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Design and Testing of Composite Heat Exchanger Applied to Industrial Self-Recuperative Gas Burners

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***Abstract* -** In the thermal treatment of steel materials and the heating and smelting processes of lightweight alloys, the dissipation of waste heat often leads to energy loss. In line with the global trends in combustion heating system development, preheating combustion systems are currently the most suitable for application in industrial furnaces operating in the range of 823K to 1223K, offering 15% to 20% energy savings and carbon reduction. However, existing heat exchangers for preheating burners are limited to individual fin or bundle designs. These designs cannot simultaneously meet the dual requirements of high heat exchange efficiency and low-pressure loss during heat exchange operations. This study proposed an innovative composite heat exchange technology for preheating combustion to address this issue. The approach involved a composite heat exchanger incorporating features of bundles and fins along with a fluid flow path-switching control module. The flexible use of the switching module modified the fluid path within the composite heat exchanger depending on the thermal treatment temperature and power requirements. This achieved maximum heat exchange efficiency and minimum pressure loss during the heating and socking processes of the heat treatment. Furthermore, the system ensured stable combustion. In the simulated analysis of the composite heat exchanger, the fin-type heat exchange efficiency reached 65%, whereas the bundle-type heat exchange efficiency reached 75%. The experimental data showed a fin-type heat exchange efficiency of 69% and a bundle-type heat exchange efficiency of 78%.

***Keywords*:** Preheating combustion burner, heat exchange efficiency, composite, heat exchanger

1. Introduction

Marco Cavazzuti et al.(4) conducted computational fluid dynamics simulations on finned concentric tube heat exchangers, considering various geometric shapes under different operating conditions to enhance heat recovery from exhaust gases and reduce the size of the downstream heat recovery system. [A1] Meisam Farzaneh et al.(5) performed numerical analysis on the two-dimensional axisymmetric issues arising in premixed combustion within porous burners integrated with heat exchangers. The physical domain was divided into two regions: porous and heat exchanger regions. The numerical solutions and experimental data were consistent, indicating that the developed numerical process [A2]is an excellent tool for studying combustion in porous burners.

Due to the application constraints and on-site spatial limitations, the volume of composite heat exchangers for burners is also restricted. Achieving high heat exchange efficiency and low-pressure loss within these limited volumes is a crucial challenge. Therefore, the size and configuration of bundles and fins within the composite heat exchanger are essential research targets in this study. The initial step involved deriving the optimal heat exchange area based on theoretical formulas for heat exchange. Subsequently, numerous feasible design schemes were formulated under engineering constraints. Schemes were analyzed using computer-aided engineering (CAE) simulation techniques to identify the most suitable solution. Following this, a prototype of the composite heat exchanger was fabricated using heat-resistant steel casting. Finally, experimental verification was conducted to assess the heat exchange efficiency and pressure loss of the model. The experimental results confirmed the relevant functionalities and efficacy, particularly the preheating temperature of air and heat exchange efficiency within the composite heat exchanger. The anticipated outcome was to provide the metal-related industry with waste heat recovery technology for high-temperature processes, promoting the localization and advancement of heat processing equipment from traditional manufacturing to advanced manufacturing. This will contribute to enhancing energy recovery efficiency and promoting energy-saving operations.

2. Procedures or Methods

2.1Research procedure

This study began by establishing target specifications, including the anticipated heat exchange efficiency of the finned-type heat exchanger and the anticipated heat exchange efficiency of the bundle-tube heat exchanger. Calculations were performed for combustion parameters such as power, air to fuel ratio, and excess air coefficient. The required heat exchange area for finned-type and bundle-tube heat exchangers was individually determined. Following this, external design and CAE simulation analyses were conducted. Finally, the composite heat exchanger prototype was manufactured and experimental tests were performed to validate the design of this study. The research process is outlined as follows :

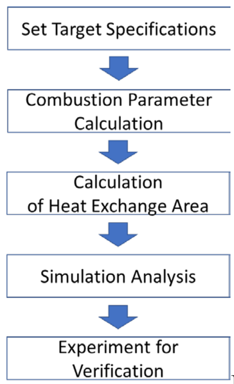

Figure 1[A3]. Research process flowchart

2.2 Research Method

2.2.1 Geometric design of heat exchangers

Initially, the temperature for heat exchange was defined, with the target temperature on the hot and cold sides set at 823K to 1223K and 300K, respectively. The heat exchange flow rate for the composite heat exchanger was 100 Nm^3/h with a flow ratio of 6.8:4.2 between the bundle-tube and finned-type heat exchangers (estimated based on experimental data and theoretical values). The target heat exchange efficiency for the finned-type heat exchanger was 65%, while that for the bundle-tube heat exchanger was 75%. Subsequently, the required heat exchange area was calculated using heat transfer formulas and the logarithmic mean temperature difference. From theoretical derivation and calculations, it was determined that the bundle-tube heat exchanger required a minimum area of 1.375 m^2, while the finned-type heat exchanger required a minimum area of 0.59 m^2. The relevant derivation formulas are as follows:

1.Room temperature: 300K 2.Furnace temperature: 1223K 3.Gas flow rate: 10Nm^3/hr (100x10^4 kcal/hr)
4.Air flow rate: 100 Nm^3/hr 5.Fluid form: counterflow 6.Finned-type heat exchanger efficiency: 65%
7.Bundle-tube heat exchanger efficiency: 75% 8.Overall heat transfer coefficient U value for Budle-tube:16 W/m^2K
9. Overall heat transfer coefficient U value for Finned-type: 23W/m^2K

10.Heat transfer equation: $\dot{Q} = UA\Delta T_m$ $\dot{Q}$ = UA? ? ? T_m
Where:
U = Overall heat transfer coefficient (W/m^2K), *A* = Heat exchange area (m^2),ΔT_m = Logarithmic mean temperature difference(K)
Logarithmic mean temperature calculation:, $T_m = (\Delta T_1 - \Delta T_2)/\ln(\Delta T_1/\Delta T_2)$, $\Delta T_1 = (T_{hi} - T_{co})$, $\Delta T_2 = (T_{ho} - T_{ci})$
T_{hi}: Inlet temperature on the hot side, T_{ho}: Outlet temperature on the hot side,
T_{ci}: Inlet temperature on the cold side.T_{co}: Outlet temperature on the cold side
Bundle-tube heat exchanger area:A_T=5852/(16x266)=1.375 m^2
Finned-type heat exchanger area: A_F=(3616/23x266)=0.59m^2

In the design of the composite heat exchanger, the initial focus was on the design of the finned-type heat exchanger (due to geometric configuration considerations, the dimensions of the finned-type heat exchanger must be determined first, before determining the dimensions of the bundle-tube heat exchanger). The design principles for the fins were based on the concept of surface area to volume ratio. A high [A4] surface area to volume ratio indicated a larger contact area between the fluid and heat exchanger, resulting in a smaller volume and weight for the heat exchanger. The fin designs in this study included circular, elliptical, flat, and airfoil shapes with the surface area to volume ratios of 0.37, 0.95, 0.80, and 1.09, respectively. The circular shape, with its excessively small surface area to volume ratio, was deemed impractical and was excluded. Relevant dimensions are illustrated in Figures 2 and 3.

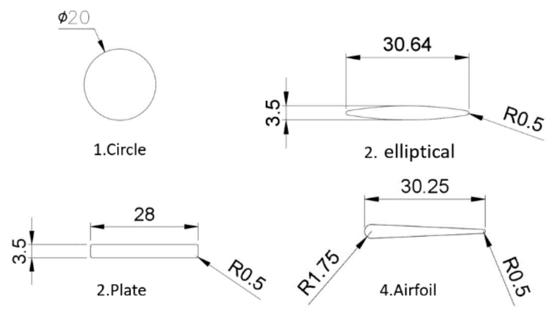

Figure 2. Designs of different fin shapes

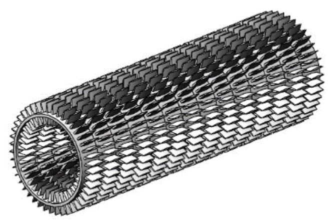

Figure 3. Finned-type heat exchanger

The arrangement of fins was also a crucial consideration in the design process. Under the same heat exchange area, different fin arrangements resulted in varying fin ratios. The definition of the fin arrangement angle was the angle between the flow direction and the line connecting the center of the fin, as shown in Figure 4. In this study, the arrangement angles were set as 15°, 30°, 45°, 60°, and 90°. The surface area to volume ratio for different arrangement angles revealed that the surface area to volume ratio reached its maximum at 30°, making it the most suitable arrangement. Therefore, utilizing a 30° arrangement was considered optimal. Subsequently, three fin types with a 30° arrangement were compared to determine the most efficient fin type.

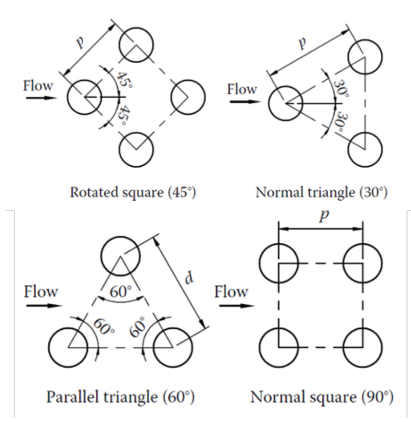

Figure 4. Definition of fin arrangement angles

In designing the bundle-tube heat exchanger, this study considered heat exchange principles related to contact area and specific constraints. The specified heat exchange area for the bundle-tube heat exchanger was 1.375 m^2. Currently available heat-resistant material, SUS 310s, for the bundle tube has a minimum specification with an outer diameter of 13.8 mm, a thickness of 2 mm, and a maximum allowable length of 600 mm (as prolonged exposure to heat may cause softening and bending). Under these limitations, a minimum of 70 tubes was required to meet the specified demands (Figure 5).

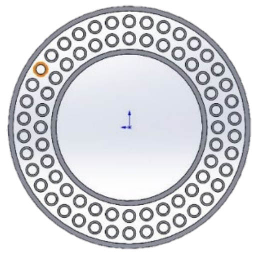

Figure 5. Design of bundle-tube heat exchanger

The configuration design of the composite heat exchanger in this study is depicted in Figure 6. The outer ring employed a bundle-tube heat exchanger, while the inner ring utilized a finned-type heat exchanger. Based on furnace temperature and pressure conditions, the fluid passage through the heat exchangers was determined by valve switching. When the furnace temperature and pressure were low, the fluid passed through the bundle-tube heat exchanger (due to its higher pressure drop). During high-power demand, the fluid passed through the bundle-tube and finned-type heat exchangers to provide high output. In the high-temperature and high-pressure range, the fluid passed through the finned-type heat exchanger (as it exhibited a lower pressure drop).This study verified through simulation and experimentation whether the bundle-tube and finned-type heat exchangers meet the specified heat exchange efficiency requirements.

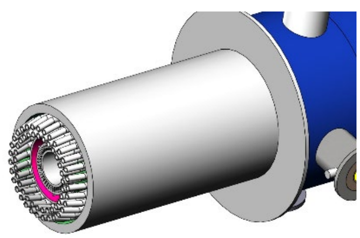

Figure 6. Design concept of composite heat exchanger

2.2.2 Simulation parameter settings for heat exchangers

The simulation in this study adopted a fluid-structure coupled analysis, and the heat exchange flow was modeled as counterflow to achieve optimal heat exchange efficiency. Ansys Fluent was utilized to simulate the fluid temperature and heat exchange efficiency as the fluid passed through the heat exchanger. Equation (1) is the definition of heat exchange efficiency.

$$\text{Heat exchange efficiency} = (T_{co} / T_{hi})*100\%, \quad (1)$$

Where T_{co} is the outlet temperature on the cold side,
T_{hi} is the inlet temperature on the hot side

As the composite heat exchanger required to be integrated into a burner, the applied burner power was $100\text{x}10^4$ kcal/hr with natural gas as the fuel. Under complete combustion conditions, the air flow rate was 100 m^3/hr, and the flow ratio between the bundle-tube and finned-type heat exchangers was 6.8:4.2 (estimated based on experimental data and theoretical values). Therefore, the boundary conditions were set as follows:

1.Flow rate of the bundle-tube heat exchanger: 61.81 m^3/hr 2. Flow rate of finned-type heat exchanger: 38.19 m^3/hr
3.Hot-side temperature: 1223K 3.Cold-side temperature: 300K

2.2.3 Heat exchanger experimental preparation

This study employed precision casting to manufacture the finned-type heat exchanger, while tubes arranged according to specifications were utilized to construct the bundle-tube heat exchanger. The two heat exchangers were assembled and combined, as illustrated in Figures 7 and 8.

Figure 7. Isometric view of the composite heat exchanger

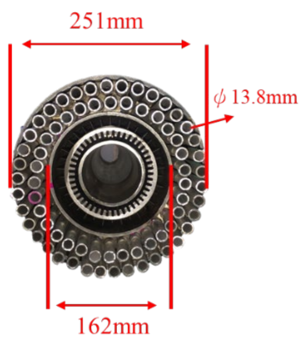

Figure 8. Front view of the composite heat exchanger

The assembled composite heat exchanger was positioned on an industrial furnace (Figure 9), and relevant channels and valves were established, including the inlet and exhaust channels for the bundle-tube heat exchanger, as well as the inlet and exhaust channels for the finned-type heat exchanger. Consequently, the channels could be switched as needed. Additionally, temperature sensors (Figure 10) were strategically placed on the composite heat exchanger to measure fluid temperatures, facilitating the calculation of heat exchange efficiency.

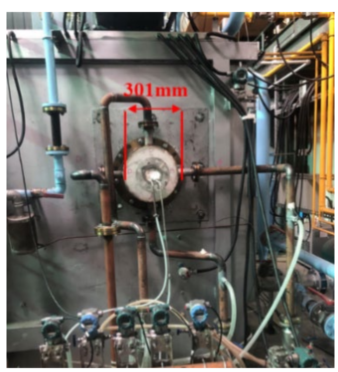

Figure 9. Composite heat exchanger positioned on an industrial furnace

Figure 10. Sensor placed on the composite heat exchanger

3.Results and discussions

3.1 Comparison of simulation analysis results

An analysis was conducted on the simulation results, focusing on different fin shapes simulated at an arrangement angle of 30° (Figures 11 and 12). The comparison involved heat exchange efficiency and pressure drop. From the simulation results, it was observed that the heat exchange efficiency followed the order: flat shape (66%) > elliptical shape (65%) > airfoil shape (62%), and the pressure drop followed the order: flat shape (357pa) > airfoil shape (248pa) > elliptical shape (210pa). Considering the pressure drop, defining an indicator as heat exchange amount divided by pressure drop, the optimal performance was observed for the elliptical shape > airfoil shape > flat shape. Therefore, the optimal choice for fin selection was using elliptical fins.

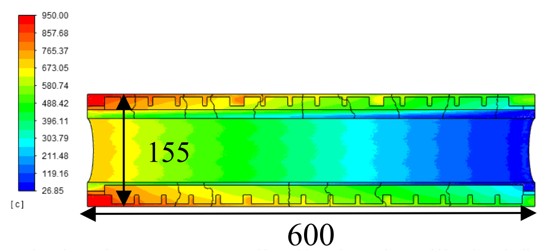

Figure 11. Simulation analysis of temperature distribution for elliptical finned-type heat exchanger

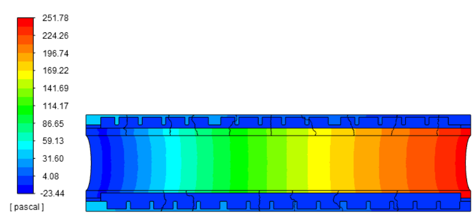

Figure 12. Simulation analysis of pressure distribution for elliptical finned-type heat exchanger

Figure 13 presents simulation data for the heat exchange efficiency with 70 tubes, and the heat exchange efficiency reaches 75%. However, the bend angle of the tubes must be considered, as it could impact combustion and subsequently affect fuel utilization. Therefore, simulation results for different bend angles must be examined for further design and manufacturing(Figure14).

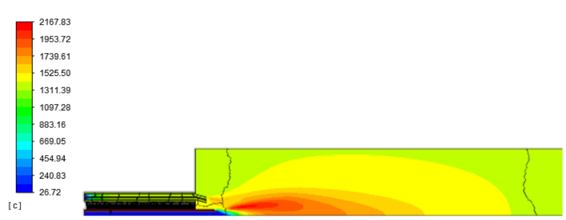

Figure 13 Simulation analysis of temperature distribution for bundle-tube heat exchanger

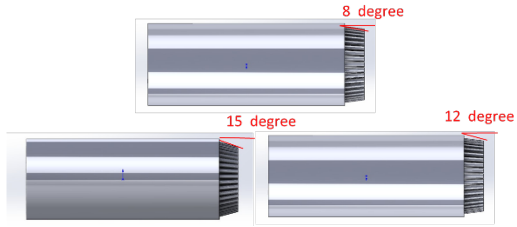

Figure 14 bundle-tube heat exchangers with bend angles ranging from 8 to 12 degrees

Table 1 presents simulation data for bundle-tube heat exchangers with bend angles ranging from 8 to 12 degrees. Key indicators included fuel mixing rate and fuel nozzle temperature. The results indicated that the nozzle temperatures for all three scenarios were below 1073K, within the acceptable range for heat-resistant steel SUS 310s. However, the fuel utilization efficiency was noticeably optimal at a bend angle of 8°. Therefore, a bend angle of 8° was deemed the most favorable in selecting a scheme.

Table 1. Comparative simulation data for different bend angles of tubes

Comparison of simulated data for tubes bent at different angles			
	Bend angle 8°	Bend angle 12°	Bend angle 15°
Inlet mass flow rate of natural gas (m^3/s)	$1.126x10^{-5}$	$1.126x10^{-5}$	$1.126x10^{-5}$
Outlet mass flow rate of natural gas (m^3/s)	$4.34x10^{-5}$	$5.82x10^{-5}$	$5.76x10^{-5}$
Fuel utilization efficiency (%)	96.14	94.82	94.88
Nozzle temperature (K)	456	311	460

3.2 Experimental testing

Figure 15 illustrates the actual testing scenario for the composite heat exchanger. Meanwhile, Table 2 presents the data from three experiments for the finned-type and bundle-tube heat exchangers along with the average data, respectively. The results indicated that the measured data for the finned-type heat exchanger reached 69%, surpassing the simulated value of 65%. Similarly, the measured data for the bundle-tube heat exchanger reached 79%, outperforming the simulated value of 75%. The measured values being better than the simulated values may be attributed to using a more rigorous solving method in the simulation phase. This method may slightly underestimate the real heat exchange efficiency, resulting in the actual heat exchange efficiency being better than the simulated value. Table 3 presents the data from three experiments which is from composite heat exchanger. The composite heat exchanger was operated by finned-type and bundle-tube heat exchangers simultaneously. Experimental data show that the heat exchange efficiency of tube bundle and fin heat exchangers operated simultaneously is slightly lower than that of separate operations. However, in practical terms, the composite heat exchanger achieved the target heat exchange efficiency. Therefore, they could be mass-produced and applied to relevant processes with specific requirements in the future.

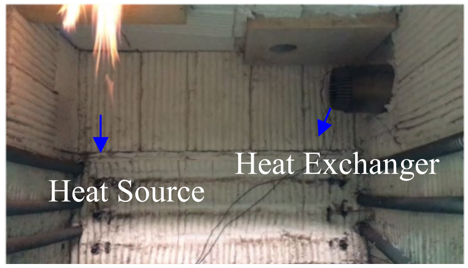

Figure 15. Actual testing of the composite heat exchanger

Table 2. Experimental data for bundle-tube and finned-type heat exchangers, respectively

Bundle-tube heat exchanger			Finned-type heat exchanger		
Experiment number	Steady-state average preheated air temperature (K)	Steady-state average heat exchange efficiency	Experiment number	Steady-state average preheated air temperature (K)	Steady-state average heat exchange efficiency
1	1020	78.6	1	908	66.8
2	1017	78.3	2	936	69.7
3	1033	80.0	3	949	71.1
Average	1023	78.9	Average	931	69.2

Table 3. Experimental data for composite heat exchanger

Bundle-tube heat exchanger			Finned-type heat exchanger		
Experiment number	Steady-state average preheated air temperature (K)	Steady-state average heat exchange efficiency	Experiment number	Steady-state average preheated air temperature (K)	Steady-state average heat exchange efficiency
1	996	76.2	1	899	65.9
2	978	74.3	2	897	65.7
3	983	74.8	3	883	64.3
Average	984	75.1	Average	893	65.3

4. Conclusions

1.This study applies waste heat recovery method to preheat the air and to achieve energy saving and carbon reduction.

2.Based on practical requirements, this study designed a composite heat exchanger that could be integrated with a burner and fluid channels. The fluid pathway could be switched according to different furnace temperatures and pressures, passing through the bundle-tube heat exchanger, finned-type heat exchanger, or both to achieve optimal operational conditions.

3.This study designed an elliptical finned-type heat exchanger with the optimal ratio of heat exchange efficiency to pressure drop, reaching the best performance in this ratio.

4.Integrating the bundle-tube heat exchanger with the burner, the nozzle temperatures caused by different bend angles (8°–15°) were <1073K, within the acceptable range for heat-resistant steel SUS 310 s.[A5]

5.Under manufacturing constraints, this study designed the bundle-tube heat exchanger with the optimal bend angle (8°), achieving the best fuel mixing rate.

6.The composite heat exchanger could be integrated with a burner for optimal waste heat recovery. The experimental values for finned-type heat exchange efficiency reached 69% (surpassing the simulated value of 65%), and the bundle-tube heat exchange efficiency reached 78% (outperforming the simulated value of 75%).

5. Acknowledgements

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