Experimental Thermal and Fluid Science 100 (2019) 144–157

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Flow patterns and hydrodynamic model for gas-liquid co-current downward flow through an orifice plate

Min Qiao[a], Wenyun Wei[a], Weixing Huang[a,*], Junfeng Li[a], Yunxiang Xue[a], Chaojun Deng[a,b]

[a] School of Chemical Engineering, Sichuan University, Chengdu 610065, China
[b] Nuclear Power Institute of China, Chengdu 610041, China

ARTICLE INFO

Keywords:
Gas-liquid two-phase flow
Orifice plate
Flow pattern
Liquid film thickness
Relative equivalent length
Pressure loss

ABSTRACT

Gas-liquid co-current downward flow through an orifice plate was experimentally investigated, in which the surface tension, gravity, gas-liquid interface friction force and fluid inertial force may have comparable effects on the flow of the liquid. In experiments, nine orifice plates with different hole-diameter and thickness were used, the gas superficial mass flux changes from 1.7 to 41.4 $kg/m^2/s$ and the liquid superficial mass flux is from 38.7 to 295.3 $kg/m^2/s$. Four flow patterns, namely, trickling, continuous, semi-dispersed and perfect-dispersed flow were identified by means of observation. Flow pattern maps were plotted using gas superficial mass flux vs. liquid superficial mass flux, and the transition mechanism of different flow patterns and the influence of the hole-diameter on the transition boundaries were discussed. Also, a statistical parameter was used to assist in understanding the transition mechanism from trickling/continuous flow to semi-dispersed flow. Next, by considering the interaction between gas and liquid, a model about the film thickness around orifice rim was proposed and the factors influencing the liquid film thickness were discussed. These discussions and the comparisons with the film thickness in the case of gas-liquid annular flow in pipe show that the model is very effective. Based on this model, an equivalent length model for the orifice friction was developed to predict the pressure loss of gas-liquid two-phase flow through the orifice, and satisfactory agreement with experimental data was obtained. In addition, by using the equivalent length method, a new correlation was proposed to successfully predict the pressure loss of single gas phase flow through the orifice plate.

1. Introduction

Gas-liquid two-phase flow through an orifice is usually encountered in many chemical devices, such as trickle bed reactor [1], airlift reactor [2], multi-phase fluidized bed reactor [3], sieve-plate packing tower [4], bubble column [5] and stereoscopic swirl tray in double effect co-current flow absorption column [6]. Generally, perforated plates are the basic configurations to provide a place for this type of contact in these devices. For example, perforated plates are used to increase the contact area between the gas and liquid and therefore intensifying the heat and mass transfer [2,4], or used as a liquid distributor in trickle bed reactor (TBR) to prevent the appearance of the damaging hot spots [1,7]. Perforated plates are also used as the pressure separation devices in the absorption heat pump to reduce the heat transfer losses of many industrial processes [8]. Therefore, obtaining comprehensive knowledge of the basic hydrodynamic characteristics of the perforated plates is of great importance for these chemical process devices as mentioned above. Usually, it is difficult to directly investigate the flow in these devices due to the complex structure of the devices. Consequently, researching the hydrodynamics of gas-liquid flow through an orifice is a useful method for understanding the hydrodynamic characteristics of the perforated plates.

Oliveira et al. [9] and Zeghloul et al. [10] investigated the flow patterns of gas-liquid flow through an orifice plate. The experimental results showed that there are mainly churn, slug, bubble and annular flow patterns. It should be noted that these studies were in regard to gas-liquid co-current upward flow or horizontal flow. Those flow modes are very different from the mode of the gas-liquid co-current downward flow where the gravity, surface tension and gas drag may have comparable effects on the flow of the liquid. In various chemical processes, the flow mode of gas-liquid co-current downward flow through an orifice may be usually encountered, such as nuclear power wastewater system, hydro-treating processes in petroleum refineries [1], recovering low-grade waste heat from many industrial processes [8], and so on. When designing and operating the perforated plate in these processes, it is important to predict the flow patterns in given operating conditions

* Corresponding author.
E-mail address: hwx@scu.edu.cn (W. Huang).

https://doi.org/10.1016/j.expthermflusci.2018.09.005
Received 23 May 2018; Received in revised form 28 August 2018; Accepted 9 September 2018
Available online 10 September 2018

Nomenclature

Latin symbols

G_{Ls}	liquid superficial mass flux (kg/m^2/s)
G_{Gs}	gas superficial mass flux (kg/m^2/s)
C_v	coefficient of variation
L	liquid mass flow rate (kg/s)
G	gas mass flow rate (kg/s)
t	the thickness of the orifice plate (mm)
d_0	hole-diameter (mm)
d	gas liquid interfacial diameter (mm)
R	the radius of the orifice (mm)
u_i	gas-liquid interfacial velocity (m/s)
u_L	liquid phase velocity (m/s)
u_G	gas phase velocity (m/s)
u_{Lm}	liquid average velocity (m/s)
u_{Lm}	gas average velocity (m/s)
u_{Ls}	liquid superficial velocity (m/s)
u_{Gs}	gas superficial velocity (m/s)
Re	Reynolds number
l_e	equivalent length (mm)

Greek letters

δ	the average liquid film thickness (μm)
η	the dimensionless liquid film thickness
β	equivalent diameter ratio
σ	standard deviation
τ_i	interfacial shear stress (Pa)
ν_L	liquid phase kinematic viscosity (m^2/s)
ρ_G	gas phase density (kg/m^3)
ρ_L	liquid phase density (kg/m^3)
μ_G	gas phase viscosity (Pa·s)
μ_L	liquid phase viscosity (Pa·s)

Subscripts

Gs	gas superficial
Ls	liquid superficial
G	gas
L	liquid
m	mean
i	interfacial

[11]. Until now, there is little literature researches the flow patterns of gas-liquid co-current downward flow through an orifice plate. In order to broaden the scope of the research on gas-liquid flow through an orifice, a large number of studies about the flow patterns of gas-liquid co-current downward flow through an orifice plate need to be carried out.

Most research pays close attention to the pressure losses when considering the dissipation characteristics of the orifice [12–16]. All of these studies pointed out that the pressure losses of gas-liquid flow through an orifice are caused by the recirculation and eddies resulting from the contraction and expansion of the fluids. Tapucu et al. [15] observed the flow region on both sides of the orifice and the results showed that the downstream recirculation zone is larger than the upstream. Oliveira et al. [9] investigated the pressure loss of gas-liquid upward flow through an orifice plate. The experiment results showed that the pressure loss increases with the increase of the gas and liquid mass flow. Fossa and Guglielmini [14] studied the pressure loss of gas-liquid flow through both thin and thick orifices and found that the pressure loss decreases with the increase of the relative thickness of the orifice.

Tapucu et al. [15] reported a homogeneous orifice flow model to predict two-phase pressure losses, in which the physical properties of the mixture were obtained by a weighted average of the individual phase properties. On the basis of a single-phase like behavior with vena contracta, Chisholm [17] put forward a formula to predict the gas-liquid two-phase pressure multiplier. The expression proposed by Kojasoy et al. [12] is very similar to that of Chisholm [17], apart from the definition of a parameter related to the thickness of the orifice. Chen et al. [18] proposed a model to calculate the local resistance of gas-liquid two-phase flow through an orifice. In this model, the void

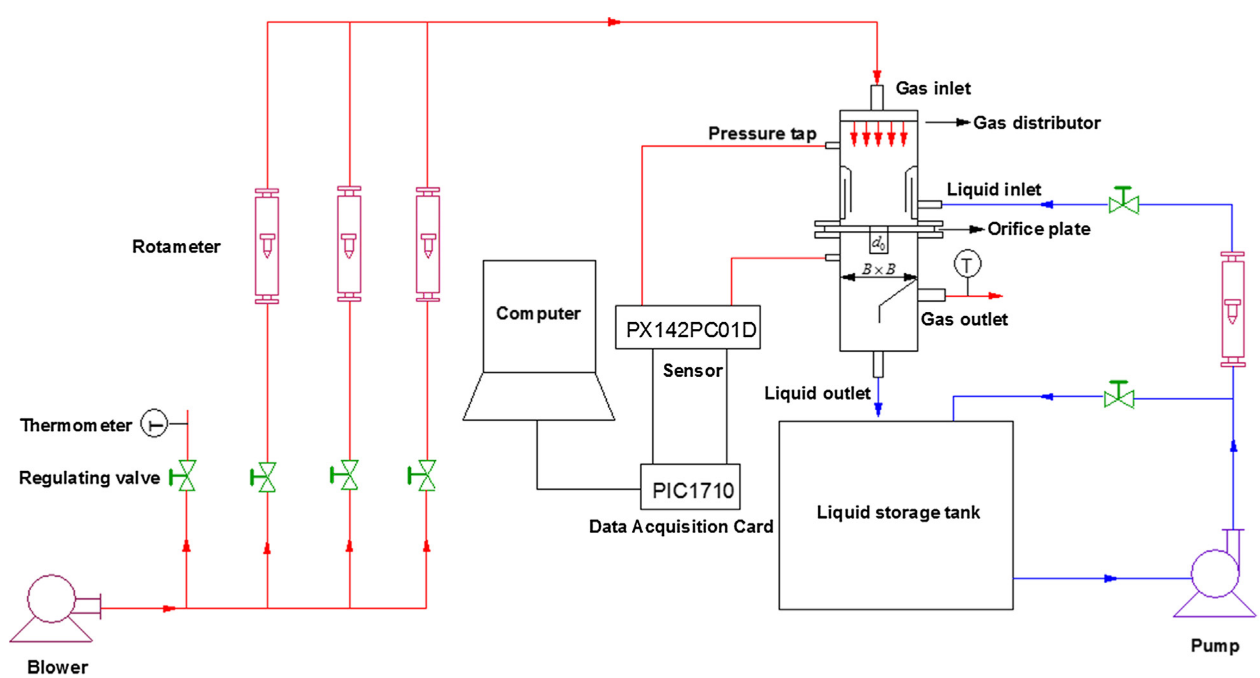

Fig. 1. Schematic diagram of the experimental setup.