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A systematic investigation of the fouling induction phenomena with artificial crystal structures and distributions

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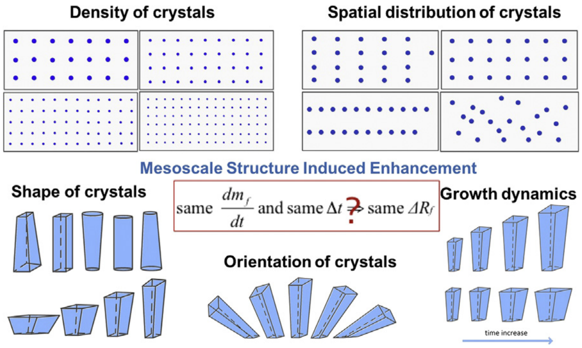
HIGHLIGHTS

- Fouling layer mesoscale crystal structures do affect heat transfer performance.
- Crystal structure induced heat transfer enhancement in fouling induction stage.
- Nusselt number ratio is a promising indicator to reveal enhancement mechanism.
- Design of structured heat-exchange surfaces with superb performance.

GRAPHICAL ABSTRACT



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ABSTRACT

It has been a challenge to understand the negative fouling resistance during the induction stage of many crystallization fouling processes. The evolution of complex fouling layer structure (i.e., mesoscale crystal structure) and its intricate interaction with heat and momentum transfer in a heat exchanger are extremely difficult to be rigorously tracked experimentally. In this work, a 3D computational fluid dynamics (CFD) model was developed for the induction stage of fouling in a microscale channel. The growth of crystals with artificially designed structures at the micrometer scale has been explicitly modeled and coupled with flow dynamics and heat transfer. This model offers unique opportunities to investigate a variety of crystal structures that include the density, distribution, shape, orientation, and growth schemes. Dominant mechanisms of heat transfer enhancement during the induction stage have been demonstrated by the quantification and analysis of Nusselt number ratios. Moreover, quantitative findings in this work can be used to guide the design of high-performance heat transfer facilities.

1. Introduction

Fouling is a most common problem in the process involving heat exchanging facilities. According to a survey, more than 90% of the heat exchangers encounter fouling problems (Quan et al., 2008) that lead to the reduced heat transfer efficiency and increased power consumption. The economic loss due to fouling, is about 0.25% of GDP in industrialized countries (Steinhagen

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Nomenclature

Symbols

A	area (m^2)
A_H	Hamaker constant, $A_H = 3.1 \times 10^{-19}$ J
C_i	concentration of species i ($kg\ m^{-3}$)
C_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
D_i	diffusion coefficient of species i (m^2/s)
D_0	minimum contact distance, $D_0 = 0.3$ nm
d	hydraulic diameter (m)
E_a	activation energy, $E_a = 40{,}400\ J\ mol^{-1}$
F_{ad}	adhesion force (N)
F_τ	shear force (N)
h	convective heat transfer coefficient of the flow ($W\ m^{-2}$ - K^{-1})
$\mathbf{I}$	unit vector (–)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_1	pre-exponential factor, $k_1 = 22.15\ m^4\ kg^{-1}\ s^{-1}$
k_B	Boltzmann constant, $k_B = 1.38 \times 10^{-23}\ J\ K^{-1}$
k_R	reaction rate constant ($m^4\ kg^{-1}\ s^{-1}$)
$\dot{m}$	rate of mass change per unit area ($kg\ m^{-2}\ s^{-1}$)
n	order of reaction, $n = 2$
$\boldsymbol{N}_i$	mass flux of species i ($kg\ m^{-2}\ s^{-1}$)
Nu	Nusselt number (–)
p	pressure (pa)
Q	rate of heat flow (W)
r'	shear rate (1/s)
r_{rms}	mean squared roughness (m)
R	universal gas constant, $R = 8.314\ J\ mol^{-1}\ K^{-1}$
R_i	reaction rate ($mol\ m^{-3}\ s$)
R_f	fouling resistance ($m^2\ K\ W^{-1}$)
Re	Reynolds number (–)
T	temperature (K)
U	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
$\boldsymbol{u}$	velocity (m/s)
$x_{1,2,3}$	weibull parameters (–)

Greek letters

Γ	removal probability
μ	fluid viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
ϕ	ratio
Ω	domain

Subscripts

b	bulk
c	crystal
d	deposition
e	solution
f	fouling
i	interface
r	removal
s	substrate

et al., 1993). Fouling can be classified into six groups depending on their different features: corrosion, crystallization, biological, particulate, solidification and chemical fouling (Bott, 1990). When the solution temperature increases, the inverse solubility salts typically form crystal layers on heat transfer surfaces due to reduction in solubility (Mwaba et al., 2006; Steinhagen et al., 1993). Crystallization fouling is the second prominent type after corrosion fouling in industrial processes and accounts for more than 25% of the total fouling. So it is necessary to study the crystallization fouling.

The thermal resistance due to fouling (or simply called fouling resistance) is commonly quantified as the difference between the heat flow resistances of the fouled and clean surfaces, i.e., $R_f = U_f^{-1} - U_0^{-1}$, where U is the overall heat transfer coefficient (Epstein, 1983; Bohnet, 1987). One would intuitively expect that the contaminated surface exhibits a lower heat transfer coefficient as compared to that of the clean surface, thus R_f should be always positive. However, as shown in Fig. 1, many experimental investigations reported that the entire crystallization fouling process could be divided into two parts: the induction stage where the fouling resistance does not increase obviously and can even become negative in some cases; and the layer growth stage where one can see a continuous increase of fouling resistance versus time (Förster and Bohnet, 1999). According to Epstein (1983), the negative fouling resistance occurs particularly in the early stage of fouling and under turbulent flow conditions. This counterintuitive phenomenon has been attributed to the deposit roughness that promotes convective heat transfer between the surface and the fluid to an extent that the increase of conduction barrier due to the deposit material itself can be counteracted. Crittenden and Alderman (1988) investigated the effect of deposit on mass transfer rates in an electrolytic cell. At high Reynolds number conditions, the resistance to mass transfer was found reduced due to the presence of deposit particles on the cathode (i.e., a rough surface). Those findings on mass transfer were used to explain analogically the negative fouling resistance in a heat transfer system. The induction stage has been receiving increasing attention because a longer induction time or a lower fouling resistance can significantly reduce the economic losses caused by fouling.

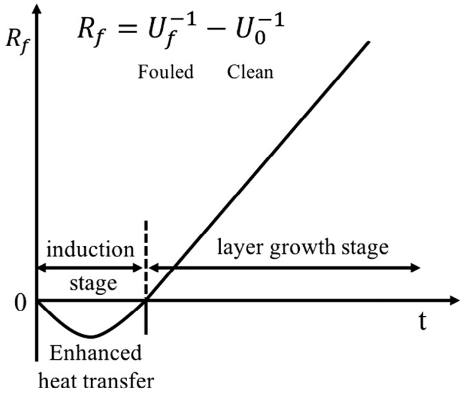

Fig. 1. A representative curve of fouling resistance evolution in a crystallization fouling process. Negative fouling resistance in the induction stage indicates improved heat transfer due to fouling and U is the overall heat transfer coefficient.

In the induction stage, large number of nuclei are generated on the heat transfer surface rapidly. Beyond that, the crystals will keep growing and finally cover the heat transfer surface to form a fouling layer (Kim et al., 2002). The heat transfer surface properties will significantly affect the nucleation rate. Although there is no quantitative relationship between surface free energy and the length of fouling induction period, surfaces with low free energy typically offer long induction time (Förster and Bohnet, 1999, 2000; Geddert et al., 2011; Rizzo et al., 2005; Yang et al., 2002; Cruz et al., 2014). Deposition and removal mechanisms are affected by the surface free energy of the solid heat transfer surface. It was found that low-energy surfaces could inhibit the nucleation rate