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Engineering design of direct contact counter current moving bed heat exchangers

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ABSTRACT

A heat transfer model was applied to simulate heat exchange in a direct contact counter current moving bed (CCMB) heat exchanger associated with a dry slag granulation process developed by CSIRO. Cold air is used to recover heat from hot solid slag granules in the heat exchanger. Experimental data was used to calibrate the heat transfer model. The model was then used to predict the solid and gas temperature distributions along the height of the bed, the heat loss, and the operating and design conditions for scale-up of the CCMB to semi-industrial and industrial operations.

Two scenarios were examined using the model to determine conditions for i) minimising the solid outlet temperature and ii) maximising the gas outlet temperature. The model can also be used to determine the nominal bed height to ensure that the designed gas outlet temperature is achieved. The modelling results suggest that a relatively small bed height (below 0.5 m) will be sufficient for heat exchange. The model also suggests that a solid to gas mass flow rate ratio of 0.8 should be used to minimise the solid outlet temperature, while a ratio of 1.0 should be used to maximise the gas outlet temperature. Therefore an appropriate operating window for a CCMB heat exchanger for recovering heat from hot slag was found with a solid to gas mass flow rate ratio between 0.8 and 1.

1. Introduction

Mining and metallurgical processes are energy intensive and there is opportunity to improve their overall energy efficiency. Two main strategies to increase the energy efficiency within the mining and metal industries are through i) process improvement and/or innovation to minimise energy consumption and ii) energy saving by recovering and reusing waste heat. The focus of this paper is on the latter strategy.

Mineral and metal production comprises high temperature processes such as calcination, roasting, drying, pyrolysis, sintering, smelting, casting and rolling. In many of these processes the solid material is first heated, and then requires cooling again before the next process stage (Saastamoinen, 2004). Cooling of the solids involves recovery of the sensible heat and can be achieved using direct or indirect contact with gas, water or steam. The recovered heat can in turn be implemented in a number of ways, depending on the temperature and heat value to generate steam, electricity, hot water, preheat gas streams or preheating/drying of solids. Examples of solid cooling include coke dry quenching (direct gas contact) of the incandescent coke after coke ovens and prior to use in the blast furnace to raise steam, electricity or preheat wet coking coal (Bisio and Rubatto, 2000; Johansson and Söderström, 2011), production of hot water using heat exchange from cooling beds in steel production (Johansson and Söderström, 2011), cooling of cast slabs after hot ingot rolling to generate steam using radiant heat pipes (Horio et al., 1982), calcined sinter coolers using air as coolant, with heat recovery in a waste heat boiler or for feed preheat (Leong et al., 2009), air cooling of clinkers in the cement industry using grate coolers (Madlool et al., 2011) with potential to generate electricity via an organic Rankine cycle (Legmann, 2002), and multistage fluidised bed direct preheating of alumina calciner feed air by cooling of the hot calcine (Klett et al., 2010). Heat could also be recovered, in the form of electricity, from the walls of reactors, furnaces and hot transfer lines by utilising thermophotovoltaic devices (Ferrari et al., 2014) or thermoelectric devices (Zhao and Tan, 2014).

This paper will focus on heat exchange between solid particles and gas in a moving bed arrangement. Various means of direct and indirect contact between the two phases are possible in the moving bed, as shown in Fig. 1.

For direct contact the effectiveness of the moving bed relies on an intimate contact of the solid granular material and gas. The contacting methods include co-current flow, counter current flow, and cross-flow. For indirect contact a gas or liquid is passed through a series of tubes. Gas at higher pressures and flow rates can be used as a cooling

Abbreviations: CCMB, counter current moving bed; DSG, dry slag granulation; HX, heat exchange; SMD, Sauter Mean Diameter.

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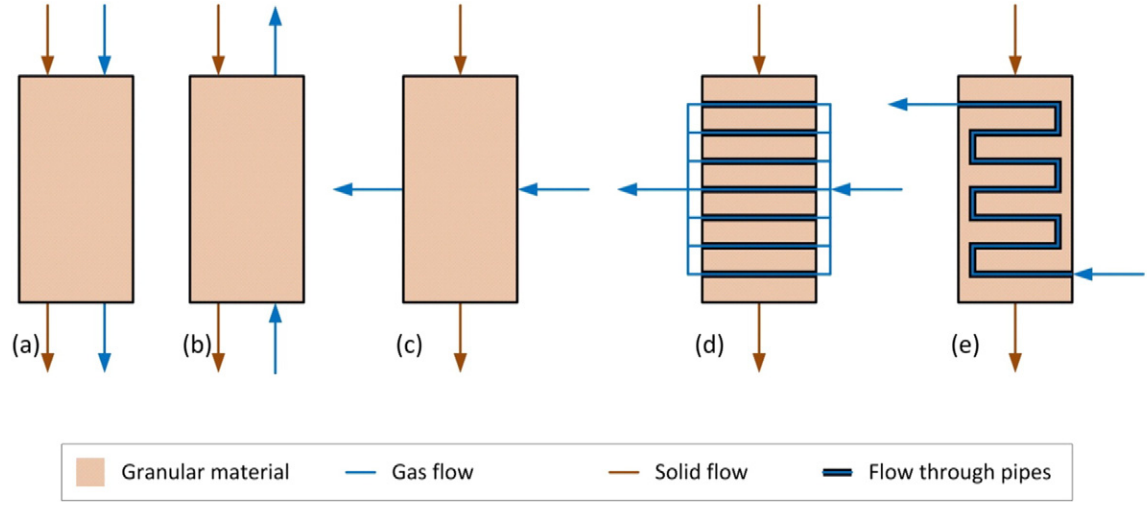

Fig. 1. Contact combinations for two-phase flow in a moving bed. (a) Co-current direct contact, (b) counter current direct contact, (c) cross-flow direct contact, (d) cross-flow indirect contact, and (e) counter current indirect contact.

medium in indirect contact as the flow is not limited to velocities which would cause fluidisation of the granular material in the moving bed (during direct contact). The temperature of the exiting gas can be increased if a counter current indirect contact method is used (as shown in Fig. 1e).

Further focus is reserved here to the direct contact counter current moving bed (CCMB) cooling of hot slag granules using air. This heat exchange forms the second stage of heat recovery in CSIRO's novel dry slag granulation (DSG) process (Xie, 2011; Jahanshahi et al., 2011, 2012). In this DSG process, the molten slag is atomised under centrifugal forces exerted by a spinning disc to produce fine molten slag droplets. In the first heat recovery stage, the molten slag droplets are simultaneously quenched and solidified using air to recover the slag heat, thereby cooling the slag to below 800 °C. In the second heat recovery stage, the hot solids (slag granules) are further cooled with air, via a CCMB heat exchanger, from ~800 °C to below 100 °C which further constitutes nearly 50% of the recoverable thermal energy. In this heat recovery stage an air outlet temperature of 650 °C is desired for raising steam, electricity generation or gas preheating in the iron-making process.

One of the factors hindering the design and scale-up of a counter current moving bed, for the cooling of slag granules, is the uncertainty in the degree of heat transfer from the solids to the air at the granular level. Therefore an appropriate model to determine and predict air temperature variation along the length of the moving bed is required. A few heat exchange models for CCMBs have been reported in literature (Fogler, 2006; Incropera et al., 2007; Rhodes, 2008). The reported models were based on an energy balance over a segment of the moving bed. However, most models assumed a known solid temperature to predict the gas temperature and neglected heat losses to bed walls in order to simplify the solution.

A heat transfer model has recently been developed by the present authors, which is able to predict both the gas and the solid temperature distributions along the height of the CCMB heat exchanger with consideration of heat losses to the heat exchanger walls (Pan et al., 2015). The present paper addresses the use of this heat transfer model, combined with engineering calculations and considerations to aid design and scale-up of a direct contact CCMB heat exchanger, and guide equipment selection.

2. Approach

The developed heat transfer model (Pan et al., 2015) was calibrated against experimental data including consideration of heat losses to the walls of the heat exchanger. Brief details are given here of the model and experimental set-up, while full details, including model development, are reported by Pan et al. (2015). The following sections describe briefly the approach adopted.

2.1. Heat exchange model

The mathematical model, describing the complex heat transfer phenomenon occurring in a direct contact CCMB heat exchanger (shown in Fig. 2), was established based on the following assumptions:

- Plug flow of gas and solid particles, with uniform lateral distributions of velocity and temperature;
- Spherical solid particles;
- Uniform temperature inside solid particles (maximum Biot number $< 10^{-2}$);
- Inter-particle heat transfer (by conduction and radiation) neglected; and
- Heat loss to the inner wall surface of the heat exchanger is by fluid (air) convection only.

The last assumption implies that heat transfer between particle and heat exchanger wall by conduction and radiation is neglected. In addition, particle–wall heat transfer by fine particle convection is also neglected due to a very small descending velocity (about 10^{-4}–10^{-5} m/s) for all the particles (both coarse and fine) under the gas flow conditions investigated in the present work. The moving bed was operated to ensure that no fluidisation occurred in any part of the moving bed, even for the smallest particles (0.9 mm), by keeping the gas superficial velocity below the minimum fluidisation velocity for these fine particles.

Based on the above-mentioned assumptions and with reference to Fig. 2, the following heat balance equations can be written for solid and gas phases in an infinitely thin layer of the bed with a thickness dH and at a height H:

$$\underbrace{G_s Cp_s dT_s}_{\substack{\text{Rate of heat}\\ \text{released from}\\ \text{solid (W)}}} - \underbrace{h_{gs} a A_b dH (T_s - T_g)}_{\substack{\text{Rate of heat transfer}\\ \text{from solid to gas by}\\ \text{convection(W)}}} \approx 0 \tag{1}$$