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Two-dimensional model of heat transfer in circulating fluidized beds. Part II: Heat transfer in a high density CFB and sensitivity analysis

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Abstract

Experiments were conducted in a 76 mm diameter jacketed riser of a dual-loop high-density circulating fluidized bed facility with FCC particles of 65 μm Sauter mean diameter as bed material. The suspension temperature and the average and local suspension-to-wall heat transfer coefficients were measured. After superimposing the heat transfer results when the suspension near the wall is allowed to move intermittently downwards and upwards, the model proposed in Part I predicts the experimental results well. The model is used to investigate the effects of various operating parameters on the heat transfer process.

1. Introduction

Circulating fluidized bed risers have been investigated extensively for the past two decades because of their practical applications, as well as their intrinsic interest. However, the overwhelming majority of such work has been conducted at net solids fluxes, G_s, less than 100 kg/m^2 s, and at superficial gas velocities, U_g, between about 2 and 8 m/s. For these conditions, the overall volumetric solids concentrations, c, is less than about 0.1 [1]. While these conditions are relevant to circulating fluidized bed (CFB) combustion, much higher solids fluxes and holdups are encountered in CFB risers used for solid catalyzed reactions like fluid catalytic cracking and production of maleic anhydride. In such cases, G_s is commonly 300–1200 kg/m^2 s, with corresponding c values ranging from 0.07 to 0.25. Grace et al. [2] defined the dense suspension upflow regime as having $G_s > 200$ kg/m^2 s, $c > 0.07$ and solids upflow on average throughout the entire riser. Published results demonstrate that such operations differ in several important respects from low-density circulating fluidized bed systems.

While numerous experiments have been carried out to investigate heat transfer in circulating fluidized beds, almost none of these applies to the high-density conditions defined above. CFB bed-to-wall heat transfer is strongly influenced by the flow pattern in the riser, especially the particle motion in the vicinity of the wall. Experimental work is needed to elucidate the heat transfer behavior in the high-density flow regime and to modify the model which was developed in Part I for low-density operating conditions.

2. Experimental facilities

2.1. High-density circulating fluidized bed system

The dual-loop high-density circulating fluidized bed (HDCFB) system located at the University of British Columbia consists of two Plexiglas risers, two PVC downcomers, a curved plate impingment separator, cyclones and an air filter baghouse. The first riser has a diameter of 76.2 mm and a height of 6.10 m, while the second riser has a diameter of 101.6 mm and height of

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Nomenclature

A_c	total inside area of the inner cylinder
C	volume fraction occupied by solids
C_{pc}	cooling water heat capacity
d_p	particle diameter
f_d	time-averaged fraction of particles moving downward in the vicinity of wall
G_s	solid circulation flux
g	acceleration due to gravity
h	bed-to-wall heat transfer coefficient
h'	bed-to-water-side wall heat transfer coefficient
h_d	bed-to-wall heat transfer coefficient due to downward particle motion in the vicinity of wall
h_u	bed-to-wall heat transfer coefficient due to upward particle motion in the vicinity of wall
L_{ar}	particle average residence length in wall layer
L_w	wall thickness
m_c	cooling water flowrate
r	radius
R	inner radius of inner tube of concentric heat exchanger
r_1	outer radius of inner tube of concentric heat exchanger
r_2	inner radius of outer tube of concentric heat exchanger
T_b	bulk temperature
T_c	cross-sectional average coolant temperature
$T_{c,in}$	T_c at inlet of heat exchanger or at inlet of each section
$T_{c,out}$	T_c at outlet of heat exchanger or at outlet of each section
T_{sbc}	suspension temperature at center of riser below heat exchanger
T_{sbw}	suspension temperature near wall below heat exchanger
T_{stc}	suspension temperature at center of riser above heat exchanger
T_{stw}	suspension temperature near wall above heat exchanger
$T_{w,in}$	T_w at inlet of heat exchanger or at inlet of each section
$T_{w,out}$	T_w at outlet of heat exchanger or at outlet of each section
U_g	superficial gas velocity
U_{mf}	particle minimum fluidization velocity
x	dimensionless radial coordinate, r/R
z	vertical coordinate, directed vertically downward
Z	height above air distributor

Greek symbols

ε_{mf}	loosely packed bed voidage
ρ_{sus}	suspension density
ΔP	pressure difference
ΔZ	distance between differential pressure ports

9.14 m. Other details of this system are provided by Xie [3].

2.2. Heat transfer measurement equipment

The heat transfer system consisted of a concentric-tube heat exchanger, a steam-water heat exchanger, a steam trap, four needle valves and a rotameter. The concentric-tube heat exchanger, shown in Fig. 1, replaced one of the Plexiglas sections near the center of the 76.2 mm diameter riser. Four K-type thermocouples were mounted on the outside surface of the inner tube to measure the wall surface temperatures. Four ports were provided on the outer tube where temperature probes can be inserted into the water flowing through the annular jacket. Water entered the bottom of the exchanger through four inlets, uniformly distributed at 90° intervals. It left the exchanger from the top, again through four evenly distributed ports. The entire riser including the heat exchange section as well as the water inlet and outlet tubes were wrapped in fiberglass insulation, with the heat exchanger being especially well insulated.

2.3. Bed material

FCC particles of Sauter mean diameter 65 μm and density 1600 kg/m^3 were used in all experiments. Their minimum fluidization velocity, U_{mf}, was 0.0032 m/s in air at atmospheric temperature and pressure. The loose packed bed voidage, ε_{mf}, was 0.45.

2.4. Measurement techniques

Superficial gas velocities were measured in both risers using orifice meters. The solids circulation flux was measured by a butterfly valve installed in the upper part of the downcomer. During measurements, the two halves were rapidly rotated upward to the horizontal position, thus trapping the downflowing solids. The solids circulation rate was calculated from the time