Applied Thermal Engineering 88 (2015) 297–305

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Bed to wall heat transfer in supercritical water fluidized bed: Comparison with the gas–solid fluidized bed

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A R T I C L E I N F O

Article history:
Received 16 June 2014
Received in revised form
16 September 2014
Accepted 20 September 2014
Available online 30 September 2014

Keywords:
Supercritical water
Fluidized bed
Heat transfer
Kinetic theory

A B S T R A C T

Supercritical water (SCW) fluidized bed is a new reactor concept for gasification of wet biomass. In this paper, the Eulerian two-fluid model based on Kinetic Theory of Granular Flow in fluidized bed was established, and the physical model of movement of single bubble up the wall was adopted. The comparison studies of particle distribution, temperature distribution and transient heat transfer characteristics between the SCW and gas–solid fluidized bed were carried out. The results show that the bubble diameter and rise velocity in SCW fluidized bed are smaller than those in gas–solid fluidized bed. With the increasing solid volume fraction near the wall, the bed-to-wall heat transfer coefficient decreases in SCW fluidized bed, while it increases in gas–solid fluidized bed. What is more, the bed-to-wall heat transfer coefficient is sensitive to superficial velocity where the solid volume fraction is low, which is different from that in gas–solid fluidized bed.

1. Introduction

Biomass is a renewable energy resource. The use of biomass for energy can cause no net increase in carbon dioxide emissions to the atmosphere. However, because of its low energy density, it is necessary to convert biomass to liquid or gas fuel, such as hydrogen, which can be used cleanly and high-efficiently in fuel cells [1]. One of the methods for producing hydrogen from biomass is supercritical water gasification (SCWG) that can avoid high drying costs in conventional thermo-chemical gasification process, especially for wet biomass [2].In the past two decades, SCWG was concerned widely by many investigators in USA [3,4], Europe [2,5], Japan [6,7], China [8,9] and other countries [10–12], and great progress has been made. Reactor design is a key issue for SCWG. Most of the research conducted in this area has employed tubular reactors. Reactor plugging is a critical problem for SCWG of biomass with a tubular reactor, which results from the formation of char at the heating section and the buildup of ash inside the reactor. Such reactor plugging will cause system shut-down, which presents a severe problem for the energy conversion process. To solve this problem, the fluidized bed reactor concept was proposed by Mastsumura and Minowa to gasify wet biomass in supercritical water (SCW) [13]. In 2008, we developed a SCW fluidized bed successfully to gasify biomass, and the reactor plugging was avoided [14]. At the same time, some problems including instability in the composition of the product gas, nonuniform fluidized bed temperature and particles overflowing from the reactor, were found during using the SCW fluidized bed reactor. The main reason is that the reactor was designed based on the classical fluidized bed theory which is not suit for the SCW fluidized bed. Therefore, it is necessary to study the flow and heat transfer for the design of a SCW fluidized bed.

Above the critical point of water (647.096 K and 22.06 MPa), the boundary between liquid and gas phases disappears. SCW has significant difference in physical properties compared with liquid water and vapour. Fig. 1 shows variation of the density, the dynamic viscosity, the specific heat and the thermal conductivity with temperature at 23 MPa. The maximum value of the specific heat defines the so-called pseudo-critical temperature. In the vicinity of the pseudo-critical temperature, properties vary especially strong with only small changes in temperature. The thermal-hydraulic behaviour of SCW is characterized by strong variations of the thermophysical properties. The significant changes in properties influence the heat transfer to supercritical water, which could lead to some special features in heat transfer such as heat transfer deterioration and enhancement [15].

Much attention has been paid consequently to the SCW heat transfer for a long time and numerical simulation is widely used for studying SCW heat transfer due to the measurement technique

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http://dx.doi.org/10.1016/j.applthermaleng.2014.09.052
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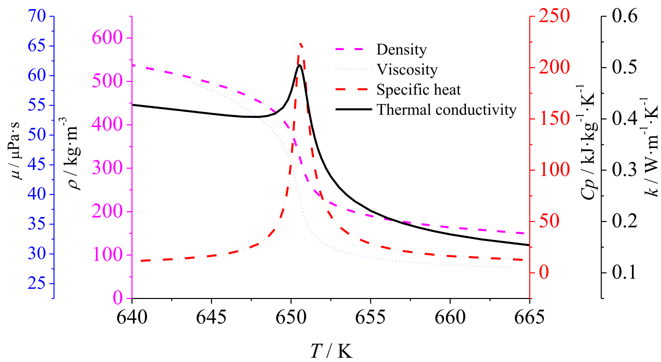

Fig. 1. Physical properties of supercritical water near the proposed critical point at 23 MPa.

limitation and costs associated with experimental study [15–25]. In recent years, some experiments about the heat transfer characteristics of supercritical pressure water have also been carried out [26,27]. Few works were done for the flow and heat transfer in a SCW fluidized bed. Potic et al. introduced the concept of a micro-fluidized bed [28], which was a cylindrical quartz reactor with an internal diameter of only 1 mm used for process conditions up to 773 K and 244 bar. Properties of the micro-fluidized bed such as the minimum fluidization velocity, the minimum bubbling velocity, bed expansion, and identification of the fluidization regime were investigated by visual inspection. However, the wall effect in micro-fluidized bed made the application of research results more difficult. In our previous work, an experimental study on the hydrodynamics of a SCW fluidized bed was conducted and a predicting correlation for the minimum fluidization velocity in a SCW fluidized bed was obtained based on the experimental results [29]. Wei et al. applied the Eulerian model incorporated with the kinetic theory for solid particles to simulate the solid and residence time distributions (RTD) of feeding materials in a SCW fluidized bed [30]. Effect of four types of feeding methods and feeding rates on solid distribution and RTD were evaluated based on the simulation results.

To the best of our knowledge, the bed-to-wall heat transfer in SCW fluidized bed, both numerical simulation and experiment, has not been reported in literature, while the heat transfer in a gas–solid fluidized bed has been investigated widely. The heat transfer in a fluidized bed contains several kinds, such as particle-fluid, particle–particle, particle–wall and fluid–wall, which are more complex than that in tube. The numerical models for the flow and heat transfer in fluidized bed are mainly TFM and DPM. In TFM, the solid phase and liquid phase are treated as two fluids governed by separate governing equations, the temperature and velocity fields for both phases are solved with Eulerian method by calculating conservation, momentum and energy equation. In DPM, particles and fluid are considered as discrete phase and continuum phase, respectively. Each particle is tracked by giving an identity code, whose movement is acquired by solving Newton's second law of motion. The fluid phase is deal with Euler's method and the force acting on it is acquired with N–S equation. Due to the small calculation amount for Eulerian two-fluid model, it is adopted by most investigators. The Eulerian two-fluid model is extensively used in simulation of the heat transfer in fluidized bed [31–39]. Some research with DPM method are also conducted [40,41]. The heat transfer forms investigated by these researchers are diverse, such as heat transfer between bed and wall, particle and fluid, bed and tube.

In this paper, the Eulerian two-fluid model incorporated with the kinetic theory of granular flow for the numerical simulation on the bed-wall heat transfer in the SCW and gas–solid fluidized bed was established. The comparison studies of particle distribution, temperature distribution and transient heat transfer characteristics between SCW fluidized bed and gas–solid fluidized bed were carried out.

2. Model description and numerical method

2.1. Governing equations

The Eulerian two-fluid model incorporated with the kinetic theory of granular flow (KTGF) was employed to describe the interactions between gas and granular particles within the fluidized bed. Separate conservation equations are formulated for mass, momentum, and thermal energy for both phases. The governing equations are summarized in Table 1.The transport equation and all the constitutive equations of the KTGF model and interphase exchange coefficient are listed in Table 2.

Numerous empirical correlations for calculating the interphase exchange coefficient β have been reported in literature, such as Wen and Yu [42], Gidaspow [43] and Syamlal and O'Brien [44]. The empirical correlations of Gidaspow is a combination of the work of Ergun [45] and Wen and Yu [42]. The equation of Ergun [45]is found applicable in SCW fluidized bed through a fixed bed according to our experiment results [29]. The equations of Wen and Yu [42]and Ergun [44]are also widely adopted in investigation of gas–solid fluidized bed, liquid–solid fluidized bed and a fluidized bed under elevated pressure or supercritical CO_2 condition. Therefore, the correlation given by Gidaspow was used in this paper.

2.2. Interphase heat transfer

The interphase heat transfer coefficient is described with the empirical relation proposed by Gunn [46] in 1978, the expression of Nusselt number as a function of particle Reynolds number and Prandtl number is given by

Table 1
Governing equations.

Conservation of mass

Fluid phase

$$\frac{\partial}{\partial t}(\alpha_f \rho_f) + \nabla\cdot(\alpha_f \rho_f v_f) = 0 \quad (1)$$

Solids phase

$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla\cdot(\alpha_s \rho_s v_s) = 0 \quad (2)$$

Conservation of momentum

Fluid phase

$$\frac{\partial}{\partial t}(\alpha_f \rho_f v_f) + \nabla\cdot(\alpha_f \rho_f v_f v_f) = \nabla\cdot\tau_f - \alpha_f \nabla p + \alpha_f \rho_f g - \beta(v_f - v_s) \quad (3)$$

$$\tau_f = \alpha_f \mu_f \left(v_f + v_f^T\right) + \alpha_f\left(-\frac{2}{3}\mu_f\right)\nabla\cdot v_f I \quad (4)$$

Solids phase

$$\frac{\partial}{\partial t}(\alpha_s \rho_s v_s) + \nabla\cdot(\alpha_s \rho_s v_s v_s) = \nabla\cdot\tau_s - \nabla p_s - \alpha_s \nabla p + \alpha_s \rho_s g + \beta(v_f - v_s) \quad (5)$$

Conservation of energy

Fluid phase

$$\frac{\partial}{\partial t}(\alpha_f \rho_f h_f) + \nabla\cdot(\alpha_f \rho_f h_f v_f) = -\nabla\cdot\alpha_f\cdot q_f + \psi\left(T_s - T_f\right) + \tau_f\cdot\nabla\cdot v_f + \alpha_f\left[\frac{\partial}{\partial t}p + v_f \nabla p\right] \quad (6)$$

Solids phase

$$\frac{\partial}{\partial t}(\alpha_s \rho_s h_s) + \nabla\cdot(\alpha_s \rho_s h_s v_s) = -\nabla\cdot\alpha_s\cdot q_s + \psi\left(T_f - T_s\right) + \tau_s\cdot\nabla\cdot v_s + \alpha_s\left[\frac{\partial}{\partial t}p + v_s \nabla p\right] \quad (7)$$