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Study on the Influence of the Cold-End Cooling Water Thickness on the Generative Performance of TEG

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At present, about 40% of the fuel energy is discharged into air with the exhaust gas when an automobile is working, which is a big waste of energy. A thermoelectric generator (TEG) has the ability to harvest the waste heat energy in the exhaust gas. The traditional TEG cold-end is cooled by the engine cooling system, and although its structure is compact, the TEG weight and the space occupied are important factors restricting its application. In this paper, under the premise of ensuring the TEG maximum net output power and reducing the TEG water consumption as much as possible, the optimization of the TEG water thickness in the normal direction of the cold-end surface (WTNCS) is studied, which results in lighter weight, less space occupied and better automobile fuel economy. First, the thermal characteristics of the target diesel vehicle exhaust gas are evaluated based on the experimental data. Then, according to the thermoelectric generation model and the cold-end heat transfer model, the effect of the WTNCS on the cold-end temperature control stability and the system flow resistance are studied. The results show that the WTNCS influences the TEG cold-end temperature. When the engine works in a stable condition, the cold-end temperature decreases with the decrease of the WTNCS. The optimal value of the WTNCS is 0.02 m and the TEG water consumption is 8.8 L. Comparin it with the traditional vehicle exhaust TEG structure, the power generation increased slightly, but the water consumption decreased by about 39.5%, which can save fuel at0.18 L/h when the vehicle works at the speed of 60 km/h.

Key words: TEG, waste heat, WTNCS, exhaust gas

List of symbols

Q	Heat transfer rate (kW)
h	Enthalpy (kJ/kg)
D	Equivalent tube outer diameter (m)
H	Convective heat transfer rate (W/m^2 K)
λ	Thermal conductivity (W/m K)
μ	Viscosity (kg/ms)
Pr	Prandtl number
T	Temperature (K)
G	Mass flux (kg/m^{2}s)
ρ	Density (kg/m^3)
d	Equivalent tube inner diameter
L	Equivalent tube length (m)
Re	Reynolds number
Nu	Nusselt number
S	Nucleate boiling correction factor
E	Film boiling correction factor
M	Molar mass (kg/k mol)
f	Mass fraction
m	Mass flow rate (kg/s)
γ	Equivalent tube thickness (m)

Subscripts

exh	Exhaust
g	Gas state
tp	Two-phase state
a, x, b	State point for exhaust gas
water	Water
nb	Nucleate boiling

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ph Preheated state
2, 3, 4 State point for cooling water

INTRODUCTION

In recent years, the development of modern industry has made the energy consumption of non-renewable energy increase dramatically, and the contradiction between energy supply and demand becomes more and more serious. The automotive industry is one of the pillar industries in China, with car ownership increasing year by year, and the proportion of the total energy consumption of each industry becomes higher and higher, which makes the energy problem more and more serious. With the development of automotive electronics, the electronic products in automobiles continue to increase, the electric load is becoming larger and larger and the electric dependence is also getting stronger; however, the efficiency of the power generation system of the vehicle is very low.[1,2] More than 40% of the heat produced in automobiles is discharged into the surroundings. Thermoelectric power generation (TEG) is one of the effective ways to solve this problem of energy consumption, as they can recover the waste heat energy of the engine exhaust and provide power for the power consumption components of the vehicle.[3] If 10% of the exhaust gas waste heat energy is recovered by the TEG, the total amount of energy saved will be huge.[4,5]

The temperature differences between the TEG hot-end and cold-end converts thermal energy into electric energy based on the Seebeck effect of the thermoelectric material.[6] There have been extensive studies of the effect on the performance of TEG power generation.[7–10] However, there is still a lack of research done on light-weight TEG cold-ends. The traditional vehicle exhaust TEG system uses the engine cooling system to dissipate heat and keep the TEG cold-end temperature low.[11] Although this structure is compact, the TEG weight and space occupied are large. In this study, the independent cooling circuit is designed with heat transfer by phase change which could control the TEG cold-end temperature more efficiently and stably. To achieve the coordination of temperature field and flow field in the cooling circuit, the influence of the water thickness in the normal direction of the cold-end surface (WTNCS) on the TEG power output characteristics and the energy consumption of the system are studied. Under the premise of ensuring the TEG maximum net output power and reducing the TEG water consumption as much as possible, the optimization of the WTNCS has been studied, resulting in lighter weight, less space occupied and better automobile fuel economy.

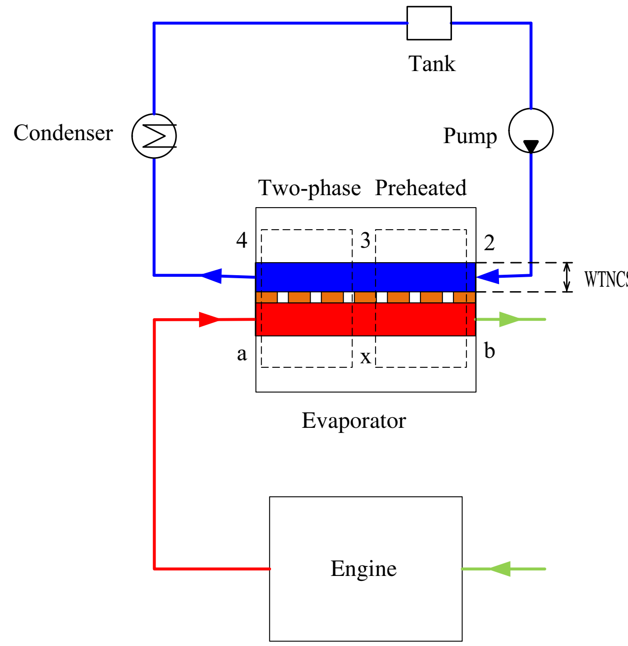

Fig. 1. TEG exhaust system schematic diagram.

SYSTEM DESCRIPTION

The schematic diagram of the vehicle exhaust TEG is shown in Fig. 1. Table I gives the detailed specification of the tested diesel engine. The exhaust gas temperature from the engine is up to 200–600°C,[3] the high-temperature engine exhaust flows into the evaporator, and a part of the heat energy is converted into electrical energy by the thermoelectric module. In this paper, Bi_2Te_3 is regarded as the thermoelectric (TE) material, whose hot-end can withstand the highest temperature of 380°C. The cold-end can withstand the temperature in the range of 20–110°C. There are 105 thermoelectric cells in total, which are in series arranged in the direction of the exhaust in the evaporator. The TEG hot-end is in contact with the engine exhaust and the cold-end is in contact with the cooling loop water. When the WTNCS is too small, the water resistance is large and the power consumption is large, but when the WTNCS is too large, then the water consumption is large.

The working process of the TEG system for the recovery of engine exhaust energy is as follows: the fresh air is mixed with the fuel, and then the air–fuel mixture is compressed to combustion in the cylinder and produces high-temperature exhaust gas, which flows through the turbine, and at the turbine outlet its temperature is up to 200–600°C. Later, the high-temperature exhaust gas flows into the evaporator and there is countercurrent heat transfer with the cooling loop water. The cooling water absorbs heat from the increased temperature and there is a phase change to gas, then the exhaust gas heat is released and temperature decreases, as the TEG hot-ends are in contact with the exhaust

Table I. Diesel engine parameters

Items	Value	Unit
Displacement	9726	ml
Cylinder diameter	126	mm
Stroke	130	mm
Rated speed	2100	r/min
Maximum torque	1500	N m
Rated power	280	kW
Compression ratio	17	/

gas, and the cold-ends are in contact with the cooling loop water. Thus, there are temperature differences between the hot-ends and cold-ends, and, according to the Seebeck effect, a part of heat energy will be converted into electric energy by the TEG system. In the preheated zone, the cooling water is changed from sub-cooled liquid of state 2 into the saturated liquid of state 3, and meanwhile the exhaust gas from the state x heat releases to the state b. In the two-phase zone, the saturated liquid of state 3 continues to absorb heat and gradually the phase changes to saturated gas of state 4, and meanwhile the exhaust gas from the state a heat releases to state x. Taking the optimal and stable TEG cold-end temperature in the two-phase zone into account, the cooling loop water temperature at the state 2 is set to 353.15 K, the evaporation pressure is set to 57.86 kPa, and the cooling loop water is set to the saturated gas at the outlet of the evaporator. The cooling loop water working parameters are configured above.

MATHEMATIC MODEL

Thermoelectric Module Model

The thermoelectric module realizes the conversion of heat energy into electrical energy directly based on the Seebeck effect. The schematic diagram of a typical thermoelectric module is shown in Fig. 2. The hole (P-type) and electron (N-type) semiconductor thermoelectric material are connected at one end, which forms a PN junction. The holes concentration in the hot-end of the P-type material is higher than at its cold-end and the electronics concentration in the hot-end of the N-type material is higher than its cold-end. Therefore, under the driving of the concentration gradient, the holes and electrons begin to spread to the cold side, thereby forming the electric voltage.

$$V = n\alpha(T_h - T_c) \tag{1}$$

Here, $\alpha = \alpha_P - \alpha_N$, α_P and α_N represent the Seebeck coefficients of the positive and negative legs, respectively.

In order to recover the exhaust energy, an external load R_L is essential. The electrical current in the circuit can be calculated by

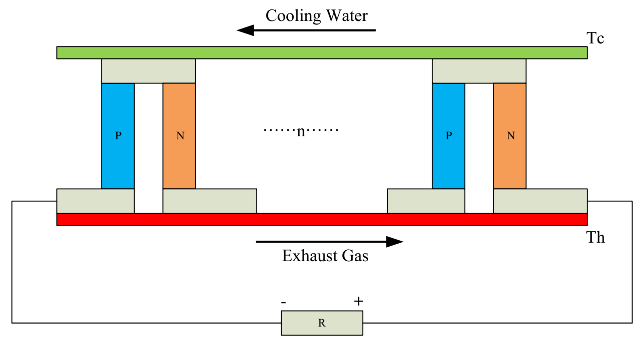

Fig. 2. Schematic diagram of a typical thermoelectric module.

$$I = \frac{n\alpha(T_h - T_c)}{R_L + R_{in}} \tag{2}$$

where R_{in} is the internal electrical resistance of the module which can be calculated by:

$$R_{in} = n\left[\frac{\rho_P L_P}{A_p} + \frac{\rho_N L_N}{A_N}\right] \tag{3}$$

where A_N and A_p are the legs from which the cross-section area of the ceramic insulation can be found, L_P, L_N are the leg heights of P-type and N-type legs.

Supposing the P-type and N-type TE materials average thermal conductivity are λ_P and λ_N, respectively, the P-type and N-type thermal conductance are calculated by

$$K_P = \frac{\lambda_P A_P}{L_P}, \quad K_N = \frac{\lambda_N A_N}{L_N} \tag{4}$$

The ceramic cover thermal conductance in the hot-end and cold-end are

$$K_{\mathrm{CH}} = \frac{\lambda_{\mathrm{CH}} A_{\mathrm{CH}}}{L_{\mathrm{CH}}}, \quad K_{\mathrm{CC}} = \frac{\lambda_{\mathrm{CC}} A_{\mathrm{CC}}}{L_{\mathrm{CC}}} \tag{5}$$

Assuming the hot-end and cold-end thermal conductance are K_H and K_C, respectively, the hot-end and cold-end total thermal conductance can be calculated by

$$\begin{aligned} \frac{1}{K_{\mathrm{H}}} &= \frac{1}{K_{\mathrm{CH}}} + \frac{1}{K_{\mathrm{CCH}}} + \frac{1}{K_{\mathrm{SH}}} \\ \frac{1}{K_{\mathrm{C}}} &= \frac{1}{K_{\mathrm{CC}}} + \frac{1}{K_{\mathrm{CCC}}} + \frac{1}{K_{\mathrm{CH}}} \end{aligned} \tag{6}$$

Here, K_{CH}, K_{CCH} and K_{SH} are the hot-end ceramic cover thermal conductance, the contact layer thermal conductance and the cooling circuit thermal conductance, respectively. K_{CC}, K_{CCC} and K_{SC} are the cold-end ceramic cover thermal conductance, the contact layer thermal conductance and the cooling circuit thermal conductance, respectively.

Evaporator Heat Transfer Model

In order to study the heat transfer characteristics of the vehicle exhaust TEG system and the TEG cold-end temperature characteristics, the evaporator heat transfer model has been established.

Assuming that the exhaust temperature at state b is known, the enthalpy of the exhaust at that point can be obtained, and then, according to the law of conservation of energy, the heat transfer rate can be determined by the following formula[12]:

$$Q_{\text{total}} = m_{\text{exh}}(h_a - h_b) = m_{\text{water}}(h_4 - h_2) \quad (7)$$

$$Q_{\text{tp}} = m_{\text{exh}}(h_a - h_x) = m_{\text{water}}(h_4 - h_2) \quad (8)$$

$$Q_{\text{ph}} = m_{\text{exh}}(h_x - h_b) = m_{\text{water}}(h_3 - h_2) \quad (9)$$

As for the exhaust side of the evaporator, the convective heat transfer coefficient can be calculated with the Dias and Young correction (single phase gas).[13]

$$\frac{DH_{\text{exh}}}{\lambda_{\text{exh}}} = 0.1378\left(\frac{DG_{\max}}{\mu_{\text{exh}}}\right)^{0.718}\text{Pr}_{\text{exh}}^{\frac{1}{3}}\left(\frac{\xi}{\delta}\right)^{0.296} \quad (10)$$

The pre-heated zone convection heat transfer coefficient of the cooling water side, according to the formula Tate Sieder (single phase liquid) is[14,15]:

$$Nu_f = 1.86\left(\text{Re}_f\text{Pr}_f\frac{d}{L}\right)^{\frac{1}{3}}\left(\frac{\mu_f}{\mu_w}\right)^{0.14} \quad (11)$$

For the cooling water in the two-phase zone, the convective heat transfer coefficient can be calculated by the Liu and Winterton correction[14] (two phase liquid).

$$H_{\text{tp}} = \sqrt{(EH_{f0})^2 + (SH_{\text{nb}})^2} \quad (12)$$

The correction factor for the film boiling is:

$$E = \left[1 + w\text{Pr}_l\left(\frac{\rho_l}{\rho_g} - 1\right)\right]^{0.35} \quad (13)$$

The convective heat transfer coefficient for the film boiling[16] is:

$$H_{f0} = \frac{0.023\text{Re}_{\text{f0}}^{0.8}\,\text{Pr}_{\text{f}}^{0.4}\,\lambda_{\text{f}}}{d} \quad (14)$$

The correction factor for the nucleate boiling is:

$$S = \frac{1}{1 + 0.055\ \text{E}^{0.1}\text{Re}_{f0}^{0.16}} \quad (15)$$

The Reynolds number corresponding to the saturated liquid state is expressed by

$$\text{Re}_{f0} = \frac{G(1-w)d}{\mu_l} \quad (16)$$

The convective heat transfer coefficient for the nucleate boiling[16] is:

$$H_{\text{nb}} = 55\left(\frac{P}{P_{\text{cr}}}\right)^{0.12}\left(-\log_{10}^{\frac{P}{P_{\text{cr}}}}\right)^{-0.55} M^{-0.5}q\prime\prime_w^{2/3}. \quad (17)$$

Thermal Model of the Exhaust Gas

The average chemical formula of diesel fuel is $C_{12}H_{23}$, the main components in the exhaust gas of a diesel engine are CO_2, H_2O, N_2 and O_2, and the combustion process of diesel fuel mixed with air can be described in the following chemical equation:

$$\begin{aligned} &x\text{C}_{12}\text{H}_{23} + y(\text{O}_2 + 3.76\text{N}_2) \rightarrow 12x\text{CO}_2 \\ &\quad + 11.5x\text{H}_2\text{O} + 3.76y\text{N}_2 + (y - 17.75)\text{O}_2 \end{aligned} \quad (18)$$

The mass fractions of these components vary with the engine's operating condition. When the vehicle engine operates at steady state, the injected fuel quantity and the intake air amount can be measured on the vehicle engine test bench. Then, the corresponding mass fraction of each component can also be determined. If the exhaust temperature and pressure are measured, the specific enthalpy and the specific heat at constant pressure and the density for component i (i represents CO_2, H_2O, N_2, O_2) can be computed by REFPROP.[17] According to the ideal gas mixture enthalpy, the calculation method of the exhaust enthalpy value can be obtained by:

$$[h_i, c_{p,i}, \rho_i] = f(T_{\text{exh}}, P_{\text{exh}}, i) \quad (19)$$

$$h_m = \sum_{i=1}^{4} mf_i h_i \quad (20)$$

$$c_{p,m} = \sum_{i=1}^{4} mf_i c_{p,i}. \quad (21)$$

Cooling Water Flow Resistance Model and Water Pump Energy Consumption Model

The flow resistance of the cooling loop water has a great effect on the energy consumption of the system. When the WTNCS is too small, the flow resistance and water pump power consumption increase, and when the WTNCS is too large, although the cooling water flow resistance is small, the water flow is large and the use of the upper water is inadequate. Therefore, it is necessary to establish a flow resistance model of cooling loop water.

The pipeline flow resistance includes frictional resistance and local resistance:

$$h = h_f + h_\varsigma \quad (22)$$

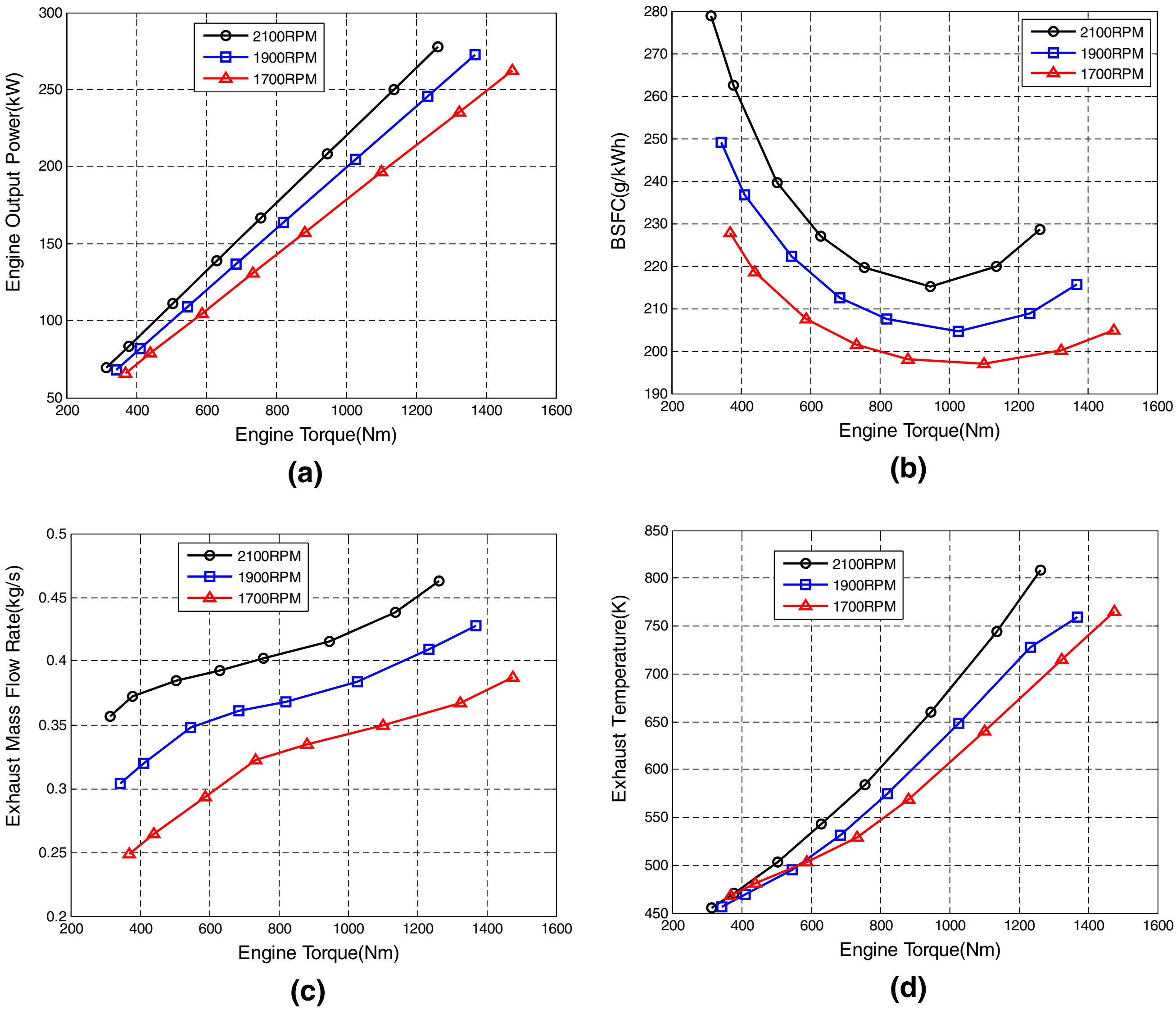

Fig. 3. Engine related features: (a) engine effective power; (b) engine brake-specific fuel consumption (*BSFC*); (c) exhaust mass flow rate; (d) exhaust temperature at engine outlet.

The cooling system water pump shaft power is:

$$P = \frac{\rho g Q h}{\eta}. \tag{23}$$

Engine Characteristics

The tested engine performances are shown in Fig. 3. As shown in Fig. 3a, the engine effective power increases with both engine speed and load, and at the rated power point the effective power is reached at 277.9 kW. The engine brake-specific fuel consumption is shown in Fig. 3b. The exhaust mass flow rate is the sum of intake air mass flow rate and fuel consumption rate which is shown in Fig. 3c. The exhaust mass flow rate increases slowly with the increase of engine load, but it varies greatly with the different speed of the engine, which is because the increase of the engine load is mainly dependent on the improvement of the injected fuel quantity, while the intake air mass flow rate is basically kept constant for a steady engine speed. Figure 3d shows the exhaust temperature at the engine outlet. The exhaust temperature increases rapidly with the increase of engine load but slowly with the engine speed, which is because the combustion energy improves significantly due to the large quantity of injected fuel for a high engine load.

RESULTS ANALYSIS

Because this paper mainly studies the influence of the WTNCS on the power generation characteristics of the TEG system, the following only analyzes the engine speed as the 2100 rpm condition.

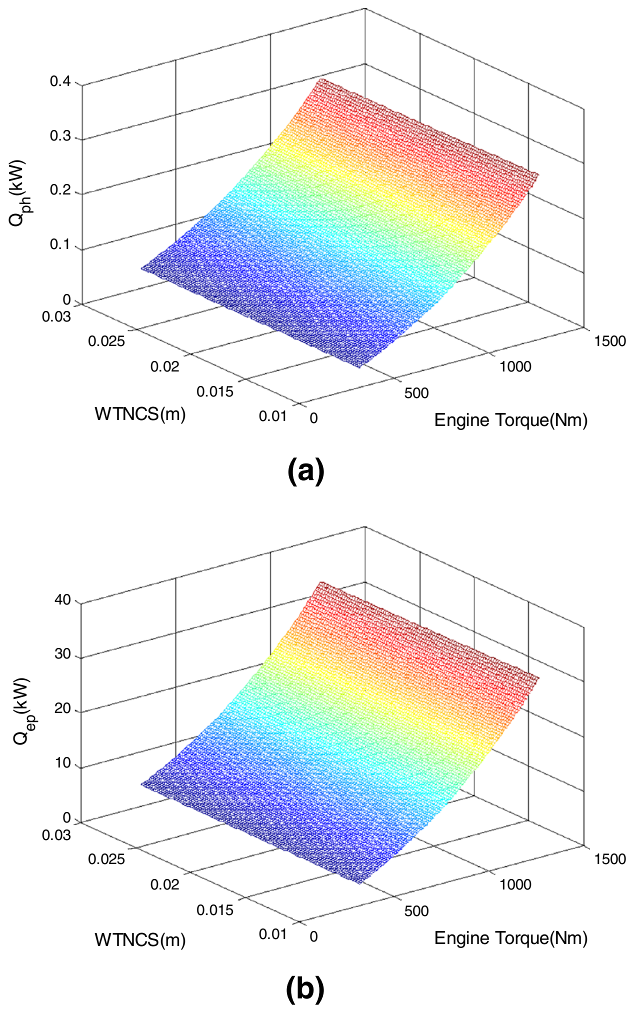

Fig. 4. Heat transfer rate of the TEG system. (a) Heat transfer rate of the preheated zone of the evaporator. (b) Heat transfer rate of the two-phase zone of the evaporator.

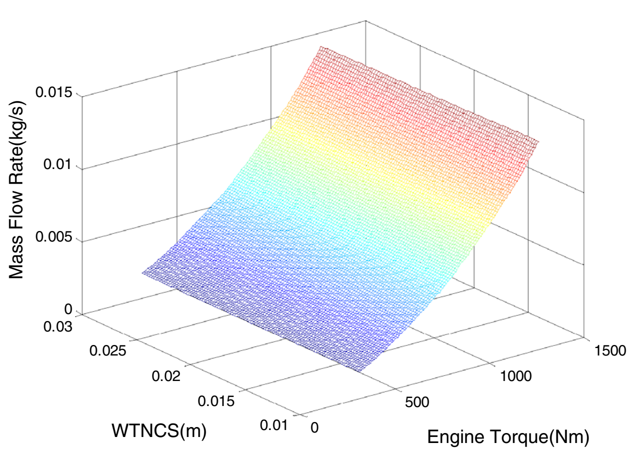

Fig. 5. Mass flow rate of the cooling water.

Heat Transfer Rate

The vehicle TEG system needs to work under different conditions of the engine, Therefore, under the premise of ensuring the high temperature of the TEG hot-end, the TEG cold-end should be cooled to a stable temperature by the cooling loop water.

The heat transfer rates for the preheated zone and the two-phase zone can be obtained by Eqs. 7–9, and the results are shown in Fig. 4. The variation of the heat transfer rate for the preheated zone is consistent with that of the two-phase zone across the common operating condition of the engine. The heat transfer rates are almost unaffected by the WTNCS. When the engine speed is constant, the heat transfer rates increase with the increase of engine load. This is because, in this paper, the thermodynamic parameters of the cooling water at states 2 and 4 are constant values. So the heat transfer rates of each zone are in proportion to the mass flow rate of the cooling loop water, and not affected by the WTNCS. When the engine load increases, in order to guarantee the temperature stability of the TEG cold-end, the mass flow rate of the cooling water must be increased. In addition, the heat transfer rate of the two-phase zone is far greater than that of the preheated zone. This is because of the set working parameters of the evaporator mentioned above. At the rated power point, the heat transfer rates of the two-phase zone reached 32.96 kW, but the heat transfer rate of the preheated zone is only 0.3 kW.

Mass Flow Rate of the Cooling Water

Assuming that there is no heat exchange between the evaporator and the outside environment, the enthalpy of the cooling water at states 2 and 4 can be obtained, and then the mass flow rate of the cooling loop water can be calculated by Eq. 7, and the result is shown in Fig. 5. The mass flow rate of the cooling water increases with the increase of the engine load, which has nothing to do with the WTNCS. The variation trend of the cooling water mass flow rate is consistent with the heat transfer rate of the two-phase zone. That can be explained because the cooling water mass flow rate is proportional to the heat transfer rate of the two-phase zone when the thermodynamic parameters of the cooling water are set. At the rated power point, the mass flow rate of the cooling loop water is 0.0144 kg/s.

Average Heat Transfer Coefficient

Based on the heat transfer model established above, the heat transfer coefficients of the exhaust side and the cooling water side can be obtained; the results are shown in Fig. 6. The variation trend of the exhaust heat transfer coefficient in the preheated zone is consistent with the two-phase zone. The heat transfer coefficient of the exhaust increases with the increase of engine load but is not affected by the WTNCS. At the rated power point of the engine, the average heat transfer coefficient of the exhaust in the preheated zone

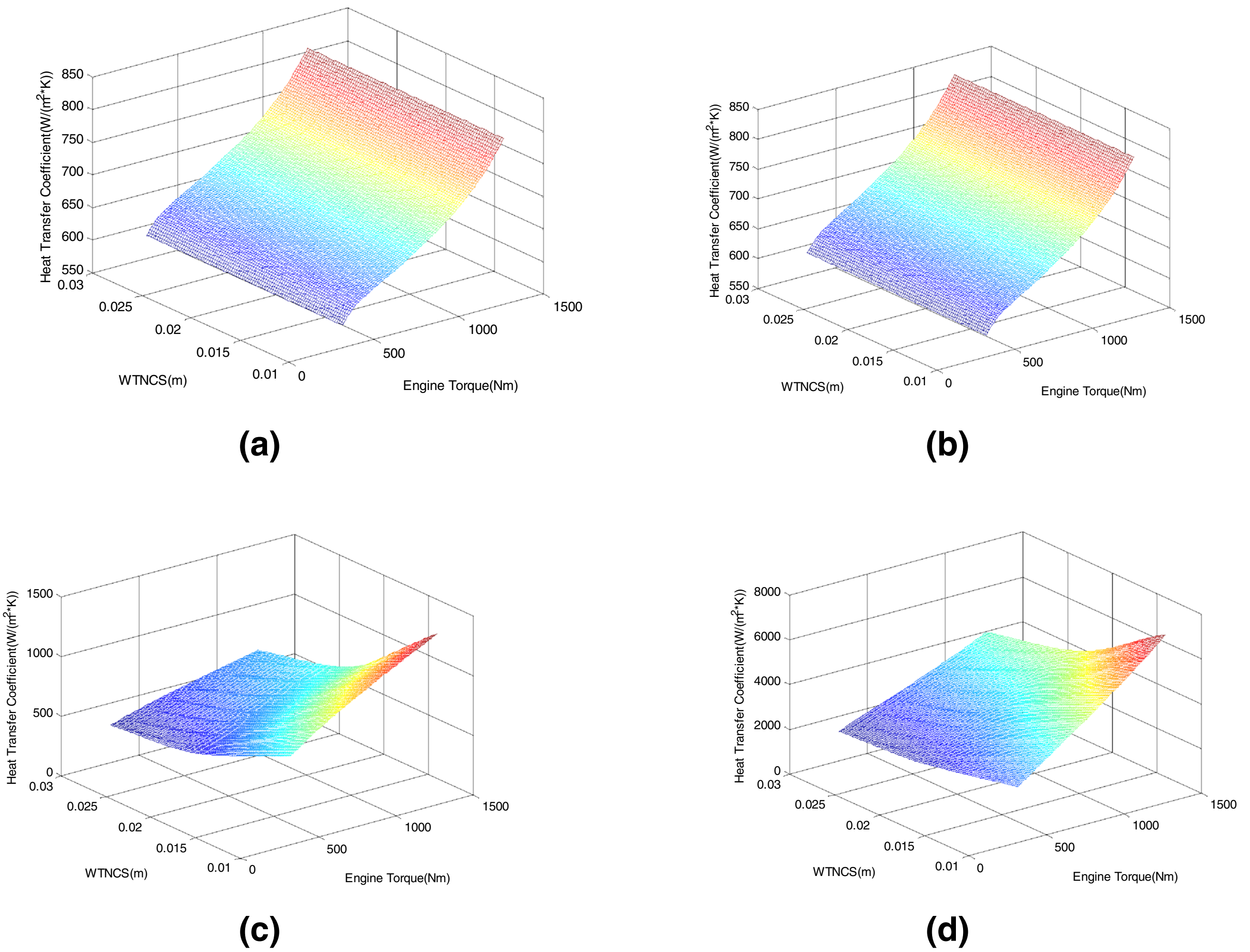

Fig. 6. Average heat transfer coefficient of the preheated zone and the two-phase zone. (a) Average heat transfer coefficient of the exhaust in preheated zone. (b) Average heat transfer coefficient of the exhaust in two-phase zone. (c) Average heat transfer coefficient of the cooling water in the preheated zone. (d) Average heat transfer coefficient of the cooling water in the two-phase zone.

and the two-phase zone are 805.3 W/(m^2 K) and 819.36 W/(m^2 K), respectively. The variation trend of the cooling water heat transfer coefficient in the preheated zone is also consistent with the two-phase zone and they are affected by the engine load and WTNCS. When the engine load is constant, the average heat transfer coefficient of the cooling water decreases with the increase of the WTNCS. When the WTNCS is constant, the average heat transfer coefficient of the cooling water increases with the increase of the engine load. The maximum heat transfer coefficient of the cooling water in the preheated zone and the two-phase zone are 1433.1 W/(m^2 K), 7553.4 W/(m^2 K), respectively.

Heat Transfer Area

The heat transfer area of the preheated zone and the two-phase zone are shown in Fig. 7, from which it appears that, when the engine load is certain, the heat transfer area of the preheated zone increases with the increase of the WTNCS. This shows that the smaller the WTNCS, the shorter the preheated zone, while the two-phase zone become longer, which results in a better cooling ability of the evaporator. This is because the average heat transfer coefficient decreases with the increase of the WTNCS, and the total heat transfer coefficient of the preheated zone becomes larger but the heat transfer rate is constant, so the heat transfer area of the preheated zone decreases. When the WTNCS is constant, the heat transfer area of the preheated zone decreases with the increase of the engine load. This can be explained because the average temperature difference between the exhaust gas and the cooling loop water in the evaporator increases, but the total heat transfer coefficient changes very little, so the heat transfer area of the preheated zone decreases. The heat transfer area affected by the change of engine load and WTNCS is very small. This is mainly because the heat transfer area of preheated zone is too small, and the heat transfer area of the two-phase zone almost occupies the whole heat transfer area of the evaporator. The

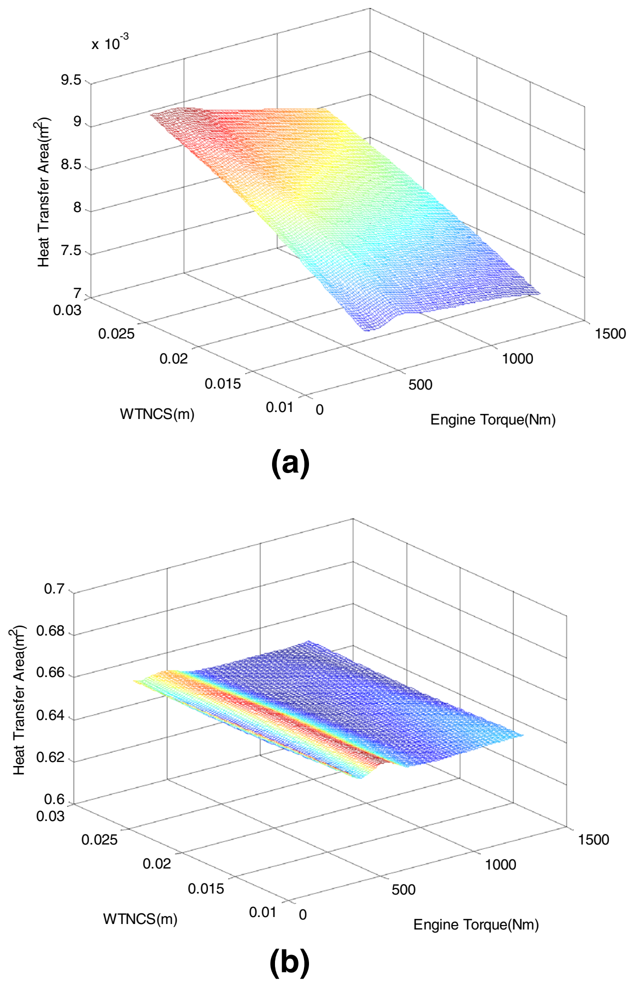

Fig. 7. Heat transfer areas of the preheated zone and the two-phase zone. (a) Heat transfer area of the preheated zone. (b) Heat transfer area of the two-phase zone.

maximum heat transfer areas of the preheated zone and the two-phase zone are 0.6535 m^2 and 0.009 m^2, respectively.

Average Temperature of Thermoelectric Modules

After the heat transfer rate in each zone and the heat transfer coefficient are obtained, the TEG cold-end and hot-end average temperatures can be calculated by Newton's law of cooling. The variation of the average temperature of the TEG hot-end and cold-end are shown in Fig. 8. It can be seen that the average temperature change trend of the hot-end in the preheated zone and the two-phase zone are basically the same. The TEG hot-end temperature is not affected by the WTNCS, but it increases with the increase of engine load. The reason can be explained as below: the injection quantity of the fuel increases as the engine load increase, which results in the temperature increases of the engine exhaust gas. At the rated power point, the TEG hot-end average temperature in the preheated zone and the two-phase zone are 540.9 K and 554.6 K, respectively.

The change trend of the cold-end average temperature of the preheated zone and the two-phase zone are also basically the same. When the engine load is certain, the average temperature of the cold-end in the preheated zone increases with the increase of the WTNCS, and the TEG cold-end average temperature in the preheated zone are greatly influenced by the WTNCS. This is because, when the WTNCS increases, the cooling water side heat transfer coefficient of the preheated zone and the two-phase zone are both decreased, while the heat transfer rates of each zone remain unchanged, in order to ensure the average temperature of the cooling water in the preheated zone and the two-phase zone are constant, the TEG cold-end temperature should be increased. When the WTNCS is constant, the TEG cold-end average temperature increases with the increase of the engine load, and the average temperature of the two-phase zone is lower than that of the preheated zone. This is mainly due to the average heat transfer coefficient of the cooling water from the preheated zone to the two-phase zone have large increases, but the average temperature of the cooling water in the preheated zone and two-phase zone show little difference. The TEG cold-end maximum temperature in the preheated zone and the two-phase zone are 413.47 K and 371.29 K, respectively.

Volume of the Cooling Loop Water

The TEG cold-end cooling water pipe in the evaporator is rectanglar, and its equivalent length is 5.88 m and the width is 0.056 m, assuming that the cooling water fills the entire pipe when the TEG works. In addition to the evaporator, the volume of water in the other pipes is 2.5 L. The water consumption of the whole cooling water circuit is shown in Fig. 9. It can be seen that the water consumption of the cooling water circuit is proportional to the WTNCS, which has nothing to do with the engine operating conditions. This is mainly because the cooling water is filled with the whole cooling pipe, so the cooling water consumption is only related to the WTNCS. When the WTNCS is 0.03 m, the cooling water consumption is 12.39 L.

When the water consumption becomes smaller, the weight of the vehicle will be reduced and the fuel economy of the vehicle will improve. When the WTNCS is 0.02 mm, compared with the non-optimized structure the fuel consumption is reduced as shown in Fig. 10. The saved fuel consumption is proportional to the vehicle speed: when the vehicle speed is 60 km/h, the saved fuel consumption is 0.18 L/h.

Resistance Loss of the Cooling Loop Water

The cooling pipe flow resistance model can be used to obtain the resistance power characteristics

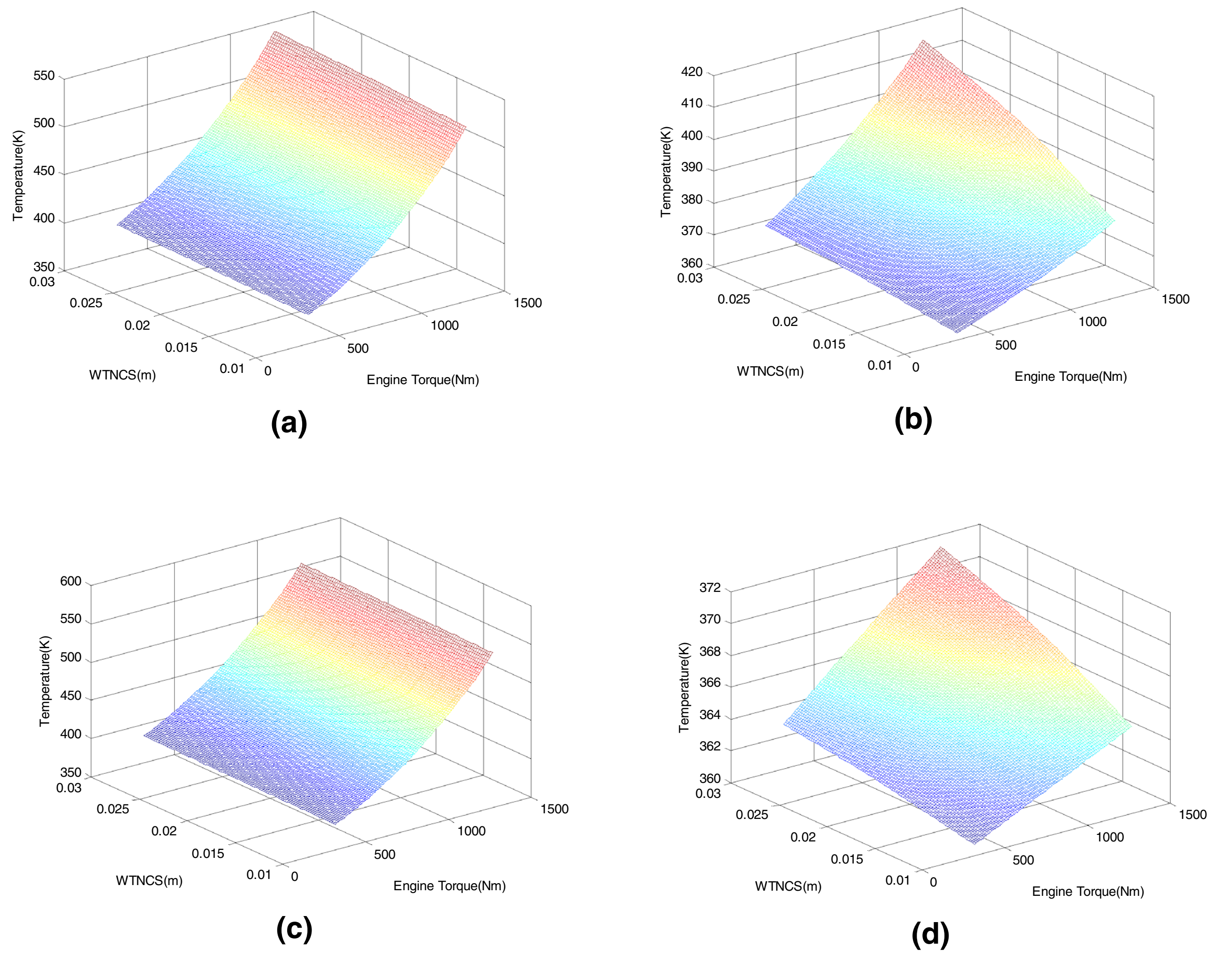

Fig. 8. Average temperature of the thermoelectric module at both ends. (a) TEG hot-end average temperature (preheated zone). (b) TEG cold-end average temperature (preheated zone). (c) TEG hot-end average temperature (two-phase zone). (d) TEG cold-end average temperature (two-phase zone).

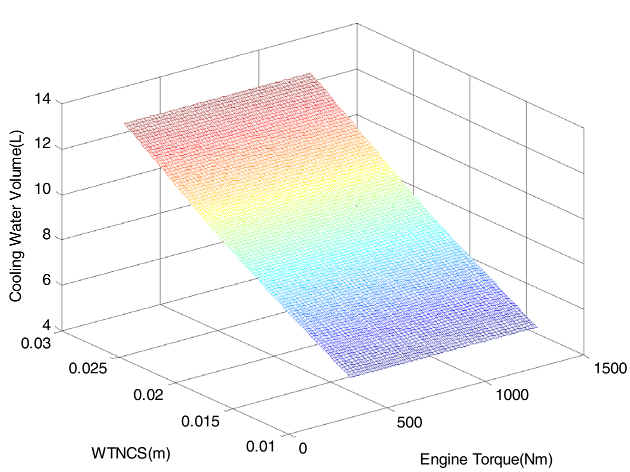

Fig. 9. Volume of the cooling loop water.

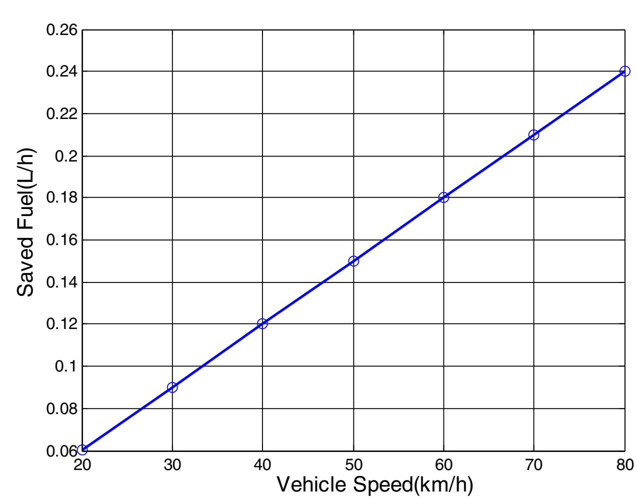

Fig. 10. Saved fuel consumption.

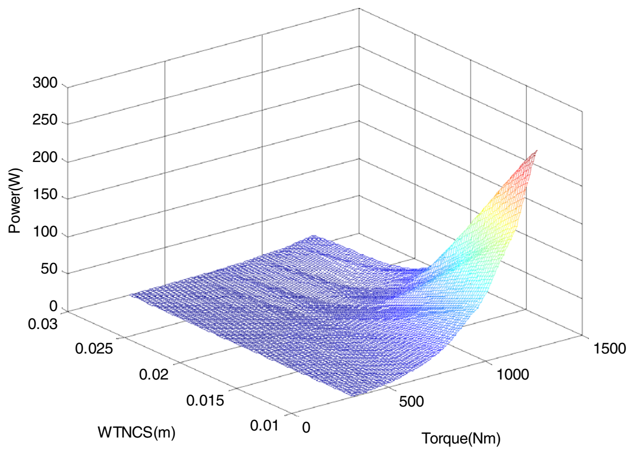

Fig. 11. Resistance loss of the cooling loop water.

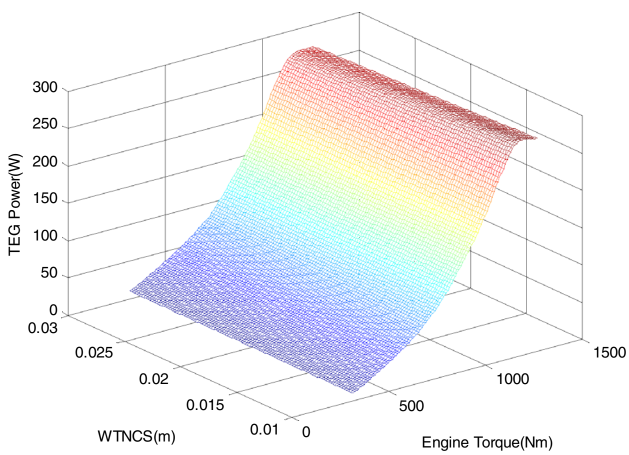

Fig. 12. Overall power generated by the thermoelectric module.

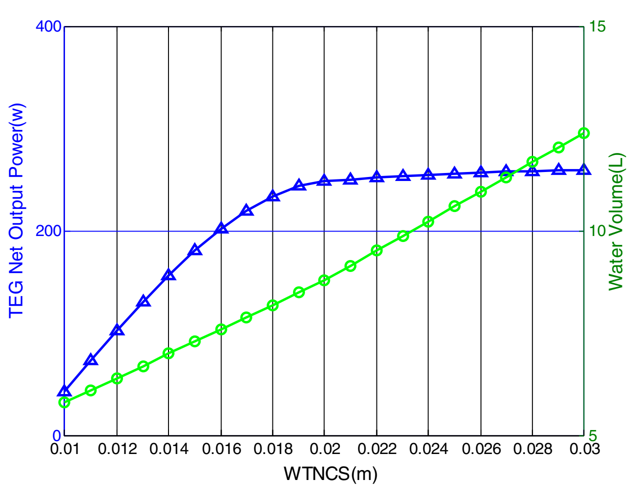

Fig. 13. Matching of net power and system water consumption.

of the cooling pipe, as shown in Fig. 11. When the WTNCS is less than 0.02 m and the engine works in the high load region, the pipeline flow resistance increases rapidly. When the WTNCS is greater than 0.02 m, the pipeline flow resistance is small, and it is hardly affected by the WTNCS and engine load. This is because, when the WTNCS is less than 0.02 m and the engine works in the high load region, the flow velocity of the cooling water in the evaporator is high and the resistance loss is large. When the WTNCS is more than 0.02 m, the flow velocity of the cooling water in the evaporator is very small, and the resistance loss is small. The maximum resistance power of the cooling water is 243 W.

Overall Power Generated by the Thermoelectric Module

In this study, Bi_2Te_3 was chosen as the thermoelectric module, and its hot-end is in contact with the engine exhaust and its cold-end is cooled by the cooling loop water keeping the cold-end temperature stable. As can be seen from Fig. 7, the heat transfer area of the preheated zone is very small compared with the two-phase zone, so the power generated by the TEG in the preheated zone can be ignored. This paper only takes the thermoelectric modules that are arranged in the two-phase zone into consideration.

It is assumed that all the module hot-end temperatures in the two-phase zone are equal to the hot-end average temperature of the whole modules. The power generated by a module can be obtained after gaining its cold-end and hot-end temperatures, which when multiplied by the number of thermoelectric modules in the two-phase zone, is the overall power, as shown in Fig. 12. The overall generation power increases with the increase of the engine load, and increases with the decrease of the WTNCS. This can be explained because when the engine load increases, the exhaust temperature increases, but the cooling water temperature is constant, and the temperature difference between the hot-end and the cold-end of the thermoelectric module becomes large, resulting in an increase of power generation. When the WTNCS decreases, the heat transfer coefficient of the two-phase zone increases, while the temperature of the cooling water of the two-phase zone is constant, which results in the temperature decrease of the cold-end, and the temperature difference between the hot-end and cold-end of the thermoelectric module becomes large resulting in an increase of power generation. The maximum power generation of the thermoelectric modules is 289.4 W.

WTNCS Optimization

Figure 13 shows the variation characteristics of the TEG net output power with the WTNCS when the engine works at its rated power condition and the variation characteristics of system water consumption with the WTNCS. As can be seen, when the WTNCS is less than 0.02 m, both the TEG net output power and the system water consumption were affected by WTNCS, but the system output power is more affected by the WTNCS. When the WTNCS is more than 0.02 m, the TEG net output power hardly affected by the WTNCS, but the system water consumption is also proportional to the WTNCS, the system water consumption increased with the increase of WTNCS. Considering the water consumption and TEG net output power, 0.02 m is the best value of WTNCS. Under this condition, when the engine works in different conditions, the water pump power and the system water consumption reach a balance. When the WTNCS is 0.02, the system water consumption is 8.8 L.

CONCLUSIONS

This article analyzes a vehicle's TEG WTNCS influence on the generative performance for recovering engine exhaust heat energy. The heat transfer model between the exhaust gas and the cooling water and the model of the cooling pipe flow resistance have been established. Based on the above analysis, we can draw the following conclusions:

1. The thinner the WTNCS, the smaller the water consumption, while the flow resistance of the cooling water in the evaporator becomes larger. In order to reduce the water consumption and ensure the TEG maximum net output power, the optimal value of the WTNCS is 0.02 m and the maximum net output power is 258.7 W.
2. When the WTNCS is 0.02 m, the water consumption is 8.8 L. Compared with the traditional TEG structure, the water consumption decreased by about 39.5% and this can save fuel of 0.18 L/h when the vehicle works at the speed of 60 km/h.
3. When the WTNCS decreases, the TEG hot-end temperature is almost unaffected, but the cold-end temperature decreases and the temperature difference between the hot-end and the cold-end of the TEG becomes larger, which results in the generated power of the TEG increasing. When the WTNCS is 0.02 m, compared with the traditional TEG structure, at the rated power point of the engine, the TEG cold-end temperature decreases from 98.1°C to 92.4°C, and the TEG generated power increased by about 1%.

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