Analysis of the Cylinder Block Thermal Condition of a Mining Truck Diesel Engine

Li Ruoting*,1, Sun Zhixin1, Guo Mengchao2 and Hu Junbiao3

[1]*Department of Mechanical Engineering, Academy of Armored Force Engineering, Beijing 100072, P.R.China*
[2]*Xi'an Military Representative Bureau of General Armament Department, Xi'an 710032, P.R.China*
[3]*Xi'an Office, Vehicle and Ship Representative Bureau, General Armament Ministry, Xi'an 71004, P.R.China*

Abstract
To study the heat distribution in the chief heated parts and cooling water for each cylinder in a mining truck diesel engine, a working process model of the diesel engine coupled with cooling system was established. Engine test results shows that the error of the model is less than 5%. The temperatures of each cylinder head, piston, cylinder liner and cooling water flowing around the cylinder liners and cylinder heads were calculated with the coupled simulation model. Results show that: the temperatures of chief heated parts are not uniform, so as the cooling water's. The surface temperature of the fifth piston is the highest and the maximum temperature difference is 40.7 ºC among the pistons. The temperatures of the first cylinder head and cylinder liner are the highest, and the maximum temperature difference are 169.6 ºC and 129.6 ºC among them. The cooling water temperature of the fifth cylinder head and cylinder liner are the highest, which reach 108.6 ºC and 105.3 ºC under the external characteristic condition of 1400 r/min, 15.3 ºC and 12 ºC higher respectively than the diesel engine outlet water temperature which is 93.3 ºC.
Key words: MINING TRUCK, DIESEL ENGINE, THERMAL CONDITION, SIMULATION, HEAT TRANSFER

1. Introduction

Mining truck diesel engines are mostly cooled by water. The temperature of the cooling water through the outlet of the water jacket is an important sign of the thermal condition of the cooling system. In general when the engine is working properly, the temperature of the cooling water should be within 70~90 ºC. The maximum value allowed to run for a short while is 105 ºC. Nevertheless the temperature and mass flux of the cooling water are not uniform in different pipes owing to the structure of the engine and cooling system. The heat exchanges between the cooling water and the engine cylinder heads or cylinder lines are varied. As a result, the water temperature in the water jacket changes much in different location. In some region the water temperature could exceed the limit point and do harm to the engine.

In recent years, many calculation studies were carried on the mass flow and heat transfer of the cooling water in the diesel engine, such as the liquid mono-phase flow and liquid-gas two-phase flow in the water jacket [1], heat transfer coupled of the liquid and solid parts [2], integration of the one-dimensional and three-dimensional simulation [3]. The velocity fields of the cooling water as well as the temperature field of the heated parts were provided to optimize the design of the cooling system. But these models didn't couple the main parts of the system with the cooling water. It means that those researchers studied the thermal condition of the main parts regardless of the actual flow route of the water in the engine.

In this paper a model coupled the working process with cooling system of a diesel engine is established to study the thermal condition of the heated parts and the cooling water. The water route is considered in this model and diesel engine tests have been conducted.

2. Calculating Theories of The Flow and Heat Transfer in the Engine

2.1. Liquid Flow and Heat Transfer in a Pipe

The equations on liquid flow in a pipe have two parts: 1) gas flow and heat transfer in the intake pipe and exhaust pipe; 2) liquid flow and heat transfer in the cooling system.

Pipe system was divided into many control volumes by one-dimensional interleaving grid. In the control volume limited-volume method was used to calculate the parameters which were One-dimensional non-constant values. Scalar quantity parameters were calculated in the center of the grid. For example, pressure, temperature, etc. Vector parameters were calculated on the interface of the grids, for example, velocity, mass flow rate, etc. Basic equations are listed below [4]:

Fluid continuity equation:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \sum_{boundaries} \dot{m} \quad (1)$$

Fluid energy conservation equation:

$$\frac{\mathrm{d}(me)}{\mathrm{d}t} = p\frac{\mathrm{d}V}{\mathrm{d}t} + \sum_{boundaries}(\dot{m}H) - h_a A_s\left(T_{\mathrm{fluid}} - T_{\mathrm{wall}}\right) \quad (2)$$

Fluid enthalpy equation:

$$\frac{d(\rho HV)}{dt} = \sum_{boundaries}(\dot{m}H) + V\frac{dp}{dt} - h_a A_s\left(T_{fluid} - T_{wall}\right) \quad (3)$$

Fluid momentum equation:

$$\frac{\mathrm{d}\dot{m}}{\mathrm{d}t} = \frac{\mathrm{d}pA + \sum_{boundaries}(\dot{m}u) - 4k_{\mathrm{f}}\frac{\rho u|u|}{2}\frac{\mathrm{d}xA}{D} - k_{\mathrm{p}}\left(\frac{1}{2}\rho u|u|\right)A}{\mathrm{d}x} \quad (4)$$

In the equation:
$\dot{m}$ – mass flow rate between boundaries;
m – mass of the volume;
V – volume;
P – pressure;
ρ – density;
A – circulation area (cross section);
e – total internal energy in specific mass;
H – total enthalpy;
h_a – heat transfer coefficient;
T_{fluid} – fluid temperature in the pipe;
u – flowing velocity of the boundary layer;
T_{wall} – wall temperature of the pipe;
k_{f} – wall friction coefficient of the pipe;
– pressure loss coefficient of the pipe;
D – equivalent diameter of the pipe.
The heat transfer through wall of the pipe was calculated by the Colburn similarity theory:

$$h_{\mathrm{g,slick}} = (\tfrac{1}{2})C_{\mathrm{f,slick}}\rho U_{\mathrm{eff}} c_{\mathrm{p}} Pr^{\left(-2/3\right)} \quad (5)$$

In the equation:
$h_{\mathrm{g,slick}}$ – heat transfer coefficient of the smooth wall;
$C_{\mathrm{f,slick}}$ – friction coefficient of smooth wall;
ρ – density of the fluid;
U_{eff} – free flow velocity of the outer edge of boundary layer;
c_{p} – specific heat at constant pressure;
Pr – Prandtl number.

Surface roughness of the wall has great affection on the heat transfer rate. The heat transfer coefficient rough surface is based on the coefficient of the smooth wall and be corrected by the followed equation.

$$h_{\mathrm{g,rough}} = h_{\mathrm{g,slick}}\left(\frac{C_{\mathrm{f,rough}}}{C_{\mathrm{f,slick}}}\right)^{r} \quad (6)$$

In the equation:
$h_{\mathrm{g,rough}}$ – heat transfer coefficient of rough pipe;
$C_{\mathrm{f,rough}}$ – friction factor of rough pipe;
r – exponent.

2.2. Heat Transfer Model in the Cylinder

The combustion gas in the cylinder exchanges heat with the cylinder wall (bottom of the cylinder head, top of the piston and inner cover of the cylinder liner) continuously.

$$\frac{\mathrm{d}Q_{\mathrm{w}}}{\mathrm{d}\phi} = \frac{1}{6n}\sum_{i=1}^{3} h_{\mathrm{w}} \cdot A_i(T - T_{wi}) \quad (7)$$

In the equation,
n – engine speed;
h_{w} – heat transfer coefficient between the gas and the cylinder wall;
A_i – area of the inner wall of the cylinder;
T – instantaneous average temperature of the gas;
T_{wi} – instantaneous average temperature of each part of the wall.
The process of heat transfer between the gas and the cylinder wall is complex. It includes heat convection, heat conduction and heat radiation. The calculation accuracy is decided by the heat transfer coefficient h_{w}. In this paper, the Woschni semi-empirical formula is used.

$$h_{\mathrm{w}} = 820D^{-0.2} \cdot p^{0.8} \cdot T^{-0.53} \cdot \left[C_1 \cdot C_{\mathrm{m}} + C_2 \cdot \frac{T_{\mathrm{a}} \cdot V_{\mathrm{s}}}{p_{\mathrm{a}} \cdot V_{\mathrm{a}}}(p - p_0)\right]^{0.8} \quad (8)$$

In the equation:
D – diameter of the cylinder;
p – pressure of the gas in the cylinder;
T – temperature of the gas in the cylinder;
C_{m} – average velocity of the piston;

p_a, V_a, T_a – gas pressure, volume and temperature when compression is begun;
V_s – working volume of the cylinder;
p_0 – pressure in cylinder when the engine is reverse towing; C_1 – velocity coefficient;
C_2 – shape coefficient of the combustion chamber.

2.3. Heat Transfer in the Cylinder

The heat released from the hot burning gas transfers to the cylinder head and cylinder liner, then radiates to the air by the engine body or converts into the cooling water. Thermal balance sketch is shown in fig. (1).

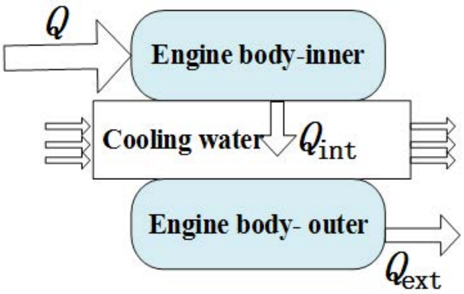


Figure 1. Thermal Balance in Cylinder

Temperature of the parts such as cylinder liners and cylinder heads are assumed to be uniform, and then the following equation can be obtained [5].

$$\frac{dT_{wall}}{dt} = \frac{Q - Q_{int} - Q_{ext}}{\rho_{wall} C_{p-wall} V_{wall}} \quad (9)$$

In the equation:
Q – the heat from the combustion gas to the engine;
Q_{ext} – the heat from the engine to the cooling water;
Q_{ext} – the heat from the engine to the air;
ρ_{wall} – the density of the engine;
$C_{p\text{-wall}}$ – the heat exchange rate of the engine;
V_{wall} – the volume of the engine body.

2.4. Heat Exchange of the Radiator

Heat exchange of the two sides of the radiator includes the heat exchange between the wall and the fluid, as well as heat transfer in the wall, as shown in fig. (2).

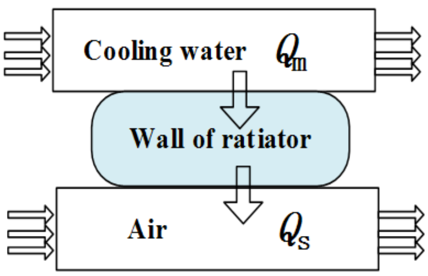


Figure 2. Heat Transfer of the Radiator

The specific heat of the radiator wall was considered when calculating the heat transfer in the wall. It means that the influence of the wall temperature fluctuation to the process of heat transfer was considered. The wall temperature was decided by the thermal balance equation of the fluid and the wall [5].

$$\frac{dT_{wall}}{dt} = \frac{Q_M + Q_S}{\rho V C_P} = \frac{(hA\Delta T)_M + (hA\Delta T)_S}{\rho V C_P} \quad (10)$$

In the equation:
ρ – density of the radiator wall;
V – volume of the radiator wall;
C_P – specific heat of the radiator wall;
h – heat transfer coefficient between the radiator wall and the fluid;
A – effective area of heat transfer with the cool fluid or the hot fluid;
ΔT – temperature difference between the radiator wall and the fluid;
Q_M – heat transfers from the hot fluid to the radiator wall;
Q_S – heat transfers from the radiator wall to the cool fluid.

The heat transfer coefficient between the radiator wall and the cool or hot fluid could be obtained by the Nusselt equation.

$$Nu = CRe^m Pr^{\frac{1}{3}} \quad (11)$$

$$Nu = \left(\frac{hL}{k}\right) \quad (12)$$

$$Re = \left(\frac{\rho v L}{\mu}\right) \quad (13)$$

$$Pr = \left(\frac{\mu C_P}{k}\right) \quad (14)$$

From equation 11~14, heat transfer coefficient could be obtained:

$$h = C \cdot k^{\frac{2}{3}} \cdot L^{m-1} \cdot (\rho v)^m \cdot \mu^{\frac{1}{3}-m} c_p^{\frac{1}{3}} \quad (15)$$

Where:
h – heat transfer coefficient between the radiator wall and the fluid;
k – thermal conductivity of the fluid;
L – specific length;
μ – dynamical viscosity of the fluid;
c_p – specific heat at constant pressure of the fluid;
ρ – density of the fluid;
v – velocity of the fluid;
C, m – correlation coefficient and exponent of the two sides of the radiator wall.

3. The Working Process Simulation Model Coupled with the Cooling System

3.1. Flowing of the Cooling Water

The cooling system of the truck is mainly made up of a pump, a fan, a radiator, a heat exchanger of the transmission oil, cooling passage and pipes. It can ensure the temperature of the cooling water in a proper range in complex circumstances. The flowing routes of cooling water are shown in fig. (3).

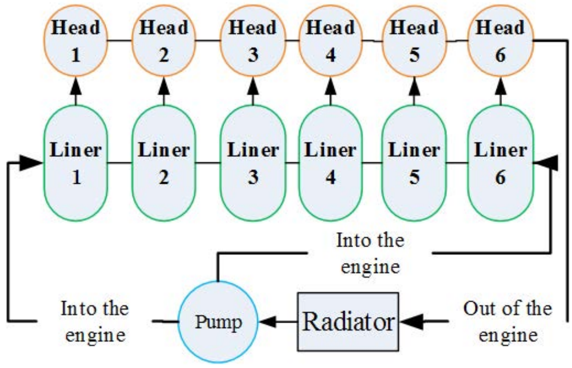


Figure 3. Cooling Water Flow in the Engine

The cooling water flowing out the pump comes into the water jacket though two entrances on the No.1 and No.6 cylinder, then flows up to the cylinder head though many connecting pipes. Finally the cooling water comes out of the engine body to the pipes installed on the back of the cylinder head and returns to the pump after cooled in the radiator.

3.2. The Simulation Model of the Diesel Engine Working Process

A working process simulation model of the diesel engine coupled with cooling system was established based on the actual diesel engine structure, as shown in fig. (4). In this model the working process and the cooling system provided boundary parameters for each other, which could promote the accuracy of the simulation [6-7].

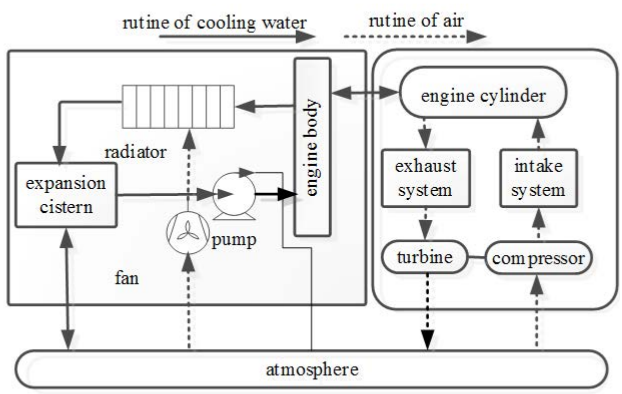


Figure 4. Diesel Engine Working Process Simulation Model Coupled With Cooling System

3.3. Thermal Balance Test on the Engine Bench

3.3.1. Test Plan

The test was carried on engine bench in the engine plant. Engine external characteristic was recorded. The engine speed was between 1200~2000 r/min and the record interval is 200 r/min. The type of the fuel was -35# diesel and the cooling water was soften water. Parameters were controlled by a control system and the following conditions must be satisfied during test:

(1) The temperature of the diesel fuel into the engine was controlled at 25±2 ºC, the same temperature as the atmosphere.

(2) Exhaust gas temperature before the turbo must be lower than 720 ºC, and after the turbo must be lower than 650 ºC.

(3) Speed of the turbo must be lower than 60 000 r/min.

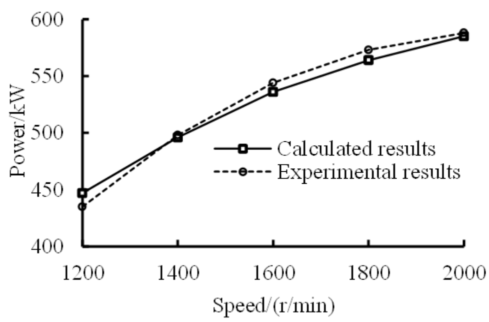
(4) Data was recorded on each test point after the engine was running for 5 minutes steadily.

3.3.2. Test Apparatus

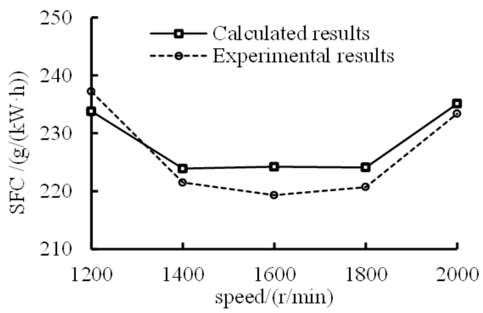
The apparatus used in the test include a mining truck engine, an water dynamometer D2600, a fuel consumption meter and a set of fuel temperature control system, an oil temperature control system, a cooling water temperature control system, a data collecting system, a fuel mass flux sensor, two water pressure sensors installed before and after the water pump, a cooling water mass flux sensor, two cooling water temperature sensors used to test the engine's inlet and outlet water temperatures and a cooling water mass flux sensor.

3.4. Analysis of the Simulation Results and the Test Results

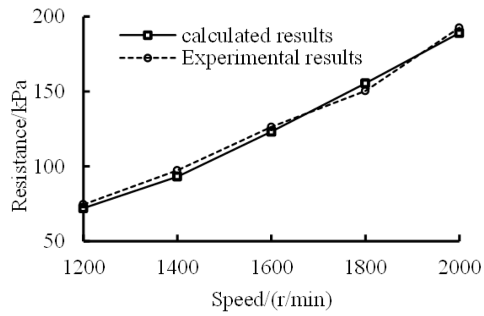
Test results of engine's the external characteristics were obtained when the atmospheric pressure is 88.9 kPa and the atmospheric temperature is 25 ºC. And they were compared with the simulation results calculated by the working process simulation model coupled with cooling system, as shown in fig. (5).



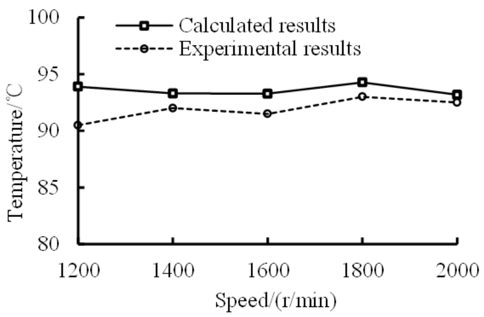
(a) Power



(b) Specific Fuel Consumption



(c) Resistance of the Cooling Water



(d) Outlet Water Temperature

Figure 5. Comparison of the Simulation Results and the Test Results

The engine's power increases with the speed. The maximum simulation error is 2.76% when the speed is 1200 r/min. Specific fuel consumption drops with the speed when the engine speed is lower than 1400 r/min, while as engine speed is higher than 1800 r/min, it increases with the speed. The maximum error of specific fuel consumption is 2.23%, as the engine speed of 1600 r/min. Resistance of the cooling system increases with the speed. The maximum error is 4.32%, at the speed of 1400 r/min. The maximum error of outlet water temperature is 3.76%. As a whole, the coupled model has high accuracy when calculating the external characteristic.

4. Analysis of the Thermal Condition of the Cylinder

The heat in the cylinder comes from the combustion gas and the friction of the piston rings with the cylinder. It transfers among the oil, the cooling water and the main parts, such as pistons, piston rings, cylinder heads, cylinder liners, inlet valves, outlet valves, inlet pipes and outlet pipes.

The heat transfer, engine parts' temperatures and cooling water temperatures under external characte- ristics condition were calculated based on the working process simulation model of the diesel engine coupled with cooling system, and the results were analyzed.

4.1. Analysis of Heat Transfer in the Engine

The heat transferred to the engine body from the combustion gas is shown in Fig. (6). It shows that the heat transferred from the combustion gas increases with the engine speed. The engine's fuel consumption and the heat released from the combustion gas goes up with the engine speed accordingly. The average heat transferred from a single cylinder to the body is 24.2 kW when the speed is 2000 r/min, which is 22.8% higher than that of 1200 r/min.

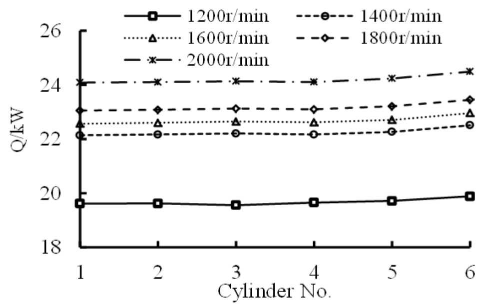


Figure 6. Heat Transferred From Combustion Gas to the Engine Body

As shown in Fig. (7), the heat transferred to the cooling water from the engine body increases with the engine speed. It's in because that when the engine speed goes up, the heat transferred to the engine body from the combustion gas increases, and the mass flow rate of the cooling water rises too. When the engine speed is 2000 r/min, the average heat transferred from a single cylinder to the cooling water is 24.9 kW, which is 34.7% higher than that of 1200 r/min. At the same time, from cylinder No.1 to No. 6, the heat transferred drops slowly at first and then goes up. The No.5 cylinder's is the minimum while the No.6 cylinder's is the maximum.

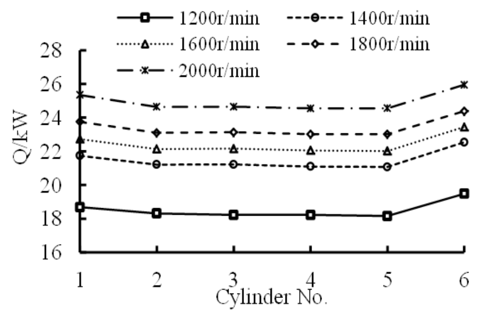


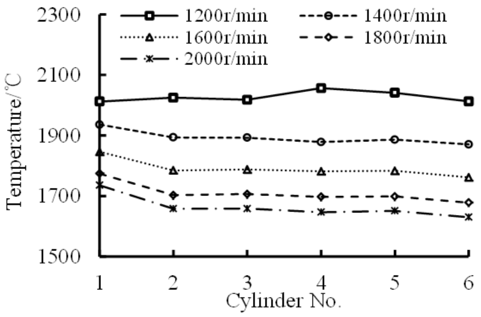
Figure 7. Heat Transferred to the Cooling Water From the Engine Body

4.2. Calculation and Analysis of the Heated Parts in the Cylinder

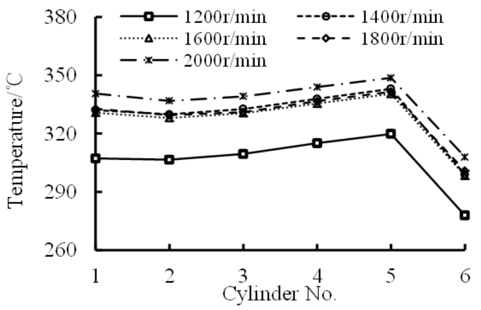
The changes of the maximum temperatures of the combustion gas, cylinder heads, pistons and cylinder liners were calculated with the coupled simulation model. The results are shown in fig. (8).

Fig. (8) (a) shows the curves of the maximum temperature of combustion gas. The gas's temperature declines with the engine speed due to the decreasing of fuel amount injected into the cylinder in each cycle.

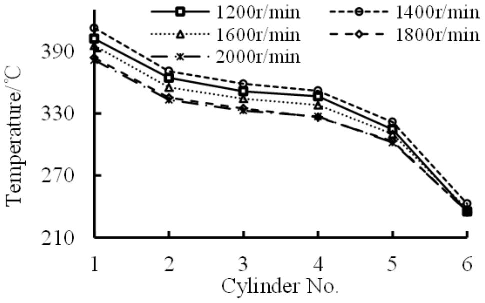
Because the cylinder No.1 is the nearest to the intake pipe, while the No.6 is the farthest, the intake air amount of No.1 cylinder is smaller. It leads to the postponing of the combustion process, causing the maximum temperature in No.1 is a bit higher.



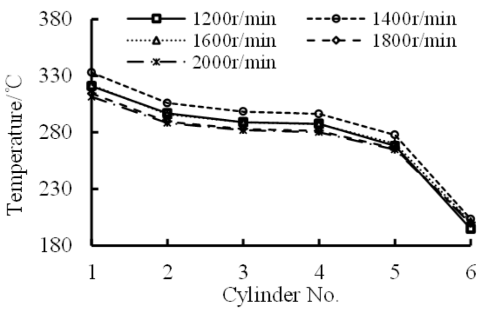
(a) Maximum Temperature of the Combustion Gas in the Cylinder



(b) Maximum Surface Temperature of the Piston



(c) Maximum Surface Temperature of the Cylinder Head



(d) Maximum Surface Temperature of the Cylinder Liner

Figure 8. Temperatures of the Heated Engine Parts

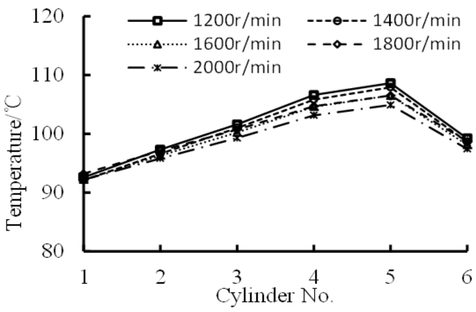
Fig. (8) (b) shows the curves of the maximum temperature of the pistons' surfaces. With the increasing of the engine speed, the heat amount, either transferred from combustion gas to the pistons or produced by the friction of the cylinder liners, pistons and piston rings, increases. The piston surfaces' temperature rises accordingly. The heat transferred among each set of the pistons, piston rings and cylinder liners and the oil are much different from others. So from cylinder No.1 to No.6, the pistons' maximum surface temperatures are different. When the engine speed is 2000 r/min, the piston No.5's maximum surface temperature is 348.6 ºC, while the No.6's is 307.9 ºC, and the discrepancy is 40.7 ºC.

Fig. (8) (c), (d) show the curves of the maximum temperatures of cylinder heads and cylinder liners. The heat transferred from the combustion gas to the cylinder heads and liners increases with the engine speed. And the heat transferred from the cylinder heads and liners to the cooling water increases either. Affected by these two factors, the maximum temperatures of the cylinder heads and liners go up at lower engine speed and go down at higher speed. The maximum value is under the speed of 1400 r/min, which is the engine's maximum torque speed.

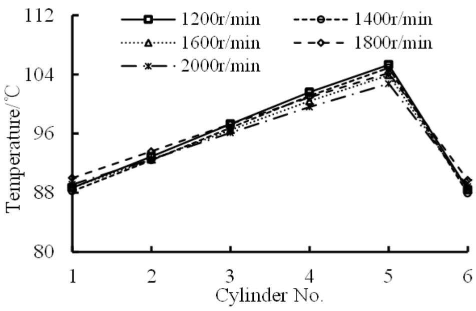
Though the working condition has little changes, the maximum temperatures of cylinder heads and liners fall from the No.1 to the No.6 due to the differences of cooling water temperatures, cooling water velocity and amount of heat exchange. The maximum surface temperatures of the cylinder head and liner of No.1 are 412.3 ºC and 332.9 ºC, while the No.6's are 242.7 ºC and 203.3 ºC.

4.3. Temperature Calculation and Analysis of the Cooling Water

Fig. (9) (a), (b) show the curves of temperatures of the pistons heads and the cooling water under the external characteristic condition. The cooling water temperatures decrease slowly with the engine speed. The surface temperatures of cylinder heads and cylinder liners increase from No.1 to No.5 and drops down apparently at the No.6. when the engine speed is 1400 r/min, the temperature of the cooling water flowing out of the engine was 93.3 ºC, while the temperature of the cooling water flowing over the surface of the No.5 cylinder head and liner are 108.6 ºC and 105.3 ºC, which are 15.3 ºC and 12 ºC higher. These results are related to the position of the intake and the outlet of the cooling water. The engine has two water intakes and one outlet. One intake is near the No.1 cylinder and the other is near the No.6. The outlet is near the No.6. The cooling water flows from the No.1 cylinder to the No.6 in turn. Heated by the engine body, the temperature of the cooling water increases gradually, so the cooling capability falls into a decline. But the temperature of cooling water of No.6 cylinder is different. It is better cooled because its position is near the outlet. A part of cooling water flows out of the engine through the outlet right after it cools the No.6 cylinder. So the temperature of the cooling water flowing over the surface of the No.6 cylinder is much lower.



(a) On the Surface of Cylinder Heads



(b) On the Surface of Cylinder Liners

Figure 9. Temperature of the Cooling Water on the Surface of Cylinder Liners and Heads

5. Conclusion

1) The study on characteristics of heat distribution in the chief heated parts and cooling water for each cylinder can reveal the thermal condition of the engine. A working process simulation model of the mining truck diesel engine coupled with cooling system was established. The model was tested by an engine bench test. Test results shows that its error is less than 5%.

2) The temperatures of the main heated parts and cooling water are not uniform. This is because the design of the cooling water intake and outlet of the engine are not rational. The uniformity of the cooling water temperature leads to the different cooling effect on the engine parts. The structure of the engine cooling passage should be optimized.

Conflict of Interest

The author confirms that this article content has no conflict of interest.

References

1. Y. X. Zhao, X. P. Bi, P. K. Wang and X. X. Liu, "Simulation of Heat Transfer and Coolant Flow in Cooling System of Vehicle Internal Combustion Engine", *Chinese Internal Combustion Engine Engineering*, vol. 24, no. 4, pp. 1-5, 2003
2. Q. G. Luo, J. T. Feng, G. F. Liu and Y. Gui, "Study on Transient Response of Diesel Engine Cooling System", *Chinese Internal Combustion Engine Engineering*, vol. 31, no. 6, pp. 32-37, 2012
3. S. S. Xiong, W. H. Zhou, C. S. Zhang and W. H. He, "CFD three-dimensional numerical calculation on flow and heat transfer of cooling-water in engine cylinder cooling jacket", *Journal of Zhejiang University*, vol. 41, no. 7, pp. 1191-1194, 2007
4. M. L. Bai, J. Z. Lu and T. X. Ding, "Numerical Simulation on Flow and Heat Transfer of Cooling System in a Six-Cylinder Diesel Engine", *Transactions of CSIC*, vol. 22, no. 6, pp. 525-531, 2004
5. Gt-Suite Cooling Systems and Thermal Management Applications Manual. VERSION 7.0. 2009
6. J. T. Feng, *"Numerical simulation on diesel engine intelligent control cooling system"*, M.S. thesis, Academy of Armored Forces Engineering , Beijing, 2009
7. S Y. Yuan, *"Research on Performance of Armored Vehicle Engine Cooling System in Plateau Environment Based on Numerical Simulation"*, M.S. thesis, Academy of Armored Forces Engineering , Beijing, 2012