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A heat transfer model for condensation accounting for non-equilibrium effects

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ABSTRACT

A heat transfer model is proposed in this paper for condensation of annular and stratified flow in horizontal smooth round tubes accounting for the non-equilibrium effects. The model is based on a non-equilibrium flow regime map and void fraction correlation that is developed from diabatic flow visualization and film thickness measurement. The model unifies single-phase and two-phase heat transfer models into one continuous function throughout the superheated, condensing-superheated, two-phase, condensing-subcooled and subcooled regions with seamless transition in between. Film heat transfer coefficient based on the interfacial temperature of the flow is used as a tool for the modeling in the presence of two-phase flow, which is later converted back to heat transfer coefficient based on the bulk temperature of the flow. The two-phase flow model is developed for the annular and stratified flow. The effects of interfacial waviness, liquid entrainment, wall subcooling, gravity, tube diameter as well as non-equilibrium are discussed in separated sections. Data obtained from different refrigerants and working conditions are used for the validation of the model.

1. Introduction

Most conventional approaches assume that the first droplet of liquid during condensation appears at quality one and the last vapor molecule disappears at quality zero, between which is the two-phase (TP) region. However, it is only true when the two phase flow is in thermodynamic equilibrium or when inlet to the condenser is saturated vapor. The condensation process in every real heat exchanger operates in non-equilibrium situation with temperature gradient and subcooling in the liquid. This is especially true in the case of vapor compression systems with high superheat at compressor discharge, or close to critical point. The consequence of the presence of temperature gradient here is that as soon as the temperature of inner wall drops below saturation temperature, the first droplet forms even though the bulk specific enthalpy indicates that the flow is in the superheated (SH) region. Once the liquid appears, the heat transfer and pressure drop mechanism deviates from single-phase mechanism and switches into two-phase mechanism. Similar to the onset of condensation, such non-equilibrium means there is still vapor at the bulk quality zero and the end of condensation is actually at a specific enthalpy indicating that the flow is in the subcooled (SC) region. Most of the condensation models ignored the two phase flow in the SH and SC region and are only developed to predict heat transfer coefficient (HTC) in the TP region. After curve fitting of the data, those models usually provide relatively satisfactory predictions from bulk quality one to zero, but discontinuity almost always exists at bulk quality one and zero, between single phase correlations and the two-phase model itself. To bridge the discontinuity at bulk quality one, Kondou and Hrnjak [1–3] proposed a correlation after extensive measurements that asymptotically combined the two-phase and single-phase correlation, and the new region where liquid exists in the SH region is defined to be condensing superheated (CSH) region. In the Kondou-Hrnjak correlation, the heat transfer is divided into two parts in the CSH region: latent heat and sensible heat, each part weighed by the temperature difference between the bulk flow and saturation, as well as the saturation and wall. Agarwal and Hrnjak [4] later refined the model by following the same logic but employing area ratio into the weighing of the latent heat and sensible heat. The area of liquid is calculated from Nusselt falling film theory. However, the nature of both of the models in the CSH region overlooks the fact that in the CSH region the mechanism of heat transfer is already a two-phase mechanism and according to the flow characterization and analysis from Xiao and Hrnjak [5], HTC fails to capture the two-phase mechanism in that region, where film HTC (HTC_f) represents the process better.

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Nomenclature

SH	superheated
CSH	condensing superheated
CSC	condensing subcooled
Re	Reynolds number
Pr	Prandtl number
HTC	conventional heat transfer coefficient (W m^{-2} K^{-1})
δ	thickness (m)
T	temperature (K)
P	pressure (Pa)
G	mass flux (kg m^{-2})
Q	heat flux (kW m^{-2})
h	specific enthalpy (kJ kg^{-1})
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
u	velocity (m s^{-1})
k	conductivity (W m^{-1} K^{-1})
g	acceleration of gravity (m s^{-2})
x	quality
ε	void fraction

Subscripts

b	bulk
sat	saturated
w	wall
f	film
sup	superficial
l	liquid
v	vapor
onset	onset of condensation
end	end of condensation

Also, the heat transfer process in the CSC region is not taken into the consideration while it should be. Therefore, a unified model that predicts HTC in both single-phase and two-phase regions with continuous heat transfer mechanism specifically explained is possible and necessary and that is the objective of this paper.

2. Literature review

2.1. Flow regime maps

Flow regime has been long recognized to influence the mass, momentum and energy transfer process. Over the years, many models and correlations predicting HTC have used flow regime map as a tool to be more generalized and realistic. Due to the subjective determination of flow regimes and numerous names given to different flow configurations, numerous flow regime maps were proposed with quite different criteria. The primary categories and physical interpretation of the flow regimes, however, are converging and reaching agreement.

One of the earliest flow regime map in horizontal tube was developed by Baker [6] from adiabatic gas-liquid flow. Since the Baker map is not developed for condensation, it needs to be validated during a condensation process. Soliman and Azer [7] did experiment with visualization section after test section where condensation happens, and found limited agreement with Baker map. It was also stated that a flow regime map constructed with Froude number and void fraction could be considered more generalized because more significant parameters would be involved in the coordinates.

One of the first and most quoted theoretical flow regime map was later developed by Taitel and Dukler [8]. Five dimensionless group were brought up to represent different competing parameters. The transition between the regimes are controlled by the balance between those groups. The transition between stratified flow and intermittent flow or annular dispersed flow was reasoned as a consequence of growing wave. As mass flow rate increases, due to Kelvin-Helmholtz instability, surface wave grows and tends to block the tube. When void fraction is high, liquid will be washed onto the upper part of the tube, creating annular flow. When void fraction is low, liquid wave will block the entire tube, creating intermittent flow. The difference of void fraction denotes the transition between intermittent flow and annular dispersed flow. Whether or not the increase in gas velocity will be sufficient to form waves represents the transition between stratified smooth flow and stratified wavy flow. The transition between intermittent flow and dispersed bubble flow is caused by the strong turbulent disturbance that overcomes the buoyancy of vapor slug or bubble. In the original approach, the parameter that balances the gravity was identified to be shear at the interface. Galbiati and Andreini [9] and Barnea et al. [10] later brought surface tension into the balance, which expanded the applicable range into small tubes. The potential problems of the Taitel and Dukler map are within the adiabatic approach. Due to the adiabatic nature, the map does not distinguish evaporation and condensation, whereas the mechanisms of the two processes are not identical. The approach of increasing mass flow rate to generate instability is closer to evaporation where liquid is converted into gas and accelerate than condensation where gas condenses into liquid and slows down. Take the effect of pressure on wavy structure as an example. Taitel and Dukler mentioned that the acceleration of gas tends to reduce pressure due to Bernoulli's effect. Thus waves are likely to grow. During condensation process, contrary to the description above, the gas decelerates and the pressure rise from deceleration might suppress the growth of waves, whose effect on heat transfer was discussed by Thome et al. [11]. Another example would be the flow regime at onset of condensation. Unlike what is predicted to be wavy flow at the onset of condensation under certain conditions, Palen et al. [12] and Xiao and Hrnjak [5] both visualized only annular flow regime in diabatic visualization section at the beginning of condensation. Even so, the approach Taitel and Dukler took to generate the map provided valuable physical insights and could be used as a base model for flow mapping under diabatic conditions.

To validate the applicability of Taitel and Dukler map in condensation, studies on flow regime specifically in condensation were performed by Palen et al. [12] and Breber et al. [13], in which the theoretical significance of Taitel and Dukler map in condensation was confirmed. A new flow regime map was developed based on dimensionless gas velocity and Martinelli parameter. The use of dimensionless gas velocity was justified as it can be essentially treated as Dukler F factor. Sardesai et al. [14] and Tandon et al. [15] made modifications to the transition criteria based on their investigations. The focus of the approach to generate Breber map was placed on distinguishing between shear-controlled flow and gravity-controlled flow. To evaluate the shear force against gravity, Jaster and Kosky [16] established a parameter called "stress ratio", which was defined as shear force over gravitational force, as an indicator of transition between annular flow and stratified flow. The expression incorporated physical parameters such as dimen-