Chemical Engineering & Processing: Process Intensification 129 (2018) 148–161

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

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

A hydrodynamic model for biomass gasification in a circulating fluidized bed riser

Mohamed I. Hassan[a,1], Yassir T. Makkawi[b,*]

[a] European Bioenergy Research Institute (EBRI), School of Engineering and Applied Science, Aston University, Birmingham, B4 7ET, UK
[b] Chemical Engineering Department, College of Engineering, American University of Sharjah, P.O. Box 26666, Sharjah, United Arab Emirates

ARTICLE INFO

Keywords:
Circulating fluidized bed
CFD modeling
Hydrodynamics
Experiment validation
Gasification

ABSTRACT

This study presents a three-dimensional Computational Fluid Dynamic (CFD) model and experimental measurements of the hydrodynamics in the riser section of a Circulating Fluidized Bed (CFB) biomass gasifier consisting of a binary mixture of polydisperse particles. The model is based on multi-fluid (Eulerian-Eulerian) approach with constitutive equations adopted from the Kinetic Theory of Granular Flow (KTGF). The study first presents an assessment of the various options of the constitutive and closure equations for a binary mixture followed by sensitivity analysis of the model to the solution time step, cell size, turbulence and the alternative formulations of the granular energy equation. Accordingly, a robust and reliable hydrodynamic model is recommended and validated using conventional pressure measurements and Positron Emission Particle Tracking (PEPT) technique. Furthermore, the model predictions and experiments revealed evidence of the particle recirculation within the lower part of the riser, which is an important feature contributing to rapid mass and heat transfer in a CFB gasifier. The present hydrodynamic model can be further developed; by incorporating appropriate reactions and heat transfer equations, in order to fully predict the performance and products of a CFB biomass gasifier.

1. Introduction

The application of Circulating Fluidized Beds (CFB) to biomass thermal conversion (gasification and pyrolysis) is currently receiving increasing attention due to its good mixing, high thermal efficiency and most importantly, its excellent scale-up potentials up to around 1000 tonnes of dry biomass feed per day [1]. However, practical experimental investigation in a CFB, for testing new feedstock or parametric sensitivity analysis, is often difficult, expensive and requires high expertise due to the complexity associated with the high-temperature operation and release of particulate and toxic/highly flammable gases. Computational Fluid Dynamic (CFD) models integrated with equations describing the heat transfer, transport of species and chemical reactions, offers an alternative solution. Such models can be solved using standard computers at a reasonable computational time to reveal detailed features of the reactor such as the solid and gas distribution, velocities, pressure, temperature, gas species concentrations and product quality. As a result, studies using CFD models for the simulation and analysis of processes involving rapid thermochemical conversion, such as in catalytic reforming of gases, combustion of solid waste and conversion of biomass to bio-fuels are nowadays frequently reported in the literature [2,3]. The advances in computational power has also been matched with the development of user-friendly commercial software. Examples of some of the widely used commercial software for particle-gas flow simulation are ANSYS (FLUENT and CFX), COMSOL and Barracuda. Other highly functional open-source CFD software is also available free for academic use such as MFIX and OpenFoam. Most of these codes offer the solution of multiphase flows in Eulerian-Eulerian or Eulerian-lagrangian approaches. The latter, which is also referred to as Eulerian-DEM, has the advantage of being more accurate by tracking each individual particle, but at the expense of high computational time (CPU time). The former treats both of the solid and gas phases as an interpenetrating continuum based on ensemble averaging, hence relatively faster in handling large systems but less revealing at the discrete particle level. Nevertheless, the Eulerian-Eulerian approach remains the most popular option among academic researchers for the simulation of multiphase flow with chemical reactions. Having said that, it must be noted that applying the Eulerian-Eulerian approach to three-dimensional simulations of polydispersed suspension requires a good understanding of the various constitutive

---

* Corresponding author.
E-mail addresses: mihassan@jazanu.edu.sa (M.I. Hassan), ymakkawi@aus.edu (Y.T. Makkawi).
[1] Current address: Chemical Engineering Department, Faculty of Engineering, Jazan University, P.O. Box 114, Jazan, Saudi Arabia.

https://doi.org/10.1016/j.cep.2018.05.012
Received 3 March 2018; Received in revised form 18 May 2018; Accepted 22 May 2018

Nomenclature

$\bar{\bar{I}}$	unit tensor (–)
C_d	particle drag coefficient (–)
C_{fr}	Friction coefficient (–)
C_1, $C_2 C_3$	turbulence model constants (–)
d_i	diameter of solid phase i (m)
e	particle restitution coefficient (–)
g_0	radial distribution function (–)
$G_k G_b$	turbulence kinetics due to velocity gradient and buoyancy, respectively (kgm^{-1}s^{-2})
$\vec{g}$	gravity (m s^{-2})
K	solid-solid momentum exchange coefficient (kg m^{-3} s^{-1})
k_e	turbulence kinetic energy (m^2 s^{-2})
w_t	turbulence dissipation energy (m^2 s^{-3})
$\sigma_e \sigma_t$	prandtl numbers for kinetic and dissipation energies, respectively (–)
N_c	Courant number (–)
P	pressure (Pa)
Re	Reynolds number (–)
t	time (s)
$\vec{u}_g$, $\vec{u}_s$	gas and solid velocity vector (m s^{-1})
u_r	particle terminal velocity (m s^{-1})

Greek letters

ε	volume fraction (–)
β	momentum exchange coefficient (kg m^{-3} s^{-1})
γ	collisional energy dissipation (kg m^{-1} s^{-3})
θ	granular temperature of solid phase i (m^2 s^{-2})
k	diffusion coefficient of granular energy (kg m^{-1} s^{-1})
$\varnothing'$	specularity coefficient (–)
ρ	density (kg m^{-3})
μ_{eff}	effective turbulence viscosity (kg m^{-1} s^{-1})
$\bar{\bar{\tau}}$	shear stress tensor (kg m^{-1} s^{-2})
Δ_{cell}	computational face cell size (m)

Subscripts

s, g	solid and gas phases, respectively
w	wall
col	wall
kin	kinetic

and closure equations in addition to careful setting of the solution procedure.

As noted above, one of the major attractive features of the CFB gasification technology is its high thermal efficiency; it allows for the supply of the heat required to derive a highly endothermic thermochemical conversion process in a closed loop without the need of external heating. For example, in steam gasification (also referred to as pyrolytic gasification), this is achieved by coupling two reactors, creating what is usually referred to as dual fluidized bed (DFB) gasifier. In this arrangement, one reactor is used for the gasification and another is used for the char combustion. In the gasifier, the biomass is brought into contact with the fluidizing gas (steam or air/steam mixture) and a heat carrier solid, ideally to maintain the gasifier within the range of 750–950 °C [2,4]. In the combustor, the transferable heat carrier solid (such as sand) is raised to a high temperature by char combustion. The use of steam in biomass gasification is particularly attractive as it enhances hydrogen production through a water gas shift reaction [5,6]. Fig. 1] shows two examples of the arrangements of a DFB reactor for biomass steam gasification. In this study, the focus is made on the simulation of the riser, shown in the left section of the CFB arrangement given in Fig. 1-b. Here, the gasification is carried out in the riser and the reaction is entirely driven by hot circulating inert solid introduced at the bottom of the riser from the connected combustor.

Review of the recent literature on modeling of biomass gasification in fluidized bed reactors show that the CFB type received less attention compared to the bubbling bed. See Table 1 for examples of the most recent studies. Modeling of the flow hydrodynamics in a CFB gasifier is challenging due to the existence of multi-solids which undergo complex collisional interactions while dispersing in a continuum gas phase. Furthermore, the accuracy of the Eulerian-Eulerian model for a polydispersed suspension is heavily dependent on a range of constitutive and closure equations, as noted earlier. Therefore, the overall objective of this study is to identify a reliable and robust hydrodynamic model, which can be used as a platform for further development of a full

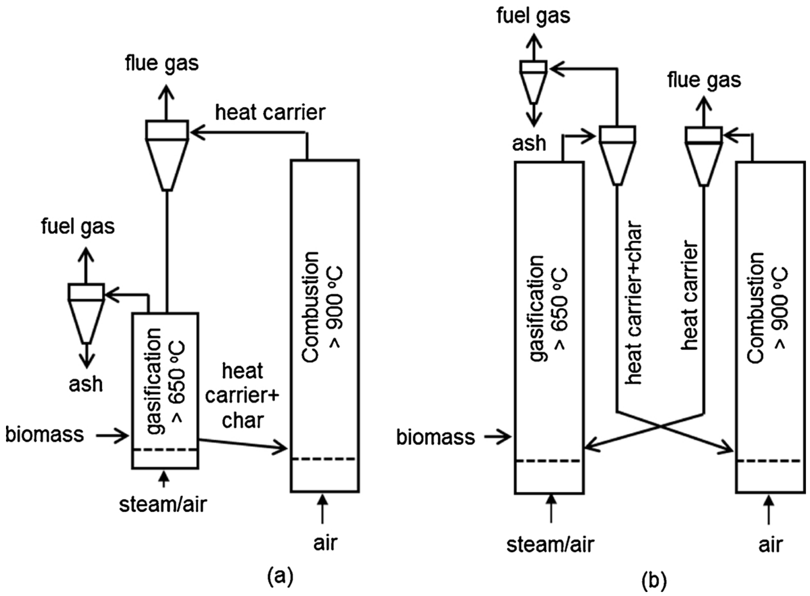

Fig. 1. Examples of dual fluidized bed reactors for biomass gasification (a) bubbling bed coupled with a riser (b) two coupled risers.