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Experimental investigation of non-boiling gas-liquid two phase flow in upward inclined pipes

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ABSTRACT

In comparison to horizontal and vertical two phase flow, very little information is available on the two phase flow phenomenon in upward inclined pipes. To explore and contribute to the current state of knowledge, the main objective of this work is to experimentally investigate the effect of upward pipe inclinations (horizontal to vertical upward) on gas-liquid two phase flow phenomenon. To accomplish this objective, experiments focused on flow visualization, void fraction, pressure drop and heat transfer measurements in non-boiling gas-liquid two phase flow are carried out in 12.7 mm I.D. polycarbonate and 12.5 mm I.D. stainless steel pipes using air-water as fluid combination. Different flow patterns are generated by varying the gas and liquid phase mass flow rates in a range of 0.001–0.2 kg/min and 1–10 kg/min, respectively. Experimental data for void fraction, pressure drop and heat transfer coefficient is analyzed for its dependency on phase flow rates and pipe inclination. Two distinct trends of the relation between these two phase flow variables and the phase flow rates or alternatively the flow patterns are observed. The experimental results show that increase in pipe inclination from horizontal significantly affects the void fraction, total pressure drop and heat transfer coefficient at low values of gas and liquid flow rates. With increase in the gas and liquid flow rates, effect of pipe inclination on two phase flow variables is observed to diminish. The issue of decreasing pressure gradient minimum in upward pipe inclinations is analyzed using non-dimensional form of gas and liquid flow rates. Finally, based on the heat transfer measurements, the circumferential variation of two phase heat transfer coefficient and its relation to the flow symmetry is discussed.

1. Introduction

Simultaneous flow of gas and liquid phase has extensive applications in petroleum (oil-gas transport), chemical (process engineering) and energy (nuclear, thermal, refrigeration) related industries. Consequently, for past few decades, substantial efforts have been expended on better understanding of two phase flow behavior using experimental and modeling techniques. However, most of these studies are focused on two phase flow in horizontal and vertical systems with little consideration given to this phenomenon in different pipe inclinations between horizontal and vertical. Owing to the wide use of deviated or undulating pipe lines carrying two phase flow in petroleum, chemical and thermal energy generation systems, it is intriguing to study the effect of pipe inclination on the gas-liquid two phase flow phenomenon. Two phase flow literature reports experimental work of Beggs [1], Nguyen [2], and Mukherjee [3] that focus on flow visualization and void fraction and pressure drop measurements for a range of upward and downward pipe inclinations. Beggs [1] and Nguyen [2] used air-water fluid combination to study two phase flow phenomenon in 25.4 mm and 45 mm I.D. pipes, respectively. Whereas, Mukherjee [3] studied two phase flow in deviated pipelines using air-kerosene and air-oil as fluid combinations in a 38 mm I.D. pipe. All these studies reported the pipe inclination to have a considerable effect on the two phase flow parameters and proposed empirical models to predict the flow pattern transition and estimate the void fraction and pressure drop. However, due to empiricism, these models are found to be restricted to a limited range of flow conditions. More recently, Perez [4] carried out liquid holdup and pressure drop measurements in 38 mm and 67 mm I.D. pipes inclined at $-20^\circ \leqslant \theta \leqslant +90^\circ$ from horizontal using air-water fluid combination. His work reported the liquid hold up to follow a decreasing and increasing trend with an inflection point at intermediate angles as the pipe is inclined from horizontal to vertical upward. With regards to the two components two phase flow, literature reports recent comprehensive work of Lips and Meyer [5] and Olivier et al. [6] based on condensing two phase flow of R134a

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Nomenclature

D	pipe diameter (m)
Δz	differential pipe length (between two thermocouple stations)
dp/dz	pressure gradient (Pa/m)
Fr	non-dimensional phase flow rate (phase Froude number)
G	two phase mixture mass flux (kg/m^{2}s)
g	acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2 K)
k	pipe wall thermal conductivity (W/m K)
L	test section length (m)
N_{ST}	number of thermocouple stations
$\dot{q}$	heat transfer rate (W)
QCV	quick closing valves
T	temperature (°C)
U	velocity (m/s)
U_d	drift velocity (m/s)
U_t	slug translational velocity (m/s)
V	volume (m^3)
x	two phase flow quality (–)

Symbols

α	void fraction
β	gas volumetric flow fraction
ρ	phase density (kg/m^3)
θ	pipe inclination (°)

Subscripts

a	accelerational
B	pipe bottom (circumferential location)
b	bulk
f	frictional
g	gas phase
h	hydrostatic
i	pipe inner wall
j	individual axial thermocouple station
l	liquid phase
m	mixture
o	pipe outer wall
s	superficial
T	pipe top (circumferential location)
t	total
tp	two phase
w	pipe wall

Superscripts

–	average value
+	non-dimensional quantity

refrigerant in 8.38 mm I.D. pipe inclined in both upward and downward directions. Their work concluded that the physical structure of two phase flow patterns as well as the two phase flow parameters such as void fraction, pressure drop and heat transfer coefficient undergo a noticeable change as the pipe is oriented in upward/downward direction from horizontal. In addition to these comprehensive studies focused on the entire range of upward pipe inclinations, two phase flow literature also reports the work of [7–16] restricted to a narrow range and/or selective measurements of two phase flow variables in upward pipe inclinations. Bonnecaze et al. [7] and Kokal and Stanislav [8] studied the slug/intermittent flow behavior in near horizontal ($-10 \leqslant \theta \leqslant 10^\circ$) pipe orientations and found the pipe inclination to have a small effect on liquid holdup. This is possibly due to the small range of pipe orientations considered in their work. Kang et al. [13] observed the effect of pipe inclination ($\theta \leqslant 15^\circ$) on the flow pattern transition however they did not measure void fraction and pressure drop. Wongwises and Pipathttakul [14] worked with two phase flow of air-water in an annular pipe oriented at $\theta = 0^\circ, +30^\circ, +60^\circ$ and observed a definite effect of pipe inclination on flow pattern transition, measured values of void fraction and two phase pressure drop. They found that the effect of increase in pipe inclination is to decrease the void fraction and increase the two phase pressure drop. Azzopardi and his co-workers [15,16] measured the liquid entrainment fraction and liquid film thickness in annular flow and concluded that these parameters undergo a change as pipe is inclined from horizontal to vertical upward direction. Note that none of these experimental studies measure non-boiling two phase heat transfer coefficient along with the void fraction and two phase pressure drop. Hestroni et al. [17] carried out non-boiling heat transfer measurements (without void fraction and pressure drop measurements) in two phase annular flow of air-water in 25 mm and 49.2 mm I.D. tubes in near horizontal ($\theta \leqslant +8^\circ$) pipe inclinations. Hestroni et al. [17] reported a variation in the circumferential liquid film distribution and local two phase heat transfer coefficient due to flow asymmetry at near horizontal pipe inclinations. However, their work did not address these local variations of heat transfer coefficient for the entire range of upward pipe inclinations. Tang and Ghajar [18–20] in series of experiments developed flow pattern maps and measured and modeled pressure drop and heat transfer coefficient in near horizontal ($\theta = +2^\circ$, $+5^\circ$, $+7^\circ$) upward pipe inclined two phase flow. Their experiments were carried out using air-water fluids in 27.9 mm I.D. pipe but they did not measure void fraction. On the modeling front, although there are a few correlations in literature for reasonable estimation of void fraction [21–24] in upward pipe inclinations, there is hardly any flow pattern and pipe inclination independent correlation for pressure drop and heat transfer based on a wide variety of two phase flow conditions. It is also clear from the above literature review that none of the experimental studies provide information on the effect of pipe inclination (entire range from horizontal to vertical upward) on all three variables in non-boiling two phase flow i.e., void fraction, pressure drop, and heat transfer coefficient. Moreover, the data available in literature for inclined flow is sparse and limited to 1 in. and larger diameter pipes at selective upward pipe inclinations. Thus, it is of interest to check if the general trends of these two phase flow variables known in horizontal and vertical upward pipe inclinations could be extended to intermediate upward pipe inclinations in smaller diameter pipes. To this end, the present study deals with measurements of volumetric void fraction, two phase pressure drop and local as well as averaged heat transfer coefficient in a 12.7 mm I.D. pipe using air-water non-boiling two phase flow. What follows is a brief description of the experimental setup and a succinct discussion on the results of these experiments.

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 variable inclination frame is capable of inclining the two phase flow setup