CLOSURE MODEL FOR TWO-PHASE LIQUID-GAS MEASUREMENT UNDER SLUG FLOW CONDITIONS

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Abstract

A series of experiments has been undertaken to investigate the behaviour and the performance of a clamp-on transit-time ultrasonic flowmeter in two-phase air/water flow. The results show the performance of the liquid ultrasonic meter to be seriously affected by the presence of free gas in a manner that is dependent on the actual flowrate of the gas and the flow regime. The data presented here covers water/air flow under slug flow regime and an evaluation of transit-time ultrasonic meter and its suitability for two-phase flow measurements. The factors affecting performance are discussed and a closure method using a transit-time ultrasonic flowmeter is introduced.

The closure method for the liquid flowrate employs a mathematical relationship, under slug flow conditions, between the estimated liquid flowrate $Q_{(Estimated)}$; the indicated liquid flowrate $Q_{(Indicated)}$; a velocity profile correction factor, $K_2(Re)$; the partial-filled area of the pipe; the cross-sectional area of the pipe and a height correction factor $K_1(h)$. This closure method for the gas flowrate uses measurements from the clamp-on transit-time ultrasonic flowmeter, an axial differential pressure transducer and a vertical differential pressure transducer.

The height of the water is obtained by using the vertical pressure transducer and applying the hydrostatic pressure equation. The height of the film reflects at the same time the functional condition of the ultrasonic flowmeter whether it is in a functional state or not. The acceptable height which keeps the clamp-on transit-time ultrasonic flowmeter to continue to function is above 50% of the pipe diameter. An axial differential pressure sensor gives the pressure drop along the slug body. The flowrate of the liquid is constant throughout the tests; the gas flowrate was increased over the range of tests.

Two main correction factors are implemented in the closure model. The Velocity Profile Correction Factor (VPCF), which is a function of Reynolds number $K_2(Re)$ for fully developed pipe flow for an assumed Reynolds Number, and the height of the water film correction factor $K_1(h)$. The $K_1(h)$ correction factor relates the velocity measured along the beam to the mean flow velocity over the entire cross-section of the flowing medium under partially filled pipe conditions.

It is found that the clamp-on transit-time ultrasonic flowmeter can be successfully applied to a horizontal slug flow regime with the application of this closure method to the indicated ultrasonic flowrate $Q_{(Indicated)}$. The average error of the clamp-on ultrasonic flowmeter measurements in two-phase flow were reduced by 50% to 75% and that is dependent on the height of the water, gas flowrate, and the slug flow characteristics. The average error of the estimated flowrate of the ultrasonic flowmeter is ±3.5% to ±6.5% relative to the reference turbine flowmeter. Applying a pressure drop closure model at a given liquid flowrate provides an air flowrate measurement with an accuracy of better than ±10%.

1. Introduction

Recent years have seen the increasing acceptance of ultrasonic techniques in gas and oil applications. Ultrasonic techniques have significant potential benefits over the traditional mechanical flow measurement with higher reliability, greater rangeability and lower velocity profile sensitivity. Lower maintenance requirements, on-line maintenance and the isolation of the transducers from hazardous or corrosive materials also provide significant advantages. In cases where the transducers are in contact with the fluid, non-intrusive measurement techniques have the advantage of minimising flow disturbance and providing no additional pressure loss. Moreover, instruments for pipes of various sizes tend to use identical transducers and electronics giving proportionately lower costs for larger size meters.(1)

Multiphase flow measurement is usually undertaken by methods which employ either partial separation or homogenisation (2). These are generally difficult to achieve in the slug regime which is one which commonly occurs in multiphase flows. There are other measurement techniques which can be employed such as neural networks (3) and closure methods such as that proposed by Stewart(4). This is based on correlations in the literature to calculate the slug characteristics such as velocities in the slug zone, velocities in film zone, lengths for the slug and film zones, and the average velocities and hence the liquid and gas flowrates. However, when applied this closure model gives a very large error in the measurement of the gas and liquid phases.

The closure method presented here is an alternative method which improves the use of the clamp-on transit-time ultrasonic flowmeter in two-phase air-water flow. This closure method introduces a VPCF (Velocity Profile Correction Factor) which corrects the indicated flowrate of the ultrasonic flowmeter to an estimated flowrate. The VPCF involves a Reynolds Number correction, K_2 (Re) which is related to a nominal Reynolds Number in an equivalent fully charged pipe and a height correction factor K_1(h). This factor correlates the fluid velocity along the acoustic path with the mean fluid velocity in the pipe in partially filled conditions.

2. Transit-time Ultrasonic Flowmeter Theory & Velocity Flow Profile

The transit-time ultrasonic method is based on the apparent difference of the sound velocity in the flow direction and the opposite direction. This method gives a flow velocity averaged along a particular acoustical path. For a single beam device, to convert this path velocity to a velocity averaged over the entire-section of the flowing medium, the knowledge of the flow velocity profile is essential (5). Ultrasonic flowmeters are affected by such distortions in velocity flow profile which often results in erroneous measurements. The velocity profile distribution is not usually flat and can vary significantly depending on the properties of the fluid and the pipe configuration in which it flows. Flow profile depends on the fluid viscosity, the Reynolds number, the relative roughness and the shape of the conduit, upstream and down stream disturbances, and whether the pipe is fully charged(5). Knowledge of the flow profile is critical in converting a flow reading along a particular beam to the velocity averaged over the entire cross-section of the flowing medium, and it can be expressed as Equation (1).

$$K = \frac{V_b}{\overline{V}} \qquad (1)$$

where,
K is the flow profile correction factor
V_b is the ultrasonic velocity (line average over the beam)
$\overline{V}$ is the area-average velocity

For fully developed flow in smooth pipes the shape of flow profile is a well-known function of Reynolds number, readily expressed in mathematical form. Accordingly, it is possible to compensate for flow profile effects by knowing the current Reynolds number (6). The meter correction factors for a transit time ultrasonic flowmeter in partially filled pipes has been investigated by Strauss (7).

3. Test Facilities

The closure method was tested on the 50mm diameter air/water facility at Cranfield University over a range of gas flows, at constant liquid flowrate, where the injected rates of the liquid are accurately known and maintained. The test facility shown in figure 1 consists of an air-water flow loop, test section, and associated instrumentation. The liquid is mains water. The water is pumped from the water storage tank and passed through the reference turbine flowmeter and then to the test section where the clamp-on transit-time ultrasonic flowmeter was installed.

Compressed air is passed through a pressure regulator, a gas turbine flowmeter, and injected into the test section. The air injector point is located at 2 m from the water inlet. The test section is a Perspex pipe 2m long and 50mm diameter. A pressure drop transducer (axial differential pressure) and differential pressure transducer (vertical differential pressure) are installed on the test section with the transit-time ultrasonic flowmeter.

The non-intrusive clamp-on transit-time ultrasonic flowmeter is mounted to the exterior of the spool within WeldSeal mounting assemblies enclosing the transducers. In addition, each transducer is coupled to the pipe with “O” ring seals to ensure that the sonic coupling compound will never need to be serviced, even in applications exposed to extreme environmental conditions. The transducers are locked into place so that movement is not possible, even where high vibration is encountered. The clamp-on transit-time ultrasonic flowmeter is operated in a 2-path diametric mode with the beam reflected from the back wall of the flow tube. Figure 2 shows the non-intrusive clamp-on transit-time ultrasonic flowmeter and its component (8).

4. Closure Method

A schematic of the proposed closure method is shown in Figure 3. The closure method removes the velocity profile correction factor introduced automatically by the flowmeter on the assumption of a fully developed flow in a fully charged pipe and substitutes it with an appropriate meter factor for a partically filled pipe. A correction factor of the cross sectional area of the flow is also made. As long as the average height of the liquid is above the 50% of the cross-section area of the pipe, the clamp-on transit-time ultrasonic flowmeter will continue to function. The closure method equation is:

$$Q_{Estimated} = Q_{Indicated} * \frac{A_{partial}}{A_{full}} * \frac{K_1(h)}{K_2(Re)} \qquad (2)$$

where:-

$Q_{(Estimated)}$ is the estimated ultrasonic liquid flowrate (m^3/s), which is the output from the closure method.

$Q_{(Indicated)}$ is the indicated ultrasonic liquid flowrate (m^3/s), which is the output from the clamp-on transit-time ultrasonic flowmeter, test output reading.

$A_{partial}$ is the partial-filled area of the pipe, which depends on the height of the water film (m^2)

A_{full} is the cross-sectional area of the full pipe (m^2).

K_1 (h): is the correction factor for the height of the water film and is given by equation (1) for partially filled pipes. In this set of experiments this is derived from the data shown in figure 4 which comes from reference [7].

K_2 (Re): is the velocity profile correction factor and it is calculated by firstly estimating a nominal Reynolds number from the experiment data and then using the following equation [9].

$$k = \frac{1}{1.119 - 0.011 * \log(\mathrm{Re})} \quad (3*10^3 \le \mathrm{Re} \le 5*10^6) \quad (3)$$

The height of the water film is obtained experimentally from the vertical differential pressure transducer and then this is used to correct the output of the ultrasonic flowmeter by using the relationship shown in Figure 4. This enables a corrected estimate of the liquid flowrate to be made. The second step of the closure method is to use the axial differential pressure to estimate the gas flowrate, since at a given liquid flowrate the relationship between the average pressure drop and the actual gas flowrate can be represented by a linear or polynomial fit.

5. Clamp-On Transit-time Ultrasonic Flowmeter Performance

Two experiments were carried out on the 50 mm diameter pipework in the two-phase air/water rig at Cranfield. The duration of both tests was 500 seconds. The flowrate of the liquid was constant in both tests, and its value was chosen from the horizontal flow pattern map [10]. The actual gas flowrates were increased gradually and their values were chosen also from the horizontal flow map [10], to ensure that both tests were undertaken under slug flow regime.

The performance of the ultrasonic flowmeter was determined by its measured flowrate, relative to that measured by the reference turbine flowmeter. Data obtained from the clamp-on transit-time ultrasonic flowmeter offers an interesting insight into how this technology performs or behaves in two-phase air/water flows in the slug flow regime, under conditions that offer a real time comparison to the turbine flowmeter.

Two-main distinguished areas were observed during each test, these areas represented the real behaviour of the ultrasonic flowmeter in two-phase slug flow. The first one is the failure area. In this condition, the ultrasonic flowmeter failed to indicate any reading due to the high Gas Void Fraction (GVF>50 %), compared with the average height of the water film or liquid holdup <50 %.

The second is the success area, where the ultrasonic flowmeter was successful in indicating a liquid flowrate reading where the (GVF<50 %) and the liquid holdup >50%. However, the uncertainties of the ultrasonic readings due to the free gas were very poor compared to the reading by the reference turbine flowmeter. In this case, a closure method was needed to improve the output readings of the clamp-on transit-time ultrasonic flowmeter in two-phase slug flow regime which was our main concern in this data analysis.

6. Test one Data Analysis

Figure 5 shows the behaviour of the clamp-on ultrasonic flowmeter under slug regime. The number of the successful period and failure period is dependent on the GVF in the system. By increasing the gas flowrate the number of the failure partition increased and the period of time of the successful partition is decreased.

In this test the number of the failure partition is 9 and 10 for the successful partition. The reference turbine reading was $1.73*10^{-3}$ (m^3/s) which gives a U_{SW} = 0.87 (m/s), the range of the actual gas flowrate in the test was between $2.99*10^{-4}$ (m^3/s) and $3.08*10^{-4}$ (m^3/s) that gives the range of the gas superficial velocity U_{SG} from 0.145 (m/s) to 0.154 (m/s).

The GVF varied in the successful partition between 17 % and 24 % , the average height of the water film being 36mm. A successful partition was chosen from the test and it was intended to choose it from the beginning of the test and with small period of time in order to study the behaviour of the ultrasonic flowmeter at that small period of time.

It was noticed from the behaviour of the ultrasonic flowmeter that the indicated liquid flowrate $Q_{(indicated)}$ was increased by ±11 % difference from the reference reading after we introduced the gas to the system which is shown in Figure 6.

By introducing the closure method to the indicated liquid flowrate $Q_{(Indicated)}$, the estimated liquid flowrate $Q_{(Estimated)}$ of the ultrasonic flowmeter showed an improvement of almost 50 %. The average deviation became ±6.5 % from the reference turbine flowmeter as shown in Figure 6.

The average height of the water film was obtained from measuring the head Pressure by using the vertical differential pressure. The range of height was between 0 mm and 50 mm equivalent to 0 to 0.072 psi respectively. This range of the differential pressure was used as a filter in the data analysis. The function of the filter was to detect the range of the height between (25mm and 50 mm) which enables the clamp-on transit-time ultrasonic flowmeter to continue to function.

Figure 7 shows the range of water film heights over which the correction factor K_1 (h) for the ultrasonic flowmeter has been applied. It shows that the minimum height of water film at which the closure method can still be applied was 26 mm which is above 50 % of the pipe diameter. Also Figure 8 illustrates the relationship between the differential pressure (vertical pressure) and the average height of the water film and it shows the real value of the water height at specific hydrostatic pressure.

7. Test two Data Analysis

Figure 9 shows the behaviour of the clamp-on ultrasonic flowmeter under slug regime in the second test. In this test, the same work methodology of analyzing the data from test-one was followed. The liquid flowrate was constant and maintained at $1.73*10^{-3}$ (m^3/s) which gives U_{SW}= 0.86 (m/s). The gas flowrate was increased and it became between $3.34*10^{-4}$ (m^3/s) and $3.39*10^{-4}$ (m^3/s) which gives the range of the gas superficial velocity U_{SG} between 0.167 (m/s) and 0.169 (m/s). The GVF was varied in the successful partition between 20 % and 25 %, the average height of the water film was 40mm. A successful partition was chosen which has a longer period of time than the one chosen in test-one.

From the performance of the ultrasonic flowmeter, the indicated liquid flowrate $Q_{(Indicated)}$ was increased by 20% difference from the reference reading. By applying the closure method to the indicated liquid flowrate $Q_{(Indicated)}$, the estimated liquid flowrate $Q_{(Estimated)}$ of the ultrasonic flowmeter improved by almost 80 % and the average deviation is ±3.5 % as shown in Figure 10.

The range of heights for which the correction factor K_1 (h) is applied to the ultrasonic flowmeter is illustrated in Figure 11. The minimum height of the water film at which the closure method can still be applied was above 50 % of the pipe diameter which is equal 32.5 mm. The relationship between the differential pressure and the height of the water film is shown for this test in Figure 12.

Test two shows better performance of the ultrasonic flowmeter in two-phase air/water application after introducing the closure method than test one. The second part of the closure method is to correlate the axial pressure drop at a given liquid flowrate measured by the first method to the gas flowrate.

Figure 13 shows the relation between axial differential pressure and the gas flowrate for a given liquid flowrate. Using a linear correlation it is possible to estimate the gas flowrate to approximately ±10%.

8. Conclusion

The clamp-on transit-time ultrasonic flowmeter measurement was obviously and seriously affected by the presence of the second phase. As a result, a large deviation from the reference turbine flowmeter was recorded. However, it has been demonstrated through the use of the closure method that the clamp-on transit-time ultrasonic flowmeter has offered a successful measurement in two-phase flow under slug flow regime which has a specific gas flowrate and a constant liquid flowrate. The two tests reflect an attempt to apply the liquid ultrasonic flowmeter in liquid and gas application with uncertainties ±3.5% to ±6.5% compared with the reference turbine flowmeter. The closure method introduces a good starting point for further research in employing the transit-time technique into two-phase flows with greater emphasis on the slug flow characteristics, slug flow height or the liquid holdup measurements, all of which can improve the closure method in two-phase applications.

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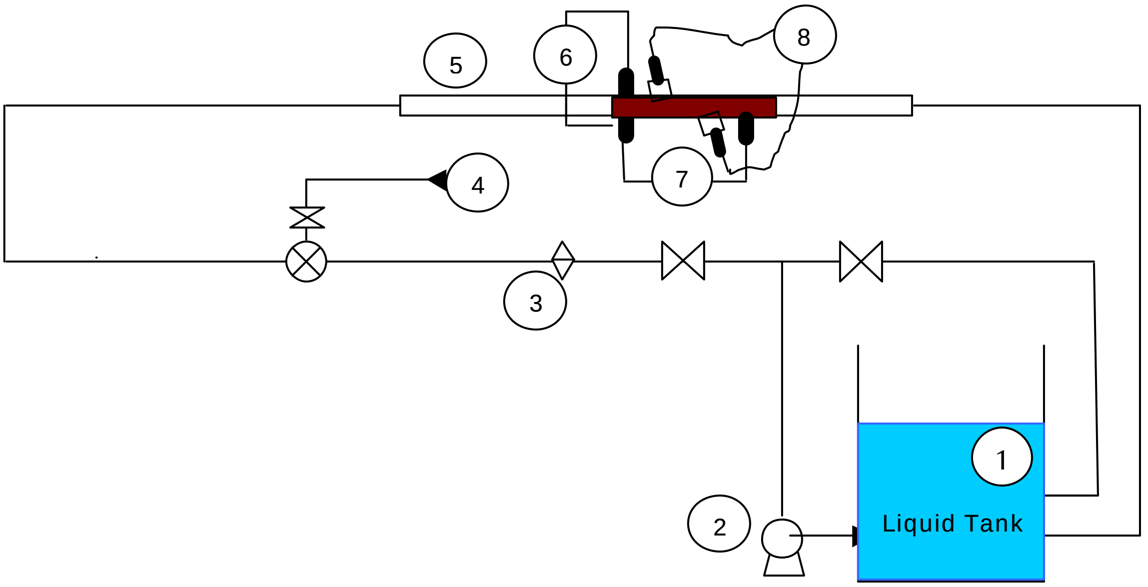


1. Water tank
2. Pump
3. Reference -Turbine Flowmeter
4. Gas-turbine meter(gas injector)
5. Test section (Perspex pipe)
6. Differential pressure transducer
7. Pressure drop transducer
8. Transit time clamp -on ultrasonic flow meter

Figure 1. Test Facilities

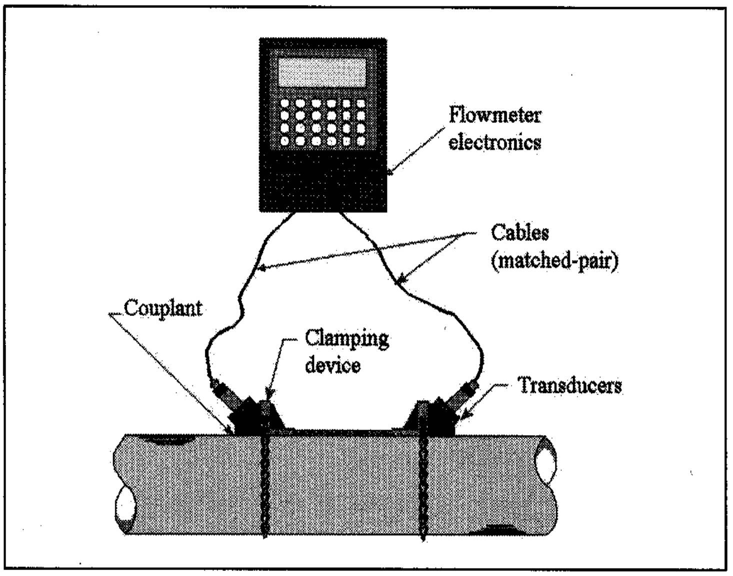


Figure 2. Clamp -On Ultrasonic Flowmeter

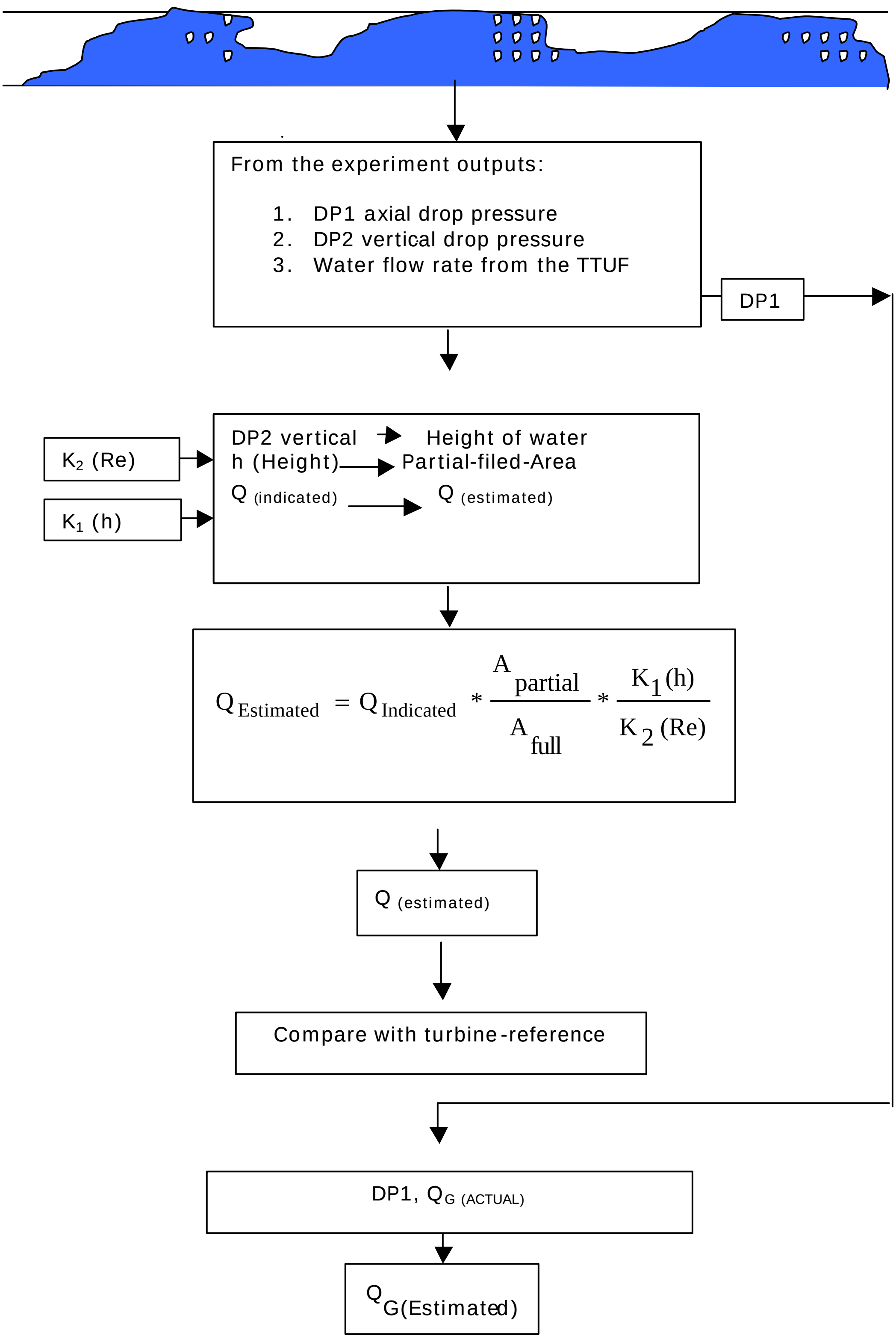


Figure 3. Closure Method Diagram

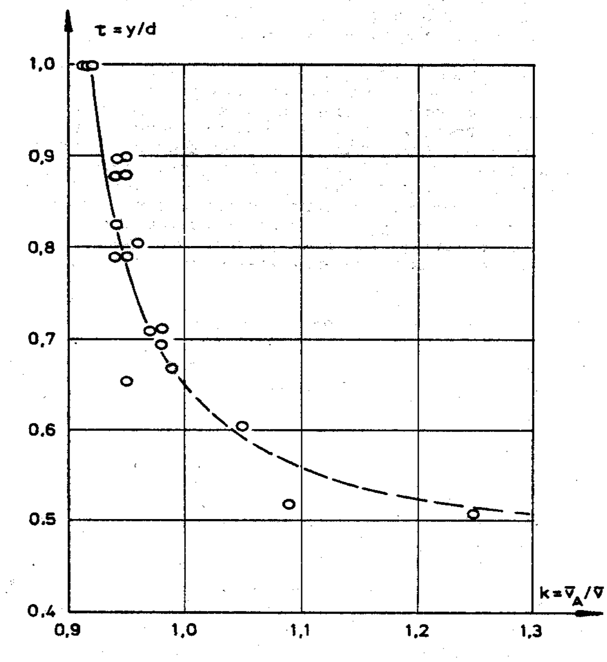


Figure 4. The relationship between the τ the relative height and $k = \frac{1}{k_1(h)}$ factor

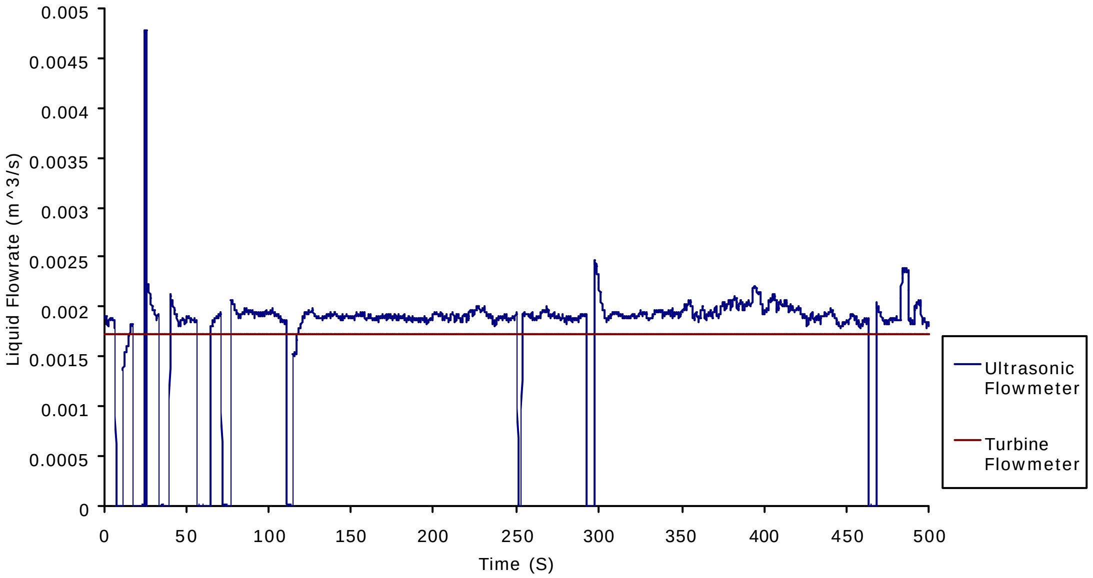


Figure 5. Ultrasonic Flowmeter Performance -Test-one

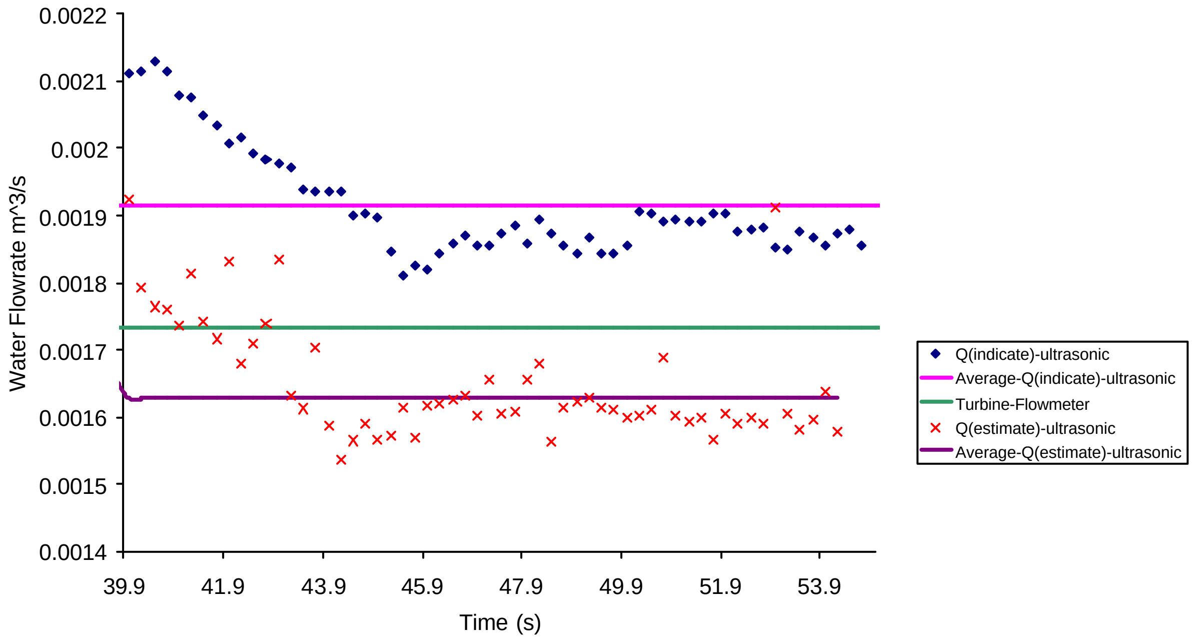


Figure 6. Test-one Closure Model

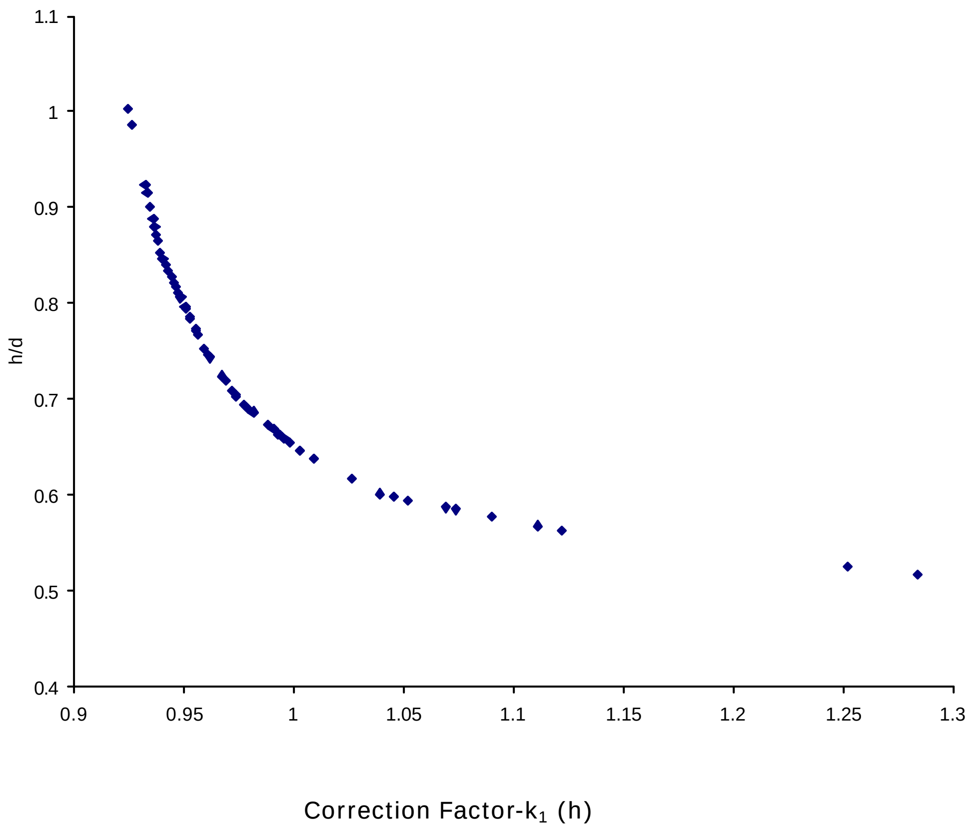


Figure 7.Test-one correction factor relative with the film height

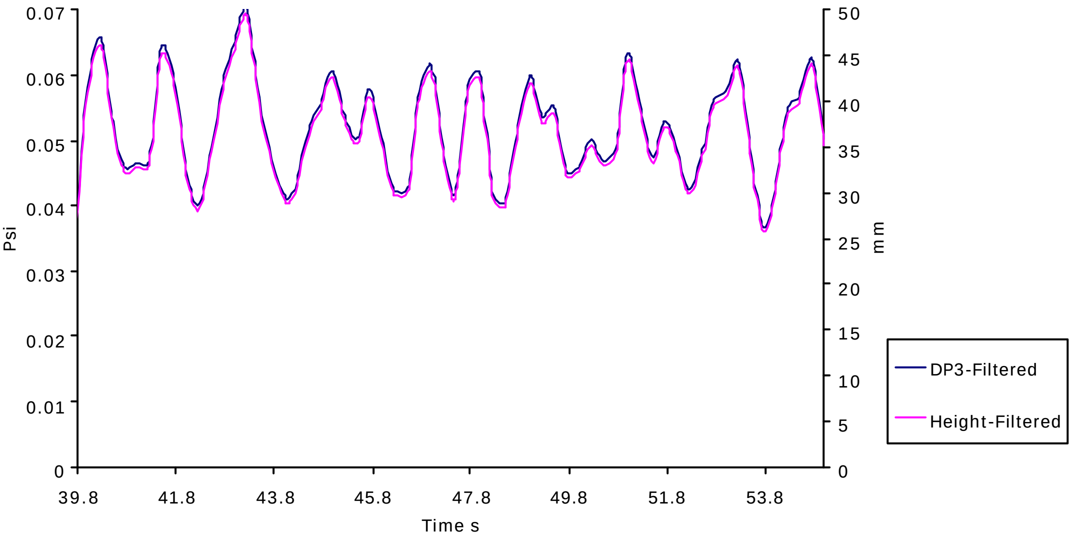


Figure 8. Water Film Height & Differential Pressure Test-one

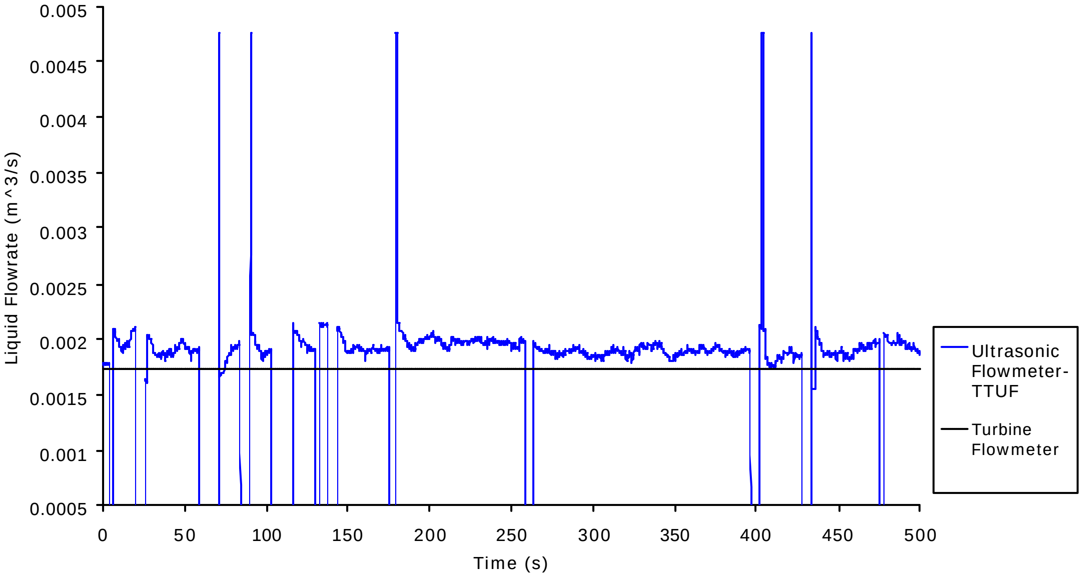


Figure 9. Ultrasonic Flowmeter Performance -Test-two

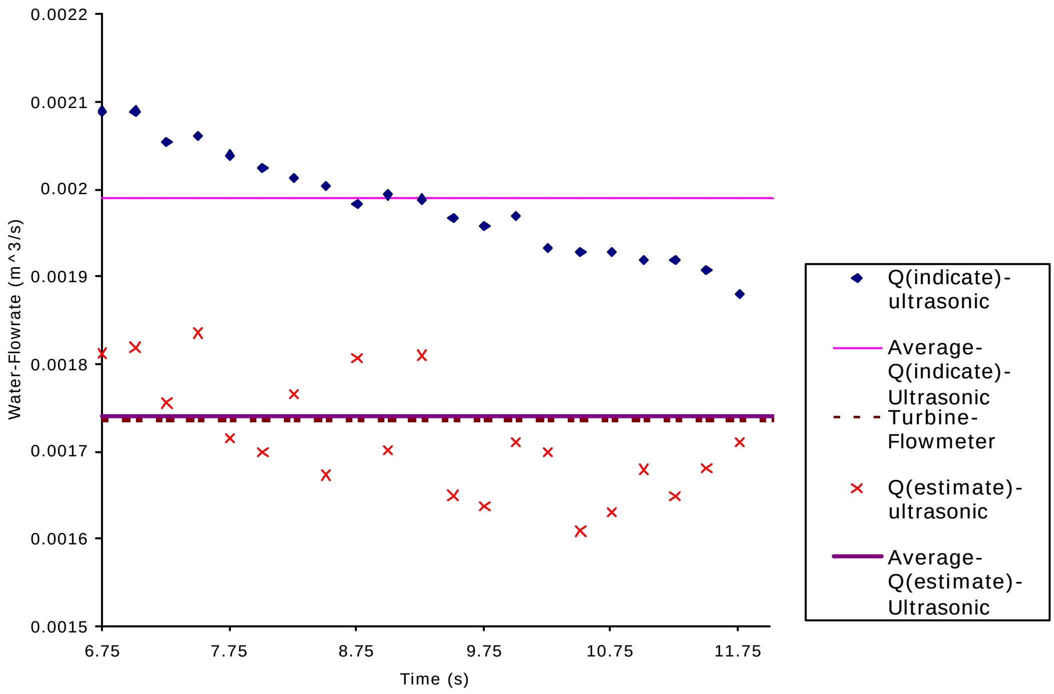
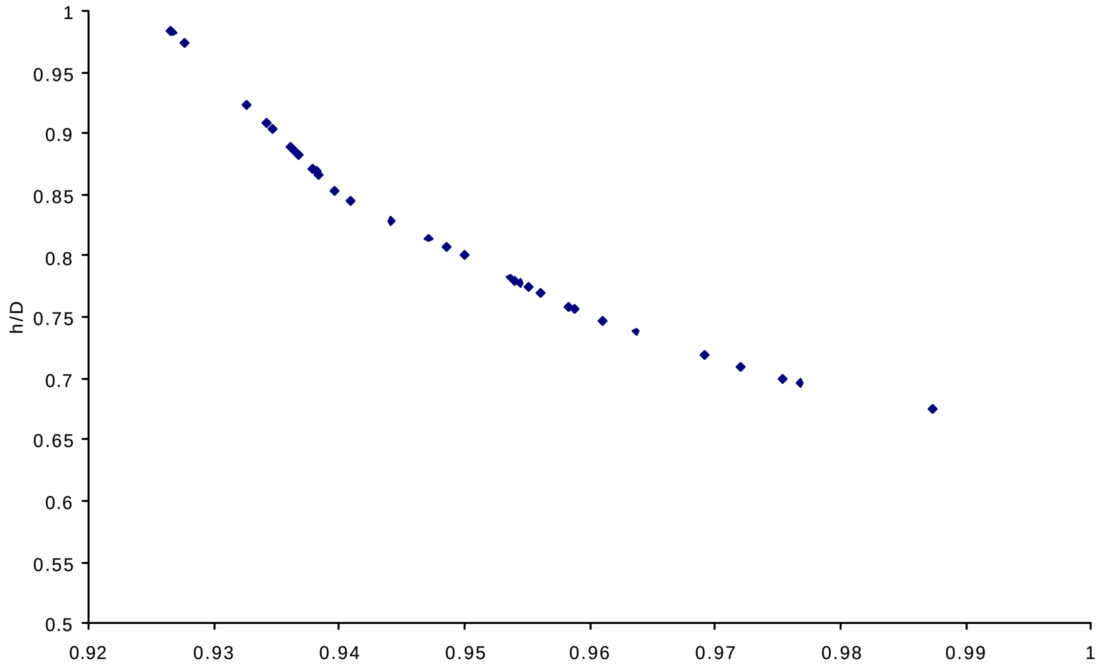


Figure 10. Test-two Closure Model



Correction Factor-K_1 (h)

Figure 11. Test-two K_1 (h)-correction Factor relative with the film height

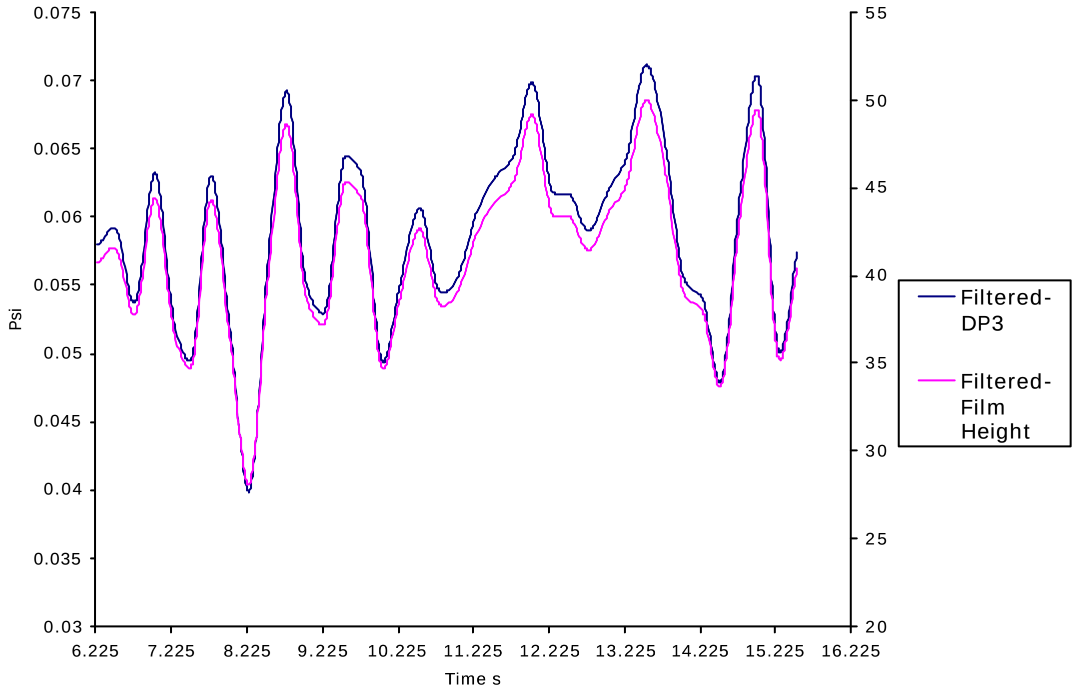


Figure 12. Water Film Height & Differential Pressure Test-two

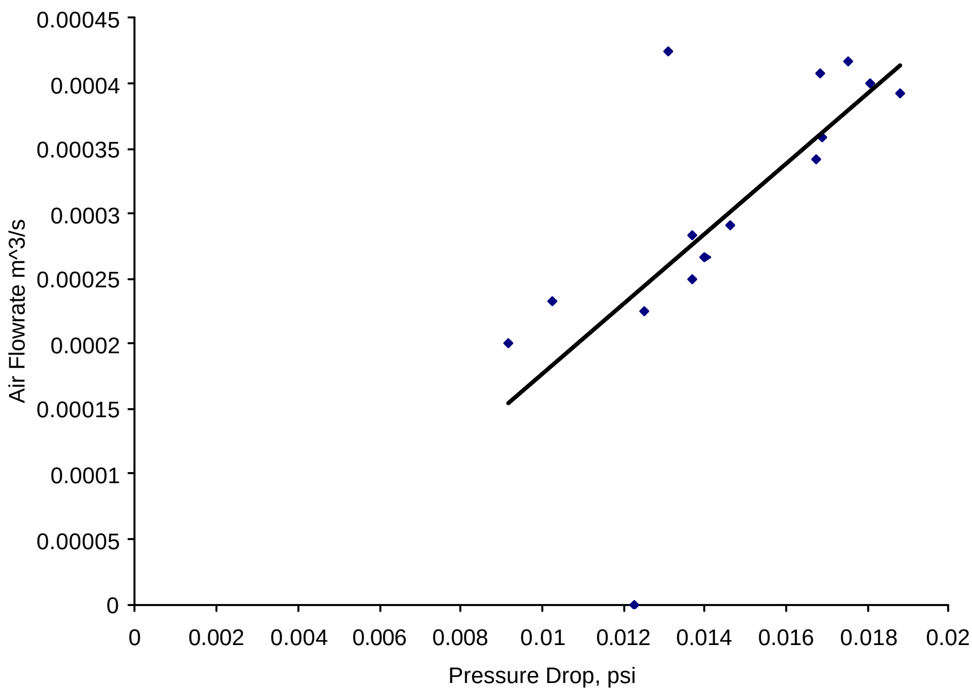


Figure 13.Pressure Drop & Gas Flowrate Relationship