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PARTIC-1088; No. of Pages 8
ARTICLE IN PRESS

Particuology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Particuology

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

Effects of liquid feed rate and impeller rotation speed on heat transfer in a mechanically fluidized reactor

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ARTICLE INFO

Article history:
Received 15 June 2017
Received in revised form 30 September 2017
Accepted 20 October 2017
Available online xxx

Keywords:
Mechanical fluidization
Induction heating
Impeller rotation
Heat transfer
Particle size

ABSTRACT

A mechanically fluidized reactor (MFR) is a novel and compact reactor used for biomass pyrolysis. Endothermic biomass pyrolysis requires heat provided from the wall of the MFR. Meanwhile, mixing with a vertical stirrer helps achieve effective heat transfer from the wall to the bed. Here, the heat transfer characteristics between the wall of a 1.0-L MFR and its bed of mechanically fluidized sand particles were studied. An induction heating system was used to heat the wall, while a vertical blade stirrer was used for mixing. Heat transfer measurements were carried out using silica sand particles, having three average Sauter mean diameters: 190, 300, and 600 μm. The overall wall-to-bed heat transfer coefficients were estimated using temperature measurements taken during continuous injection of water onto the fluidized bed. The overall heat transfer coefficient for bed temperatures of 500–700 °C increased as particle size increased or superficial velocity of the vaporized liquid increased. Effect of impeller rotation speed also was investigated. Typically, the overall heat transfer coefficient increased as rotation speed increased. The wall-to-bed heat transfer coefficients obtained in this study are comparable to estimates from traditional bubbling fluidized beds, even at vapor velocities below the minimum fluidization velocity.

Introduction

Pyrolysis is an endothermic process that converts biomass into a dense higher energy liquid, biochar, and gases through thermal decomposition in the absence of oxygen. It is an efficient substitute to combustion of fossil fuels, making use of renewable resources to obtain high yields of chemicals and fuels while reducing greenhouse gas emissions (Fortin, Pelletier, François, & Dufour, 2016; Jahirul, Rasul, Chowdhury, & Ashwath, 2012). The success of commercial pyrolysis reactors depends on effective heat transfer to the biomass particles (Bridgwater, 2012). At lower temperatures ($T < 400\,^\circ C$), pyrolysis of biomass mostly results in biochar, with minor vapors and permanent gases (e.g., carbon dioxide and water), while higher molecular weight volatile products, such as liquid biofuels and bio-derived chemicals, are obtained at higher temperatures ($400\,^\circ C < T < 600\,^\circ C$). Therefore, recent research has focused on the higher temperature range (Elliott, 2015).

Different methods of providing heat include partial combustion, direct heat transfer using a hot gas or circulating solids, and indirect heat transfer using exchange surfaces (e.g., tubes, walls) (Bridgwater, 2012). Pyrolysis and other thermal cracking reactors depend on heat transfer from a surface, such as the reactor wall, to the reactor bed to convert the solid or liquid feedstock into cracked vapor products. Bubbling and turbulent fluidized beds are popular configurations for these conversions, as they provide good wall-to-bed heat transfer via effective bed-to-particle heat transfer (Kunii & Levenspiel, 1991).

One advantage of conventional fluidized beds is that they have a high heat transfer coefficient between the bed and the heat transfer surface, such as the wall or heat exchanger tube (Stefanova, Bi, Lim, & Grace, 2011). Conventional fluidized beds, however, require a considerable amount of fluidizing gas and are limited to bed solids that can be readily fluidized (e.g., fine sand). This complicates the recovery of the valuable biochar co-product, as well as increases the size and cost of the downstream condensation train (Stefanova et al., 2011). Pyrolysis equipment, such as Augur reactors, do not require a fluidizing gas. However, these reactors, which are mechanically driven, also cannot achieve the fast pyrolysis conditions required to obtain good yields of high quality liquid product (Bridgwater, 2012). Agitation was used by Reed and Fenske (1955) to enhance the heat transfer between the bed and the immersed heat exchange surface. They observed that there was an increase

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https://doi.org/10.1016/j.partic.2017.10.007

Nomenclature

A	heat transfer area (wall) (m^2)
A_L	area of heat losses (m^2)
c	specific heat capacity of fluidized solids (kJ/kg K)
c_g	specific heat capacity of gas (kJ/kg K)
c_p	specific heat capacity of particle (kJ/kg K)
C_{P_L}	specific heat of water (kJ/kg K)
Cp_v	specific heat of steam (kJ/kg K)
d_p	particle diameter (μm)
F_L	liquid injection flow rate (mL/min)
g	acceleration due to gravity (m/s^2)
k_g	gas thermal conductivity (W/m K)
T_1	temperature of the wall in the top part of the reactor (°C)
T_2	temperature of the wall in the center part of the reactor (°C)
T_3	temperature of the wall in the bottom part of the reactor (°C)
T_4	temperature of the vapor exiting from the vapor exit hole in the reactor (°C)
T_5	temperature of the vapor in the freeboard region of the reactor (°C)
T_{bed}	particle bed temperature in the reactor (°C)
T_{room}	room temperature (°C)
T_{wall}	wall temperature (°C)
$T_{w_{average}}$	average wall temperature (measured at 3 locations) (°C)
U	overall heat transfer coefficient (W/m^2 K)
$U_{average}$	average of overall heat transfer coefficient values measured at different rpm for mixing at a selected liquid flow rate (W/m^2 K)
$U_{correlation}$	oveall heat transfer coefficient from the Molerus correlation (W/m^2 K)
U_L	overall heat transfer losses (W/m^2 K)
U_{max}	maximum of all overall heat transfer coefficient values measured at different rpm for mixing at a selected liquid flow rate (W/m^2 K)
u	superficial steam velocity (m/s)
u_{mf}	minimum fluidization velocity (m/s)

Greek letters

ε_{mf}	void fraction at minimum fluidization, dimensionless
μ	viscosity (kg/m s)
ρ_g	gas density (kg/m^3)
ρ_p	particle density (kg/m^3)
ΔH_v	latent heat of vaporisation (kJ/kg)
$\Delta H_{v_{ref}}$	latent heat of vaporisation (at the reference temperature of 100 °C) (kJ/kg)

Dimensionless group

Ar	Archimedes number $= {d_p}^3 \left(\rho_p - \rho_g\right) \rho_g g/\mu^2$
Pr	Prandtl number=$c_g \mu / k_g$

in pressure drop related to this configuration, especially at low gas flow rates. The mechanically fluidized reactor (MFR) is a novel technology that can achieve fast pyrolysis conditions, without the use of an inert fluidizing gas, because of bed aeration by product gases and vapors, as well as mechanical mixing from a stirrer (Dosta et al., 2016; Lago, Greenhalf, Briens, & Berruti, 2015). This aeration process is demonstrated in Animation 1 (see the supplementary material). Thus, pure char products can easily be obtained from these reactors. Furthermore, the MFR is compact and can be used as the core component of mobile and cost efficient pyrolyzers.

A better understanding of the heat transfer characteristics of the MFR is needed at relevant bed temperatures to customize them for pyrolysis. Specifically, the impacts of particle size, impeller rotation speed, and rotation direction need to be evaluated. Use of MFRs for pyrolysis is limited by their heat transfer rate from the hot wall, which is heated by induction, to the bed of biomass. In this work, we attempt to optimize the wall-to-bed heat transfer in a MFR and compare its efficiency with heat transfer in conventional fluidized beds.

Table 1
Specifications of the mechanically fluidized reactor (MFR) used in this study.

Wall thickness (m)	0.0032
Inner diameter (m)	0.1015
Height (m)	0.127
Static bed height (m)	0.116
Total internal volume (L)	1.03
Heat transfer area (wall) (m^2)	0.0405

Fig. 1. Vertical blade stirrer (vertical length = 0.11 m, thickness = 0.0025 m).

Materials and methods

Experimental system

Experiments were performed using a stainless steel MFR, with dimensions listed in Table 1. In this setup, a mixing system is mounted on top of the reactor vessel, with the driveshaft at the center of the reactor flange. A 90-V permanent magnet DC gear motor (Leeson Electric Corporation, Grafton, WI, USA) and a Vari-Drive™ DC motor speed control (KB Electronics, Inc., Coral Springs, FL, USA) were used to drive the impeller. The rotational speed range of the model is 0–165 rpm. This rotation is independent of the bed fluidity, i.e., it is independent of the steam velocity through the bed. A pressure relief valve is included in case of an exhaust blockage. A vertical blade stirrer is used for mixing, as it has previously been shown to require less power and torque at all aeration rates and appears to enhance wall-to-bed heat transfer (Lago et al., 2015). The blade stirrer has two vertical blades (Fig. 1); blade orientation is designed to scrape the wall, drawing solids away from the wall. A syringe pump (Model: NE-1010; New Era Pump Systems, Inc., Farmingdale, NY, USA) is used to inject liquid in a semi-continuous manner at user-defined flow rates. The vapor generated from liquid

Please cite this article in press as: Kankariya, D., et al. Effects of liquid feed rate and impeller rotation speed on heat transfer in a mechanically fluidized reactor. *Particuology* (2018), https://doi.org/10.1016/j.partic.2017.10.007