Powder Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Powder Technology

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

Gas-solid mixing and mass transfer in a tapered fluidized bed of biomass with pulsed gas flow

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ARTICLE INFO

Article history:
Received 15 May 2016
Received in revised form 21 September 2016
Accepted 13 October 2016
Available online xxxx

Keywords:
Fluidized bed
Biomass drying
Mass transfer
Tapered bottom section
Drying model

ABSTRACT

Improvement in fluidization quality and mass transfer rate was made to the pulsed fluidized bed for the fluidization of biomass particles without the need of inert bed materials by modifying the rectangular cross-section to a tapered bottom section to eliminate the dead-zones. Batch biomass drying tests were performed as an indirect indicator of gas-solid contact efficiency and mass transfer performance. Compared to the original design, biomass particles were able to be fluidized in the tapered column at a wider range of gas pulsation frequencies with significantly reduced channeling and gas bypassing. Faster drying and improved mass transfer were also observed and confirmed by measured instantaneous drying rate and final moisture content of the biomass sample. A model based on two-phase theory for biomass drying in fluidized bed verified such findings, where under the same operating condition fluidized bed with tapered bottom showed higher effective diffusion coefficients than the original design.

1. Introduction

Biomass is an abundantly available energy resource comprised of various types of organic feedstock including forest and agricultural residues as well as municipal solid waste, which have been increasingly utilized for fuel/energy production. Second-generation biofuels with the aim of alleviating environmental pressure by using ligno-cellulosic biomass have shown great promise to bring new regional and industrial interests to the biofuel value chain [1]. When compared with fossil fuels, it has been demonstrated that bioenergy derived from ligno-cellulosic biomass such as forest residues could reduce CO_2 and other greenhouse gas (GHG) emissions in the long term [2,3]. In Canada, the national GHG emissions in 2014 were estimated at 732 million tonnes CO_2-equivalent from all sources [4], nearly one third of which was attributed to the transportation sector. Research by Mabee and Saddler has demonstrated that second-generation feedstock could meet 50% of Canada's transportation fuel needs [5]. As a result, a number of cost-effective thermal conversion processes have arrived in the spotlight and shown great promise, including biomass torrefaction, pyrolysis and gasification, which convert biomass into high heating value solid fuel or biogas. To facilitate compact storage and long-distance transport, biomass residues are commonly made into pellets. Global pellet production reached 24.1 million tonnes in 2014 [6]. The EU accounted for nearly half of global production, followed by North America (33%). In Canada, wood pellet production capacity is approximately 3.4 million tonnes per year as of 2012 [7], and pellet production capacity in British Columbia alone accounted for 66% of Canada's total pellet capacity [8]. However, there are estimated 32 million tonnes of biomass residues available each year in British Columbia (BC) alone. If these biomass residues could be properly utilized, it would be able to replace half of the fossil fuel consumption in BC.

The road to commercial utilization of biomass is often held back by the marked difference between biomass and traditional solid fuels in terms of physical and chemical properties. Compared to traditional fuels, biomass materials often possess high moisture and ash content, low bulk density and energy density, irregular shapes and low carbon-to-nitrogen ratio. Sawdust that comes from sawmill contains up to 60% moisture. Depending on the source, municipal solid waste (MSW) from developed countries contains 20–30% water, in developing countries it is typically 50% and could be as high as 70% [9]. Despite the unusual nature of biomass materials, fluidized bed reactors with high flexibility, heat and mass transfer rate are often chosen over fixed bed reactors for the processing (e.g. drying, pyrolysis and gasification) of biomass residues. To ensure smooth and stable fluidization inert particles such as sand are often mixed with biomass particles. Studies have shown that the addition of sand particles reduces the occurrence of undesired phenomenon such as channeling and gas bypassing [10]. Bed material also serves as heat carrier in certain cases, for instance biomass gasification [11–15]. For biomass torrefaction where the main product is

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http://dx.doi.org/10.1016/j.powtec.2016.10.031
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Please cite this article as: D. Jia, et al., Gas-solid mixing and mass transfer in a tapered fluidized bed of biomass with pulsed gas flow, Powder Technol. (2016), http://dx.doi.org/10.1016/j.powtec.2016.10.031

Nomenclature

A	Cross-section area of the fluidized bed column, m^2
A'	Interfacial area of particle per unit volume of dense phase, m^2/m^3
d_b	Bubble diameter, m
d_{b0}	Initial bubble diameter at multi-orifice distributor plate, m
d_{bm}	Maximum attainable bubble diameter, m
d_p	Particle diameter, m
D_{eff}	Effective diffusivity, m^2/s
D_0	Pre-exponential factor in Arrhenius equation, m^2/s
D_t	Hydraulic diameter of the column, m
D_v	Molecular diffusivity of water vapor in air, m^2/s
E_a	Activation energy, kJ/mol
G_b	Gas flow rate in bubble phase per unit volume of bed, $m^3/(m^3s)$
G_d	Gas flow rate in dense phase per unit volume of bed, $m^3/(m^3s)$
f	Pulsation frequency, Hz
f_N	Natural frequency, Hz
K_c	Mass transfer coefficient across bubble boundary, m/s
K_i	Particle surface mass transfer coefficient, m/s
m_{wet}	Water content in wet biomass samples, g
m_{dry}	Water content in dried biomass samples, g
M	Mass flow rate of drying air, g/s
N_{or}	Number of orifices in distributor
p	Water vapor pressure, Pa
p_s	Saturated water vapor pressure, Pa
r	Radial distance, m
R	Universal gas constant, $J/(kg \cdot K)$
Re_{mf}	Reynolds number at minimum fluidization, $\rho_g d_p U_{mf}/\mu_g$
R_p	Radius of particle, m
Sc	Schmidt number, $\mu_g/\rho_g D_v$
t	Time, s
T	Temperature, K
U	Superficial gas velocity based in the non-tapered section, m/s
$\overline{U}$	Average gas velocity, m/s
U_b	Bubble rise velocity, m/s
U_{mf}	Minimum fluidization velocity, m/s
U_z	Superficial gas velocity at certain bed height z in the tapered section, m/s
w	Weight of the sample, g
W	Drying rate, g/s
X	Moisture distribution within a biomass particle, dry basis
X_e	Equilibrium moisture content of biomass samples, dry basis
X_{Exp}	Experimentally obtained moisture content of biomass samples, dry basis
X_0	Initial moisture content of biomass samples, dry basis
$\overline{X}$	Average moisture content of the biomass particles at a given time, dry basis
Y_b	Absolute humidity in the bubble phase, kg-water/kg-air
Y_d	Absolute humidity in the dense phase interstitial gas, kg-water/kg-air
Y_i	Absolute humidity of the inlet gas, kg-water/kg-air
Y_o	Absolute humidity of the exit gas, kg-water/kg-air
Y_p	Absolute humidity at particle surface, kg-water/kg-air
z	Height above gas distributor, m

Greek letters

ε_b	Bubble volume fraction
ε_{mf}	Bed voidage at minimum fluidization
η	Amount of water being removed
μ_g	Gas viscosity, $kg/(m \cdot s)$
ν	Simplified term, K^{-1}
ρ_p	Particle density, kg/m^3
ρ_g	Air density, kg/m^3
τ	Period of the pulsation, ms
φ	Mole fraction of non-diffusing component, dimensionless
Φ	Moisture ratio
χ^2	Reduced chi square
ω	Mass rate of evaporation of water per unit volume of bed, $kg/(m^3s)$

solid biofuel instead of biogas, fines of inert bed material generated by attrition are often adhered to the product, which dramatically increases the ash content of the torrefied biomass. Not only will the higher ash concentration undermine the quality of the product, but it also poses a threat to biomass operated turbines and boilers, where increased ash content in fuel pellets could lead to sintering and fouling, causing malfunctions of the unit and eventually leading to unscheduled shutdowns.

Currently the design and operation of many processes and equipment involving biomass rely on the knowledge of conventional fluidization and the assumption that biomass behaves similar to other conventional particles. However, the unusual properties of biomass and the possible influence on fluidization are largely underestimated [16]. The poor fluidization quality of biomass is likely caused by its low bulk density, irregular shapes and high moisture content that inevitably lead to strong inter-particle forces. Seville and Clift [17] found that the minimum fluidization velocity and bed voidage increased with liquid loading on particle surfaces, and the resulting stronger inter-particle forces could also explain the shift in fluidization behavior of Group B particles toward Group A and Group C particles. Additional energy from imposed electric field [18–20], magnetic field [21–25], vibration [26–35] and oscillating gas flow [36–43] could be introduced to the fluidized bed to break down the cohesive forces so as to achieve good fluidization.

The oscillating gas flow could be generated by installing a rotating distributor that makes the gas stream sweep across specified chambers [44–46], adding a perforated rotating disk below the distributor to periodically redistribute gas flow [47–49], or simply installing a solenoid valve [50–52]. The additional acceleration brought by the pulsation could break down some of the cohesive forces between particles and improve fluidization quality. The interaction between natural frequency of the bed and pulsation frequency of the gas flow also played an important role here. Wong and Baird studied the effect of flow pulsations ranging from 1 Hz to 10 Hz in a gas-solid fluidized bed [53], and found that at a high pulsation frequency the pressure fluctuation conformed with external oscillation with the pressure fluctuation following the gas pulsation. At a low pulsation frequency dampened pressure oscillations were observed, indicating the external pulsation frequency was higher than the natural frequency of the bed. It was shown that by operating in the vicinity of the natural frequency of the fluidized bed, heat and mass transfer could be enhanced [54].

In many industrial processes mechanical vibration is favored due to its simplicity in setting up. Yoshida and Kousaka [55] and Zaitsev et al. [56] discovered that vibration could overcome the inter-particle forces, leading to fluidization of particles that otherwise could not be fluidized. In addition, Zaitsev et al. [56] observed a state of fluidization introduced by vibration, which was otherwise impossible with only gas flow. The effects of vibration were attributed to overcoming the binding forces between particles and preventing particles from agglomerating. This is especially true for extremely fine particles of 1–5 μm in diameter. Bed

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