International Journal of Heat and Mass Transfer xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Assessment of body force effects in flow condensation, Part I: Experimental investigation of liquid film behavior for different orientations

Ilchung Park, Lucas E. O'Neill, Chirag R. Kharangate, Issam Mudawar *

Boiling and Two-Phase Flow Laboratory (BTPFL), School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA

A R T I C L E I N F O

Article history:
Received 25 January 2016
Received in revised form 11 May 2016
Accepted 13 May 2016
Available online xxxx

Keywords:
Flow condensation
Annular flow
Condensation heat transfer coefficient
Gravity effects
Orientation effects

A B S T R A C T

Body force effects in flow condensation vary depending on channel orientation and fluid mass velocity, making the design of systems intended to operate in multiple orientations more complicated than those at a fixed orientation. This study examines the effects of body force on liquid film development for flow condensation of FC-72 in horizontal, vertical upflow, and vertical downflow orientations. Two test sections are utilized, one capable of providing high-speed imaging of liquid film development, and the other designed to allow detailed measurements of flow condensation heat transfer coefficient. High speed imaging shows that for low FC-72 mass velocities, flow regimes differ significantly among the three orientations, with vertical upflow exhibiting falling film behavior, horizontal flow showing stratification, and vertical downflow displaying annular co-current flow. For the case of low mass velocity horizontal flow, interfacial disturbances in the form of a sinusoidal wave are clearly visible with wavelengths on the order of 1–10 mm. As mass velocity is increased, the liquid film is seen to exhibit similar behavior for all three orientations due to interfacial shear stress negating body force effects. Heat transfer measurements reinforce these trends, with circumferential variations in heat transfer coefficient present for horizontal flow at low mass velocities, and differences in the axial variations in heat transfer coefficient seen when comparing vertical upflow to vertical downflow. As mass velocity is increased, differences in heat transfer coefficient are reduced, with the highest mass velocities exhibiting almost no variation with orientation. This convergence of values indicates the ability of interfacial shear stress to mitigate body force effects at sufficiently high mass velocities.

1. Introduction

1.1. Importance of gravity to interfacial behavior and condensation heat transfer

In flow condensation, both pressure drop and heat transfer characteristics change significantly depending on flow regime. Numerous investigations that are dedicated to condensation flow regime identification can be found in the literature, with the vast majority focusing on flow regimes in horizontal tubes [1–8]. However, it has been shown that tube inclination angle has a strong influence on the distribution of liquid and vapor inside the tube, and therefore both flow regime and heat transfer coefficient during flow condensation [9]. It is therefore important to develop a more comprehensive understanding of the influence of gravity on interfacial behavior in flow condensation. This is particularly the case for the annular flow regime, which both provides the highest heat transfer coefficients and typically prevails over the longest axial span of a condensation tube as compared to all other condensation flow regimes combined.

Multiple approaches exist to investigate the effect of gravity, or the lack thereof, on flow condensation. Experimental data have been obtained in microgravity that is achieved in about 15-s durations in parabolic flight aircraft [10]. But the simplest and most cost effective approach is to perform condensation experiments in Earth gravity at different tube orientations. This allows test data for the different orientations to be compared, and the relative influence of gravity on flow regimes and condensation heat transfer carefully analyzed.

Several investigations have relied on adiabatic air–water experiments to construct a flow regime map for the entire range of channel orientations [11], investigate pressure drop in inclined tubes

* Corresponding author. Tel.: +1 (765) 494 5705; fax: +1 (765) 494 0539.
E-mail address: mudawar@ecn.purdue.edu (I. Mudawar).
URL: https://engineering.purdue.edu/BTPFL (I. Mudawar).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.065
0017-9310/

Please cite this article in press as: I. Park et al., Assessment of body force effects in flow condensation, Part I: Experimental investigation of liquid film behavior for different orientations, Int. J. Heat Mass Transfer (2016), http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.065

Nomenclature

C	empirical constant
c_p	specific heat at constant pressure
D	tube diameter
G	mass velocity
g	gravity
h	heat transfer coefficient
h_{fg}	latent heat of vaporization
j^*	dimensionless superficial mass velocity
k	thermal conductivity
$\dot{m}$	mass flow rate
P	pressure
q	rate of heat transfer from FC-72 to water
Re_f	liquid film Reynolds number
T	temperature
x_e	thermodynamic equilibrium quality
z	axial coordinate

Greek symbols

ρ	density

Subscripts

avg	average
bottom	bottom of tube's perimeter
f	liquid
FC	FC-72
g	vapor
i	inner diameter
in	inlet to heat transfer measurement length
o	outer diameter
out	outlet of heat transfer measurement length
sat	saturation
ss	stainless steel
top	top of tube's perimeter
w	water
wall	stainless steel tube wall

[12], and develop a correlation for void fraction for different orientations [13]. However, findings from these adiabatic studies are not directly applicable to condensing flows.

As indicated by Lips and Meyer [9], the number of studies addressing flow condensation for varying tube orientations is quite small. In one early investigation of the effects of channel inclination, Chato [14] showed that the heat transfer coefficient increases with increasing inclination angle during downflow condensation in tubes with a slight downward inclination due to decreased depth of liquid in the tube. Wang and Du [15] performed an experimental and theoretical investigation of laminar condensation in inclined tubes using steam as working fluid. They reported that the condensation heat transfer coefficient can be increased or decreased by changing the tube's inclination angle, depending on the tube diameter, vapor quality, and mass velocity. The results were explained by relating the effect of gravity to liquid film thickness. An analytical model was developed to predict the liquid–vapor interfacial shape for stratified flow, and heat transfer coefficients predicted by the model compared favorably with experimental results. Akhavan-Behabadi et al. [16] experimentally investigated the effects of inclination angle on flow condensation of R134a inside a microfin tube. Their work showed that heat transfer coefficients for downflow condensation are higher than those for upflow condensation. Nitheanandan and Soliman [17] performed experiments to investigate the influence of small inclination angles (±10°) on flow regime boundaries for steam condensation. The influence on the boundary of the annular flow regime was virtually insignificant, while even a small angle of inclination strongly influenced wavy and slug flow regime boundaries. Later, Nitheanandan and Soliman proposed a mechanistic model to predict the transition between stratified and non-stratified flows [18]. More recently, Lips and Meyer [19] performed an experimental study of R134a condensation over the entire range of tube orientations between vertical downflow to vertical upflow. They determined that the condensation heat transfer coefficient is dependent on flow regime, which in turn is dominated by a balance between gravitational force, interfacial shear, and surface tension. Flow images captured using a high-speed camera showed that the flow became annular and was unaffected by inclination angle at higher mass velocities with high vapor quality, where interfacial shear stress dominates gravitational force. On the other hand, inclination angle had a strong influence on flow regime at low mass velocities with low vapor quality.

In recent years, research shifted to condensation in mini/micro-channels. Wang and Rose [20] constructed an analytical model to explore the effect of channel inclination on condensation of R134a in square micro-channels, where surface tension and surface curvature of the condensing film were accounted for, while inertia and convection terms were neglected. The model provided predictions for liquid film thickness, mean heat flux, and mean condensation heat transfer coefficient around the channel's perimeter for a range of channel inclinations varying from vertical downflow to vertical upflow. A theoretical and numerical analysis of stratified condensation of R141b, R11, and R134a by Saffari and Naziri [21] showed that condensation is strongly influenced by tube inclination angle, and an inclination of 30–50° above horizontal proved optimal for heat transfer. Da Riva and Del Col [22] numerically simulated condensation of R134a in a circular mini-channel for horizontal flow and vertical downflow in Earth's gravity, and for vertical downflow in zero gravity. They showed that gravity effects were dominant at low mass velocities, resulting in higher heat transfer coefficients for horizontal flow than those for vertical downflow. But simulations for high mass velocities showed a substantial diminution in the gravity effects, with the liquid film flow dominated by interfacial shear.

1.2. Objectives of study

Clearly, the exact influence of gravity on flow condensation remains quite illusive, with no mechanistic guidelines available to ascertain when this influence may be neglected. These issues are the basis for the present two-part study. In this first part, the influence of gravity on flow condensation is isolated by conducting identical experiments at three different flow orientations: horizontal flow, vertical downflow, and vertical upflow, using FC-72 as working fluid. Two separate test modules are developed for this purpose. The first is used to conduct detailed high-speed video motion analysis of the flow characteristics, with particular attention paid to interfacial behavior, for different flow orientations. The second module is used to obtain detailed heat transfer