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Experimental study of calcium sulfate fouling in a heat exchanger during liquid-solid fluidized bed with cylindrical particles

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ABSTRACT

Calcium sulfate fouling was determined experimentally in a heat exchanger during liquid-solid fluidized bed with cylindrical particles and forced convective (without particles) heat transfer. The effects of bed voidage, wall temperature and foulant concentration on fouling resistance were studied during fluidized bed heating and compared with corresponding cases in forced convective (without particles) heating. The results show that fouling resistance was considerably decreased during fluidized bed heat transfer compared with forced convective heat transfer (without particles). Maximum fouling removal as heat transfer occurred at bed voidages ranging from 0.6 to 0.8; under these conditions, fouling resistance was lowered to at least one-seventh that of similar cases in forced convective heat transfer.

1. Introduction

Many industries face the challenge of deposition of solids on heat exchanger tube walls, often referred to as fouling or scaling [1,2]. The fouling may be crystalline, biological material, the products of chemical reactions including corrosion, or particulate matter. The character of the deposit depends on the fluid passing through the heat exchanger. Fouling can occur as a result of the fluids being handled and their constituents in combination with operating conditions such as temperature and velocity. The formation of scale on heat transfer surfaces is a common phenomenon where aqueous solutions are involved. It involves the deposition of salts from solution, either by crystallization on the heat transfer surface or in the bulk liquid phase.

The result can be a cohesive and tough scale, generally called as a hard scale that may be difficult to remove [3]. Fouling considerably decreases overall heat transfer coefficients and increases pressure drop; therefore, it is the main challenge for industries. In order to limit redundant fouling, heat exchangers are periodically cleaned, which requires highly priced maintenance stops. Another way to mitigate excessive fouling is to equip heat exchangers with fouling control techniques, such as expensive mechanical scrapers that continuously remove scale from the walls [1,2,4–6].

A favorable preference for these common fouling control methods is the liquid-solid fluidized bed heat exchanger, which requires less investment and lower maintenance costs. This heat exchanger usually consists of a vertical shell-and-tube structure with a fluidized bed of metal particles in the tubes. The fluidized particles continuously clash the walls and are therefore able to keep them free of deposits [1,2,5,7–9]. Another succeeding of fluidized bed systems is the increase of heat transfer coefficients, which may be up to eight times higher than that for ordinary convection heat transfer cases (without particles) [2,7,8,10,11]. Liquid-solid fluidized bed heat exchanger applications are found in different parts of industry where violent fouling occurs, such as wastewater treatment, desalination plants, paper industry, refineries and geothermal plants [2,7,9,12], or in high temperature heat exchanger applications such as chemical reactors and coal combustors due to their excellent heat transfer performance [13].

The capability of liquid-solid fluidized bed heat exchanger to remove deposits from heat exchanger walls and enhancement of heat transfer rates can be attributed to the impact of particles with the wall and perturbation of the hydrodynamic boundary layer, which is related to bed voidage. This means that knowing the bed voidage is necessary to investigate heat transfer coefficient and deposit removal [2,11,14,15].

Spherical or cylindrical metal particles with aspect ratios of ~ 1 (usually 1×1 *to* 4×4 mm stainless steel wire cut) may be used in industrial liquid-solid fluidized bed heat exchangers depending on the hardness of the deposits [2,7,11,16]. Richardson et al. [16], have reported a slightly higher heat transfer coefficient for cylindrical particles in comparison to spherical particles of the same volume. This increase in the heat transfer coefficient can be attributed to the more perturbation of the laminar sub-layer by cylindrical particles and by increased

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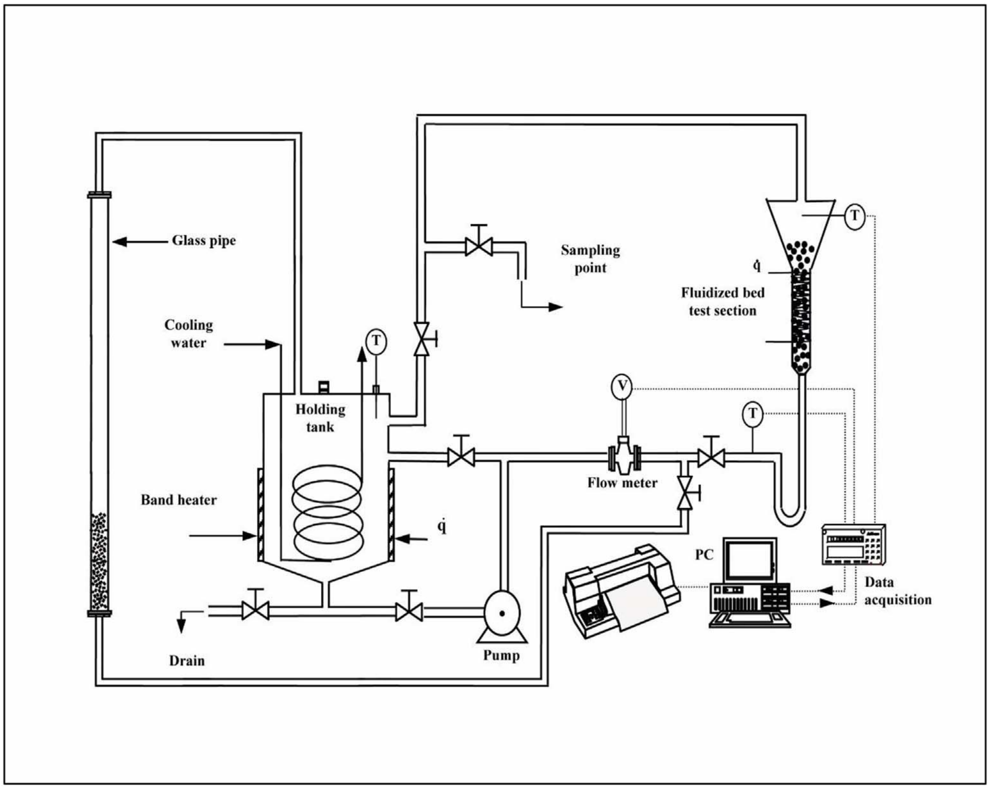

Fig. 1. Schematic diagram of test apparatus.

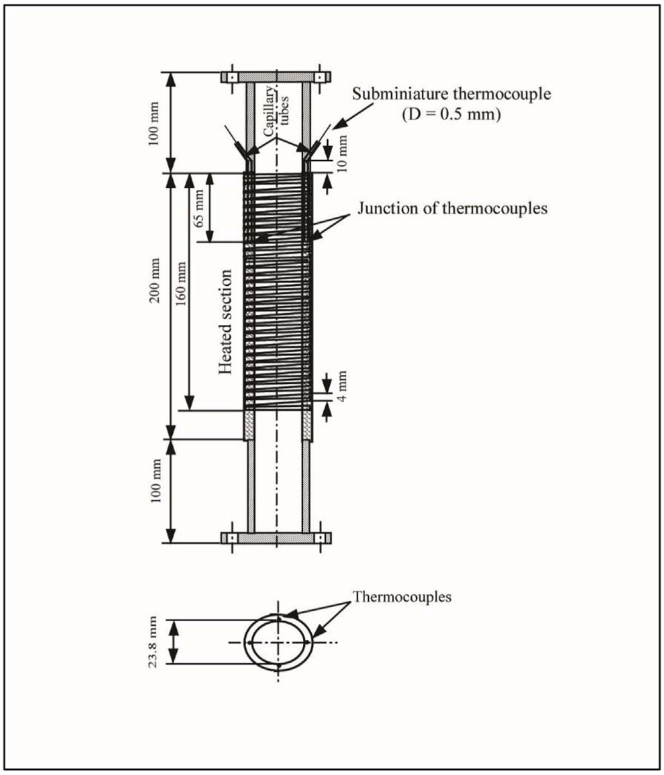

Fig. 2. Schematic diagram of heating section.

Table 1
The range of experimental parameters.

Flow velocity (m/sec)	$0.15 \le u \le 0.52$
Bed voidage	$0.57 \le \varepsilon \le 0.98$
Heat flux rate (kW/m^2)	$25 \le q \le 82$
Fluid bulk temperature ($°C$)	$T_b = 65$
Wall temperature ($°C$)	$67 \le T_w \le 75$
Calcium sulfate concentration (kg/m^3)	$1.2 \le C \le 1.9$
Size and material of fluidized particles (mm)	1.6 × 1.6 *Stainless steel wire cut*

Table 2
Comparison of experimental heat transfer coefficient in forced convective heat transfer with Gnielinski [16] equation.

Water velocity (m/s)	Experimental α ($W/m^2.K$)	Calculated α from Gnielinski eq. (1986) ($W/m^2.K$)	% relative error (Relative to Gnielinski Eq. (1986))
0.15	1595	1478.6	7.8
0.21	2515	2344.9	7.2
0.41	3522	3467.7	1.6
0.52	4180	4326.5	−3.3

heat conduction to the particles as a consequence of the increased contact area [2,10,16].

One of the most frequent crystalline fouling materials encountered in industries is calcium sulfate. The deposition of calcium sulfate onto the walls of heat exchangers is a serious obstacle encountered in many industries [12,17,18].

In this work, calcium sulfate fouling was studied experimentally in a heat exchanger during liquid-solid fluidized bed with cylindrical particles and forced convective heat transfer (without particles). The effects of bed voidage, wall temperature, and foulant concentration on heat transfer coefficient and fouling resistance were studied during