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Numerical investigation of conjugated heat transfer in a channel with a moving depositing front

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ABSTRACT

This article presents numerical simulations of conjugated heat transfer in a fouled channel with a moving depositing front. The depositing front separating the fluid and the deposit layer is captured using the level-set method. Fluid flow is modeled by the incompressible Navier–Stokes equations. Numerical solution is performed on a fixed mesh using the finite volume method. The effects of Reynolds number and thermal conductivity ratio between the deposit layer and the fluid on local Nusselt number as well as length-averaged Nusselt number are investigated. It is found that heat transfer performance, represented by the local and length-averaged Nusselt number reduces significantly in a fouled channel compared with that in a clean channel. Heat transfer performance decreases with the growth of the deposit layer. Increases in Reynolds, Prandtl numbers both enhance heat transfer. Besides, heat transfer is enhanced when the thermal conductivity ratio between the deposit layer and the fluid is lower than 20 but it decreases when the thermal conductivity ratio is larger than 20.

1. Introduction

Conjugated heat transfer in a channel with a deposit layer gradually growing on the wall is widely encountered in many engineering applications such as fouling in heat exchangers [1–4]. In these systems, the working fluid carries particles either of an organic or inorganic origin flowing into channels. These particles have a tendency to deposit onto the wall of the channels, forming a deposit layer. The continuously growing and increasingly thicker deposit layer, formed by the deposited particles, normally has a low thermal conductivity. With heat transfer involved, such deposit layer introduces extra thermal resistance and consequently leads to a low heat transfer performance of the system. Besides, the deposit layer reduces flow cross sectional area of the channel and directly responsible for inducing a larger pressure drop. Unfortunately, the deposition process, although highly undesirable for heat transfer, can only be minimized. Therefore, such kind of system normally operates with a formed deposit layer of a tolerable thickness. As such, a good understanding of the conjugated heat transfer coupling the evolving deposit layer and fluid flow is important.

Conjugated heat transfer with a moving depositing front can be investigated experimentally. Nuntaphan and Kiatsiriroat [1] studied the effect of fly ash on the heat transfer performance of a heat exchanger with spiral finned-tubes. They found that the thermal resistance caused by the fouling of the fly ash increases with time in the testing period of 8 h. The growing of silica deposition in a heat exchanger during combustion of siloxane with gas was experimentally studied by Turkin et al. [2]. Their results showed that particle distribution of the silica had no much effect on the deposition flux. However, the deposition flux of silica increases linearly with the siloxane concentration in the mixture. Li et al. [3] investigated fouling in corrugated heat exchangers. They found that increase of inlet fluid velocity reduces fouling resistance. Fouling in a twisted tube heat exchanger is studied by Al-Hadhrami et al. [4]. Their results showed that the heat input had significant effect on fouling resistance when the inlet fluid velocity was low. Genić et al. [5] investigated fouling in 8 plate heat exchangers. They found that fouling depends strongly on the fluid velocity. Wax deposition in a crude oil pipeline system was studied by Valinejad and Nazar [6]. It was shown that a waxy crude oil with high wax content resulted in more solid wax deposited on the walls. Zhang et al. [7] conducted experimental and theoretical investigations of fouling on four corrugated plate heat exchangers. The effects of plate height, plate spacing and plate angle on the fouling process were studied. They

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Nomenclature

C	particle concentration (kg/m^3)
c_p	specific heat (J/kg K)
D	diffusion coefficient (m^2/s)
f	friction coefficient
H	height of domain (m)
$H(\phi)$	smoothed heaviside function
k	thermal conductivity (W/m K)
r_d	reaction rate for deposition (m/s)
L	length of domain (m)
Nu	Nusselt number
$\hat{n}$	unit normal at the interface
$\vec{q}$	deposition flux (kg/m^2 s)
p	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
$\overline{sign}(\phi)$	Sign function
S	signum function
T	temperature (°C)
t	time (s)
$\bar{t}$	pseudo time (s)
$\vec{u}$	velocity vector (m/s)
u_t	tangential velocity (m/s)
x,y	Cartesian coordinate
Δx	mesh size (m)

Greek symbols

δ	height of the deposit region (m)
$\delta(\phi)$	Dirac delta function
$\tilde{\Gamma}$	diffusion coefficient (m^2/s)
θ	dimensionless temperature
ϕ,ϕ'	level set function (m)
φ	component of $\vec{u}_{i,\mathrm{ext}}$
ε	interface thickness (m)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
τ	shear stress (Pa)
Ω	domain of interest

Subscripts

b	bulk
d	deposit
i	interface
i,ext	extension velocity
in	inlet
out	outlet
w	wall
+	fluid region
−	deposit region
*	dimensionless
0	initial status

concluded that the plate heat exchanger with the largest diameter and height to pitch ratio gave the best antifouling performance. Their theoretical results agreed well with the experimental data. Crystallization fouling in a microscale heat exchanger was studied by Mayer et al. [8]. They found that fouling in the microscale is similar to that occurred in the macroscopical scale. Generally, experimental study may involve large time scale. One of the examples is fouling in heat exchangers. Fouling of heat exchanger can occur in weeks, months, years or even longer. Once the heat exchanger is fouled, cleaning process is necessary. Physical cleaning generally involves dismantling and reassembling of the equipment. In certain industries, chemicals can be used to remove the deposit. If not performed properly, these cleaning processes will inevitably damage the equipment and thus shorten the life of the equipment. Therefore, the cost for experimental study of fouling could be substantial. Occasionally, experiments demand extreme cautiousness because of high pressure and hazardous chemical materials. In view of this, theoretical investigations, especially numerical simulations, play an important role in understanding conjugated heat transfer with a moving depositing front.

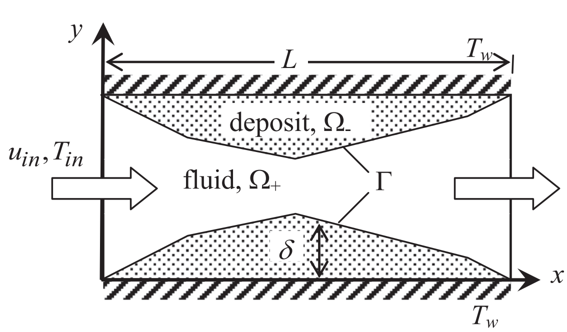

Fig. 1. Schematic of a two-dimensional channel.

The channel with a moving depositing front is generally divided into two regions, i.e. a fluid region and a deposit region formed by the deposited solid particles. In clean channels where no particle deposit on the walls; heat is directly transferred to the incoming fluid in the form of convection heat transfer between the hot surface and the incoming fluid. However, with particle deposition formed on the wall of the channel, heat has to be conducted first through the additional deposit layer from hot wall to the depositing front. Then the incoming fluid carries the heat downstream. From a modeling point of view, this kind of problem is governed by conservation equations for mass, momentum, species and energy, coupled with the appropriate interfacial condition at the depositing front separating the fluid from the deposit layer. In particular, the depositing front is a moving boundary. All of these should be incorporated in the numerical model so that the heat transfer with a moving depositing front can be studied more realistically especially when the deposit layer is not thin relative to the characteristic length. Giving the difficulties in capturing the moving depositing front, most of the existing numerical works are based on a known fixed depositing front. Sunden [9] studied the conjugated heat transfer in a circular cylinder with a heated core inside. The heat core is assumed to be the deposit layer. It is found that thermal conductivity ratio between the deposit layer and fluid has significant effect on the heat transfer. Owen et al. [10] investigated the thermal resistance of the deposit layer on the surface of the tube in heat exchanger without considering fluid flow. Their results show that heat transfer can increase or decrease depending on the

Table 1
Thermo-physical values of the fluid and deposit layer.

	ρ (kg/m^3)	c_p (J/kg K)	μ (kg/m s)	k (W/m K)
Fluid	1.0	(1.0–5.0)	2.14×10^{-3}	0.01
Deposit layer	1.0	(1.0–5.0)	∞	(0.005–1)