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Investigation of a Novel High Temperature Heat Exchanger with Hybrid Internally and Externally Finned Tubes

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In this paper, a novel HTHE with hybrid internally and externally finned tubes is presented with the help of an improved heat exchanger design program. It can be used in high temperature environment, such as the waste heat recovery system and high temperature reactor. The proposed HTHE can be divided into two regions according to different temperatures of tube walls. H-type fins and twisted-tape insertions are welded inside and outside the tubes in high temperature region. Wave-like longitudinal fins are welded inside the tubes in low temperature region. Thermal calculations are performed to determine the heat transfer characteristic of the HTHE with a similar twisted-tape-inserted tube HTHE as comparison. The effectiveness and pressure drop are obtained at the gas temperature between 600 °C and 900 °C. The calculation results indicate that the volume flow-rate on both sides has significant effects on pressure drop, while the effectiveness has a small increment as the gas temperature increases. Comparison between the novel HTHE and the traditional HTHE indicates that the proposed HTHE has better heat transfer performance.

1. Introduction

Energy consumption in the iron and steel industry accounts for around 15 % in the whole industrial energy consumption of China, in which the proportion of waste heat and surplus energy from rolling heating furnace is around 70 % (Wu, 2014). General approach to recycle this part of waste heat is placing a heat exchanger in the path of the high temperature exhaust gas from combustion chamber. However, the utilization rate of the waste heat in traditional heat exchangers is only around 30 % - 50 % with still a large part of the heat energy being wasted (Cai et al., 2007). Therefore, a high temperature heat exchanger (HTHE) is required to guarantee the efficiency and safety of the waste heat recovery process.

Previous works aiming to enhance the heat transfer performance of tube heat exchanger with gas as working fluid can be divided into two categories, enlarging the heat transfer area by using finned tube and heightening the turbulence intensity of fluid by using insertion in tube. In regards to the first approach, Yu et al. (1999) found that the internally finned tube with blocked inner tube brought more significant heat transfer enhancement compared with the internally finned tube without blocked inner tube. Afterwards, the study of Wang et al. (2008) focused on the effect of the diameter of inner blocked tube on the performance of internally finned tube. It was found that the optimum ratio of the diameter of inner tube to outer tube ranged from 0.5 to 0.625 under identical mass rate and ranged from 0.44 to 0.50 under identical pressure drop. Externally finned tubes are widely employed to enhance heat transfer outside tubes. Jin et al. (2013) numerically predicted the effects of different geometric parameters of H-type finned tube bank on heat transfer and pressure drop characteristics. The results showed that the spanwise tube pitch had the most important effect while slit width had the least important effect. As for the second approach, Chiu and Jang (2009) proposed that the tube with twisted-tape insertion had superior heat transfer coefficient compared with the tube with longitudinal strip insertion and the plain tube without insertion. Experimental study was conducted to investigate the effects of geometric parameters of the twisted-tape insertion (Bas and Ozceyhan, 2012), and the results showed that the Nusselt number decreased as the twist ratio and clearance ratio increased. Finally, a hybrid heat transfer enhancement technique was proposed by simultaneously using the Al_2O_3/water nanofluid and twisted tape tabulator (Shekarian et al., 2016) and the required heat transfer area of associated heat exchanger was reduced up to 10 %.

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However, little open literature studied the gradient utilization methods for heat energy according to different gas temperatures. There also exist many unsolved problems in traditional HTHEs with internally and externally finned tubes, such as high pressure drop and expensive cost for manufacturing materials. In this paper, a novel HTHE with hybrid internally and externally finned tubes is proposed. Further, the heat transfer and pressure drop characteristics of the proposed HTHE are discussed according to thermal calculations.

2. Design of HTHE

2.1 Thermal design method

Most of the traditional heat exchangers used in waste heat recovery process have a structure that the tubes are fixed between the top wind box and bottom wind box with several different tube passes being arranged in parallel and connected with each other by wind boxes. Each tube pass includes at least one tube rows arranged in aligned or staggered.

The air is heated by high temperature exhaust gas flowing through each tube pass in sequence with cross flow direction. There exists large temperature difference between the inlet air and outlet air as well as the inlet gas and outlet gas, for which the specific heat capacity, volume flow rate and heat transfer coefficient of both working fluids fluctuate greatly in operation. As a result, the traditional integral Log-Mean Temperature Difference (LMTD) method for design of heat exchanger bring large calculation errors. So an improved method, segmented LMTD method, is introduced for the design of HTHE. The tubes are divided into several identical small heat transfer units along the tube length direction and each small heat transfer unit meets the requirement of small temperature difference for LMTD, as illustrated in Figure 1. In this study, a new design program based on segmented LMTD is written by commercial software MATLAB R2014a for the convenience of heat exchanger design under different working conditions and different HTHE geometric parameters.

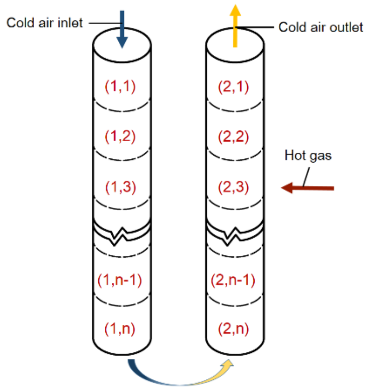

Figure 1: Schematic diagram of segmented tube

2.2 Basic equations

The internally wave-like longitudinal finned tube with fins welded in the annulus between the outer tube and the blocked core tube is used in the design HTHE. Numerical study about this kind of internally finned tube has been conducted in reference (Wang et al., 2008), in which the Nusselt number and friction factor are fitted as follows:

$$Nu = 0.058 Re^{0.825} \left(\frac{s}{d_e}\right)^{0.256} \left(\frac{l}{d_e}\right)^{-0.452} \tag{1}$$

$$f = 40 Re^{-0.481} \left(\frac{s}{d_e}\right)^{0.748} \left(\frac{l}{d_e}\right)^{-1.166} \tag{2}$$

The H-type fins are employed on outside tubes in the design HTHE. The corresponding Nusselt number and Euler number are determined by (Jin et al., 2013):

$$Nu = 0.093 Re^{0.853} \left(\frac{F_p}{d_o}\right)^{0.62} \left(\frac{F_t}{d_o}\right)^{0.066} \left(\frac{s_1}{d_o}\right)^{-1.82} \left(\frac{s_2}{d_o}\right)^{0.739} \left(\frac{HL}{d_o}\right)^{-0.835} \left(\frac{HS}{d_o}\right)^{0.756} \left(\frac{W}{d_o}\right)^{0.0716} \tag{3}$$

$$Eu = 7.94 Re^{-0.135} \left(\frac{F_p}{d_o}\right)^{-0.653} \left(\frac{F_t}{d_o}\right)^{0.335} \left(\frac{s_1}{d_o}\right)^{-4.33} \left(\frac{s_2}{d_o}\right)^{0.84} \left(\frac{HL}{d_o}\right)^{-0.17} \left(\frac{HS}{d_o}\right)^{2.9} \left(\frac{W}{d_o}\right)^{-0.002} \tag{4}$$

The effectiveness of the heat exchanger ε can be determined by:

$$\varepsilon = \frac{t_{air,out} - t_{air,in}}{t_{gas,in} - t_{air,in}} \tag{5}$$

2.3 Validation of design program

In order to validate the reliability of this design program, the well-known Gnielinski correlations (6-7, Gnielinski, 1975), as shown below, are employed in the program for smooth tube heat exchanger.

$$Nu = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\sqrt{f/8}(\mathrm{Pr}^{2/3}-1)}\left[1+(\frac{d_e}{l})^{2/3}\right]c_t \tag{6}$$

$$f = (1.82\lg \mathrm{Re} - 1.64)^{-2} \tag{7}$$

The predicted heat transfer coefficient, effectiveness and air-side pressure drop from the program are compared with those obtained from the experimental results in Anshan Iron and Steel Co., Ltd, with the average air velocity ranging from 5.9 m/s to 8.3 m/s and the corresponding gas temperature ranging from 660 °C to 790 °C, as shown in Figure 2. It can be seen that the maximum deviation in the heat transfer coefficient k, effectiveness ε and air-side pressure drop Δp_{air} are less than 10.0 % with the average deviation being 4.2 %, 5.0 % and 5.9 %. The good agreement between the computational results and tested results indicates that the design program is reliable.

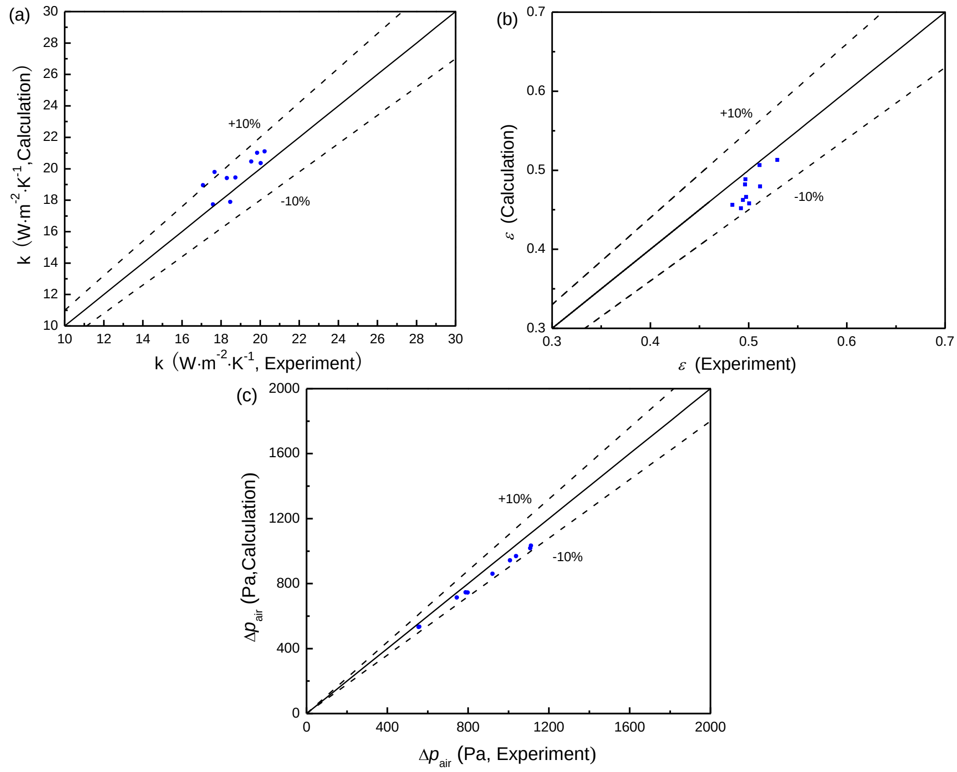

Figure 2: Validation of design program (a) Heat transfer coefficient k, (b) Effectiveness ε*, (c) Air-side pressure drop* Δp_{air}

2.4 Novel HTHE

The novel HTHE with hybrid internally and externally finned tubes includes at least two tube passes arranged in parallel, which is divided into two regions, high temperature region and low temperature region, according to different temperature of tube wall. The air is heated by high temperature exhaust gas flowing through the high temperature region and low temperature region in sequence with cross flow direction. H-type fins and twisted-tape insertions are welded inside and outside the tubes in high temperature region. H-type finned tube has excellent ability of self-cleaning because of its unique groove structure in flow stagnation zone and wake separation zone, the most likely place for sediment incrustation. Twisted-tape-inserted tube is adopted in waste

heat recovery system for heat transfer with the advantage of simple construction and convenient installation. Wave-like longitudinal fins are welded inside the tubes in low temperature region. The tube has a double-pipe structure with the inner blocked tube as an insertion. The fins are in the annulus and span its full width. The internally wave-like longitudinal fins enlarge the heat transfer area inside the tube to a great extent. The fluid inside the tube has high turbulence intensity because of the wave-like flow channels. The H-type fins could also be arranged in low temperature region for further enhancement if the temperature of tube wall is far below the critical dangerous temperature of the welding technology.
In this novel HTHE, the utilization rate of waste heat in exhaust gas is improved by achieving gradient utilization according to different gas temperatures. It is worth noting that more than two tube passes could be arranged in the HTHE to ensure the gradient utilization at a high level when the temperature of gas is much higher or the duty for heat transfer is much heavier than that in practical operation. In order to avoid the potential safety hazard from thermal expansion of straight tube, expansion joints could be installed at both ends of the tubes or bending tubes with a certain deflection could be adopted in the proposed HTHE.

3. Results and Discussion

3.1 Compactness

The heat transfer area on both sides and the volume of the novel HTHE compared with the traditional HTHE is shown in Table 1. The traditional HTHE has similar appearance and structure to the proposed HTHE with replacing the finned tubes to twisted-tape-inserted tubes. It can be seen that the heat transfer area on air-side and gas-side of novel HTHE is 4.35 times and 3.98 times more than that of the twisted-tape-inserted tube HTHE. The novel HTHE has more compact structure with increasing the ratio that heat transfer area to total heat exchanger volume on air-side and gas-side by 21.81 m^2/m^3 and 42.30 m^2/m^3.

Table 1: Compactness of the novel HTHE (HTHE1) and the twisted-tape-inserted tube HTHE (HTHE2)

Parameters	Unit	HTHE1	HTHE2
Width	m	0.87	0.87
Height	m	1.10	1.10
Length	m	2.00	2.00
Volume	m^3	1.91	1.91
Heat transfer area of air-side	m^2	54.10	12.43
Heat transfer area/volume of air-side	m^2/m^3	28.32	6.51
Heat transfer area of gas-side	m^2	56.48	14.18
Heat transfer area/volume of gas-side	m^2/m^3	29.57	7.42

3.2 Effectiveness

The effectiveness of the novel HTHE compared with the traditional HTHE is shown in Figure 3. The gas inlet temperature ranges from 600 °C and 900 °C in seven different design conditions. The air volume flow rate is 750 Nm^3/h, 800 Nm^3/h, and 850 Nm^3/h and the ratio of gas volume flow rate to air volume flow rate equals 1.5 under identical gas inlet temperature. It can be seen that the effectiveness of the traditional HTHE increases more quickly than that of the proposed HTHE as the gas temperature increases. The effectiveness of both HTHEs decreases as the air flow rate increases under identical gas temperature, which indicates that lower air flow velocity brings higher effectiveness with providing longer time for heat transfer process. The effectiveness of traditional HTHE in all design conditions is below 0.56 with an average value of 0.53, while the average effectiveness of the proposed HTHE is 0.67. It indicates that the novel HTHE has better capacity in heat transfer enhancement.
For further enhancement of heat transfer, augmentation techniques such as using the slit fin, perforated fin, slit tape insertion and perforated insertion could be adopted on the air side and using the louver fin could be adopted on the gas side.

3.3 Pressure drop

The pressure drop on both sides of the novel HTHE compared with the traditional HTHE is shown in Figure 4. The volume flow rate of air and gas ranges from 700 Nm^3/h to 900 Nm^3/h and from 1,050 Nm^3/h to 1,350 Nm^3/h in five different design conditions, and the gas inlet temperature is 650 °C, 700 °C, and 750 °C under identical air and gas volume flow rate. It can be seen that the pressure drop on both sides of these two HTHEs increases drastically as the volume flow rate increases. The pressure drop on both sides increases as the gas inlet

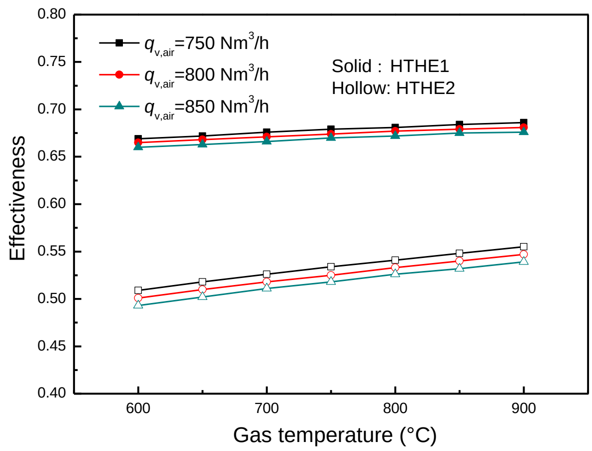

Figure 3: Effectiveness comparison between the novel HTHE (HTHE1) and the twisted-tape-inserted tube HTHE (HTHE2)

temperature increases under identical volume flow rate. The pressure drop on air-side and gas-side of the proposed HTHE is about 1.5 and 1.2 times than that of the traditional HTHE, with an average value 1,112 Pa and 17 Pa.

It should be noted that the pressure drop of the proposed HTHE has still a relatively small value and is perfectly accepted in practical operation under such a large flow rate. The flow resistance of air side could be decreased further by decreasing the wave number of inner wave-like fins and the diameter of the blocked core tube.

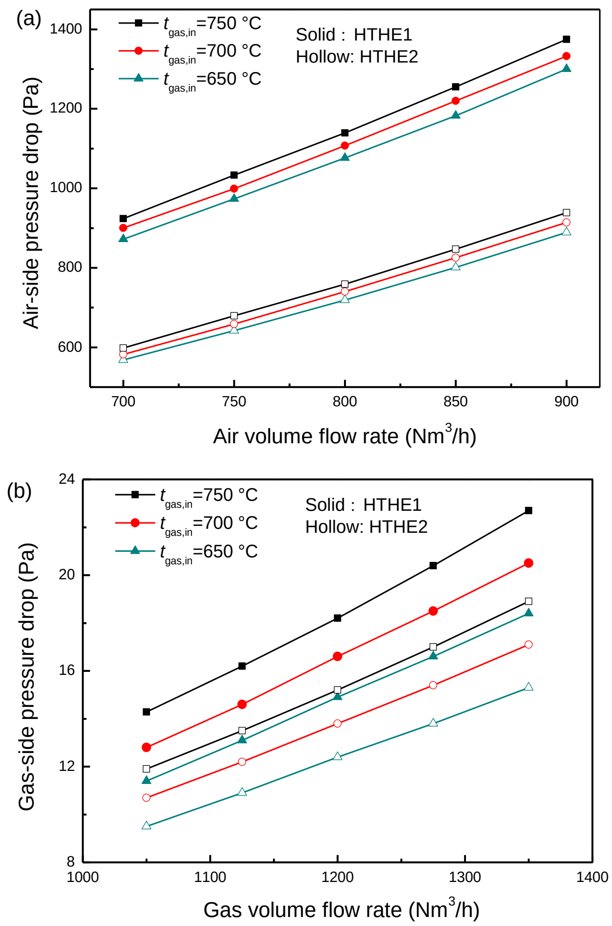

Figure 4: Pressure drop comparison between the proposed HTHE (HTHE1) and the twisted-tape-inserted tube HTHE (HTHE2) (a) Air-side pressure drop (b) Gas-side pressure drop

4. Conclusions

In this paper, a novel HTHE with hybrid internally and externally finned tubes is presented with the help of an improved heat exchanger design program. The heat transfer and pressure drop characteristics of the novel HTHE are investigated under multiple design conditions with a similar twisted-tape-inserted tube HTHE as comparison. The major findings are as follows:

1) Based on the segmented LMTD, a design program is written for the design of internally and externally finned tube heat exchanger. The program is proved to have superior convenience and high predictive accuracy.
2) A novel HTHE with hybrid internally and externally finned tubes is designed for recycling the waste heat energy from rolling heating furnace. The proposed HTHE has superior potential to increase the heat transfer performance by achieving gradient utilization of the waste heat.
3) The results of thermal calculations show that the proposed HTHE has better capacity in heat transfer enhancement than traditional HTHE with increasing the effectiveness by 14 % averagely. The pressure drop on both sides of the proposed HTHE is perfectly accepted in practical production.

Acknowledgments

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References

Bas H., Ozceyhan V., 2012, Heat transfer enhancement in a tube with twisted tape inserts placed separately from the tube wall, Experimental Thermal and Fluid Science, 41(41), 51-58.

Cai J.J., Wang J.J., Chen C.X., Lu Z.W., 2007, Recovery of residual-heat integrated steelworks, Iron and Steel, 42(6), 1-7.

Chiu Y.W., Jang J.Y., 2009, 3D numerical and experimental analysis for thermal–hydraulic characteristics of air flow inside a circular tube with different tube inserts, Applied Thermal Engineering, 29(2), 250-258.

Gnielinski V., 1975, New equations for heat and mass transfer in the turbulent flow in pipes and channels, Nasa Sti/recon Technical Report A, 75(2), 8-16.

Jin Y., Tang G.H., He Y.L., Tao W.Q., 2013, Parametric study and field synergy principle analysis of H-type finned tube bank with 10 rows, Heat and Mass Transfer, 60(1), 241-251.

Shekarian E., Jafari Nasr M.R., Tarighaleslami A.H., Walmsley T.G., Atkins M.J., Sahebjamee N., Alaghehbandan M., 2016, Impact of hybrid heat transfer enhancement techniques in shell and tube heat exchanger design, Chemical Engineering Transactions, 52, 1159-1164.

Wang Q.W., Lin M., Zeng M., 2008, Effect of blocked core-tube diameter on heat transfer performance of internally longitudinal finned tubes, Heat Transfer Engineering, 29(1), 107-115.

Wang Q.W., Lin M., Zeng M., Lin T., 2008, Computational analysis of heat transfer and pressure drop performance for internally finned tubes with three different longitudinal wavy fins, Heat and Mass Transfer, 45(2), 147-156.

Wu C., 2014, Analysis on waste heat and surplus energy using in iron and steel enterprise, Energy for Metallurgical Industry, 33, 54-57.

Yu B., Nie J.H., Wang Q.W., Tao W.Q., 1999, Experimental study on the pressure drop and heat transfer characteristics of tubes with internal wave-like longitudinal fins, Heat and Mass Transfer, 35(1), 65-73.