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NON-BOILING HEAT TRANSFER IN HORIZONTAL AND NEAR HORIZONTAL DOWNWARD INCLINED GAS-LIQUID TWO PHASE FLOW

Tabassum Aziz Hossainy, Swanand M. Bhagwat and Afshin J. Ghajar*,
*Author for correspondence
School of Mechanical and Aerospace Engineering,
Oklahoma State University,
Stillwater OK 74078,
USA.
E-mail: afshin.ghajar@okstate.edu

ABSTRACT

Heat transfer in non-boiling gas-liquid two phase flow has significant practical applications in chemical and petroleum industry. To date, majority of the research in this field have been conducted for two phase flow in horizontal and vertical pipe systems. To explore and enhance the general understanding of heat transfer in non-boiling two phase flow, the main focus of this work is to experimentally measure local and average convective heat transfer coefficients for different flow patterns in horizontal and near horizontal downward inclined two phase flow. In total, 380 experiments are carried out in a 12.5 mm I.D. schedule 10S stainless steel pipe at 0, -5, -10 and -20 degrees pipe orientations using air-water as fluid combination. For each pipe orientation, the superficial gas and liquid Reynolds number is varied from 200 to 19,000 and 2000 to 18,000, respectively. The measured values of the average two phase heat transfer coefficient are found to be in a range of 500 W/m^2K to 7700 W/m^2K. Comparisons are drawn between the two phase heat transfer coefficients in the above mentioned pipe orientations. It is found that the increase in inclination of the pipe in downward direction causes the two phase heat transfer coefficient to decrease. This trend of two phase heat transfer data is explained based on the flow visualization and establishing its connection with the flow pattern structure and the two phase flow physics.

INTRODUCTION

Investigation of heat transfer in non-boiling two phase flow in pipe is of great practical importance for industrial applications such as reduction of paraffin wax deposition in petroleum transport lines, air lift system, solar collectors, nuclear reactors and several chemical processes. Despite having great practical applications, the effect of inclination on the two phase flow in pipe has been rarely investigated. Some of the experimental data available in the two phase flow literature for horizontal, near horizontal upward inclined two phase flow is that of Ghajar and Tang [1], Tang and Ghajar [2], Hestroni et al. [3, 4]. For vertical downward flow the only experimental work available in the literature is that of Bhagwat et al. [5], Oshinowo et al. [6] and Chu and Jones [7]. In comparison to these pipe orientations there is hardly any experimental data available on downward inclined two phase flow. Tang and Ghajar [2] established that there is a significant increase in the heat transfer in two phase air-water flow when pipe is inclined slightly upward from the near horizontal position. Bhagwat et al. [5] and Oshinowo et al. [6] conducted experiments on vertical downward flow and concluded that there is reduction in heat transfer compared to vertical upward flow. The outcome of these experiments pose some fundamental questions about the reason of such increase or reduction in heat transfer and creates a room for further investigation to establish a more comprehensive qualitative and quantitative physical understanding of two phase flow at inclined orientations. Furthermore, such investigation can pave the way for the development of a robust heat transfer correlation in two phase flow which can account for the effect of pipe orientation. To accomplish this objective this study presents new data on horizontal and near horizontal downward flow at -5^o,-10^o, and -20^o using air-water mixture. The different flow patterns observed in horizontal and downward pipe inclinations are mapped using air and water mass flow rates. The flow pattern map generated in this work is useful in getting an idea of the effect of pipe orientation on the transition boundaries between different flow patterns. Due to complex nature of the two phase flow, sufficient experimental data are collected for each flow pattern and for comparable mass flow rates at different pipe inclinations so as to establish a clear trend of two phase heat transfer in downward inclinations. The experimental data are then analyzed to establish the trend of two phase heat transfer coefficient for different pipe orientations.

NOMENCLATURE

dz	[m]	Differential change in axial direction
D	[m]	Pipe diameter
G	[kg/m^2s]	Mass flux

h	[W/m^{2}K]	Heat transfer coefficient
$\bar{h}$	[W/m^{2}K]	Circumferentially averaged heat transfer coefficient
L	[m]	Pipe length
Nu	[-]	Nusselt number
N_{ST}	[-]	No. of thermocouple stations
Re	[-]	Reynolds number
T	[^{o}C,K]	Temperature
U	[m/s]	Phase velocity
x	[-]	Two phase flow quality
z	[m]	Axial direction

Special characters

μ	[Pa-s]	Phase dynamic viscosity
ρ	[kg/m^3]	Phase density
θ	[deg.]	Pipe orientation
Δ		Differential operator

Subscripts

b	Bulk
G	Gas
i	Pipe inlet
L	Liquid
o	Pipe outlet
S	Superficial
TP	Two phase

EXPERIMENTAL SETUP

The experimental set up used for measuring two phase convective heat transfer coefficient as shown in Figure 1 consists of 12.5 mm I.D. schedule 10 S steel pipe of roughness 0.0152 mm. The setup also consists of a 12.67 mm I.D. transparent polycarbonate pipe that can be used for flow visualization and measurement of void fraction and pressure drop. The fluid combination used for generating two phase flow is compressed air-distilled water. The air is supplied through an Ingersoll Rand T-30 Model 2545 compressor, passed through a regulator and filter-lubricator circuit before it is fetched to the water submerged coil heat exchanger. Next, the air is passed through Coriolis mass flow meter and controlled by the Parker needle valve (Model 6A-NLL-NE-SS-V) before it is mixed with water in the static mixer. The liquid phase, i.e., distilled water is stored in a 55 gallon tank and is circulated in the system using a Bell and Gosset (series 1535, model number 3445 D10) centrifugal pump and passed through an Aqua-Pure AP12-T purifier followed by the flow through a ITT model BCF 4063 shell and tube heat exchanger. The water is then directed to flow meter through Emerson (Micro Motion Elite Series model number CMF 100) Coriolis mass flow meter and then allowed to mix with air in a static mixer. The water mass flow rate is controlled by a gate valve placed after the water mass flow meter. The CO1-T type thermocouples with an accuracy of ±1^{o}C are used to measure wall temperatures at seven different stations spaced 127 mm apart along the pipe length.The thermocouple probes (TMQSS-06U-6) used to measure temperature at the pipe inlet ($T_{i,b}$) and outlet ($T_{o,b}$) are inserted inside through pipe wall till it almost touched the other end of the pipe wall in order to ensure that the probes are always in contact with the two phase mixture.

The thermocouples at each station (four thermocouples at each station) are arranged radially along the pipe circumference as shown in Figure 2. The uniform heat flux in a range of 7500 W/m^2 to 57,000 W/m^2 is supplied by Lincoln DC-600 welder having a maximum current supply of 750 Amp. In order to ensure no heat transfer takes place from the system to surrounding, a 0.076 m (3 in.) thick Micro-Lok Fiber Glass insulation with thermal conductivity of 0.042 W/m^{o}C is used. The local inside wall temperature, wall heat flux and convective heat transfer coefficient is calculated using a finite difference formulation based data reduction program developed by Ghajar and Kim [8]. The two phase convective heat transfer coefficient is represented by the average of the measured local values at each station as shown in Eq. (1).

$$h_{TP} = \frac{1}{L}\int \bar{h}\,dz = \frac{1}{L}\sum_{j=1}^{N_{ST}} \bar{h}_j \Delta z_j \tag{1}$$

The uncertainty of the experimental data for single phase heat transfer coefficient is calculated using Kline and McClintock [9] uncertainty analysis. The validity of the single phase heat transfer data is also confirmed by comparing it against the correlations of Gnielinski [10], Ghajar and Tam [11] and Sieder and Tate [12]. As shown in Figure 3 the measured single phase heat transfer coefficient is found to be within ±10% of the predicted values by Seider and Tate [12]. The average and maximum deviation in measurement of single phase heat transfer coefficient with respect to the correlations of Gnielinski [10] and Ghajar and Tam [11] was found to be 4.8%, 14.82% and 0.86%, 3.7%, respectively.

Minimum and maximum uncertainty in measurements of two phase heat transfer coefficient at different pipe inclination and for each observed flow pattern is presented in Table 1. Maximum uncertainty was observed for stratified flow regime with 31.54%, 31.09% and 27.42% at -5^0, -10^0 and -20^0, respectively. Interestingly, the minimum value of uncertainty is also observed in the same flow pattern with 7.1%, 7.42% and 6.26% at -5^0, -10^0 and -20^0, respectively.

One of the probable reasons for very high values of percentage uncertainty in stratified region might be the higher heat balance error compared to other flow patterns. In stratified flow, the heat balance error is in between 8% to 16% compared to intermittent and slug region where it is around 1% to 7%. No clear trend can be established on the effect of pipe inclination on uncertainty in measurement of two phase heat transfer coefficient. However, for slug and stratified flow, the minimum percentage uncertainty is observed to decrease with increase in the downward pipe orientation.

Table 1 Uncertainty in two phase heat transfer coefficient.

Flow Pattern		**0^0**	**-5^0**	**-10^0**	**-20^0**
Bubbly	Max. %	12	11.3	10.7	11.1
	Min. %	10	10.3	10.3	10.8
Slug	Max. %	13	12.4	10.5	11.5
	Min. %	9	8.6	8.6	7.8
Stratified	Max. %	27	31.5	31.1	27.4
	Min. %	10	7.1	7.4	6.3
Intermittent	Max. %	25	17.3	28.6	29
	Min. %	11	9.2	10.3	11.1

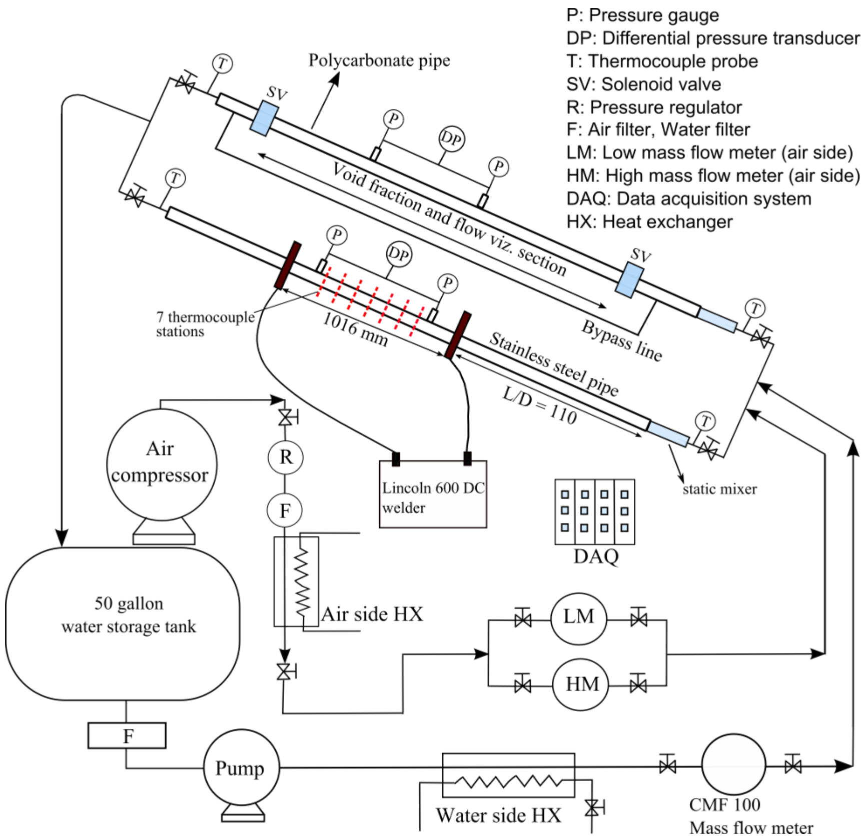


Figure 1 Experimental setup used for two phase heat transfer measurements.

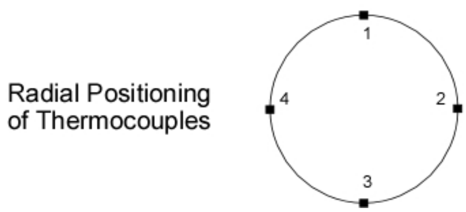


Figure 2 Radially arranged thermocouples at pipe circumference.

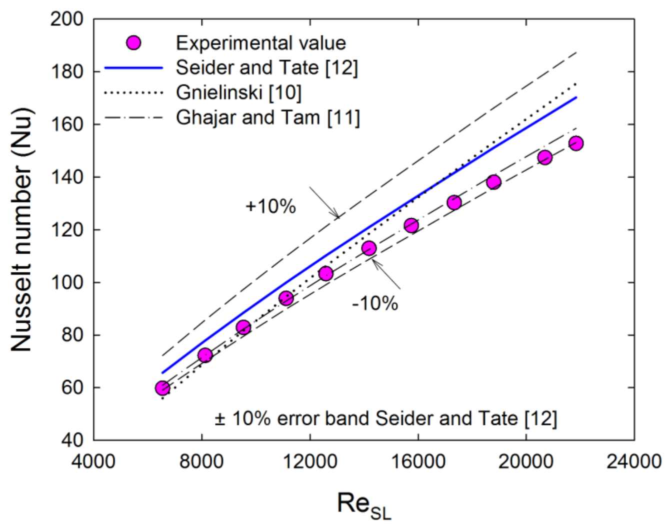


Figure 3 Uncertainty in measurement of single phase Nusselt number.

RESULTS AND DISCUSSION

Flow Patterns and Flow Pattern Maps

The two phase flow literature reports that the physical structure of flow patterns is significantly influenced by the pipe orientation which further significantly affects the two phase heat transfer coefficient in gas-liquid two phase flow. The flow pattern maps are essential for the estimation of the sequence of appearance of different flow patterns with change in the gas and liquid flow rates. The definitions of flow patterns and their transitions are highly qualitative in nature and are mostly based on the individual's perception. The key flow patterns observed in horizontal and downward inclined two phase flow are bubbly, slug, intermittent, stratified and annular flow regimes as shown in Figure 4. These flow patterns are generated by changing the gas and liquid flow rates (superficial gas and liquid Reynolds numbers) in a range of 0.001 kg/min to 0.2 kg/min (Re_{SG} = 200 to 19,000) and 1.5 kg/min to 12.5 kg/min (Re_{SL} = 2000 to 18,000), respectively. The superficial gas and liquid Reynolds number is defined in terms of superficial phase velocity, phase density and viscosity and pipe diameter as represented in Eqs. (2) and (3). The flow visualization is carried out in transparent polycarbonate pipe using Nikon D3100 camera and 200mm f/5.6 lens with a shutter speed of 1/4000 s.

$$Re_{SG} = \frac{\rho_G D U_{SG}}{\mu_G} = \frac{GxD}{\mu_G} \tag{2}$$

$$\mathrm{Re}_{SL} = \frac{\rho_L D U_{SL}}{\mu_L} = \frac{G(1-x)D}{\mu_L} \quad (3)$$

The bubbly flow regime is characterized by the dispersion of small bubbles in the continuous liquid medium while the slug flow is identified as a flow structure consisting of elongated gas slugs that flow alternate to a liquid plug. The stratified flow is featured by the flow of liquid film parallel to the gas phase. The annular flow is observed in form of liquid film flowing in contact with the pipe wall that surrounds a fast moving gas core. The definition of intermittent flow is vague since there is no particular way in which gas and liquid phases are aligned across the pipe cross section. In the present study, the intermittent flow pattern is identified based on the pulsating and chaotic nature of the two phase flow. Thus the flow structure tagged as intermittent flow in the present study consists of slug-wavy, stratified-wavy and annular-wavy flow patterns for moderate liquid and moderate gas flow rates, low liquid and moderate gas flow rates and low to moderate liquid and high gas flow rates, respectively.

As shown in Figure 4, for all pipe orientations considered in this study, the bubbly flow exists for low gas and high liquid flow rates. At low liquid flow rates, increase in the gas flow rate causes the flow pattern to shift from stratified to intermittent and finally to annular flow. Whereas, for moderate liquid flow rates, the flow pattern shifts from slug to intermittent to annular flow as the gas flow rate is increased from low to moderate to high flow rates. It is also evident from this flow pattern map that the transition boundaries between different flow patterns with the exception of boundary between intermittent and annular flow are significantly influenced by the change in pipe orientation. It should be noted that for horizontal flow, there is no stratified flow pattern for gas mass flow rates lower than 0.01 kg/min.

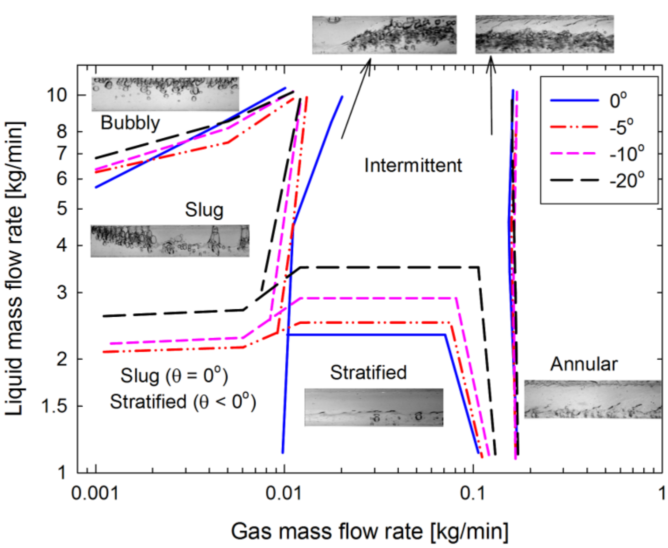


Figure 4 Flow regime map for horizontal and downward inclined two phase flow.

In the present study, majority of the data points for the two phase heat transfer coefficient have been collected for slug, stratified and intermittent flow regimes. Although the flow patterns for similar gas and liquid superficial Reynolds number might be identical, it is important to acknowledge that the physical characteristics of these similar flow patterns may not completely be identical. For instance, the translational velocity of the slug through pipe, the thickness of liquid layer at the bottom of the pipe in the stratified flow regime, frequency of the disturbance waves in annular flow regime and intensity of turbulent mixing in the intermittent flow pattern varies as the pipe orientation is taken from horizontal to downward inclinations.

In total 380 two phase heat transfer measurements are made at different inclinations with 95 data points in each inclination. The number of data points for different flow patterns in each orientation is tabulated in Table 2. Majority of the data points are taken in the stratified, intermittent and slug flow regions. Due to limitations on the range of mass flow meters and difficulty in generating a sufficient enough temperature difference across pipe inlet and outlet, only few data points could be measured in bubbly and annular flow regimes.

Table 2 Number of data points in different flow patterns at different pipe inclinations.

Flow pattern	**0°**	**-5°**	**-10°**	**-20°**
Stratified	5	17	22	23
Slug	28	22	18	18
Intermittent	58	52	51	50
Bubbly	4	5	5	5

Effect of Flow Patterns and Pipe Orientation on Two Phase Heat Transfer Coefficient

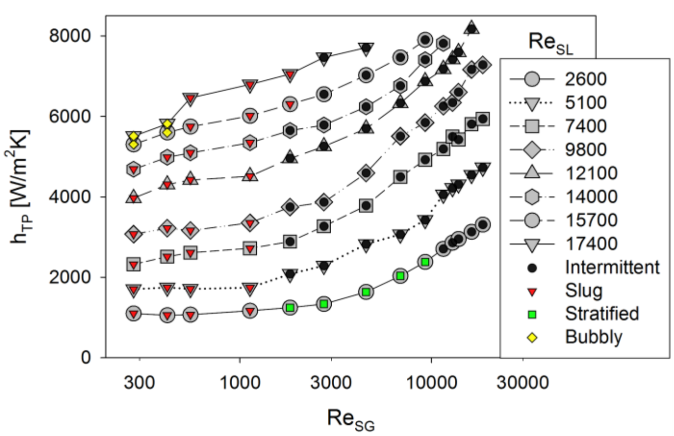
Since the two phase heat transfer coefficient is affected by the change in physical structure of flow patterns which is in turn a function of pipe orientation; it is interesting to take a look at the combined effect of phase flow rates (or alternatively the flow patterns) and the pipe orientation on the two phase heat transfer coefficient.

The effect of pipe inclination on the two phase heat transfer coefficient is investigated by comparing its magnitude at different pipe inclinations and similar liquid and gas flow rates (or alternatively superficial Reynolds numbers). Figure 5 represents the change of two phase heat transfer coefficient (h_{TP}) with superficial gas Reynolds number Re_{SG} measured at constant Re_{SL}. The flow pattern corresponding to combination of each Re_{SL} and Re_{SG} is also identified in the figure. It is observed that the two phase heat transfer coefficient increases with the increase of Re_{SG} and Re_{SL}. Overall it is observed that the two phase heat transfer increases at low Re_{SG} (stratified and slug flow patterns), then it remains virtually unchanged at the middle range of Re_{SG} (intermittent flow) and then increases in the higher range of Re_{SG} (transitional intermittent flow approaching annular flow). In stratified flow, $\mathrm{Re}_{SG} < 3000$ and $\mathrm{Re}_{SL} < 2600$ the heat transfer coefficient value increases slowly with the increase in Re_{SG}. For similar Re_{SL} and $2600 < \mathrm{Re}_{SG} <$ 10,000, the flow is still stratified but the h_{TP} indicates steeper slope. This is probably due to shear driven nature of the stratified flow compared to low inertia stratified flow occurring at Re_{SG} < 2600. In this range of Re_{SG} (2600 to 1000) corresponding to the stratified flow, disturbance waves are frequently observed that locally accelerates the two phase flow mixture resulting into increase in the heat transfer coefficient.

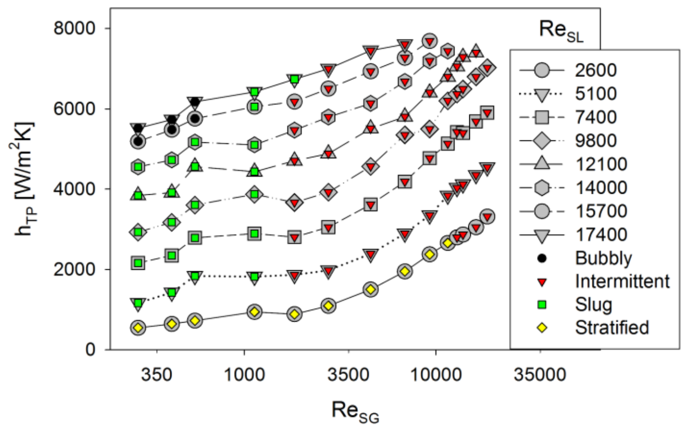
When Re_{SG} <1200 and the liquid superficial Reynolds number is increased beyond 6000, the stratified flow in the downward inclined orientations transits to slug flow. The value of h_{TP} increases with higher Re_{SL} in the slug flow regime. This is consistent with the observation made by Bhagwat et al. [5] and Oliver and Wright [13]. The reason for such increase is the length of slugs traversing through the pipe. Slug length and slug frequency are one of the main factors affecting the two phase heat transfer in slug flow regime.

An increase in the liquid flow rate for a fixed gas flow rate results into a short length slug that traverses with comparatively high frequency through the pipe causing increase in the two phase heat transfer. It can also be observed from Figure 5 that for all pipe orientations, initially at low Re_{SG} in slug flow regime heat transfer increases steadily, however, at higher Re_{SG} (approximately above 1200) which is the onset of the intermittent (slug-wavy) flow, the slope of h_{TP} becomes less stepper.. With a further increase in Re_{SG}, the two phase heat transfer coefficient increases rapidly. Albeit, the flow pattern for these two cases i.e., 1200 < Re_{SG} ≤ 10,000 and Re_{SG} > 10,000 is intermittent, the physical structure of the intermittent flow is significantly different. For the low values of Re_{SG}, the intermittent flow is essentially slug-wavy in nature while for high values of Re_{SG}, the intermittent flow is wavy-annular (shear driven) in nature. At this point, the intermittent flow starts to develop continuous thin liquid film that is in contact with the pipe top wall and is very conducive to heat transfer due to better contact with the liquid at the pipe upper surface.

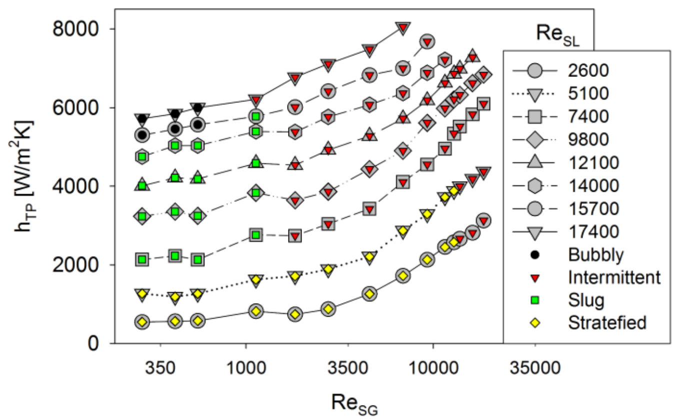
Overall, in the intermittent flow region, the flow is induced with significant mixing and turbulence which contributes to the enhancement in two phase heat transfer. Pipe inclination plays a major role in heat transfer in two phase flow. As the pipe is inclined downward from horizontal to -5°, -10° and -20°, the two phase heat transfer coefficient is found to decrease systematically.



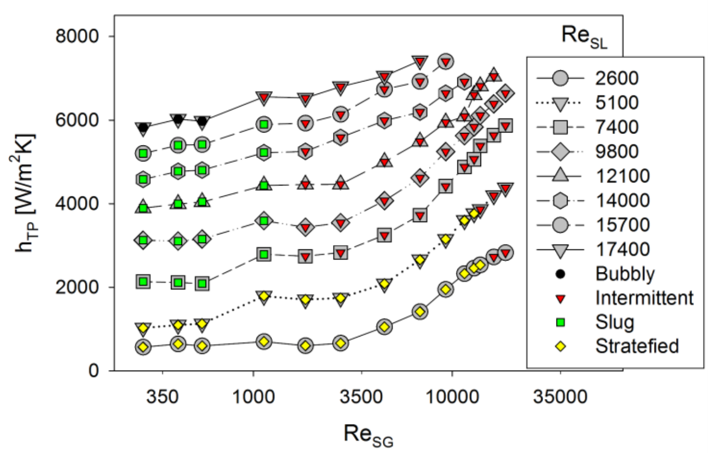
(a) 0 degree



(b) -5 degree



(c) -10 degree



(d) -20 degree

Figure 5: Variation of two phase heat transfer coefficient at fixed Re_{SL} and increasing Re_{SG} (a) 0 degree, (b) -5 degree, (c) -10 degree, (d) -20 degree.

This observation of reduction of heat transfer at downward inclination is consistent with the observations of Oshinowo et al. [6]. They found the two phase heat transfer coefficient to decrease when the pipe is oriented from vertical upward to vertical downward. It is also worthwhile to mention that the amount of decrease in two phase heat transfer depends on the flow pattern. As observed from Figure 6 the highest average percentage decrease in heat transfer from horizontal is observed in stratified flow with 15%, 22% and 27% reduction at -5^o, -10^o and -20^o, respectively. The effect of pipe orientation is also prominent for intermittent flow with an average reduction of 4%, 6% and 10% corresponding to -5^o, -10^o and -20^o inclinations, respectively. Slug flow region shows less sensitivity to the change in pipe inclination with around 2%, 2% and 5% reduction in two phase heat transfer coefficient at to -5^o, -10^o and -20^o inclinations, respectively. However, it should be mentioned that due to highly random slug length and slug frequency at inclined flow in some instances, reduction in two phase heat transfer is much higher than the average values. For example, the highest percentage reduction obtained in slug flow is 31%, 17% and 20% at -5^o, -10^o and -20^o, respectively which is fairly high compared to its average reduction.

The comparisons of two phase heat transfer coefficient at different pipe inclinations with respect to horizontal are presented in Figures 7 and 8. In Figure 7, the ratio of two phase heat transfer coefficient at a fixed inclination to that of horizontal flow is plotted against $Re_{SL.}$ It shows how the effect of pipe orientation on heat transfer varies with Re_{SL}. At Re_{SG} = 4500, initially, at low Re_{SL} the lines are more spread out indicating the greater effect of pipe inclination on $h_{TP.}$ At low Re_{SL} the ratio has a minimum value of about 0.67 at -20^0 degree. As the liquid flow rate is increased, for all orientations the ratio gradually approaches 1 and the different curves start to converge indicating the effect of inclination on heat transfer is reduced at high Re_{SL}. In Figure 8, the h_{TP} values are plotted against Re_{SG} at horizontal, -5^o,-10^o and -20^o in the same graph to show how the effect of inclination varies with Re_{SG}. A considerable decrease in the heat transfer is observed in Figure 8 (a) at Re_{SG} < 2200 from horizontal to the downward inclined flow with highest reduction of 49%, 50% and 51% at -5^o,-10^o and -20^o pipe orientations, respectively. This greater reduction takes place due to the difference in flow pattern in the downward inclined flow compared to the horizontal flow. In the given range, the horizontal flow pattern is slug compared to stratified flow in downward inclinations. Slug flow has higher heat transfer than stratified flow due to greater contact between liquid surface and the pipe upper wall surface. In this range, -5^o,-10^o and -20^o has similar flow pattern (stratified) with relatively similar heat transfer coefficient values at low Re_{SG}. However, higher difference in the two phase heat transfer coefficient is observed as the gas flow rate is increased in stratified flow pattern. It might be due to the fact that in this region the flow is induced with disturbance waves which are a decreasing function of pipe inclination. As mentioned earlier, the disturbance wave locally accelerates the two phase flow mixture that triggers the enhancement in the heat transfer. It is speculated that the flow through steeper pipe inclinations in downward direction causes the frequency of disturbance waves to reduce (due to opposite direction of buoyancy force) and hence results into reduction in two phase heat transfer coefficient. From Figures 8 (b), (c) and (d), it can be observed that for higher Re_{SL} the flow transits from stratified to slug region. Slug flow regime has highest percentage reduction of 31%, 18% and 20% at -5^o,-10^o and -20^o pipe orientations, respectively. In this region, the heat transfer trend becomes highly irregular making it difficult to establish a clear trend. With the increase of Re_{SG} the slug length increases which contributes in making the h_{TP} less steeper. Initially at low Re_{SG} the effect is not very pronounced and a steady increase in the h_{TP} value is observed. However, as Re_{SG} increases the slug length increases considerably to adversely affect the heat transfer. This effect of retardation of heat transfer due increased slug length has been observed at a lower value of Re_{SG} (Re_{SG} = 400) for the 0^o and -5^o compared to -10^o and -20^o (Re_{SG} = 1200).

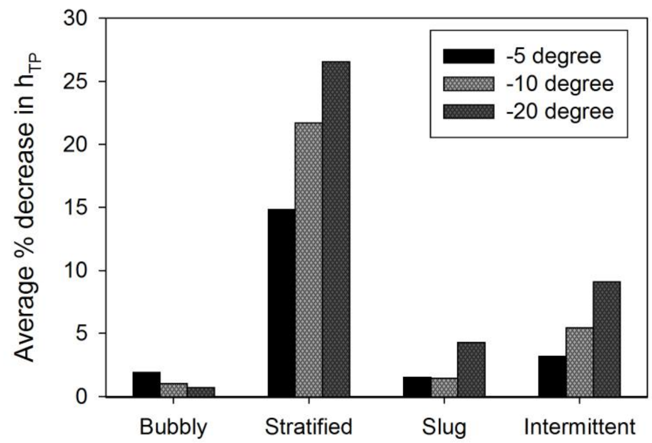


Figure 6: Average percentage decrease in h_{TP} for different inclinations with reference to horizontal orientation.

Due to this reason, the trend of h_{TP} comparison between different inclinations becomes highly irregular in this region. The irregularity in the trend can also be attributed to the fact that in the inclined flow the slug traversing through the pipe faces resisting force due to buoyancy that increases its residence time in the test section. This resistance force causes the gas slugs to move in quite random and irregular manner while the liquid phase slips past the gas phase in downward direction. It is observed during flow visualization that slug moves very slowly and at times even appears stationary for an extended period due to its inability to overcome the shear due to dominant buoyant force acting opposite to the direction of two phase flow.

These types of random events might cause the heat transfer coefficient to differ randomly from one orientation to the other. At Re_{SL} > 5000 (i.e., Figures 4 (b), (c) and (d)) the effect of inclination on heat transfer is more prominent at the mid-range of Re_{SG} (2000 < Re_{SG} < 10,000). In this range, the flow is in the intermittent region which mainly consists of slug-wavy, stratified-wavy and wavy-annular flow. The onset of the intermittent flow regime is slug-wavy in nature where the effect of buoyancy is pronounced and it can be observed from Figure 8 that in this region there is significant difference in heat transfer from one orientation to the other. The buoyancy force causes the gas phase in the slug to move slowly. This effect is enhanced as the setup is inclined more in downward orientation. Another reason for higher heat transfer at lower inclinations might be the higher amount of turbulence and mixing at lower inclination compared to higher inclinations due to higher gas velocity and less resistance of buoyancy force. The highest percentage reductions observed in this region are 9%, 10% and 17% in -5°, -10° and -20°, respectively compared to the horizontal two phase flow. As the Re_{SG} is further increased beyond 10,000, it is observed from the graph that the difference between the h_{TP} values is gradually reduced and the values at different inclination start to converge. This reduced effect of inclination on h_{TP} can be attributed to the fact that as the flow starts to approach the annular region, a more continuous and stable film of liquid starts to develop at the top surface making the flow pattern almost similar in different inclinations and results in almost similar h_{TP} value. Furthermore, as the Re_{SG} value is increased, gas phase starts to accelerate further and the inertia force starts to dominate the buoyancy force of the liquid.

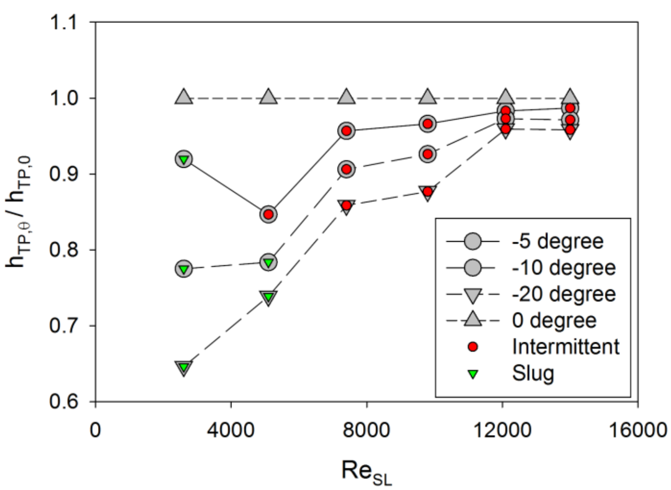
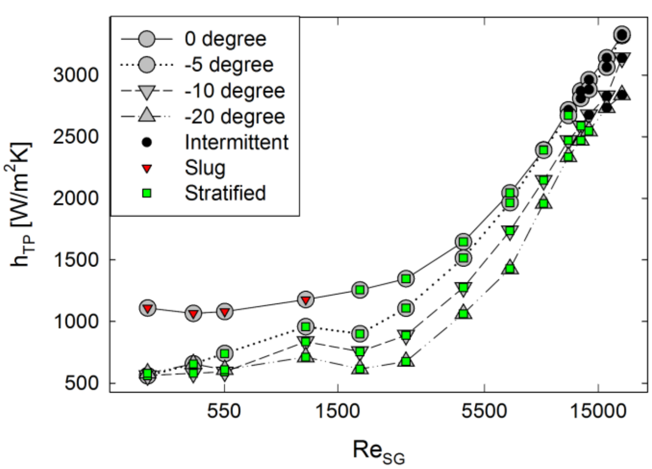
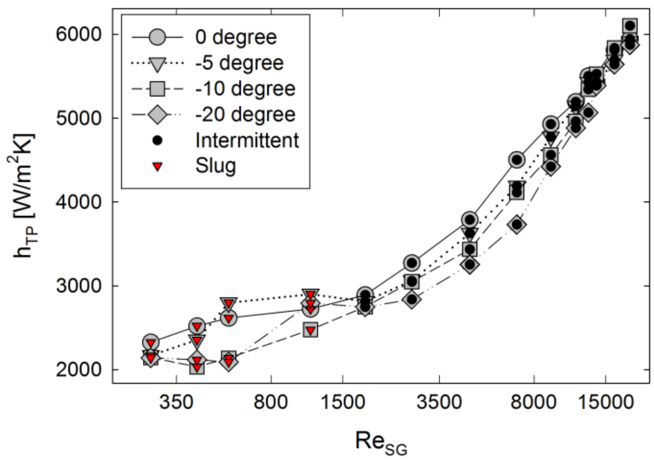


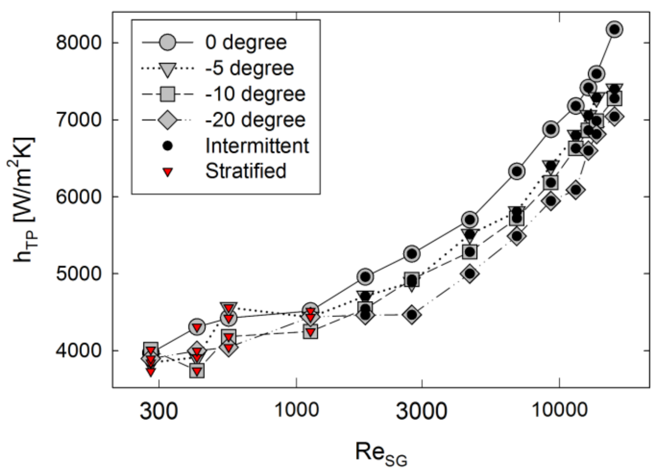
Figure 7 Comparison of $h_{TP,\theta}/h_{TP,0}$ at different inclinations at Re_{SG} = 4500.



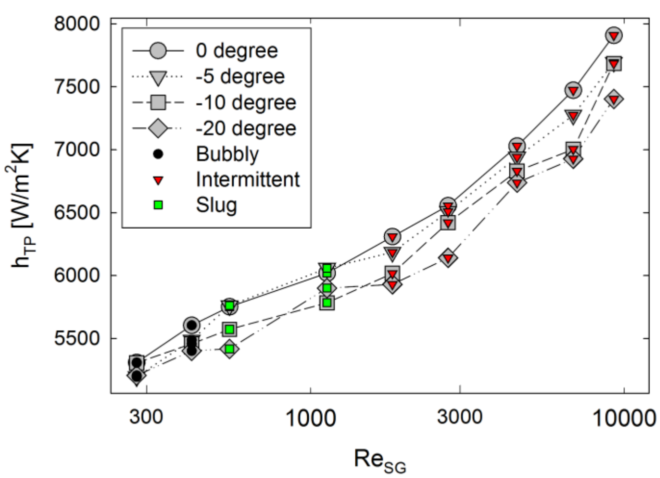
(a) Re_{SL} = 2600



(b) Re_{SL} = 5100



(c) Re_{SL} = 7400



(d) Re_{SL} = 9800

Figure 8 Comparison of two phase heat transfer coefficient h_{TP} at different liquid Re_{SL}, (a) Re_{SL} = 2600, (b) Re_{SL} = 5100, (c) Re_{SL} = 7400, (d) Re_{SL} = 9800.

At this point the nature of two phase flow is shear driven, the effect of buoyancy in reduction of heat transfer in downward inclination is diminished gradually and considerable difference in heat transfer between different inclinations is not found.

CONCLUSIONS

Present study provides new data of two phase heat transfer coefficient in horizontal and near horizontal downward inclined two phase flow for mainly slug, stratified and intermittent flow regimes. A flow pattern map for horizontal and downward inclined flow for 12.5 mm I.D. pipe using air-water fluid combination is also presented. In all flow regimes increase in the two phase heat transfer coefficient have been observed with the increase in superficial gas Reynolds number at fixed superficial liquid Reynolds number. In stratified flow regime, h_{TP} value increases slowly at low Re_{SG} and shows a much steeper slope as Re_{SG} increases. Onset of intermittent flow (slug wavy region) is characterized by flat slope of h_{TP} which becomes steeper with higher Re_{SG} due to higher mixing and turbulence. The highest slope of h_{TP} is observed towards the end of intermittent flow regime characterized by wavy annular flow. Development of continuous and stable liquid film at the top pipe surface is found to be the reason for such high rate of increase of h_{TP} in this region.

A comparison is drawn between the two phase heat transfer coefficients at similar Re_{SL} and Re_{SG} to establish the trend of h_{TP} at different pipe inclinations. A systematic reduction in h_{TP} value is observed as the flow in inclined from 0^o to -5^o,-10^o and -20^o in intermittent and stratified regions. Highest reduction in heat transfer coefficient is observed at low Re_{SG} in downward flow at stratified flow regime compared to horizontal orientation due to slug flow pattern prevailing in horizontal flow. No clear conclusion can be drawn about the effect of inclination in the slug flow regime due to inconsistency in the change of h_{TP}. This inconsistency might be due to random slow moving slug traversing through the flow at low Re_{SG}. As slug flow transitions to wavy-slug flow the inconsistency is eliminated and pronounced effect of buoyancy in reduction of h_{TP} is observed at higher Re_{SG}.

Based on the results and conclusions drawn in this study, it would be interesting to check the trends of two phase heat transfer coefficient for steeper orientations and see if at all the h_{TP} at any downward inclination exceeds its corresponding value measured in horizontal pipe orientation. Furthermore, it is also important to check the validity and performance of existing non-boiling two phase heat transfer correlations against this data in downward inclinations.

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