HYDRODYNAMICS AND HEAT TRANSFER IN UPWARD INCLINED GAS-LIQUID TWO-PHASE TWO-COMPONENT FLOWS

by

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19th,November,2015

EN 216 (MAE conference room)

OUTLINE

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  - General Heat Transfer Correlation

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INTRODUCTION

Definition:

$$\text{Phase} \xrightarrow{\text{simultaneous movement of any two out the three phases}} \text{Two-phase flows}$$

(solid, liquid and gas)

Two-phase flows are divided into one-component two-phase flows (Ex: steam-water flows) and two-component two-phase flows(Ex: air-water flows).

Focus:

Primary focus of this research is two-phase two-component gas-liquid flows. Due to their immense applications in oil and natural gas, processing and chemical industries.

INTRODUCTION contd.

Applications:

- Oil and natural gas industry: To avoid gas hydrate and wax deposition blockages in pipes leading to severe production and functioning problems (McClaflin and whitfill (1984)). These can result in huge economical losses(Singh et al. (2000)).
- Increased heat transfer in reduced spaces(refrigeration and space craft cooling designs). Celata et al. (1999) observed a 20-40% increase in heat transfer coefficient, when two-phase two-component flows are used.

Additionally, industries that involve long distance transportation it is very important to see the effect of phase flow rates, flow patterns, pipe inclination, pipe diameter and fluid combinations on the heat transfer phenomenon in two-phase two-component flows.

Thus, it is very important to study these two-phase two-component flows from both economical and engineering stand point of view.

INTRODUCTION contd.

Research objectives

- To investigate the effect of phase flow rates and pipe orientations on flow patterns.
- To investigate the effect of phase flow rates, pipe orientations, flow patterns, pipe diameters and fluid combinations on two-phase heat transfer coefficient.
- To recommend the best performing heat transfer correlation for two-phase two-component flows.

Tasks Undertaken

- Measure h_{TP} in upward pipe inclination at 0^0, $+5^0$, $+10^0$, $+15^0$, $+20^0$, $+30^0$, $+60^0$, $+75^0$ and $+90^0$ and also review the related experimental works to collect additional data for varying pipe diameter and fluid combinations.
- Analyse the experimental results with respect to all the 5 variables (phase flow rates, pipe orientations, flow patterns, pipe diameters and fluid combinations) involved in the flow to establish the heat transfer trends.
- Identify the existing relevant heat transfer correlations for two-phase two-component flows are analysed to recommend the best performing correlation.

LITERATURE REVIEW

Experimentation in Two-phase Flows

- Vijay (1978), Sujumnong (1998) and Aggour (1978) conducted there experiments in 11.7 mm I.D. pipe at vertical orientation.

- Vijay (1978) and Sujumnong (1998) conducted experiments on water, mixtures of glycerin + water, glycerin in combination with air and concluded that liquid viscosity adversely effects the h_{TP} by hindering the flow turbulence.

- Aggour (1978) experimented on water in combination with helium, air and feron-12. He concluded that the rate of increase in h_{TP} increases with increasing gas flow rate and this trend of variation is common to all fluids combinations employed in his study.

- Tang and Ghajar (2007) experimented on air-water flows at near horizontal inclinations (0^0 to $+7^0$) by covering all the flow patterns at each inclination and was able to conclude that h_{TP} was not only effected by phase flow rates and flow patterns but also by pipe inclinations, due to the effect of gravity on denser liquid phase.

- Franca et al. (2008) experimented on slug flows in a 18.7 mm I.D horizontal pipe and observed a mostly constant h_{TP} with respect to increasing gas flow rates.

Hence we can see that the heat transfer in two-phase two-component flows is effected by fluid properties, phase flow rates, flow patterns and pipe inclinations in-addition to pipe diameter.

LITERATURE REVIEW contd.

General Heat Transfer Correlations

- Need for empirical model.
- 13 widely accepted and highly used heat transfer correlations are identified and are tabulated as seen in Handout-1.
- Look at Handout-1. Identified defects:

➢ limited to specified phase flow rates and superficial Reynolds numbers. Which implies that these correlations were confined application to only specified flow patterns

Ex: Knott et al. (1959), Khoze et al. (1976), Ravipudi and Godbold (1978) and Chu and Jones (1980).

➢ limited by pipe orientations, pipe diameters and fluid combinations.

Ex: Rezkallah and Sims (1987)

Unfortunately, none of the 13 identified heat transfer correlations were tested for all the 5-variables and it can also be seen from their structure, that many of these correlations did not include for the effects of interactions between the phases completely, which are intern shaped by the viscosity, buoyancy, gravity, inertia and surface tension.

LITERATURE REVIEW contd.

Case study:

Knott et al. (1959)	$$\frac{h_{TP}}{h_L} = \left(1 + \frac{V_{SG}}{V_{SL}}\right)^{\frac{1}{3}}$$	12.7 mm Vertical pipe Oil-nitrogen mixture	6.7≤Re_{SL}≤162 126≤Re_{SG}≤3920

by attributed the increase in h_{TP} to the increase in mean velocity of the mixture caused by the gas-phase.

Shah (1981)	$$\frac{h_{TP}}{h_L} = \left(1 + \frac{V_{SG}}{V_{SL}}\right)^{\frac{1}{4}}$$	4 to 70 mm tubes 10 liquid-gas mixtures	At both horizontal and vertical inclinations

modification of Knott et al. and is purely an inertial force based correlation.

LITERATURE REVIEW contd.

Case study:

Kim and Ghajar (2006)

Horizontal pipe
Air-water flows
All flow patterns

Flow patterns factor(F_P)
[Effective wetted perimeter]

$$h_{TP} = h_L \times F_p \left(1 + 0.7\left[\left(\frac{x}{1-x}\right)^{0.08}\left(\frac{1-F_p}{F_p}\right)^{0.06}\left(\frac{\Pr_G}{\Pr_L}\right)^{0.03}\left(\frac{\mu_G}{\mu_L}\right)^{-0.14}\right]\right)$$

$$F_P = (1-\alpha) + \alpha[\frac{2}{\pi}(tan^{-1}\sqrt{\left(\frac{\rho_{G}\,(V_G-V_L)^2}{gD_i(\rho_L-\rho_G)}\right)}]^2$$

Tang and Ghajar (2007)

Near horizontal inclinations
Air-water flows

Flow pattern factor(F_P)
and
Inclination factor(I)

$$\frac{h_{TP}}{h_L} = F_P\left\{1 + 0.55\left[\left(\frac{x}{1-x}\right)^{0.1}\left(\frac{1-F_P}{F_P}\right)^{0.4}\left(\frac{Pr_G}{Pr_L}\right)^{0.25}\left(\frac{\mu_L}{\mu_w}\right)^{0.25} I^{0.25}\right]\right\}$$

$$I = 1 + \frac{[(\rho_L-\rho_G)gD_i{}^2|sin\,\theta|]}{\sigma}$$

EXPERIMENTAL SETUP

Details of Experimental Setup

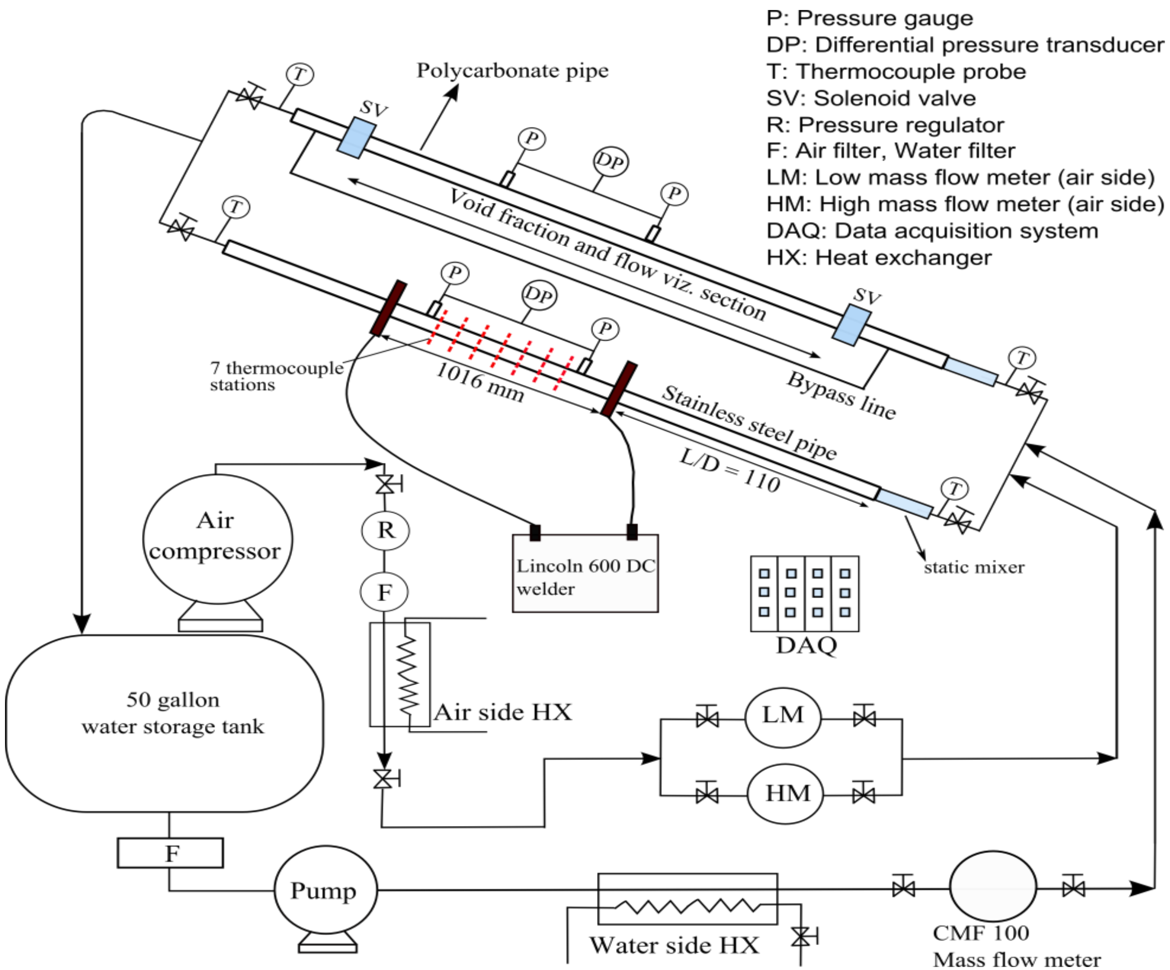


Figure: Experimental setup circuit diagram

- Variable inclination frame $-90^0 \leq \theta \leq +90^0$
- Compressed air- distilled water fluid combination
- 12.5 mm I.D. stainless steel pipe, 12.7 mm I.D. polycarbonate pipe and a length of 101.6 cm.
- Heat is supplied using a Miller Maxtron 450 arc welder
- Inlet and outlet temperature measurement using thermocouple probes.
- Seven thermocouple stations are used to measure the outer wall temperature
- Also, capable of measuring pressure drop and void fraction for both single phase and two-phase non-boiling flows.

EXPERIMENTAL SETUP contd.

Validation of Experimental Setup

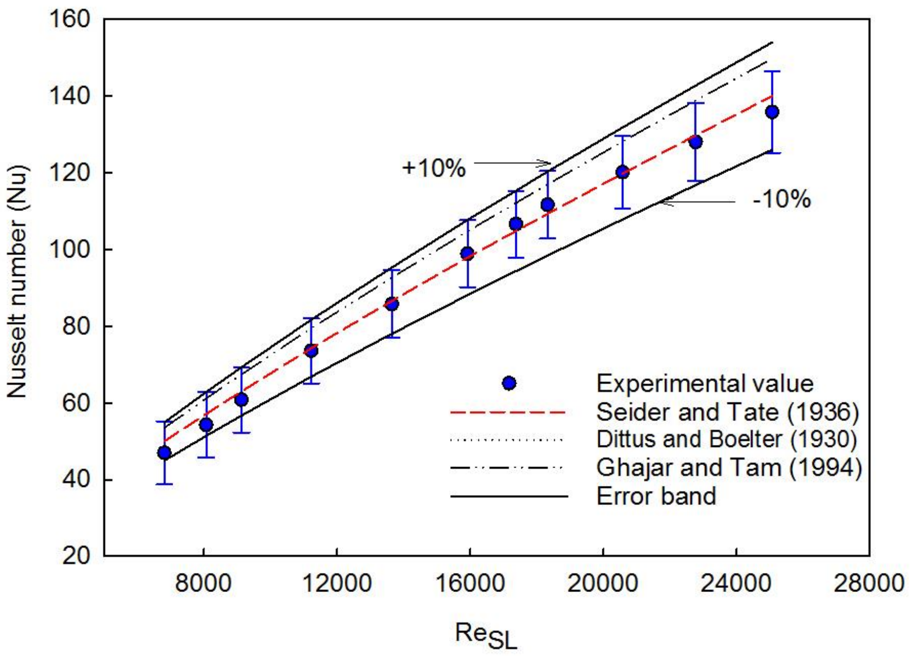


Figure 11.1: Comparison between measured and predicted values of single phase heat transfer coefficient

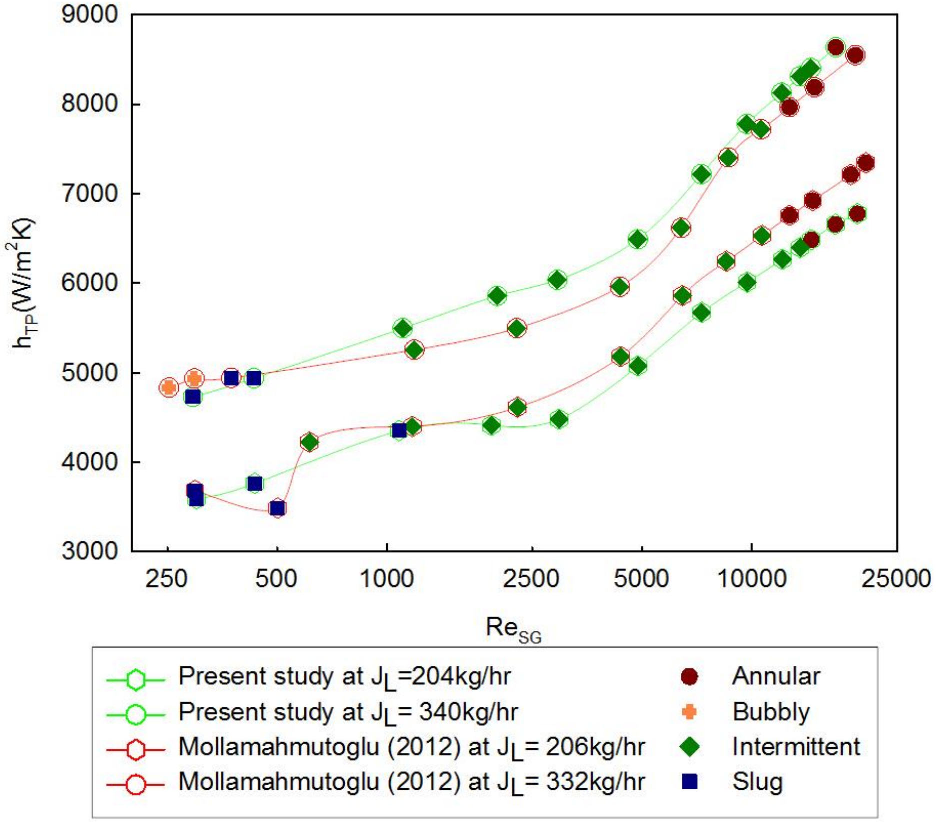


Figure11.2: Comparison of h_{TP} obtained in present work with respect to Mollamahmutoglu (2012)

- Single phase data was taken in-between a Re_L range of 6800 to 25000 at 0^0.
- All the Single-phase correlation used were able to predict the data within ±15%.

- Comparison with respect to past data for similar flow rates at vertical pipe inclinations.
- Homologous reproduction of trends, when used against comparable data from the past.

EXPERIMENTAL SETUP contd.

Uncertainty Analysis for Two-phase and Single-phase Flows

Table: Minimum and maximum uncertainty in measured h_{TP} for different flow patterns

Flow pattern	Minimum uncertainty (%)	Maximum uncertainty (%)	Average uncertainty (%)
Stratified	15.08	24.81	20.05
Slug	5.68	13.49	11.08
Intermittent	6.08	28.81	15.33
Bubbly	5.7	12.31	9.55
Annular	6.19	30.25	18.72

- These uncertainties are calculated using the method proposed by Kline and McClintock (1953).
- The higher magnitudes of uncertainty for two-phase flows is observed in stratified, intermittent, and annular flows are due to inability to maintain a higher temperature difference and the higher values of heat balance error associated with these flow patterns.
- The maximum and minimum uncertainty for the Single flows are ±10.64% and ±8.22%.

Results and Discussion

- **Flow Patterns and Flow Pattern Maps**
- **Heat Transfer in Two-Phase Two-Component Flows**
- **Analysis of Heat Transfer Correlations Performance**

Flow Patterns and Flow Pattern Maps

Effect of Fluid Flow Rates on Flow Patterns

This flow occurs at moderate to high liquid flow rates and low gas flow rates.

Occurs at low to moderate gas and liquid flow rates.

This flow occurs at moderate gas flow rates for all the given liquid flow rates.

Occurs at high gas and liquid flow rates.

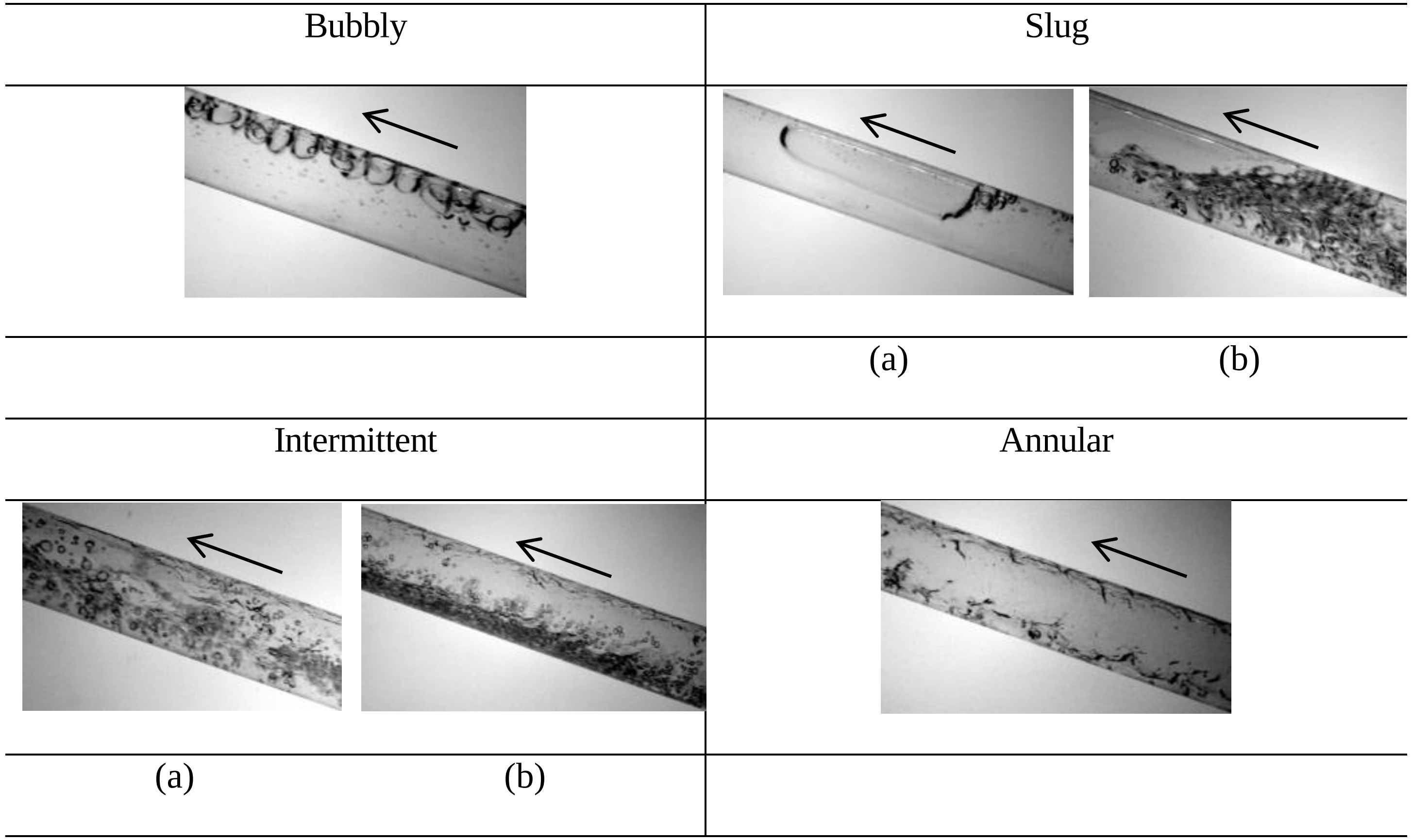


Figure: Flow patterns observed in upward inclined two phase flows at $+20^0$ (Korivi et al. (2015)).

Flow Patterns and Flow Pattern Maps

Effect of Pipe Orientation on Flow Pattern

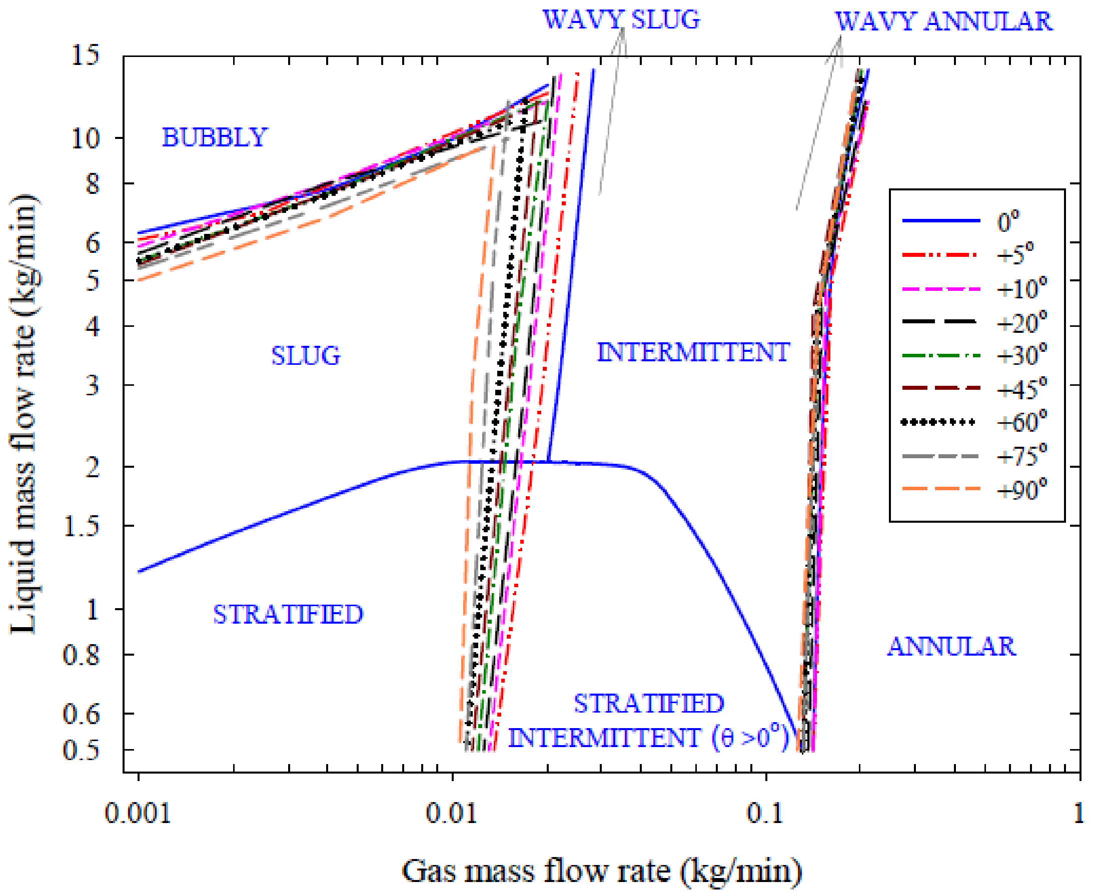


Figure: Combined flow pattern map for upward inclined pipe orientations (Bhagwat (2015)).

- •Promotes an early Slug-bubbly and slug-intermittent transition
- •Higher pipe orientations favors inertial flows at higher gas flow rates and homogenous flows at lower gas flow rates.
- •These effects of increasing pipe orientations are more clearly seen at higher liquid flow rates compared to low liquid flow rates.
- •Annular-intermittent transition boundary is relatively independent of change in orientations.

Heat Transfer in Two-Phase Two-Component Flows

Effect of phase flow rates and pipe inclinations

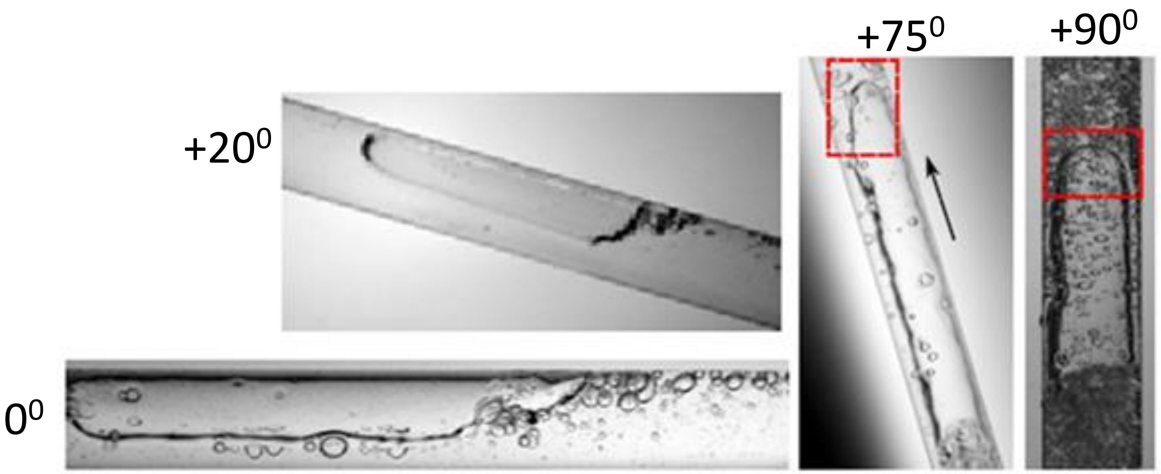


Figure: Variation of flow pattern (slug flow pattern) shape with respect to inclination.

Study the effect of variations of buoyancy, inertia and gravity.

Classified based on Pipe inclination and on Flow rates as:

- ($0^0 \leq \theta \leq +30^0$) Horizontal and near horizontal
- ($+30^0 < \theta \leq +60^0$) Mid range
- ($+60^0 < \theta \leq +90^0$) Vertical and near vertical
- $Re_{SL} \geq 9850$, $3300 < Re_{SL} > 9850$ and $Re_{SL} \leq 3300$
- $Re_{SG} \geq 4800$, $425 < Re_{SG} > 4800$ and $Re_{SG} \leq 425$

Heat Transfer in Two-Phase Two-Component Flows contd.

Effect of Flow Patterns and Pipe Inclination on h_{TP}

- Change in physical structure of flow patterns effects the h_{TP} . Theses variations are different for different flow patterns in correspondence to the unique geometrical distribution of fluid phases.

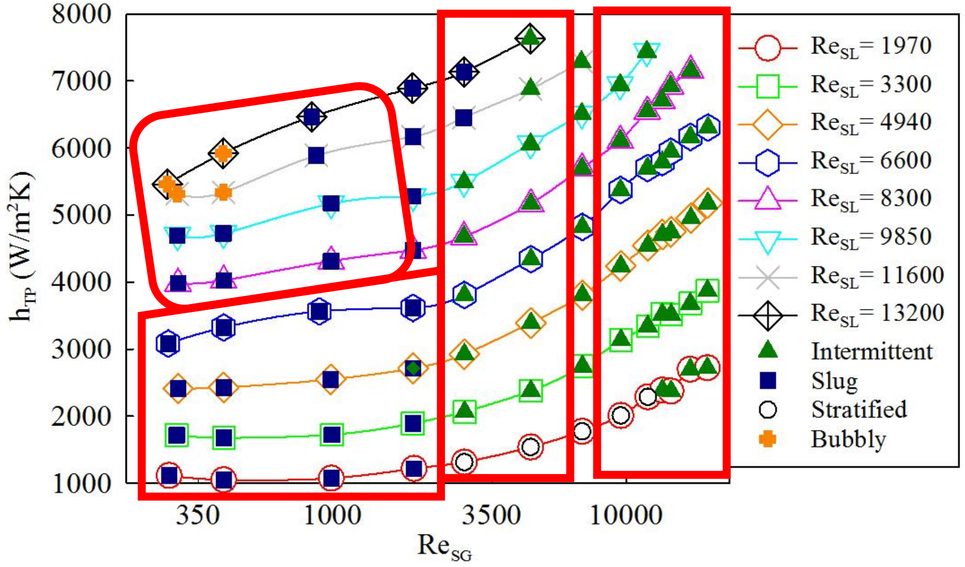
- For slug flows (low to moderate gas and liquid flow rates) h_{TP} is insensitive to the increase in gas flow rates for horizontal and mid-range pipe inclinations. However there is gradual increase in h_{TP} with respect to gas flow rates in vertical and near vertical pipe orientations.

- For Bubbly flows (low gas and high liquid flow rates) there is a gradual increase in the h_{TP} with respect to gas flow rates due the increase in dispersion of the gas phase, which is seen at all pipe orientations.

- During the onset of intermittent flows (slug-wavy at moderate gas flow) there is an gradual increase in h_{TP} with respect to gas flow rates with an increasing slope.

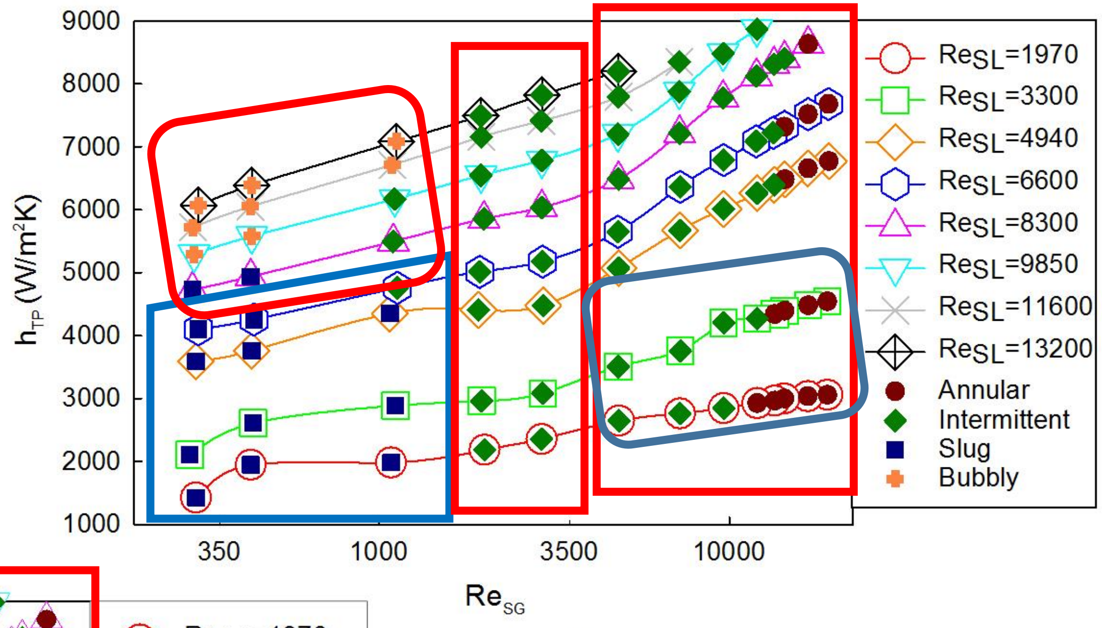
- This increase in h_{TP} is converted into a rapid rise during the onset of Annular flows (high gas flow rates) because of the large interfacial wall-liquid interfacial area. This is seen at all liquid flow rates for all pipe orientations.

- However, this trend in Annular flows is not observed at low liquid flow rates due to the liquid hold up and flow reversal.



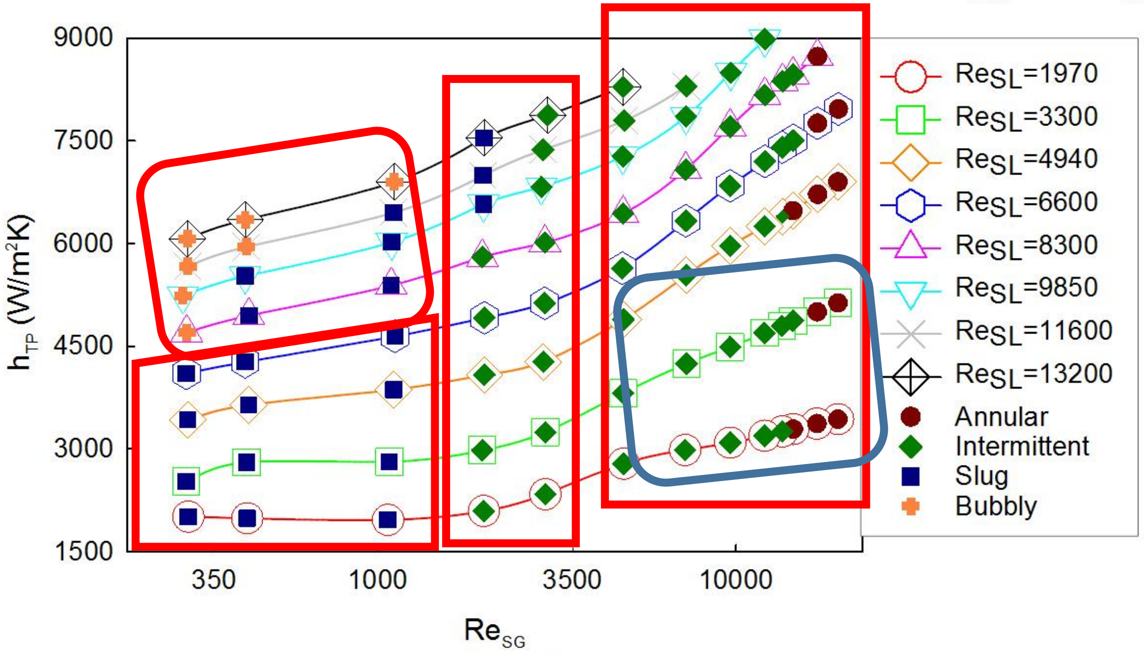
$\theta = 0^0$

Figure: horizontal and near-horizontal oriented two phase flows ($0^0 \leq \theta \leq +30^0$)



$\theta = +90^0$

Figure: vertical and near-vertical oriented two phase flows ($+60^0 < \theta \leq +90^0$)



$\theta = +60^0$

Figure: mid-range inclined two phase flows ($+30^0 < \theta \leq +60^0$)

Heat Transfer in Two-Phase Two-Component Flows contd.

Effect of Flow Patterns and Pipe Inclination on h_{TP}

- These variations are shaped by the increasing axisymmetric flow distribution and liquid hold-up caused mainly due to the changing interactions between the gravitational and buoyancy forces.
- Increasing the pipe orientation tends to increase the h_{TP} with respect to increasing pipe inclinations. The h_{TP} tends to achieve a maximum in-between $+60^0$ to $+75^0$ depending on the liquid flow rate.
- Effects of gravitational force tends to promote liquid hold up and buoyancy force promotes a gas phase motion. Causing a decrease in h_{TP} from $+75^0$ to $+90^0$ at low liquid flow rates. But the high liquid content at high and medium liquid flows rates were able to maintain the h_{TP} constant after $+75^0$ to $+90^0$.
- There is a significant rise h_{TP} when air is introduced into the water flow. This increase in h_{TP} is high for low liquid flow rates compared to high liquid flow rates due to the addition of gas to already chaotic and inertia dominated flows at high liquid flow rates as shown in the above figure.

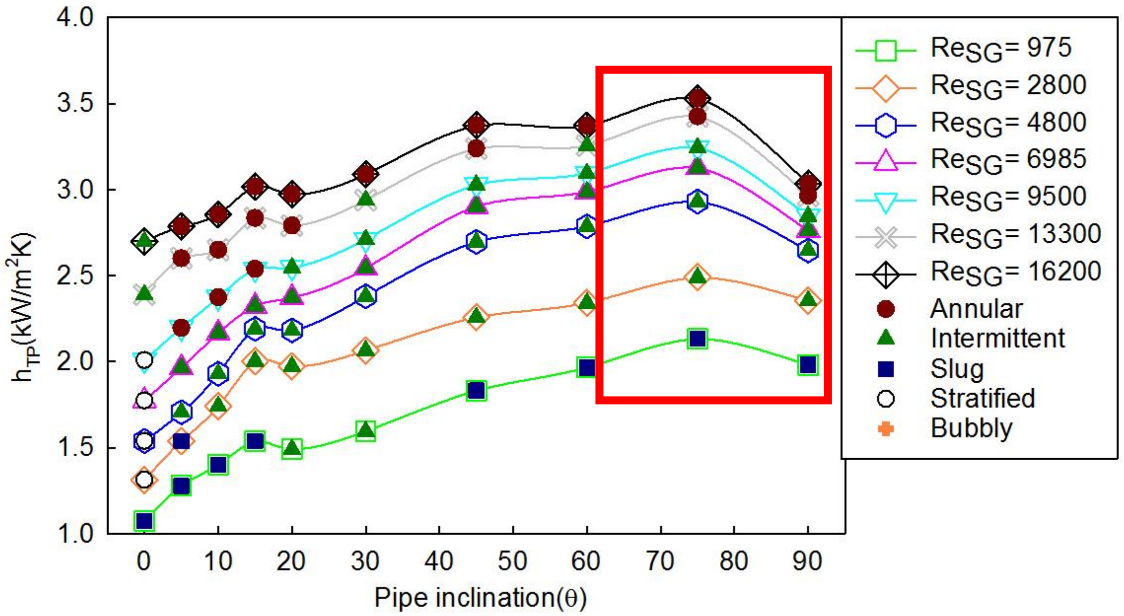


Figure: At low liquid flow rate (Re_{SL}= 1970)

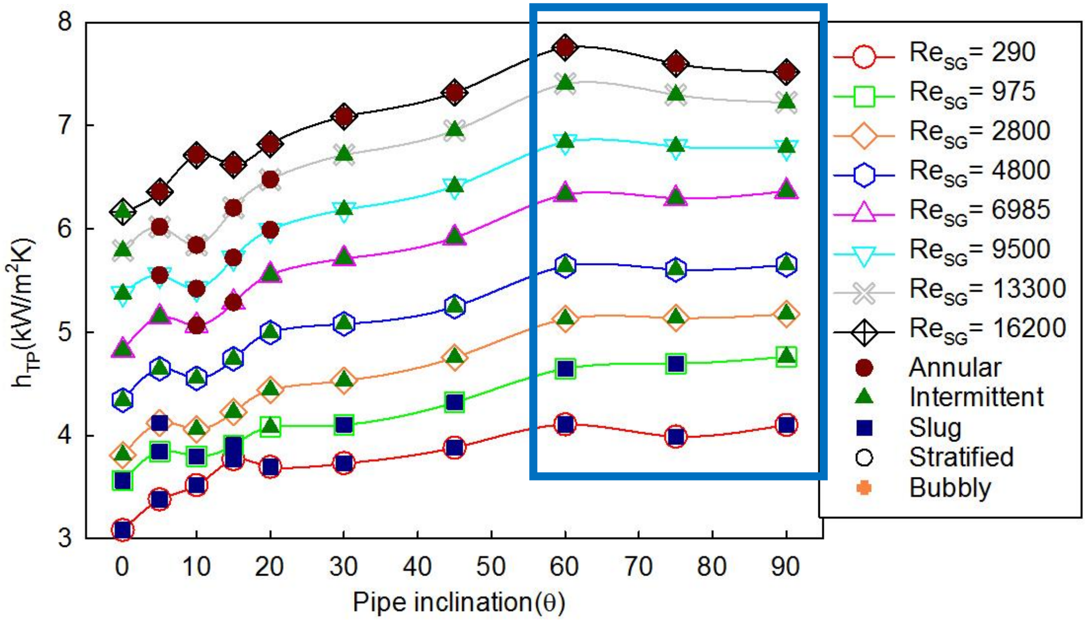


Figure: At medium liquid flow rate (Re_{SL}= 6600)

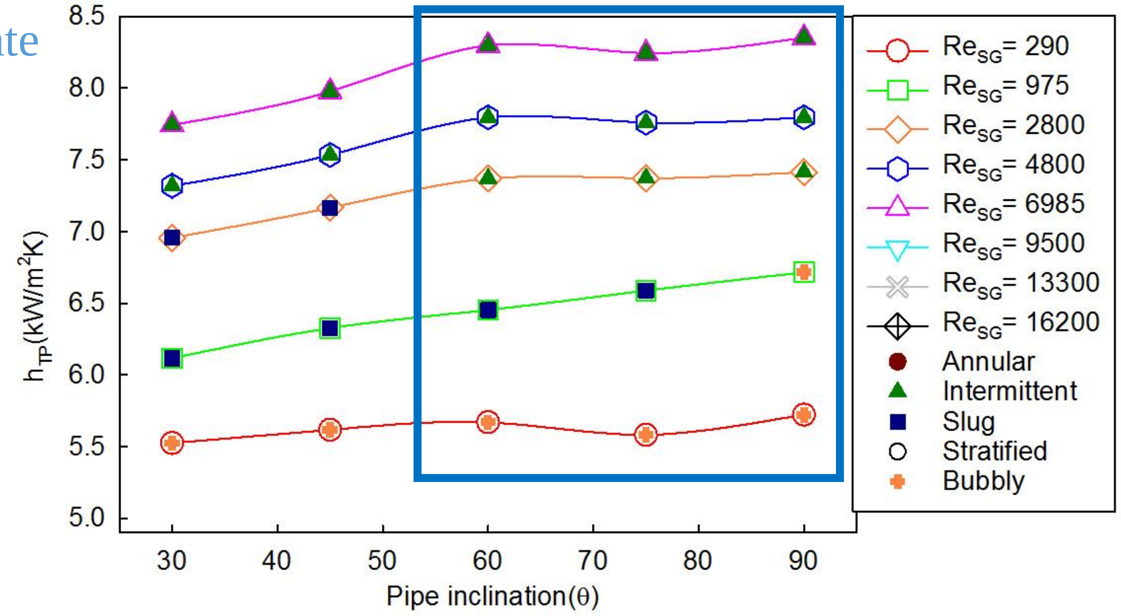


Figure: At high liquid flow rate (Re_{SL}= 11600)

Similar observations in vertical and near vertical orientations by :
Spedding and Chen (1984)
Bhagwat (2015)

Analysis of Heat Transfer Correlations Performance

Effect of phase flow rates and pipe inclinations

- This analysis is done using 617 data points measured in 12.5 mm I.D. pipe to cover all the upward orientations($0° \leq \theta \leq +90°$) and all the flow patterns (Annular, bubbly, slug and intermittent). The results are tabulated and given in Handout-2.
- The performance of a correlation is considered satisfactory if 70% of the data points were predicted within ±30% error band and was said to be doing exceedingly well if 90% of the data points were predicted within an error of ±30%.
- For horizontal and near horizontal orientations consisting of a total 287 data points. Tang and Ghajar (2007) proved to be the best performing correlation by predicting 91% of the data within an error limits of ±30%, while shah was only able to predict 83% of the data points.
- For mid-range and vertical and near vertical orientations, Shah (1981) proved to be the best performing correlation by predicting 100% of the data points within an error band of ±30% and this is very closely followed by Tang and Ghajar (2007) for these pipe orientations which was able to predict 95% of the data points within an error limit of ±30%. This pipe orientation range consist of 330 data points.
- Almost all the correlations seem to perform pretty well in bubbly flow regime, while certain correlations like Kim and Ghajar (2006) were able to do reasonably well even in slug flow regime also. However the only correlations able capture the steep rise in Annular and intermittent flows were Tang and Ghajar (2007) and Shah (1981).

Analysis of Heat Transfer Correlations Performance contd.

Effect of phase flow rates and pipe inclinations

- Shah (1981) failed to predict the two-phase heat transfer coefficients for low liquid flow rates properly, especially at horizontal and near horizontal inclinations because of the inertial structured correlation.
- It can be seen from the figures below that Tang and Ghajar (2007) was able to predict 100% of Annular, slug, bubbly flows but was only able to 87% of the intermittent flow data with in an error limit of ±30%, where it mostly under predicted the data.

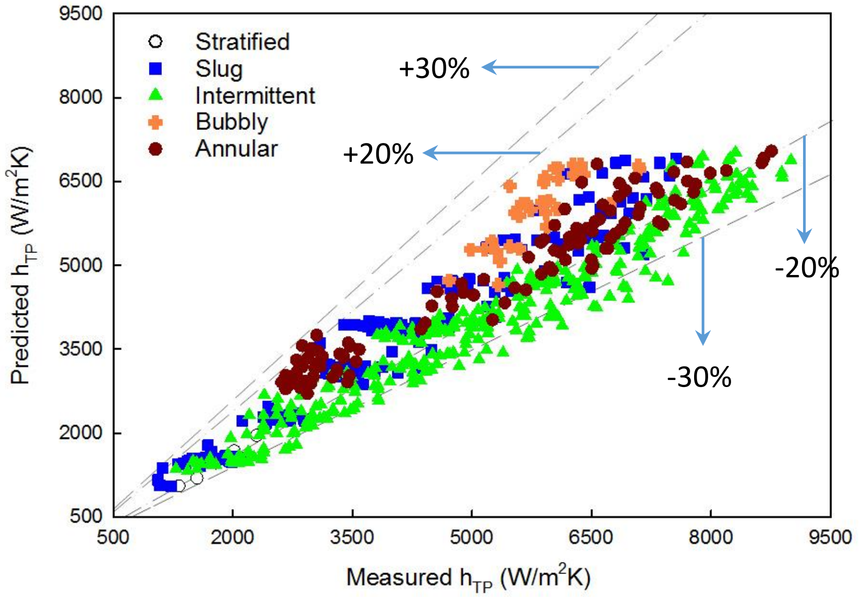


Figure: Performance of Tang and Ghajar (2007) correlation for all flow patterns

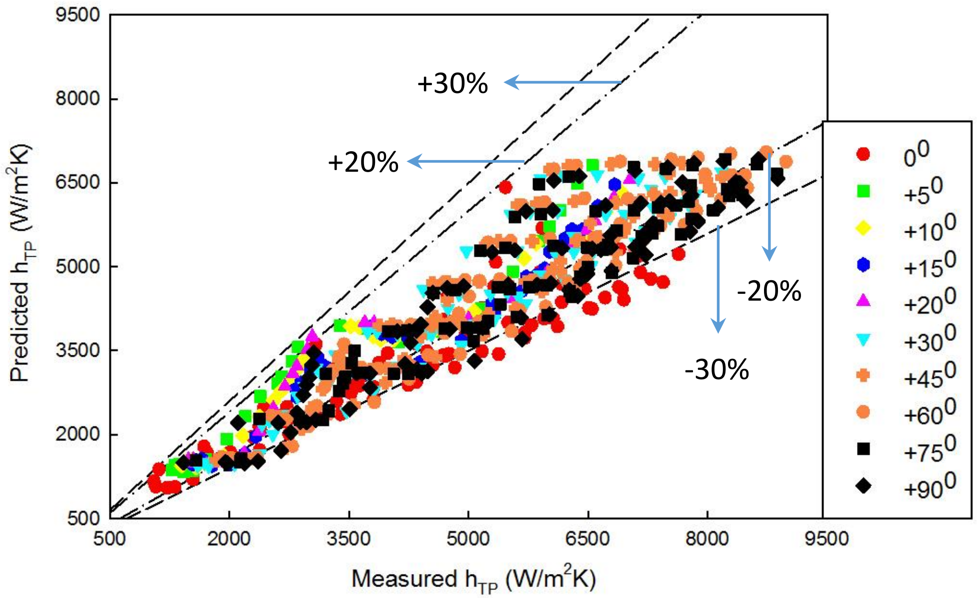


Figure: Performance of Tang and Ghajar (2007) correlation with respect to pipe orientations ($0^o \leq \theta \leq +90^o$)

Heat Transfer in Two-Phase Two-Component Flows contd.

Effect of Pipe Diameter on h_{TP}

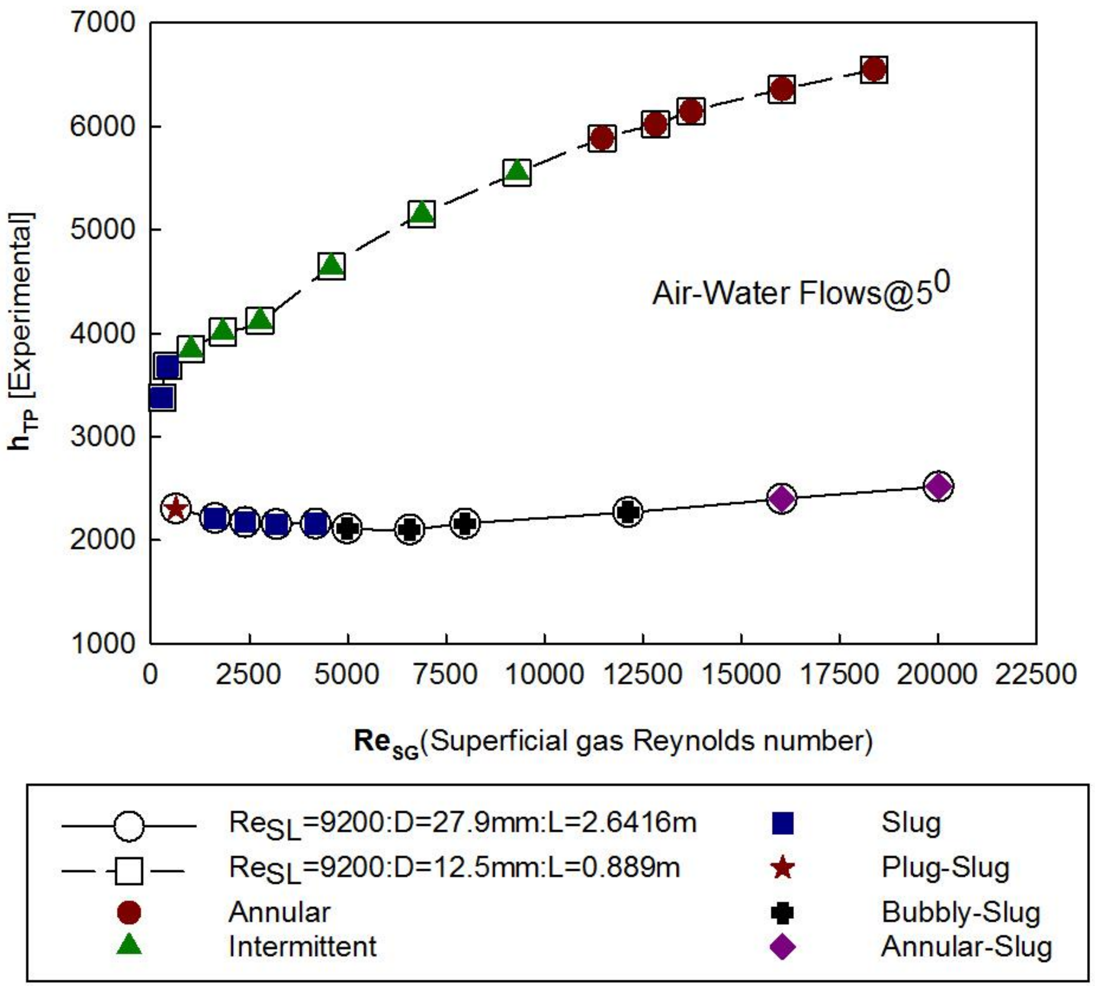


Figure: Variation of h_{TP} with respect to Re_{SG} for pipes with different diameter (for Di=12.5mm and Di= 27.9mm)

- Similar to single phase flows, h_{TP} is inversely proportional to pipe diameter for both buoyancy driven flows and inertia driven flows and we can also observe that increasing the pipe diameter tends to delay the transmission towards the inertial driven flow patterns.

- The effect of pipe diameter is significantly large in inertia driven flows, which comprise of annular and wavy-annular flow regimes. These variations are due the increase in cross sectional area available to the flows, which reduces the velocity of the mixture and hence conversely effecting the heat transfer coefficient.

Analysis of Heat Transfer Correlations Performance contd.

Effect of Pipe Diameter on h_{TP}

- A total of 759 data points were used to include 12.5mm diameter pipe,11.7mm diameter pipe, 27.9mm diameter pipe and 18.6mm diameter pipe by using air-water as working fluid. This data considered for this analysis consists of $+90^0$, $+0^0$ and $+5^0$ pipe orientations. The results are tabulated and given in Handout-3.
- It can been seen that Tang and Ghajar (2007) was able to do well for all the pipe diameters, at all the pipe orientations by predicting not less then 80% of data points for each combination.
- Knott was only able to perform good for 11.7mm and 12.5mm pipes, where it was able to predict 92% of the data within a limit of ±30% but failed in remaining cases.
- It can been seen that Shah (1981) was able to predict h_{TP} good for the 12.5 mm pipe but failed to predict at-least satisfactorily at higher diameter pipes like 27.9 mm pipe and 18.7 mm pipe. Where it was only able to predict 36% of the 364 data points for 27.9 mm diameter pipe within an error band of ±30%.
- Apart from the vertical pipe orientations. Kim and Ghajar (2006) was able to do perform satisfactorily for all the diameter pipes by predicting not less then 70% of the data for each of the case.

Heat Transfer in Two-Phase Two-Component Flows contd.

Effect of Fluid Properties on h_{TP}

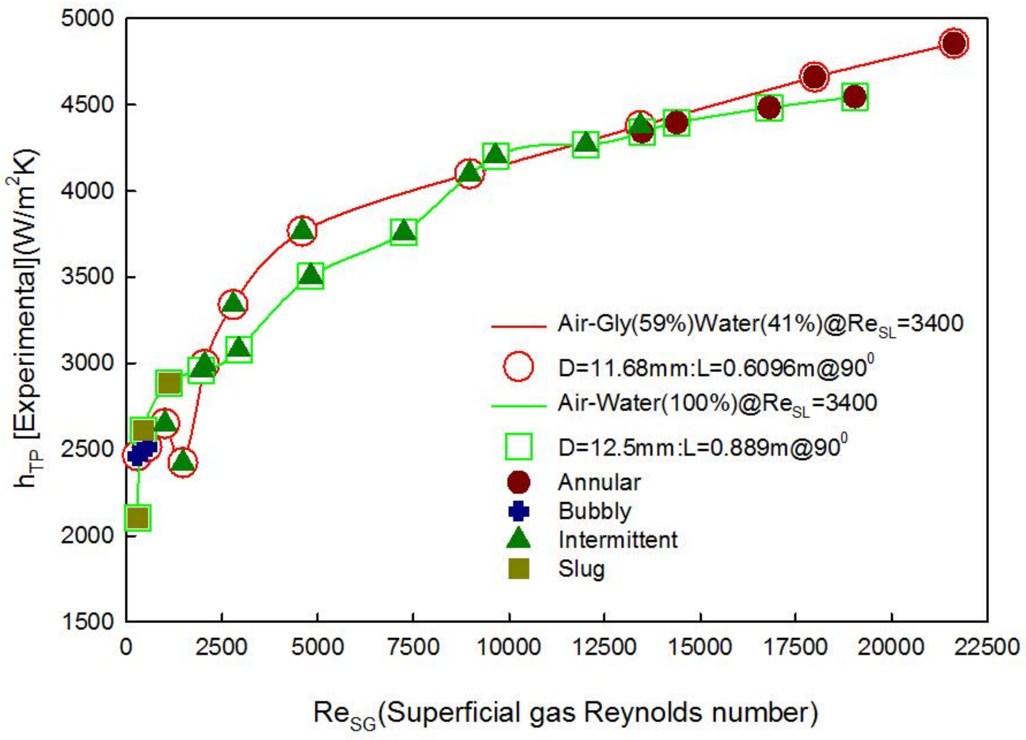


Figure 24.1: At low liquid flow rate (Re_{SL}= 3400)

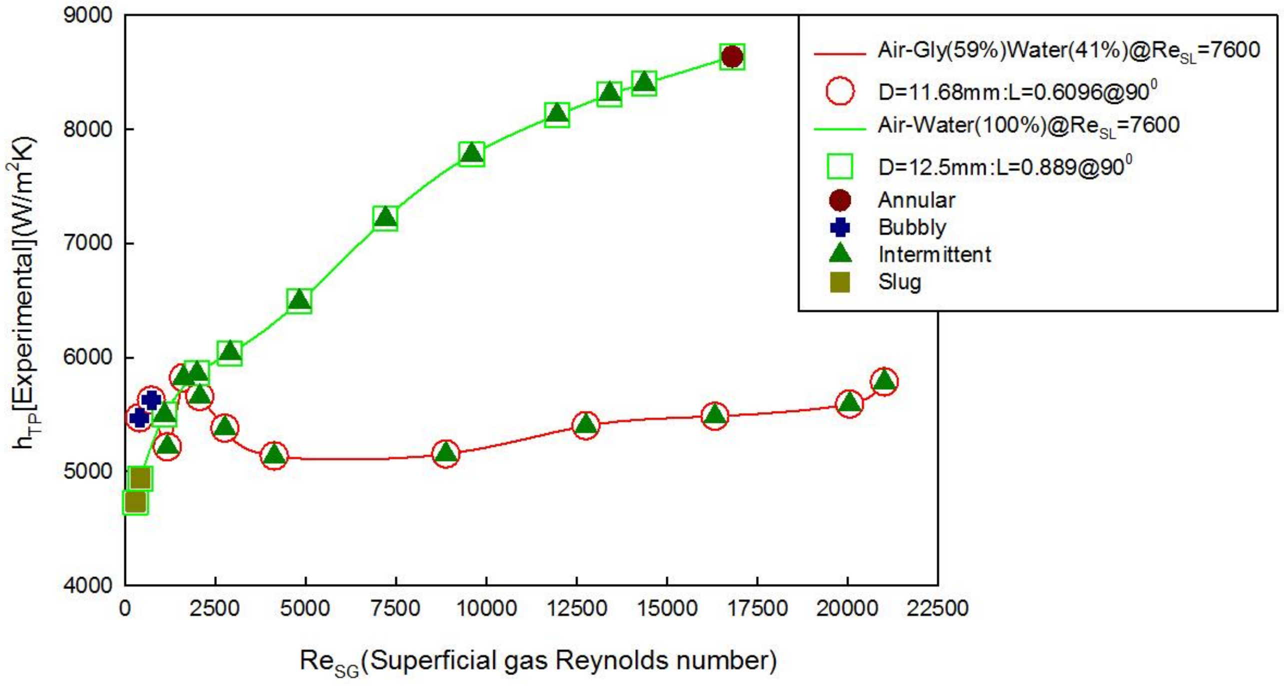


Figure 24.2: At high liquid flow rate (Re_{SL}= 7600)

- Glycerine(59%)+water(41%) has only half the value of thermal conductivity of water and ten times higher viscosity than water. Even though there have equivalent surface tension.
- Almost identical trends at low Re_{SL} because of the rise in h_{TP} at this range was due rise in the velocity of the mixture by the gas phase.
- Differed at high Re_{SL}, significantly in the inertia dominated flow patterns because of the significant influence of the liquid phase at these Re_{SL} ranges.

Analysis of Heat Transfer Correlations Performance contd.

Effect of Fluid Properties on h_{TP}

- For this purpose 382 data points of different gas-liquid combinations was used. These measurements were done in 11.7 mm diameter pipe at vertical orientation ($+90^0$) and the results are given to you in Handout-4
- It should be noted that air-glycerine (59%) +water (41%) and air-silicone are used to see the effect of varying viscosity on the performance of correlations with respect to air-water and in a similar way, feron12-water and helium-water are used to see the effect of varying gas density on the performance of heat transfer correlations with respect to air-water.
- Despite failing to predict the effects of pipe diameter and pipe orientation on h_{TP}, certain correlations like Knott et al. (1959) (≥ 90%) and Shah (1981) (≥70%) were able to perform well for all the fluid combinations used, except for flows with high gas density corresponding to feron12-water.
- It was also observed that Ghajar and Tang (2007) (≥70%) was able to predict h_{TP} satisfactorily for fluid combinations with varying liquid viscosity and for fluid combinations with high gas density corresponding to feron12-water but was only able to predict only 50% of the data points corresponding to fluid combinations with very low gas density(helium-water) as seen in Handout-4. This might be because of ignoring the influence of the surface tension and the contact angle of each phase on the effective wetted perimeter as mentioned in Tang (2011).

CONCLUSIONS AND RECOMMENDATION

Conclusions of Results

- Based on 1351 different measurements from the present study and also from the literature. We have determined that pipe inclination, phase flow rates, pipe diameter and fluid combination are the major parameters that influence the two-phase two-component heat transfer and flow patterns in upward pipe flows.

- Different flow patterns exhibited in these upward flows were identified and examined thoroughly. It was concluded that an increase in gas flow rates tends to shifts buoyancy driven flow patterns towards inertial flow patterns and an increase in liquid flow rates was found to enable a homogeneous flow structure.

- It was observed that the variation in h_{TP} was flow patterns specific, due to the peculiar geometrical distribution of the phases associated with each flow pattern.

- These variations in h_{TP} for a particular flow patterns are susceptible to changes in pipe orientations, due the influence of gravity on denser liquid phase and by the influence of changing buoyancy direction on the gas phase.

CONCLUSIONS AND RECOMMENDATION

Conclusions of Results

- It was observed that Kim and Ghajar (2006) heat transfer correlation was able to predict h_{TP} well for varying pipe diameters and flow patterns at horizontal and near horizontal pipe inclinations.

- It was observed that the correlations of Knott et al. (1959) and Shah (1981) were only applicable to small diameter pipes ($Di \leq 12.5$ mm).

- It was identified that Tang and Ghajar (2007) was the only correlation capable of predicting h_{TP} irrespective of pipe inclinations, phase flow rates, pipe diameters and fluid combinations.

CONCLUSIONS AND RECOMMENDATION contd.

Future Recommendations

1) Incorporate the experimental results and analysis of John et al. (2015) for downward pipe orientations ($-90^0 \leq \theta \leq 0^0$) and perform an overall analysis to cover the full range of pipe orientations ($-90^0 \leq \theta \leq +90^0$) for the present experimental setup.

2) Test the heat transfer correlations for variable fluid properties at larger diameter pipes also, to see the best performing correlations.

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THANK
YOU!

QUERIES??

Heat Transfer in Two-Phase Two-Component Flows contd.

Effect of Flow Patterns and Pipe Inclination on h_{TP}

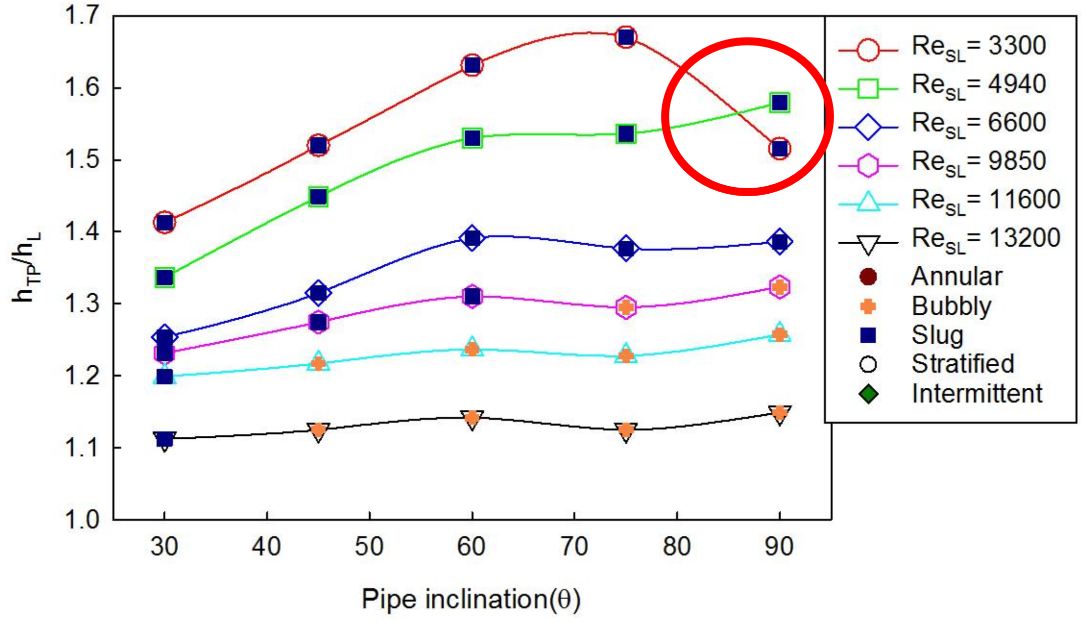

Figure: At low gas flow rate (Re_{SG}= 425)

- At these steeper orientations the liquid holdup is seen due to the influence of gravity and density on the fluid combination, resulting in different velocities for each fluid phase. This effect favors the lighter phase (air) to move faster than the heavier liquid phase resulting in the holdup of liquid near to the wall due to the slippage between both of these phases. This holdup of near wall liquid is also called liquid holdup.

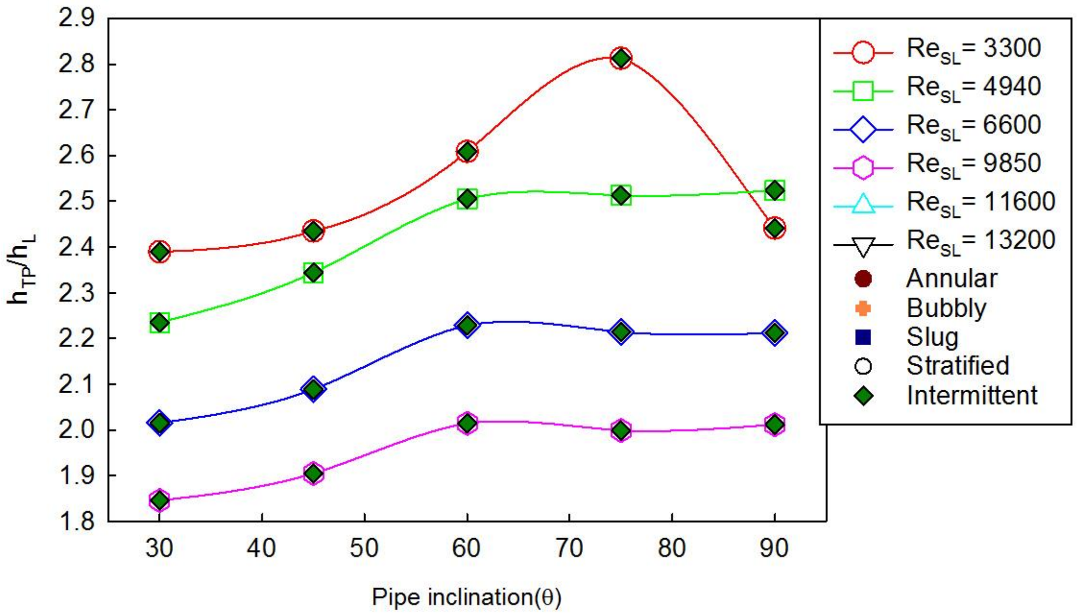

Figure: At high gas flow rate (Re_{SG}= 9500)

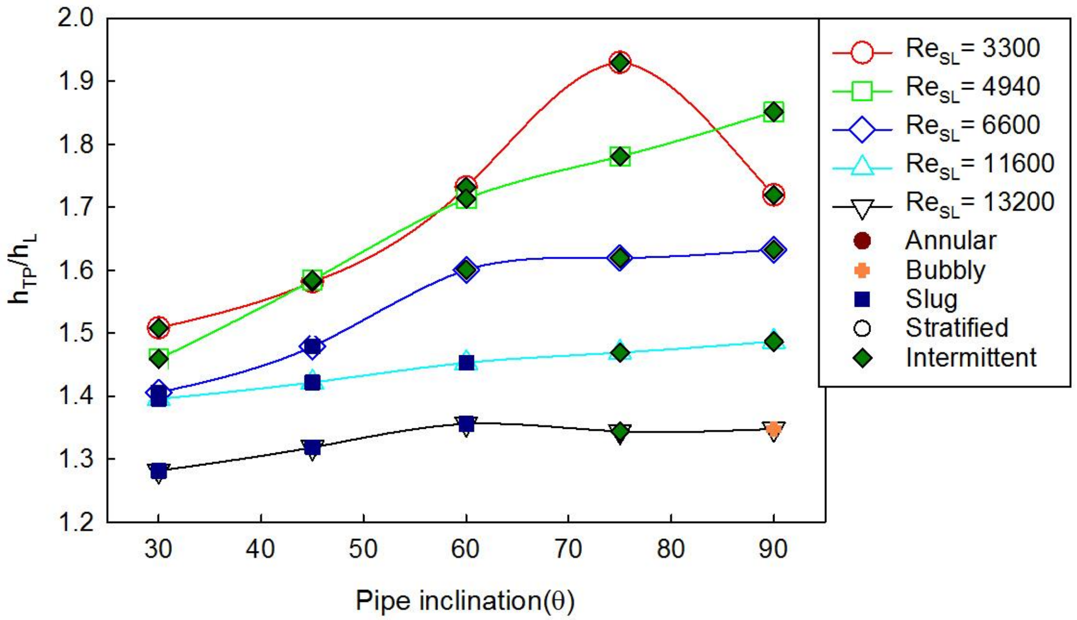

Figure: At medium gas flow rate (Re_{SG}= 1900)

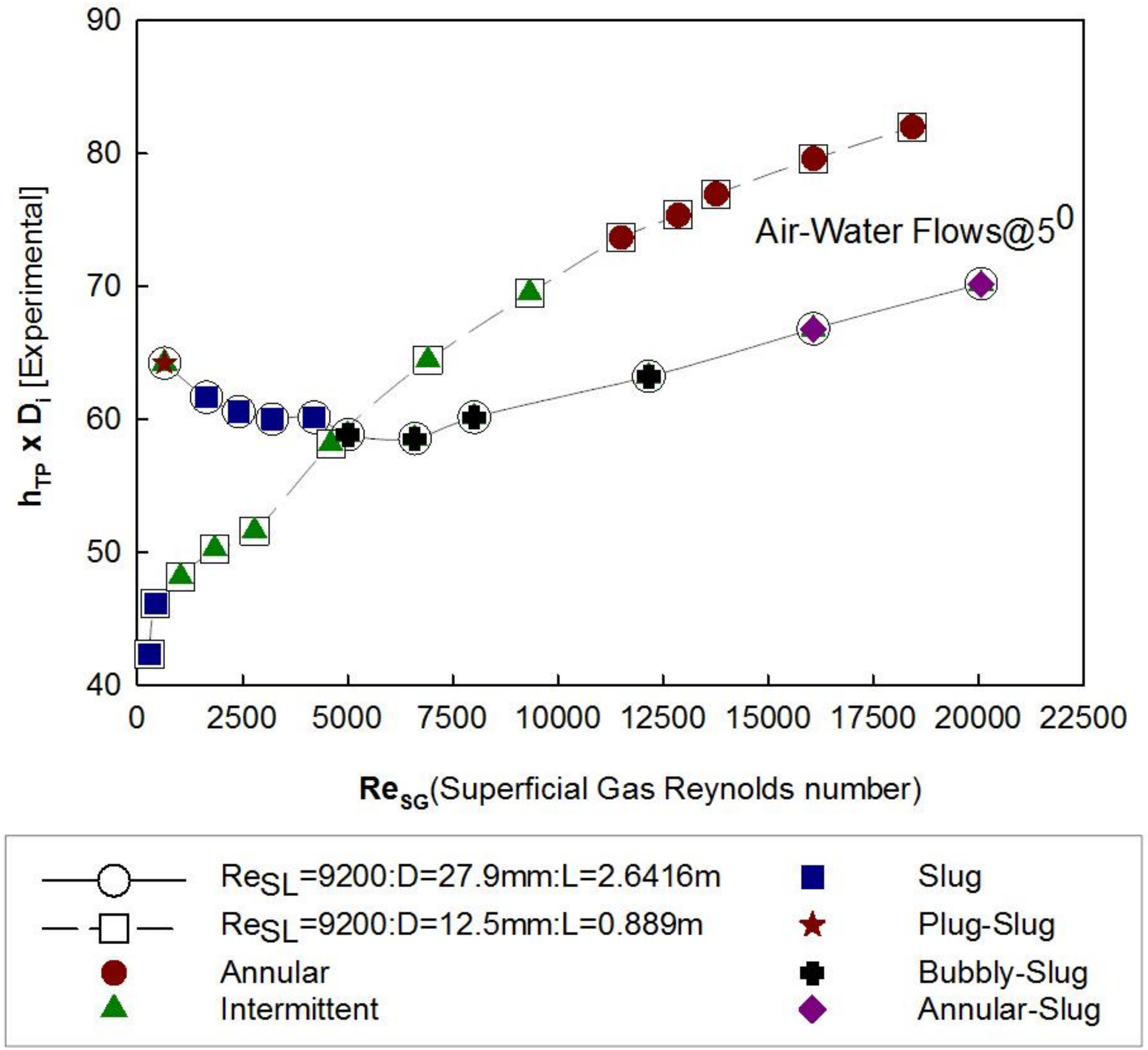

Figure: Variation of Nusselt number

Same fluid combination = Same thermal conductivity