

Numerical Simulation of the Thermoelectric Model on Vehicle Turbocharged Diesel Engine Intercooler

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Abstract: A thermoelectric gas-solid heat transfer numerical model was established between an air-cooling tube-fin intercooler's intake and cooling air passage channel on vehicle turbocharged diesel engine. The outlet temperature of intake air, the output power of the thermoelectric components and the thermal conversion efficiency are considered as the research objectives. When load value is constant, the outlet temperature of intake air decreases with the number of thermocouples increases and there exist maximum values for output power and thermal conversion efficiency; when the number of thermocouples is constant, there is little effect on the outlet temperature of intake air with the load value increases. When the load was been optimal designed, set the load value throughout equals to the value of thermoelectric component total internal resistance, the values of the maximum output power was increased by 20.3% and the thermal conversion efficiency was increased from 1.78 to 3.48%.

Keywords: Air cooling tube-fin intercooler, gas-solid heat transfer, optimal design, thermoelectric

INTRODUCTION

In order to improve a diesel engine's intake air density, thereby increasing the injection quantity of the fuel to improve the mean effective pressure, it is generally need to install turbocharger in front of a diesel engine. However, due to the high temperature of the air after the turbocharger impacting the diesel combustion and emissions (Li, 2008; Lu, 2004), an intercooler should be installed at the exit of compressor outlet, in order to achieve the desired combustion standards. There is a certain temperature difference between the intake air and the cooling air, some heat is dissipated to the environment through the cooling air by convection away. Recent years, thermoelectric conversion device based on the principle of thermoelectric power generation (Thermoelectric Generator TEG), making use of the temperature difference to generate electricity, driven by the advantages of no pollution, no noise and no need for intermediate components, low-quality heat can be converted into high-quality electrical energy, is extensively researched and made utilization (Meng *et al.*, 2010; Hoffman *et al.*, 1997; Francis, 2009). In this study, a model of thermoelectric power generation devices between intake air passage channel and cooling air passage channel on air-cooling tube fin intercooler within a turbocharged diesel engine is researched and optimized, modeling and numerical study for future design applications provide a scientific basis for the new thermoelectric generator based on the intercooler.

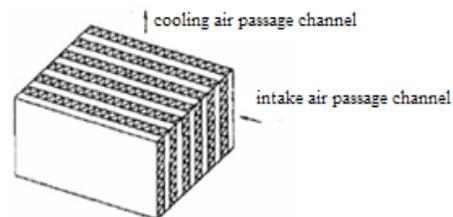


Fig. 1: Schematic diagram of tube-fin intercooler

MODELING

Thermoelectric couples' arrangement: The schematic diagram of a typical air-cooled tube-fin intercooler is shown in Fig. 1, the pressurized hot air and cooling air using the cross-flow heat exchanger arranged, can effectively exchanging heat. Since the thermoelectric appliances need to work in the temperature difference conditions, so several pairs of thermocouples are arranged between each layer of the intake air passage channel and the cooling air passage channel. The thermocouples are in array arrangement, electrically connected in series, as shown in Fig. 2.

Thermoelectric generator computing modeling: The schematic diagram of the thermoelectric generator model is shown in Fig. 3. Between the intake air passage channel and the cooling air passage channel, uniformly arranging m thermocouples, the intake air passage channel imported state respectively is

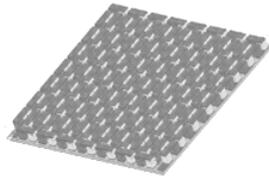


Fig. 2: Schematic diagram of the array of thermoelectric couples

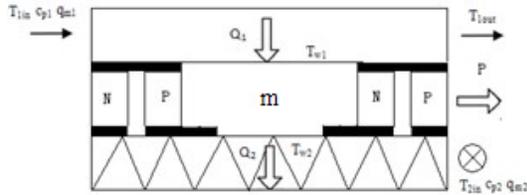


Fig. 3: Diagram of thermoelectric generator model

temperature T_{1in} , mass flow q_{m1} and constant volume specific heat capacity c_{p1} , outlet temperature is T_{1out} ; the cooling air direction is perpendicular to the paper, inlet temperature, mass flow and the constant volume specific heat capacity of cooling air are T_{2in} , q_{m2} and c_{p2} respectively, the cooling air passage outlet temperature is T_{2out} . The heat flow taken from intake air passage to thermoelectric generation elements is Q_1 and the heat flow taken from thermoelectric generation elements to cooling air passage is Q_2 . External output power of the thermoelectric power generation elements is P . T_{w1} , T_{w2} are respectively the intake and the cooling air passage channels' wall temperatures.

Taking into account the general characteristics of the thermoelectric generator, make the following assumptions (Chen and Wu, 2000):

- Ignoring the thermoelectric units and thermoelectric units with air convection heat transfer and radiation heat transfer
- Ignoring the second stage of Thomson effect
- The temperature difference between the intake air channel and the cooling air channel are ignored
- The thermoelectric unit performance does not change with temperature
- Ignoring the contact resistance of the contact surfaces and the contact thermal resistance

According to the theory of non-equilibrium thermodynamics, thermoelectric power generation device for pumping heat from the hot end is:

$$Q_1 = n[\alpha IT_{w1} + K(T_{w1} - T_{w2}) - 0.5I^2R] \quad (1)$$

Heat to the cold end is:

$$Q_2 = n[\alpha IT_{w2} + K(T_{w1} - T_{w2}) + 0.5I^2R] \quad (2)$$

where

$\alpha = \alpha_P - \alpha_N$, α_P and α_N are seebeck coefficients of P and N-type semiconductor material

I = The working current

R = The total resistance

K = The total thermal conductivity

For the intake air and cooling air passage channel, there exists convective heat transfer. When the fluid flows through the wall, according to the theory of heat transfer, the heat exchange is:

$$Q = h(T_{in}, T_{out}) * A * (T_{bm} - T_w) \quad (3)$$

$h(T_{in}, T_{out})$: The convective heat transfer coefficient, if the airflow passage size and mass flow are fixed, it depends on the inlet and outlet temperature of air

T_{bm} : The average temperature of the gas stream

$T_{bm} = (T_{out} - T_{in}) / 2$, T_w : The wall temperature

A : The effective area of the heat exchanger

Convective heat transfer coefficient can be calculated as follows (Chen and Wu, 2000):

$$h = Nu\lambda / D \quad (4)$$

where,

Nu = The Nusselt number of the gas stream

λ = The airflow rate of the thermal conductivity

D = The equivalent diameter of the airflow channel

$$Nu_f = 0.023 Re_f^{0.8} Pr_f^{0.3} \quad (5)$$

$$Nu_f = 1.86(Re_f \cdot Pr_f \cdot \frac{D}{L})^{1/3} (\frac{\mu_f}{\mu_w})^{0.14} \quad (6)$$

$$\lambda = 1.717 \times 10^{-5} (T_{bm} / 273)^{0.683} / \rho_c \quad (7)$$

$$D = 4F / U \quad (8)$$

(5) is proposed by Dittus and Boelter (Cao, 2001) apply to wall temperature turbulent convective heat transfer, the Reynolds number Re and the Prandtl number Pr are groups of parameters of the thermal conductivity λ , thermal diffusivity a , etc. These physical parameters are functions of temperature, so determining the Reynolds number and Prandtl number, it must give the characteristic temperature, subscript f represents the average temperature of the fluid inlet characteristic temperature; (6) is the convective heat transfer formula proposed by Sieder and Tate (Cao, 2001) suitable for wall temperature laminar convective heat transfer, L represents the pipe length, μ_f and μ_w respectively represent the coefficient of dynamic viscosity of the fluid at a characteristic temperature and the wall temperature; ρ_c represents the air density, F

represents a cross-sectional area of the airflow passage, U represents the wet perimeter of the channel.

According to energy conservation, the thermoelectric power generation modules pumping heat from the hot end Q_1 , should be equal to the heat release from the cold end Q_2 plus the foreign output power P:

$$Q_1 = Q_2 + P \tag{9}$$

Thermal conversion efficiency is:

$$\eta = P / Q_1 \tag{10}$$

SOLUTION OF THE MODEL AND OPTIMIZATION IMPROVEMENTS

Solution of the intercooler thermoelectric power generation elements model: For a particular model of diesel engine turbocharger and intercooler (Li, 2008), the size of the structure and the intake air temperature, intake mass flow, velocity and other physical parameters were chosen to be the initial conditions for numerical calculation. The inlet temperatures of the intake air and the cooling air are set for $T_{1in} = 453.1K$, $T_{2in} = 315K$ respectively, the outlet temperature of intake air and cooling air, the wall temperature, the output power and thermal conversion efficiency of thermoelectric power generation elements are output variables. There are 43 intake air passage channels and 44 cooling air passage channels; each intake air passage channel's structure is the same and each cooling air passage channel's structure is also the same, as shown in Fig. 4 and 5. After calculation, the wet perimeter of the intake air passage and cooling air passage respectively are $U_h = 10.29 m$, $U_c = 74.62 m$, the gas flow area of the intake passage and the cooling air passage respectively are $F_h = 0.01 m^2$, $F_c = 0.26 m^2$. Airflow velocity of the intake air channel is $u_h = 18.1 m/s$, the cool air airflow velocity $u_c = 3.717 m/s$, the Reynolds numbers of the intake air passage and the cooling air passage can be calculated, are respectively 7948 and 3567, determined as turbulent flow state (Cao, 2001), so choose (5) as a Nusselt number calculation formula. There exist total 86 contact surfaces between the intake air passage and the cooling air passage channels and m thermocouples are uniformly arranged in each of the contact surface.

Selecting commercial thermoelectric material bismuth telluride (Bi_2Te_3), having the characteristics of the lower temperature range (270-450K) (Richard and Dan, 2009), the physical parameters are shown in Table 1, thermoelectric couple leg size is $2 \times 2 \times 1 cm$, λ is the thermal conductivity rate, σ is the conductivity, K is the thermal conductivity, R is the internal resistance.

Using trusted domain dogleg algorithm in MATLAB, it can solve Eq. (1) to (4), (5) and (7)

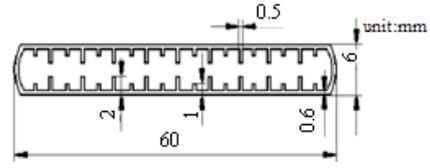


Fig. 4: Schematic diagram of intercooler intake air passage channel

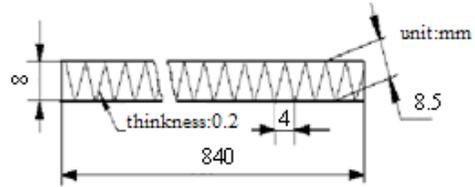


Fig. 5: Schematic diagram of intercooler cooling air passage channel

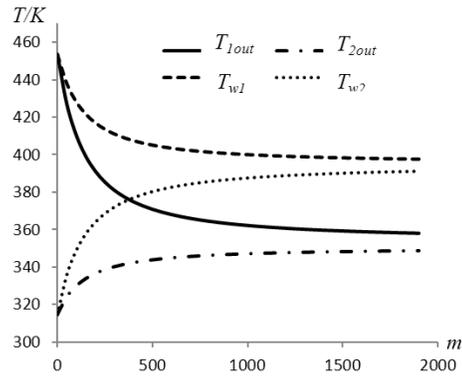


Fig. 6: The relationships between the outlet-temperatures and the wall temperatures of intake and cooling air vs. the number of thermocouples

$\alpha / (V/K)$	$\lambda / (W/m/K)$	$\sigma / (\Omega^{-1}/m)$	$K / (W/K)$	R / Ω
4.28×10^{-4}	1.6	1×10^3	0.032	3.5×10^{-3}

to (10). The objectives of the research are the respective outlet temperature and the wall temperature of the intake air and the cooling air passage, thermoelectric generator output power and the thermal conversion efficiency, with the number of thermo couplesm and the load R_L respectively changes, using process control variable method, that is, when the number of thermo couplesm changes, set the load R_L a constant and vice versa.

Figure 6 shows the relationships between the outlet temperatures and the wall temperatures of intake and cooling air vs. the number of thermocouples, the external load is set to be $R_L = 2\Omega$. As can be seen, as m increases, the outlet temperature of the intake air T_{1out} and the wall temperature T_{w1} gradually decrease, the outlet temperature of the cooling air T_{2out} and the wall temperature T_{w2} gradually increases, the heat transfer is strengthened and the cooling effect of the intercooler is better. The temperature curve decreases rapidly before

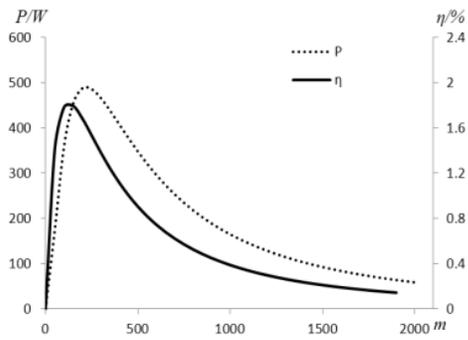


Fig. 7: The relationships between the output power and the thermal convection efficiency vs. the number of thermocouples

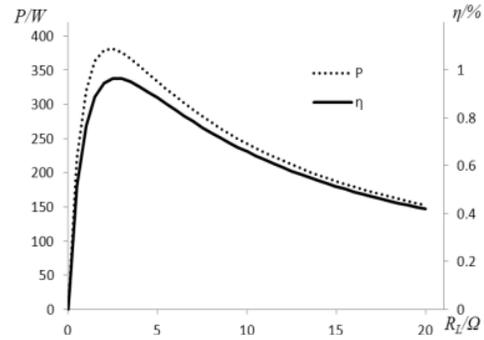


Fig. 10: The relationships between the output power and the thermal convection efficiency vs. the value of external load

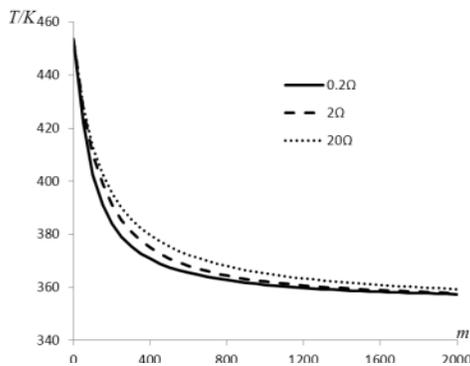


Fig. 8: The relationships between the temperatures of intake air vs. the number of thermocouples at different fixed load values

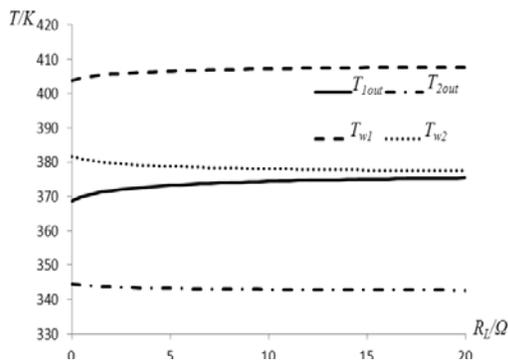


Fig. 9: The relationships between the outlet temperature and the wall temperature vs. the value of external load

m equals 500, because the temperature difference between the intake air and cooling air passage channel is bigger, the performance of thermoelectric generator is working on an ideal condition; the curve becomes flat after m equals 1000 because the intake and cooling air passage channel wall temperature difference is relatively small, continuing to increase m has little effect on the heat exchanger.

Figure 7 shows the relationships between the output power and the thermal convection efficiency vs.

the number of thermocouples, setting the external load $R_L = 2\Omega$. As can be seen, the output power and the thermal conversion efficiency curves increase rapidly as m increases, reach the maximum value, respectively 497W and 1.78%; after the maximum points, as m increases, the cooling effect is enhanced and the intake and cooling air passage channels' temperature difference is reduced, the output power and the thermal conversion efficiency are decreasing.

Figure 8 shows the relationships between the temperatures of intake air vs. the number of thermocouples at different fixed load values. With the number of the thermocouples increases, outlet temperatures of intake air for three different fixed load values decrease. Larger the load, smaller the power consumption and smaller the heat exchange from the intake air to the cooling air, the worse effect of heat transfer, the outlet temperature is relatively higher.

As shown in Fig. 7, in the case of thermoelectric generator load unchanged, there respectively exist corresponding numbers of thermocouples, so that the output power and the thermal conversion efficiency reach maximum values. Meanwhile, the outlet temperature of intake air is too high to meet the cooling requirements of the diesel engine cooler, it should choose a slightly bigger number of thermocouples than the output power and thermal conversion efficiency's optimal points, in order to take the energy recycling and intercooler cooling effect of the turbocharger airflow into account.

Figure 9 and 10 respectively gives when m equals 500, the relationships between the four temperatures shown in Fig. 6 and the corresponding output power and the thermal conversion efficiency vs. the value of external load. As can be seen from Fig. 9, when load increases, the outlet temperature of the intake air increases, while the outlet temperature of the cooling air decreases, load values increase reduces the output power of the load, but each of the temperature changing width is only 2~3K, indicating very limited impact, so the size of the load can be chosen more flexibility

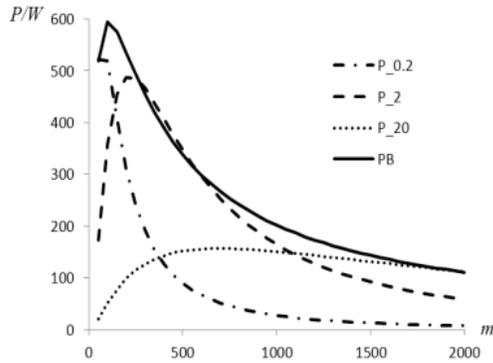


Fig. 11: The relationships between the output power vs. the number of thermocouples at different load values and the optimal load value

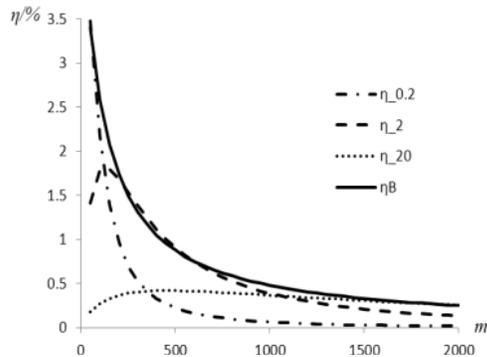


Fig. 12: The relationships between the thermal convection efficiency vs. the number of thermocouples at different load values and the optimal load value

according to the actual situation. Figure 10 shows the output power and thermal convection efficiency similar with Fig. 7, there are still respectively optimal R_L value, the value of the load has a great impact on the output power and the thermal conversion efficiency.

Optimization of intercooler thermoelectric power generation elements model: According to the thermoelectric theory (Gao and Rowe, 1996), the output power obtained by the external load is:

$$P_0 = \frac{\alpha^2(T_1 - T_2)^2 R_L}{(R_L + R)^2} \quad (11)$$

When the total internal resistance R equals to the external load R_L , that is, $R_L/R = 1$, the load can obtain the maximum output power from the thermoelectric elements, its value is:

$$P_{\max} = \frac{\alpha^2(T_1 - T_2)^2}{4R_L} \quad (12)$$

In some practical applications, achieving the maximum output power in order to get the best

performance of electrical appliances is often required. With the number of thermocouples changes in the analysis of Fig. 7, the single thermocouple has the same electrical properties and the internal resistance is also unchanged, but due to total internal resistance of the thermoelectric element is equal to a single thermocouple internal resistance multiplied by the number of thermocouples, thermoelectric elements total internal resistance R will also changes. Thermoelectric generators can't always guarantee operating at its maximum output power regardless of any constant load value.

So in numerical simulation, optimize the load value for the thermoelectric generation elements model. With the change of m , setting load R_L is always equal to the thermoelectric elements' total internal resistance R , it can reach the maximum output power P_{\max} on any corresponding m . Figure 11 shows comparison between the output power respectively corresponds to load 0.2Ω , 2Ω , 20Ω and the output power after optimization of the load, P_B . As can be seen, P_B curve entirely locates above the curve of the output power on three different fixed load values and the adaptation range is wider. The peak of output power curve researches $598W$, increased by 20.3% compared with the peak of the power curve in Fig. 7.

Figure 12 shows comparisons between the thermal conversion efficiency respectively corresponds to load 0.2Ω , 2Ω , 20Ω and the thermal conversion efficiency after optimization of the load, η_B . As can be seen, η_B curve also entirely locates above the curve of the thermal conversion efficiency on three different fixed load values, η_B curve peak rises from 1.78 to 3.48% compares with Fig. 7.

CONCLUSION

- When thermoelectric generator's external load doesn't change, the outlet temperature of the intake air decreases with the number of thermocouples increases, indicating that the heat exchanger between the intake air passage channels and the cooling air passage channels is strengthening.
- When the number thermocouples is constant, the value of thermoelectric generator external load's change has little effect on the outlet temperature of cooling air, changing width is only about $2\sim 3K$.
- After thermoelectric generator load optimization, thermoelectric power generation elements achieve the best working conditions, the output power increases by 20.3% compared with previous simulations, thermal conversion efficiency increases from 1.78 to 3.48% .

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