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Onset of flow reversal in upflow condensation in an inclinable tube

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ABSTRACT

This work performs an experimental analysis of the onset of flow reversal in upflow condensation of refrigerant 134a in an inclinable 5-mm diameter tube. As the upward unidirectional annular flow regime is established, solitary waves are generated on the liquid substrate and are initially carried upwards by the vapor. With an increase in the condensate flow rate, the liquid film grows thicker and more disturbed, leading to a wider range of film flow structures as well as oscillatory changes in the liquid velocity. These changes mark the onset of flow reversal in the liquid film and the subsequent transition to churn flow. Image processing techniques have been applied to high-speed video sequences of the two-phase flow to identify the onset of film flow reversal and properties of the interfacial waves. A film structure characterized by the existence of the so-called primary and secondary waves was observed to exist near the region of transition to bidirectional flow. Spatio-temporal maps of the liquid film thickness have been generated aiming to quantify the influence of the operating conditions on the wave behavior. Adaptations of existing correlations for the critical vapor velocity associated with the point of flow reversal and wave frequency (Strouhal number) have been proposed.

1. Introduction

The point of flow reversal in upward two-phase flow is defined as the condition at which the momentum flux of the vapor phase is no longer capable of lifting the entire liquid phase up the channel. As a result, part of the liquid starts to flow downward and liquid flow velocity oscillations are observed. In the large diameter tubes where droplet entrainment was observed to be significant, flow reversals initially took place in the liquid film [1] and were characterized by regions of falling liquid film between large upward moving waves [2]. The point of flow reversal has been associated with the point of minimum pressure drop in upward gas–liquid flow, and has been used as a criterion to correlate the transition from annular flow to churn flow in terms of the superficial gas velocity [3].

In gas–liquid flows, the term *flooding* is used to describe the transition from a falling film flow to a bidirectional (upward and downward) flow, following an increase in gas velocity. In reflux condensation, flooding is said to occur when the condensate flow moves from a gravity-controlled regime to a shear-controlled regime [4]. As the upward gas velocity is further increased, the downward liquid flow rate is reduced until the liquid is totally carried upward. This condition is also known as the zero penetration limit [5]. Hysteresis effects associated with the onset of flooding for increasing and decreasing gas flow rates have been discussed in Refs. [6,7].

Numerous correlations have been proposed for the critical gas velocity associated with flooding in vertical and inclined pipes. The correlation due to Wallis [3] is given by:

$$(J_G^*)^{1/2} + m_1 (J_L^*)^{1/2} = C_1 \tag{1}$$

where J_k^* is a densimetric Froude number of phase k defined as:

$$J_k^* = J_k \left[\frac{\rho_k}{(\rho_L - \rho_G) g D} \right]^{1/2} \tag{2}$$

where m_1 and C_1 are empirical constants that depend on the test section geometry and flow inlet conditions. Typical values of m_1 and C_1 range from 0.5 to 1.0 and 0.7 to 1.0, respectively [6,7].

The Tien–Kutateladze correlation [8,9] is based on the Kutateladze numbers for each phase in the following form:

$$(Ku_G)^{1/2} + m_2 (Ku_L)^{1/2} = C_2 \tag{3}$$

where Ku_k is defined in terms of the Laplace length scale as follows:

$$Ku_k = J_k \left[\frac{\rho_k^2}{(\rho_L - \rho_G) g \sigma} \right]^{1/4} \tag{4}$$

where $m_2 \approx 1$ and $C_2 \approx 1.7 - 2$ are empirical constants [10].

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Nomenclature

Roman

A	empirical constant in the Strouhal number correlation [–]
B	empirical constant in the Strouhal number correlation [–]
c_p	specific heat capacity at constant pressure [J/kg K]
C_1	empirical constant in the Wallis correlation [–]
C_2	empirical constant in the Tien–Kutateladze correlation [–]
D	tube diameter [m]
f	frequency [Hz]
g	acceleration of gravity [m/s^2]
h_{LG}	enthalpy of vaporization [J/kg]
J_k	superficial velocity of phase k [m/s]
J_k^*	densimetric Froude number of phase k [–]
Ku_k	Kutateladze number of phase k [–]
$\dot{m}$	mass flow rate [kg/s]
m_1	empirical constant in the Wallis correlation [–]
m_2	empirical constant in the Tien–Kutateladze correlation [–]
P	pressure [Pa]
$\dot{Q}$	heat transfer rate [W]
Re_k	Reynolds number of phase k [–]
St_k	Strouhal number of phase k [–]
T	temperature [°C, K]
x	vapor quality [–]

Greek

θ	inclination with the horizontal [°]
ν	kinematic viscosity [m^2/s]
ρ_k	mass density of phase k [kg/m^3]
σ	surface tension [N/m]

Subscripts

cond	condensation
G	gas phase
i	inlet
L	liquid phase
o	outlet
r	refrigerant
s	secondary fluid (glycol solution)
sat	saturation

Eqs. (1) and (3) can be used to predict the total carry-up (zero penetration) limit by setting the superficial liquid velocity terms to zero. The expression resulting from the Wallis correlation, $J_G^* = C_1^2$, suggests that the critical superficial gas velocity at the point of flow reversal is proportional to the square root of the tube diameter. The Tien–Kutateladze correlation, on the other hand, suggests that the critical gas velocity is independent of the tube diameter. The data of Pushkina and Sorokin [11] for the zero penetration limit were correlated with $Ku_G \approx 3.2$. The classical Turner correlation [12] for the onset of liquid loading in gas wells suggests a critical Ku_G of approximately 3.67.

The apparent contradiction between the Wallis and Tien–Kutateladze correlations as regards the dependence of the critical superficial gas velocity on the tube diameter has been settled by Richter [13], who found that the critical gas velocity was independent of the tube diameter only for large values of D (larger than 0.1 m). According to Hewitt [14,15], for small diameter tubes (less than 0.05 m in diameter) with smooth liquid inlets and outlets (e.g., a porous wall segment), flooding is initiated by a large coherent wave formed at the liquid outlet. For larger tubes, the waves formed are not coherent and the earliest mechanism of liquid transport is droplet entrainment from the tips of the waves. A number of empirical and semi-empirical flooding correlations have been presented for isothermal flows, which take into account the effects of channel geometry, inclination and physical properties [16–21]. Comprehensive reviews have been presented in Refs. [10,22,23].

Few authors investigated flooding and flow reversal phenomena in condensing refrigerants. In small capacity refrigeration systems, the use of oil-free compressors creates new options for how the system components can be positioned relative to each other in the refrigerator. Oil-free compressors no longer need to be at the lowest position in the cooling circuit because oil return to the sump is no longer a design constraint. Nevertheless, although there is more freedom to position the heat exchangers relative to the compressor, some system configurations are more desirable than others to avoid condensate flow reversal in the condensing line.

Some fundamental differences can be identified when comparing studies of flooding and flow reversal of condensing substances and adiabatic flows of a liquid and a non-condensable gas: (i) the ratio of the liquid and vapor densities of condensing refrigerants is generally between 30 and 40, while the density ratio in water–air systems near the atmospheric pressure is of the order of 1000; (ii) in experiments without phase change, the liquid phase is injected and/or removed at specific points along the tube via small orifices or sintered segments of the tube. During condensation, the liquid phase is formed continuously along the tube. If the tube is inclined, then the condensation rate is not circumferentially uniform; (iii) in order to identify the points of flooding and flow reversal in experiments without condensation, the phase flow rates are independently controlled. Usually, the liquid flow rate is kept fixed, while the gas flow rate is slowly increased or decreased. In upflow condensation experiments, the total mass flow rate is constant and vapor mass quality decreases along the test section. As a result, different flow regimes may exist simultaneously along the tube.

Fiedler and co-workers [24–27] investigated flooding phenomena during reflux condensation of R-134a in vertical and inclined tubes (7-mm ID, 500-mm long). The flooding point was identified through a combination of ultrasound measurements and flow visualization at the outlet of the test section. A specially-designed test section enabled measurements of the flow rate of condensate collected at the bottom. The optimum inclination angle corresponding to the maximum flooding velocity was between 45° and 60° from the horizontal. A mathematical model was proposed to determine the flooding velocity. Park and Mudawar [28] studied upflow condensation of FC-72 in a 1.22-m long 10.16-mm ID vertical tube. High-speed video sequences were acquired to investigate the condensation flow regimes and local heat transfer coefficients were determined for the various flow regimes. The onset of film flow reversal was correlated using the Wallis flooding relationship [3].

As mentioned above, flooding and flow reversal are intimately related to the formation and propagation of waves in the liquid film. Waves in annular flow can be divided into two categories, (i) ripples and (ii) solitary waves. In the classical description [29],