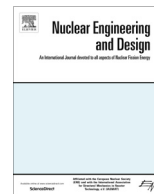




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Large Eddy & Interface Simulation (LEIS) of disturbance waves and heat transfer in annular flows

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HIGHLIGHTS

- A numerical strategy coupling the Large Eddy Simulation and the level-set method was proposed to handle the highly turbulent multiphase flow.
- The evolution of disturbance wave in vertical steam-water annulus was simulated.
- The influence of disturbance wave on heat transfer in annular flow was investigated.
- The inception criteria of disturbance wave were explored by adjusted the mass flux of saturated water inside the annulus system.

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ABSTRACT

A numerical method for forced convective boiling in an annulus needs to be developed in order to elucidate the reason for nucleation enhancement by disturbance waves. We first developed a numerical strategy to model the development of disturbance waves in annular flows where the highly turbulent gas core flow drives the laminar liquid flow upwards using advanced CFD tool TransAT. In which, the interface tracking method (e.g. Level-set) combined with a scale-resolving turbulence simulation technique (Large Eddy Simulation) was employed to capture dominant turbulence and interfacial scales. Then, the disturbance wave phenomenon in a vertical steam-water annulus system was investigated and analyzed. The finding reported in the present work provides insight into the evolution of disturbance wave and its influence on the heat transfer in annular flow. The modeling results revealed that locally hot 'spots' occurred upstream of disturbance wave. These locally overheated zones could play key roles in activating the nucleation boiling sites. In addition, the inception criteria of disturbance wave were explored by adjusting the mass flux of saturated water. And it was found no disturbance waves occurred at liquid film Reynolds number lower than the critical value, 225.

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1. Introduction

Annular two-phase gas-liquid (or vapor-liquid) flow occurs in a wide range of industrial equipment (boilers, condensers, pipelines, etc.) and is characterized by the presence of a thin, wavy liquid film driven along the wall by the shear force exerted by the gas (or vapor) phase in the core (Hall Taylor et al., 1963). The film/core interface is covered by a complex pattern of waves. These waves are typically of two main types, namely ripples which are of small amplitude and cover the whole film surface and disturbance waves. The disturbance waves have the amplitude of the order of 5–6 times the mean film thickness and travel along the interface at much higher velocity than do the ripples (Hewitt and Nichols,

1969). Calculation of the mean heat transfer coefficient in annular flow based on mean film thickness and mean interfacial shear stress gives rise to a gross over-prediction of the coefficient (Jayanti and Hewitt, 1997) and it is evident that the intermittent nature of annular flow (and in particular the influence of disturbance waves) needs to be taken into account. Moreover, the experiments observed that nucleate boiling occurred in the disturbance wave itself and was suppressed in the substrate regions (Barbosa et al., 2003). Possible explanations of this behavior include the following: Reduction of pressure in the wave region (Hewitt and Jayanti, 1996); Decrease of saturation temperature induced by pressure reduction (Hewitt et al., 1996); Bubble entrainment in waves (Cherdantsev et al., 2014). The aim of present work attempts to improve fundamental understanding of the evolution of disturbance wave and its influence on the heat transfer and nucleate

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boiling in a steam–water annular flow using Large Eddy & Interface Simulation (LEIS) method.

To this end, we have developed a numerical strategy to model the development of disturbance waves in annular flows where the highly turbulent gas core flow drives the laminar liquid flow upwards using CFD tool TransAT (TransAT, 2015). In which, the interface tracking method (e.g. Level-set) combined with a scale-resolving turbulence simulation technique (e.g. Large Eddy Simulation) was employed to capture dominant turbulence and interfacial scales. The method involves filtering continuity and Navier–Stokes equations *a priori* defined for the one-fluid formulation. And a direct phase change model was employed to predict the mass transfer rate of saturated water caused by the local temperature gradients. Then, the mass- and heat- transfer processes in the non-boiling annular flow was investigated to provide insight into the temperature gradient underneath the wave region. The modeling results are indicative and showing that disturbance waves trigger the locally overheated zones that could play key roles in activating the nucleation boiling sites. Furthermore, the characteristics of disturbance wave and its inception criteria have been studied and compared to those obtained from literature reports.

The rest of this paper is organized as follows. In Section 2, we present the details of our model. A discussion of our numerical results is provided in Section 3. Finally, Section 4 is devoted to concluding remarks.

2. Numerical experiment

2.1. Target experiment setup

The target experiment is a specially constructed annulus test section used to study the onset of nucleate boiling in upwards co-current annular flow (Barbosa et al., 2003). The schematic of the test section was briefly illustrated in Fig. 1. The main test section consists of a heated inner tube (outer diameter 19.05 mm), a concentric glass tube (inner diameter 32 mm) and a further glass tube (inner diameter 48 mm). The saturated water (temperature 373.15 K) is injected at the bottom end of the test section and flows as a film coating the inner tube surface dragged upwards by the steam (temperature 393.15 K, pressure 1.9 bar) entering at the bot-

tom header and flowing in the annular gap between the inner tube and a concentric glass tube. In the present work, only part of the annulus is used for the simulations as discussed in Section 2.4.

In the experiment, the wall heat flux was adjusted to create fully developed nucleate boiling in the liquid film. The total mass flux and mass quality were also adjusted to obtain a range of liquid film Reynolds number (100–800).

2.2. Governing Equations

To predict the transient turbulent interfacial flow field accurately, the one-fluid formulation coupled with a wall-resolved Large Eddy Simulation (LES) approach is employed within the Finite Volume Method framework (Lakehal, 1999). The governing equations of a mixture of two incompressible phases consist of two continuity equations, Eq. (1) for the mass of mixture and Eq. (2) for the phase marker function, and a single set of momentum and energy equations, Eqs. (3) and (4), respectively. The filtered governing equations solved herein can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \bar{u}_i) = 0 \quad (1)$$

$$\frac{\partial \bar{\phi}}{\partial t} + \frac{\partial}{\partial x_i} (\bar{u}_i \bar{\phi}) = -\frac{\rho}{\rho_L \rho_G} \left[\frac{\partial \bar{\phi}}{\partial x_i} \right] \quad (2)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\rho} \frac{\partial \sigma_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} + \mathbf{g} + \sigma \kappa \mathbf{n} \delta(\phi) \quad (3)$$

$$\frac{\partial C_p \bar{T}}{\partial t} + \frac{\partial}{\partial x_i} (\bar{u}_i C_p \bar{T}) = \frac{1}{\rho} \frac{\partial}{\partial x_i} \left(\lambda \frac{\partial \bar{T}}{\partial x_i} \right) + \dot{q} \quad (4)$$

where $\bar{p}$, $\bar{u}$, $\bar{T}$, and $\bar{\phi}$ are the filtered pressure, velocity, temperature and level-set function for the mixture, respectively. The phasic ensemble averaged velocity split into mixture and drift velocities. A simple algebraic slip formulation (TransAT, 2015) was employed to define the slip velocity between carrier (gas) and dispersed (water) phases. ρ , C_p and λ are the density, heat capacity and thermal conductivity of the mixture that are linked directly to the property of each phase (the subscripts, L and G denoting the phase index for liquid phase and gas phase, respectively) and updated using $\bar{\phi}$. And $\dot{q}$ is the volumetric heat source. More details of level-set function and mass transfer term, $\dot{m}$, in Eq. (2) can be found in Section 2.3.

On the right-hand-side of the filtered momentum equation (Eq. (3)), the term $\sigma \kappa \mathbf{n} \delta(\phi)$ refers the surface tension force, with σ for the surface tension coefficient of taking the value of 0.05497 N/m for steam–water at 393 K, κ for the surface curvature, $\mathbf{n}$ standing for the normal vector to the interface, and $\delta(\phi)$ for a smoothed Dirac delta function centred at the interface. $\mathbf{g}$ is the gravitational body force. The subscripts, i , j and k are the vector components in the i th, j th and k th directions, respectively. The viscous stress tensor σ_{ij} is written as:

$$\sigma_{ij} \equiv \left[\mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial \bar{u}_k}{\partial x_k} \delta_{ij} \right] \quad (5)$$

where μ is the molecular viscosity of the mixture.

The unknown term, τ_{ij} , is the sub-grid scale stress defined as $\tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j$. In the present case, an eddy viscosity approach was chosen to the model the sub-grid stress tensor such that $\tau_{ij} = -2\mu_t \bar{S}_{ij}$ with μ_t being the sub-grid scale turbulent viscosity. Here, $\bar{S}_{ij}$ is the mean rate-of-strain tensor for the resolved scales defined by:

$$\bar{S}_{ij} = \frac{1}{2} \left(\frac{\partial \bar{u}_j}{\partial x_i} + \frac{\partial \bar{u}_i}{\partial x_j} \right) \quad (6)$$

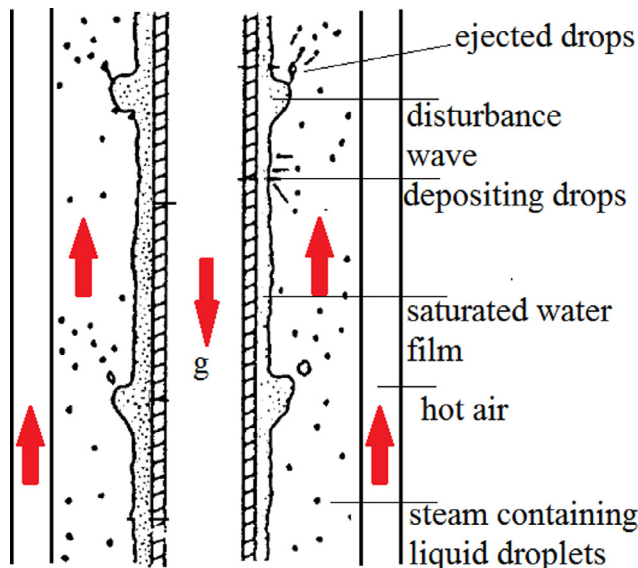


Fig. 1. The schematic of disturbance wave in the annulus.

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