Computers & Fluids 108 (2015) 43–56

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Effect of gravity levels on the flow pattern modulation by the phase separation concept

Dongliang Sun [a,b], Jinliang Xu [b,*], Yanning Wang [b], Jian Xie [b], Feng Xing [b]

[a] School of Mechanical Engineering, Beijing Institute of Petrochemical Technology, Beijing 102617, China
[b] The Beijing Key Laboratory of Multiphase Flow and Heat Transfer, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Article history:
Received 11 December 2013
Received in revised form 23 November 2014
Accepted 25 November 2014
Available online 4 December 2014

Keywords:
Phase separation concept
Liquid film
Mesh cylinder
Two-phase flow
Heat transfer

ABSTRACT

Suspending a mesh cylinder in a tube modulates flow patterns with gas bubbles in the annular region to form thin liquid film on the wall. We investigate the effect of gravity levels on the modulated flow patterns. The volume of fluid (VOF) method simulates the slug bubble train flow in bare tube and modulated flow sections. The bubble population density along the flow direction (β) and averaged liquid film thickness (δ_α) synthesize a parameter β/δ_a to characterize the enhancement of phase change heat transfer. It is found that at the normal gravity on earth, counter-flow appears with fast upward flow in the annular region and downward liquid flow in the core region. A lower β due to sparsely populated bubbles and thin liquid film form a larger β/δ_a to enhance the phase change heat transfer. Convective heat transfer in liquid plugs is enhanced by the fast fluid movement in the annular region and liquid circulations at three length scales. At the miniature gravity, quasi-co-current flow happens with upward flows in both annular region and core region, except that a liquid layer inside mesh cylinder flows downward. Bubbles are more densely populated than those at the normal gravity. Liquid circulation occurs only at the bubble length scale. At the micro gravity, the two-phases are thoroughly separated with co-current flows in both annular region and core region. Gas flows slowly and the residence time of gas is increased to result in $\beta = 1$. The liquid film is ultra-thin. These two factors create a significantly large β/δ_a to enhance the phase change heat transfer. We demonstrate the effectiveness of the phase separation concept at miniature and micro gravity environment.

1. Introduction

The condenser tubes have wide applications at various gravity levels. At normal earth gravity, condensers have wide applications in various industry sectors. For example, a condenser is a key component to cool the organic fluid vapor into liquid in an Organic Rankine Cycle [1]. Sometimes the in-tube condensation heat transfer coefficients are even smaller than those at the outside tube side [2]. New concept and device should be developed. The condensation heat transfer at micro gravity is a challenging issue. The liquid film is significantly thicker at micro gravity than those at normal earth gravity. Fig. 1 shows the liquid film distribution over the tube cross section at normal earth gravity (horizontal flow) and at micro gravity. Due to the negligible buoyancy force between liquid and gas phases at micro gravity, liquid films are uniformly distributed on the wall and they are thick, introducing a large liquid thermal resistance. Delil [3] computed the ammonia vapor condensation heat transfer in a 16.1 mm diameter tube at normal earth gravity and micro gravity. The flow direction was downward. It was found that the condenser length at zero gravity was eleven times of that at normal earth gravity. Da Riva and Sanz [4] performed the numerical simulations of condensation heat transfer in horizontal tubes with different working fluids. They pointed out that the condensation lengths at zero gravity are 28, 19, 15 and 18 times of those at normal earth gravity for ammonia vapor, water vapor, R11 vapor and R22 vapor, respectively. In summary, the tube length required to achieve complete condensation at the micro gravity is an order of magnitude larger than that at normal earth gravity.

Conventionally, microstructures fabricated at the wall surface are adopted to enhance condensation heat transfer. Micro groove tubes [5], micro-fin tubes [6], herringbone tubes [7] and helically corrugated tubes [8] belong to the enhanced condensation tubes. The heat transfer enhancement mechanism is attributed by mixing the fluid boundary layers and limiting the growth of fluid boundary layers close to the wall surfaces. The phase distribution does not coordinate with the heat transfer in conventional tubes.

* Corresponding author. Tel.: +86 10 61772268.
E-mail address: xjl@ncepu.edu.cn (J. Xu).

http://dx.doi.org/10.1016/j.compfluid.2014.11.028
0045-7930/

Recently, a phase separation condenser tube was proposed by our group to modulate the flow pattern, as shown in Fig. 2a. The phase separation condenser tube serves to create thin liquid film on the wall to enhance the condensation heat transfer. The configuration consists of a bare tube section (region 1) and a modulated flow section (including a core region 2 and an annular region 3). Regions 2 and 3 are interfaced by a mesh cylinder. Single-phase gas or liquid can pass through the mesh pores freely. But the mesh screen surface blocks any intermittent (plug, slug or bubble) gas–liquid interface, leaving gas phase flowing in the annular region to form thin liquid film on the wall. The mesh cylinder includes a flat bottom mesh surface and a circular side mesh surface. The mesh cylinder exit is open to discharge the separated liquid. Inside of the mesh cylinder is empty. The phase separation condenser tube works under the forced convective condition. The slightly superheated or saturation vapor enters the tube inlet. Heat is dissipated via the cooling on the outside wall.

The flow pattern modulation processes in the phase separation condenser tube at normal earth gravity have been studied by the experimental and numerical methods [9,10]. The objective of this study is to explore the possibility that the phase separation concept can be used at reduced and micro gravity levels. In order to do so, we investigate the forced convective adiabatic air–water slug flows in the vertical phase separation condenser tube at three gravity levels: $g = g_0 = 9.81$ m/s^2 (normal earth gravity), $g = 10^{-1}g_0$ (miniature gravity) and $g = 10^{-3}g_0$ (micro gravity). The forced convective adiabatic air–water slug flows are consecutively flowing in the bare tube section and modulated flow section. Thus the modulated flow parameters can be compared with those in the bare tube section with effect of gravity levels.

2. The physical problem

2.1. The basic working principle

Either single-phase liquid or gas can pass through the mesh pores freely driven by the pressure gradient. However, when an intermittent bubble interface interacts with the mesh cylinder, bubbles are difficult to enter the mesh cylinder (core region), leaving gas bubbles flowing in the annular region to yield thin liquid films on the wall. Gravity levels influence the buoyancy force caused by the density difference of liquid and gas, changing the modulated flow parameters and structures. But the gas bubbles always stay in the annular region.

Chen et al. [9] performed the surface energy analysis to explain why bubbles are difficult to enter the core region. Considering that a large bubble with its diameter identical to the condenser tube is penetrating a square mesh pore (see Fig. 3), the surface energy of the gas bubble between state *A* (initial state) and *B* (ending state) is

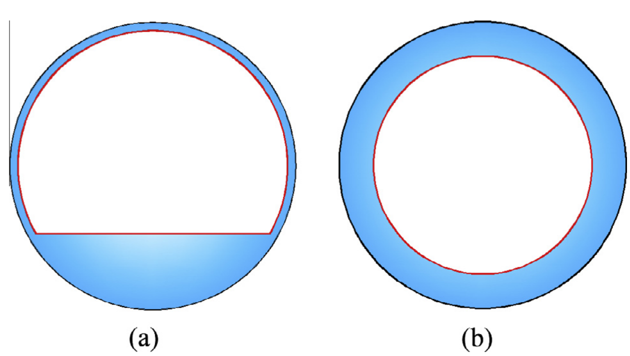

Fig. 1. The liquid film distributions at the (a) earth gravity (horizontal position) and (b) micro gravity.

$$dE = 4\sigma w ds_2 - \sigma\pi D ds_1 \quad (1)$$

where E is the surface energy, σ is the surface tension, w is the square mesh pore width, D is the inner tube diameter, ds_1 is the moving distance from state *A* to *B* in the bare tube, ds_2 is that within mesh pores (see Fig. 3). Chen et al. [9] applied the gas bubble volume conservation principle between the two states of *A* and *B*, and assumed that the increased surface energy equals to the required work for the bubble moving from the state *A* to *B*. The final pressure difference between the two states is expressed as

$$p_1 - p_2 = 4\sigma\left(\frac{1}{w} - \frac{1}{D}\right) \quad (2)$$

where p_1 and p_2 are the gas bubble pressures at the state *A* and *B* respectively. Because $D \gg w$, the second term of the right side of Eq. (2) contributes less to the pressure difference. A pressure difference of 1.94 kPa is required to penetrate a bubble interface within mesh pores with $\sigma = 0.07275$ N/m and $w = 150$ μm at 20 °C. Alternatively, if a bubble in the annular region of the condenser tube is penetrating over a mesh pore, the pressure difference is [11]:

$$p_1 - p_2 = 4\sigma\left(\frac{1}{w} - \frac{1}{d_{an}}\right) \quad (3)$$

where d_{an} is the annular gap ($d_{an} = 2.67$ mm here), which is about eighteen times of w, p_1–p_2 is also on the order of 2 kPa. Usually, a large pressure difference is needed to penetrate a bubble interface within mesh pores. Examining Eqs. (2) and (3) identify that the pressure difference is inverse to the pore size. The smaller the mesh pores, the larger the pressure difference is, constructing the major mechanism for gas bubbles to flow in the annular region.

2.2. The 3D to 2D-axisymmetric conversion of mesh screen

Fig. 2b shows a practical mesh screen used in our experiment. The square mesh wire has a thickness of $\delta = 70$ μm. The square mesh pore has a width of $w = 150$ μm. The number of mesh pores attains 680,000 for a mesh cylinder with its diameter of 10.36 mm and length of 1000.0 mm. The number of grids is in the order of 100-million, requiring a very huge computation resource and it is impossible. It is necessary to perform the 3D to 2D-axisymmetric conversion for simplification purpose.

The 3D mesh screen can be converted into a 2D-axisymmetric stripe-type mesh screen, by replacing the square mesh thickness of δ and square mesh pore width of w (see Fig. 2b) with the stripe-type mesh thickness of δ' and stripe-type mesh gap of w' (see Fig. 2c). The following criteria should be satisfied:

The equal equivalent diameter criterion: The square mesh pore has an equivalent diameter of w, the stripe-type mesh pore has an equivalent diameter of $2w'$. The equal equivalent diameter criterion for both types of mesh pores yields $w' = 0.5w$.

The equal flow area criterion: The projective area of the total mesh pores (see Fig. 2b) should be equal to that shown in Fig. 2c. The equal flow area criterion gives $[w/(w+\delta)]^2 = w'/(w'+\delta')$. Thus we can obtain $\delta' = \delta + \delta^2/2w$.

The equal capillary pressure criterion: The capillary pressure influences the gas–liquid interface near mesh pores. Once the above equal equivalent diameter and flow area criteria are satisfied, the equal capillary pressure criterion is automatically satisfied. This is because the capillary pressure created by the square mesh pores is $\Delta p = 4\sigma\cos\theta/w$, which equals to $\Delta p = 2\sigma\cos\theta/w'$ for the stripe-type mesh pores, where θ is the contact angle.

The above deduction yields $w' = w/2 = 75$ μm, $\delta' = \delta + \delta^2/(2w) = 86$ μm. After the conversion, the number of stripe-type mesh pores is reduced to 6211 for a 1 m-long mesh cylinder. The detailed structure parameters of the phase separation condenser tube are shown in Table 1.