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Prediction of the onset of flooding in an inclined tube at cryogenic temperatures

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ABSTRACT

Prediction of the onset of flooding in the cryogenic temperatures still primarily relies on the empiricism and semi-empirical correlations obtained from the room temperature fluids due to the lack of cryogenic experimental data. In order to probe the mechanism of flooding for cryogenic fluids, this study aims to predict the onset of flooding of liquid nitrogen and its vapor in an inclined tube. A theoretical model for the critical relative velocity of the interfacial instability was derived based on the linear stability analysis, in which the pressure disturbances in both directions are taken into account. The model solution was extended to obtain a correlation to predict the onset of flooding by assuming the disturbed wave length proportional to the unperturbed liquid film thickness. A visualization experimental facility for flooding using liquid nitrogen and its vapor was built to validate the feasibility of the correlation. Some distinctive phenomena for cryogenic flooding, such as mist flow and the much lower flooding velocities, were observed, which are different from the room temperature fluids. The comparisons of flooding velocity between the calculations and the experiments show that the proposed correlation agrees well with the data for both room-temperature and cryogenics.

1. Introduction

Flooding phenomena are great concerns for the engineers in the design of the compact heat exchangers, the distillation column in chemical industry, and the emergency cooling system in the nuclear reaction engineering. The occurrence of flooding is usually undesired since the heat and mass transfer will be suspended while the pressure drop increases abruptly [1]. For example, flooding is the major limiting factor for the operating capacity of a structured packing column in the cryogenic air separation system, which is comprised of many identical element of structured packing. Each element is made up of an ensemble consisting of a large number of triangular channels having identical cross-sections, where liquid flows down due to gravity and gas flows up in the left space. Counter-current two-phase flow in tubes is considered an essential element of the complicated flow field of a structured packing column [2,3]. The present study improves the physical understanding of the compact reflux type contactor of corrugated plates.

Researchers have paid much attention on the mechanisms of the flooding in a vertical tube characterized by the symmetric flow, and great progresses have been made both in numerical modeling [4,5] and experimental measurements [2,4,6–8]. Besides, several theoretical prediction of the onset of flooding in a vertical tube have also been developed, which can be mainly categorized into three groups: (a) the drop dynamics models [9], which bases on the assumption that flooding occurs when the gravity force exerted on a liquid droplet is in a balance with the drag force by gas flow; (b) the liquid film dynamics model [10], which considers the flooding to occur when the net liquid flow rate becomes zero; (c) the wave dynamic model [11], which recognizes that the flooding originates from the interfacial instability. The classical linear stability analysis, belonging to the wave dynamic model, is the well accepted one to predict the interfacial instability associated with the gas–liquid flow [12,13]. Different from the vertical tubes, the horizontal condition is the other special case. The interfacial instability is calculated by the linear stability analysis usually based on the one-dimensional assumption, in which the cross-section averaged velocities for both phases are used in the mass and momentum conservative equations [14–16]. However, for the cases with large inclinations, the two-dimensional approach should be applied. A well-known statement was given by Squire [17] that for the problem of disturbed flow between parallel planes, two dimensional waves have a greater tendency to instability than three dimensional ones. And it follows that a two dimensional analysis is adequate if only the stability of a flow is in question. Carey [18] described the behavior of gas and liquid interface in a

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Abbreviations: LN_2, liquid nitrogen; VN_2, nitrogen vapor.

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Nomenclature

A	amplitude of perturbation, m
F	phase fraction
L	tube length, m
q	volume flow rate of liquid, m^3/s
R	radius of the tube, m
t	time, s
U	superficial velocity, m/s
D	diameter of the tube, m
H	thickness of liquid film, m
p	pressure, Pa
r	curvature radius, m
S	flow area, m^2
u	velocity, m/s

Greek letters

α	interfacial wave number
λ	wavelength, m
ρ	density, kg/m^3
φ	tube inclination to the horizon, degree
θ	circumferential angle, degree
μ	dynamic viscosity, Pa s
σ	surface tension, N/m
Θ	maximum circumferential angle, degree

Subscripts

0	initial value
i	interfacial value
l	liquid phase
z	axial direction
g	gas phase
m	average value
y	radial direction

stratified flow, while the depths of fluid layers are considered as "infinite" for simplicity. In the work of Chen [19] and Funada [20], although the tube walls were considered as the boundary for both phases, the pressure fluctuations normal to the interface, which is a source to induce the interfacial instability, are ignored. Different from the theoretical analysis, the experimental studies on flooding in an inclined tube at room temperatures have been widely reported. The flow rates of liquid and gas and the pressure drops are measured to validate the correlations [3,7–8,21–25].

There are few experimental researches on flooding at cryogenic temperatures at present, and the correlations obtained from the experimental data at room temperature are generally used in the cryogenic cases [26]. Table 1 lists the comparison of physical properties for the water/air pair and the cryogenic pair: liquid nitrogen (LN_2) and its vapor (VN_2). It can be identified that the density ratio of water to air is 831.6, almost fivefold larger than that of 177 for LN_2/VN_2, while the surface tension and viscosities of water/air is one order of magnitude larger than that of LN_2/VN_2. Therefore, are the existing correlations for room temperature applicable to the cryogenic fluids?

This study aims to predict the onset of flooding in an inclined tube, in particular for the cryogenic fluids. Firstly, the two-dimensional approach of the linear stability analysis is used to develop an expression for the critical relative velocity of the interfacial instability, in which the pressure disturbances in both directions are taken into account. Then, the method similar to Imura et al. [27] is adopted, combined with the above instability criterion, to predict the onset of flooding. An experimental setup with LN_2/VN_2 as the working media was built to validate the correlation. It is found that the calculated critical velocities for the onset of flooding agree well with the room-temperature data in the literatures and the cryogenic data obtained in this study.

2. Theoretical model

The schematic for gas/liquid countercurrent flow in an inclined tube is shown in Fig. 1, where φ is the inclination, h_0 indicates the unperturbed thickness of the liquid film, and h is the instantaneous one. The liquid flows down along the lower wall of the tube with the radius of R, while the gas flows counter-currently. Fig. 1(a) is the simplified circumferential cross section (z, y) that represented by the dash line in Fig. 1(b).

A significant experimental observation is the fact that the mean film thickness remains essentially unaffected by the countercurrent gas flow almost up to the critical flooding conditions [2–3], therefore, the shear stresses in the interface are ignored. Assuming the pressure disturbances in both directions as sinusoidal forms, and following the general process of linear instability analysis (see the appendix for details), yielding the differential equation for the perturbation pressure:

$$\frac{d^2\hat{p}_{g/l}}{dy^2} = \alpha^2 \hat{p}_{g/l} \tag{1}$$

Then the wall effects on the pressure disturbance are considered as the boundary conditions. The following expression can be deduced:

$$\beta = -i\alpha\frac{\rho_l P\bar{u}_{z,l} - \rho_g Q\bar{u}_{z,g}}{\rho_l P - \rho_g Q} \pm \frac{\alpha\sqrt{-\rho_l\rho_g PQ(\bar{u}_{z,l} + \bar{u}_{z,g})^2 + \frac{M}{\alpha}(\rho_l P - \rho_g Q)}}{\rho_l P - \rho_g Q} \tag{2}$$

$$\text{in which} \quad P = \frac{1 + e^{2\alpha h_0}}{1 - e^{2\alpha h_0}}, Q = \frac{1 + e^{-2\alpha(D-h_0)}}{1 - e^{-2\alpha(D-h_0)}},$$
$$M = (\rho_l - \rho_g)g\cos\varphi + \sigma\alpha^2 \tag{3}$$

P and Q in Eq. (3) are dimensionless quantities. The detailed calculation process is shown in the appendix.

The value of P is always negative, implying that β has an imaginary part. It means any velocity component parallel to the surface in either fluid will produce waves at the interface. Making the inclination equal to 0°, Eq. (2) is similar as the solution of Carey [18] for the horizontal case, while the difference comes from the different boundary conditions applied to the pressure perturbation. The amplitude of the perturbation will grow with time if β has a positive real part by referring to Eq. (A.11). This can be reached only if the sum of the two terms inside the radical sign is greater than zero. As the second term is negative and diminishes the sum, the surface tension and gravity always tend to stabilize the interface.

Table 1
Thermodynamic properties of working pairs.

Working pair	T (K)	ρ_l (kg/m^3)	ρ_g (kg/m^3)	σ (N/m)	μ_l (Pa s)
Water–air	300	998	1.2	0.072	0.001
LN_2–VN_2	77	806.59	4.56	0.0089	0.00016