

Measurements of Void Fraction, Pressure Drop and Heat Transfer in Horizontal and Downward Inclined Gas-Liquid Stratified Flow

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Abstract

The main aim of this work is to measure and study the variation of stratified and non-stratified flow transition boundary, void fraction, pressure drop and non-boiling heat transfer in air-water stratified flow. The experiments are carried out in a 12.7 mm I.D. (transparent) and 12.5 mm I.D. (stainless steel) pipe oriented at different inclinations from horizontal towards vertical downward. Unlike majority of other experimental investigations reported in two phase flow literature, this study considers smooth stratified, wavy stratified, rolling waves and falling film type of the flow that covers entire spectrum of stratified flow pattern. A change in pipe inclination is found to significantly affect the extent of stratified flow on a flow regime map as well as the magnitude of measured two phase flow variables. In general, depending upon the nature of stratified flow (smooth or wavy) void fraction, pressure drop and heat transfer coefficient are found to be coupled to the variation in both gas and liquid flow rates with a strong dependence on liquid flow rate and relatively loose reliance on gas flow rates. A change in pipe inclination is found to substantially alter the two phase heat transfer coefficients whose trends could be explained based on the interaction between buoyancy and gravity acting on gas and liquid phase, respectively.

Keywords: stratified flow, void fraction, pressure drop, non-boiling heat transfer

1. Introduction

Gas-liquid stratified flow is often encountered in several applications such as simultaneous transport of oil-gas in undulating pipe lines, heat exchangers and process engineering. Most of the existing two phase flow literature is dedicated to the study of gas-liquid stratified flow in horizontal pipes while limited attention is given to the understanding of this flow pattern in downward pipe inclinations. Some of the prior experimental investigations involving stratified flow in downward pipe inclinations comprise of the work of [1–7]. Work of [1, 3, 4] focused on the entire range of pipe inclinations and dealt with measurements of void fraction and two phase pressure drop. Similar measurements were carried out by Ref. [5] however, their work was limited to near horizontal pipe inclinations. Experiments of Ref. [6] and Ref. [7] dealt with flow visualization and did not report pressure drop in stratified flow. All of these studies concluded that stratified flow predominantly exists in all downward pipe inclinations and the correct modeling of this flow pattern may depend on several flow variables. One of the comprehensive and pioneering work in modeling of gas-liquid stratified flow is that of Ref. [8] who provided mechanistic model to predict stratified flow transition and estimate void fraction and pressure drop using momentum balance equation based on a graphical solution. Later, Barnea and co-workers [6, 9] studied effect of downward pipe inclination on the transition of stratified flow and proposed unified models (based on the theory of Ref. [8]) to identify its existence for a given set of flow conditions. These models for stratified flow modeling are implicit in nature and need the solution of either graphical or iterative forms. Two phase flow literature also cites work of Ref. [10] dedicated to the experiments and modeling of stratified flow in downward pipe inclinations. However, their work is based on condensing two phase flow of refrigerants in a small diameter pipe and hence their work may not provide a correct quantitative representation of void fraction, pressure drop

and non-boiling heat transfer of interest to two component two phase flow. Nevertheless, their work is important to qualitatively understand the combined effect of stratified flow and downward pipe inclinations on flow pattern transitions and two phase flow variables. Later, Refs. [11] and [12] worked on modeling of void fraction and pressure drop using ARS (artificial rough surface) and double circle models, respectively. However, their work focused only on the wavy region of the stratified flow pattern that corresponds to inertia driven stratified flow with very high void fraction ($\alpha \gtrsim 0.9$). Similar work is reported by Ref. [13] that deals with measurements and modeling of stratified flow with very low liquid loading. All of these experiments [11–13] study the flow characteristics of wavy stratified flow as identified by the Taitel and Dukler [8] model while they provide very limited experimental data on the two phase flow variables in smooth stratified flow regime. Moreover, these studies are carried out in horizontal or near horizontal pipe inclinations and hence do not provide insightful discussion on the combined effect of stratified flow and pipe inclination on two phase flow variables. It must be mentioned that none of these studies provide non-boiling heat transfer data in stratified flow regime. Thus, for better understanding of the variation of two phase flow variables in the entire spectrum of stratified flow, this study aims at measurements of void fraction, pressure drop and heat transfer coefficient in downward inclined stratified flow. The gas and liquid flow rates considered in this work cover smooth stratified, wavy stratified as well as rolling wave regime of the stratified flow pattern.

2. Experimental setup

The experimental setup shown in Fig. 1 is used for two phase flow measurements that consists of a 12.7 mm I.D. polycarbonate pipe and a 12.5 mm I.D. schedule 40S stainless steel pipe test sections mounted on a variable inclination frame. The transparent section made of polycarbonate material is used for flow visual-

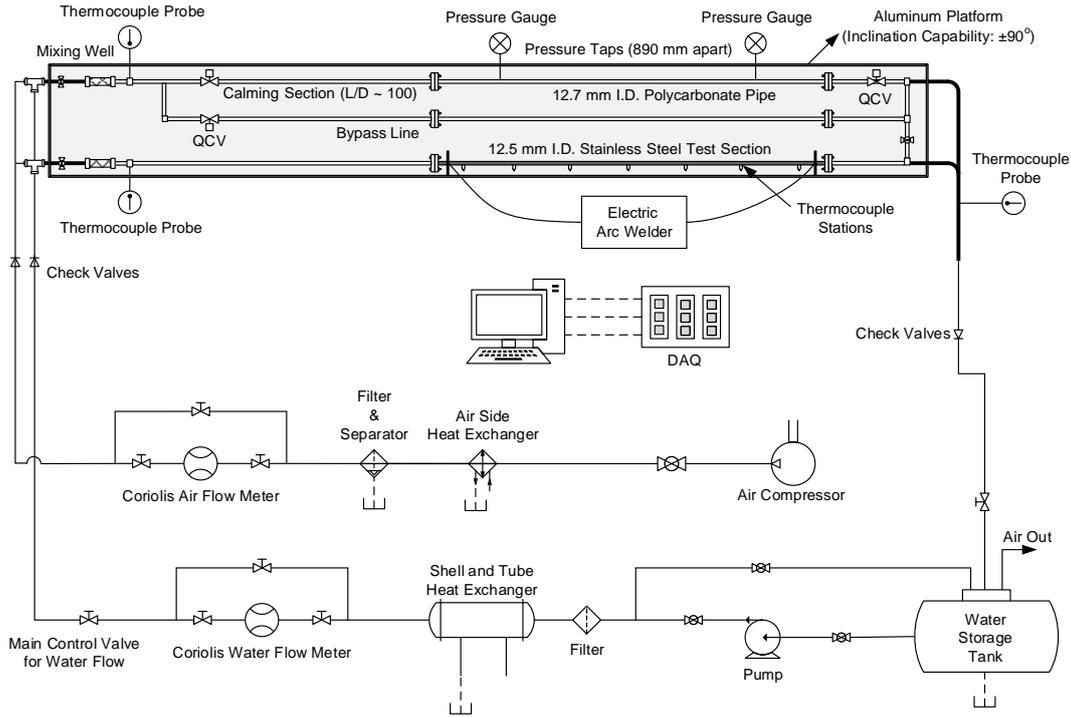


Figure 1: Experimental setup used for flow visualization, void fraction, pressure drop and heat transfer measurements.

ization, void fraction and pressure drop measurements. Whereas, stainless steel pipe section is used for non-boiling convective heat transfer measurements. The fluid combination used for generating two phase flow is compressed air and distilled water. The air supplied by Ingersoll Rand T-30 Model 2545 compressor first passes through a regulator, filter and lubricator circuit and then through a submerged helical coil heat exchanger. Next, the air is again passed through a filter and then fetched to Micro Motion Elite Series Model LMF 3M and CMF 025 Coriolis gas mass flow meters where the mass flow rate of air is controlled precisely using a Parker (24NS 82(A)-8LN-SS) needle valve. The compressed air is then allowed to enter the test section through a spiral static mixer. The liquid phase in form of distilled water stored in a 50 gallon tank is circulated in the system using a Bell and Gosset (series 1535, model number 3445 D10) centrifugal pump. The distilled water is first passed through Aqua-pure AP12-T purifier and then through ITT model BCF 4063 shell and tube heat exchanger. The distilled water is then passed through an Emerson Coriolis mass flow meter (Micro Motion Elite Series model number CMF 100) where the mass flow rate of the liquid phase entering the test section is controlled. Later, the water is allowed to mix with air in Koflo model 3/8-40C-4-3V-23/8 static mixer. The mixer is mounted right before the entrance to the test section. Two phase flow measurements are carried out for all major flow patterns by systematically varying the gas flow rates for fixed value of liquid flow rates. For each combination of gas and liquid flow rate, void fraction (α) is measured using quick closing valves. The total two phase pressure drop ($(dp/dz)_t$) across pressure taps placed 890 mm apart is measured using a DP15 variable reluctance Validyne pressure transducer having an accuracy of 0.25% of full scale range of the diaphragm. The two pressure diaphragms with a upper limit of 3.5 kPa and 14 kPa are used to measure total two phase pressure drop. From the measured total two phase pressure drop, frictional component ($(dp/dz)_f$) is calculated by subtracting hydrostatic component ($(dp/dz)_h$) as given by Eqn. (1) to Eqn. (3). Hydrostatic component of pressure drop is a function of void fraction, gas and liquid phase density

(ρ_l and ρ_g) and the pipe inclination (θ). Note that accelerational pressure drop ($(dp/dz)_a$) is negligible for non-boiling flows and hence can be ignored.

$$\left(\frac{dp}{dz}\right)_t = \left(\frac{dp}{dz}\right)_h + \left(\frac{dp}{dz}\right)_f + \left(\frac{dp}{dz}\right)_a \quad (1)$$

$$\left(\frac{dp}{dz}\right)_h = [\rho_l(1 - \alpha) + \rho_g\alpha] g \sin \theta \quad (2)$$

$$\left(\frac{dp}{dz}\right)_f = \left(\frac{dp}{dz}\right)_t - \left(\frac{dp}{dz}\right)_h \quad (3)$$

For heat transfer measurements, a constant heat flux is provided to the test section using Miller Maxtron 450 electric arc welder. The two phase inlet and outlet temperature is measured using Omega TMQSS-06U-6 thermocouple probes. CO1-T type thermocouples with an accuracy of $\pm 0.5^\circ\text{C}$ are used to measure wall temperatures at seven different stations spaced 127 mm apart along the 1016 mm ($\approx 80D$) long heated test section. At each axial location, four thermocouples equally spaced over the pipe circumference (top, bottom and two side walls of the pipe) are cemented to the pipe outer wall. Based on the pipe outer wall temperature measurements, the local and average values of two phase heat transfer coefficients are determined using the finite difference method based data reduction program developed by Ref. [14]. The uncertainty associated with measurements of void fraction, two phase frictional pressure drop and heat transfer coefficient is determined using Ref. [15] method. Based on this method, the worst case uncertainty associated with void fraction and heat transfer coefficient is $\pm 6\%$ and $\pm 30\%$, respectively. The high value of uncertainty associated with two phase heat transfer coefficient (h_{tp}) is essentially due to the high heat balance error and low temperature difference between pipe inner wall and bulk temperature. Note that the value of $\pm 30\%$ represents the worst case scenario and appropriate care is taken to ensure that uncertainty in h_{tp} is well below this limit.

3. Results and discussion

The existence of stratified flow at different pipe inclinations and various gas and liquid flow rates is confirmed by visual observations as well as still photographs. Stratified flow pattern defined in this work consists of smooth stratified, rolling wave as well as wavy stratified flow depicted in Fig. 2 that comprise the broad definition of stratified flow pattern reported in two phase flow literature. The smooth stratified flow is defined as a flow with ripple/disturbance free interface that can exist at low gas flow rates for a given liquid flow rate. With increase in gas flow rate, waves start to generate at the gas liquid interface giving rise to rolling wave structure of the stratified flow. Rolling wave passing through a certain cross section is visually found to create a sweeping action at the gas-liquid interface as well as the pipe top wall and hence is expected to enhance frictional pressure drop as well as heat transfer characteristics of two phase flow compared to the smooth stratified flow.

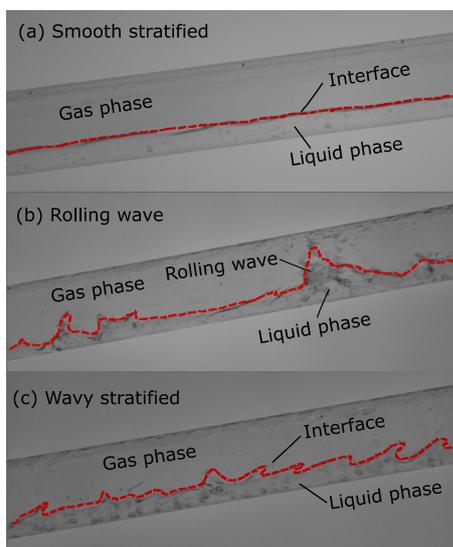


Figure 2: Stratified flow in near horizontal downward pipe inclinations (a) Smooth stratified (b) Rolling wave (c) Wavy stratified.

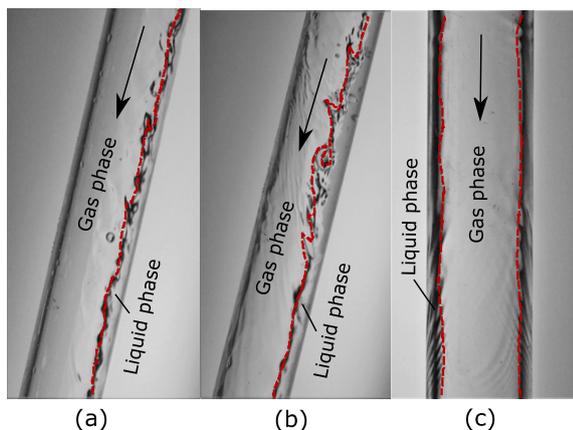


Figure 3: Stratified flow in near vertical pipe inclinations (a) and (b) stratified flow at $\theta = -75^\circ$, (c) falling film flow at $\theta = -90^\circ$.

Finally, the wavy stratified flow is characterized by wavy (visually rough) gas-liquid interface. The fast moving gas phase

shears the gas-liquid interface with portions of the liquid phase appear stretched to form thin filaments or “fingers” of liquid. At near vertical and vertical downward pipe inclinations, the gas-liquid interface of stratified flow tries to climb up the pipe periphery (Fig. 3 (a)) and is also present in form of falling film flow (Fig. 3 (b) and (c)). Note that the falling film flow pattern is regarded as a special case of stratified flow in near vertical and vertical pipe inclinations. Measurements of void fraction show that stratified flow with relatively smooth interface (at low gas flow rates) is significantly influenced by the interaction between buoyancy acting on gas phase and gravity acting on liquid phase. Whereas, the rolling wave and wavy stratified flows are inertia driven in nature and hence are relatively insensitive to the change in downward pipe inclination.

3.1. Stratified/non-stratified flow transition

The flow visualization carried out in this work shows a significant effect of pipe inclination on the transition between stratified and non-stratified flow patterns. Based on the gas and liquid flow rates or alternatively the gas and liquid superficial velocities (U_{sg} and U_{sl}) combination that correspond to gravity driven stratified flow (at high liquid and low gas flow rates) and inertia driven stratified flow (at low liquid and high gas flow rates), two distinct trends in the transition line between stratified and non-stratified flows are observed. As shown in Fig. 4, at high liquid and low gas flow rates, the transition between stratified and intermittent flow regime is very gradual (as a function of liquid flow rate and relatively independent of gas flow rate) until a threshold value of the gas flow rate ($U_{sg} \lesssim 5$ (m/s)) is attained where the gas liquid surface becomes significantly unstable and the liquid phase is splashed frequently on the pipe top wall. Beyond this gas flow rate, the second trend in stratified and non-stratified flow transition line is observed such that it is a strong function of gas flow rate with a loose dependence on the liquid flow rate. At low to moderate gas and high liquid flow rates, stratified flow shares a boundary with slug and intermittent flow patterns while at low liquid and high gas flow rates, it shares the transition boundary with wavy annular and annular flow patterns. An increase in downward pipe inclination from horizontal is found to shift the transition from stratified to non-stratified flows towards higher liquid flow rates until $\theta \approx -45^\circ$. Any further increase in downward pipe inclination from $\theta \approx -45^\circ$ towards vertical downward position is found to lower the liquid flow rates corresponding to the stratified/non-stratified flow transition boundary. It is evident that the generic shape of the transition line between stratified and annular flow (at low liquid and high gas flow rates) is relatively insensitive to the change in pipe inclination. This region of stratified flow typically corresponds to the wavy stratified and rolling wave flow which are inertia driven in nature. Note that at near downward vertical pipe inclination, falling film flow coexists with stratified flow in the region near to the transition line. At these orientations, the edges of gas-liquid interface tend to climb up the tube periphery such that it occupies most of the pipe circumference. With increase in liquid flow rate, a thin film of liquid is observed at the pipe upper wall and falling film flow is said to exist. As mentioned earlier, falling film flow is a special case of stratified flow for vertical and near vertical downward pipe orientations and hence no distinction is made between these two phase flow patterns on the flow map in Fig. 4. For vertical downward flow, stratified flow is always in form of falling film due to the flow symmetry. On a qualitative basis, these observations are consistent with the flow visualization experiments of [4, 6, 7]. However, at near vertical and vertical downward inclination, flow maps of Ref. [6] show existence of annular flow between stratified and intermittent flow patterns. Considering the flow physics and definition of annular flow pattern (wavy liquid film surrounding fast moving turbulent gas core that results into significant interfacial shear and liquid entrainment), this observation of existence of an-

nular flow pattern at low gas flow rates seems to be unlikely unless a different definition of annular flow is adopted by Ref. [6]. The existence of stratified flow pattern or alternatively the transition line between stratified and non-stratified flow patterns can be predicted with a reasonable accuracy by using [8, 9] mechanistic models as well as empirical models of [7, 16]. Note that mechanistic models of [8, 9] are implicit and/or based on the graphical solution while the models of [7, 16] are explicit and empirical based on a wide variety of experimental data.

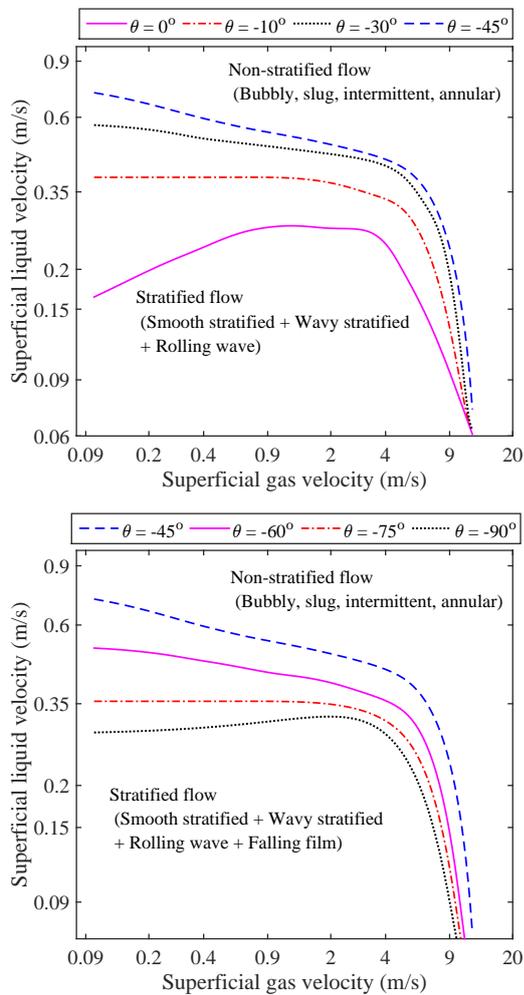


Figure 4: Effect of change in downward pipe inclination on the transition between stratified and non-stratified flow patterns.

An important mention worthy phenomenon present in the near transition line region at low gas flow rates is the transient behavior of two phase flow. This transient behavior results into simultaneous existence of multiple flow patterns (usually stratified, slug and bubbly) in the test section as verified by analyzing pressure drop signal depicted in Fig. 5. Hence, any two phase flow parameter such as void fraction, pressure drop or heat transfer measured over a period of time is expected to be affected by this transient behavior. Considering this behavior, appropriate care is exercised to ensure that the average values of pressure drop and heat transfer data in near transition region at steeper pipe inclinations are a representation of time dependent data measured over a substantial longer time period compared to other data points. For this flow regime, steady state conditions are hardly attained and a different sampling time would yield a different magnitude of two phase pressure drop. As such, the transient region in downward inclined two phase flow has little significance with no definite

flow structure and hence this region must be avoided for all practical purposes. Similar flow visualization observations have been reported by [3, 7].

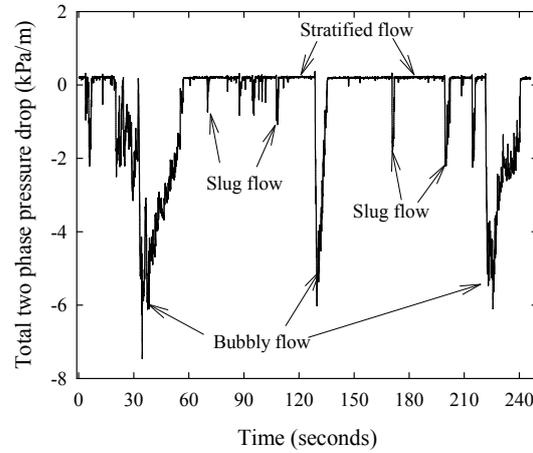


Figure 5: Pressure drop variation corresponding to transient behavior of two phase flow in downward pipe inclinations.

3.2. Effect of phase flow rates

At a fixed pipe inclination, the stratified flow pattern and its associated two phase flow variables are in general found to remain insensitive to the increase in gas flow rates until a threshold value and then increases sharply thereafter. From Fig. 6 this trend is observed to be more prominent in steeper pipe inclinations at low to moderate gas flow rates ($U_{sg}/U_{sl} \lesssim 20$ m/s) where stratified flow (with the exception in horizontal inclination) is gravity driven in nature. Until this point, gas-liquid stratified flow behaves more like a free surface channel flow where the pressure drop is a function of liquid flow rate only. Beyond this point, the region of stratified flow is inertia driven in nature and is characterized by the formation of rolling waves at the gas-liquid interface that enhances the pressure drop. This trend of pressure drop variation with change in gas flow rates is in agreement with the observations of Ref. [2]. In case of horizontal flow, hydrostatic component of pressure drop is absent and hence total and frictional components of two phase pressure drop overlay on each other. Also note that the change in void fraction with increase in gas flow rate is much more rapid in comparison to steeper downward pipe inclinations. This trend is possibly due to the difference in physical structure and stability of the gas-liquid interface at horizontal inclination compared to $\theta = -45^\circ$ and $\theta = -90^\circ$. Flow visualization shows that at very low gas flow rates, horizontal stratified flow consists of a thicker liquid layer height (at pipe bottom) and experiences a momentarily bridging of the pipe cross section. This reduces the effective volume occupied by the gas phase and hence reduces the void fraction. Increase in gas flow rates gradually makes the stratified flow inertia driven in nature with co-current flow of both phases in downstream direction and hence void fraction increases linearly with increase in the gas flow rate. Contrary to this trend, gas phase in steeper downward inclinations and vertical downward flow experiences a significant buoyancy force and hence tries to move in a direction to that of the liquid phase. This phenomenon increases the residence time of the gas phase in the test section and hence increases the in-situ void fraction. A graphical description of the effect of buoyancy force on the gas phase and change in its flow direction/velocity profile in gas-liquid stratified flow described by Ref. [17] is shown in Fig. 7.

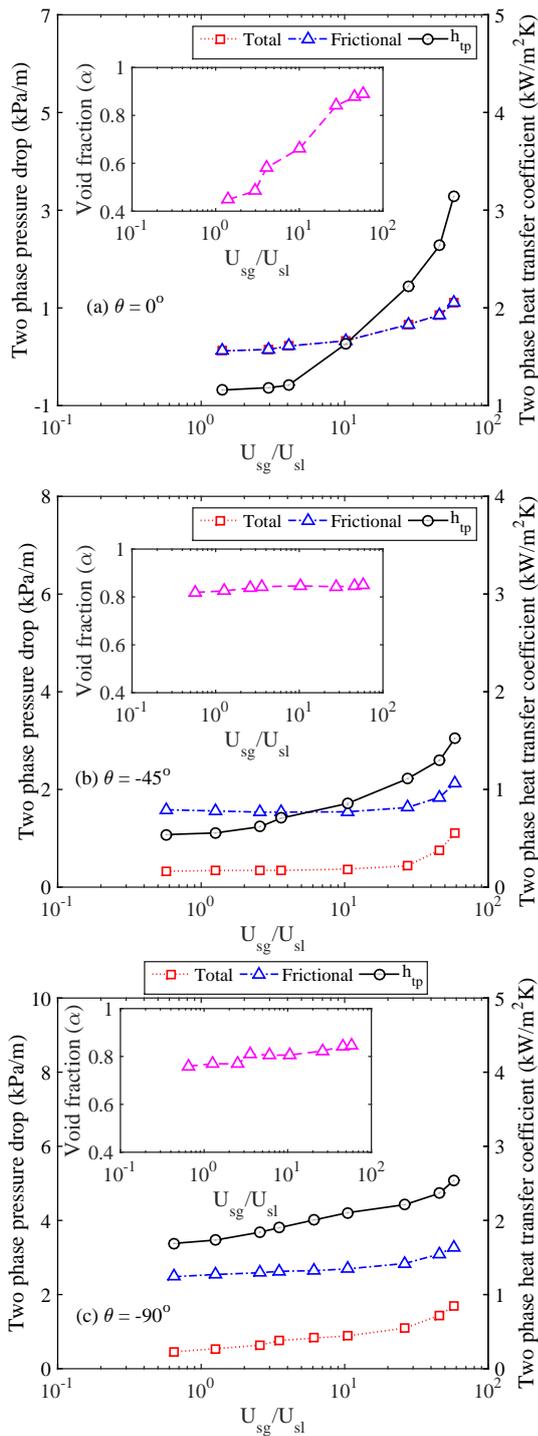


Figure 6: Effect of phase flow rates on void fraction, pressure drop and heat transfer in stratified flow ($U_{sl} = 0.15$ m/s).

For horizontal flow, in comparison to pressure drop, heat transfer coefficient (h_{tp}) responds quickly and rapidly in moderate to high gas flow rate range. Note that this trend is similar to that of the change in void fraction as a function of increase in gas flow rate. Figure 4 shows that in comparison to other downward inclinations, horizontal two phase flow experiences an early transition (at lower gas flow rates) between stratified and non-stratified flow patterns. Thus, for $U_{sg}/U_{sl} \gtrsim 30$ m/s, two phase flow is very close to the transition line and hence behaves more like a wavy annular flow rather than wavy stratified flow. Obvi-

ously, due to better wetting and continuous presence of the liquid film throughout the pipe circumference, h_{tp} increases rapidly with increase in the gas flow rate. Moreover, the flow of gas and liquid phase is always co-current and any increase in the gas flow rate contributes to the enhancement of two phase heat transfer coefficient. In case of downward pipe inclinations, gas phase in stratified flow experiences a higher residence time and hence results into a very gradual increase in void fraction as well as two phase heat transfer coefficient. Also, at high gas flow rates (compared to horizontal flow at $U_{sg}/U_{sl} \gtrsim 30$ m/s), flow pattern in these pipe inclinations remains stratified in nature and hence show a relatively gradual increase in two phase flow quantities.

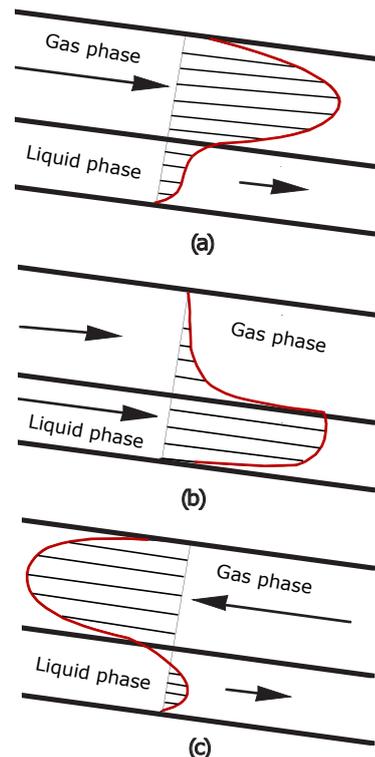


Figure 7: Co-current and counter current flow of gas phase in gas-liquid stratified flow (adapted from Ref. [17]).

3.3. Effect of pipe inclination

Experimental results show that depending upon the gas and liquid flow rates, stratified flow responds sharply to a change in downward pipe inclinations. This effect is again essentially due to the interaction between the buoyancy (acting on gas phase) and gravity (acting on liquid phase) at different downward pipe inclinations. The effect of change in downward pipe inclination on the void fraction in gas-liquid stratified flow is reported in Fig. 8. Effect of downward pipe inclination on void fraction is prominent at low gas flow rates and this effect gradually goes away as the stratified flow becomes inertia driven in nature. At low gas flow rates, void fraction is first observed to increase with increase in downward pipe inclination with a maximum in between -45° and -60° and then decreases again as the pipe is inclined towards vertical downward position. As mentioned earlier, the higher values of void fraction at steeper pipe inclinations (up to $\theta \approx -60^\circ$) are due to the higher residence time of the gas phase in the test section. Further for $U_{sl} = 0.3$ m/s and at near vertical pipe inclinations, the transient behavior of two phase flow results into decreased magnitudes of the void fraction. Also note that the effect of pipe inclination on void fraction is more prominent

for near horizontal flows compared to steeper pipe inclinations. This is due to the fact that stratified flow in horizontal orientation undergoes a rapid change in its flow structure/gas-liquid phase distribution across pipe cross section while that at steeper pipe inclinations remains virtually unaltered.

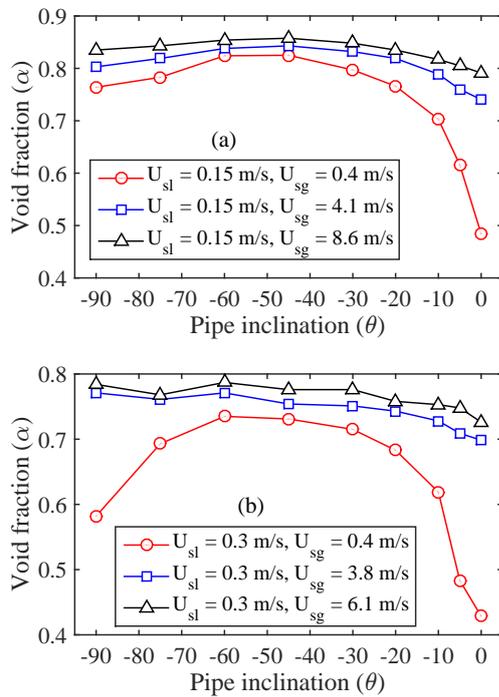


Figure 8: Effect of change in downward pipe inclination on void fraction.

Figures 9 and 10 show variation of different components of two phase pressure drop and heat transfer coefficient for selected gas flow rates measured at $U_{sl} = 0.15$ m/s and 0.3 m/s, respectively. For any given combination of gas and liquid flow rates, the total two phase pressure drop given by Eqn. (1) changes very gradually and can be treated as virtually insensitive to the increase in downward pipe inclination measured from horizontal. It is evident that this trend of the total two phase pressure drop is due to the balance between the relative magnitudes (increasing and decreasing trends) of the hydrostatic and frictional component of the two phase pressure drop. At $U_{sl} = 0.3$ m/s and $U_{sg} = 0.4$ m/s, a sudden change in this trend is observed since at these flow rates, flow pattern in vertical downward flow is very close to the transition line and is affected by the transient behavior of two phase flow described earlier. The frictional component of two phase pressure drop is found to consistently increase with increase in downward inclination due to the fact that the velocity profile of the liquid layer in downward pipe inclinations is much more steeper compared to that in horizontal flow [3, 17]. Steeper velocity profiles results into increased wall shear stress and hence the two phase frictional pressure drop in downward inclinations is higher than that in horizontal flow. In comparison to pressure drop, two phase heat transfer coefficient responds sharply to the change in downward pipe inclination. Two phase heat transfer coefficient initially decreases with increase in downward pipe inclination measured from horizontal with a minimum approximately in between -30° and -45° and then increases again reaching a maximum value as the pipe is inclined towards vertical downward position. This trend could be explained using the argument of the variation in liquid film thickness and its circumferential distribution as a function of pipe inclination. At near vertical and vertical downward pipe inclinations ($\theta = -75^\circ$ and -90°), the flow pat-

tern is stratified and falling film flow, respectively. At $\theta = -75^\circ$, the visual observations show that the gas-liquid interface of stratified flow pattern is unstable such that the liquid phase splashes on the pipe top wall and momentarily bridges the pipe cross section.

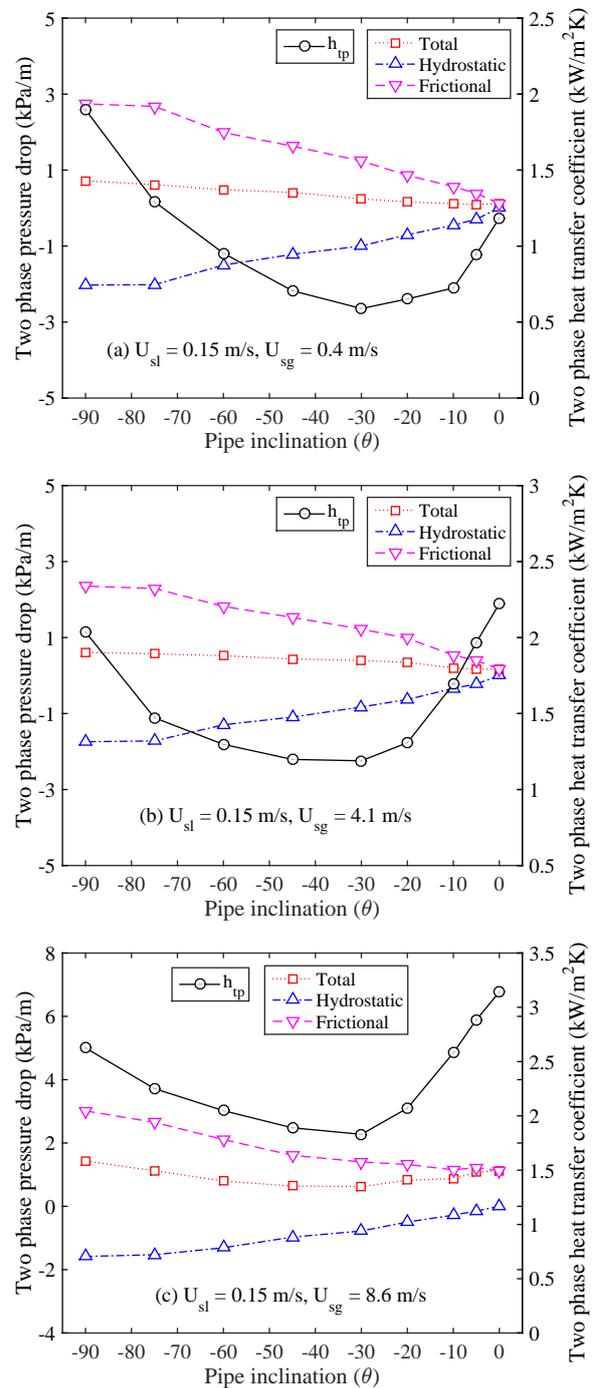


Figure 9: Variation of two phase pressure drop and two phase heat transfer coefficient as a function of pipe inclination.

Barnea et al. [6] also reported that at steeper pipe inclinations, liquid lumps are torn away from the unstable gas-liquid interface all the way to the top wall of the pipe. Also, the gas-liquid interface in steeper pipe inclinations tend to become concave and the liquid film climbs the tube periphery with increase in the liquid flow rate. This implies that, compared to near hori-

zontal downward pipe inclinations, a greater fraction of the pipe circumference is in contact with the liquid phase for near vertical downward pipe inclinations and hence permits higher rates of two phase heat transfer. For vertical downward flow, the entire pipe circumference is in contact with a thin liquid film and compared to the stratified flow structure, an axisymmetric thick liquid film allows higher heat transfer rates and hence higher values of two phase heat transfer coefficient. The three different forms of stratified flow with variation in the liquid film thickness and its circumferential distribution as a function of pipe orientation are depicted in Fig.11.

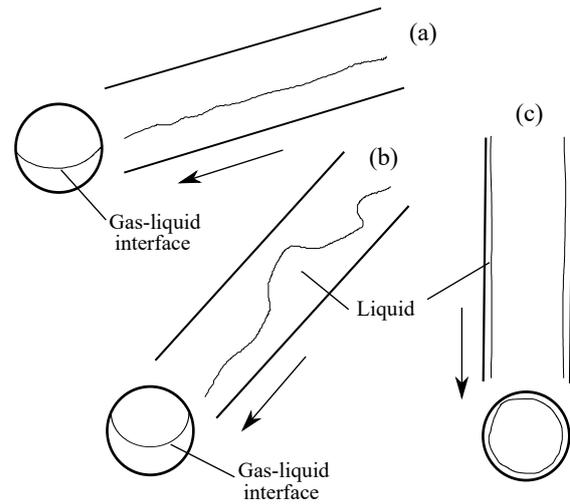


Figure 11: Variation in the liquid film thickness and distribution of the stratified flow with change in pipe orientation (a) Near horizontal (b) Near vertical downward (c) Vertical downward.

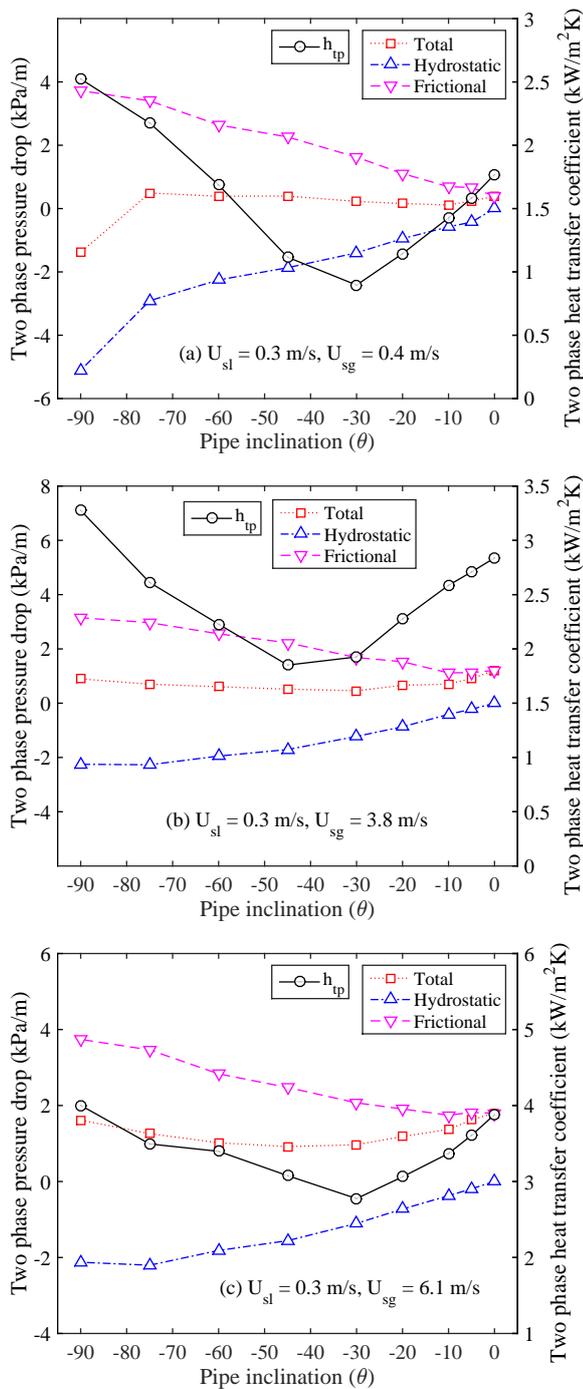


Figure 10: Variation of two phase pressure drop and two phase heat transfer coefficient as a function of pipe inclination.

It is clear from above discussion that the two phase flow variables (void fraction, frictional pressure drop and heat transfer coefficient) are affected by the change in downward pipe inclination. Thus, it is obvious that the two phase flow models used to predict these quantities must be functions of the pipe inclination. In comparison to void fraction and heat transfer coefficient, frictional pressure drop shows a linear increase with increase in the pipe inclination where as the change in void fraction and heat transfer coefficient is non-linear. It would be of interest to know the performance of existing models while operating in downward inclined stratified flow regime. A detailed performance analysis and modeling of these flow variables is beyond the ambit of this work and hence it is attempted here to provide a brief account on the findings and conclusions of some of the recent studies dealing with performance verification of different two phase flow models. Analysis of the void fraction data by Ref. [18] shows that existing flow pattern independent correlations fail to predict the void fraction correctly. Though, the two phase flow literature reports a few stratified flow pattern specific models, these models are developed mostly for the wavy stratified flow and their accuracy for the entire spectrum of stratified flow needs to be verified against a broad range of experimental data. The performance analysis for condensing two phase flow of refrigerants carried out by Ref. [19] shows that the mechanistic model of Ref. [8] under predicts the void fraction data in steeper downward pipe inclinations (at low two phase qualities and low mixture mass fluxes corresponding to buoyancy affected region of stratified flow). Thus, this finding also advocates the need of developing a robust flow pattern specific two phase flow model dedicated to stratified flow. The experimental work of Ref. [19] also finds the correlation of Ref. [8] to reasonably predict the total two phase pressure drop in downward inclined stratified flow. Note that use of Ref. [8] yields both void fraction and total two phase pressure drop (since these two quantities are coupled together in their model) and it is interesting to see that this model successfully predicts total two phase pressure drop while under predicts the void fraction. A recent experimental and analysis work of Ref. [20] shows that in general all of the existing two phase flow models give poor accuracy in prediction of two phase heat transfer coefficient in downward inclined stratified flow. The performance of some models like Refs. [21] and [22] is improved drastically outside the stratified flow regime. Again, this observation supports the need of developing a flow pattern specific model to predict stratified two phase flow behavior in downward pipe inclinations. The above

brief discussion with evidence from multiple studies concludes that a further experimentation and analytical modeling is required to verify these trends and develop/modify the existing stratified flow models to improve the prediction of stratified flow behavior in downward pipe inclinations.

4. Conclusions

This paper presents new data on flow transition, void fraction, pressure drop and non-boiling two phase heat transfer measurements in horizontal and downward inclined gas-liquid stratified flow. Experimental observations conclude that downward pipe inclinations have a noticeable effect on the transition between stratified and non-stratified flow patterns as well as other two phase flow variables. Some of the important observations of this work could be summarized as follows:

(1) Increase in downward pipe inclination from horizontal consistently raises this transition boundary towards higher liquid flow rates until $\theta \approx -45^\circ$ and then again shifts it towards lower liquid flow rates as pipe is inclined towards vertical downward position. (2) At steeper pipe inclinations, stratified flow near and above the transition line is affected by the transient behavior of two phase flow such that stratified, slug and bubbly flow patterns may exist simultaneously in the test section. (3) Frictional pressure drop is found to increase with increase in downward pipe inclination from horizontal inevitably due to the steeper velocity profiles and the gravity acting on the liquid phase. (4) Two phase heat transfer coefficient exhibits a decreasing and increasing trend as the pipe is inclined away from horizontal. During this variation, minimum value of h_{tp} is observed in the vicinity of $\theta \approx -30^\circ$. Based on the observations in this study, it appears that study of stratified flow in downward pipe inclinations with varying fluid properties and a range of pipe diameters would be quite intriguing and necessary to provide better insight for accurate modeling of this flow pattern over a wide range of flow conditions.

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