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Research Paper

Prediction of fouling tendency in PHE by data of on-site monitoring. Case study at sugar factory

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HIGHLIGHTS

- The data of PHE fouling monitoring in sugar factory are presented.
- Mathematical model for fouling deposition development in time is proposed.
- The model parameters are determined according to industrial tests data.
- The discrepancies between test data and model results are within 8%.
- The model can be used for design and service scheduling of PHEs.

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ABSTRACT

The fouling deposition on heat transfer surfaces can have significant detrimental effect on heat recuperation and jeopardise the efficiency of energy usage, increasing fossil fuels consumption and harmful environmental effects. The data of plate heat exchanger (PHE) thermal performance monitoring in fouling conditions are presented. PHE is installed at sugar factory for preheating purified thin juice before evaporation. The character of deposits on plate heat transfer surface is examined by opening PHE after the tests. It reviled the scaling and particulate fouling mechanism. Mathematical model for prediction of fouling deposition development in time is proposed, which accounts for shear stress at the channel walls and surface temperature. The model parameters are determined according to industrial tests data. The ways of fouling mitigation in PHE are discussed using the model predictions. It is shown that fouling mitigation in PHE is possible by increasing wall shear stress at the same pressure drop in heat exchanger. It requires to eliminate additional pressure loss in connections and to optimize the number of plates and their arrangement adding some plates with higher corrugation angle. These recommendations are discussed and some are implemented at the factory conditions. That allowed increase the operation time between stops for PHE cleaning maintenance. The proposed model can be directly used for design and maintenance scheduling at the specific factory. It can also be used as a preliminary guidance for energy saving reconstructions in other sugar factories. But the direct model application requires data of fouling formation monitoring to identify its parameters for work with specific media streams prone to fouling.

1. Introduction

The efficient use of energy is a corner stone for reduction of fossil fuels consumption, fighting of environmental pollution by harmful emissions of combustion processes including carbon dioxide that is regarded as the main cause of the global warming [17]. In many industrial processes the efficiency of energy usage is determined by recuperation of the heat available in hot streams with heating of the cold streams of the process. It takes place in heat exchangers, which efficiency highly determines the level of heat recuperation and allows save energy, which in other way would be wasted. However, to increase the amount of heat recuperated in heat exchanger the increasing of the heat transfer surface area can be required, that can be not economically attractive. One of the solutions for this problem is the use of modern compact heat exchangers (CHEs) with efficient heat transfer inten-

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Nomenclature

b	is an empirical coefficient, $Pa^{-1}\cdot s^{-1}$
E	is the activation energy constant, $J\cdot mol^{-1}$
D_e	is the equivalent diameter of PHE channel, m
G	is the flowrate, $kg\cdot s^{-1}$
h	is the film heat transfer coefficients for hot/cold side, $W\cdot m^{-2}\cdot K^{-1}$
Q	is heat transfer load, W
R	is the gas constant per mole, 8.3143 $J\cdot mol^{-1}\cdot K^{-1}$
Re	is the Reynolds number; $Re = w\cdot D_e\cdot\rho/\mu$
R_f	is the fouling thermal resistance, $m^2\cdot K\cdot W^{-1}$
t_{ij}	is fluid temperature, °C; where i indicates hot (1) or cold (2) stream, j indicates inlet (1) or outlet (2)
T_s	is the surface temperature, K
U_0	is the overall heat transfer coefficient in clean conditions, $W\cdot m^{-2}\cdot K^{-1}$
U_f	is the "dirty" overall heat transfer coefficients in PHE with fouling deposits, $W^{-2}\cdot K^{-1}$
w	is the fluid velocity, $m\cdot s^{-1}$

Greek letters

β	is the corrugation inclination angle to main flow direction, degrees
δ_w	is the thickness of the plate, m
ζ_s	is the coefficient of total hydraulic resistance for the unit length of channel
ζ_τ	is the friction factor corresponding to the part of pressure drop caused by friction on the wall
θ	is time, hours
τ_w	is wall shear stress, Pa
λ_w	is the thermal conductivity of the plate metal, $W\cdot m^{-1}\cdot K^{-1}$
μ	is the fluid dynamic viscosity, Pa·s
ρ	is the fluid density, $kg\cdot m^{-3}$
φ_d	is the deposition rate of fouling, $m\cdot h^{-1}$
φ_r	is the removal rate of fouling, $m\cdot h^{-1}$
ψ	is the share of pressure losses due to friction in total pressure loss at channel main corrugated field

sification ([10]). As show the experience in a number of industries, one of the most promising types of CHEs is Plate Heat Exchanger (PHE) [18]. This type of heat exchanger is much smaller and consumes much less metal for its production, much lower footprint, than traditional tubular units.

PHE possess considerable advantages over conventional shell-and-tube heat exchangers, such as smaller occupied volume and sizes, lower cost, less fouling tendency, flexibility in adjusting the heat transfer surface area, accessibility for cleaning, and, what is very useful, for efficient heat recuperation, a close temperature approach of heat exchanging streams down to 1 K. The high heat transfer coefficients in PHEs as a rule enable to perform the same heat duty with much less heat transfer surface area. These features allow obtaining economically favourable options in different applications with less cost of heat exchangers, as is reported by Hajabdollahi et al. [12] for water-water heat exchanger, Kapustenko et al. [14] for the use of PHEs in chemical industry, and for waste heat utilisation by Arsenyeva et al. [4]. The correct selection of PHE for specific duty necessitates accounting of all factors influencing it performance. In many industrial applications the fouling on heat transfer surface can significantly influence the performance of PHE and its capability to maintain the parameters required by the process conditions. For intensified surfaces with high heat transfer coefficients the adverse impact of the same fouling layer as in shell-and-tubes will be much more significant. The fouling formation on corrugated surface of plates determines not only the thermal performance, but leads to additional pressure losses and excessive pumping power consumption, increases costs of cleaning. The efficient solution of this problem can be regarded as one of significant challenges, as is discussed by Crittenden et al. [8].

The fouling phenomena can to a great extent reduce the efficiency of heat transfer process not only by forming fouling deposition layer with additional resistance to heat flux, but also by decreasing the free space for flow movement in channels partly blocking it with fouling deposits. In some cases leads to excessive pressure loss in channels and makes possible their final clogging. The analysis of a number of publications made by Crittenden and Yang [7] revealed that in industrially developed countries the increase of costs due to fouling is about 0.25% of GDP (Gross Domestic Product). There is also estimated that about 2.5% of the carbon dioxide emissions are caused by fouling. The most common approach to compensate the adverse effects of fouling on heat exchanger performance is the introduction of some additional fouling thermal resistances into basic equations of thermal design. It does not account for a number of different factors influencing fouling deposition rate and leading to excessive increase of heat transfer surface area. As it is discussed by Muller-Steinhagen [20], with proper accounting of fouling development in time the economically beneficial values of fouling thermal resistance could be selected. It is especially important to PHEs with enhanced heat transfer, where the same thermal resistance of fouling layer as in tubular heat exchangers can cause much worse effect. However, as it was observed by Panchal and Knudsen [22], one of the efficient methods to mitigate fouling is the use of surfaces with intensified heat transfer. The reduction of fouling on enhanced heat transfer tubes with special dimpled surface was observed by e.g. Kukulka et al. [19], while Webb [29] has found increase of fouling rate in tubes with three-dimensional cone roughness and helical-rib tubes. The reduction of fouling in PHEs is much more certain as is discussed in book by Klemeš et al. [18] and can reach up to 10 times compare to fouling in shell-and-tubes heat exchangers for the same duty. The mitigation of fouling coupled with heat transfer enhancement gives even more advantages to the application of PHEs in different process industries. Wang et al. [27] have discussed that the accurate estimation of fouling in heat exchangers with intensified heat transfer has primary importance in solving the heat exchanger network optimization problems, as well as for the design of heat exchangers using cooling water from centralised factory network studied by Picón-Núñez et al. [23].

The fouling deposition on heat transfer surface is a complex phenomenon of simultaneous physical and chemical processes. Its intensity depends on the number factors, mainly covered by the nature of stream media and fouling substance, their concentration, temperature of the surface, flow velocity and flow structure, surface material and its roughness. The development of fouling deposit on heat transfer surface can be characterized by three main stages. The first one is initiation (or induction) period at which fouling deposit is starting to develop after some time delay. This is followed by the stage of fouling growth. When the fouling growth rate is decreasing in time, this stage can end with zero fouling growth rate, when the thickness of fouling layer reaches some asymptotic value. The existence and duration of this stages, as well as character of their development are determined by the type of fouling mechanism and process conditions. The description of different fouling types on enhanced heat transfer surfaces and corre-