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Biomass drying in a pulsed fluidized bed without inert bed particles

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HIGHLIGHTS

- Fluidization of biomass without bed material is achieved with pulsed gas flow.
- Reducing opening time in a pulsation cycle benefits fluidization of wet particles.
- The addition of fines improves heat and mass transfer.
- Two-phase model can reasonably predict fluidized bed drying.
- Mass transfer rate at different frequencies is reflected by effective diffusivity.

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ABSTRACT

Batch drying was performed in the pulsed fluidized bed with various species of biomass particles as an indicator of gas–solid contact efficiency and mass transfer rate under different operating conditions including pulsation duty cycle and particle size distribution. The fluidization of cohesive biomass particles benefited from the shorter opening time of pulsed gas flow and increased peak pressure drop. The presence of fines enhanced gas–solid contact of large and irregular biomass particles, as well as the mass transfer efficiency. A drying model based on two-phase theory was proposed, from which effective diffusivity was calculated for various gas flow rates, temperature and pulsation frequency. Intricate relationship was discovered between pulsation frequency and effective diffusivity, as mass transfer was deeply connected with the hydrodynamics. Effective diffusivity was also found to be proportional to gas flow rate and drying temperature. Operating near the natural frequency of the system also favored drying and mass transfer.

1. Introduction

Biomass has been considered as a promising alternative to fossil fuels. Globally, biomass is responsible for 4.1% of the energy consumption in 2013, and by the end of 2014, share of renewable electricity production is 22.8%, among which power generated by biomass has increased by approximately 9% to 433 TWh [1]. In addition to renewable electricity generation, a number of cost-effective thermal conversion processes have also shown great promise, including biomass torrefaction, pyrolysis and gasification, which convert biomass into high heating value solid fuel or liquid fuels. To facilitate easy storage and transport over long distances, biomass resources such as industrial waste, industrial coproducts, food waste, agricultural and forest residues are commonly densified into pellets or briquettes. In 2014 the global wood pellet production reached 24 million tonnes, in which United States and Canada are the largest exporters, with a combined capacity of over 5 million tonnes per year. Despite most of the pellets Canada exported are from the province of British Columbia (BC), there are estimated 32 million tonnes of biomass residues available each year in BC alone. If these biomass residues could be properly utilized, it would be able to replace half of the fossil fuel consumption in BC. Biomass power generation could also replace beehive burners and significantly reduce the amount of particulate emissions [2].

One of challenges related to the utilization of biomass as an alternative energy source is that the physical and chemical properties are so different from traditional fuels that they may impact the design and operation of biomass related processes such as torrefaction, pyrolysis, gasification and combustion. Typically, the following characteristics are desired for a suitable source of fuel,

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Nomenclature

A	cross-sectional 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, $m^3/(m^3\ s)$
G_d	gas flow rate in dense phase per unit volume of bed, $m^3/(m^3\ s)$
f	pulsation 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 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, m/s
$\overline{U}$	average gas velocity, m/s
U_b	bubble rise velocity, m/s
U_{mf}	minimum fluidization velocity, 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_o	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
μ_g	gas viscosity, kg/(m s)
η	amount of water removed
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
Φ	moisture ratio
χ^2	reduced Chi square
ω	mass rate of evaporation of water per unit volume of bed, $kg/(m^3\ s)$

such as high energy density, low nitrogen, sulfur and ash contents, regular shapes, narrow particle size distribution, high bulk density and low moisture content. Nevertheless, biomass originated from various sources often exhibits different physical properties and chemical compositions. Sawdust, straw, rice hull, bagasse, switchgrass as well as sewage all come in different sizes and shapes. Biomass collected from the source also contains a considerable amount of water. Sawdust for instance contains up to 60% moisture, and for sewage it could be as high as 98% [3]. Ligno-cellulosic biomass consists mainly of cellulose, hemicellulose and lignin, and is fibrous in nature [4].

A reactor needs to be carefully designed so as to accommodate a wide range of raw biomass materials with distinct properties. Fluidized beds can offer good heat and mass transfer rates, in addition to reduced operating cost when compared to other reactors suitable for biomass processing, such as rotary drum and moving bed reactors. Due to the poor flowability and highly cohesive nature, channeling, bypassing and defluidization frequently occur in fluidized beds with biomass alone. One of the common solutions involves adding inert bed particles into fluidized bed together with biomass to stabilize the gas–solid flow, and also to serve as heat carrier in some cases [5–9]. One key disadvantage of such a strategy is that fine powders of bed particles (e.g. sand) are produced via attrition during fluidization, which will adhere to the biomass particles and be included in the biomass products. In the case of torrefaction where torrefied biomass will later be densified into pellets as a biofuel, the increased ash content of torrefied pellets will bring negative impacts on sintering and fouling, causing unscheduled shutdowns of the plant.

The cohesiveness of biomass particles could be attributed to low bulk density, irregular shapes and high moisture content. It is evident that even a thin layer of liquid on particles will render the particles more cohesive [10]. As liquid bridges and other inter-particle forces increase, the minimum fluidization velocity and minimum bubbling velocity will increase consequently. Many approaches have been proposed aiming at improving the fluidization quality of cohesive, fine or irregular particles, such as designing new distributors [11–13] and imposing electric field [14–16], magnetic field [17–21], sonic wave [22–24] and vibration [25–35] to the system, as well as pulsed gas flow [36–46]. Among all pulsation is greatly favored in many processes due to its ease of adaptation and non-invasive nature. The additional acceleration introduced by pulsation is beneficial to overcoming the inter-particle forces during fluidization and therefore reducing channeling and bypassing. As demonstrated by van den Bleek et al., the behavior of the gas bubbles in a gas–solid fluidized bed is chaotic [47]. Pulsation among other approaches could stabilize or “structure” the bed behavior and result in regular bubble patterns. A number of successful applications of fluidized beds with pulsed gas flow could be found, especially for the drying of