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Flow regime transitions during condensation in microchannels

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ABSTRACT

Heat transfer and pressure drop for two-phase flow inside tubes are closely related to the corresponding flow mechanisms. The flow patterns formed in microchannels during condensation differ from those observed in conventional tubes. Using an extensive R134a condensation flow-regime database ($1 < D_h < 4.91$ mm, $150 < G < 750$ kg m^{-2} s^{-1}), new flow regime transition criteria are proposed. The data are used to understand the physical mechanisms and the governing influences for each of the identified flow regimes and develop dimensionless transition criteria. These criteria can be utilized to identify the flow regimes and transitions for various fluids, operating conditions and channel sizes, thereby generalizing their applicability. This mechanistic determination of condensation flow regimes in different operating conditions and geometries will assist in the development of models for predicting condensation heat transfer and pressure drop, enabling the development of optimized microchannel heat exchangers.

Transition dans les régimes d'écoulement pendant la condensation dans des microcanaux

Mots clés : Ecoulement multiphasique ; Schéma de régime d'écoulement ; Condensation ; Visualisation de l'écoulement ; Microchannel Microcanaux

1. Introduction

In an effort to increase system efficiency and reduce system footprint and refrigerant inventory, microchannel condensers have become increasingly common in HVAC&R equipment. Condensers with circular and noncircular microchannel tubes are being used in applications ranging from automotive space-conditioning systems to mobile refrigerated transport. Optimal design of these condensers requires a detailed understanding of condensation heat transfer and pressure drop at small hydraulic diameters.

As condensation progresses, various flow regimes are observed resulting from the changes in the relative magnitudes of forces acting upon the two phases. Examples include

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Nomenclature

$\tilde{A}_G$	Dimensionless vapor area (–)
AF	Annular film (–)
Bo	Bond number (–)
D	Diameter (m)
D	Dispersed (–)
$\tilde{D}_L$	Dimensionless liquid diameter (–)
DcW	Discrete wave (–)
DpW	Disperse wave (–)
Fr_{mod}	Modified Froude number (–), Eq. (10)
G	Mass flux (kg m^{-2} s^{-1})
g	Gravitational acceleration (m s^{-2})
h_G	Vapor height in Eq. (5) (m)
I/AF	Intermittent and annular film (–)
I/DcW	Intermittent and discrete waves (–)
M	Mist (–)
$\tilde{S}_i$	Dimensionless interface perimeter
T	Dimensionless dispersed transition parameter
U	Superficial velocity (m s^{-1})
$\tilde{u}_L$	Dimensionless liquid velocity (–)
v	Liquid volume (m^3)
We_G	Vapor-phase Weber number (–)
x	Vapor quality (–)
X_{tt}	Turbulent–turbulent Martinelli parameter (–)
$X_{tt,mod}$	Modified Martinelli parameter (–), Eq. (2)
y	Bubble radius in Eq. (5)
$X_{tt,slug}$	Slug Martinelli parameter (–), Eqs. (8)–(9)

Greek Letters

α	Aspect ratio (–)
ρ	Density (kg m^{-3})
σ	Surface tension (N m^{-1})
μ	Dynamic viscosity (kg m^{-1} s^{-1})

Subscripts

G	Gas phase
L	Liquid phase
h	Hydraulic diameter

gravity-dominated regimes (e.g. stratified, wavy) and shear-dominated (e.g. annular) regimes. In larger diameter tubes, it has been shown that the heat transfer and pressure drop mechanisms in condensing flows are different in each flow regime. Thus, an understanding of the occurrence of, and transition between, different flow regimes as a function of fluid properties, tube size and vapor quality is necessary to accurately model condensation heat transfer and pressure drop.

Early two-phase flow regime studies generally focused on larger diameter tubes ($D_h > 5$ mm) and adiabatic air–water mixtures. Baker (1954) developed the first generalized flow pattern map based on the air–water and air-oil data of Jenkins (1947), Alves (1954), and others. The map defined transitions between stratified, slug, plug, dispersed, bubble and wavy flow with property corrected gas and liquid mass velocities as the coordinate axes. Mandhane et al. (1974) combined data and the flow maps of Baker (1954), Hoogendoorn (1959) and Govier and Omer (1962) into a new flow map which defined flow regime transitions using superficial vapor and liquid velocities as the coordinate axes and physical property correction factors for different fluids. Up to this point, the effects of tube diameter on flow regime extent and transition were not explicitly addressed by these models. Taitel and Dukler (1976) developed one of the most widely used flow regime transition models based on physical considerations rather than empirical data. A set of five dimensionless parameters that addressed the effects of tube diameter, buoyancy forces and Kelvin-Helmholtz wave instabilities demarcated the transitions between flow regimes. Good agreement was found between the theoretically derived map and the empirically based Mandhane et al. (1974) flow map; however, the effects of surface tension forces were not considered in the transition criteria.

Griffith and Lee (1964) conducted one of the earliest studies on two-phase flow regime mapping in small diameter channels ($D_h = 1$ mm) with an air–water mixture. Focusing on the annular-to-slug transition, they proposed that surface tension forces at the liquid–vapor interface pull interfacial liquid waves in the annulus towards the center of the tube which eventually block the passage, thereby forming slugs. The critical wavelength for the annulus to be unstable was found based on the instability analysis of Rayleigh (1892). The effect of surface tension on slug formation in small tube diameters for the stratified-to-slug transition was observed by Barnea et al. (1983). They proposed a modification to the Taitel and Dukler (1976) map to account for a balance between surface tension and gravitational forces in the stratified-to-slug transition. Coleman and Garimella (1999) investigated circular and rectangular tubes ($1.3 < D_h < 5.5$ mm) using air–water mixtures. Observed mechanisms were categorized into four major flow regimes: stratified (stratified smooth and stratified wavy), intermittent (elongated bubble and slug), annular (annular-wavy and annular) and dispersed (bubble and dispersed). By comparing their data with predictions of flow maps for small (Damianides and Westwater, 1988; Fukano et al., 1993) and large (Taitel and Dukler, 1976; Weisman et al., 1979), tubes, they concluded that maps developed for large diameter tubes ($D_h > 10$ mm) could not be extended to small diameter channels. A new flow regime map based on superficial liquid and vapor velocities as the coordinate axes was proposed; however, the effects of different fluid properties on transitions were not considered. Other adiabatic small diameter channel studies, including air–water flow in circular and semi-triangular channels by Triplett et al. (1999) and two-phase R134a flow in circular channels by Yang and Shieh (2001), resulted in flow regime maps with transition criteria using superficial liquid and vapor velocities as the co-ordinate axes, limiting wider applicability.

Relatively fewer studies have been conducted to understand two-phase flow regimes during condensation. The physical properties of refrigerants, especially the ratio of