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Theoretical model of linear instability for condensation flow in circular channels

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ABSTRACT

The paper presents a theoretical model for liquid-vapor interface instabilities for R134a condensation flow in tubes. The model is based on linear Kelvin-Helmholtz instability and capillary instability theories that neglect the effect of gravity and take into account the surface tension and shear stress effects. The normal mode method was used to analyze the system instability reactions to various perturbation wave lengths and physical conditions. Three modes were obtained with one giving the greatest instability wave length for each condition. The cooling temperature had little effect on the greatest instability. The greatest instability wave length increased with decreasing R134a mass flux and quality, with jumps between two instability states. This instability state transition can be used to predict condensation flow regime transitions for intermittent flow. The dimensionless intermittent flow criterion is in good agreement with available experimental data in the literature.

1. Introduction

Condensation flows in channels are encountered in many applications, such as in fuel cells, aerospace systems and refrigeration systems. The first step in understanding condensation flows in channels is to characterize the flow regimes. As an important flow regime, wavy flow exists during condensation flow in channels with hydraulic diameters smaller than 1 mm. According to the previous experimental investigation conducted by Coleman and Garimella [1,2], discrete and disperse wavy flow regimes dominate condensation flows of R134a over a large range of qualities in channels with hydraulic diameters of 1.0–4.91 mm. Médéric et al. [3] experimentally studied the condensation flow characteristics of n-pentane in single glass tubes with inner diameters of 10, 1.1 and 0.56 mm. Wavy flow appeared in three tubes with different diameters. Quan et al. [4] observed wavy annular flow in steam condensation flows in a trapezoidal channel with a hydraulic diameter of 128 μm. They provided a flow pattern map for smooth annular flow and wavy annular flow. Fang et al. [5] used optical interferometry to measure the liquid film thickness of steam condensation flows in a rectangular channel with a hydraulic diameter of 285.7 μm. They observed a wave-like instability with amplitudes on the order of a few microns on the liquid–vapor interface during annular flow. Kim et al. [6] experimentally investigated condensation of FC-72 in parallel, square micro-channels with a hydraulic diameter of 1 mm and a length of 29.9 cm. Five distinct flow regimes were identified with the smooth-annular and wavy-annular regimes being the most prevalent. These wavy flows result from the liquid-vapor interface instability. Therefore, the flow instability mechanisms on the liquid-vapor interface need to be understood to characterize the flow patterns for condensation flows in channels.

Flow instability theory can also be used to describe the formation of intermittent flow. Barnea et al. [7] attributed the transition from stratified flow to intermittent flow to the Kelvin-Helmholtz instability in large channels. They also claimed that capillary forces cause the transition to intermittent flow in small tubes with wetting liquids. Damianides and Westwater [8] found that the Kelvin-Helmholtz instability could not be used to predict the onset of slugging. Wang et al. [9] observed three annular-to-intermittent transition forms during condensation flow in microchannels and claimed that one of them was caused by wave growth due to flow instabilities.

The effect of heat and mass transfer on the two-phase interface stability has been studied by researchers. Hsieh [10,11] calculated the Rayleigh-Taylor and Kelvin-Helmholtz stabilities of the interface between two inviscid fluids with mass and heat transfer. He noted that the mass and heat transfer tends to enhance the system stability when the vapor is hotter than the liquid for the Rayleigh-

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Nomenclature

a'	ratio of the local condensation mass flow rate to the vapor mass flux rebounding from the interface
b	real part of eigenvalue n (1/s)
c	perturbation growth rate (1/s)
d	channel diameter (m)
$\mathbf{D}$	differential operator $\mathbf{D} \equiv \frac{\partial^2}{\partial r^2} - \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$
f	friction factor
G	refrigerant mass flux (kg/(m^2 s))
i	imaginary unit number
I	modified Bessel function of the first kind
k	wave number (1/m)
K	modified Bessel function of the second kind
L	latent heat (J/kg)
m''	mass flux at the liquid-vapor interface due to condensation (kg/(m^2 s))
Ma	Mach number
n	eigenvalue from the normal modes method (1/s)
p	pressure (Pa)
p_d	disjoining pressure (Pa)
Q	heat flow rate through a given cross section due to phase change (W)
r	radius (m)
Re	axial vapor Reynolds number
R_g	ideal gas constant (J/(kg K))
Re_r	radial vapor Reynolds number
t	time (s)
T	temperature (°C)
u	radial velocity (m/s)
$u_{v,i}$	vapor suction velocity at the liquid-vapor interface due to condensation (m/s)
u'	radial perturbation velocity (m/s)
U_v	superficial velocity (m/s)
w	axial velocity (m/s)
w'	axial perturbation velocity (m/s)
We	Weber number
x	quality
X_{tt}	Martinelli parameter
z	axial position (m)
Z	vapor compressibility factor

Greek symbols

β_v	constant used to calculate the vapor pressure drop
γ	specific heat ratio
ζ	displacement in the radial direction of a particle on the interface (m)
κ	thermal conductivity (W/(m K))
λ	wave length (m)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ξ	constant used to calculate the interfacial thermal resistance
ρ	density (kg/m^3)
σ	surface tension (N/m)
ς	liquid-vapor interfacial thermal resistance (m^2 K/W)
τ	shear stress (Pa)
ϕ_j	amplitude of the Stokes current function perturbation (m^3/s)
ψ	Stokes stream function of a perturbation (m^3/s)

Subscripts

0	equilibrium condition
a	amplitude
i	liquid-vapor interface
in	channel inlet
j	l or v
l	liquid
max	maximum
sat	saturation
$tran$	transition
v	vapor
w	channel wall

Taylor stability. Nayak and Chakraborty [12] studied the Kelvin-Helmholtz stability of a cylindrical interface between the vapor and liquid phases of an inviscid fluid in the presence of heat and mass transfer. They concluded that the heat and mass transfer have a destabilizing influence in the Kelvin-Helmholtz instability. They also claimed that axisymmetric and asymmetric disturbances have similar effects on the Kelvin-Helmholtz instability in the cylindrical geometry. Elhefnawy and Moatimid [13] analyzed the effect of an axial electric field on the Kelvin-Helmholtz instability of a cylindrical interface between two inviscid, incompressible fluids in the presence of heat and mass transfer without gravity. Their results indicated that the instability criterion of the system is independent of the heat and mass transfer coefficients but differs from that in the same problem without heat and mass transfer. Lee [14,15] studied nonlinear Kelvin-Helmholtz stabilities for planes and cylindrical interfaces between the vapor and liquid phases of an inviscid, incompressible fluid. He used multiple time expansions to deal with the nonlinear problem and found that the heat and mass transfer plays an important role in this nonlinear stability analysis. Adham-Khodaparast et al. [16] presented linear Rayleigh-Taylor and Kelvin-Helmholtz stability analyses of a plane liquid-vapor interface with an adverse gravitational field with heat and mass transfer. When analyzing the Kelvin-Helmholtz stability, they modeled the liquid as viscous with the motionless and vapor as inviscid flow with a horizontal velocity.

Interface instabilities during two-phase flow in tubes have been analyzed by some researchers. Liquid-vapor interface instabilities of condensate films in small-diameter thermosyphons was analyzed by Teng et al. [17] by neglecting the effect of the mass transfer and shear stress on the vapor-liquid interface. The assumptions may be acceptable for thermosyphon two-phase flows due to their low vapor velocities but are not appropriate for convective condensation in heat exchangers. Guo et al. [18] conducted linear and non-linear analyses of interface instabilities in incompressible gas-liquid two-phase flows through a circular pipe. They proposed a one-dimensional model that did not include the effects of heat and mass transfer. They concluded that the phase velocity destabilized and the surface tension stabilized the system. Kuczyński et al. [19] experimentally studied the influence of artificial flow instabilities on R134a and R404A condensation heat transfer coefficients. Kuczyński [20,21] then used a one-dimensional pressure wave propagation model to predict their experimental data with different instability frequencies and flow regimes.

As a conclusion, the role of liquid-vapor interface instability during condensation flow regime transition in channels is still unclear. This paper addresses these deficiencies in the literature by proposing a theoretical model of liquid-vapor interface instabilities for refrigerant R134a condensation flow in a circular channel without the effect of gravity. First, stable annular condensation flow of R134a is modeled assuming steady laminar flow. Then,