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Hydrogen production by supercritical water gasification of biomass: Particle and residence time distribution in fluidized bed reactor

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ABSTRACT

Particle distribution and residence time distribution (RTD) in supercritical water fluidized bed reactor (SCWFBR) greatly affect the hydrogen yield through determining the two phase mixing and reaction time. A Eulerian model incorporating the kinetic theory for solid particles was applied to simulate the solid distribution and RTD of feeding materials. The effect of four types of feeding methods and feeding rates on solid distribution and RTD were evaluated based on the simulation results. Results showed that double symmetrical feeding pipe with an feeding mouth angle of 45° provides more uniform solid distribution and longer residence time compared with those of other three types. A nonlinear relationship between feeding rate and RTD was observed, and an optimum feeding rate was found to be related to the best solid-fluid mixing in the study.

1. Introduction

It is necessary to find new renewable and environment-friendly energy due to the depletion of limited fossil energy resources and the pollution problems caused by combustion of fossil fuels [1]. Hydrogen is viewed as a new ideal energy carrier in future for its high energy density, low pollution after combustion, and good performance in transportation [2]. Hydrogen production from utilizing biomass has attracted more and more attention in recent years. Using fluidized bed as the reactor and supercritical water (SCW) as a work fluid to gasify biomass is a new promising technology for hydrogen production. This technology combined with the advantages of SCW gasification and fluidized bed: (1) biomass with high moisture content can be gasified in SCWFBR without a drying process which consumes much energy and money; (2) SCWFBR prevents the tubular reactor plugging and carbon deposition on the wall of the reactor; (3) the solid particles in SCWFBR enhance the heat and mass transfer and prolong the mean resident time of biomass, which is useful for complete gasification [3,4]. The conception of SCW fluidized bed reactor was proposed by Mastsumura and Minowa for avoiding reactor plugging [5]. Latter, Lu et al. [4] successfully developed an SCW fluidized bed system, which can prevent the reactor plugging effectively, improve the biomass gasification efficiency, and continuously produce high component of hydrogen. However, there are some problems in present SCW fluidized bed system, such as instable composition of product gas, bed materials outflow, and bed temperature non-uniformity, due to lack of unperfected design theory and operating method [6,7]. A complete biomass gasification reaction and stable composition of product gas in SCWFER

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Nomenclature

C_D	drag coefficient
C(t)	concentration of the tracer at time of t
D_i	diffusion coefficient
d_s	particle diameter, m
E(t)	residence time distribution
e_{ss}	restitution coefficient
F(t)	cumulative residence time distribution
g	acceleration due to gravity, m/s^3
$g_{o,ss}$	radial distribution coefficient
H	bed height, m
$\bar{\bar{I}}$	stress tensor
I_{2D}	second invariant of the deviatoric stress tensor
k_{θ_s}	diffusion coefficient for granular energy, kg/s m
K_{fs}	gas/solid momentum exchange coefficient
PDF	probability density function
R	feeding rate $R_{fd} = \upsilon_{fd}/\upsilon_{ms}$
RTD	residence time distribution
Re	Reynolds number
SCW	supercritical water
SCWFBR	supercritical water fluidized bed reactor
U_i	superficial fluid velocity, m/s

Greek letters

α_i	volume fraction
δ	standard deviation
∂	mathematical operator of partial derivative
$\gamma_{\Theta s}$	collision dissipation of energy, kg/s^3 m
ε_i	voidage
Θ_s	granular temperature, m^2/s^2
λ_i	bulk viscosity, kg/s m
μ_i	shear viscosity, kg/s m
υ_i	velocity, m/s
ρ_i	density, kg/m^3
φ	angle of internal friction, degree

Subscripts

f	fluid
i	general index
s	solids
mf	minimum fluidization
sim	simulated vales
exp	experimental values
fd	value in feeding pipe
ms	value in mainstream

depend upon good contact between feeding materials and catalyst particles, and enough residence time. However, the reacting biomass materials usually do not flow through the reactor uniformly due to the agglomeration of catalyst particles or the attachment on the wall of reactor because those sections in the fluidized bed provide much resistance to flow and a major portion of fluid flowing through some other places with little resistance. Those results in bad mixing between flow and solid phase, short residence time of feeding materials, incomplete reaction, and low component of hydrogen production [8].

The residence time distribution (RTD) of reactor is one of the characteristics of the mixing procedure. The basic definitions and systematic descriptions of RTD were introduced by the classical chemical work [9]. The RTD of primary phase (e.g. gas phase for gas–solid fluidized bed) or second phase (e.g. solid phase for gas–solid fluidized bed) in gas–solid bubble or circulating fluidized bed reactor are determined by experimental methods, RTD models and numerical simulation [10–13]. Experimental study of hydrodynamics of SCW fluidized bed can be hardly conducted due to the restrictions of measuring methods and precision. The RTD models of SCW fluidized bed are inconclusive because the complicated two phase flow in SCWFBR is still unclear. However, numerical simulation provides a powerful method for determination of RTD. Numerical simulations of the multiphase flow in fluidized beds give information about the local values of phase holdups and their spatial distributions especially in the regions where measurements are either difficult or impossible. Rodríguez-Rojo and Cocero [14] simulated the supercritical CO_2 fluidized bed based on Eulerian model. The RTD of primary phase was obtained and the simulation results showed a good agreement with the experimental data. Kalage et al. [15] simulated the solid–liquid circulating multistage fluidized bed to predict the RTD. They found that excellent agreement between the calculated results and the experimental values of RTD.

Solid distribution is another important characteristic of SCWFBR. The solid distribution always depends on the interaction of fluid and particles group and the interaction between particles. Solid distribution is relative to the flow structure of fluidized bed [16–18]. The relationship between solid distribution and RTD, and the effect of injection or feeding methods on solid distribution are little reported in literature.

In this paper, particle distribution and RTD are obtained by numerical simulation with a Eulerian model incorporating the kinetic theory for solid particles model. The mechanism of feeding materials transportation is analyzed on the basic of the simulation results. Effect of feeding ways and feeding rate on solid distribution and RTD are analyzed by statistical methods.

2. Mathematical modeling

2.1. *Physical model*

An SCW fluidized bed has been produced by State Key Laboratory of Multiphase Flow in Power Engineering (SKLMF), and present simulation is in accordance with this apparatus [4]. The SCW fluidized bed reactor and four types of feeding pipes are shown in Fig. 1. Here we name those feeding method according to the capital letters in Fig. 1 (for example, the method of feeding way with a capital letter of A is called type A). The early reactor includes three parts: a fluidized section (the height of 300 mm), a suspension section (the height of 615 mm) and a single feeding pipe (type A) [4]. The bed materials are quartz sands (Geldart-group B) which load with

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