International Journal of Heat and Mass Transfer 80 (2015) 7–15

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Phase distributions of boiling flow in helical coils in high gravity

Liyao Xie, Yongqi Xie *, Jianzu Yu

School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form 27 August 2014
Accepted 27 August 2014
Available online 26 September 2014

Keywords:
Phase distribution
High gravity
Helical coils
Boiling flow
Acceleration

ABSTRACT

Phase distributions of boiling flow in helical coils in high gravity are investigated both experimentally and numerically. The study focuses on the boiling flow in helical coils of inner diameter 8.9 mm and coil diameter 150 mm at mass velocity 134 kg/(m^2 s), heat flux from 452 to 3164 W/m^2. The simulation uses the volume of fluid (VOF) multiphase model with user defined functions. Its results agree with the experimental visualization. In terrestrial gravity, the flow patterns in ascending and descending half-coils show differences. In high gravity, the phase distributions are different from those in terrestrial gravity and evolve highly depending on the high gravity direction and magnitude. An analysis on the acceleration calculation makes a prediction of the pressure gradient and the phase distribution.

1. Introduction

As massive bulk of high-power compacted avionics employed in aircrafts, the heat loads for environmental control system (ECS) increased substantially. The traditional air cycle refrigeration system cannot meet the needs for modern performance flight vehicles. Among the cooling techniques for electronic devices, integrated two-phase cooling is drawing increasing attentions. However, military and civil flight vehicles are subjected to the high gravity with different directions and magnitudes when performing accelerating, decelerating and other maneuvers with acceleration profiles. The high gravity is greatly larger than the terrestrial gravity, so the two-phase distribution, pressure drop and heat transfer characteristics would be distinctive from those in terrestrial.

Generally, there are difficulties conducting experiments with elevated high gravity in terrestrial condition. Based on our research, conducting experiments in a rotating platform is a cost-effective way to bridge the gap between terrestrial experiments and real flight testing to investigate the high gravity effects. A Centrifuge Table Test Facility [1] in the Propulsion Directorate of the Air Force Research Laboratory consists of a 2.44 m diameter rotating table driven by a 20 hp DC electric motor and is capable of radial acceleration up to 12 g. Yerkes et al. [2,3] studied the meniscus distribution in the capillary tube experimentally with the facility. His analytically predicted results agree well with the experimental data of the meniscus shape for transverse acceleration component of less than 2 g. Moreover, investigations on boiling flow in high gravity were original and valuable. Yao et al. [4] investigated the pressure drop and heat transfer of the boiling flow on a rotating platform providing up to 2 g high gravity. Similarly, Xu et al. [5] studied the pressure drop of R134a in a 2.168 mm tube on a centrifugal acceleration machine providing up to 3.16 g high gravity. Xie et al. [6] presented the visualization of the boiling flow in helical coils in high gravity up to 11 g and found that the heat transfer coefficient highly depends on the high gravity direction. Additionally, investigations on air convection in a rotating chamber were also carried out with high gravity effects. Ker et al. [7] and Lee et al. [8] studied the transient convection of air in a heated rotating cubic cavity in 1996. Recently, He et al. [9] studied the non-uniformity of the temperature field in a closed cavity with centrifugal acceleration in simulations and experiments. On the other hand, extensive research focusing on microgravity [10–12] also introduced valuable data of the boiling flow in high gravity more or less. However, their mutual limitation is that the experiments are conducted in the on-board parabolic flight, so their maximum accelerations of 2 g is insufficient for manned or unmanned flight vehicles.

Curved pipes including helical coils, serpentine tubes and other shape pipes have been widely employed in energy and cooling systems such as air conditioning, heat exchangers, and steam generators. Particularly, serpentine and helical tubes can be applied in the evaporator or condenser of the evaporation refrigeration system in aircraft ECS. Thus, the development of heat exchangers with high-gravity resistance is crucial in modern ECS design. Dean [3] was the first one mathematically describing the flow in a coiled tube and a dimensionless Dean number was proposed to measure the intensity of the secondary flows induced by the curvature. Since

---

* Corresponding author. Tel.: +86 10 82338081.
E-mail address: xyq@buaa.edu.cn (Y. Xie).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.094
0017-9310/

Nomenclature

$\boldsymbol{a}$	acceleration
c_p	specific heat
D	coil diameter
E	sensible enthalpy
$\boldsymbol{f}$	shear stress
$\boldsymbol{F_{vol}}$	interface volumetric force
$\boldsymbol{g}$	gravitational acceleration
G	mass velocity
h	vaporization latent heat
$\boldsymbol{i}$	X-direction unit vector
$\boldsymbol{j}$	Y-direction unit vector
$\boldsymbol{k}$	Z-direction unit vector
p	pressure
q	heat flux
Q	heat source term
$\boldsymbol{r}$	position vector in reference frame *OXYZ*
$\boldsymbol{R}$	position vector in reference frame *O′X′Y′Z′*
S	mass source term
t	time
T	temperature
$\boldsymbol{v_r}$	velocity in reference frame *OXYZ*
x	quality
Greek letters	
α	volume fraction
γ	interphase heat transfer coefficient
θ	rotational angle in helical coils
ρ	density
$\boldsymbol{\omega}$	angular velocity in reference frame *OXYZ*
$\boldsymbol{\Omega}$	angular velocity in reference frame *O′X′Y′Z′*
Subscripts	
l	liquid
v	vapor
sat	saturation
ref	reference

then, single-phase heat transfer and flow characteristics in helical coils have been wide studied by researchers both experimentally and theoretically. Furthermore, investigations on two-phase boiling flow are more challenging, and research methods are not confined to experiments and analytically theory [13,14]. Several investigations on helical coils primarily concentrated on numerical simulations and visualization of the boiling flow. Yamamoto et al. [15] used a smoke visualization technique to investigate the flow in the helical pipe with a large torsion. Recently, Meng et al. [16], Wu et al. [17] and Yang et al. [18] carried out simulations to visualize the boiling flow in serpentine tube with VOF multiphase model, and the simulation results agreed well with corresponding experiments. In a recent study, Zhang et al. [19] also used VOF model to quantitatively describe the bubbling behavior in bubble columns.

The present study aims to the phase distributions in helical coils in high gravity, which can be deemed as a complement of our previous research [6] on heat transfer in helical coils. Phase distribution is essential for boiling flows, but it is significant in understanding the interaction and mechanism induced by the high gravity. Therefore, we run numerical simulations and validate them by experiments on a rotating arm to clarify the high gravity effects in helical coils.

2. CFD modeling and solution method

2.1. Physical model

Helical coils with a reference frame *OXYZ* are positioned in a rotating platform *O′X′Y′Z′* as shown in Fig. 1. Two configurations, axial and radial are tested in the current experiment and simulation. The coil walls are applied with uniform heat flux for the first five coils and the last coil is used for visualization. Subcooled working fluid n-pentane (R601) flows into the helical coils and is heated to a positive quality at outlet. When the reference frame *O′X′Y′Z′* keeps static, the flow boils in terrestrial gravity. When the whole system rotates at a constant angular speed $\boldsymbol{\Omega}$ with rotational radius $\boldsymbol{R}$ about the Y' axis, the boiling flows are subjected to the centrifugal and the Coriolis force induced by the rotation which can simulate the boiling flow in high gravity condition.

2.2. Governing equations

The modeling of the boiling two-phase flow is achieved by using CFD commercial software Fluent 6.3 with the volume of fluid (VOF) model [20], sliding mesh and the user defined function (UDF) defining the interphase heat and mass transportation rate. The VOF model can model two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each fluids throughout the domain. It can be specifically employed in tracking the time-varying liquid–gas interface. In this study, the liquid phase n-pentane is set as the primary phase and its vapor phase is set as the secondary phase. The tracking of the interface between the phases is accomplished by the solution of a continuity equation for the volume fraction of the phases expressed as follow:

$$\frac{\partial}{\partial t}(\alpha_v \rho_v) + \nabla \cdot (\alpha_v \rho_v \boldsymbol{v}_r) = S \tag{1}$$

The volume fraction equation will not be solved for the primary phase; the primary-phase volume fraction will be computed based on the following constraint:

$$\alpha_l + \alpha_v = 1 \tag{2}$$

The momentum and energy equations are shown as follow, respectively,

$$\rho \frac{\partial \boldsymbol{v}_r}{\partial t} + \rho \boldsymbol{v}_r \cdot \nabla \boldsymbol{v}_r = -\nabla p + \boldsymbol{f} + \rho(\mathbf{g} - 2\boldsymbol{\Omega} \times \boldsymbol{v}_r - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{R})) + \boldsymbol{F_{vol}} \tag{3}$$

Where $2\boldsymbol{\Omega} \times \boldsymbol{v_r}$ is the Coriolis acceleration and $\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{R})$ is the centrifugal acceleration when observed in the reference frame *O′X′Y′Z′*, and $\boldsymbol{F_{vol}}$ is the interface-induced volumetric force calculated from the continuum surface force (CSF) model [21].

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\rho E + p)\boldsymbol{v}_r = \nabla \cdot (k \nabla T) + Q \tag{4}$$

$$E = \frac{\alpha_l \rho_l E_l + \alpha_v \rho_v E_v}{\alpha_l \rho_l + \alpha_v \rho_v} \tag{5}$$

$$E_l = c_{p,l}(T_l - T_{ref}) + \frac{v_r^2}{2}, \quad E_v = c_{p,v}(T_v - T_{ref}) + \frac{v_r^2}{2} \tag{6}$$

All the two-phase fluid properties, such as density, thermal conductivity and viscosity are all volume-fraction-averaged. The sensible enthalpy and temperature are mass-averaged expressed in Eq. (5). In VOF equation discretization, the geometric reconstruction scheme is used, which represents the interface between fluids using a piecewise-linear approach.