Experimental Thermal and Fluid Science 98 (2018) 1–11

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Investigation on interphase mixing and flow condensation process in a vertical channel

Kang Zhu[a], Yanzhong Li[a,b,*], Yuan Ma[a], Jiaojiao Wang[a], Lei Wang[a], Cui Li[a]

[a] Institute of Refrigerating and Cryogenic Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing 100028, China

ARTICLE INFO

Keywords:
Two phase flow
Interphase mixing
Flow condensation
Phase distribution
Interfacial transfer

ABSTRACT

In this paper, an experimental study is performed on the mixing of superheated gas and subcooled flowing liquid and the subsequent flow condensation process in a vertical visual flow channel using R123 as the working fluid. The flow patterns of the two phase flow in the vertical channel are verified and the flow condensation lengths of the gaseous phase under different operating conditions are obtained. Test results indicate that under the operating conditions in this experiment, the gaseous phase forms a cavity or a film at the gas orifices, and then forms a dispersive bubbly flow in the downstream region. The flow condensation length of the gaseous phase through a single orifice increases approximately linearly with the gas flow rate over a range of 0.35–0.76 m, and it is reduced to a range of 0.27–0.56 m by using multiple gas injection orifices. A computational fluid dynamics (CFD) model is established to simulate the two phase flow and interfacial heat and mass transfer in the channel. The simulation capability and prediction accuracy of the CFD model are validated by comparing numerical results of phase distributions as well as the flow condensation lengths with test data, and satisfying agreements are obtained. This work could be beneficial to the understanding and handling of interphase heat and mass transfer problems in in-tube two phase flows.

1. Introduction

The phenomenon of gas injection into flowing liquid occurs in various processes and industries such as chemical engineering, water treatment, metallurgical industry and aerospace industry, to promote heat and mass transfer between the gaseous phase and the liquid phase. In the relevant processes, there are two main aspects that is of importance, meaning the two-phase flow pattern and the interfacial heat and mass transfer. As for the flow pattern, bubbly flow, continuous gas jet flow or film flow could occur under certain circumstances.

The formation of bubbles during gas injection into static or flowing liquid and the following interphase mixing process have been studied by many researchers over the past few decades. Kumar and Kuloor [1] reported a comprehensive review of the investigations on bubble formation before 1969. They elucidated the growing process of a bubble in the liquid phase, summarized different measuring methods of bubble volume and frequency, and analyzed influences of various factors on bubble size, including orifice parameters, operating conditions and physical properties of the fluids. Marshall [2] performed both analytical and experimental studies on the bubble formation process in horizontal liquid crossflow. The bubble growth process was predicted by a theoretical model. In the model, gas flow during the bubble formation process was divided into three stages, i.e., gas flow within the gas chamber, through the orifice and within the bubble. For the gas chamber, the mass conservation and the first thermodynamic law were applied to establish the relationship among the pressure in the chamber, the gas inflow rate and outflow rate. For the orifice, the orifice equation was used to obtain the gas flow rate through it. For the growing bubble, the mass conservation and the first thermodynamic law were applied to describe the relationship between the bubble growth rate and the gas flow rate. The researcher observed several regimes of bubble formation during tests, i.e., the single-bubble flow, the multiple pulse bubble flow and the jet flow. Nahra and Kamotani [3,4] proposed a two-dimensional one-stage theoretical model for bubble formation in liquid crossflow based on a global force balance on the bubble, and carried out experiments to investigate the effects of liquid velocity, gas flow rate and orifice diameter on bubble formation.

Apart from the disperse bubble flow regime, other kinds of gas flow regimes may arise in the interphase mixing process. Bai and Thomas [5] conducted an experimental study on bubble formation during horizontal gas injection into liquid downflow, and they found that the gaseous phase formed a continuous curtain along the pipe wall under

---

[*] Corresponding author at: Institute of Refrigeration and Cryogenics, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail address: yzli-epe@mail.xjtu.edu.cn (Y. Li).

https://doi.org/10.1016/j.expthermflusci.2018.05.012
Received 22 December 2017; Received in revised form 20 March 2018; Accepted 13 May 2018

Nomenclature

c_p	specific heat, J/(kg·K)
E	internal energy, J/kg
F	external body force, N
g	gravity acceleration, m/s^2
h	enthalpy, J/kg
h_{fg}	latent heat, J/kg
l	length, m
P	pressure, Pa
Q_g	gas volume flow rate, m^3/h
r_i	mass transfer intensity factor, s^{-1}
S	mass source per unit volume, kg/(m^3·s)
t	time, s
T	temperature, K
U	velocity, m/s
v	velocity, m/s

Greek symbols

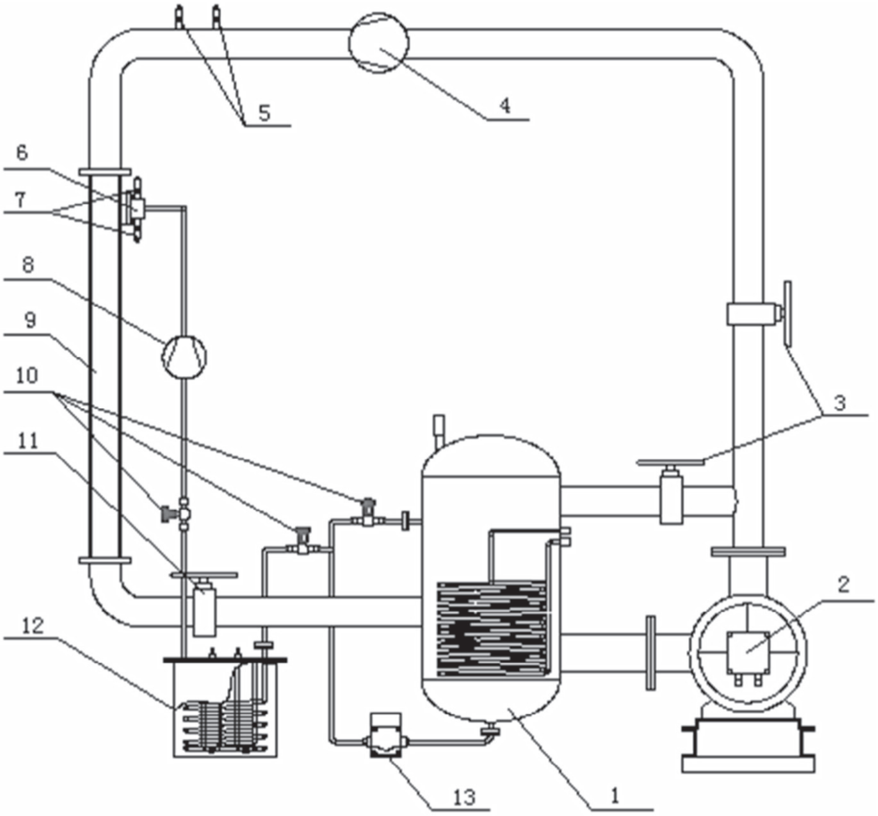
α	volume fraction
ΔT	temperature difference, K
λ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

eff	effective
g	gas
h	heat
in	incoming fluid
l	liquid
sc	subcooled
sp	superheated

high liquid velocities and very large gas injection rates. Forrester and Rielly [6] presented a group of tests on bubble formation from cylindrical, flat and concave sections in strong liquid crossflow. Test results indicated that the predominant gas flow mode was jet flow when the orifice was positioned in unseparated liquid flow. Furthermore, they stated that the gas jet flowed into the wake region and formed a large clinging gas cavity behind the blade at very high gas flow rates.

The condensation of bubbles in subcooled liquid upflow has been investigated by researchers using experimental methods, and different heat transfer correlations between two phases have been proposed [7–9]. The CFD method has also been applied to simulate the condensation processes of bubbles [10–13]. Lee et al. [14] performed both experimental and numerical studies on the vertical downflow condensation of FC-72 vapor. The axial distributions of the wall heat flux



1—Working fluid container; 2—Circulating pump of the liquid loop; 3, 11—Ball Valves; 4—Liquid flowmeter; 5, 7—Pressure and temperature sensors; 6—Gas supplying chamber; 8—Gas flowmeter; 9—Visual flow channel; 10—Needle valves; 12—Gas generating heater; 13—Circulating pump of the gas loop;

Fig. 1. The schematic diagram of the experimental apparatus.