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Performance Analysis and Matching of Tube-fin Evaporator in Organic Rankine Cycle (ORC) System for Diesel Engine

Wujie Zhang[1*], Fubin Yang[1,2], Hongguang Zhang[1], Xu Ping[1]
1 MOE Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Beijing Key Laboratory of Heat Transfer and Energy Conversion, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing, 100124, China
2 Key Laboratory for Thermal Science and Power Engineering of MOE, Beijing Key Laboratory for CO2 Utilization and Reduction Technology, Tsinghua University, Beijing, 100084, China
15235365060@163.com

ABSTRACT

In this paper, the tube-fin evaporator used in diesel engine–Organic Rankine Cycle experiment is built, simulated and analyzed. By changing the inlet conditions on the shell side of the evaporator, the relationship between the internal heat transfer performance, flow performance and inlet conditions of the evaporator is analyzed. The heat transfer performance of the evaporator is analyzed by using Field Synergy Theory and the maximum pressure rise of the cross section of the front tube bundle(p_m), the influence degree of ORC system on diesel engine is determined, and the matching relationship between the evaporator and diesel engine is evaluated. The results show that, due to the unique exhaust characteristics of diesel engine, the evaporator needs to coordinate with diesel engine, so as to achieve better heat transfer and flow performance, reduce losses and make full use of energy with little influence on the power performance and economy of diesel engine.

Keywords: Organic Rankine cycle, tube-fin evaporator, diesel engine, performance analysis, waste heat recovery

NONMENCLATURE

Abbreviations	
ORC	Organic Rankine Cycle
Symbols	
p_m	Maximum pressure rise of the cross section of the front tube bundle
ρ	Density
μ	Dynamic viscosity
C_p	Heat capacity at constant
H_f	Fin thickness
T_i	Shell side inlet temperature.
β	Intersection angle between velocity and temperature gradients
v_{outer}	Shell side inlet velocity

1. INTRODUCTION

Energy recovery and reuse is a very important way to save energy. As the mainstream means of transportation, cars consume a lot of energy. Oil-fueled automobiles account for the majority of the total number of automobiles, while gasoline engines and diesel engines lose a lot of energy in the working process, and exhaust is the main carrier of waste heat [1-2].

Organic Rankine Cycle (ORC) system can efficiently recover low-grade heat energy at medium and low temperature. The ORC system for vehicles requires the volume and weight to be as small as possible, the heat exchange efficiency and system efficiency to be as high as possible, and the coupling between components to be high. Many scholars had studied the coupling of various components of ORC system. Yang et al. had made experimental research on the operating characteristics of multistage centrifugal pump, hydraulic diaphragm metering pump , and roto-jet pump used in ORC system for vehicles, which are matched with ORC system[3].Maria Anna Chatzopoulou et al. analyzed the coupling between the heat exchanger and the ORC system[4].Some scholars had studied the ORC system under different exhaust temperature conditions, they compared and analyzed the net power generation obtained by ORC system, and obtained the working conditions when the net power generation was maximum[5-9].

Shi et al. thought that compared with other medium and low temperature heat sources, the exhaust of diesel engine has a large-gradient temperature drop characteristic. If ORC system suitable for other heat sources is applied to the system with diesel engine as heat source, it will probably lead to the decrease of cycle efficiency and the deterioration of working performance [10]. So, it is necessary to make special research on ORC system suitable for diesel engine.

In this paper, the model of tube-fin evaporator is constructed, and the matching problem between the evaporator and working conditions of diesel engine is studied. The exhaust entering the evaporator under different working conditions is simulated, and the results are analyzed. The Field Synergy Principle [11-13] and the pressure impact on the front tube bundle are used to evaluate the evaporator performance under different temperatures of heat source.

2. MODEL AND ANALYSIS

2.1 Model building

In this paper, the model of tube-fin evaporator is established by COMSOL, and the parameters of exhaust gas under experimental conditions are calculated. Structural parameters of the model and physical parameters of exhaust are as follows:

Table 1: Structural parameters of evaporator

Parameter	Numerical
Height	0.25 m
Length	0.27 m
Width	0.31 m
Fin Number	49
Tub bundle arrangement	Stagger

Table 2: Physical parameters of exhaust

Parameter	Numerical
Density (ρ)	0.65 kg/m^3
Constant pressure heat capacity (C_p)	1096 J/(kg· K)
Thermal conductivity (k)	4.2×10^{-2} W/(m· K)
Dynamic viscosity (μ)	2.8×10^{-5} kg/(m· s)

The model is as follows:

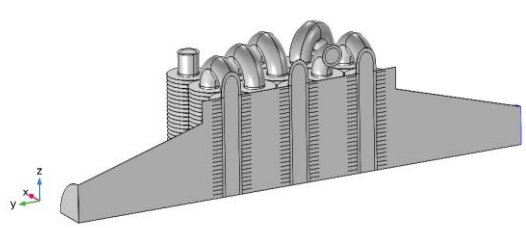

Fig.1 Model structure

Using custom materials to define exhaust parameters. Select the physical field of fluid heat transfer in COMSOL to solve the heat transfer process of exhaust. Set the boundary except the pipe wall as adiabatic condition. Set the fins as thin layers and define the thickness as H_f. The exhaust temperature of diesel engine is 628 K, that is, the inlet temperature component is T_i=628 K, and the outlet boundary is outflow. By calculating the Re number of exhaust, it can be known that the exhaust is turbulent flow, and the standard k-ε model is used to simulate the exhaust flow [14]. The wall of evaporator adopts non-slip wall, and the inlet condition is speed inlet. According to mass conservation and diesel combustion chemical equation, the exhaust flow rate of diesel engine is Q=0.06788 kg/s; Set the outlet condition as pressure outlet, and the outlet pressure is 1atm. Finally, heat transfer and turbulent physics interfaces are coupled by using COMSOL multiphysics field coupling function.

2.2 Grid independence verification and model accuracy

The numbers of the three kinds of grids are 489533, 918223 and 2353922, respectively. Compare and analyze the simulation results with the experimental results, and get the curves in the Fig.2. The errors between the results obtained by the three grids and the experimental results are 0.22%, 1.12% and 1.17%, respectively.

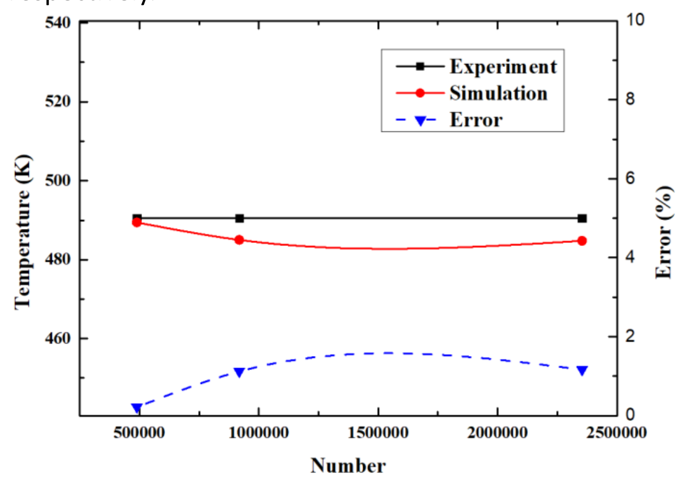

Fig.2 Comparison of experimental and simulation results

It can be seen from Fig.2 that the model obtained by numerical simulation is in good agreement with the experimental results. The number of grid elements has little influence on the accuracy of the model, so it can be considered that the accuracy of the model has nothing to do with the grid division.

2.3 *Result*

The evaporator under experimental conditions is simulated, and the results are shown in Fig.3.

It can be seen from Fig.3 (a) that when exhaust exchanges heat with pipes, the heat exchange of the first two rows of pipes is relatively strong and the temperature drops rapidly. And the color legend of temperature gradient in Fig.3(b) is shown in red here. The temperature gradient decreases from the third row of pipes, and then the color is blue in large area. It can be seen from Fig.3(c) that due to the impact with the tube bundle, the exhaust has a large backflow area before contacting with the tube bundle, and the impact in this area leads to the damage of kinetic energy and the decrease of velocity; In the tube bundle, the structure is compact, the resistance is large and the speed is reduced. So the color in this area is blue.Fig.3(d) shows the compression of the front tube bundle.

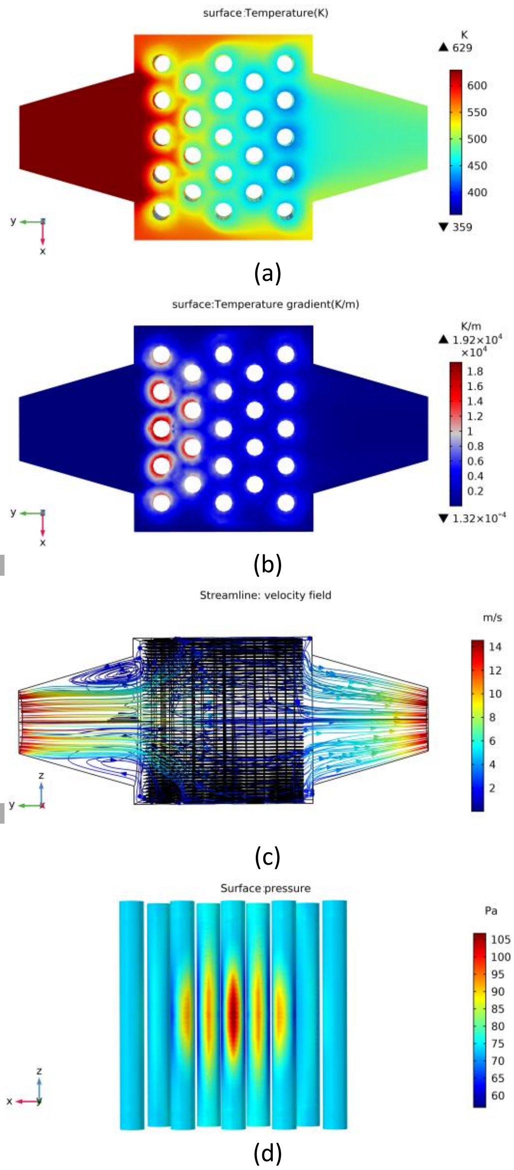

Fig.3 (a) Temperature distribution in X-Y plane, (b) Temperature gradient distribution in X-Y plane, (c) Streamline distribution in Y-Z plane, (d) Pressure impact on the front tube bundle

The Field Synergy Theory is used to evaluate the heat transfer performance of exhaust in evaporator. The magnitude of β can directly reflect the synergy degree of velocity field and temperature field and the heat transfer performance. The β obtained by evaporator simulation is plotted in Fig.4.

According to the distribution of β in Fig.4, it can be seen that |cosβ| has a large value at the entrance of the pipeline, and with the flow, |cosβ| decreases when it reaches the rear of the tube bundle, resulting in poor heat transfer effect. At the same time, the |cosβ| in the recirculation zone before the first row of tube bundles is relatively large, due to the strong disturbance, resulting in enhanced heat transfer.

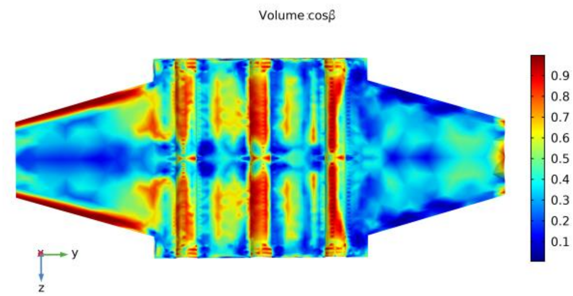

Fig.4 Value of |cosβ| in Y-Z plane

3. VARIABLE WORKING CONDITION ANALYSIS

The impact of diesel engine exhaust entering the evaporator will interfere with its normal operation. In this paper, in order to determine the influence of this phenomenon on diesel engines, the maximum pressure rise on the windward side of the front tube bundle is selected as the evaluation standard. Parameterized scanning is adopted, and simulation analysis is carried out with inlet velocity (v_{outer}) as variable, and the results are drawn as shown in Fig.5 below:

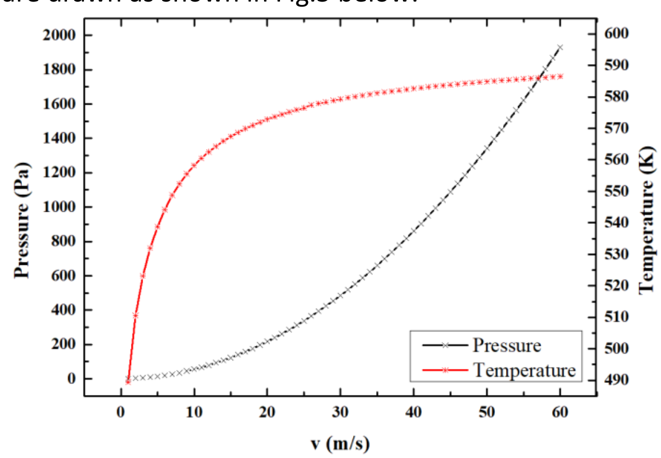

Fig 5 Relationship of pressure and temperature with v_{outer}

It can be seen from Fig.5 that with the increase of exhaust inlet flow rate, the pressure on the front tube bundle gradually increases, and the outlet temperature on the shell side shows a trend of rapid increase at first and then gradual stabilization, that is, with the increase of flow rate, the heat transfer performance decreases.

4. CONCLUSION

1. By simulating the evaporator and analyzing the distribution of temperature field, temperature gradient and pressure, it is found that the heat transfer performance of the front tube bundle is much better than that of the rear tube bundle. And the front tube bundle bears high pressure and impact, which may affect the normal operation of diesel engine. By analyzing the combination of diesel engine exhaust characteristics and ORC system, the best working condition of the whole system can be obtained.

2. The working characteristics and exhaust characteristics of diesel engine make the ORC system more complex. As a result, it is necessary to design ORC system according to actual working conditions when diesel engine is used as high temperature heat source.

3. The evaporator has a working point with better overall performance in the diesel engine -ORC combined system, which makes the ORC system have less influence on the diesel engine, and has good heat transfer performance, which can achieve higher energy recovery rate.

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