Powder Technology 283 (2015) 447–454

Contents lists available at ScienceDirect

Powder Technology

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

Bed-to-surface heat transfer in conical spouted beds of biomass–sand mixtures

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ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 28 May 2015
Accepted 30 May 2015
Available online 9 June 2015

Keywords:
Heat transfer
Spouted bed
Sawdust
Sand
Conical
Biomass

ABSTRACT

The effects of superficial gas velocity, bed composition and other operating parameters on bed hydrodynamics and bed-to-surface heat transfer were investigated the influence of bed height and gas velocity sawdust, sand and 30–70, 40–60 and 50–50 mixtures of biomass and sand in a conical spouted bed. Experiments were performed at minimum spouting velocity and 10 and 20% above this. At each superficial velocity, experiments were conducted at three heights, 0.1, 0.2 and 0.3 m above the inlet. A specially designed heat transfer probe measured the bed-to-surface heat transfer coefficient. The heat transfer coefficient increased from the wall to the spout, and also was observed to increase with increasing percentage of biomass in the blend. The experimental results are compared with published results, showing good agreement with the influence of height of the bed and gas velocity.

1. Introduction

The spouted bed was developed by Mathur and Gishler for drying of wheat [1] and then applied in multiple processes. Spouted beds have been used in drying suspensions, solutions, and pasty materials [2–7]. Chemical reaction applications, such as catalytic polymerization [8], coal gasification [9,10], and waste pyrolysis [11–13], have also been under development. Since the 1990s, there has been considerable interest in the hydrodynamic regimes of conical spouted beds [14].

Although spouted beds have been widely used and studied during the last twenty years, expansion of laboratory scale units to industrial sizes is still a challenge, due to the instability in the expansion and operation with fine materials [15,16]. An important limitation is that there is a maximum spoutable bed height [16–18] which is usually controlled by one of three mechanisms: fluidization of the top annulus, choking of the spout, or growth of instabilities [18]. Another challenge is the formation of dead zones in the outer annulus ring of large columns. When operated in a continuous mode, heat transfer plays an important role in processes such as drying, pyrolysis and combustion [18,19]. For spouted beds, heat transfer is dependent on the character of the flow of particles in multiple zones [20].

Englart et al. [20] and Kmiec and Englart [21], assumed that spouted beds consist of two parts: spout and annulus. They argue that heat transfer coefficients should be calculated separately for each region, taking into account the structure of the bed, although it is problematic to specify perfectly the boundary between zones.

Spouted beds are typically used for drying, so that studies of heat transfer reported in the literature are mainly centered on that process [22–26]. Several authors have developed mechanistic models for heat transfer in spouted bed drying, requiring sophisticated numerical and mathematical methods for solving systems of differential equations [4,21,27–30]. Similarly, the influence of temperature on spouted bed hydrodynamics in cylindrical columns has been studied by a number of authors [1,16,31,32]. Zabrodsky and Mikhalik [33] measured heat transfer coefficients using silica gel particles of 4 mm diameter and obtained values in the 190–260 W/m^2 K range. Freitas and Freire [18] measured these coefficients for wall-to-bed transfer and obtained values below 100 W/m^2 K for a draft tube conical spouted bed with glass beads. Makibar et al. [16] evaluated heat transfer coefficients for wall-to-bed transfer and obtained values around 170 W/m^2 K for pyrolysis conditions, whereas, for an immersed sphere, values around 220 W/m^2 K were obtained with silica sand of diameter 1.05 mm.

Although some studies have reported the radial distribution of the concentration of solids, the relation between the average solids concentration of the cross-section and the local concentration of solids at the wall depends on the geometric configuration. Makibar et al. [16] recommend that more attention be paid to the annular region where particles spend most of their time. Knowing the wall-to-bed heat transfer coefficient is essential when part of the heat of reaction is supplied through

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http://dx.doi.org/10.1016/j.powtec.2015.05.046
0032-5910/

the reactor wall, although particle convection also makes an important contribution.

Previous studies evaluating heat transfer in spouted bed mostly made measurements using thermocouples located at different axial and radial positions in order to measure temperature changes within the reactor. Similarly, the air temperature was measured at the inlet of the system, to evaluate the changes in the various sections of the reactor and thereby determine the best correlations [16,20,22,34]. This kind of system is effective, but not accurate in determining the wall-to-bed heat transfer, whereas in fluidized beds different probes have been used, allowing measurements which are easier and more accurate. Different materials have been used for the probe, including copper, brass, stainless steel and bakelite. The probe is small in order to improve accuracy [35–38]. Other authors have worked with commercial probes [39–42].

Some authors have used platinum because it has better electrical properties, thus improving both heat flux measurement and probe temperature. Wu [43] developed a platinum film coated on a glass support to satisfy the above requirements. He designed a system that maintained a constant probe temperature and a less complex analog circuit than reported by other authors [44,45]. This probe successfully measured heat transfer in a circulating fluidized bed [43,46,47], proving that the heat transfer coefficient is determined by the arrival of particles at the probe. Not only did the results help elucidate the mechanisms of heat transfer, but they also provided valuable information on the hydrodynamics of circulating fluidized beds.

There is little published literature with respect to heat transfer in conical spouted bed, so this work aims to evaluate the heat transfer coefficient from wall-to-bed, based on the methodology of Wu [43], but with platinum replaced by palladium, in order to improve the precision and accuracy of the data. Because of the importance of biomass for reducing greenhouse gas emissions, the tests were conducted with sawdust particles, both on their own and mixed with sand.

2. Experimental

2.1. Heat transfer measurement instrumentation

For measuring the heat transfer coefficient, a probe and a control circuit were designed to maintain the probe at a constant temperature, in accordance with the previous work of Wu [43]. The heat transfer was measured based on the power required to hold the probe temperature constant.

Other studies have used similar heat transfer probes, showing disadvantages as the temperature was not maintained constant or a complex analog circuit was needed [44,45]. Wu [43] improved the conditions, using simple digital control to maintain the probe temperature constant.

Manufacture of the heat transfer probe included a thin palladium film deposited by electroless plating onto a glass disk of approximately 10 mm diameter and 1 mm thickness. In order to make accurate local heat transfer measurements, it was necessary that both the surface area of the probe and its mass be small. Both the heat flux from the probe and its temperature are determined with relative ease and high accuracy.

Fig. 1 shows the circuit designed to maintain the probe temperature constant. It is connected at one end to a programmable direct current power supply (BK Precision model 1696) and at the other to a resistor of known resistance. Current from the power supply passes through the probe and the reference resistor before it is grounded. This causes the palladium film to heat up like any resistance heating element. Voltages before and after the probe, V_1 and V_2 respectively, are data-logged (at a frequency of 20 Hz) using an AD–DA interface card (Tecmar Labmaster TM-40) connected to a personal computer. Since the reference resistance, R_f, is known, the current passing through the circuit, I, can be calculated from

$$I = \frac{V_2}{R_f} \tag{1}$$

The resistance of the probe, R_{pb}, is given by

$$R_{pb} = \frac{(V_1 - V_2)}{I} \tag{2}$$

which, using Eq. (1), becomes

$$R_{pb} = R_{f*}\frac{(V_1 - V_2)}{V_2} \tag{3}$$

The probe is mounted at one end of guard heater consisting of a 57 mm long aluminum rod, 22 mm in diameter (Fig. 2). The heating element is a cartridge heater (High Density Cartridge Heater HDC00030) inserted into the middle of the rod from its other end. The temperature of this guard heater, measured by a thermistor, is maintained slightly lower than that of the probe. This minimizes and stabilizes heat loss from the back of the probe. It also stabilizes and limits the temperature variations of the glass support. During our experiments, the average temperatures of the probe and guard heater were maintained at 83 °C and 80 °C, respectively. The small difference was needed to maintain the stability of the controller. Allowance was made for this temperature difference in determining the heat transfer coefficient.

The temperature of the probe, T_{pb}, can be obtained from the resistance of the probe which varies nearly linearly with temperature. Fig. 3 shows a typical plot of the variation of probe resistance with probe temperature, obtained by measuring the resistance of the probe immersed in a water bath at different temperatures. T_{pb} is controlled

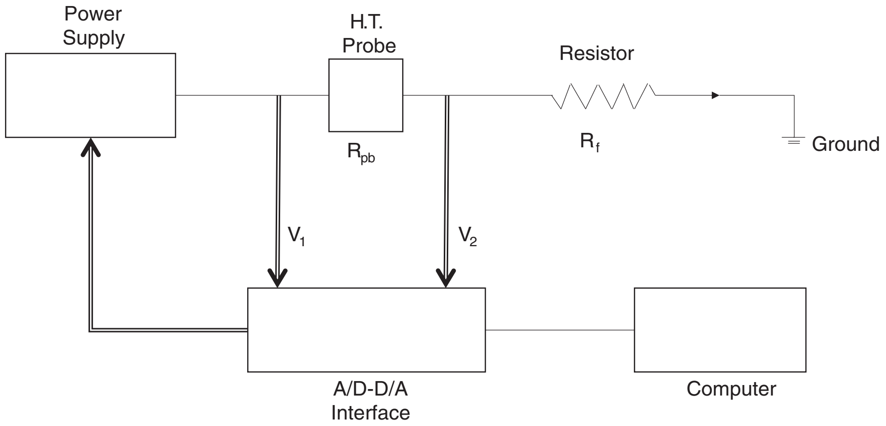

Fig. 1. Schematic of circuit for controlling the temperature of the heat transfer probe.