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Prediction of two-phase condensation in horizontal tubes using probabilistic flow regime maps

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Abstract

A flow regime based condensation model is developed for refrigerants in single, smooth, horizontal tubes utilizing a generalized probabilistic two-phase flow map. Flow map time fraction information is used to provide a physically based weighting of heat transfer models developed for different flow regimes. The developed model is compared with other models in the literature, with experimentally obtained condensation data of R134a in 8.92 mm diameter tubes, and with data found in the literature for 3.14 mm, 7.04 mm, and 9.58 mm tubes with R11, R12, R134a, R22, R410A, and R32/R125 (60/40% by weight) refrigerants and a wide range of mass fluxes and qualities.

Keywords: Condensation; Two-phase; Probabilistic; Flow regime map; Horizontal tubes

1. Introduction

Numerous two-phase condensation models are available in the literature for specific flow configurations. Recently, flow regime map based models have been developed that span multiple flow regions. The most recent of the flow regime map based models are seen to predict heat transfer for a wide range of tube sizes, fluids, and flow conditions. However, these models are difficult to implement and require interpolation to transition between flow regimes without discontinuities as a result of the flow regime maps used.

In the present study probabilistic two-phase flow map condensation models, similar to the multi-port microchannel pressure drop and void fraction models developed by Jassim and Newell [1], are developed for single, smooth, horizontal tubes in order to predict condensation heat transfer in multiple flow regimes with statistically correlated transitions. An overall condensation heat transfer coefficient is predicted as the sum of the flow regime time fractions, fractions of time that particular flow regimes are observed for given flow conditions, multiplied by representative heat transfer models for each respective flow regime. The time fractions were obtained from a generalized probabilistic two-phase flow regime map for horizontal tubes developed by Jassim [2]. Condensation heat transfer models were identified for the intermittent, stratified, and annular flow regimes. Due to the flexible nature of this model, different condensation models can be implemented. The models developed in the present study predict condensation data of R134a in 8.915 mm diameter smooth tube for a range of qualities and mass fluxes from 100 to 300 $kg/(m^2\ s)$ experimentally obtained in the present study with a mean absolute deviation of 6%. The present models developed and other flow map based condensation models in the literature are statistically compared to a database of 772 condensation points found in the literature for 3.14 mm, 7.04 mm, and 9.58 mm tubes with R11, R12, R134a, R22, R410A, and 60/40 R32/R125 by weight and a wide range of mass fluxes and qualities. Using this database the present models are found to have errors largely comparable to the models identified in the literature but

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Nomenclature

A_L	cross-sectional area of tube occupied by liquid (m^2)
C_p	specific heat (kJ/(kg K))
D	hydraulic diameter (m)
dP	pressure drop (kPa)
dz	length (m)
e	deviation (−)
e_A	mean absolute deviation (−)
e_R	average deviation (−)
F	observed time fraction (−)
fi	interfacial roughness factor (−)
Fr_{vo}	vapor only Froude number (−)
G	mass flux (kg/(m^2 s))
g_a	gravitational acceleration (9.81 m/s^2)
h	heat transfer coefficient (W/(m^2 K))
h_{lv}	latent heat of vaporization (kJ/kg)
i	intermittent flow regime curve fit constant (−)
k	thermal conductivity (W/(m K))
N	total number of data points(−)
Pr	Prandtl number (−)
Re_l	superficial liquid Reynolds number (−)
Re_{lt}	Reynolds number of the liquid film (−)
s	stratified flow regime curve fit constant (−)
T	temperature
We_{vo}	vapor only Weber number (−)
x	flow quality (−)
Xi	dimensionless group correlating the intermittent/liquid flow regime (−)
Xs	dimensionless group correlating the stratified flow regime (−)
X_{tt}	turbulent–turbulent Lockhart – Martinelli parameter (−)

Greek symbols

α	void fraction (−)
α_{ra}	predicted void fraction given by Eq. 24 (−)
δ	liquid film thickness of annular ring (m)
μ	dynamic viscosity (kg/(m s))
ρ	density (kg/m^3)
σ	surface tension (N/m)
σ_N	standard deviation
θ	upper angle of the tube not wetted by stratified liquid (radians)

Subscripts

ann	pertaining to the annular flow regime
h	homogeneous
int	pertaining to the intermittent flow regime
int + liq	pertaining to the intermittent and liquid flow regime
l	liquid
liq	pertaining to the liquid flow regime
sat	corresponding to saturation conditions
strat	pertaining to the stratified flow regime
v	vapor
vap	pertaining to the vapor flow regime
wall	at the wall

are found to improve predictions of traditional flow regime map based models in the flow regime transition regions. Consequently, probabilistic two-phase flow regime map modeling is a promising new modeling technique for condensation heat transfer and will allow pressure drop and void fraction to be modeled with the same flow regime based time fraction information.

2. Literature review

Numerous two-phase flow condensation models can be found in the literature, and most of these models can be categorized as stratified flow or annular flow models. The Chato [3] stratified flow model considers film condensation at the top of the tube and neglects the vapor shear driven condensation at the bottom of the tube because the bottom liquid layer is assumed to be thick. Jaster and Kosky [4] modified the Chato [3] model by introducing void fraction to account for liquid pool depth variation, but also neglects heat transfer in the liquid pool. This modification is reported by Dobson and Chato [5] to negatively effect the heat transfer predictions in the stratified flow regime. Rosson and Meyers [6] developed a model for condensation of acetone and methanol in the stratified and slug plug flow regimes which considered both film condensation and vapor shear driven condensation.

Annular flow heat transfer models can be further divided into two-phase multiplier based, shear based, and boundary layer based models. Two-phase multiplier models often resemble a modified Dittus–Boelter [7] relation such as the condensation models by Akers et al. [8], Shah [9], Cavallini and Zecchin [10], Bivens and Yokozeki [11], and Tang [12]. Shear based models were originally developed by Carpenter and Colburn [13] which was subsequently modified by Soliman et al. [14] who's model was then modified by Chen et al. [15]. Examples of boundary layer correlation based heat transfer models can be found in Traviss et al. [16], Cavallini and Zecchin [10] and Hurlburt and Newell [17]. All of the above models tend to predict heat transfer most accurately in the flow regime for which they were derived.

Recently, flow regime map based two-phase flow heat transfer models were developed in order to predict condensation heat transfer in multiple flow regimes. Haraguchi et al. [18] and Dobson and Chato [5] developed flow regime map based two-phase flow condensation heat