Effect of Different Heat Recovery Tube Structure on the Exhaust Heat Utilizing Ability in Internal Combustion Engine

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Abstract. In recent years, environmental pollution and depletion of fossil fuel resources are hot issues, attracting scientists' attention to research. Among the methods to solve these problems, utilizing exhaust gas energy of internal combustion engines (ICE) is a promising approach in improving thermal efficiency, reducing fuel consumption and exhaust gas of ICE. This paper will present the results of the study on the waste heat utilizing ability of the exhaust heat recovery tank (EHR) with two different structures by simulation method using Ansys fluent software. The study shows that the waste heat utilizing efficiency depends mainly on: heat exchange area, movement of fluid flow and working mode of the ICE. With a reasonable structure of the EHR, the heat recovery of the exhaust gas can be achieved up to 40%.

Keywords: Internal combustion engine · Waste heat · Exhaust gas recovery tank

Nomenclature

ICE	Internal Combustion Engines
EHR	Exhaust gas Heat Recovery
GDI	Gasoline Direct Injection
HCCI	Homogeneous Charge Compression Ignition
VVTi	Variable Valve Timing intelligence
ORC	Organic Rankine Cycle
TEG	ThermoElectric Generator
TWC	Three-Way Catalytic converter
CFD	Computational Fluid Dynamics
TEx	Exhaust Gas Temperature (K)
ΔTEx	Reduction of Exhaust Gas Temperature
ηRe	Heat Recovery Efficiency (%)
ρ	Density (kg/m3)

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p	Pressure (Pa)
u	Velocity Component (m/s)
k	Thermal Conductivity (W/m.K)
Cp	Specific Heat in Constant Pressure (J/kg.K)
μ	Viscosity (Pa.s)

1 Introduction

In today's society, energy is an important part of our lives and one of the decisive factors for the sustainable economic development of countries around the globe. The increase of population and the improvement of people's living standards has increased energy consumption worldwide while energy resources are increasingly depleted. One of the solutions to effectively overcome this problem is to effectively use renewable energy sources. In addition, another way to approach the situation is to improve conventional energy systems to increase the maximum efficiency of the system obtained from an energy source.

Currently, ICE is the main driving force in the fields of transportation, agriculture, forestry and fishery. It accounts for 60–70% of the total fossil fuel consumption worldwide [1]. However, the average efficiency of ICE can only reach 30–40% [2], some studies show that the efficiency of ICE can reach up to 48% [3]. In recent years, rising fuel prices and global warming are major issues affecting the automotive and ICE industry. There have been studies to increase performance as well as reduce fuel consumption in the ICE. Advanced technologies have been used in the engine such as direct fuel injection (GDI) [4], Homogeneous Charge Compression Ignition (HCCI) [5], turbocharger [6], high injection pressure, advanced injection timing [7], VVT-i (Variable Valve Timing intelligence) [8]. The ability to improve fuel efficiency of the engine can be evaluated through experiments or numerical methods based on mathematical simulation. The experimental process requires a lot of time and cost while numerical simulation methods can reduce the expenditure of a research.

Despite great efforts of developers and scientist to apply advanced technologies into the ICE, there is still about 50% of fuel energy lost to exhaust gas and cooling water in the form of waste heat (of which cooling water accounts for 15–30% and exhaust gas accounts for 25–35%). Exhaust gas in ICE contains large amount of energy and has a high temperature, therefore exhaust heat recovery is one of the simple and effective way to improve fuel efficiency and heat efficiency of the system. Some technologies are studied that utilizing exhaust gas energy such as: Organic Rankine Cycle (ORC), thermoelectric generator (TEG), etc. Liu Tong et al. analyzed and simulated the recovery performance of a waste heat recovery system based on the Organic Rankine Cycle under different engine conditions and the results showed that the rated power of the motor is improved by up to 50% [9]. Haoqi Yang and his colleagues studied the optimization of the combination of TEG and the three-way catalytic converter (TWC), the results showed that the engine power increased by 37% and with a reasonable structure, the performance of TEGs can be improved by more than 16% compared to a single set of TEGs [10]. Hoang Anh Tuan [11] has studied the use of exhaust heat to heat up biofuels used on marine engines. In this study, the test object was the D243 engine (4-stroke, 4-cylinder diesel, unified combustion chamber, cylinder capacity of 4.75 L, rated capacity of 58.8 kW). Experimental results show that the exhaust heat used is 5.62 kW when the engine is working at 100% load and 2000 rpm.

From the above reasons, the content of this article will study, calculate, and optimize the design structure of the exhaust heat recovery tank (EHR) to evaluate the ability to utilize waste heat of the exhaust gas according to the working modes of the ICE using CFD simulation. In which the boundary conditions of the model are determined through experiments on the D243 engine at the research center for engines, fuels and emissions, Hanoi University of Science and Technology.

2 Numerical Model

Figure 1 shows the structure of the exhaust heat recovery (EHR) tank. In which the exhaust gas from the ICE goes inside the core of the tube and it exchange heat with 9 inner blades, these blades are evenly arranged in the tube along its body. Along the outside length of the pipe body, guide vanes are arranged to increase the heat exchange capacity between sea water, the pipe wall and exhaust gas. In this paper, the research team conducts a simulation with two cases in order to select the appropriate structure. Case 1 (EHR 1) with 9 triangular wings has a height of 55 mm and an acute angle of 8° and case 2 (EHR 2) with a plate-type structure which has 9 channels, each channel has a width r = 3 mm and is arranged along the tube body.

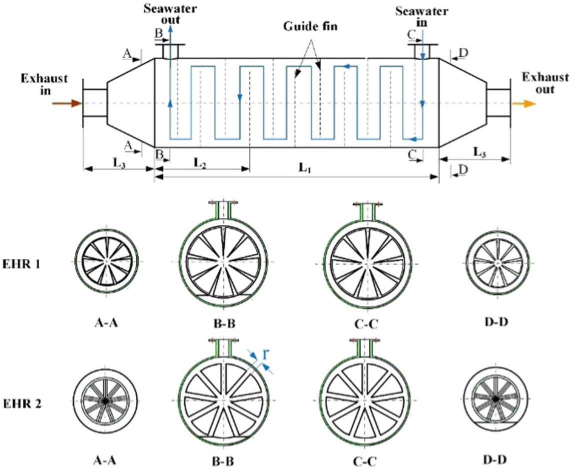

Fig. 1. EHR structure with 2 different cases.

2.1 Computational Theory in Ansys Fluent

In order to solve the problem using the Ansys Fluent software, governing equations for the flow and conjugate transfer of heat were customized according to the conditions of the simulation setup. The governing equations for mass, momentum, energy, turbulent kinetic energy and turbulent energy dissipation are expressed as follow [12].

- *Continuity equation*

$$\frac{\partial u}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

- *Momentum equation*

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = \frac{\partial}{\partial x_i}(\mu \frac{\partial u_j}{\partial x_i}) - \frac{\partial p}{\partial x_j} \tag{2}$$

- *Energy equation*

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}(\frac{k}{C_p} \frac{\partial T}{\partial x_i}) \tag{3}$$

In this research, standard k–ε turbulence model is adopted because it can provide improved predictions of near-wall flows. In addition, the standard k-ε model is a semi-empirical model synthesized from experimental phenomenon and has been widely used in heat exchange simulation because of its economy and accuracy factors. For this reason, the standard k-ε model was chosen to simulate heat transfer and flow in the EHR.

- *Turbulent kinetic energy:*

$$\frac{\partial}{\partial t}(\rho k) + div(\rho k u_i) = div\left(\frac{\mu_t}{\sigma_k} grad(k)\right) - \rho\varepsilon + 2\mu_t S_{\mathrm{ij}}.S_{\mathrm{ij}} \tag{4}$$

- *Turbulent energy dissipation:*

$$\frac{\partial}{\partial t}(\rho\varepsilon) + div(\rho\varepsilon u_i) = div\left(\frac{\mu_t}{\sigma_\varepsilon} grad(\varepsilon)\right) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t S_{\mathrm{ij}}.S_{\mathrm{ij}} \tag{5}$$

The equations contain five adjustable constants: C_μ, σ_k, σ_ε, $C_{1\varepsilon}$ and $C_{2\varepsilon}$. The standard k–ε model employs values for the constants that are arrived at by comprehensive data fitting for a wide range of turbulent flows:

$C = 0.09$, $\sigma_k = 1.00$, $\sigma_\varepsilon = 1.30$, $C_{1\varepsilon} = 1.44$ and $C_{2\varepsilon} = 1.92$

2.2 Boundary Condition

Velocity and temperature were applied to the inlet of the exhaust heat recovery tank as boundary conditions of the model, with values used according to prior studies [13, 14]. For the outlet, a pressure boundary condition was selected, where the measured pressure of the exhaust and seawater outlet was set to 0 Pa. The input velocity profile is assumed to be uniform. Based on the studied model size, the hydraulic diameter and turbulence at the inlet and outlet of the exhaust gas are 0.05 m and 5%. The hydraulic diameter and turbulence of seawater inlet and outlet are 0.02 m and 5%. The non-moving wall boundary condition is applied to the outer enclosure and the heat flux here is 0 (assuming the enclosure is completely insulated). A simple algorithm for the velocity-pressure coupling is adopted, second-order upwind method for energy, momentum, turbulent kinetic energy, and turbulent dissipation rate equation is prescribed. Under relaxation factors 0.4 for pressure, 0.6 for momentum, 0.75 for turbulent kinetic energy, 0.75 for turbulent dissipation rate, 0.75 for energy equation and 1 for turbulent viscosity are considered. The meshing model of the EHR is presented in Fig. 2.

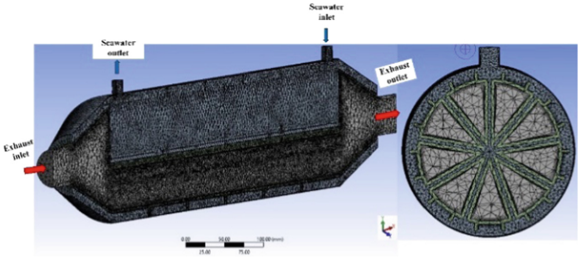

Fig. 2. Meshing model of EHR.

2.3 Meshing

In CFD analysis, the accuracy of the results and the computation time are two important parameters that are determined by the quality of the mesh, so grid independence is checked. In this problem 6 different mesh sizes (756636; 1251891; 1926205; 2515164; 4474689; 7606640) were tested to find the effect on the calculated Nusselt number at a distance of 500 mm from the exhaust stream inlet. There were no significant change in Nusselt number when the grid size is from 2515164 onwards, as shown in Fig. 3. Based on the above analysis, the grid size 2515164 was selected for the simulation models. The simulation is considered to be convergent when the remainder of the energy and mass equations is less than 10^{-4} and the other remainders are less than 10^{-6}.

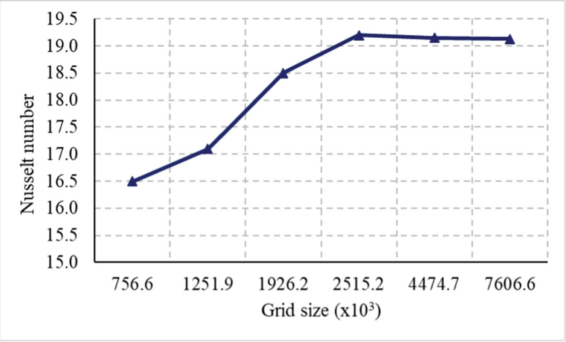

Fig. 3. Comparison of Nusselt number for different grid sizes.

3 Results and Discussion

3.1 Distribution of Temperature and Velocity in the Exhaust Heat Recovery Tank

Figure 4 shows the distribution of exhaust gas and seawater temperature in EHR in 2 cases. The results show that, in both cases, the exhaust gas temperature and sea water

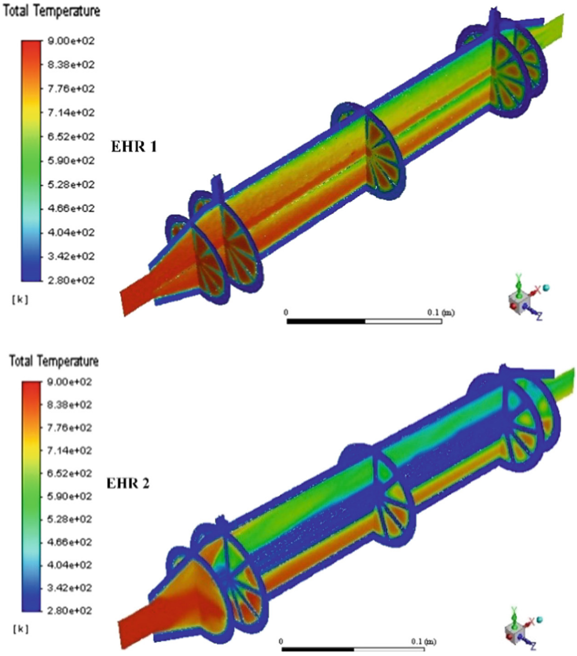

Fig. 4. Temperature distribution of exhaust gas and seawater in EHR with 2 cases when the engine is working at 100% load and 2200 rpm.

temperature are relatively similar, the exhaust gas temperature tends to decrease gradually along the EHR length; Exhaust gas temperature between blades or between channels is always higher than other locations. Meanwhile, seawater temperature tends to increase gradually from inlet to outlet along the body of the EHR, details as shown in the cross-sections in Fig. 4.

The distribution of flue gas and seawater flow velocities in the EHR for the two cases is shown in Fig. 5. However, it can be seen that the nature of the turbulent motion of the liquid depends on factors such as velocity, flow, number of blades, blade type. Regarding case 2 (EHR 2), with the advantage of channel structure, the velocity of sea water can be increased and can enhance the heat transfer capacity between pipe wall and sea water [15].

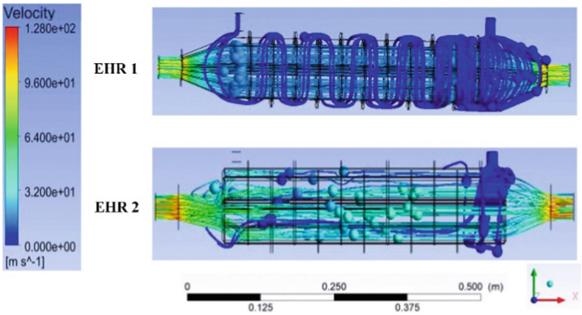

Fig. 5. Velocity distribution of exhaust gas and seawater in EHR with 2 cases when the engine is working at 100% load and 2200 rpm.

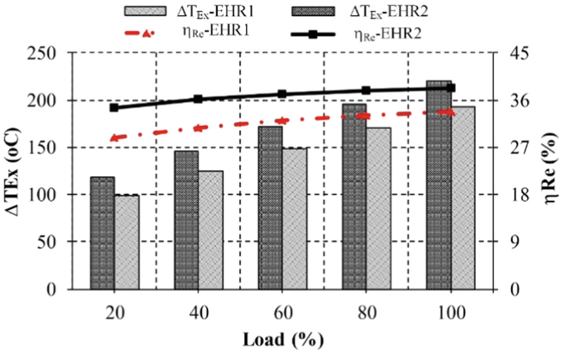

Fig. 6. The temperature reduction and heat recovery efficiency of the exhaust gas in 2 cases when the power generator is working at a speed of 2200 rpm.

3.2 Effect of Engine Load on Exhaust Heat Recovery

The reduction in exhaust gas temperature ΔT_{Ex} and exhaust heat recovery efficiency η_{Re} (recovered exhaust heat of EHR divided to the exhaust heat of ICE discharged into the environment) in the two cases are shown in Fig. 6. The results show that, in both cases, ΔT_{Ex} and η_{Re} increase when the load of ICE increases. However, in the case of EHR 2, ΔT_{Ex} and η_{Re} are higher than in the case of EHR 1. This may be because in the case of EHR 2 it is a plate-type structure, so seawater moves in the form of a thin film, which is the main factor leading to an improved heat transfer coefficient, thereby increasing the heat transfer of the exhaust gas to seawater compared to the case of EHR1. Specifically, the case of EHR 1 has $\Delta T_{Ex} = 193.4$ °C and $\eta_{Re} = 33.81\%$; EHR 2 has $\Delta T_{Ex} = 219.9$ °C and $\eta_{Re} = 38.38\%$ when the ICE works at 100% load and speed of 2200 rpm.

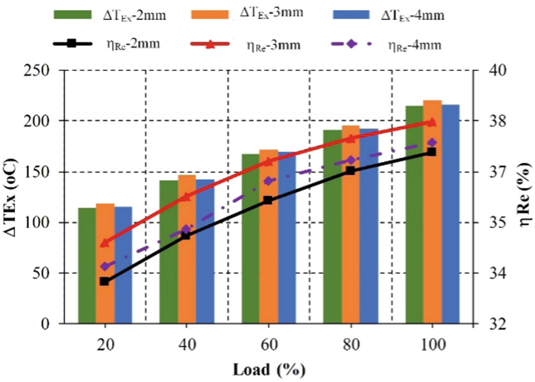

Fig. 7. Temperature drops and heat recovery efficiency of EHR 2 as r varies.

Table 1. Reduction of exhaust gas temperature ΔT_{Ex} and efficiency η_{Re}

	ΔT_{Ex}			η_{Re}		
Load (%)	r = 2 mm	r = 3 mm	r = 4 mm	r = 2 mm	r = 3 mm	r = 4 mm
20	114.2	118.2	115.4	33.3	34.6	33.8
40	141.6	146.6	143.6	34.8	36.1	35.0
60	166.9	172.1	169.8	35.9	37.1	36.5
80	191.0	196.0	192.4	36.8	37.8	37.2
100	214.8	219.9	216.1	37.4	38.4	37.7

3.3 Effect of Tank Structure on Heat Recovery of Exhaust Gas

Figure 7 and Table 1 show the reduction in exhaust gas temperature ΔT_{Ex} and exhaust heat recovery efficiency η_{Re} in the case of EHR 2 plate-type structure when r varies from 2 to 4 mm. The results show that, when r increases, ΔT_{Ex} and η_{Re} both increase; however, r = 3 mm will give the best results compared to the other 2 cases. Therefore, the research team will choose r = 3 for the next studies to evaluate the heat utilization of the exhaust gas in the ICE.

4 Conclusion

The article has succeeded in building a model of exhaust gas heat recovery tank as well as evaluating the influence of EHR structure on exhaust heat recovery. The simulation results show that with the EHR2 plate-type structure, the exhaust heat recovery is better. In addition, when we change the width of the channel (r), it will affect the heat recovery efficiency of the exhaust gas and in the case of $r = 3$ mm then η_{Re} reaches the maximum value of 38.38% when the engine is working at 2200 rpm and 100% load. The results of this study will be an important factor to calculate, design and build a system to utilize exhaust gas energy to generate useful work in the ICE.

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