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Characteristics of fouling development in shell-and-tube heat exchanger: Effects of velocity and installation location

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ABSTRACT

The purpose of this study was to investigate the effects of wastewater velocity and installation location of a shell-and-tube heat exchanger on particle fouling deposited within the heat exchanger. Three long-term fouling tests with the heat exchanger installed at the shoot-outlet of a pump with varied wastewater flow rates (low, medium, and high), and one test with the heat exchanger installed at the suction-inlet of a pump at a constant (medium) flow rate were conducted. Variation of the heat transfer coefficient and fouling resistance was measured for each test and a sample of the accumulated foulant was collected at the end of each test to determine its particle size distribution. The particle size distribution of the foulant collected from each test case was analyzed and compared to the size distribution of particles in the wastewater. Results suggested that the diameters of particles deposited on the tube surfaces were mainly in the range of 1.5–88 μm. The average particle diameter of fouling was 40.8 μm at a velocity of 0.31 m/s (low), 24.4 μm at a velocity of 0.46 m/s (medium), and 18.6 μm at a velocity of 0.69 m/s (high). Asymptotic fouling resistances were 1.1×10^{-3}, 0.59×10^{-3}, and 0.22×10^{-3} m^2 K/W respectively for the low, medium and high velocities. In addition, negative fouling resistances were observed at the beginning of fouling development with low and medium wastewater velocities. Results also showed that both the asymptotic fouling resistances and the average particle diameter of fouling obtained with the heat exchanger installed at the suction-inlet of pump were larger than that with heat exchanger installed at the shoot-outlet. On average, 71% (by mass) of fouling consisted of ash ingredient.

1. Introduction

A heat exchanger exposed to wastewater is likely to form fouling, which is a biofilm that covers the heat exchanger surfaces. Fouling deposit is a major problem in heat exchanger operation as it increases both thermal resistance and pressure drop, thus affecting the initial capital investment as well as operating costs [1]. The cost of fouling and corrosion in the US industry was $3–10 billion in 1985 [2]. This problem therefore calls for research on characterization of fouling deposition and development of appropriate fouling mitigation methods.

Mechanisms of fouling development are widely investigated. Previous studies mainly focused on several factors including operation time, geometric structure [3], surface material of heat transfer tubes, hydrodynamic flow conditions [4], and fluid temperature [5]. It was noted that tubes bundled with un-equal cylinders achieved a significant (30%) reduction of particle deposition rate [6]. Enhanced tubes with cone roughness had a higher asymptotic fouling resistance than plain tubes [7]. Increasing the start number and the helix angle of enhanced tubes with internal helical ridges could increase the potential of fouling [8]. It also has been demonstrated that titanium tubes are more prone to be fouled than brass tubes [9]. In a low velocity range (<0.5 m/s), the deposition process is mainly controlled by mass transfer [10]. As velocity increases, the asymptotic limit of fouling resistance decreases accordingly [9].

In general, there are five types of fouling mechanisms: precipitation, particulate, chemical reaction, biological, and corrosion [11]. Natural fouling usually combines two or more fouling mechanisms, which gives rise to the complexity of the research. To understand the phenomenon of fouling, researchers always focused on one specific fouling mechanism, such as particle fouling. Webb and Kim [12] reported particulate fouling deposited on three internally-ribbed tubes and a plain tube. Freeman [13] investigated the effects of particulate fouling on augmented

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Nomenclatures

A_o	total heat transfer area, m^2
C_b	bulk particle concentration, kg/m^3
C_1	positive constant
C_2	positive constant
c_p	specific heat of water at constant pressure, J/(kg K)
D	Brownian diffusivity, m^2/s
d_o	outer and inner diameter of tube, m
d_i	inner diameter of tube, m
d_x	outer diameter of fouling layer, m. $d_x = d_o + 2\delta_f$
d_p	diameter of the particle, m
F_T	variation coefficient of temperature difference, 0.96–0.98
h_{cw}	convective heat transfer coefficient of the circulating water, $W/(m^2 K)$
h_{ww}	convective heat transfer coefficient of wastewater, $W/(m^2 K)$
K	constant
K_B	Boltzmann constant (1.38E−23 J/K)
K_D	particle deposition coefficient, m/s
K_m	mass transfer coefficient, m/s
k_f	thermal conductivity of deposition, W/(m K)
m	mass of particle, kg
Nu	Nusselt number
P	sticking probability
Pr	Prandtl number
R	total thermal resistance, m^2 K/W
R_f^*	asymptotic fouling resistance, m^2 K/W
R_f	real-time fouling resistance, m^2 K/W
R_l	overall thermal resistance of heat transfer per unit length, m K/W
$R_{f,min}$	minimum fouling resistance, m^2 K/W
Re	Reynolds number
r	distance from the particle to center of tube, m
Sc	Schmidt number
T_{wwi}	wastewater temperatures at the inlet of the heat exchanger, K
T_{wwo}	wastewater temperatures at the outlet of the heat exchanger, K
T_{cwi}	circulating water temperatures at the inlet of the heat exchanger, K
T_{cwo}	circulating water temperatures at the outlet of the heat exchanger, K
T	absolute temperature, K
t	operation time, s
t_r^+	dimensionless relaxation time
U	total heat transfer coefficient, $W/(m^2 K)$
$U(0)$	heat transfer coefficient of clean heat exchanger, $W/(m^2 K)$
$U(t)$	heat transfer coefficient of heat exchanger at time t, $W/(m^2 K)$
u	fluid velocity (wastewater), m/s
u^*	friction velocity, $(=\sqrt{\tau_s \rho_p})$, m/s
$\dot{V}$	flowrate of circulating water, m^3/s
V_r	radial velocity of particle, m/s
V_{fl}	fluid velocity normal to the surface, m/s
V_B	Brownian velocity, m/s

Greek symbols

a	radius of the tube, m
β	constant
δ_f	thickness of fouling, m
θ	angle of location of the particle in polar coordinate system, Degree
λ_t	conductivity factor of the tube, W/(m K)
λ_f	conductivity factor of fouling, W/(m K)
μ	absolute viscosity, N s/m^2
ν	kinematic viscosity, m^2/s
ξ	deposit strength factor, N s/m^2
ρ_f	density of deposition, kg/m^3
ρ_p	density of particle, kg/m^3
ρ	density of wastewater, kg/m^3
τ_s	surface shear stress, N/m^2

surfaces in double-pipe heat exchangers, and showed that the asymptotic fouling resistance decreased with the increase of Reynolds number and the decrease of particle concentration. Following that, Chamra and Webb [14] investigated particulate fouling in heat exchangers where three different-size particles existed in a flowing water stream; their results showed that the asymptotic fouling resistance increased with particle concentration.

Most studies were carried out based on artificial wastewater with a fixed particle size. Since the development of fouling depends on fluid parameters and operation conditions, fouling research using real wastewater is needed. Understanding the development of fouling, especially by real wastewater, is very important for the modeling of fouling and the design of fouling mitigation strategies. However, at present, there is limited knowledge and data about fouling from actual wastewater sources.

Another area of interest while looking at the development of fouling in a heat exchanger subject to wastewater is the supporting system design. A water pump is a necessary device to circulate water through a heat exchanger. The turbulent behavior of fluid at the suction-inlet and shoot-outlet of a water pump is different, which may affect fouling development. There is no data available about the effects of the pump installation location relative to a heat exchanger, thus, there is a need to characterize this phenomenon.

The purpose of this study is to investigate the effect of wastewater velocity and installation location of a heat exchanger relative to a wastewater pump on the fouling deposition onto the surface of bundled tubes in a shell-and-tube heat exchanger. The variation of fouling resistance and particle size distributions measured at different operation conditions are presented with detailed analysis.

2. Material and methods

2.1. Materials

Wastewater used in this experiment was sampled from a sump containing wastewater discharged from a pig farm. Wastewater

Table 1
Character of wastewater.

Parameters	Value
Total dry matter concentration (mg/mL)	3.04
Volatile dry matter concentration (mg/mL)	2.67
Suspended dry matter concentration (mg/mL)	1.65
Volatile suspended matter concentration (mg/mL)	1.47
Suspended ash matter concentration (mg/mL)	0.18
PH	7.9
Ammoniacal nitrogen (as NH^{3+}) (mg/mL)	0.71
COD (mg/mL)	3.44
Phosphate (mg/mL)	0.056