Applied Soft Computing 13 (2013) 1674–1685

Contents lists available at SciVerse ScienceDirect

Applied Soft Computing

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

Prediction of flow pattern of gas–liquid flow through circular microchannel using probabilistic neural network

Seim Timung, Tapas K. Mandal*

Department of Chemical Engineering, Indian Institute of Technology Guwahati, Guwahati 781 039, India

ARTICLE INFO

Article history:
Received 8 February 2012
Accepted 14 January 2013
Available online 19 January 2013

Keywords:
Hydrodynamics
Multiphase flow
Microchannel
Microstructure
Probabilistic neural network
Turbulence
Transition boundary

ABSTRACT

The present study attempts to develop a flow pattern indicator for gas–liquid flow in microchannel with the help of artificial neural network (ANN). Out of many neural networks present in literature, probabilistic neural network (PNN) has been chosen for the present study due to its speed in operation and accuracy in pattern recognition. The inbuilt code in MATLAB R2008a has been used to develop the PNN. During training, superficial velocity of gas and liquid phase, channel diameter, angle of inclination and fluid properties such as density, viscosity and surface tension have been considered as the governing parameters of the flow pattern. Data has been collected from the literature for air–water and nitrogen–water flow through different circular microchannel diameters (0.53, 0.25, 0.100 and 0.050 mm for nitrogen–water and 0.53, 0.22 mm for air–water). For the convenience of the study, the flow patterns available in literature have been classified into six categories namely; bubbly, slug, annular, churn, liquid ring and liquid lump flow. Single PNN model is unable to predict the flow pattern for the whole range (0.53 mm–0.050 mm) of microchannel diameter. That is why two separate PNN models has been developed to predict the flow patterns of gas–liquid flow through different channel diameter, one for diameter ranging from 0.53 mm to 0.22 mm and another for 0.100 mm–0.05 mm. The predicted map and their transition boundaries have been compared with the corresponding experimental data and have been found to be in good agreement. Whereas accuracy in prediction of transition boundary obtained from available analytical models used for conventional channel is less for all diameter of channel as compared to the present work. The percentage accuracy of PNN (∼94% for 0.53 mm ID and ∼73% for 0.100 mm ID channel) has also been found to be higher than the model based on Weber number (∼86% for 0.53 mm ID and ∼36% for 0.05 mm ID channel).

1. Introduction

Green technology and safety aspect of chemical industries are the two important issues of concern to the modern civilization. Compact microstructure reactor system (such as microreactors) and other microfluidic devices can fulfil these requirements. That is why the present era is entering into micro fabrication techniques which have become popular and established technology in electronic industries. Now-a-days, microstructure devices (micro heat exchanger, micro heat pipes and microreactors) and many micro analysis chips are also used in chemical and biological applications, as these micro devices are capable to provide high rate of heat and mass transfer due its high surface to volume ratio [1,2]. Highly exothermic reactions can be well controlled with high productivity. Also these microstructure devices are suitable for handling of highly explosive and hazardous chemicals. Due to these advantages many industries like DuPont have preferred to use microreactors and other microfluidic devices rather than conventional reactors [3]. These microstructure devices often gets heated which hampers the optimum performance of the devices. In order to maintain a constant performance there is a need to constantly remove the excess heat from these devices. This requirement would bring two-phase flow into picture. Some applications of two-phase flow in a microchannel include chemical reactions like fluorination, chlorination and bromination of organic compounds, hydrogen production by ethanol steam reforming, fluidization, compact heat exchanger and cooling system for various microelectronics devices, air-condition and refrigeration, unit operations like evaporation, condensation and many more [4–8]. The design of such microstructure device would naturally require the complete knowledge of hydrodynamics of two-phase flow in such channel confinement.

Till date, few experimental studies on two-phase flow through a microchannel have been reported in literature. Most of them has been for gas–liquid flow and very few for liquid–liquid flow. All of the past researchers have concentrated on the study of

---

* Corresponding author. Tel.: +91 361252211; fax: +91 0 361 2582260x2291.
E-mail address: tapasche@iitg.ernet.in (T.K. Mandal).

1568-4946/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.asoc.2013.01.011

Nomenclature

D_h	hydraulic diameter (mm)
g	acceleration due to gravity (m/s^2)
U_{GS}	superficial velocity of gas phase (m/s)
U_{LS}	superficial velocity of liquid phase (m/s)
U_M	fluid superficial mixture velocity (m/s)
R	regression constant
X	input vector
f_M	friction factor
d_{CD}	critical bubble diameter above which the bubble will get deformed (mm)
d_{CB}	critical bubble diameter below which migration of bubbles is prevented (mm)
$d_{c\gamma}$	maximum bubble size above which the bubbles are deformed (mm)
d_{cb}	maximum size of bubble above which buoyant forces will overcome turbulent dispersive forces (mm)
β'	angle of pipe inclination w.r.t. horizontal line (°)
μ_L	viscosity of liquid phase (centipoise)
μ_G	viscosity of gas phase (centipoise)
α	gas holdup
γ	surface tension (N/m)
λ	Laplace constant
ε	volume fraction
Φ	smoothing parameter
ρ_L	density of liquid phase (kg/m^3)
ρ_G	density of gas phase (kg/m^3)
Co	confinement number
Eo	Eotvos number
Ca	capillary number
N_{vg}	gas viscosity number
Re	Reynolds number
We	Weber number
Fr	Froude number

hydrodynamics of such flow which includes flow pattern, holdup and pressure. They have identified the flow pattern by analysing the image of flow patterns captured from a high speed camera or video recordings. But the main difficulty with this flow visualization technique is that, sometimes confusion does exist while identifying the flow patterns. This automatically results in the lack of consistency in the flow pattern terminology and makes the study of gas–liquid flow much more complex.

The study of two-phase flow phenomena in a microchannel is not possible without the knowledge of flow pattern. This is because many hydrodynamic parameters such as holdup, pressure-drop, mixing characteristics, etc. are influence by the flow pattern encountered [9]. So, in order to better understand the past research works on gas–liquid flow in microchannel, a detailed literature survey has been made.

In the past literature it has been reported that flow patterns in microchannel diameter, $D_h \geq 200\,\mu$m and diameter $D_h < 200\,\mu$m are not same. Triplett et al. [10] performed the experiments to study the hydrodynamics of air–water flow through microchannel of two different geometry namely; circular and semi-triangular. For circular channel they have selected two diameter, – (1) 1.45 mm and (2) 1.09 mm and hydraulic diameters for semi-triangular channels are 1.49 mm and 1.09 mm. They have identified bubbly, slug, slug-annular, annular and churn flow by photographic technique in both the cases. Kawahara et al. [11] made their study on the flow patterns of nitrogen–water flow through microchannel with diameter 100 μm and observed the simultaneous occurrence of two or more types of flow patterns at the same flow condition. This is the first work where such occurrence of flow patterns has been reported by researcher. The nomenclature of such flow patterns has been made based on the probability of appearance of the flow configuration and named as slug-ring, ring-slug, semi-annular and multiple flow. Serizawa et al. [12] studied the flow pattern characteristics of air–water flow in circular tubes with inner diameter of 20, 25 and 100 μm. The flow pattern observed has been found to be quite different from those in conventional and minichannel. It has also been confirmed that surface roughness of the inner wall of the tube is an important parameter for the gas–liquid flow in microchannel. Dispersed bubbly flow, gas slug flow, liquid ring flow, liquid lump flow, annular flow, frothy or wispy annular flow, rivulet flow, liquid droplets flow has been some of the flow patterns observed. Chung and Kawaji [13], studied the effect of channel diameter on the flow pattern for nitrogen–water system, from $D_h \sim 1$ mm to the range of micrometre. Experiments have been conducted using mixture of nitrogen and water in circular channels with diameter of 530, 250, 100, and 50 μm. The flow pattern for 530 and 250 μm have found to be similar to those observed in minichannel. The serpentine-like gas core as observed by Kawahara et al. [11] has also been observed in 100 and 50 μm microchannel [13]. The flow patterns observed in 100 and 50 μm has been found to be quite similar to Kawahara et al. [11]. This clearly depicts the difference in mechanism that exist inside a microchannel with diameter, $D_h < 200\,\mu$m, where turbulence is opposed by strong surface tension and viscous forces. Saisorn and Wongwise [14] carried out experiment to study flow pattern of air–water two-phase flow in microchannel with diameter, $D_h = 0.53$, 0.22 and 0.15 mm. Slug, throat-annular, churn and annular-rivulet flow have been observed which is quite similar to flow pattern observed by Saisorn and Wongwise [7]. A new flow pattern with serpentine like gas core flow has observed in channel diameter 0.15 mm which is characterized by small ripples on gas–liquid interface. The simultaneous occurrence of different flow patterns at same flow condition has also been observed in case of air–water flow through microchannel of diameter, $D_h = 0.15$ mm as previously observed by Chung and Kawaji [13]. Apart from channel diameter, investigation on the effect of channel geometry on the flow patterns has been studied by Dessimoz et al. [15] with the help of three different microreactors of different channel geometries. The microreactors has been composed of a T-shaped entry section with hydraulic diameter of 400 μm, same entry section but having a trapezoidal cross-section with hydraulic diameter of 400 μm and a Y-shaped chicane mixer with circular cross-section of diameter 1 mm. The flow patterns have been identified using a high speed camera. The flow patterns observed have been bubbly, slug, slug-annular and annular flow. The trend of flow pattern transition has been observed quite similar to Triplett et al. [10]. It has been observed that the dominant flow pattern during the experiments were slug and annular flow. The presence of an unstable slug flow has also been reported. Apart from air–water, Rahim et al. [16] made their study on two-phase flow regimes using refrigerant, R134a and R245fa as working fluid, flowing through 0.509 and 0.790 mm horizontal tubes. The flow pattern obtain has been characterized as bubble, bubbly/slug, slug, slug/semi-annular, semi-annular, wavy-annular and smooth annular flow. No stratified flow and a very small region of bubbly flow have been observed in this case. Annular and different forms of slug flow have been found to be dominating as reported by Dessimoz et al. [15].

From literature, it has been observed that the hydrodynamics of multiphase flow inside a microchannel with diameter, $D_h < 200\,\mu$m is still not clear and due to this reason, no physical model for two-phase flow in microchannel has come into light so far. Classical two-phase flow regime models [17–19] usually used for conventional channels cannot be used to predict the flow pattern occurring in microchannels. The results of Triplett