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Determination of condensation heat transfer inside a horizontal smooth tube

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ABSTRACT

A mathematical model has been developed with the open source toolbox OpenFOAM to simulate the heat transfer process during flow condensation inside a smooth horizontal tube. The proposed model borrows some of the ideas of a recent boiling model, already developed in OpenFOAM 4.0. Modifications have been brought to this model to take into account the specific nature of flow condensation. A new coefficient called the "condensation area fraction" is introduced and a new library is added to the solver to simulate the wall heat flux during the condensation process. In order to assess the performance of the new model, numerical simulations are conducted for mass fluxes ranging from 100 to 750 kg/m^2 s, with a nominal saturation temperature of 40 °C and a hydraulic diameter between 7 and 12 mm. The numerical predictions are compared to the results of two experimental works and good agreement has been found between measurements and model's predictions. It shows the validity of the suggested numerical solution for modeling of flow condensation inside of a horizontal smooth tube. Moreover, the effect of some parameters such as mass flux, tube hydraulic diameter, vapor quality and difference between the wall and saturation temperature on the heat transfer coefficient are investigated. Finally, a new relationship for the prediction of the total heat transfer coefficient of flow condensation is proposed.

1. Introduction

Two-phase flow studies on boiling and condensation have attracted attention of researchers due to the high heat fluxes found during these processes. The condensers and evaporators are regularly used in air conditioning systems, ventilation systems, heat sinks and heat pipes. Lower service costs, higher thermal efficiency, less occupied space and easier monitoring, manufacturing and maintenance are some of the advantages of using these systems which explain the increasing use of such equipment in the industry. The ultimate goal of designing a cooling system is to get high heat transfer coefficients with a negligible pressure drop.

Mechanisms of heat and momentum transfer for in-tube condensation or boiling (called flow condensation and flow boiling) are strongly dependent on the prevailing two-phase flow regime. For flow condensation inside a horizontal smooth tube, gravity and inertial forces are the two primary driving forces influencing the flow regime, which can be classified into stratified, stratified-wavy, transient and annular regime, depending on the flow conditions. In stratified and stratified-wavy flow regime, the gravitational force is more dominant than the inertial force and causes accumulation of the liquid film at the bottom of the tube. The liquid film then acts as a thermal resistance and decreases the heat transfer coefficient. At higher velocities, as the flow is entering the so-called annular regime, the shear stress forces control the flow, the liquid film thickness is diminished, and the heat transfer coefficient is increased [1]. Other types of flow regime like slug or mist flow are less frequent than stratified and annular regimes. Since heat transfer is strongly dependent on the interaction between gravity and inertial forces, suggested correlations for the calculation of heat transfer coefficients must be based on the prevailing flow pattern.

Studies on flow pattern map applied to condensation applications started with the work of Palen et al. [2]. Thome et al. [1] proposed a flow pattern map for flow condensation based on correlations established for different refrigerants taken from the literature and also studied the effects of interfacial roughness and mixtures of refrigerants on the heat transfer coefficient. Their suggested model predicted acceptable results for low-reduced pressure conditions. However, it shows significant discrepancy with experimental results at high-reduced pressure. Dobson and Chato [3] conducted an experimental study on the impact of the flow regime on the heat transfer coefficient for condensation inside

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Nomenclature

Variable

A	area, m^2
A_b	boiling area fraction, –
A_{cd}	condensation area fraction, –
A''_w	contact area at wall per unit volume, m^2/m^3 = m^{-1}
C_p	specific heat capacity at constant pressure, J/kg K
Co	condensation Number, –
D	hydraulic diameter of tube, m
d_w	diameter of detached bubble, m
f	frequency of detachment, s^{-1}
G	mass flux, kg/m^2 s
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
H_c	Stanton heat transfer coefficient of single-phase convection-, W/m^2 K
h_{lv}	latent heat of vaporization, J/kg
i	specific enthalpy, J/kg
J_v	dimensionless vapor velocity, –
L	length of tube, m
$\vec{M}_a$	interfacial momentum transfer of phase a, kg/m^2 s^2
$\dot{m}_e$	evaporating mass flux, kg/m^2 s
$\dot{m}_{cd}$	condensation mass flux, kg/m^2 s
Nu	Nusselt number, –
P	pressure, Pa
Pr	Prandtl number,–
∇P	gradient of pressure, Pa/m
q, Q	heat flux, W/m^2
q_a, q_a^t	molecular & turbulent heat flux of phase a, W/m^2
q''_w	wall heat flux, W/m^2
$q_w^{e''}$	evaporation heat flux, W/m^2
$q_w^{q''}$	quenching heat flux, W/m^2
$q_w^{c''}$	single-phase convection heat flux, W/m^2
$q_w^{cd''}$	condensation heat flux, W/m^2
R, R^t	viscous & turbulent stress tensor, Pa, kg/m s^2
Re	Reynolds number, –
T	temperature, K
t	time, s
$\vec{U}$	velocity, m/s
U_{adj}	vapor/liquid velocity adjacent to the wall, m/s
x	vapor quality, –
X_{tt}	Martinelli number, –

Greek symbols

Γ^+_{ab}	volumetric mass source from phase a to b, kg/m^3 s
α	volume fraction, –
λ	thermal conductivity, W/m K
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3

Subscripts

a	phase a, dispersed phase
b	phase b, continuous phase
cr	critical
$corr$	correlation
e	equivalent
exp	experimental
in	inlet
i	inner side
l	liquid
out	outlet
o	outside
r	refrigerant
ref	reference value
sat	saturation
sim	simulation
sub	sub-cooled
t	turbulent
v	vapor
w, $wall$	wall

horizontal tubes with diameter ranging from 3 to 7 mm using various refrigerants including R-12, R-22 and R134a. Simulated flow pattern map was compared with the experimental observations. Moreover, the heat transfer coefficients for different flow regimes have been compared with the proposed correlations with noticeable discrepancies.

Several correlations have been proposed to estimate the heat transfer coefficients of flow condensation. Each correlation is restricted to specific regimes with a validity range for parameters such as mass flux, Reynolds number etc. However, a few correlations, like Thome [1], Dobson and Chato [3], Shah [4], Cavallini [5], Travis [6] and Akers [7], can cover the entire range of flow regimes including stratified and annular regimes. However, using such correlations in a wide range of flow conditions necessarily leads to inevitable errors beyond acceptable range (±25%).

Numerous experimental studies have been performed to investigate the heat transfer coefficient and pressure drop in flow condensation and compare experimental measurements with the estimations obtained from suggested correlations. Cavallini et al. [8] measured the heat transfer coefficients using different refrigerants such as R22, R134a, R32, R125, R410a and R407c in a horizontal 8 mm diameter tube for various ranges of mass flux, saturation temperature, vapor quality and temperature difference between saturation and wall (T_{sat}-T_{wall}). They concluded that in stratified regime, the heat transfer is considerably affected by the temperature difference, T_s-T_{wall}. However, in annular regime, the effect of parameters like mass flux, vapor quality and saturation temperature on the heat transfer coefficient is more significant than the temperature difference. Suliman et al. [9] performed an analysis on the heat transfer coefficient of R-134a inside a smooth horizontal tube for a nominal saturation temperature of 40 °C and mass fluxes of 75–300 kg/m^2 s. Their experimental results showed a deviation of 15% and 18% when compared to Thome's [1] and Cavallini's [5] correlations, respectively. In addition, a new improved flow pattern map and a revised correlation for the calculation of the heat transfer coefficient were suggested. Hossain et al. [10] measured the heat transfer coefficient and pressure drop of different working fluids like R22, R1234ze and R410a inside a horizontal smooth tube having a diameter of 4.33 mm and a length of 3.6 m. They analyzed their experimental data to determine which fluid conducts higher heat transfer coefficients. They finally concluded that, at the same conditions, R32 produces a heat transfer coefficient of 70% and 20–45% higher than R410a and R1234ze, respectively. Panitapu [11] compared experimentally determined heat transfer coefficients and pressure drops with existing correlations. It is concluded that Shah's correlation [4] is more suitable for annular regime and Dobson's relation [3] leads to better predictions for the stratified regime.

Although there are many experimental works for the estimation of heat transfer coefficients in flow condensation regimes, only a few investigations are presented on the development of numerical models. With the help of such models, the behavior of important variables such as velocity, pressure, temperature and volume fraction of each phase can be separately observed. In commercial