International Journal of Heat and Mass Transfer 72 (2014) 210–221

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A parameter study of tube bundle heat exchangers for fouling rate reduction

Hui Han, Ya-Ling He *, Wen-Quan Tao, Yin-Shi Li

Key Laboratory of Thermo-Fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

A R T I C L E I N F O

Article history:
Received 11 October 2013
Received in revised form 25 December 2013
Accepted 2 January 2014
Available online 29 January 2014

Keywords:
Particulate deposit
Heat exchanger
Heat transfer
Pressure drop
Numerical simulation

A B S T R A C T

The formation of particulate deposits on flue gas heat exchanger surfaces will reduce heat transfer efficiency, increase the instability of equipment operation and introduce a major uncertainty into the heat exchanger design. In this paper, a numerical model was developed to predict the flue-ash particle deposition rate by considering particles transport, sticking and rebound behaviors based on the software FLUENT, extended by user-defined functions (UDFs). The numerical model was applied to cross-flow tube bundle heat exchangers with a 6-row tube arrangement. The effects of six parameters (particle diameter, flow velocity, spanwise tube pitch, longitudinal tube pitch, tube geometry shape, and arrangement) on fouling rate, as well as on the heat transfer and hydrodynamics performance, were examined. It was found that particle deposits accumulated primarily in the flow stagnation region, recirculation region, the vortex separation and reattachment regions. Increasing particle diameter moved the deposition zones towards the windward side of tubes. Using both oval tubes and staggered arrangements can reduce the fouling rate. With the increase in longitudinal tube pitch, both the particulate deposit rate and the heat transfer performance increased. To account for fouling and heat transfer performance, a tube spacing value of 2 was recommended.

1. Introduction

Particulate fouling on the heat exchanger surfaces is a major problem in waste heat recovery equipments that can lead to significant efficiency deterioration [1]. In cooler areas of the heat exchanger, such as the economizer, a powdery fouling layer of a few millimeters thick can lead to a reduction in heat transfer coefficient of 25% [2]. To counter the effect of fouling in the design of a heat exchanger, theoretical models are needed that can describe the main mechanism resulting in the formation of deposits. Then parameters can be picked, and geometry designs can be formulated for the purpose of fouling rate reduction. So far extensive studies have been reported around the following topics.

Many studies focused on the mechanism of particulate deposition and the development of numerical models simulating the deposition. Rather than studying fouling behavior in a high temperature superheater, the current study focused on waste heat recovery with a temperature below 300 °C where particulate accumulation is responsible for most of the deposited mass. The fouling rate on the heat exchanger surfaces is determined by the transport mechanism of suspended particles in boiler flue gas and the impact behaviors of incident particles hitting the heat transfer surface. Generally, the flue-ash particles are carried to the heat transfer surface by transport mechanisms [3] such as inertial impact, thermophoresis, condensation, and turbulent diffusion. Inertial impact on the particle motion is expected to be the dominant transport mechanism for the particles with larger diameters; while the transportation process of the smaller particles, especially for sub-micron particles, is controlled by eddy transport and thermophoresis [4]. Van Beek et al. [5] confirmed that the majority of deposit particles on economizers varied in size from 1 to 10 μm. With the development of computational fluid dynamics, the motion of the particulate phase can be well predicted by solving the gas–solid two-phase flow. However, modeling the particle–wall impact process in conjunction with gas-particle two-phase flow remains difficult. When the flue-ash particles collide with a heat transfer surface, the particles may adhere to the surface if the incident velocity is below the critical sticking velocity and may rebound or remove other deposited particles if the incident velocity is above the critical sticking velocity [6]. In previous years, researchers have sought to obtain a reliable model to accurately describe the sophisticated impact, deposition and removal behaviors of particles. Rogers and Reed [7] calculated the critical sticking velocity for micron particles hitting a solid surface. Bouris and Bergeles [8] modeled the particle layer as a solid surface and used the normal coefficient of restitution to describe the outcome of the impact. To consider the effect of the deposit surface, Werner [9] proposed using an effective mass for the

* Corresponding author. Tel.: +86 29 82665930; fax: +86 29 82665445.
E-mail addresses: yalinghe@mail.xjtu.edu.cn, hylepe@gmail.com (Y.-L. He).

0017-9310/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.01.010

Nomenclature

A_f	frontal area (m^2)
a	contact diameter (m)
C_D	drag coefficient
C_f	skin friction coefficient
d_p	particle diameter (m)
D	tube diameter (m)
e_n	normal restitution coefficient
Eu	Euler number
E^*	effective Young's modulus ($N\,m^{-2}$)
F_{ad}	adhesive force (N)
F_B	Brownian force (N)
F_L	Saffman's lift force (N)
F_{TH}	thermophoretic force (N)
F_t	tangential force acting on the contact surface (N)
G^*	effective shear modulus ($N\,m^{-2}$)
k_t	tangential stiffness ($N\,m^{-1}$)
m_d	particle deposition rate ($kg\,s^{-1}$)
m^*, m_1, m_2	effective mass ($=m_1m_2/(m_1+m_2)$), incident particle mass, target particle mass (kg)
Nu	Nusselt number
p	pressure (Pa)
$Q_{A,a}$, Q_{el}, Q_{pe}, Q_k, Q_p	adhesive energy, elastic energy, elastic energy in plastic deformation, kinetic energy, plastic deformation energy loss (J)
R	particle radius (m)
Re	Reynolds number based on the tube diameter
S	modulus of the mean rate-of-strain tensor
S_1	longitudinal tube pitch (m)
S_2	spanwise tube pitch (m)
Stk	particle Stokes number ($=\rho_p d_p U/18\mu D$)
T	temperature (K)
U	fluid velocity ($m\,s^{-1}$)
v	particle velocity ($m\,s^{-1}$)
V	heat exchanger volume (m^3)
x, y	Cartesian coordinates (m)

Greek Symbols

α	impact or deposit angle (°)
β	effective coefficient of the contact radius
Γ	surface energy ($J\,m^{-2}$)
θ_i	local impact angle (°)
μ_{min}	minimum friction coefficient
μ_t	turbulent viscosity ($kg\,m^{-1}\,s^{-1}$)
μ^*	effective friction coefficient
Φ	heat transfer rate (W)

Subscripts

cr	critical
in	inlet
inj	injection
n	normal direction
r	rebound
t	tangential direction
w	tube wall

target particle to replace the deposit layer, thus simplifying the interaction between an incident particle and the deposit to a two-body collision. Werner [9] and Tanaka et al. [10] modeled the dynamic response of a two-dimensional bed of particles subjected to an impact with a spherical projectile using the discrete element method (DEM). Thornton and Ning [11] studied the normal impact of elastic-perfectly plastic spheres and gave an analytical solution for the coefficient of restitution. Konstandopoulos [12] introduced the new criterion of critical impact angle for oblique impacts. Van Beek [13] developed a two-body collision deposition model for particle impact with a powdery layer. In addition to studies focusing on particle deposition and rebound mechanism, some research has also been conducted to model the fouling removal. Rodriguez et al. [14] indicated that the fouling removal is largely dependent on gas flow velocity. Abd-elhady et al. [15] experimentally investigated the minimum gas speed at which particulate fouling can be avoided. Pan et al. [16] presented an integrated inertial impact mechanism model that considered the combined particles deposition and the fouling removal process. Abd-Elhady et al. [6] numerically predicted the critical sticking and removal velocities for an incident particle hitting a bed of particles. Although the discrete element method (DEM) seems to easily solve the fouling removal behavior, the excessive computing resource consumption needed to solve the motion of all bed particles involved in the interaction unfortunately limits its practical application. Similarly, the integrated model presented by Pan et al. gives the analytical solution of a critical removal velocity. However, not only the calculation parameters related to the force propagation characteristics of pre-deposited medium were indefinite, but also the model ignored the particle motion after removal from the fouling layer.

In the present study, the impact between the incident particle and target particle was modeled based on the rigid body theory of Goldsmith [17]. The interaction was modeled as the outcome of a 2-body collision between an incident particle and a target particle that presented a developing fouling layer [13]. The Rogers and Reed model [7] was used to solve the normal restitution coefficient of the particles based on an energy balance during an impact process. Here, the deposit rate of powdery fouling layers in heat exchangers was linked to the sticking and rebounding of particles without considering the process of particle removal from the deposit bed.

Compared to the amount of research on the development and improvement of impact deposit models, there are relatively few studies in published literature that focus on the heat exchanger design for the particle fouling rate reduction. Bouris et al. [18] found a 73% reduction of deposition rate on lignite utility boiler heat exchangers by using elliptical tubes arranged in an in-line layout. Both the heat transfer coefficient and pressure drop also decreased significantly. Subsequently, Bouris et al. [19] proposed a drop-shaped cross-section for the heat transfer tube, which attains higher heat transfer performance with a 75% lower fouling rate and 40% lower pressure. The mechanism for the reduction in particle deposition rate is attributed to the low fluctuation levels and weak periodic activity in the wake region behind the tubes. Abd-Elhady et al. [20] proposed the addition of cones to the front of normal circular tubes to minimize the stagnation area and reduce particulate fouling. It was found that particulate fouling ceased if the apex angle of the cones were smaller than 90°. Recently, Mavridou and Bouris [21] proposed a novel heat exchanger geometry using unequally-sized cylinders placed alternately in tandem. As compared to the common tube bundle heat exchanger consisting of tubes with an equal diameter, a 30% deposition rates reduction and 28% heat transfer enhancement per unit volume were reported. Although tube bundle geometry and arrangement significantly affect the particle fouling rate, as well as heat transfer and fluid flow performances, no systematic study has been conducted and no common design criteria has been proposed to guide the specific applications.