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Full Length Article

Heat transfer and fouling performance of finned tube heat exchangers: Experimentation via on line monitoring

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ABSTRACT

An on line experimental system was set up in a heating boiler so as to reproduce dusty working environments in heat recovery systems and to investigate heat transfer and fouling performance of different kinds of finned tube heat exchangers. Measurements are reported for the heat transfer coefficients, fouling and the effect of fouling on heat transfer performance of five different H-type finned tube heat exchangers. Fouling resistance and the weakened degree of heat transfer coefficient are employed to evaluate the effect of fouling on the heat transfer performance. Numerical simulations are also conducted on the fouling performance of each heat exchanger bundle and compared to the measurements. Double H-type fins can slightly reduce the heat transfer performance but also reduce fouling. Elliptical finned tubes with the same tube pitch decrease heat transfer performance and increase fouling, and with the same relative tube pitch, significantly increase the heat transfer performance before fouling, and can effectively reduce fouling.

1. Introduction

Ash-related issues are among the most challenging problems in boiler systems, and they mainly can be divided into slagging and fouling problems, which usually leads to significant deterioration of heat transfer performance, unscheduled shut downs and even the failure of the systems with serious economic consequence [1–4]. The slagging problem mainly happens in the radiant section of a boiler [2]. When the gas flows to a lower temperature region, some of the vaporised metals nucleate and condense on the heating surfaces and form a sticky initial slagging layer. Then the coarse fly ash, with or without a self-surface sticky layer, will deposit on the surface of the sticky initial slagging layer by inertial impaction. Niu et al. [4] systematically reviewed the slagging problems in biomass combustion systems, including slagging formation mechanisms, damages, ash utilization, and related countermeasures. While the fouling problem mainly occurs in the convective passes of boilers [2]. For example, in waste heat recovery systems, which plays an important role in reducing the energy loss and increasing energy efficiency in many industrial processes, fouling can be the major problem for the heat exchangers.

Extensive research has been carried out on the heat transfer and fouling performance of heat exchangers, and research methods can be divided into numerical methods and experimental methods. The numerical method has its unique advantages: (1) It can reduce costs and save time, and (2) a large number of comparative studies can be done to determine the optimal scheme without the workload of the experimentation. We have previously presented several of numerical investigations of heat transfer and fouling performance both for circular tube heat exchangers [5–7] and finned tube heat exchangers [8–11]. Although numerical methods have obvious advantages, their reliability and accuracy should be first verified, and validation must be based on comparison with experimental results. Even when an optimal design is obtained numerically, experimental testing is necessary before the formal industrial production of the equipment.

Experimental research on the performance of heat exchangers mainly consists of heat transfer test, fouling processes, and the effect of fouling on heat transfer performance. Experimental methods can be further divided into cold state, hot state and on line experimentation. Cold state experiments mainly focus on the fouling without heat transfer performance. Abd-Elhady et al. [12] experimentally studied fouling performance as well as the influence of flow direction with respect to gravity on fouling. They found that the best orientation for lingering particulate fouling is the downward flow, where the flow stagnation point coincides with the top point of the heat exchanger tubes, and the growth of the fouling layer only starts from one point. Zhan et al. [13] experimentally investigated the particle fouling

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Nomenclature

a	major semi-axial diameter, mm
A_o	outside overall area, m^2
b	short semi-axial diameter, mm
c_p	specific heat capacity, J/(kg·K)
D	tube diameter, mm
E	Young's modulus, GPa
F_p	fin pitch, mm
G	fin gap, mm
H	fin length, mm
k	heat transfer coefficient, W/(m^2·K)
Q	heat transfer capacity, W
q	volume flow rate, m^3/s
R_f	fouling resistance, m^2·K/W
s	cross-sectional area, m^2
S_1	transverse pitch, mm
S_2	longitudinal pitch, mm
T	temperature, K
ΔT_m	log mean temperature difference, K
u	fluid velocity, m/s
W	fin width, mm
Y	Yield stress, N/m^2

Greek symbols

Γ	work of adhesion, J/m^2
δ	fin thickness, mm
ε	deposit porosity
η_o	overall fin surface efficiency
λ	thermal conductivity, W/(m·K)
ρ	density, kg/m^3
σ_1	relative transverse pitch
σ_2	relative longitudinal pitch
υ	Poisson's ratio
φ	weaken degree of heat transfer coefficient
ϕ	heat balance deviation

Subscripts

0	initial clean state
ave	average
f	fouling
g	flue gas
in	inlet
out	outlet
w	water

characteristics of wavy fin-and-tube heat exchangers, and the effects of fin pitch, particle concentration and air velocity. They found that the particles mostly deposit on the leading edge of the fins and the front part of tubes.

Lee et al. [14] investigated air-side heat transfer characteristics of spiral-type circular fin-tube heat exchangers in hot-flow experiments. Empirical correlations for *j*-factors were developed for in line and staggered fin alignment. Kawaguchi et al. [15] experimentally compared the heat transfer and pressure drop characteristics of spiral fin and serrated fin heat exchangers. Nuntaphan et al. [16] investigated the effect of fouling on thermal performance of a spiral fin-and-tube heat exchanger, and developed an empirical model for evaluating the thermal resistance of the heat exchanger. Bell et al. [17] experimental analysed the effect of fouling on the heat transfer and pressure drop performance of a hybrid heat exchanger. They also investigated air-side pressure drop and heat transfer performance, as well as the effect of fouling on the plate-fin heat exchanger [18].

Both cold state and hot state experiments have been mainly the laboratory experiments compared to on line experiments because it is difficult to recover actual operating environments and heat exchanger performance. As for on line experiments, Shi et al. [19] experimentally investigated the fouling performance of helical finned tube heat exchangers in a circulating fluidized bed (CFB) boiler. Li et al. [20] also conducted experiments in a CFB boiler, and studied fouling characteristics and the effect of fouling on the heat transfer performance of H-type finned tube heat exchangers.

The H-type finned tube heat exchanger has been proposed as a new kind of anti-wear and anti-fouling heat exchanger. The H-type finned tube is comprised of two separate fins welded on both side of a tube, and forms a narrow gap between the two fins. Its appearance resembles the letter H, hence the name "H-type finned tube". It has been found that fouling on finned tubes mainly occurs in the stagnation region in front of tubes and in the recirculation region behind the tubes [8]. The existence of the narrow gap between the fins just eliminates the support of deposited ash, which enable easy cleaning of tube bundle by steam (soot blowing) and mitigates fouling. Due to anti-wear and anti-fouling performance, the H-type finned tube heat exchanger recently has been widely used in the waste heat recovery systems. Jin et al. [21] numerically investigated heat transfer and pressure drop characteristics of the H-type finned tube heat exchanger and correlations of Nusselt number and Euler number were obtained. Chen et al. [22] experimentally investigated the heat transfer and pressure drop performance with the effects of geometric parameters. Li et al. [23] also studied the air side heat transfer and pressure drop of H-type finned tube heat exchangers with in line layouts, and correlations of Nusselt number and Euler number were developed.

In previous numerical work, we found that double H-type fins can reduce fouling compared to that of single H-type fins [24]. Han et al. [5] also found that elliptical tubes and staggered arrangements can reduce the fouling on heat exchangers. However few experimental studies have investigated anti-fouling measures with the use of double H-type fins and elliptical tubes, especially with on line experimentation and monitoring.

In this paper, an on line fouling experimental system is described and used for measurement of heat transfer and fouling performance of five H-type finned tube heat exchangers. Flue gas properties and coal ash particle properties are first analyzed, then heat transfer, fouling and the effect of fouling on the heat transfer performance of each heat exchanger is determined. Numerical simulation of the fouling performance are also conducted and compared with the experiments. Anti-fouling measures and structures are also discussed with implications for the design of anti-fouling heat exchangers.

2. Experimental and methods

2.1. Experimental system

The on line experimental system is shown in Fig. 1. The system is set up on the back side of the gravity settling chamber of a heating boiler and the front side of the bag dust collector. Fig. 2 shows the schematic of the experimental system and includes a heat exchanger (test unit), a flue gas circulation loop, a water circulation loop, and a test system with data collection and monitoring.

The flue gas with fly ash particles is drawn from the boiler by an induced draft fan and then crosses the flue gas circulation loop to produce fouling on the heat exchanger surfaces. The red solid line in Fig. 2 represents the water circulation loop. The hot water in the water circulation loop comes directly from the heating pipe of the boiler system, and is heated by the flue gas in the heat exchanger and then sent back to the boiler system. The blue dashed line represents the test