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Numerical study of the effect of fouling on local heat transfer conditions in a high-temperature fin-and-tube heat exchanger

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ABSTRACT

The paper presents the numerical analysis of a flow around a bundle of externally finned elliptical tubes, used in cross-flow heat exchangers of a flue-gas/water type, arranged serially in two rows. An algorithm that enables determining the variations of flue-gas temperature and local heat transfer coefficient from gas to the tube wall was presented. On the basis of calculations, it was found that the intensity of heat transfer processes differs significantly in different rows. The intensity is higher in the first row and lower in the second one. This fact is confirmed by the values of the local heat transfer coefficients calculated for the case of heat transfer from gas to a wall determined at the same location. The coefficients, calculated for the first row of tubes, are higher compared with those of the second row. The appearance of fouling deposits on the tube's wall inner surface has an impact on the average temperature along the exhaust gas flow path. It also affects the local heat transfer coefficients from the gas-side to the tube walls. The presence of fouling increases the flue-gas temperature, while its influence on the heat transfer coefficient is slight.

1. Introduction

In recent years, the fin-and-tube heat exchangers and their components attracted broad scientific attention due to the high heat transfer efficiency and a compact size [1–10]. Fin-and-tube heat exchangers are widely used in a variety of applications in the WHRU (waste heat recovery units), HVAC&R systems, chemical processing plants and other units and systems. The main advantage of fin-and-tube heat exchangers is a vast heat transfer area, which is achieved through extended surfaces (fins) [11–13]. Fins are usually used to utilize efficient heat exchange between the gasses (flue-gas, air) and liquids (water, refrigerants, and oils). Therefore, the fin-and-tube heat exchangers are efficient mainly in a situation when a significant difference in the HTC (heat transfer coefficients) exists (i.e., low HTC for gas and high for a liquid). In industrial applications, the fin-and-tube heat exchangers are used as coolers, condensers, evaporators, and heaters. Elliptical tubes are preferred to circular ones, due to larger heat transfer efficiency and lower pressure drop [1,4].

With the rapid growth in computational power, the CFD (Computational Fluid Dynamics) simulations [14,15] have become a useful tool for modeling the heat transfer and fluid flow processes occurring in heat exchange devices. Most of the new concepts of solutions are tested with the computer simulations, and an optimum design solution is found. Many numerical and experimental studies have been performed to optimize the gas-side heat transfer [16–28] including the application of vortex generators, the optimization of tube array arrangement or fin and tube profile shapes. Meanwhile, the liquid side heat transfer is optimized e.g. by reducing the fluid flow maldistributions inside the tubular space of the heat exchanger. Łopata and Ocłoń [29] proposed a new type of a heat exchanger manifold, which allows the flow maldistribution to be reduced. Moreover, the two-phase flow in a tubular space of the heat exchanger can increase the heat transfer coefficient [30].

Most of the recently published articles concerning numerical and experimental studies of fin-and-tube heat exchangers assumed that the heat exchanger tube's wall inner and outer surfaces are clean (i.e. without fouling deposits). There are a few research reports that take into account the fouling on the tube's wall inner surface [31–33], fin surface [34] or thermal contact resistance between a fin and tube [9,10]. Most often the authors analyze the global effect of fouling on the working fluids temperature difference, heat transfer efficiency or heat transfer coefficients. Moreover, the low-temperature HVAC&R applications are usually considered. Based on the performed literature survey it can be stated that the effect of inner fouling deposits on the local heat

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Nomenclature

a	semi-major axis of an ellipse, mm
A	area, m^2
h	heat transfer coefficient, $W/(m^2K)$
h_{in}	water-side heat transfer coefficient, $W/(m^2K)$
k	thermal conductivity, W/(mK)
m	mass flow rate, kg/s
ne	number of finite elements within evaluation line or plane
p	pressure, bar
q	heat flux, W/m^2
T	temperature, °C
w	velocity, m/s
y	coordinate parallel to flue-gas flow direction, m
y^+	dimensionless distance between the wall and the near-wall node of fluid

Greek symbols

ξ	dimensionless ratio of y coordinate and semi-major axis of an ellipse
δ	thickness, mm

Subscripts

s	steel
f	fouling (limescale)
e	equivalent
g	flue-gas
o	outer
i	inner
wt	water
w	tube wall

transfer parameters in a fin-and-tube heat exchanger is not fully understood. With the presence of fouling depositions inside a tube, the local heat transfer conditions degrade significantly [29]. Fouling inside high-temperature heat exchanger tubes may lead to the generation of hot-spot, which, in turn, can lead to the excessive thermal stresses and consequently to the heat exchanger failure. What is also important is the fact that when elliptical tubes are used, significant temperature variations may occur on the tube circumference [35–37]. Therefore, the proper determination of local wall temperature variations plays a crucial role in the evaluation of thermal and structural behavior of a high-temperature fin-and-tube heat exchanger.

The present study analyzes an array of finned elliptical tubes that was installed in an industrial high-temperature fin-and-tube heat exchanger. The numerical simulations are performed to determine the effect of tube's wall inner surface fouling on the local heat transfer parameters. This paper presents a CFD-based method for determination of a local heat transfer coefficient variation along the elliptical tube circumference in a direction perpendicular to the tube bundle. Fouling deposition influence on the local heat transfer conditions (i.e. the flue-gas and wall temperature variations along the gas flow path) is studied for different thermal conductivities of a fouling deposit layer with a thickness of 1.5 mm. Moreover, the influence of the water-side heat transfer coefficient on the local heat transfer conditions is analyzed. The CFD simulation conducted in this study allows the observation of the effect of fouling deposit layer parameters (i.e. thickness and thermal conductivity) on the tube wall temperature. The results obtained with the CFD simulation approach can be easily incorporated into the structural FEM (Finite Element Method) analysis of a high-temperature fin-and-tube heat exchanger.

The novel contribution presented in this manuscript is related to the new method of determining the local equivalent HTC (heat transfer coefficients), referred to the tube outer and inner wall surface. The obtained values of HTC can be implemented in further thermal and structural analysis of the high-temperature fin-and-tube heat exchangers, by using the method presented in this paper.

2. High-temperature fin-and-tube heat exchanger

Fin-and-tube heat exchangers belong to a group of pressure equipment. In some industrial applications (high-temperature fin-and-tube heat exchangers), working fluids temperatures are relatively high. Consequently, the finned tubes are exposed to high temperatures and the resulting thermal loads. Such a cross-flow high-temperature fin-and-tube heat exchanger, which was used in the metallurgical industry for the recovery of exhaust heat, was described in Ref. [29]. The nature of the damage and the analysis of operating conditions were presented in Refs. [29,36–38]. The reason for the heat exchanger failure was an improper water flow distribution in the tubular space of the heat exchanger. Consequently, because of the improper heat reception, substantial differences in heat transfer coefficient of the liquid were observed for particular zones of tubes. Because of large heat fluxes that were transferred from the hot flue-gas to the fluid such flow maldistributions resulted in different tube wall temperatures. Since the heat exchanger sieve plates are stiff, the tubes with high wall temperature are being compressed while the tubes with a low wall temperature are being extended. Slender and thin-walled elliptical tubes of heat exchanger are prone to buckling under low compressive loads. Therefore, the heat exchanger failure can occur within tube zones where the wall temperature is significantly higher than in the adjacent tubes.

Unfavorable phenomena that were mentioned above are intensified by the presence of fouling (e.g. boiler scale) on the inner surface of the heat exchanger tube. Limescale deposition usually results in degraded heat transfer and can lead to a significant reduction in the flow cross-sectional area of the tube. Fouling increases the flow resistance and causes the wall temperature rise. Ocłoń et al. [35] performed a numerical study of the effect of inner tube surface fouling deposit on a temperature distribution in finned tubes and exhaust gas. They studied the deposit layers with different thermal conductivities and thicknesses. The CFD analysis were performed for a fin-and-tube heat exchanger with two rows of tubes in an in-line arrangement. The variations of the bulk temperature, tube wall temperature, heat flux density and flue-gas velocity along the flow path were presented for different flue-gas Reynolds numbers within the 550–1100 range. Also, the influence of fouling thermal resistance and the Reynolds number on the heat flow transferred to the first and the second tube row was analyzed. However, in Ref. [35] no method for determining the local gas-side equivalent heat transfer coefficients, necessary for the thermal and structural analysis of fin-and-tube heat exchangers [29], was presented. This paper discussed the CFD simulation-based method for the numerical determination of the local heat transfer coefficients.

Fig. 1 shows working fluids flowchart for a high-temperature cross-flow fin-and-tube heat exchanger. The heat exchanger was installed in one of the metallurgical factories in Poland and crashed due to improper operating conditions. The heat exchanger utilized