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Research paper

Identification of two-phase water–air flow patterns in a vertical pipe using fuzzy logic and genetic algorithm

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HIGHLIGHTS

- We identify the two phase flow pattern by fuzzy logic and genetic algorithm.
- We investigate four turbulence modeling to simulate the two phase flow.
- Image processing was employed to identify the flow pattern.
- Fuzzy logic code predicts the flow pattern very well.

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ABSTRACT

An automatic and intelligent system to recognize the two-phase water–air flow regime in a vertical tube based on fuzzy logic and genetic algorithm is proposed. Two approaches, volume of fluid (VOF) and Eulerian model, were used for the numerical simulation of gas–liquid two-phase flow. Four different turbulence models, i.e., k–ε RNG, k–ε standard, Reynolds stress and k–ε realizable, were employed. Image processing procedure was implemented to obtain the flow pattern. It was found that the k–ε RNG gives best results for turbulence modeling and the fuzzy logic code predicts the flow pattern well.

1. Introduction

Multiphase flow problem is related to energy, process engineering, oil and gas industry and many other engineering areas. The features of the flow pattern in a multiphase flow are of significant importance in design and implementation in industrial processes. Many researchers have investigated the flow pattern in straight tubes with different diameters [1–5]. Banasiak et al. [6] studied two-phase flow regime identification by means of a 3D electronic capacitance tomography (ETC) and fuzzy-logic classification. They studied two-phase gas–liquid mixtures flow pattern identification using combination of fuzzy logic and volumetric 3D ECT images. Mesquita et al. [7] used fuzzy inference on image analysis to determine two-phase flow patterns. A fuzzy classification system for two-phase flow instability patterns was developed and the flow pattern was classified based on the obtained experimental images. They also optimized the fuzzy inference to use single gray scale profiles and concluded that good results could be obtained if enough image acquisition parameters were used.

In general the flow pattern identification is done either by visual observation or by using flow pattern maps [8–10]; but sometimes the visualization method cannot be used and other techniques like nuclear radiation attenuation, impedance electrical technique are exploited. Zeguai et al. [11] studied the flow pattern of a two-phase laminar flow in a horizontal tube. They proposed flow maps and performed some pattern rearrangements. Pietrzak [12] studied two-phase liquid–liquid flow in a pipe bend. A flow map was proposed based on the experimental results. Zhao et al. [13] studied the flow pattern of two-phase flow in a vertical pipe experimentally. A new method was proposed to study the flow patterns and good agreement was observed between the experimental results and their model.

A growing number of studies have been carried out with the use of fuzzy-neural networks to recognize flow pattern which are used

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Nomenclature

$\boldsymbol{F}$	body force (kg m/s^2)
$\boldsymbol{g}$	gravity acceleration (m/s^2)
G_k	generation of turbulence kinetic energy due to the mean velocity gradients (m^2/s^3)
k	turbulent kinetic energy (m^2/s^2)
S	strain rate (1/s)
α_q	void fraction of phase q
$\boldsymbol{v}_q$	velocity of phase q (m/s)
ρ_q	density of phase q (kg/m^3)
$\dot{m}_{pq}$	mass transfer between air and water (kg/s)
μ	dynamic viscosity (kg/m s)
σ_{ij}	surface tension (kg/s^2)
μ_t	turbulent viscosity (kg/m s)
ε	turbulent energy dissipation (m^2/s^3)
C_μ	empirical constant
$C_{1\varepsilon}$	empirical constant
η_o	empirical constant
σ_k	empirical constant
σ_ε	empirical constant
β	empirical constant

in many industries like petroleum, energy and so on [14–23]. Gao et al. [24] carried out gas–liquid two phase flow experiments in a small diameter pipe for measuring local flow information from different flow patterns. They proposed a modality transition-based network for mapping the experimental multivariate measurements into a directed weighted complex network. Gao et al. [25] developed a new distributed conductance sensor for measuring local flow signals at different positions and then proposed a novel approach based on multi-frequency complex network to uncover the flow structures from experimental multivariate measurements. They demonstrated how to derive multi-frequency complex network from multivariate time series based on the Fast Fourier transform. Ghanbarzadeh et al. [26] studied gas–liquid two-phase flow pattern recognition using image processing technique to obtain information from each flow regime. This information consists of number of bubbles, area, perimeter and the height and width of the second phase. They concluded that their results could predict the flow patterns in a vertical pipe. Many investigations about flow regime recognition based on experimental and numerical results have been carried out. These methods are mostly time-consuming effortful and subjective. The objective of this paper is to propose an automatic and intelligent system to recognize the flow regime based on fuzzy logic and genetic algorithm. This intelligent controller system is simple and more accurate comparing with other methods for two phase flow pattern recognition. Fuzzy controllers are very simple conceptually. They consist of an input stage, a processing stage, and an output stage. The input stage maps sensor or other inputs, such as switches, thumbwheels, and so on, to the appropriate membership functions and truth values. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules. Finally, the output stage converts the combined result back into a specific control output value. Fuzzy rules are linguistic IF-THEN-constructions that have the general form “IF A THEN B” where A and B are (collections of) propositions containing linguistic variables. A is called the premise and B is the consequence of the rule. In effect, the use of linguistic variables and fuzzy IF–THEN-rules exploits the tolerance for imprecision and uncertainty. In this respect, fuzzy logic mimics the crucial ability of the human mind to summarize data and focus on decision-relevant information. The present study explains how accurate and useful this method can be applied for gas–liquid two phase flow pattern identification.

2. Governing equation

Two approaches, the volume of fluid (VOF) and Eulerian model, will be used for the numerical simulation of gas–liquid two phase flow. The VOF model is applicable for modeling of two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each of the fluids throughout the domain. Prediction of motion of large bubbles in a liquid and the steady or transient tracking of any gas–liquid interface are the main applications of VOF. The VOF formulation depends on the fact that two or more fluids (or phases) are not interpenetrating. In the computational cell of each control volume for each additional phase is added to the model, the volume fraction of the phase is introduced. The volume fractions of all phases sum to unity. Volume-averaged values represent that the fields for all variables and properties are shared by the phases as long as the volume fraction of each phase is known at each location. Therefore, the variables and properties in any given cell by considering the volume fraction values can either purely represent one of the phases or a mixture of the phases. The appropriate properties and variables will be assigned to each control volume within the domain by considering the local value of volume fractions.

The Eulerian model is used to model droplets or bubbles of secondary phase or phases dispersed in continuous fluid phase (primary phase) [27]. For each phase, the Eulerian modeling system is based on ensemble-averaged mass and momentum transport equations. Eulerian model solves momentum, enthalpy, and continuity equations for each phase and tracks volume fractions. It uses a single pressure field for all phases and allows for virtual mass effect and lift forces. Multiple species and homogeneous reactions are in each phase and allows for heat and mass transfer between phases. In the present study, both models were examined and the VOF model was used for further investigation. The continuity equations for both Eulerian and VOF models are the same.

2.1. Continuity equation

The continuity for the qth phase is expressed as the following form:

$$\frac{1}{\rho_q}\left[\frac{\partial(\alpha_q\rho_q)}{\partial t}+\nabla\cdot(\alpha_q\rho_q\boldsymbol{v}_q)=\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{pq})+S\right] \tag{1}$$

where α_q, $\boldsymbol{v}_q$ and ρ_q are the void fraction, velocity and density of phase q, respectively. It is assumed that mass transfer between air and water is zero ($\dot{m}_{pq}=\dot{m}_{qp}=0$), and the source term on the right-hand side of Equation (1), S, is zero. Then for the water–air two phase system (n = 2) the right hand side of Equation (1) becomes zero. The volume fraction equation will not be solved for the primary phase and the primary-phase volume fraction will be calculated based on the following constraint:

$$\sum_{q=1}^{n}\alpha_q=1 \tag{2}$$

2.2. Momentum equation for VOF model

A single momentum equation is solved throughout the domain, and then the computed velocity field is shared among the phases. The momentum equation, which relies on the volume fractions of all phases, is: