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Research Paper

$CaSO_4$ fouling characteristics on the rectangular channel with half-cylinder vortex generators

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HIGHLIGHTS

- A numerical simulation method was used to study the fouling characteristics.
- The crystallization fouling of $CaSO_4$ was analyzed in the rectangular channel with half-cylinder vortex generators.
- The effects of different operating conditions and structures on the fouling resistance were investigated.
- The simulated results were validated based on the experimental dates.

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ABSTRACT

In order to study the fouling characteristics on the rectangular channel with half-cylinder vortex generators, the deposition process of $CaSO_4$ fouling were studied by numerical simulation method. The fouling characteristics under different operation conditions and structures such as the concentration of $CaSO_4$, the wall temperature, the inlet velocity, the length, the radius and the spacing of the half-cylinder vortex generators were investigated. The results show that the asymptotic value of fouling resistance increases with the increase of the surface temperature and the concentration, and decreases with the increase of the inlet velocity. The value of fouling resistance first decreases and then increases with the increase of the length. The value of fouling resistance reaches the minimum when the length was 4/8 H. The value of fouling resistance increases with the increase of the spacing. The value of fouling resistance reaches the maximum when the spacing was more than 55 mm, and the fouling characteristics tends to be similar as the situation without the vortex generators. The value of fouling resistance decreases with the increase of the radius.

1. Introduction

Fouling, was the accumulation of solid matter on a heat transfer surface, which reduces the heat transfer rate and increases the pressure drop of equipment, such as evaporators, heat exchangers, crystallizers, membranes etc. It can cause a decline in operating efficiency of heat exchangers, power plants and other chemical industries [1]. In heat exchangers, the fouling was usually caused by supersaturation of the fluid due to a change in temperature [2]. The principal mode of calcium sulfate deposition was referred to as crystallization fouling. The normal solubility salts scales on cold surfaces, while the inverse solubility salts causes the scaling on heated surfaces. The calcium sulfate was belongs to inverse solubility salts.

The fouling model of heat transfer surfaces was established often based on the approach of Kern and Seaton [3] in which the difference between the mass deposition rate and the mass removal rate was the overall mass deposited on the surface. Hasson [4] as the founder of crystallization fouling research, proposed a classical ion diffusion model in study of $CaCO_3$ fouling problems. Afterward, many scholars have done a lot of research on this basis [5–8]. In order to account the temporal and spatial variations in the fluid properties of complex heat exchangers, the Computational Fluid Dynamics (CFD) can be used [9–12]. Brahim et al. [9] in a preliminary simulation the case of the crystallization fouling of $CaSO_4$ on the flat heat transfer surfaces based on models for the mass deposition and removal rates, and used the model to calculate the fouling process under different conditions. Mwaba et al. [10] evaluated the changes that resulting from a non-uniform fouling layer in the heat flow distribution, and simulated a case where calcium sulfate fouling forms on for a heated plate subjected to a shear flow. Zhang et al. [11] studied a new computational fluid

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Nomenclature

A	the length of the vortex generator (m)
B	width of the rectangular channel (m)
c_F	concentration of salt solution (kg/m^3)
c_S	saturation concentration (kg/m^3)
C_{in}	inlet concentration (kg/m^3)
D	diffusion coefficient (m^2/s)
d_h	hydraulic diameter (m)
d_p	mean crystal diameter (m)
E, F	inlet, outlet extending zone (m)
G	spacing between two vortex generators (m)
H, L	height, length of the rectangular channel (m)
P/K	cohesion coefficient (kg·m/s^2)
k_t	mass transfer coefficient (m/s)
k_R	rate of reaction (m^4·kg/s)
m	total mass (kg/m^2)
$\dot{m}_d$	deposition mass rate (kg/m^2·s)
$\dot{m}_r$	removal mass rate (kg/m^2·s)
R	radius (m)
R_f	fouling resistance (m^2·K/W)
Re	Reynolds number
Sh	Sherwood number
Sc	Schmidt number
T_f	temperature of fouling layer surface (K)
T_w	temperature of heat transfer surface (K)
ΔT	temperature gradient (K)
Δt	computing time step (s)
S_ϕ	source term
u,v,w	velocity component (m^2/s)
x_f	thickness of crystal layer (m)

Greek symbols

ρ	density of salt solution (kg/m^3)
ρ_f	density of fouling layer (kg/m^3)
λ_f	thermal conductivity of fouling layer (W/(m·K))
δ	linear expansion coefficient
ϕ	generalized variable
Γ_ϕ	diffusion coefficient
η	dynamic viscosity (kg/m·s)

dynamics (CFD) model and developed the method how to characterize a crystallization fouling process mathematically. Pääkkönen et al. [12] used CFD to simulate the $CaCO_3$ crystallization fouling on an idealized heat exchanger, and then used to analyze further the crystallization fouling mechanism.

The most papers show that the researches were committed to the simple geometric model to mainly study the crystallization fouling mechanism. Recently, the vortex generators (VGs) as a new heat transfer enhancement technique, has received more and more attention. It was a passive heat transfer element by a special type of extended surface that was possible to generate vortices with parallel to the flow direction [13]. The vortex generators which can produce longitudinal vortices were widely used in the field of the heat transfer enhancement, because the longitudinal vortices can thin and destroy the wall boundary layer and then to achieve heat transfer enhancement [14–18]. In this paper, CFD was often used to model the $CaSO_4$ crystallization fouling on the rectangular channel with half-cylinder vortex generators. The fouling characteristics under different operation conditions and structures such as the concentration of $CaSO_4$, the wall temperature, the inlet velocity, the length, the radius and the spacing of the half-cylinder vortex generators were investigated.

2. Mathematical model

2.1. Geometry description

The rectangular channel with half-cylinder vortex generators was shown in Fig. 1. The channel has a length L = 420 mm, height H = 10 mm, and width B = 30 mm. In order to keep the inlet velocity stability, and to avoid the backflow of the outlet, the actual calculation region was expanded to include an inlet extending zone of E = 50 mm; and the out extending zone of F = 150 mm. The half-cylinder vortex generators were equally distributed along the base of the rectangular channel. The spacing between two vortex generators was G. The length of the vortex generator was A, and the radius was R.

2.2. Mathematical formulation

The governing equations in physical space for continuity, momentum, energy and species equations in the calculation region can be expressed generally as follows [19]:

$$\frac{\partial(\rho\phi)}{\partial t} + \mathrm{div}(\rho U\phi) = \mathrm{div}(\Gamma_\phi \mathrm{grad}\phi) + S_\phi \tag{1}$$

where ρ was the density of the fluid, t was time, ϕ was generalized variable, it represents the variables of u, v, w, T, etc. Γ_ϕ was generalized diffusion coefficient. S_ϕ was generalized source term. The extended equations applied in this paper were presented more detailed in Ref. [12].

FLUENT has provided many choices of turbulence models [20]. Whereas the standard k-ε turbulence model was usually developed for fully turbulent flows, and the RNG k-ε turbulence model was better adapted to low Reynolds numbers. In the present work, the flow regime in the set-up was turbulent in the studied conditions with the bulk Reynolds numbers between 8900 and 23900. Therefore, the standard k-ε turbulent model was adopted in the calculation region [21].

2.3. Crystallization fouling model

In this paper, the following crystallization fouling model of Brahim [9] and Krause [22] was carried out to CFD:

$$\dot{m}_d = k_t\left\{\frac{1}{2}\frac{k_t}{k_R} + \Delta c - \left[\frac{1}{4}\left(\frac{k_t}{k_R}\right)^2 + \frac{k_t}{k_R}\Delta c\right]^{\frac{1}{2}}\right\} \tag{2}$$

where Δc was the total concentration difference: $\Delta c = c_F - c_S$. c_F was the mainstream concentration of salt solution and c_S was the saturation concentration and was calculated as a function of T_f [9,23].

$$\log(c_s) = -\frac{\Delta L H_0}{2.3\cdot h\cdot T_f} + \frac{\Delta c_p}{h}\cdot\log(T_f) + C \tag{3}$$

The mass transfer coefficient was k_t, which can be determined as:

$$k_t = \frac{ShD}{d_h}. \tag{4}$$

Sherwood number can be calculated by the following semi-empirical approach according to Lammers [23]:

$$Sh = 0.034 Re^{0.875} Sc^{1/3}$$

where $Re = \frac{\rho u d_h}{\eta}$, $Sc = \frac{\eta}{\rho D}$. D can be obtained by the Bird [24]: