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Mitigation of ice crystallization fouling in stationary and circulating liquid–solid fluidized bed heat exchangers

P. Pronk, C.A. Infante Ferreira *, G.J. Witkamp

Process and Energy Laboratory, Delft University of Technology, Leeghwaterstraat 44, 2628 CA Delft, The Netherlands

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ABSTRACT

Liquid–solid fluidized bed heat exchangers are attractive ice crystallizers since they are able to mitigate ice crystallization fouling and exhibit high heat transfer coefficients. Experiments show that the fouling removal ability of stationary fluidized beds increases with decreasing bed voidage (95–80%) and increasing particle size (2–4 mm). The removal of ice crystallization fouling appears to be more effective in circulating fluidized beds, especially at high circulation rates. Fouling removal is realized by both particle–wall collisions and pressure fronts induced by particle–particle collisions. A comparison between ice crystallization experiments and impact characteristics shows that the removal rate is proportional to the impulse exerted on the wall. A model based on these phenomena is discussed and predicts the transition temperature difference for ice crystallization fouling in both stationary and circulating fluidized beds with an average absolute error of 9.2%.

1. Introduction

The application of liquid–solid fluidized beds is an attractive technique to mitigate fouling in heat exchangers [1,2]. The main advantages of this technique are the relatively low investment and maintenance costs compared to other removal techniques such as rotating scrapers. An additional advantage is the enhanced heat transfer coefficient, which can be up to eight times higher than for the case without particles [3–5]. Liquid–solid fluidized bed heat exchangers have successfully been applied for heat transfer processes with fouling liquids such as oil products and waste waters [6]. Recently, the application in crystallization processes with severe crystallization fouling has also been considered, for example for cooling crystallization of sodium sulphate [1].

A potential new application of liquid–solid fluidized bed heat exchangers is the crystallization of small ice crystals from aqueous solutions forming an ice suspension [7–9]. Ice crystals have a marked tendency to adhere to cooled heat exchanger walls and ice crystallization processes exhibit therefore severe fouling. Typical ice crystallization processes are freeze concentration of beverages and waste waters [10–12] and the utilization of ice suspensions as heat transfer fluid in indirect refrigeration systems [13–16]. Especially the latter application has received great interest in the last decade, since ice suspensions have much higher heat capacities than conventional heat transfer fluids without phase change, which enables cold thermal storage and reduction of energy consumption.

Similar to other applications [2,17,18], liquid–solid fluidized bed heat exchangers for ice crystallization appear to have a heat flux limit or transition temperature difference above which fouling is not mitigated [7,8]. This phenomenon is explained by the generally accepted idea that fouling is only mitigated when the removal rate exceeds the deposition rate. In the case of ice crystallization, the deposition rate is related to the growth rate of ice crystals on the wall, which is proportional to the temperature difference between wall and solution [19,20]. The removal of deposits is attributed to collisions of particles on the wall and to impacts by liquid pressure fronts induced by particle–particle collisions. It has been shown that frequency and force of these impacts depend on fluidized bed conditions as bed voidage, particle size and particle density [21]. It is therefore most likely that the removal rate also varies with these changing conditions. However, the influence of fluidization parameters on the removal rate has hardly been studied, both practically and fundamentally, up to now.

The aim of this paper is to study the influence of fluidized bed parameters on the fouling mitigation ability and to determine the mechanisms that influence the removal rate in liquid–solid fluidized beds. For this purpose, the case of ice crystallization fouling is experimentally studied for both stationary and circulating fluidized beds with three different particle sizes at various bed voidages. The transition temperature difference, which was experimentally determined for each condition, is used to evaluate the removal rate. The obtained values are compared to two parameters that might determine the removal rate, namely the impulse

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* Corresponding author. Tel.: +31 15 2784894; fax: +31 15 2782460.
E-mail address: c.a.infanteferreira@tudelft.nl (C.A. Infante Ferreira).

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Nomenclature

A	area, m^2
Ar	Archimedes number $\left(d_p^3(\rho_p - \rho_{liq})\rho_{liq} g \mu_{liq}^{-2}\right)$
c_{prop}	constant in Eq. (12)
c_e	constant in Eq. (15)
c_j	constant in Eq. (18)
d	diameter, m
d_p	equivalent particle diameter, m
D	diffusion coefficient, m^2 s^{-1}
E	energy on wall, W m^{-2}
$e_{p\text{-}w,avg}$	average energy of single particle–wall collision, J
$f_{p\text{-}w}$	particle–wall collision frequency, m^{-2} s^{-1}
g	acceleration due to gravity, m s^{-2}
$g_{0,adj}$	defined in Eq. (16)
G	growth rate, m s^{-1}
h	height, m
J	impulse on wall, N m^{-2}
$j_{p\text{-}w,avg}$	average impulse of single particle–wall collision, N s
k	mass transfer coefficient, m s^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
M	molar mass, kg mol^{-1}
p	pressure, Pa
Δp	pressure drop, Pa
$\dot{Q}$	heat, W
R	removal rate, m s^{-1}
Re_p	particle Reynolds number $\left(\rho_{liq} d_p u_s \mu_{liq}^{-1}\right)$
Sc	Schmidt number $\left(\mu_{liq} \rho_{liq}^{-1} D^{-1}\right)$
t	time, s
T	temperature, K
T^*	equilibrium temperature, K
ΔT_{trans}	transition temperature difference, K
ΔT_{ln}	logarithmic temperature difference, K
u_s	superficial liquid velocity, m s^{-1}
U	overall heat transfer coefficient, W m^{-2} K^{-1}
v_{slip}	slip velocity, m s^{-1}
$v_{p,avg}$	average particle velocity (see Eq. (26)), m s^{-1}
v_z	upward particle velocity, m s^{-1}
$\dot{V}$	volume flow rate, m^3 s^{-1}
x	mol fraction
x^*	equilibrium mol fraction

Greek letters

α	heat transfer coefficient, W m^{-2} K^{-1}
δ	thickness, m
λ	thermal conductivity, W m^{-1} K^{-1}
ε	bed voidage
μ	viscosity, Pa s
ρ	density, kg m^{-3}
φ	mass flow rate per unit area, kg m^{-2} s^{-1}

Subscripts

b	bulk
cool	coolant
cfb	circulating fluidized bed
d	deposition
fr	friction
H_2O	water
i	inner
ice	ice
in	inlet
l	location
layer	fouling layer
liq	liquid
liq–w	liquid–wall
meas	measured
o	outer
p	particle
p–w	particle–wall
pb	packed bed
pred	predicted
lpf	liquid pressure front
r	removal
sfb	stationary fluidized bed
sl	slurry
total	total
w	wall

exerted by impacts on the wall and the kinetic energy of impacts [21]. In conclusion, a model is proposed to predict the transitional temperature difference in liquid–solid fluidized bed heat exchangers for ice crystallization.

2. Experimental set-up

2.1. Single-tube fluidized bed heat exchanger

A single-tube fluidized bed heat exchanger as shown in Fig. 1 was used to produce ice crystals from a 7.7 wt% aqueous sodium chloride solution with an initial freezing temperature of –4.9 °C. The heat exchanger was made of two stainless steel tube-in-tube heat exchangers connected by a transparent section. The fluidized bed in the inner tube consisted of cylindrical stainless steel particles of approximately 2, 3 or 4 mm in both height and diameter with a density of 7900 kg m^{-3}. The average equivalent particle diameters were determined from weight measurements and measured 2.1, 3.2 and 4.3 mm respectively. The inner tubes had an inside diameter of 42.7 mm and the heat exchanger had a total length of 4.88 m. The fluidized bed was operated in stationary or in circulation mode. In the latter mode, particles flowed out at the top of the heat exchanger and were recirculated to its inlet via a downcomer tube with an internal diameter of 34 mm. Part

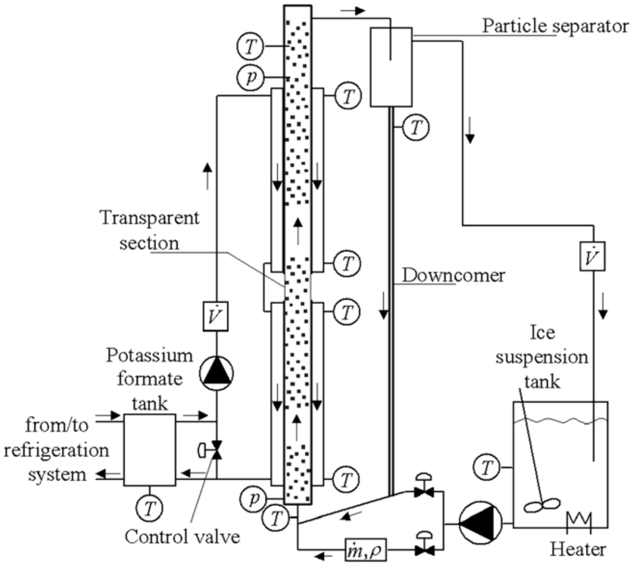

Fig. 1. Schematic layout of experimental set-up.