International Journal of Heat and Mass Transfer 66 (2013) 31–45

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Flow condensation in horizontal tubes

Hyoungsoon Lee [a], Issam Mudawar [a,*], Mohammad M. Hasan [b]

[a] Boiling and Two-Phase Flow Laboratory (BTPFL), School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA
[b] NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135, USA

ARTICLE INFO

Article history:
Received 30 April 2013
Received in revised form 20 June 2013
Accepted 20 June 2013

Keywords:
Condensation
Horizontal flow
Interfacial waves

ABSTRACT

This study examines condensation heat transfer in horizontal channels. Two separate condensation modules are tested using FC-72 as condensing fluid and water as coolant. The first module is dedicated to obtaining detailed heat transfer measurements of the condensing flow, and the second to video capture of the condensation film's interfacial behavior. Four dominant flow regimes are identified: smooth-annular, wavy-annular, stratified-wavy and stratified, whose boundaries show fair agreement with published flow regime maps. The film's interface is observed to feature an array of small ripples and relatively large waves, with the largest waves tending to merge into yet larger waves having greater liquid mass, amplitude and speed. This behavior is believed to influence condensation heat transfer, especially downstream. The local condensation heat transfer coefficient is highest near the inlet, where quality is near unity and the film thinnest, and decreases monotonically in the axial direction in response to the film thickening. This variation is very sensitive to the mass velocity of FC-72, and the heat transfer coefficient decreases sharply in the inlet region but this decrease slows significantly in the downstream region because of the combined effects of turbulence and interfacial waviness. The measured condensation heat transfer coefficient shows good agreement with a select number of correlations.

1. Introduction

Phase change processes play a crucial role in the operation of power generation, chemical, pharmaceutical and heating and air conditioning systems. However, newer applications have emerged during the past three decades whose performance is highly dependent on the ability to dissipate large amounts of heat within limited volume. These include computer data centers, hybrid vehicle power electronics, avionics, lasers, and X-ray medical devices [1]. These applications have created a need to adapt two-phase processes into compact configurations that promise several orders-of-magnitude enhancement in evaporation and condensation heat transfer coefficients compared to those possible with single-phase liquid cooling alone. This shift is manifest in the surge of studies concerning virtually all possible evaporation and flow boiling configurations, including pool boiling [2,3], channel flow boiling [4,5], jet [6–8] and spray [9,10], as well as enhanced surfaces [11,12] and hybrid cooling configurations [13,14].

But heat acquisition constitutes only part of the challenge. Often achieved with the aid of a closed two-phase flow loop, heat acquisition by evaporation or flow boiling requires commensurate heat rejection capability that relies mostly on condensation. There is therefore a need for design tools for high performance condensation hardware, with particular emphasis on increasing the ratio of heat dissipation rate to pressure drop.

For internal condensing flows with superheated vapor inlet conditions, condensation is initiated with the formation of a thin liquid film along the inner walls of the tube, which marks the initiation of the annular flow regime. Axial thickening of the wavy condensate film ultimately causes wave crests from diametrically opposite sides of the tube to merge, which commences formation of the slug flow regime. Continued axial condensation causes a reduction in the length of the slug flow bubbles. The bubbly flow regime is initiated where the length of the slug flow bubbles drops below the tube diameter. Eventually, the flow is converted to pure liquid. Among these flow regimes, annular flow is by far the most important because it is typically prevalent over a large fraction of the condensation length, and its ability to provide the highest condensation heat transfer coefficients. This explains the emphasis researchers place on the annular regime compared to all other regimes combined.

Predicting pressure drop and heat transfer in annular condensing flows relies on (a) semi-empirical correlations [15–18], whose applicability is limited to fluids and operating conditions of specific databases, (b) universal correlations [19,20], which are derived from consolidated databases for many types of fluids and covering broad ranges of geometrical and flow parameters, and (c) theoretical control-volume-based models [21,22].

* 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).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.06.044

Nomenclature

Bo	bond number
$C_{D,w}$	drag coefficient on wave
c_p	specific heat at constant pressure
D, D_i	inner diameter of condensation tube
D_h	hydraulic diameter
D_o	outer diameter of condensation tube
G	mass velocity of FC-72
g	gravitational acceleration
G_w	mass velocity of water
h	local condensation heat transfer coefficient
$\bar{h}$	average condensation heat transfer coefficient
h_{fg}	latent heat of vaporization
j	superficial velocity
j^*	dimensionless superficial velocity
j'_g	modified superficial vapor velocity
k	thermal conductivity
$\dot{m}$	mass flow rate
MAE	mean absolute error
P	pressure
P_R	reduced pressure, $P_R = P/P_{crit}$
Pr	Prandtl number
q''	heat flux
Re	Reynolds number
Re_{eq}	equilibrium Reynolds number
T	temperature
T^+	dimensionless temperature
u_w	wave velocity
v^*	shear velocity
W	outer channel width of condensation module CM-FV
We	Weber number
We^*	modified Weber number
X	vapor quality
x_e	thermodynamic equilibrium quality
X_{tt}	Lockhart–Martinelli parameter
Z	stream-wise coordinate

Greek symbols

δ^+	dimensionless film thickness
μ	dynamic viscosity
ρ	density
σ	surface tension
ϕ	two-phase pressure drop multiplier

Subscripts

air	air
crit	critical pressure
exp	experimental
f	saturated liquid
FC	FC-72
film	liquid film
fo	liquid only
fr	frictional
g	saturated vapor
i	inner surface of condensation tube
in	inlet of condensation length
o	outer surface of condensation tube
pred	predicted
sat	saturation
ss	stainless steel
tt	turbulent liquid – turbulent vapor
w	water
wall	wall

One useful tool investigators often rely upon to aid the prediction of condensing flows is the use of flow regime maps. By pinpointing the dominant flow regime, they are better able to tailor models to this particular regime. Several types of flow regime maps have been recommended, which employ different coordinates to segregate flow regimes, such as mass velocity versus quality [17,23,24], and superficial velocity of vapor, j_g, versus that of liquid, j_f [25,26]. Large disagreements in the predictions of regime maps for different working fluids has lead some to incorporate dimensionless groups, such as j^*, X_{tt} and We^*, that are more effective at capturing the dominant forces associated with different regimes [27,28]. A key drawback to flow regime maps in general is the difficulty representing the many dimensionless groups governing multiple flow regimes using a single two-dimensional plot.

The present study is a part of a long-term NASA-supported initiative to develop the Flow Boiling and Condensation Experiment (FBCE), which is scheduled for future deployment in the International Space Station (ISS). This initiative is rooted in the realization that, despite the few useful published studies concerning flow boiling and condensation in microgravity [29–33], the corresponding databases and reliable predictive tools are quite sparse. The overall objectives of the NASA initiative are to (i) obtain flow boiling and condensation databases in microgravity, (ii) develop mechanistic models for flow boiling and condensation, and (iii) determine the minimum flow rate required to ensure gravity-independent cooling. A key tactic in assessing the influence of gravity is to compare data from experiments that are conducted separately in microgravity and Earth's gravity. The present study explores horizontal flow condensation at Earth's gravity. First, video motion analysis is used to explore both the interfacial behavior of the condensing film and longitudinal transitions between condensation regimes. Secondly, detailed heat transfer measurements are made to ascertain the axial variations of the condensation heat transfer coefficient in response to variations in mass velocities of the condensing fluid and cooling water. Results are then compared to predictions of flow regime maps and popular correlations for the condensation heat transfer coefficient.

2. Experimental methods

2.1. Condensation facility

The condensation facility constructed for this study is designed to condense FC-72 by rejecting heat to water. Fig. 1(a) shows this facility consists of two separate sub-loops, one for FC-72 and the other for the cooling water, and an accessory that is used for FC-72 deaeration. As depicted in Fig. 1(b), the components of the facility are segregated into three separate rigs: (i) the main condensation rig, (ii) water conditioning rig, and (iii) deaeration rig.

In the FC-72 sub-loop, the FC-72 is circulated with the aid of a magnetically driven Micropump GB gear pump, followed by a flow control valve, filter, and Flow Technology FTO-3 turbine flow meter. The FC-72 is the heated through a CAST-X 3000 circulation heater to a quality slightly higher than unity before entering one of two condensation modules that are described below. Exiting the