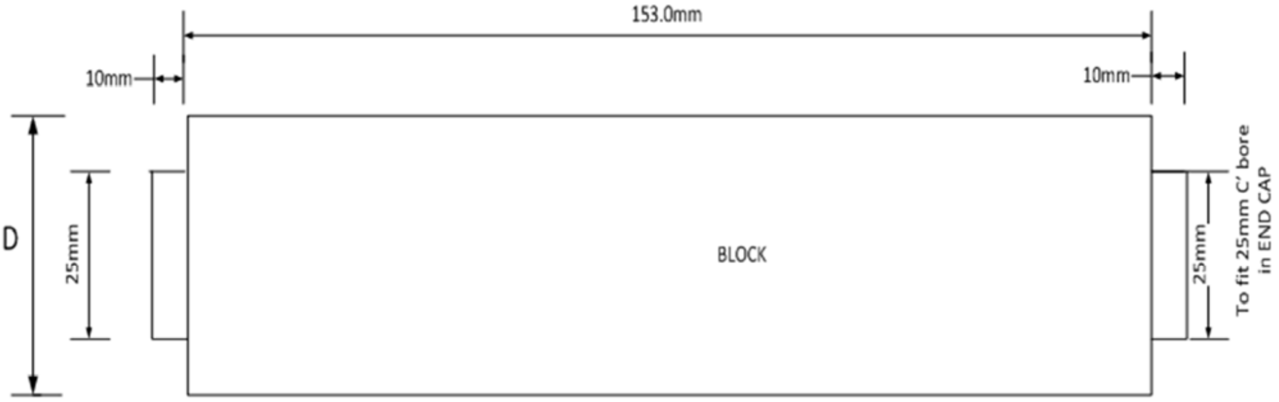


Figure 8. *Annular flow calibration blocks and the end cap design.*

Table 1. *Annular flow calibration using conductivity ring sensors (C1, C2)/ conductance probe (S) for liquid-up and film thickness.*

	C1	C2					S	
Full-water	4.925262295	5.10790164	Full water=292.50g			Full-water	*6.46542623*	
Empty pipe	*0.02547541*	*0.036*		*Liq. Fraction (HL)*	*Hg=1-HL*	Empty pipe	*0.005016393*	
					Void Fractn (Hg)	*Normalized*	*Normalized*	*Normalized*
Pipe (mm)	*Block (mm)*	*Ref. Thickness*	*Weighed (g)*	*weighed/292.50g*	*being Blocks*	*C1*	*C2*	*S2*
50	45	5	59.71	0.204136752	0.795863248	0.308131782	0.300900466	0.660690799
50	46	4	49.9	0.170598291	0.829401709	0.261322738	0.256795468	0.616074366
50	47	3	35.98	0.123008547	0.876991453	0.20213115	0.195324346	0.528680445
50	48	2	24.41	0.083452991	0.916547009	0.140175288	0.143814916	0.429357457
50	49	1	13.5	0.046153846	0.953846154	0.074205961	0.077638693	0.269987439
50	50	0	0	0	1	0	0	0

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