Numerical Investigation of Heat Transfer and Erosion Characteristics of a New Waffle Primary Surface Heat Exchanger

Xiang-yang XU\textsuperscript{1,}\textsuperscript{*}, Wen-xiao CHU\textsuperscript{2}, Yao-ting WANG\textsuperscript{1} and Min ZENG\textsuperscript{2}

\textsuperscript{1}China Academy of Space Technology (Xi’an), Xi’an, Shaanxi 710000, China
\textsuperscript{2}Key Laboratory of Thermo-Fluid Science and Engineering, MOE, Xi’an Jiaotong University, Xi’an, Shaanxi 710049, China

*Corresponding author

Keywords: Waffle primary surface heat exchanger, CFD, Thermal-hydraulic performance, Erosion.

Abstract. In this paper, the heat transfer and pressure loss of a new waffle primary surface heat exchangers (WPSHX) with square, spherical and elliptical primary surface structures are numerically investigated. Meanwhile, the discrete phase model (DPM) coupling with the continuous air is applied to study the erosion problem in the primary surface heat exchanger. It is indicated that the elliptical WPSHX may decrease the air pressure loss with 87.3\% at general operating condition and the heat transfer performance will decrease about 30.2\% as well. The empirical correlations of the Nusselt number and friction factor are figured out with the form of Dittus-Boelter equation. The numerical result shows that the major erosion issue happens in the front of the heat exchanger due to the direct hit of particles. The elliptical WPSHX, which has much streamline structure, can reduce the erosion rate of the material effectively.

Introduction

In the conventional power plant, the coal combustion is still the major heat source. The air entering into the boiler may reach very high temperature by combusting with the pulverized coal. Simultaneously, the water is heated from the subcooled temperature to saturated temperature and boiling inside the tubes. In order to improve the thermal efficiency of the steam Rankine cycle, the saturated steam continues to be heated up to superheated steam in the superheater. Then, the steam will flow into the steam Rankine cycle for energy conversion. On the other side, the heat of the exhaust gas will be further utilized for preheating the water in the economizer. Afterwards, the temperature of the flue gas may decrease to 120°C, which should be further cooled down below 60°C in order to reduce the heat emissions to the environment. The primary surface heat exchanger (PSHX) is a kind of high-efficient and compact plate heat exchanger without any secondary heat transfer surfaces, which is generally recommended to be used as the recuperator or cooler in the gas turbine system. The following is a complete literature review of PSHX studies and the erosion simulation studies.

Wang et al. [1] summarized the development of PSHXs using for heat recovery systems in detail, which the cross-wavy (CW) type, cross-corrugated (CC) type and cross-undulated (CU) type PSHXs are included. Utriainen and Sunden [2] studied the thermal-hydraulic performance of the CW-PSHX, which the heat transfer efficiency may be enhanced by up to 600\% compared to the straight duct PSHX under a similar order increase of pressure drop. A modified CC-PSHX was investigated by Doo et al. [3] for an intercooler in the aero-engine, which the low-Reynolds number k-\varepsilon turbulence model was used and the numerical approach was validated against experimental data. The results also showed that the modified corrugation surface would improve the heat transfer performance by enhancing flow mixing with little pressure increase. Kim et al. [4] studied the CC-PSHX and developed a new parameterization method to evaluate the overall performance. The CW-PSHX was experimentally investigated by Wang et al. [5], which the genetic algorithm was applied to optimize geometrical parameters. Ma et al. [6] investigated the effect of small-scale longitudinal heat conduction which was usually neglected during analysis of CW-PSHX considering the variation of inlet temperature, temperature difference, and the Reynolds number.
The erosion issue was investigated for the superheater and economizer previously, which the types were tube-and-fin heat exchangers. In order to measure the velocities and instantaneous incident of rebound particles, the two-dimensional laser-Doppler anemometry (LDA) technique was proposed by Morsi et al. [7]. The particle rebound zone was detected during the process of particle-wall impact interaction, and the mean particulate flow pattern was modified due to the contribution of the rebound particles. The distributions of particle collision frequency and the erosion on tube surface caused by the turbulent flow were numerically studied by Jin et al. [8]. The erosion caused by the flue gas with solid particles in the economizer was numerically studied by Tu et al [9]. Comparing with the experimental results, the maximum erosion was found at different position depended on the maximum particulate velocity and concentration. Zhao et al. [10] numerically investigated the heat transfer and erosion characteristics for a single oval tube with longitudinal vortex generator (LVG). The results showed that the optimized H-type finned oval tube heat exchanger may significantly improve the heat transfer efficiency and reduce the wear loss at the same time. The erosion of tubes by particles during coal combusstion was numerically studied by Fan et al. [11], in which the new protection methods for heat exchanger tubes were proposed. Additionally, the effects of relative length of fins, velocity and particle size on erosion damage of tube were discussed. Gao et al. [12] investigated the erosion of a two-pass shell-and-tube heat exchanger for different feed fluid rates and particle sizes.

It can be seen that few literature has mentioned the erosion problems in the primary surface heat exchangers, which may affect the safety operation. In this paper, the heat transfer, pressure loss and erosion characteristics in the square, spherical and elliptical WPSHXs are investigated coupling the continuous fluid with the discrete particle model (DPM). Furthermore, the empirical correlations are proposed as well.

**Numerical Study Model**

The test sample of the WPSHX with square shape primary surface is shown in Figure 1. It can be seen that the flow channels are the same on both sides, which are forms of cross-flow.

![Figure 1. Structure of WPSHX with square shape primary surface.](image1)

The computational model and the geometrical parameters are shown in Figure 2, which the boundary conditions are illustrated as well. The waffle primary surface is arranged up and down alternatively along the flow direction. The inlet and outlet region has been extended 200 mm and 500 mm for ensuring the full development at the inlet and preventing backflow at the outlet, respectively. Due to the great difference of specific heat capacity between the air and water, the major heat transfer resistance is on the air side which the wall temperature boundary is applied to the CFD model.

![Figure 2. Structure of computational model and boundary conditions.](image2)
The CFD model is calculated by FLUENT assembled in ANSYS 17.2 software [13]. The shear-stress transport (SST) $k$-$\omega$ turbulence model which has a wall function treatment near walls is used to simulate the fluid flow. The $y^+$ is controlled lower than 1.0.

The erosion is analyzed by the two-phase flow coupling with the DPM method. The trajectory of particles is calculated by integrating the force balance on particles, which can be written as Eq. 1.

$$\frac{du_p}{dt} = F_D(u-u_p) + g_x \left( \rho_p - \rho \right)/\rho_p + F_x$$  \hspace{1cm} (1)

where $u$ is the fluid velocity, $u_p$ is the particle velocity, $\rho$ and $\rho_p$ are the density of fluid and particles, respectively. The $F_D(u-u_p)$ is the particle drag force per unit mass and $F_x$ is the force required to accelerate the fluid surrounding the particle due to the pressure gradient. In this study, the particle size is 50 μm and the particle mass flow rate is 0.001 kg·s$^{-1}$ based on the practical application. The fluid phase is the incompressible air and the thermal physical properties of the fluid are only related to the temperature. The second order upwind scheme and the QUICK scheme are used to discretize the momentum equation and the energy equation, respectively. The convergence is determined when the residuals of continuity, velocities, $k$, and $\omega$ are controlled below $10^{-5}$. The grid independence verification is studied with the number of mesh nodes varying from 600,000 to 2,100,000. The double precision is used in the computation of whole length model. The mesh node number with 1,780,000 is applied to CFD models while the Nusselt number and friction factor are less than 1% compared to the results with the finest mesh.

**Results Discussion**

**Study of Thermal-hydraulic Performance**

Figure 3 shows the air temperature distribution on the middle plane along the air flow direction. The temperature difference where the upper and lower plate contact is greater compared with the temperature at the central line, which means that the primary surface may enhance the heat transfer by destroying the viscous boundary layers. Meanwhile, it can be found that the temperature difference between inlet and outlet in the square WPSHX is greater than the other two models.

![Figure 3. Temperature distribution of three models along flow direction.](image)

It is shown in Figure 4 that the Nusselt number of the WPSHXs with square and spherical structures are almost the same. On the other hand, the pressure loss of the WPSHX with spherical structure can be reduced 10% averagely comparing to the WPSHX with square structure. The heat performance of the WPSHX with elliptical structure is the weakest in these three models, while the pressure loss is the lowest as well. Assuming the cooler operates at the $Re=5,200$, the WPSHX with elliptical structure may reduce the pressure loss by 87.3% with the decrease of heat transfer performance by 30.2%. Thus, the WPSHX with elliptical structure is suggested instead of the square structure in order to improve the comprehensive performance effectively. In addition, the empirical correlations of three WPSHXs with the form of Dittus-Boelter equation [14] are listed in Table 1.
Figure 4. Nusselt number and pressure loss vs. Reynolds number.

Table 1. Thermal-hydraulic correlations of three different WPSHXs with the form of Dittus-Boelter equation [14] by numerical studies.

| WPSHX                  | $N_u_{num}$ | $f_{num}$   |
|------------------------|------------|------------|
| Square primary surface | 0.003$Re^{1.028}$ | 250.7$Re^{-0.246}$ |
| Circle primary surface | 0.0034$Re^{0.993}$  | 257.9$Re^{-0.262}$  |
| Ellipse primary surface| 0.0037$Re^{0.938}$  | 102.7$Re^{-0.316}$  |

Study of Erosion

Figure 5 shows the erosion effect of the discrete particles in the three heat exchanger models. It can be found that the erosion at the stationed point is much critical. The erosion will be more concentrated while the spherical structure is applied. Meanwhile, the erosion in the front of the heat exchanger is the most serious, which may gradually weaken along the air flow direction. It is investigated that the WPSHX with elliptical structure may reduce the erosion effect almost one order of magnitude with the better streamline shape. The erosion rate will be calculated in our later studies based on the erosion model proposed by Tabakoff et al. [15], which the amount of mass loss of the target metal material will be figured out.

Conclusions

In this paper, the CFD method is applied to compare three different structures of WPSHX. It is found that the WPSHX with elliptical structure is suggested considering the effective decrease of pressure loss. The major erosion issue happens in front of the heat exchanger and it will gradually weaken along the flow direction. The WPSHX with elliptical structure can reduce the erosion effect almost one order of magnitude.
References

[1] Q.W. Wang, M. Zeng, T. Ma, X.P. Du, J.F. Yang, "Recent development and application of several high-efficiency surface heat exchangers for energy conversion and utilization," Appl. Energy, 135, pp, 748-777, (2014)

[2] E. Utriainen, B. Sunden, "A numerical investigation of primary surface rounded cross wavy ducts," Heat and Mass Transfer, 38 (7-8), pp, 537-542, (2002).

[3] J.H. Doo, M.Y. Ha, J.K. Min, Stieger R., Rolt A., Son C., "An investigation of cross-corrugated heat exchanger primary surfaces for advanced intercooled-cycle aero engines (Part-II: Design optimization of primary surface)," Int. J. Heat Mass Transfer, 61, pp, 138-148, (2013).

[4] M. Kim, M.Y. Ha, J.K. Min, R. Stieger, A. Rolt, C. Son, "Numerical study on the cross-corrugated primary surface heat exchanger having asymmetric cross-sectional profiles for advanced intercooled-cycle aero engines," Int. J. Heat Mass Transfer, 66, pp, 139-153, (2013).

[5] Q.W. Wang, D.J. Zhang, G.N. Xie, "Experimental Study and Genetic-Algorithm-Based Correlation on Pressure Drop and Heat Transfer Performances of a Cross-Corrugated Primary Surface Heat Exchanger," J. Heat Transfer, 131 (6), pp, 8-15, (2009).

[6] T. Ma, J. Zhang, S. Borjigin, Y.T. Chen, Q.W. Wang, M. Zeng, "Numerical study on small-scale longitudinal heat conduction in cross-wavy primary surface heat exchanger," Appl. Therm. Eng., 76, pp, 272-282, (2015).

[7] Y.S. Morsi, J.Y. Tu, G.H. Yeoh, W. Yang, "Principal characteristics of turbulent gas-particulate flow in the vicinity of single tube and tube bundle structure," Chem. Eng. Sci., 59 (15), pp, 3141-3157, (2004).

[8] J. Jin, J.R. Fan, X.Y. Zhang, K.F. Cen, "Numerical simulation of the tube erosion resulted from particle impacts," Wear, 250, pp, 114-119, (2001).

[9] J.Y. Tu, C.A.J. Fletcher, M. Behnia, J.A. Reizes, D. Owens, P. Jones, "Prediction of flow and erosion in power utility boilers and comparison with measurement," J. Eng. Gas Turbines Power, 119 (3): 709-716, (1997).

[10] X.B. Zhao, G.H. Tang, X.W. Ma, Y. Jin, W.Q. Tao, "Numerical investigation of heat transfer and erosion characteristics for H-type finned oval tube with longitudinal vortex generators and dimples," Appl. Energy, 127, pp, 93-104, (2014).

[11] J.R. Fan, P. Sun, Y.Q. Zheng, X.Y. Zhang, K.F. Cen, "A numerical study of a protection technique against tube erosion," Wear, 225, pp, 458-464, (1999).

[12] W.M. Gao, Y.G. Li, L.X. Kong, "Numerical investigation of erosion of tube sheet and tubes of a shell and tube heat exchanger," Comput. Chem. Eng., 96, pp, 115-127, (2017).

[13] ANSYS® Academic Research Workbench, Release 17.2, ANSYS Inc., (2017).

[14] F. Dittus, L. Boelter, "Heat transfer in automobile radiator of the tube type," Publication in Engineering, University of California, Berkley, 2, pp, 250, (1930).

[15] W. Tabakoff, R. Kotwal, A. Hamed, "Erosion study of different materials affected by coal ash particles," Wear, 52 (1), pp, 161-173, 1979.