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Research Article

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The Effect of Flow Inlet Temperature on Pressure Drop and Fouling Deposit in the In-line Tube Bundle

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Abstract

This paper investigates the influence of inlet temperature on the pressure drop and fouling deposit in a tubular heat exchanger. The tube bundle comprises three columns and six rows of copper tubes with a diameter of 0.015 m. The transverse distance between the tubes is 0.0225 m, and the longitudinal distance between the tubes is 0.03 m. Three levels of inlet air temperature: 30, 60, and 90 °C, were varied to examine the effect of inlet temperature using both numerical and experimental methods. For the numerical study, computational fluid dynamics using Ansys Fluent 2021 R1 was employed to observe the temperature distribution in the tube bundle and the normalized pressure drop at different inlet temperatures and Reynolds numbers. Simultaneously, an airflow experiment in the heat exchanger was conducted to monitor the pressure drop and fouling deposit at varying inlet temperatures. The results indicate that the temperature in the tube bundle increases with the inlet temperature, and the space between each transverse tube exhibits a lower temperature than other areas. Additionally, the increase in the inlet temperature leads to a reduction in fouling deposit and pressure drop. However, there is a discrepancy between the pressure drop obtained from the numerical and experimental studies. Heat exchange takes place on a nanometric scale.

Keywords

Fouling deposit, Inlet temperature, Pressure drop, Computational fluid dynamics

Introduction

In the present day, our world is experiencing a continuous increase in energy consumption, particularly from rapidly growing industries. However, due to the limited availability of energy resources, it is necessary to conserve and use energy as efficiently as possible to meet future demands. Heat exchangers are widely used devices with significant roles in various industries, including power plants, food processing, chemical plants, and even in households. Therefore, if we aim to save energy or utilize the limited energy resources effectively, optimizing or designing appropriate operating conditions for heat exchangers can significantly improve their efficiency. Heat exchangers used in coal-fired steam generators, for example, are employed to recover waste heat from flue gases for preheating the air before entering the combustion chamber (known as an air preheater) or heating the feed water (known as an economizer), which is one way to save a considerable amount of fuel used in boilers [1]. There are various types of coal-fired steam generators and circulating fluidized bed technology is widely utilized in different industries due to its advantages such as fuel flexibility, low emissions, and higher combustion efficiency compared to conventional boilers [2]. Despite advancements in

coal steam generator technologies aimed at reducing pollution and increasing efficiency, the issue of ash accumulation in the heat exchanger area remains unresolved.

The exhaust gas obtained from the combustion process can be utilized to preheat the feed water in steam generators. The exhaust gas temperature should not exceed 60 °C to reduce air pollutants [3]. However, lowering the temperature can lead to the accumulation of ash on the heat exchanger surfaces since the exhaust gas contains vapor and particles with a low melting point, such as ash particles. When these particles come into contact with the pipe surface, they melt and form a layer of fouling over time [4]. This fouling formation results in a decrease in heat exchanger efficiency. The adhesion of ash to the heat exchanger surface is also influenced by humidity. Fouling tends to be more viscous in high-humidity conditions, while it becomes dry in low-humidity conditions [5]. Both types of fouling, whether viscous or dry, can affect heat transfer, pressure drop, thermal performance, and thermal resistance in the heat exchanger [6]. The moisture content affecting ash adhesion depends on the temperature of the inlet air [7].

Therefore, the objective of this paper is to comparatively study the effect of the inlet air temperature on pressure drop, and fouling deposition in a tubular heat exchanger. This study simulates airflow through a bundle of tubes in the tubular heat exchanger using computational fluid dynamics (CFD) and experimental methods. The results of this study are expected to provide guidelines for designing optimal operating conditions and cleaning methods for tubular heat exchangers in practical industrial applications.

Methodology

Airflow through a tube bundle using an experimental and CFD method

Simulation of fouling deposition was performed by constructing a heat exchanger apparatus as shown in figure 1. The process commenced by raising the air temperature using a blower (19) to draw air through a group of heat exchange tubes. The air was further heated through a heating coil (1). Subsequently, the airflow was made uniform as it passed through a honeycomb (2). The air velocity was measured using a pitot tube (3) and could be adjusted using a valve (20). Fly ash particles (4) were released into the airflow via a screw feeder at a rate of 0.00016 kilograms per second. Gravity caused the ash to fall, and a fixed blade (5) was responsible for mixing the ash with the air. The mixed air and ash then passed through the honeycomb (6) once more before entering the tube bundle test set (7). Inlet air temperature (measured at point (8)) and outlet air temperature (measured at point (9)) were recorded, and the pressure drop was measured using an inclined manometer (10).

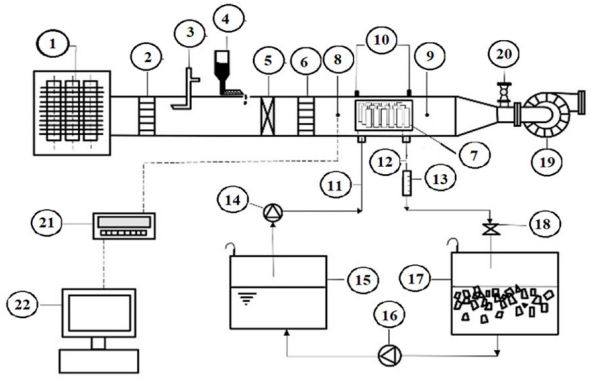

Figure 1: Experimental setup diagram.

The tube bundle in figure 2a was arranged in six rows (Figure 2b) and three columns as a straight-line configuration (Figure 2c). The tube bundle was designed in an in-line arrangement, and the central passageway diameter was 15 millimeters. The vertical spacing between the tubes was 22.5 millimeters, and the longitudinal spacing between the tube rows was 30 millimeters, as shown in figure 3. To facilitate water flow inside the tubes, a pump (14) was used to draw water from a tank (15) maintained at 0 degrees Celsius. The inlet and outlet water temperatures were measured using T-type thermocouples at their respective temperature measuring points (11) and (12). The water flow rate was measured using a rotameter (13) and could be adjusted using a flow control valve (18). Water flowed through the inner channels of the tube bundle and then returned to the lower cold-water tank (17) of the tube bundle test set.

This research study aimed to investigate fouling deposition in correlation with CFD to study the temperature distribution in the tube bundle of heat exchanger under various boundary conditions. To reduce computational complexity, a 2D model

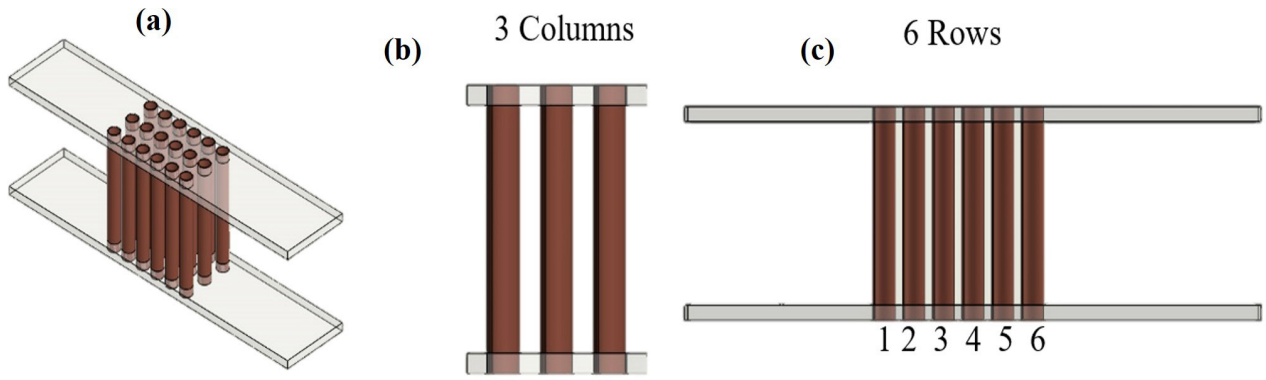

Figure 2: Heat exchanger tube bundle.

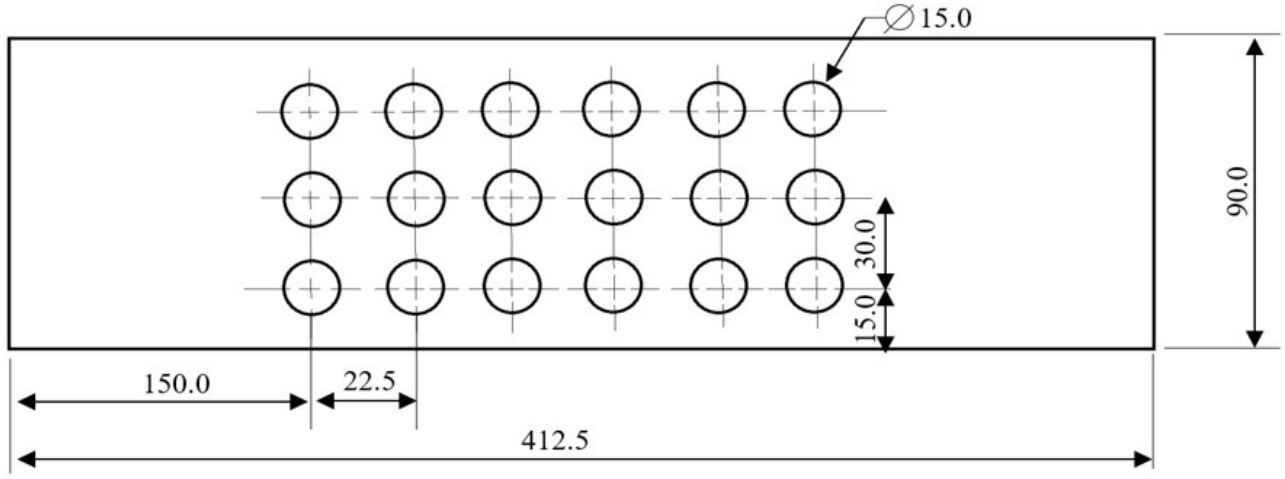

Figure 3: The dimension of the tube bundle.

with triangular elements was utilized, as shown in figure 4a. For increased accuracy, finer elements were added around the tube surface, as illustrated in figure 4b and 4c. After conducting a mesh independence study within the range of 28963-33980, values for NU and ΔP were obtained under constant inlet air temperature of 90 °C and Reynolds number of 12000 - 30000 with an error within 10% compared to Grimson's theoretical values, as shown in figure 5 and figure 6. The selected element range was then used to set the inlet air temperature conditions at 30, 60, and 90 °C with a Reynolds number of 12930.

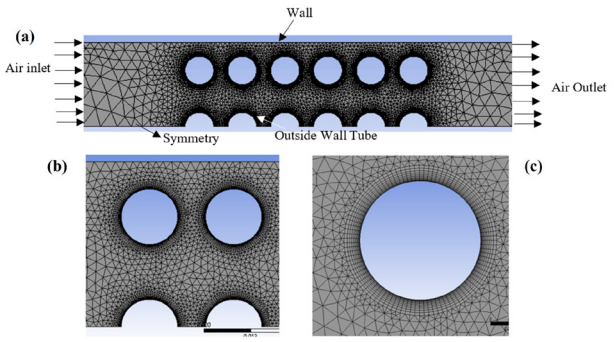

Figure 4: Two-dimensional computational domain and mesh.

Mathematical Model

Ash deposition in the tube bundle when time, t, is changed to the saturation time, T. At this point, there is no change in thermal resistance [5, 6]. Considering the thermal resistance, R_f, changing with time [$W^{-1}m$ °C] can be determined in equation (1).

$$R_f = \left(1/U_f\right) - \left(1/U_c\right) \quad (1)$$

Where U_f is the total heat transfer coefficient on the pipe surface due to fouling deposition [W/m^2K] and U_c is the total heat transfer coefficient on the pipe surface before fouling deposition [W/m^2K]. The total heat transfer coefficient can be determined using equation (2).

$$U = Q_w \Big/ \left(\sum A_0 \Delta T_{lm}\right) \quad (2)$$

Where Q_w is the rate of heat transfer to water [kW] that can be obtained from equation (3), ΔT_{ln} is the logarithm mean temperature difference) [°C] that is obtained from equation (4), and ΣA_0 is the total heat exchanger tube surface area [m^2].

$$Q_w = \dot{m}_w C_{p,w} \left(T_{w,out} - T_{w,in}\right) \quad (3)$$

Where $\dot{m}_w$ is the mass flow rate of water [kg/s], $C_{p,w}$ is the specific heat of water [kJ/kg.K], $T_{w,out}$ is the outlet temperature [°C], $T_{w,in}$ is the inlet water temperature [°C].

$$\Delta T_{ln} = \left[\left(T_{a,in} - T_{w,out}\right) - \left(T_{a,out} - T_{w,in}\right)\right] \Big/ \ln\left[\left(T_{a,in} - T_{w,out}\right) \Big/ \left(T_{a,out} - T_{w,in}\right)\right] \quad (4)$$

Where, $T_{a,in}$ is the inlet air temperature [°C], $T_{a,out}$ is the outlet air temperature [°C]. The pressure drop across the tube bindles can be calculated in equation (5).

$$\Delta P = \rho_a g h_w \quad (5)$$

Where, ρ_a is the air density [$kg.m^{-3}$], g is the gravitational acceleration, h_w is the pressure difference [m].

In this study, the pressure drops, ΔP, at the inlet air temperature of 30 °C, and 60 °C were compared and normalized with the pressure drop at the inlet air temperature of 90 °C, ΔP, expressed in a term of normalized pressure drop, $\Delta P/\Delta P_0$.

Moreover, the mass of fouling, M, at the inlet air temperature of 30 °C, and 60 °C were compared and normalized with the mass of fouling at the inlet air temperature of 90 °C, M_0, that expressed in a term of normalized pressure drop, M/M_0.

Results and Discussion

The validation of the experimental results and the use of CFD method for flow analysis

From constructing a heat exchanger apparatus, fouling deposition was simulated, and flow analysis was conducted using a pre-existing software. When considering the average heat transfer coefficient (hm) and pressure drop (ΔP) as shown in figure 5 and figure 6, at Re equal to 12,000, the hm was 10 and ΔP was 10. As Re increased to 13,000, 14,000, and 15,000, hm values became 30, 40, and 50, respectively, while the cor-

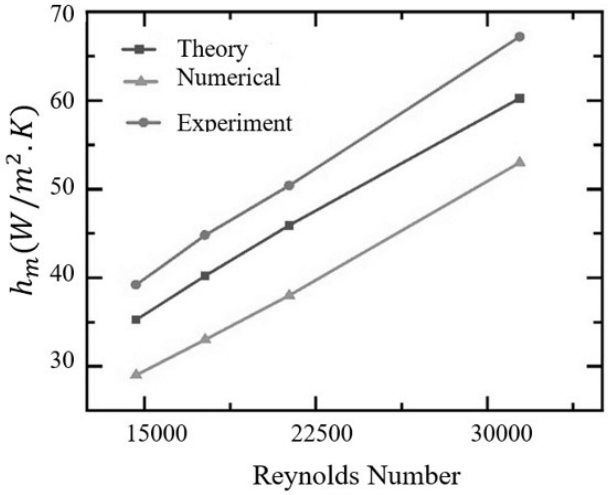

Figure 5: The relationship between average heat transfer coefficient and Reynolds number.

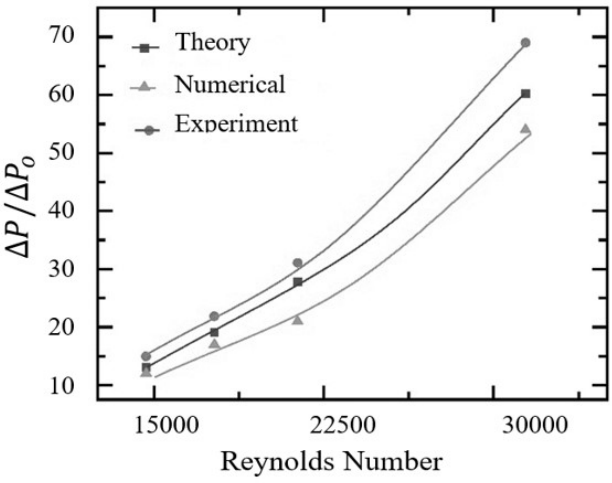

Figure 6: The pressure drop ratio ($\Delta P/\Delta P_o$) between the pressure drops at different Reynolds numbers.

responding ΔP values were 45, 55, and 65. These relationships were observed consistently in both the experimental and CFD simulation results, aligning with Grimson's theoretical values.

The effect of the inlet air temperature on the temperature distribution of the airflow across the tube bundle

The temperature distribution of the airflow across the tube bundle at different inlet air temperatures: 30 °C, 60 °C, and 90 °C is shown in figure 7, obtained from the airflow through a tube bundle using Ansys Fluent 2021 R1. The temperature distribution increased as the air inlet velocity increased. The maximum temperature of 89.85 °C was observed at the entrance of the computational domain when the inlet air temperature was 90 °C. For all levels of inlet temperature, the maximum temperature was found at the entrance of the flow channel. Meanwhile, the temperature of the air in the space between each transverse tube was lower than in other areas. Simultaneously, the minimum temperature was found on the tube surface. This phenomenon is caused by the in-line tube obstructing the airflow, resulting in a low-temperature distribution between the transverse tubes.

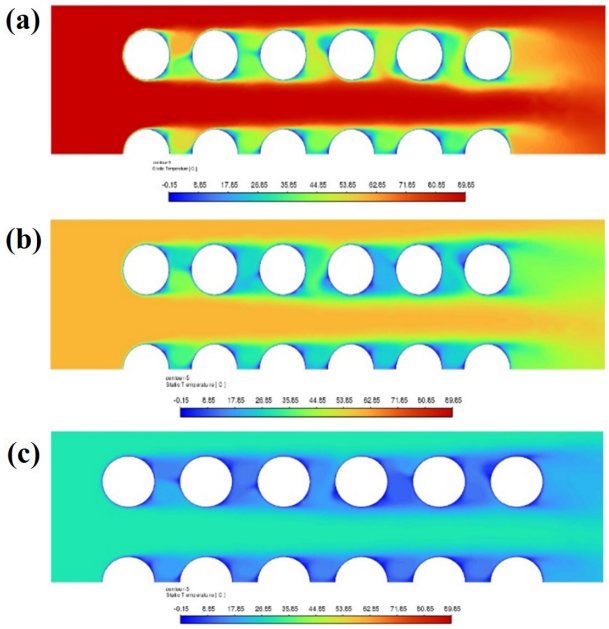

Figure 7: The temperature distribution of the airflow across the tube bundle at three inlet air temperatures: **(a)** 30 °C, **(b)** 60 °C, and **(c)** 90 °C.

The effect of the inlet air temperature on the pressure drop of the airflow across the tube bundle

The results of the pressure drop reduction, in the presence of fouling in the tube bundle, from both experimental and CFD methods, are shown in figure 8. They indicate that the pressure drop decreases as the inlet air temperature changes to 30 °C, 60 °C, and 90 °C, respectively. In the case of fouling accumulation, higher inlet air temperatures result in a greater reduction in pressure drop. However, in the numerical method, the pressure drop remains constant for all changes in temperature, as the fouling deposit was disregarded in the numerical study. The fouling deposit significantly affects both the reduction of the flow channel and the pressure drop. Disregarding the ash particles and fouling deposits in the numerical study leads to a different relationship between the pressure drop and the inlet temperature. In contrast, the ash particles were

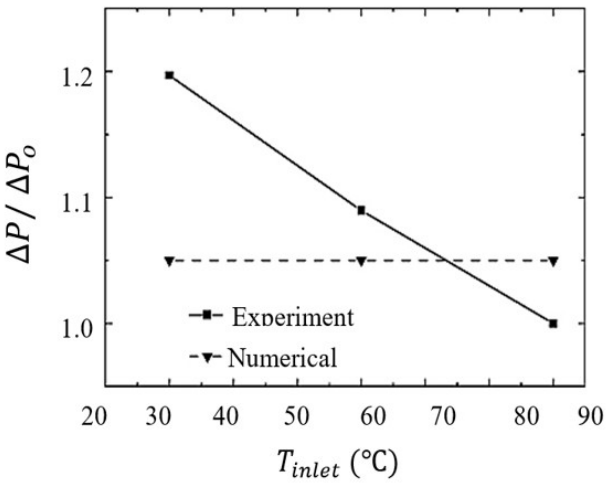

Figure 8: The relationship between the normalized pressure drops and inlet air temperature.

introduced into the experimental device, resulting in fouling formation on the surface of the tubes. An increase in the inlet temperature induced a decrease in fouling accumulation in the experiment, as shown in figure 9.

The effect of the inlet air temperature on the fouling deposit on the surface of the tube bundle

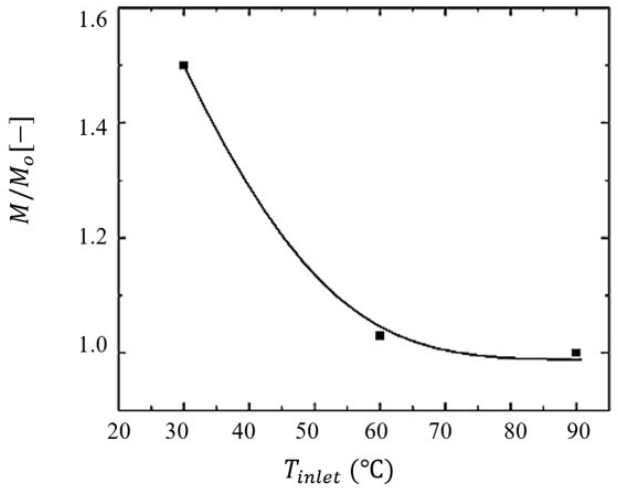

Figure 9: The relationship between the normalized mass of fouling and inlet air temperature.

Figure 9 illustrates the variation of the normalized mass of fouling with the inlet air temperature. The normalized masses of fouling were 1.5, 1.03, and 1 at the inlet air temperatures of 30 °C, 60 °C, and 90 °C, respectively. The normalized mass of fouling decreased as the inlet air temperature increased. The higher temperature induces a looser bond of the fouling molecules in the sticky layer, resulting in a reduction in the fouling mass deposited on the surface of the tube bundle.

Figure 10 presents the fouling deposit characteristics on the tube bundle surface at three inlet air temperatures. At the inlet air temperature of 30 °C, the ash particles stick together, forming a thick layer of sticky and moist mud due to the high strength of molecular bonds of fouling at low temperatures, leading to an increase in the rate of accumulation. At the inlet air temperature of 60 °C, the characteristics of the ash fouling were sticky and friable. In contrast, the ash fouling was more friable at the inlet air temperature of 90 °C. The loose bond of the fouling molecules at high temperatures reduces the rate of fouling accumulation. These results also correspond to the reduction of the pressure drop at high temperatures. The reduction of fouling at high temperatures increases the cross-sectional area of the airflow channel compared to the lower temperature condition, leading to a decrease in the pressure drop at higher temperatures.

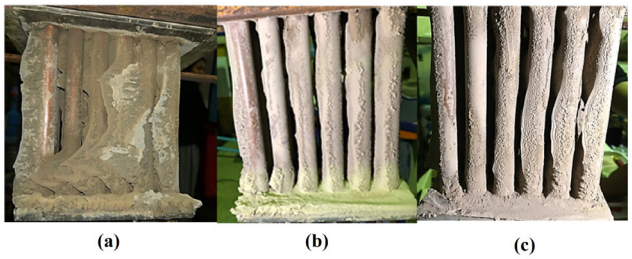

Figure 10: The fouling deposit on the surface of the tube bindle at three inlet air temperatures: **(a)** 30 °C, **(b)** 60 °C, and **(c)** 90 °C.

Conclusion

This paper focuses on the influence of inlet air temperature on temperature distribution, pressure drop, and fouling deposit in the tubular heat exchanger. The study revealed that the variation in inlet temperature had an impact on the pressure drop observed during the experiment and affected the fouling accumulation on the tube bundle surface. Higher temperatures induced a reduction in both the pressure drop and fouling mass accumulation due to the loosening of the chemical bond of fouling and ash molecules at high temperatures.

Acknowledgements

None.

Conflict of Interest

None.

References

1. Sedić A, Guzović Z, Pavković D, Rašković P, Anastasovski A. 2018. Integration of waste heat in the crude oil atmospheric distillation plant. In Proceedings of 3rd South East Europe Sustainable Development of Energy Water and Environment Systems Conference, Novi Sad, Vojvodina, Srbija.
2. Kim S, Choi S, Yang J. 2016. Dynamic simulation of a circulating fluidized bed boiler system part I: description of the dynamic system and transient behavior of sub-models. *J Mech Sci Technol* 30: 5781-5792. https://doi.org/10.1007/s12206-016-1148-8
3. Chen Y, Xiaolong G. 2006. Dynamic modeling and simulation of a 410t/h pyroflow CFB boiler. *Comput Chem Eng* 31(1): 21-31. https://doi.org/10.1016/j.compchemeng.2006.04.006
4. Ma Z, Iman F, Lu P, Sears R, Kong L, et al. 2007. A comprehensive slagging and fouling prediction tool for coal-fired boilers and its validation/application. *Fuel Process Technol* 88(11-12): 1035-1043. https://doi.org/10.1016/j.fuproc.2007.06.025
5. Baxter LL, DeSollar RW. 1993. A mechanistic description of ash deposition during pulverized coal combustion: predictions compared with observations. *Fuel* 72(10): 1411-1418. https://doi.org/10.1016/0016-2361(93)90417-Z
6. Kaiser S, Antonijevic D, Tsotsas E. 2002. Formation of fouling layers on a heat exchanger element exposed to warm, humid and solid loaded air streams. *Exp Therm Fluid* Sci 26(2-4): 291-297. https://doi.org/10.1016/S0894-1777(02)00139-5
7. Kazi SN. 2012. Fouling and Fouling Mitigation on Heat Exchanger Surfaces. In Heat Exchangers-Basics Design Applications. IntechOpen.