

Research Article

Simulation on Cooling System of Automotive Waste Heat Thermoelectric Generator

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Abstract: The cooling system of automobile waste heat Thermoelectric Generator (TEG) is researched in the study. Integrated model of cooling system and vehicle is built based on GT-Cool, analysis of the different cooling ways shows that when using independent cooling system, the ratio between power consumption and output is high and system performance is poor; By using integrated cooling system, the expectation of keep constant engine warm up time and synchronous change of water temperature between different tanks is realized after water tanks are improved.

Keywords: Automobile waste heat, cooling system, simulation, Thermoelectric Generator (TEG)

INTRODUCTION

About 20% to 40% fuel consumption energy is wasted through exhaust gas for traditional internal combustion engine automobile. This part of the energy which is converted to automobile waste heat and released to atmosphere causes the economic loss and environmental pollution (Hussain *et al.*, 2009). With the continuously development of the thermoelectric materials research field, the world's major automotive manufacturing companies carry out a series of research work as the way of thermoelectric generator aim to recycling high temperature energy. Among them the BMW, there have achieved a certain research achievements in the BMW 5 Series, the General Motor Company has realized the loading test in one of pickup (Serdar and Ann, 2008; LaGrandeur *et al.*, 2006).

Currently designed of vehicle exhaust waste heat thermoelectric power generation device (Thermal Electric Generator, TEG), installed in the engine exhaust system, taking into account the operating temperature range of thermoelectric materials, put installed in the three-way catalytic converter and muffler, the typical structure integrated with the engine shown in Fig. 1. TEG includes waste-gas flue tank, cooling water tank and thermoelectric materials between two tanks. When high temperature exhaust gas gets through waste-gas flue tank, the waste heat is converted to electric energy by passing the heat to thermoelectric materials hot side block, it can generate temperature difference with cold side block maintaining low temperature adopted compulsory water cooling

system. TEG cooling system concludes two modes, the cooling system integrated into engine and independent cooling circuit. This study has established the TEG cooling system simulation model, carried on comparison research about its performance.

TEG COOLING SYSTEM DESIGN AND ESTABLISHMENT OF SIMULATION MODEL

Problems needed considered in the design of TEG cooling system: First, the connection way of three cooling water tanks should choose the parallel structure. Compared with series structure, this way can decrease water flow resistance, decrease water pump energy consumption and guarantee the coolant temperature liquid of water tank synchronous raise or lower. In this way, the design can ensure thermoelectric materials endure same temperature, output same voltage consider three different tank. Second, differences from three tank. For tank 2, the sides of each layer of thermoelectric material, internal coolant heat is twice that of the other two tanks, so the others to ensure temperature change the synchronization, inside the coolant flow rate should be twice of the other two boxes, it can be guaranteed in the design of the tank import and export of caliber size.

Cooling system heat transfer effect and flow resistance effect simulation: GT-Cool is now commonly used as the engine cooling system simulation software. It has water pump model, cooling fan model, radiator model, fluid pipeline model and so

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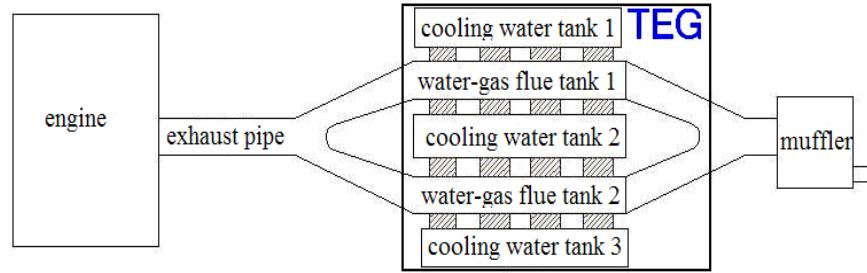


Fig. 1: Integration of TEG and engine

on. This study has established simulation model of TEG cooling system, it use of this software⁴. Ignoring establishment of the cooling water tank three-dimensional structure, this study only has simulated the transfer effect from TEG internal high temperature exhaust to cooling fluid and flow resistance effect simulation.

As for the simulation of heat transfer effect, the key point is calculation of the heat flux, that is to say, considering the heating effect of water tank to cooling fluid. The heat energy transferred from the high temperature exhaust gas to waste gas flue tank can be calculated by formula 1.

$$P = C_p * M * \Delta T \tag{1}$$

where,

- C_p = The constant pressure specific heat capacity of exhaust gas
- M = Exhaust mass flows
- ΔT = Temperature difference between waste gas inlet temperatures and outlet temperatures

Supposing that the other surfaces of waste gas flue tank are adiabatic, P (W) is the heat flux by cooling fluid absorbing from thermoelectric materials. M and ΔT are depended on the engine condition, vary from the change of engine condition, when we do some simulation analysis in different conditions, their value can be decided by engine waste gas mass flow load characteristics and exhaust gas temperature-load characteristics. During the process of establishing the simulation model, the load condition should be stored in the software “Lookup2D” model in the form of MAP, when the model was performed, at the same time, Real-time input engine speed and power, the value of M and ΔT can be determined through the method of automatic interpolation.

As for the simulation of water tank flow resistance effect, we can use the “Pressloss” model in the model library of GT-Cool. Then we can obtain the data of water flow-pressure loss (Table 1). When the simulation model was performed, the corresponding

Table 1: Data of rate of flow-pressure loss

Mass flow rate (kg/s)	Pressure loss (Pa)
0.100	227
0.162	600
0.431	4200
0.600	8100

pressure loss value is depended on water mass flow rate through the method of automatic interpolation.

The establishment model of cooling system and engine integrated into vehicle: Adding the cooling system model to the simplified engine model which includes external characteristic curve and fuel consumption MAP, The purpose of connecting the pump's cooling system to mimic the engine flywheel and water pump at a constant speed and power of the input shaft of the drive roller to determine the engine operating point, we can simulate the performance of the cooling system in a stable condition. The simulation model is shown as Fig. 2. After that it enables the vehicle model integrated with TEG cooling system model which is accomplished through the use of road model, environment model and drive system to the whole vehicle model. Figure 3 shows the integrated model and the simulation analysis can be performed by the input of vehicles running condition.

THE SIMULATION ANALYSIS OF THE INDEPENDENT COOLING SYSTEM TEG

According to the See beck effect of thermoelectric materials, the voltage produced by the thermoelectric materials can be calculated through formula 2. Inferring from the formula, we know that the power generation capacity of thermoelectric materials is not only related with itself characteristics but also with the value temperature difference:

$$V = \alpha_{PN} * \Delta T \tag{2}$$

$$\alpha_{PN} = \alpha_p - \alpha_N \tag{3}$$

where, α_p and α_N are the See beck coefficient of P pole, N pole respectively, they are the physical parameters of

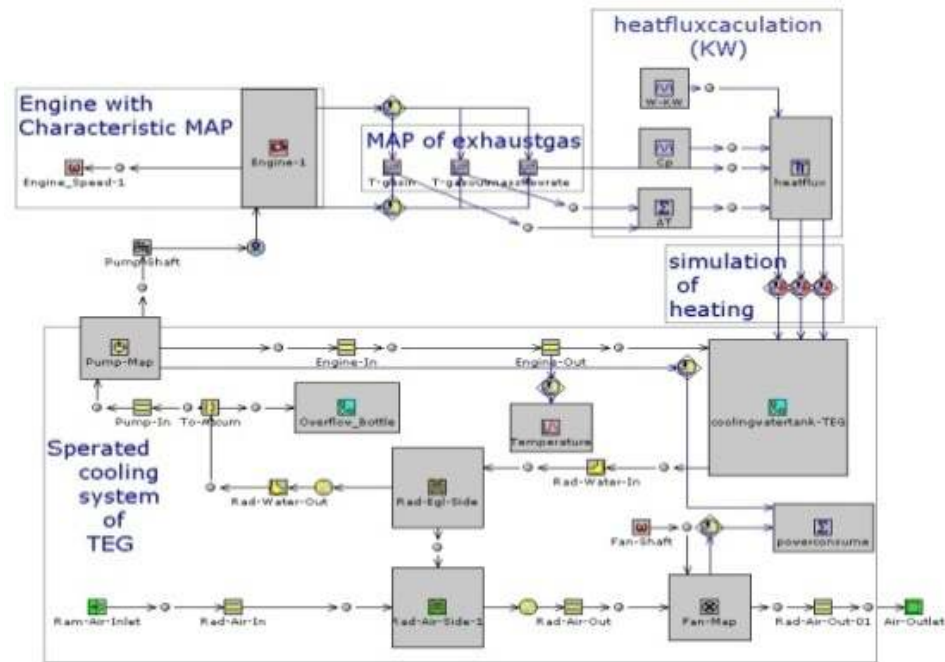


Fig. 2: Simulation model of cooling-system with engine

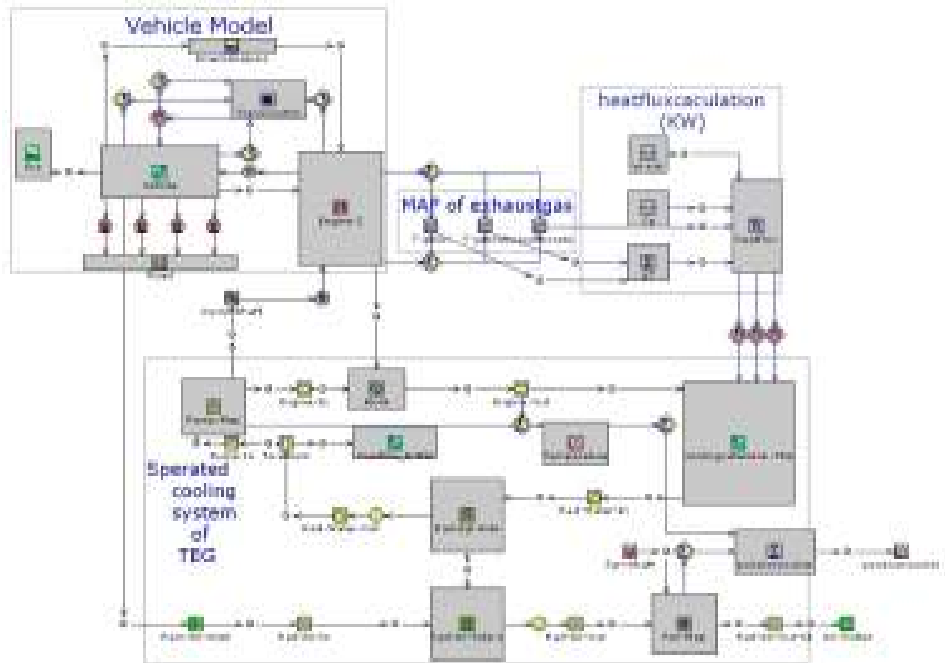


Fig. 3: Simulation model of cooling-system with vehicle

thermoelectric materials, their values are related to the material temperature. α_{PN} is the relative Seebeck coefficient, ΔT (K) is the value temperature difference of thermoelectric materials cold side block.

Currently adoptive low temperature thermoelectric materials, its hot side operating temperature range is from 250°C to 300°C, just which has limited the usable

range of materials and the temperature difference advanced increment. Given that demands more progressive design for TEG system to pursue high thermoelectricity effect. In this study, we propose separate cooling methods, were designed for the trimethylene glycol system in order to reduce the cold junction temperature close to room temperature, the

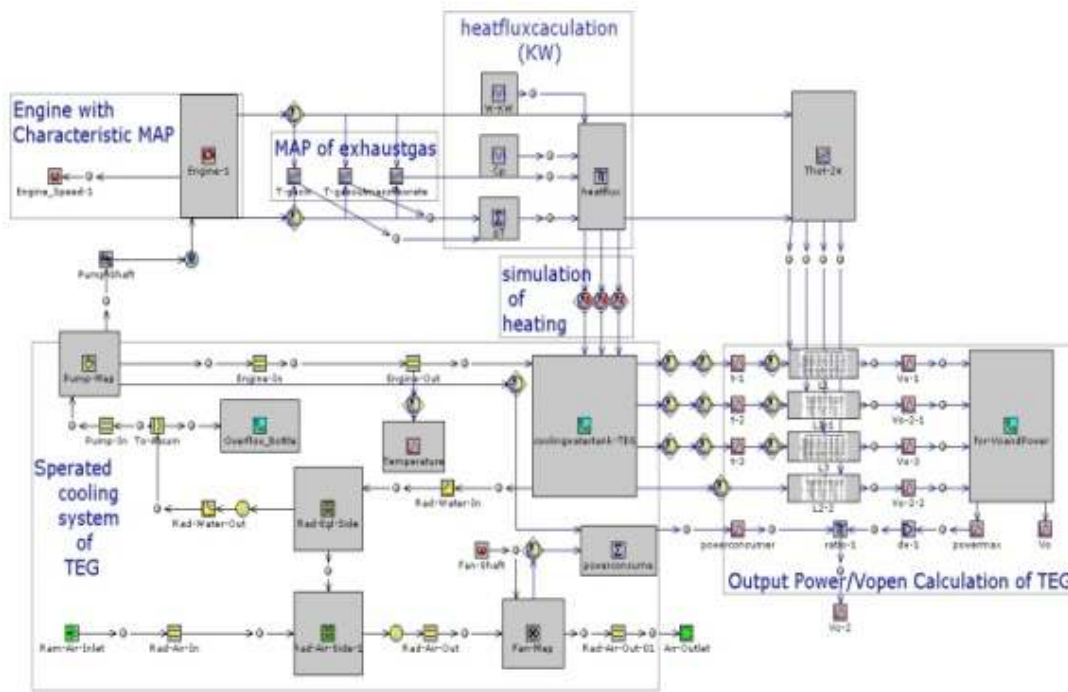


Fig. 4: Simulation model with power calculation

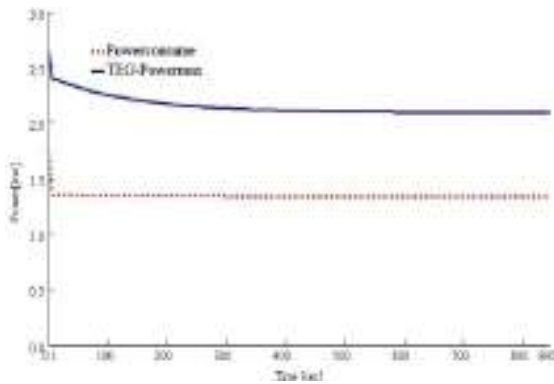


Fig. 5: The maximum power of TEG and the power consumption of water pump and fan of separate cooling system

level of the material, further improve the output efficiency of the material. However, for this independent cooling system, two problems are considered. First, this cooling system has put forward higher requirements for general arrangement of vehicle. Second, independent water pump and cooling fan have increased energy consumption. So this system requires comparative analysis with generate electricity capacity of TEG, if the consumption energy of independent cooling system is far less than the generated energy of TEG, this type of cooling is reasonable, if not, this system is useless. The simulation model combined with TEG generating capacity calculation program is shown as Fig. 4. We can perform a separate cooling system

and energy between this simulation model glycol-based simulation analyses.

The experiment is performed under the steady condition of engine speed 1500 r/min ,power 24 kW, Fig. 5 shows the comparison of outputting maximum power in the condition of matched load among engine water pump, cooling fan total power consumption and TEG system.

It is obvious that the total consumption energy of water pump and cooling fan is about 1.3 kW constituting up to 60% of the maximum output power of TEG. Therefore it is unreasonable to adopt independent cooling system.

THE SIMULATION ANALYSIS OF INTEGRATION COOLING TEG SYSTEM

The TEG system connected in minor cycle of engine cooling system: Generally, the temperature of engine cooling water is kept from 80°C to 95°C, which can guarantee favorable thermal state and performance for the engine. Therefore, if the temperature of thermoelectric materials cold point is reduced by the use of engine cooling water, the range of cold point temperature should be from 80°C to 95°C too. As for the way of TEG cooling water combined with engine cooling system, there are two schemes. One is connected with minor-cycle stage; another is connected with major cycle stage. The process of transferring heat from high temperature exhaust gas to the cooling water is equal to independent heat source heating the cooling

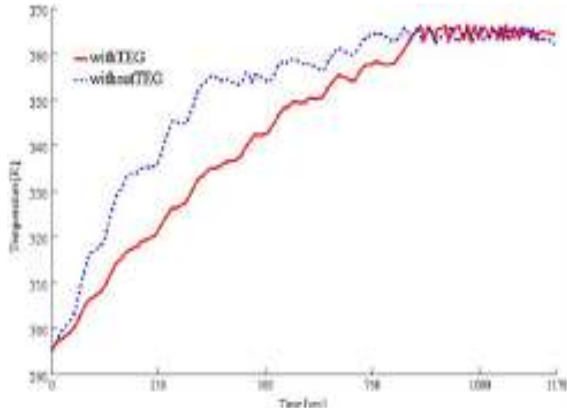


Fig. 6: Change of water temperature with shorter cooling circulation

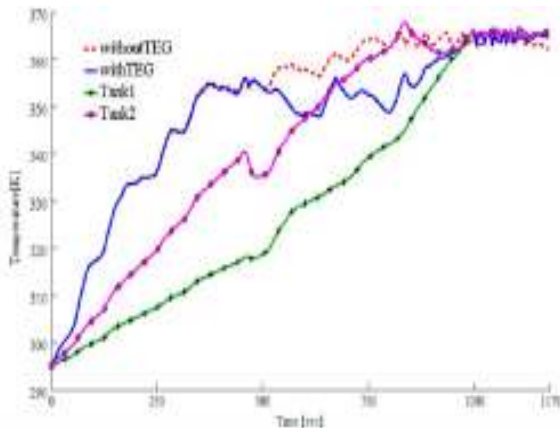


Fig. 7: Change of water temperature with longer cooling circulation

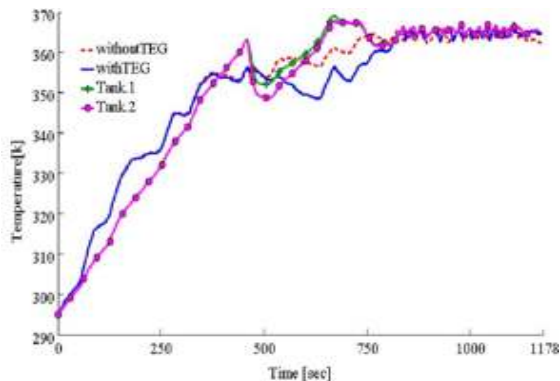


Fig. 8: Change of water temperature with improvement of water tank volume

water. In this way the cooling system has influence on the engine warm-up time⁵. Since the warm-up time has some certain relationship with fuel economy, lubricating property and emissions, the scheme of applying minor-cycle connection should meet the requirement that the engine warm-up time reduction or unchanged. The integrated vehicle system model is shown as Fig. 3, during experiment set the driving

condition as NEDC driving cycles and minor-cycle connection. Figure 6 displays water temperature change situation of cooling system. We can conclude that the engine warm-up time has prolonged to a certain extent. Supposing the water temperature is 350K, the engine warm-up time has about prolonged 290s.

The TEG system connected in major cycle of engine cooling system: In this cooling system, we have aimed to install the TEG cooling water tank between the thermostat and the radiator. When open the thermostat, the cooling water will flow into the major cycle. Figure 7 is a temperature profile of cooling water at the exit of the engine water jacket. As the Fig. 7 shows, there is no change for the engine warm up time compared with the results of without TEG system ,in addition, there is no difference for the maximum temperature when the water temperature keep constant. In the condition of NEDC driving cycle, the time has been extended about 200 before the engine water temperature reaches a steady state; do not have the water temperature curve of the TEG system compared to a big difference. At the same time, the increment of water temperature is not synchronous for water tank 1 and water tank 2⁵.

Improved design and analysis: The cooling water tank capacity has been decreased to 1L and 2L with the purpose of optimizing the TEG cooling water tank capacity. The analysis result is shown as Fig. 8. We can estimate that the temperature curve of cooling water at the exit of the engine water jacket is almost similar to the change curve without TEG system. Besides the steady maximum temperature is not increased although the reduction of flow water. Therefore, we can conclude that the engine cooling capacity in the previous match still to meet the increased cooling load requirements in the engine system, including TEG structure. Before the thermostat is open, Glycol cooling water tank of cooling water in the static heating state, the maximum temperature moment came in the 480s, the thermostat is open. At this point the temperature is about higher 10°C than the water temperature of engine cooling system but still has a big difference with the boiling temperature of cooling water. After the thermostat is open, the water temperature variation among water tank has good synchronicity. In addition, the water temperature of the entire system a certain degree of reduction, then an overall increase of glycol mixed with water coolant loop. So the TEG cooling system has little influence on the previous engine cooling circuit, because of the approximate time reaching the stable temperature compared with no TEG.

CONCLUSION

- TEG internal heat transfer effects, the simulation of the water tank flow resistance effect, TEG cooling system model, integrated with the engine, vehicle

model, the establishment of a system model simulation and analysis of multiple loading conditions.

- Simulation results show that using an independent cooling system, water pump and fan energy consumption accounted for 60% of the TEG energy output should not be used; with integrated cooling system, access in the small loop stage, approximately 350K standard engine warm-up time will extend the 290s, if cycle access in the large stage, the engine warm-up time, but TEG cooling water tank temperature is not synchronized.
- The analysis of optimization and simulation for TEG water tank capacity had shown that the temperature curve of cooling water at the exit of the engine water jacket is almost similar to the change curve without application of TEG system. After the thermostat was open, the water temperature variation among water tank has good synchronicity and the TEG cooling system has little influence on the previous engine cooling circuit.

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