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Determination of flow regimes and heat transfer coefficient for condensation in horizontal tubes

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ABSTRACT

This study explores condensation of FC-72 in horizontal tubes. Using high-speed video motion analysis, dominant condensation flow regimes are identified for different combination of mass velocities of FC-72 and cooling water. Additionally, detailed heat transfer measurements are used to explore both axial and circumferential variations of the condensation heat transfer coefficient. Four different regimes are identified: *stratified*, *stratified-wavy*, *wavy-annular with gravity influence*, and *wavy-annular without gravity influence*. In the latter regime, which is achieved at high FC-72 mass velocities, annular film transport is dominated by vapor shear with negligible gravity effects. Using different types of regime maps, prior relations for transitions between regimes are assessed, and new, more accurate transition relations developed. The heat transfer coefficient is shown to be highest near the inlet, where quality is near unity and the film thinnest, and decreases gradually along the condensation length because of axial thickening of the liquid film. This study also explores the predictive capabilities of prior heat transfer correlations and a control-volume-based annular flow model. The experimental data of both the local and average condensation heat transfer coefficients show fair to good agreement with predictions of prior and popular correlations. But superior predictions in both trend and magnitude are achieved with the annular flow model.

1. Introduction

For many decades, condensation has been implemented in power generation, chemical, pharmaceutical, and refrigeration and air conditioning applications. The high heat transfer coefficients associated with condensation have also made possible the development of thermal management solutions for a number of modern technologies that demand the transfer or dissipation of large amounts of heat from small volumes. These include cooling systems for high power density electronic and power devices. These cooling systems generally rely on boiling to acquire the heat from the device, and reject the heat to the ambient by condensation [1]. Much of the research on these systems has been focused on the heat acquisition by boiling, including pool boiling [2–4], channel flow boiling [5–7], jet [8–11] and spray [12–15], as well as enhanced surfaces [16–18] and hybrid cooling configurations [19]. Condensation, however, has received far less emphasis, and most of the design tools for condenser design are adopted directly from tools developed decades ago for more conventional power generation and refrigeration and air conditioning applications.

Several well-defined flow regimes have been identified for condensation inside horizontal tubes which, in order of decreasing quality, include pure vapor, annular, slug, bubbly and pure liquid [20]. Both flow regime maps and regime transition relations have been recommended to determine dominant flow regimes [21–26]. The annular regime has attracted the most attention because of its prevalence over a large fraction of the tube length and ability to deliver high heat transfer coefficients. The annular regime consists of a thin film that sheathes the inner walls of the condensation tube, shear driven by a faster moving central vapor core.

While vapor shear is the main driving force in annular condensation, gravity can also play an important role for condensation inside horizontal tubes, which is manifest in stratification of liquid toward the bottom of the inner surface. This results in a relatively thick liquid film towards the bottom, compared to a very thin film or no film at the top. Conditions that yield pronounced stratification effects are generally associated with a strong influence of gravity on the magnitude and spatial variations of the condensation heat transfer coefficient.

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Nomenclature

A^+	constant in eddy diffusivity function
$A_{f,*}$	flow area in liquid control volume
c_p	specific heat at constant pressure
D	diameter
f_i	interfacial friction factor
G	mass velocity
g	gravitational acceleration
h	heat transfer coefficient
$\bar{h}$	condensation heat transfer coefficient averaged over region where $x < 1$
h_{fg}	latent heat of vaporization
j	superficial velocity
j^*	dimensionless superficial velocity
j'_g	modified superficial vapor velocity
K	Von-Karman constant
k	thermal conductivity
$\dot{m}_f$	mass flow rate of FC-72 liquid film
$\dot{m}_{FC}$	total mass flow rate of FC-72
$\dot{m}_g$	mass flow rate of FC-72 vapor core
$\dot{m}_w$	mass flow rate of cooling water
P	pressure
P_f	perimeter
Pr	Prandtl number
Pr_T	turbulent Prandtl number
q	heat transfer rate
q''	heat flux at distance y from inner wall of inner stainless steel tube
q''_w	heat flux at inner wall of inner stainless steel tube
q_w	heat transfer rate from FC-72 to cooling water
Re	Reynolds number
Re_f	FC-72 film Reynolds number, $Re_f = G(1-x)D/\mu_f$
T	temperature
u	velocity
u^*	friction velocity
$\bar{u}_g$	mean vapor core velocity
We^*	modified Weber number
x	mass quality
x_e	thermodynamic equilibrium quality
X_{tt}	Lockhart–Martinelli parameter
y	distance perpendicular to inner wall of inner stainless steel tube
z	stream-wise distance

Greek symbols

Γ_{fg}	rate of mass transfer due to condensation per unit distance
δ	thickness of condensing film
ε_m	eddy momentum diffusivity
ε_h	eddy heat diffusivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
τ	shear stress
ϕ	two-phase multiplier

Subscripts

air	air
avg	average
bottom	bottom surface
exp	experimental, measured
f	saturated liquid; liquid film
FC	FC-72
g	saturated vapor; vapor core
i	interfacial; inner wall of inner stainless steel tube
in	inlet
o	outer wall of inner stainless steel tube
out	outlet
pred	predicted
sat	saturation
ss	inner stainless steel tube
top	top surface
TP	two-phase region
w	water; wall
wall	wall of inner stainless steel tube

Superscript

+	dimensionless

Numerous condensation heat transfer correlations and models have been published in the past. Most of these predictive tools are valid for specific fluids and relatively narrow ranges of operating conditions. Predictive tools for annular condensation heat transfer can be grouped into (a) semi-empirical correlations [27–30], which are limited to specific fluids and operating conditions, (b) universal correlations [31,32], which are based on consolidated databases for a large number of fluids and broad ranges of operating conditions, and (c) analytical control-volume-based models [33]. There is a far smaller number of empirical correlations for annular condensation involving pronounced gravity effects in horizontal tubes [34–36].

As indicated above, there are several types of flow regime maps that employ different coordinates to segregate flow regimes, such as mass velocity versus quality [23,24,29], and superficial velocity of vapor, j_g, versus that of liquid, j_f [21,36]. Large disagreements in the predictions of early regime maps has spurred the development of maps that rely on dimensionless groups; these maps are deemed more effective at capturing the dominant forces associated with different flow regimes [37,38]. Nonetheless, a key drawback to dimensionless flow regime maps is the difficulty representing the many dimensionless groups governing multiple flow regimes using a single two-dimensional plot.

The primary objectives of the present study are to (1) identify dominant condensation flow regimes encountered inside horizontal tubes, (2) construct regime maps, (3) explore the axial and circumferential variations of the condensation heat transfer coefficient, (4) assess the predictive capabilities of prior heat transfer correlations, and (5) assess the effectiveness of a control-volume-based model in predicting the condensation heat transfer coefficient. Long term, these findings are intended for design of thermal control systems for future space vehicles. As follow-up to [39], findings from the present study will be used in the future to ascertain the influence of body force by comparing data for condensation in upflow [40], downflow [33] and horizontal flow with those in microgravity [41]. This comparison will help identify the minimum mass velocity (i.e., minimum pumping power) that would negate the influence of body force on condensation in space vehicles.

2. Experimental methods

2.1. Condensation flow loop

As shown in Fig. 1(a) and depicted in Fig. 1(b), the condensation facility used in this study consists of a primary loop for the condensing fluid, FC-72, and two water cooling loops. Condensation