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Investigation into overall heat transfer coefficient in indirectly heated rotary torrefier

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ABSTRACT

This paper investigates into the heat transfer from the wall to solids moving inside an indirectly heated rotary reactor with flights. The cluster renewal mechanistic model was used to develop a model for estimating the effective heat transfer coefficient (EHTC) from wall to solids. The overall heat transfer coefficient (OHTC) considered the heat transfer from the reactor wall to solids, and that from the wall to gases in the reactor whose wall temperature is maintained at constant temperature. Predictions from the OHTC model showed a good agreement with values measured in the reactor fed with brass particles. The model for estimating the EHTC was compared with the published experimental values of Herz et al. (2012), and showed a better agreement than the existing models. The developed model could therefore be applied for designing rotary torrefier or used for overall performance model of rotary torrefier.

1. Introduction

Rotary reactors due to their simplicity in construction and flexibility in operation are often used in many industrial applications. These reactors can handle both the wet [1] and dry solids. The rotary reactor could easily be installed with a different type of flights. The addition of flight not only enhances the mixing of solid but also increases the heat transfer rate to the solids [2] and also helps in producing a uniform product. Its shape could influence the specific solid inventory of the reactor. For instance, rotary reactors with the rectangular shapes of flights usually have a higher solid holding capacity compared to that with the straight flights [3].

Much has been published emphasizing the importance of the rotary reactors especially in the drying process, but these are also used in the thermal pretreatment of municipal solids [4], the calcination of limestone [5], the pyrolysis of solid wastes [6], the production of sponge iron ore [7], and the biomass torrefaction process [8–10]. The application of the rotary reactor for torrefaction process being in infancy, only limited works of literature are published.

Irrespective of the industrial applications, rotary reactor, whether either directly or indirectly heated types, involves the solid transportation and the heat transfer to solids. Hot flue gases are often deployed as a heat carrier and serve as a means of heat transfer in the directly heated reactors whereas externally heated drum or steam tubes inside the reactor provides indirect heating of the solid. Though both the direct and indirect heating methods have their own benefits, the effective heat transfer rate is lower in an indirectly heated rotary reactor compared to that in a direct heating type [11].

There are many advantages of using an indirectly heated rotary reactor. For instance, the torrefaction in an indirectly heated rotary reactor prevents possible spontaneous combustion inside the reactor and obtains uniformly torrefied solid products. In addition to this, rotary reactors could allow easy separation of the drying and devolatilization processes of the torrefaction process. This design has been used by authors [10] as it simplifies the collection of solid and separates the water vapor released during drying from the volatile gases evolved during the devolatilization stage of the torrefaction process.

In this paper, a mechanistic model is developed to evaluate the overall heat transfer coefficient of a cylindrical rotary reactor with flights operated with a constant wall temperature. Published experimental data points were used to validate effective wall to solid heat transfer coefficient (EHTC). On the other hand, an indirect experimental method was deployed to estimate and validate the overall heat transfer coefficient. Experiments were conducted in a temperature range of 150–340 °C, which could be used in the drying and devolatilization sections of a continuous two-stage rotary torrefier. The inert test materials (brass particles)

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Notations

A_{lsr}	Lateral surface area of the reactor [m^2]
BFR	Solid flow rate [kg min^{-1}]
C_{pbs}	Specific heat capacity of brass particle [J kg^{-1} K^{-1}]
C_{pC}	Specific heat capacity of collector [J kg^{-1} K^{-1}]
C_{pw}	Specific heat capacity of water [J kg^{-1} K^{-1}]
d_p	Effective particle diameter [m]
D	Reactor diameter [m]
e_{bs}	Voitage factor of bulk brass particle [–]
F_{ff}	Solid filling fraction [–]
$F_{ff,designated}$	Designated solid filling fraction [–]
g	Acceleration due to gravity [m s^{-2}]
L_f	Width of lift (flight) [m]
LMTD	Log mean temperature difference [°C]
m_b	Mass of collected brass particles in the container [kg]
m_c	Mass of the container [kg]
m_c	Mass of water in the container [kg]
N	Angular speed of reactor [RPM]
h_{ewb}	Effective wall to solid bed heat transfer coefficient [W m^{-2} K^{-1}]
h_o	Overall heat transfer coefficient of reactor [W m^{-2} K^{-1}]
h_{sb}	Heat transfer coefficient from solid surface to bed [W m^{-2} K^{-1}]
h_{wf}	Wall to gas heat transfer [W m^{-2} K^{-1}]
h_{ws}	Heat transfer coefficient from wall to solid surface [W m^{-2} K^{-1}]
k_f	Thermal conductivity of gas [W m^{-1} K^{-1}]
k_{bs}	Thermal conductivity of solid (brass) [W m^{-1} K^{-1}]
Pr_f	Prandtl number of gas [–]
Q_{gain}	Rate of heat gain by particles [W]
Ra_D	Rayleigh number [–]
t_c	Average solid contact time with hot surface per cascaded cycle [s]
T_e	Equilibrium temperature of water in the solid collector [°C]
T_{ex}	Temperature of solid at exit of reactor [°C]
T_{fc}	Final temperature of collector [°C]
T_{ic}	Initial temperature of collector [°C]
T_{iw}	Initial temperature of water in the collector [°C]
T_f	Final temperature of water inside the reactor [°C]
T_w	Reactor wall temperature [°C]
y_s	Virtual solid bed height in the reactor at stationary condition [m]

Symbols

α_f	Thermal diffusivity of gas [m^2 s^{-1}]
β	Inclination of reactor [°]
β_V	Volumetric expansion coefficient of gas [K^{-1}]
δ_d	Average fraction of area covered by solid on area of reactor [–]
Ω	Angle between flight and inclined solid bed surface [°]
ω	Angular speed of reactor [rad s^{-1}]
ϕ_s	Solid half-filling angle at stationary condition [°]
ψ	Dimensionless virtual thickness of gas film [–]
υ_f	Kinematic viscosity of gas at mean temperature of gas [m^2 s^{-1}]
ρ_{bs}	Bulk density of solid [kg m^{-3}]
θ_1	Angle of inclination of flight just before completing cascaded cycle [°]
θ_2	Angle subtended by solids at flight to center at the end of cascaded cycle [°]

were used to avoid reaction terms as an undesirable influence on the heat transfer mechanism. The effects of the different operating parameters on the overall heat transfer coefficient were also discussed. The experimentally determined overall heat transfer coefficient (OHTC) was then validated with the model predicted value.

2. Model development

2.1. Heat transfer mechanism in rotary reactor

Heat transfer from the reactor wall to the granular mass of solids involves three parallel mechanisms such as particle convection, conduction at the solid-wall contact surface, and radiation [12]. The radiation heat transfer is considered to be negligible at temperatures less than 527 °C [12]. A study by Canales et al. [13] has reported that the heat transfers to the particles in the directly heated system is mainly from the convection mode. A detailed review of the wall to solid heat transfer in a rotary kiln thermoreactor is presented in Li et al. [14]. A number of investigations to estimate the heat transfer coefficient between the reactor wall and the contact bed for the rotary kilns [15–17] and the circulating fluidized bed [18] can be found in the literatures.

In an indirectly heated rotary reactor without through gas flow, the effective heat transfer coefficient from the reactor wall to solid can be determined using the penetration theory [17]. However, the penetration model presented by Wes et al. [17] overestimates the effective heat transfer coefficient. Schlunder [19] has, therefore, presented a two-steps heat transfer mechanism from the hot wall to solid: (i) the wall-solid surface; and (ii) the solid surface-solid bed. According to this, the heat transfer rate depends on the surface contact resistance and the heat penetration (conduction) resistance of the solid bed. Similar two-steps heat transfer first through a thin layer of gas on the wall and then to rest of the body of solids in the circulating fluidized bed reactor was also studied in Basu [18], and is known as cluster renewal theory.

A complete analysis of detailed heat transfer phenomenon in the rotary reactor involves a number of parameters and becomes a complex process. In a rotary inclined reactor, the solids fed at one end continuously move down to the opposite end of the reactor. No gas is blown through the rotary torrefier under consideration. Only the volatiles released during torrefaction fills the void in the reactor. Here, the solids are swept up the rotating cylindrical wall by friction as well as by the flights attached to the wall, and then they drop down on the floor of the cylinder under the gravity force (Fig. 1). Thus, the packets of solids come in periodic contact with a section of the wall. Such motion of the solids is very similar to that in fluidized beds where cluster or packets of solids randomly come in contact with the wall and leave after a certain period of residence on the wall. So, we could make use of the cluster renewal model developed by Basu and Subbarao [20] to develop a mechanistic model for the effective wall to solids heat transfer in an indirectly heated rotary reactor.

A close examination of the heat transfers from wall to solid cluster or packets in a fluidized bed shows that the heat conduction through the actual contact area of solids on the wall is negligible. Major heat transfer occurs through conduction across thin layer gas trapped between the wall and the first layer of solids [18,21]. Further heat conduction from the first layer into the bulk solids occurs through transient heat conduction similar to that developed by Mickley and Fairbanks [22] for fluidized beds. Since the heat transfer depends mainly on the area of the reactor covered by