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EXPERIMENTAL AND THEORETICAL STUDY OFANNULAR FLOW USING A VENTURI WITH CONDUCTANCE SENSORS

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ABSTRACT

Wet gas metering is becoming an increasingly important problem to the oil and gas industry. The Venturi meter is a favoured device for the metering of the unprocessed wet natural gas production flows. Various combinations of techniques have been employed in annular gas-liquid two phase flows to measure the flow parameters (e.g. liquid film thickness, gas volume fraction and the phase flow rates). One of the most useful techniques which has proven attractive for many multiphase flow applications is the electrical conductance technique.
This paper presents an advanced Conductance Venturi Meter which is capable of measuring the gas volume fractions at the inlet and the throat of the Venturi. This model is based on the measurement of the gas volume fractions at the inlet and the throat of the Venturi meter using a conductance technique. We measure conductance using two ring electrodes flush with the inner surface of the Venturi throat and two ring electrodes flush with the inner surface of the Venturi inlet. The basic operation of the electrical conductance technique in a multiphase flow is that the conductance of the mixture depends on the gas volume fraction in the water. An electronic circuit was built and calibrated to give a dc voltage output which is proportional to the conductance of the mixture which can then be related to the water film thickness in annular flow.

Keywords: Venturi meter, electrical conductance technique, annular flow.

1 Introduction

Wet gas, as a special gas/liquid two-phase flow, exists widely in gas/oil, power, heating and chemical industries. The Venturi meter is playing an increasingly important role in wet gas metering. Annular gas-liquid two phase flow widely occurs in flow channels of nuclear processes. In water continuous multiphase flow, the electrical conductance technique has proven attractive for many industrial applications. The idea behind this technique is that an electric current is made to flow through the gas-water mixture, between two ring electrodes in contact with the mixture, and the resultant measured voltage drop is proportional to the mixture conductance. The gas volume fraction can then be determined from this measured mixture conductance. Differential pressure devices can be used in multiphase flow metering. The most common differential pressure device is the Venturi meter, but orifice plates have also been used widely. The advantage of the Venturi meter over the orifice plate is that the Venturi meter is much more predictable and repeatable than the orifice plate for a wide range of flow conditions. Further, the smooth flow profile in a Venturi meter reduces frictional losses which (i) increases the reliability of the device and (ii) improves the pressure recovery. An interesting result, relevant to this paper was obtained by (Malayeri et al. 2001) who studied the behaviour of gas liquid upward flow. This paper develops a new advanced design of Venturi meter with the conductance sensors, which is capable of measuring the gas volume fraction at the inlet and the throat of the Venturi in annular gas-water two phase flows. The basic operation of the electrical conductance technique in a multiphase flow is that the conductance of the mixture depends on the gas volume fraction in the water. An electronic circuit was built and calibrated to give a dc voltage output which is proportional to the conductance of the mixture and which can then be related to the water film thickness in annular flow.

2 The measurements and mathematical modeling

The following is a description of the measurements and mathematical model which enable the gas and liquid mass flow rates in annular flow to be determined.

- The measurements we need to make and how these measurements will be integrated into the mathematical model to give the liquid and gas flow rates.
- Measuring the film velocity U_f in wet gas flow
- Measuring the film thickness δ
- Measuring the gas volume fraction α_1 at the Venturi inlet
- Measuring the water conductivity $\sigma_{w,m}$
- Measuring the gas volume fraction α_2 at the Venturi throat
- Differential pressure in wet gas flow ΔP

The reason for measuring the film thickness, the film velocity, the gas volume fraction at the inlet and the throat of the Venturi are to determine the gas mass flow rate and the water mass flow in annular flow.

The film velocity measurement: U_f

The film velocity in wet gas flow can be measured by the cross-correlating the conductance signals between two upstream ring sensors at the inlet of the Venturi, using the associated conductance electronic circuits of the two sensors (Qahtan S. K. Al-Yarubi PhD 2010).

The film thickness measurements δ

The film thickness in wet gas can be measured using a digital level sensor at the inlet of the Venturi (upstream), once the film thickness δ is obtained the water volume fraction at the Venturi inlet can be determined using the equation below:

$$\alpha_{w,1} = (1-\alpha_1) = \frac{2\delta}{R} + \left(\frac{\delta}{R}\right)^2 \tag{1}$$

We make these measurements to get the volumetric flow rate Q_f of the liquid in the film by the equation

$$Q_f = \pi R^2 \alpha_{w,1} U_f \tag{2}$$

The Gas volume fraction measurement α_1

One of the upstream conductance sensors needs to be calibrated in order for its cell constant to be determined. This is done using a bench calibration system for one upstream ring sensor. Nylon rods are inserted through inlet of the Venturi meter. The gap between the outer surface of the rod and the inner surface of the pipe wall is filled with water, representing the water film that would occur in a real annular flow. From the conductance circuit we know the feedback resistance R_{fb} and the excitation voltage V_{in}

The voltage measurement equation is

$$V(\alpha_1) = V_{in} R_{fb} \sigma_{w,ref} K(\alpha_1) \tag{3}$$

We therefore have

$$K(\alpha_1) = \frac{V(\alpha_1)}{V_{in} R_{fb} \sigma_{w,ref}} \tag{4}$$

And hence we can find the relationship between the cell constant $K(\alpha_1)$ and the gas volume fraction α_1 at the inlet to the Venturi (figure 4).

If $|V_{in}|$ and R_{fb} are known constant and we also take account of the offset voltage V_{off} when $\sigma = 0$, then we may define $\bar{K}(\alpha_1)$ as

$$\bar{K}(\alpha_1) = \frac{\{V(\alpha_1)\}_p - V_{off}}{\sigma_{w,ref}} \tag{5}$$

When $\{V(\alpha_1)\}_p$ is the peak value of $V(\alpha_1)$ and V_{off} is a dc offset

The water conductivity measurements

We now need to know how the conductivity sensor will be used with the digital level sensor in a real application to find the water conductivity. We find δ from the digital level sensor. Then using the equation

$$\alpha_1 = 1 - \frac{2\delta}{R} + \left(\frac{\delta}{R}\right)^2$$

We find α_1. From α_1 we can find the cell constant $\bar{K}(\alpha_1)$ (from our calibration data). Then using the equation below

$$\sigma_{w,m} = \frac{\{V(\alpha_1)\}_p - V_{off}}{\bar{K}(\alpha_1)} \tag{6}$$

We can find the water conductivity $\sigma_{w,m}$ under the actual flowing conditions.

The Gas volume fraction measurement at the throat α_2

The measurement of the gas volume fraction at the throat of the Venturi relies upon knowing the water conductivity $\sigma_{w,m}$ under actual flowing conditions. We have performed a bench calibration (similar to that for the inlet ring sensor) and so we know the relationship between the cell constant $\bar{K}^t(\alpha_2)$ of the throat conductance sensor and the gas volume fraction α_2 at the throat (see figure 5 for example). If $|V_{in}|$ and R_{fb} are known constant and we also take account of the offset voltage $V^t{}_{off}$ when $\sigma = 0$, then we may define $\bar{K}^t(\alpha_2)$ as

$$\bar{K}^t(\alpha_2) = \frac{\{V^t_m(\alpha_2)\}_p - V^t{}_{off}}{\sigma_{w,m}} \tag{7}$$

Because water conductivity is already known, we may determine $\bar{K}^t(\alpha_2)$ and so, if the relationship between $\bar{K}^t(\alpha_2)$ and α_2 is known we can determine the gas volume fraction α_2 at the Venturi throat

Differential pressure in wet gas flow ΔP

The differential pressure will be measured by the dP cell.

$$\Delta P_{TP.wg} = (P_1 - P_2) \tag{8}$$

Measuring the gas flow rate in annular flow $\dot{m}_g$

We make the above measurements to combine them to enable the gas flow rate in annular flow to be determined using the equation (Abbas Hameed Ali Mohamed Hasan PhD 2010).

$$\dot{m}_g = C_{dg,wg} \frac{\left(2\rho_{g1}\{\Delta P_{TP,wg} - \Delta P_H\}\right)^{\frac{1}{2}} A_1 A_2 \alpha_1 \alpha_2}{\left\{(\alpha_1 A_1)^2 \left(\hat{P}\right)^{\frac{-1}{\gamma}} - (\alpha_2 A_2)^2\right\}^{\frac{1}{2}}} \tag{9}$$

Measuring the mass flow rate of water in annular flow $\dot{m}_f$

The mass flow rate of water in the film can also be obtained from the equation

$$\dot{m}_f = \frac{Q_f}{\rho_w} \tag{10}$$

Where the volumetric flow rate Q_f is given by equation (2)

3 Design of the conductance multiphase flow meter.

To determine the gas flow rate in equation (9), the measurement of the gas volume fractions at the inlet and the throat (α_1 and α_2) must be achieved. To do so, a new Venturi meter with the conductance sensors at the inlet and the throat was designed and constructed (see figure 1). This Venturi meter is capable of measuring the gas volume fractions at the inlet and the throat of the Venturi (α_1 and α_2 respectively). Four ring electrodes were used (two at the inlet section and two at the throat section). The ring electrodes were designed to be flush mounted to the inner surfaces of the inlet and the throat of the Venturi) in order to avoid flow disturbances. One of the most advanced features of this design is that, all parts can be assembled /disassembled easily including the threaded flanges.

4 Bench Tests on the Venturi with the Conductance sensors

Before the Venturi meter will be used dynamically in the flow loop, a number of experimental bench testing procedures were carried out. A bench test rig was designed and built in order to calibrate the conductance measurements at the inlet and the throat. One of the upstream conductance sensors needs to be calibrated in order for its cell constant to be determined. This is done using a bench calibration system for one upstream ring sensor. To simulate the water film in the vertical Venturi meter, different diameters of nylon rods were inserted through the Venturi. The gap between the outer surface of the rod and the inner surface of the pipe wall was then filled with water, representing the water film that would occur in a real annular flow (see figure 2). A nylon rod holder at the bottom of the system was used to hold different diameters of nylon rod in the static tests to ensure that the nylon rod was located at the precise center of the system. At the beginning of the experiment the circuit was adjusted so that zero output voltage was obtained when no water (only air) was present between the electrodes. The area between the electrodes of the Venturi throat was then completely filled with water and a maximum dc output voltage was obtained by adjusting the variable resistance. The complete block diagram of the measurement electronic system is shown in figure 3. The static measurements were taken at laboratory conditions in which the temperature of the water was kept constant at 21°C. Measurement of the water conductivity value was changed and was measured three times for each experiment using a conventional conductivity meter. Conductivity values of 145μScm^{-1}, 175μScm^{-1} and 195.7μScm^{-1} were used. A similar procedure was used to calibrate the conductance measurement system at the throat of the Venturi. Measurement of the water conductivity was taken three times for each experiment using a conventional conductivity meter. The water conductivity values were 64μScm^{-1}, 92.4μScm^{-1} and 166.5μScm^{-1}. The water conductivities were different in 2 sets of experiments because of the difficulty in achieving a precise conductivity value by adding salt to water.

5 Results from Bench Tests

As described above, bench tests were performed by inserting non-conductive nylon rods with different diameters through the inlet and throat. The dc output voltages from the electronic measurement circuits were recorded which were related to the liquid water film at the throat and inlet of the Venturi.

$K(\alpha_1)$ VS α_1 and $K(\alpha_2)$ VS α_2 are independent of the water conductivity σ_w (see figures 4 and 5)

6. Conclusions

The results reported in the present paper indicate that a Venturi meter with conductance sensors can be used for the measurement of the gas flow rate in annular gas-water two phase flows (wet gas flows). An advanced Venturi was designed and tested successfully which is capable of measuring the gas volume fraction at the inlet and the throat of the Venturi.
The dc output voltage of the test is a function of a volume fraction dependent cell constant, the water conductivity, and excitation voltage and resistance feedback.

7 References

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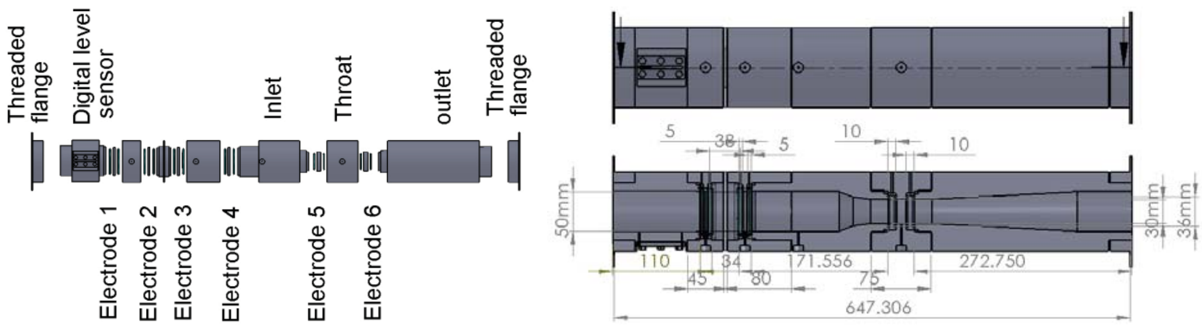

Figure 1: The design of the Venturi with the conductance sensors

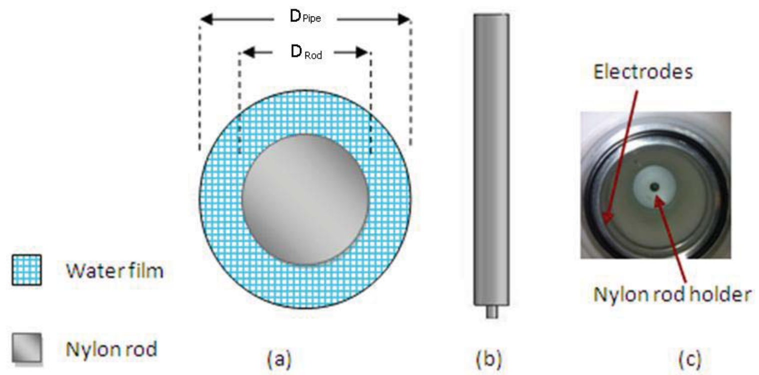

Figure 2: Bench test experimental setup

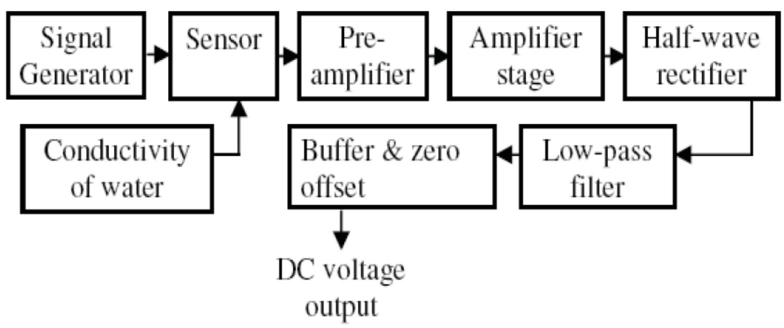

Figure 3: The block diagram of the measurement electronics system

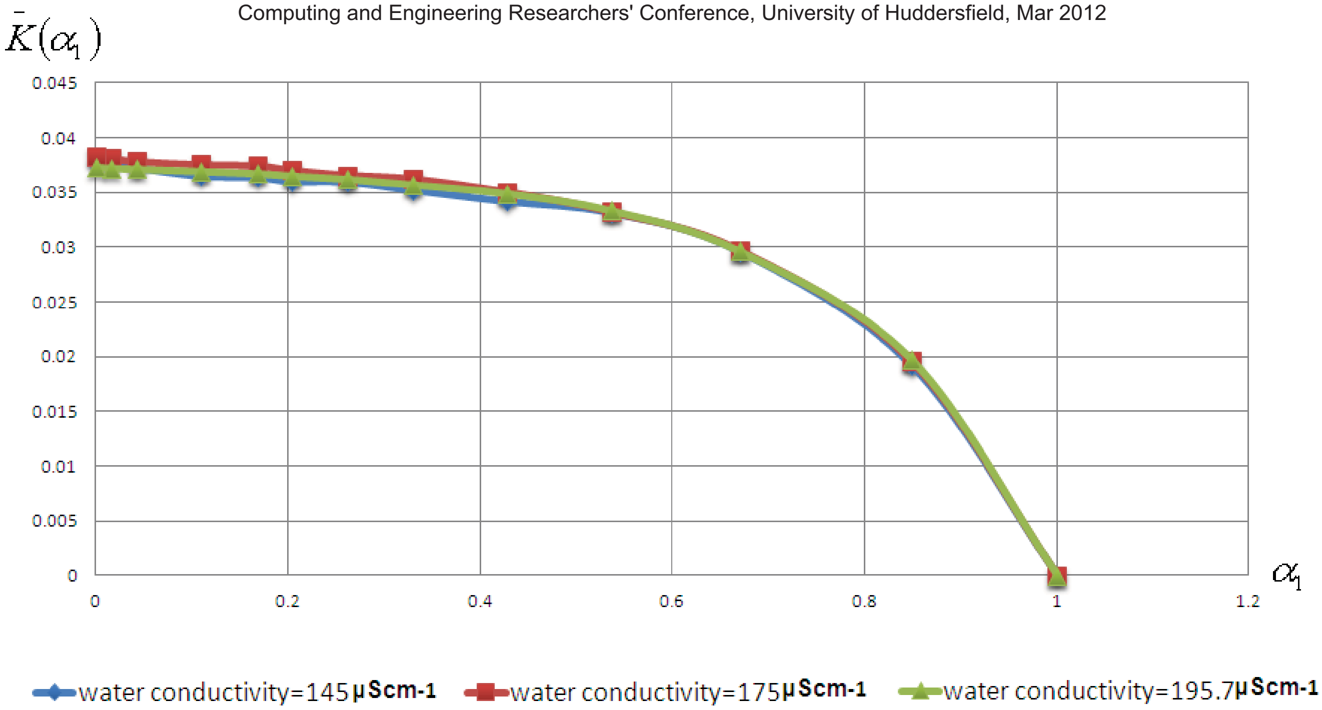

Figure 4: Calibration curve for upstream conductance sensors at the inlet $\bar{K}(\alpha_1)$ **VS** α_1

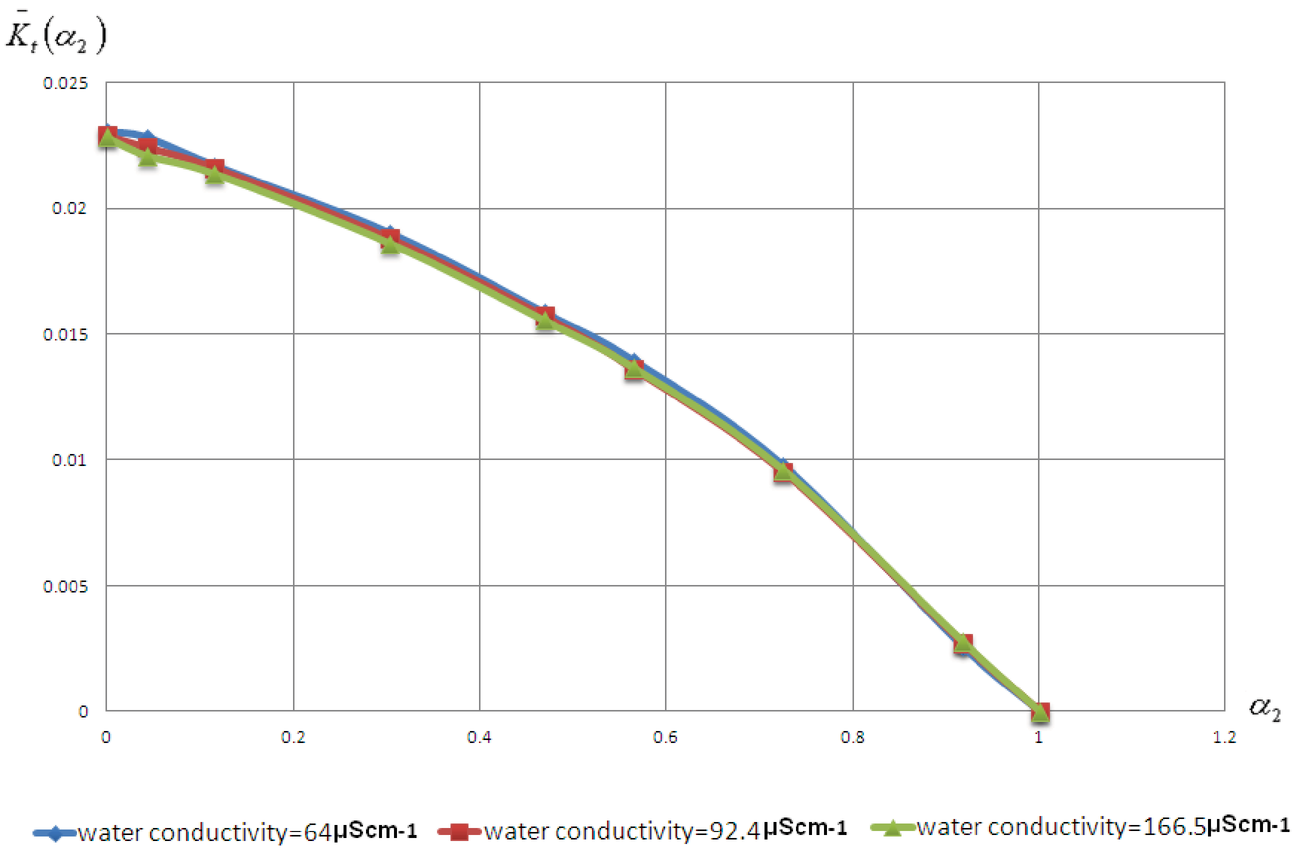

Figure 5: Calibration curve for conductance sensors at the throat $\bar{K}^t(\alpha_2)$ **VS** α_2