Int. J. Heat Mass Transfer. Vol. 34, No. 8, pp. 2019–2027, 1991
Printed in Great Britain

0017-9310/91 $3.00+0.00

Instantaneous local heat transfer and hydrodynamics in a circulating fluidized bed

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(*Received* 16 *November* 1989 *and in final form* 20 *September* 1990)

Abstract—Local heat transfer mechanisms and hydrodynamics are studied in a 9.3 m tall, 152 mm i.d. transparent cold model circulating fluidized bed for 171 μm Ottawa sand. Instantaneous measurements at the wall are made with platinum-coated heat transfer probes. For some conditions, simultaneous local voidages are determined using a capacitance probe. Results show that the sudden and dramatic peaks in the measured instantaneous heat transfer coefficients are directly caused by the arrival of strands of particles at the heat transfer surface. Analyses of the capacitance probe signals indicate that these strands possess wide distributions of voidages which vary with the local time-averaged area-averaged suspension density. Simultaneous heat transfer probe measurements further suggest the existence of characteristic residence lengths for these strands. The average falling velocity of the strands is 1.26 m s^{-1} using high-speed cinematography.

INTRODUCTION

WHILE circulating fluidized beds continue to gain in popularity, especially for gas–solids reactions like combustion, fundamental understanding in critical areas like heat transfer and hydrodynamics remains seriously inadequate [1, 2]. For reliable design, modelling, and scale-up of circulating fluidized beds, it is important to know the underlying mechanisms involved in the heat transfer between gas–solids suspensions and cooling surfaces which are usually in the form of membrane waterwalls. Turndown of circulating fluidized bed boilers, for instance, is commonly achieved by varying the suspension density in the reactors. Moreover, advances in the modelling of heat transfer in circulating fluidized beds also depend heavily on a better understanding of the fundamental mechanisms involved.

Although it is obvious that there exists a close relationship between heat transfer and hydrodynamics in circulating fluidized beds, no studies have been published in this area. In this paper, we present a comprehensive study of the heat transfer mechanism in a cold model circulating fluidized bed and its relationship with the local hydrodynamics. Important hydrodynamic parameters like the strand falling velocity and residence length of strands, both of which affect the heat transfer process, are also examined.

EXPERIMENTAL EQUIPMENT

Circulating fluidized bed

All experimental data reported here were obtained in the cold model circulating fluidized bed unit shown in Fig. 1 and described previously in refs. [3, 4]. It consists of a riser, a storage column, an L-valve, and two cyclones. Except for the two cyclones, the entire unit is constructed of 6.4 mm thick transparent polyacrylic material (Plexiglas) for easy visual hydrodynamic observation.

The riser column is 9.3 m tall and has a 152 mm i.d. Solid particles in the riser are entrained in the fast fluidization regime by air introduced to the bottom of the column through a perforated plate distributor. Particles carried out of the riser are captured by pri-

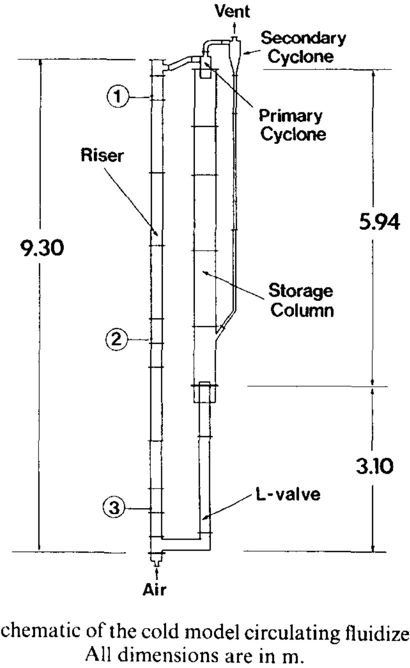

FIG. 1. Schematic of the cold model circulating fluidized bed. All dimensions are in m.

NOMENCLATURE

a	separation distance between two heat transfer probes [m]
a_{int}	length defined in equation (1) [m]
a_{tan}	value of a where tangent to $r_{\max}$ vs a curve (e.g. Fig. 11) at $a = 0$ intersects a-axis [m]
$a_{0.5}$	value of a corresponding to $r_{\max} = 0.5$ on $r_{\max}$ vs a curve (e.g. Fig. 11) [m]
$A_1, A_2, \ldots, A_8$	areas defined in Fig. 7 [m^2]
f	time fraction of wall coverage by strand
$f_1, f_2, \ldots, f_5$	wall coverage time fractions defined in Fig. 7
G_s	circulation flux of solids [kg m^{-2} s^{-1}]
h_i	instantaneous heat transfer coefficient [W m^{-2} K^{-1}]
r	cross-correlation coefficient
$r_{\max}$	maximum cross-correlation coefficient for a given set of conditions
r_0	limiting value of r at large a (see Fig. 11).

Greek symbols

ε	local voidage of strand near the wall
ρ_{susp}	suspension density at a given level averaged over column cross-section and derived from vertical profiles of static pressure [kg m^{-3}]

mary and secondary cyclones and are recirculated via a 5.94 m tall, 343 mm i.d. storage column and an L-valve to the bottom of the riser. The rate of recirculation of solids, G_s, is controlled by adjusting the aeration just above the vertex of the L-valve and is measured by tracking particles in the downflow leg of the L-valve and assuming plug flow across the section. Suspension densities of solids in the riser are estimated from the pressure profiles obtained along the column assuming accelerational and frictional terms to be negligible, as in most circulating fluidized bed studies. Particles used in the experiments were Ottawa sand of surface-volume mean diameter 171 μm. The size distribution and other key fluidization properties of the particles are given in Table 1.

Instantaneous heat transfer probes

The instantaneous heat transfer probes consisted of thin platinum films deposited on pieces of glass of area approximately 10 × 10 mm. Fabrication, calibration, and operation procedures have been described in detail in refs. [4, 5]. In brief, each platinum film is first bonded to its glass support by curing a piece of glass coated with platinum solution in a 650°C oven. It is then connected to a programmable power supply and a known reference resistor. Figure 2 shows the probe circuit designed to measure instantaneous heat transfer coefficients. The platinum film functions simultaneously both as a heater element and a temperature sensor. Its temperature is maintained constant and the instantaneous power dissipation from the probe is measured by means of an IBM XT Personal Computer coupled with an A/D–D/A interface board (Tecmar Labmaster TM-40).

Table 1. Particle size analyses and fluidization properties for Ottawa sand

Size range (μm)	Percentage weight (%)
707–500	0.1
500–354	2.3
354–250	14.6
250–177	43.6
177–125	27.5
125–88	6.9
88–53	3.0
53–44	1.2
44–0	0.8
Mean particle size (μm)	171
Particle density (kg m^{-3})	2650
Calculated terminal settling velocity for mean size at room temperature and pressure (m s^{-1})	0.99
Minimum fluidization velocity at room temperature and pressure (mm s^{-1})	31
Voidage at minimum fluidization	0.43

The probe is mounted at one end of a guard heater with its surface flush with the inner wall of the column, as shown in Fig. 3. The guard heater minimizes the heat loss from the back of the probe and limits the temperature variations of the glass support. A 10 μm thick plastic film is used to cover the platinum film to protect it from wear due to the particles. The response time of the probe assembly shown in Fig. 3 was determined experimentally [5] to be about 45 ms.

Capacitance probe

A capacitance probe was used in some of the experiments to measure the local instantaneous con-

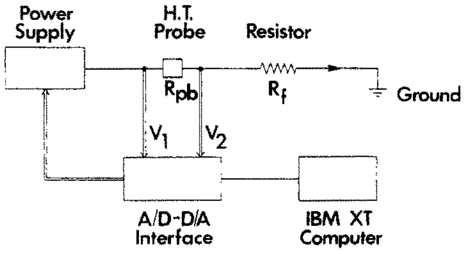

FIG. 2. Schematic of the circuit for controlling the temperature of the heat transfer probe and measuring the instantaneous heat transfer coefficients.