

Heat Pipe with High Heat Transfer Rate by Reciprocating Motion

(Examination of Application to Automotive Engine Piston)

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ABSTRACT

The flow of gas and liquid in heat pipes is generally impaired by factors such as oscillation and inclination, with the result that the heat transfer becomes excessively low. For this reason, there are no known cases of heat pipe use in cars and motorcycles, etc.

The authors, therefore, proposed a new heat pipe that controls the two-phase flow of gas and liquid without reducing the amount of heat transport, by reducing the friction energy loss inside the pipe and forcibly inducing self-oscillation.

Measurement results in the condition with oscillation applied by reciprocating motion showed an increase in the heat transfer coefficient by a factor of 1.6 compared with that at standstill. That mechanism is thought to be as follows. In the initial stage, the liquid sealed in the heat pipe is broken up into fine droplets by reciprocation. The droplets then acquire drive force in a constant direction macroscopically while contacting the gates, producing a unidirectional flow. Further, a loop flow channel enables transfer of gas and liquid from condensed areas to evaporation areas without gas-liquid collision.

This study performed thermal analysis of the case when applied to an engine piston. The results showed that the temperature at the piston head center was reduced by 39 K and ΔT was also reduced from 140 K to 75 K, and thus thermal stress reduction effects can be anticipated.

1. Introduction

With electric vehicles (EV) and hybrid electric vehicles (HEVs) targeting better energy efficiency and environmental compatibility, a cooling/heating system for the motor, power control unit (PCU), battery, etc. is an increasingly crucial subsystem of vehicles for reasons such as performance improvement and suppression of deformation⁽¹⁾⁻⁽³⁾. Temperatures are usually controlled by direct and indirect methods such as an oil jet to motor surfaces and coolant in a cooling channel. However, thermal conductivity of currently used cooling media lower than the specific heat of H_2O and NH_3 , resulting in reduced cooling effect⁽⁴⁾.

Meanwhile, it is well known that the thermal conductivity of heat pipes used in computers and air conditioners is 10 or more times higher than that of the above-noted cooling media⁽⁵⁾⁻⁽⁸⁾. Due to the structural characteristics of heat pipes, however, the flow of gas and liquid is impaired by factors such as axial accelerations, with the inevitable result that the amount of thermal conductivity becomes excessively low⁽⁹⁾. For this reason,

there are no known reports of their use for cooling of automotive parts.

The objective of this study is to investigate of a new cooling heat pipe that controls the two-phase flow of gas and liquid and maintains a high heat transfer by (1) friction control inside the pipe, and (2) forced self-oscillation. Verification of prototype design used reciprocating motion, which is relatively easy to control, as an applied force, and was conducted using a high-speed reciprocation apparatus with a stroke width of 50 mm.

The design concept of the heat pipe was then applied to cooling passage in an engine piston of an internal combustion engine (ICE). Analysis results of the heat transfer performance in the piston are also reported herein.

2. Design and Prototyping of New Heat Pipe

Figure 1 shows a commercially available heat pipe and the newly designed heat pipe. The commercially available heat pipe has a metal mesh-type wick inside. Specimens with the same shape were used for attachment to the high-

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speed reciprocation testing apparatus.

The investigation initially planned to compare the amounts of thermal conductivity between the newly designed heat pipe and a commercially available heat pipe with a metal mesh-type wick inside. As described in a past report⁽²⁰⁾, however, when the commercially available heat pipe is oscillated, the thermal conductivity decreases by the cross-section integral of the pipe, so the test results were compared with those of a bulk aluminum cylinder. The aluminum cylinder material was aluminum 4000 NP12P.

Figure 2 shows the working principle of the commercially available heat pipe⁽¹⁰⁾ which transfers heat as follows: a small amount of working fluid sealed in the vessel evaporates in the evaporator, the vapor passes through the center of the pipe to the condenser and the condensed water vapor then flows back to the evaporator due to the capillary force of the fine metal mesh wick attached to the inner wall of the vessel.

Figures 3 and 4 show the structure⁽¹¹⁾ and the cross-section of the newly designed heat pipe. The pipe has an internal structure with gate-shaped protrusions at regular intervals that control the flow of liquid and gas. The geometrical design enables the liquid to move along the inner wall of the pipe under an oscillation, and generate fine droplets by collision. The resultant two-phase flow transfers heat energy efficiently.

Table 1 shows specifications of the heat pipe.

Figure 5 shows the prototype process of the heat pipe.

The prototype was prepared by adding pure water as a coolant into the pipe at room temperature using a fluid injector (Fig. 5, top).

Table 1 Heat pipe specifications

Pipe length	144 mm
Pipe size	Φ8 mm
Number of gates	10
Gate size	D9 x T5 x V5.3, θ15°

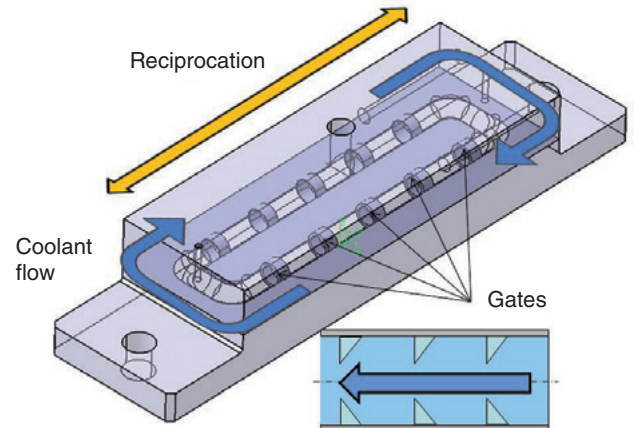


Fig. 3 Newly designed heat pipe

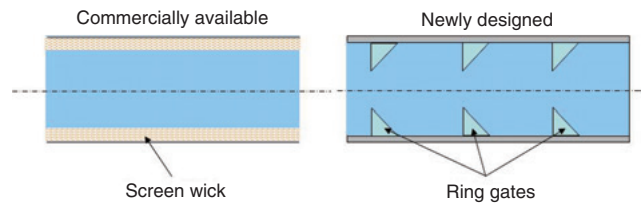


Fig. 4 Inner structures of heat pipes

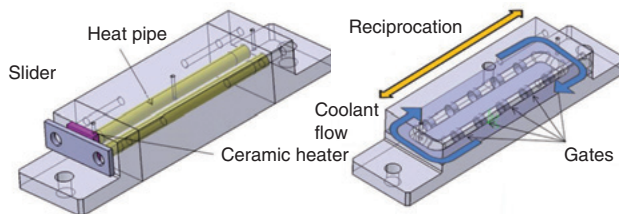


Fig. 1 Structures of specimen using commercially available heat pipe (left) and specimen using newly designed heat pipe (right)

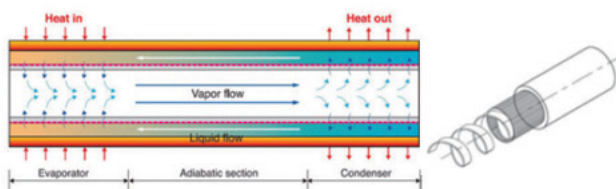


Fig. 2 Working principle of wick heat pipes

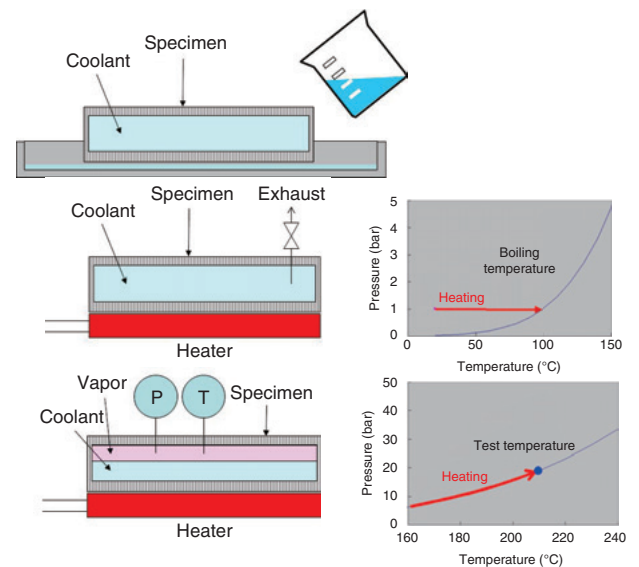


Fig. 5 Prototype process of newly designed heat pipe

The pressure and temperature were measured while heating the bottom side of the aluminum specimen at atmospheric pressure (Fig. 5, middle), internal vapor was exhausted while measuring the specimen mass, and the pipe was then sealed by inserting an iron ball into the hole at the prescribed coolant mass. After sealing, the specimen was heated to the test temperature, and the saturated vapor pressure (Fig. 5, bottom) was confirmed. The heat pipe was attached to a high-speed reciprocation testing apparatus as shown in Fig. 6, and thermocouples were attached to the specimen in three locations. A ceramic heater was used to apply heat. Heat radiation was performed using a cooling fin for personal computer CPUs. Temperature variations at the measurement points and heat transfer coefficient were examined while oscillating the heat pipe in the axial direction.

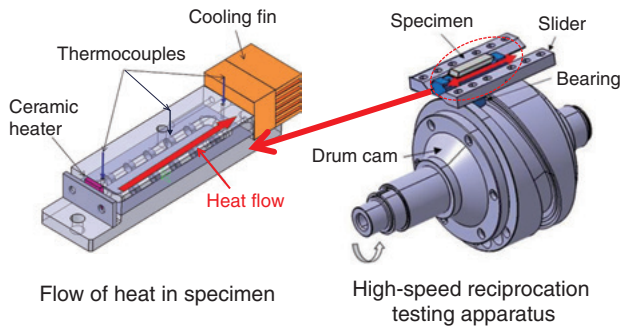


Fig. 6 Flow of heat in specimen and high-speed reciprocation testing apparatus

3. High-speed Reciprocation Test (Reciprocating Motion)

Table 2 shows the conditions.

A commercially available heat pipe and three newly designed heat pipes with respective water-to-air ratios of 50/50, 70/30, and 80/20 were prepared to determine the optimal ratio.

In addition, a bulk aluminum specimen of the same shape without a heat pipe was also tested for comparison (Fig. 7).

In the test, a constant sliding speed was maintained until temperature at each measurement point reached an equilibrium, after which the speed was changed to the test conditions. The temperatures were then measured at prescribed speed.

The heat source was a ceramic heater in close contact with the specimen, and a cooling fin was fixed to the opposite side. A commercially available silver paste was applied to the interface between the heater and the specimen. The heat input was set to 30 Watt.

Table 2 Conditions of reciprocation test

Reciprocating speed range	0.0 to 3.0 m/sec
Reciprocating stroke	50 mm

The tests were conducted using a high-speed reciprocation testing apparatus⁽¹²⁾. The specimen was covered by an aluminum cover and an insulator to suppress a thermal radiation outside the specimen. Figure 8 shows the specimen and its surroundings configurations.

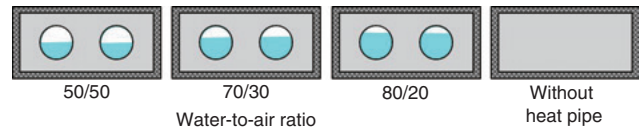


Fig. 7 Comparison of heat pipes with different water-to-air ratios

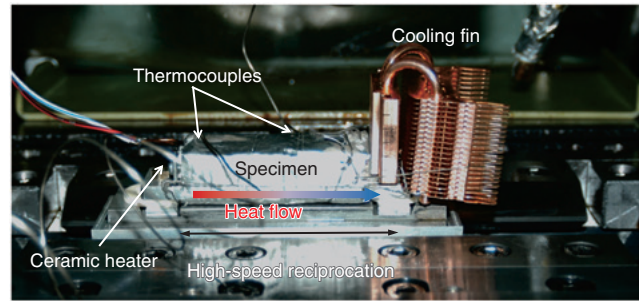


Fig. 8 Specimen during high-speed reciprocation test (3 m/sec)

4. High-speed Reciprocation Test Results

The heat flux was calculated by Eq. (1) and Eq. (2) below.

$$q = \lambda_e A_e \frac{\Delta T}{L} \quad (1)$$

q : Heat flux (W/m^2)

λ_e : Heat transfer coefficient ($\text{W/m}^2\text{K}$)

A_e : Cross-sectional area

L : Length

Calculation was made for two different cross-sections (aluminum specimen with and without a heat pipe inside). Heat radiation from the specimen was assumed to be

uniform. The ratio for the heat balance calculation was calculated from the cross-section.

$$q = (\lambda_1 A_1 + \lambda_2 A_2) \frac{\Delta T}{L} \quad (2)$$

λ_1 : Heat transfer coefficient of aluminum

A_1 : Cross-sectional area of aluminum

λ_2 : Heat transfer coefficient of heat pipe

A_2 : Cross-sectional area of heat pipe

Figure 9 shows the heat pipe test results during high-speed reciprocation.

The effective thermal conductivity of the bulk aluminum specimen without a heat pipe inside is constant at 140 W/m K under the test speed.

Meanwhile, the thermal conductivity at standstill in the specimen with a water-to-air ratio of 70/30 and a heat pipe ratio to the bulk base area ratio of 10% in the heat balance calculation is lower than that of bulk aluminum specimen. This is thought to be because the air inside the heat pipe lowers the thermal conductivity and reduces the cross-section integral⁽¹³⁾⁻⁽²³⁾.

The thermal conductivity is slightly higher than that of the bulk aluminum specimen at a sliding speed of 2 m/sec, and reaches 620 W/m K at speed of 3 m/sec. Recalculating this effect for the heat pipe alone results in thermal conductivity of 4900 W/m K at a speed of 3 m/sec.

For reference, the thermal conductivity of the bulk aluminum specimen is 140 W/m K, and many commercially available heat pipes have a thermal conductivity at standstill of around 3000 W/m K, so the newly designed heat pipe exhibited thermal conductivity 35 times that of bulk aluminum and 1.6 times that of commercially available heat pipes. Figure 10 shows the effect of the heat pipe filling ratio.

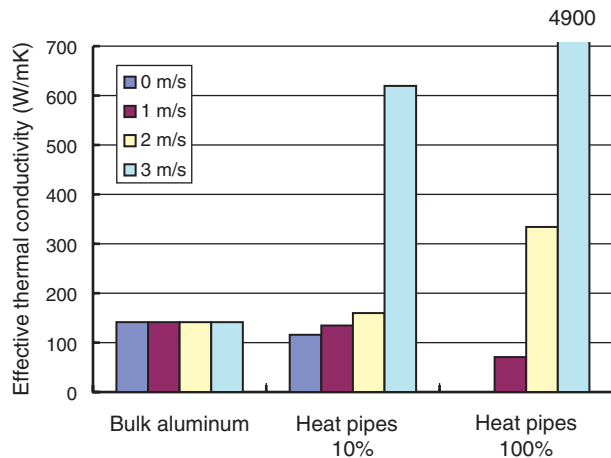


Fig. 9 Effectiveness of heat pipes during high-speed reciprocation

At a water-to-air ratio of 50/50, the effective thermal conductivity increases with the sliding speed. Furthermore, although the thermal conductivity at a water-to-air ratio of 70/30 is lower than that of a ratio of 50/50 up to a sliding speed of 2 m/sec, it rises sharply to 620 W/m K at a speed of 3 m/sec. At a water-to-air ratio of 80/20, the highest thermal conductivity of 235 W/m K appears at a speed of 1 m/sec, but drops to 180 W/m K at a speed of 3 m/sec.

Figure 11 shows a conceptual diagram of droplets inside the newly developed heat pipe.

The reason why the newly designed heat pipe exhibited high heat conduction is under investigation. However, it is thought that in the initial stage, the fluid sealed inside the heat pipe is broken up into fine droplets by reciprocation. The droplets then acquire drive force in a constant direction macroscopically while contacting the gates, producing a unidirectional flow. Further, use of a loop flow channel enables transfer of gas and liquid from condensed areas to evaporation areas without gas-liquid collision.

This made it possible to exhibit higher performance under high-speed reciprocating conditions compared to the heat transfer amount of bulk aluminum at standstill.

As the above results showed that increasing the oscillation inertial force is an effective means of heat transport, application to the cooling of ICE engine pistons was then investigated.

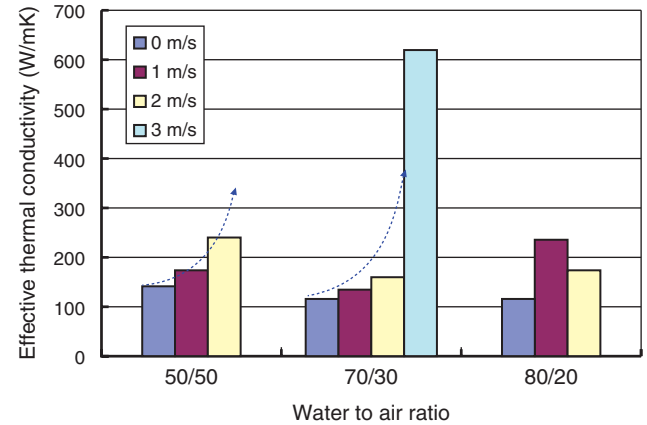


Fig. 10 Effectiveness of heat pipe filling ratio

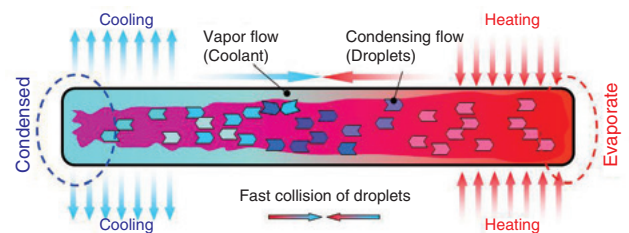


Fig. 11 Diagram of droplet movement

5. Application to Engine Pistons

Application to engine pistons was investigated based on the above data, and thermal analysis was performed⁽²⁴⁾⁻⁽²⁷⁾.

Wang et al. incorporated heat pipes into the skirt area of a piston to verify the effects, and reported that the high thermal conductivity of 3980 W/m°C was achieved. However, the structure used in that study produces a skewed working fluid distribution due to the angle of inclination of the cylinder, and the heat conduction efficiency may be non-uniform. Therefore, the structure shown in Fig. 12 below was adopted and a prototype piston with heat pipes arranged based on this drawing was prepared.

The heat pipes are arranged to transfer heat from the piston top, where cooling is most needed, to the piston skirt.

The heat pipes use the shape shown in Fig. 3, with backflow-reducing gates arranged inside the pipe to control the flow of gas. A copper alloy piston ring was installed in the skirt area to transfer heat from the piston to the sleeve.

Figure 13 shows actual prototypes of a piston produced by optical molding and an aluminum alloy piston produced using a 3D printer. In addition, Fig. 14 shows a CT scan image of the interior of the piston with heat pipes arranged. This shows that the gates provided inside the piston are formed with directionality.

5.1. Calculation Method

Thermal conduction calculations (numerical solution of a steady-state three-dimensional heat conduction equation)

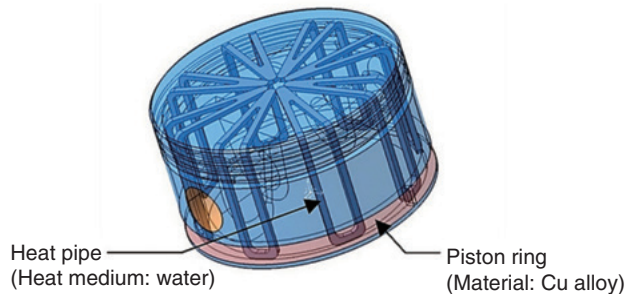


Fig. 12 Piston with built-in heat pipe



Fig. 13 Prototype produced by optical molding (left), prototype produced by metal 3D printer (right)

were made for a piston with heat pipes embedded from the top to the skirt area, and the heat radiation characteristics of the piston were estimated as described below. The thermal conduction of the heat pipes was set to 2000 W/m K and the half value of 1000 W/m K based on the data obtained in Fig. 9, the thermal conductivity of the piston ring raw material, and the thermal conductivity obtained from measurements during operation⁽²⁸⁾.

The basic formula (3) is shown below.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (3)$$

The boundary conditions are shown below. (Bulk Body = BULK)

Piston bore diameter: $\phi 110$

Thermal conductivity of base material: 150 W/m K

Thermal conductivity of heat pipe: 1000 W/m K, 2000 W/m K

Shape: Piston (1/4 model)

Figure 15 shows different areas of the piston and an example of thermal analysis.

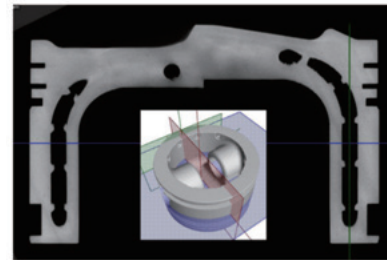


Fig. 14 Sectional image of piston with built-in heat pipes

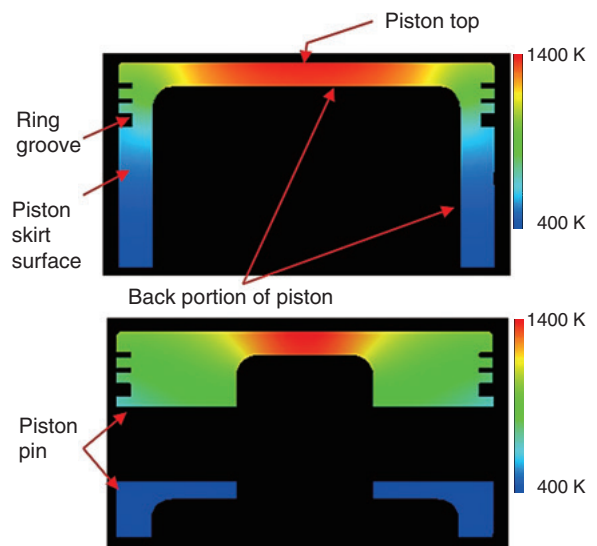


Fig. 15 Example of thermal analysis

The thermal conductivity and temperature within the cylinder were determined as time averages from the in-cylinder pressure data using the Woschni model. Although it is preferable to introduce a contact thermal resistance model, for simplicity this study applied the same thermal conductivity scheme to the metal contact areas.

Table 3 shows the heat transfer boundary conditions of different areas.

Uniform temperature in the heat pipe insertion area was assumed and a constant temperature was used for calculation.

A piston top area temperature of 200 K was set as the design target in this calculation.

Figure 16 shows the arrangement of heat pipes in the piston.

5.2. Calculation Results

Figure 17 shows the results of heat transfer calculation for a single piston without heat pipes.

The temperature reached 583 K (310°C) in the central piston top area and 523 K (250°C) at the piston top edge. The temperature in the skirt area was 443 K (170°C). The difference between the highest and lowest temperatures on the piston was $\Delta T = 140$ K. Figure 18 shows the results of heat transfer calculation for a single piston with heat pipes (1000 W/m K) installed.

The temperature reached 557 K (284°C) in the central piston top area and 518 K (245°C) at the piston top edge.

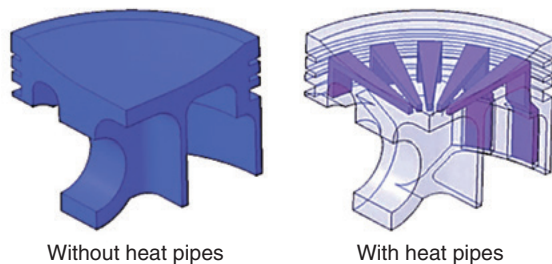


Fig. 16 Arrangement of heat pipes in piston

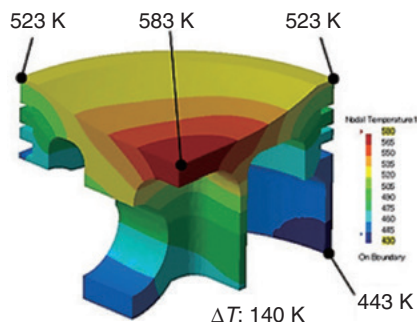


Fig. 17 Results of heat transfer calculation without heat pipes

Table 3 Heat transfer boundary condition

Area	Heat-transfer coefficient (W/m ² K)	Temperature (K)
Piston top	423	1373.15
Ring groove	2878	403.15
Piston skirt surface	300	403.15
Piston pin	1471	403.15
Back portion of piston	232	403.15

The temperature in the skirt area reached 461 K (188°C) due to heat transfer by the heat pipes. The difference between the highest and lowest temperatures on the piston was $\Delta T = 96$ K.

Figure 19 shows the results of heat transfer calculation for a single piston with heat pipes (2000 W/m K) installed.

The temperature reached 544 K (271°C) in the central piston top area and 517 K (244°C) at the piston top edge. The temperature in the skirt area reached 469 K (196°C) due to heat transfer by the heat pipes. The difference between the highest and lowest temperatures on the piston was $\Delta T = 75$ K.

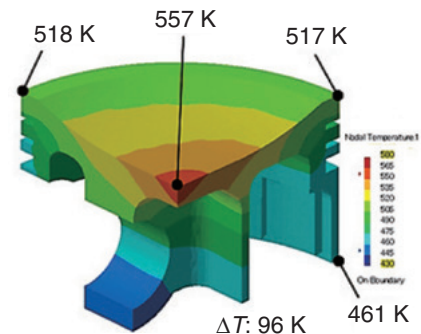


Fig. 18 Results of heat transfer calculation for piston with heat pipes (1000 W/m K)

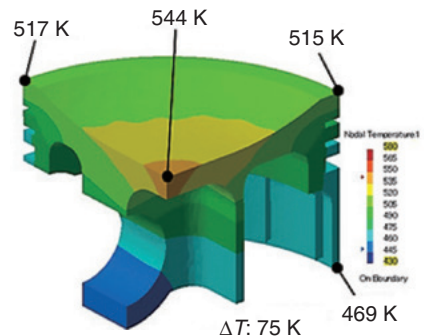


Fig. 19 Results of heat transfer calculation for piston with heat pipes (2000 W/m K)

Figure 20 summarizes these calculation results.

This shows that the temperature of the central piston top area, that is to say the highest temperature on the piston, dropped due to heat transfer by the heat pipes.

Conversely, the temperature of the piston skirt area increased slightly due to the presence of heat pipes. This shows that heat pipes have the effect of reducing thermal stress on the piston by equalization of the piston temperature distribution.

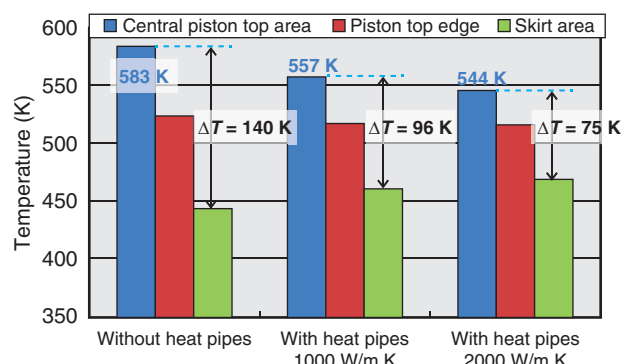


Fig. 20 Comparison of calculation results

6. Conclusion

- (1) The thermal conductivity of a heat pipe that uses protrusions at regular intervals to control the flow of liquid and gas during reciprocation tends to increase sharply as the reciprocating sliding speed increases.
- (2) Component unit conversion indicates that the newly designed heat pipe has thermal conductivity 1.6 times that of a commercially available heat pipe at standstill.
- (3) Although water was used as the working fluid in the calculations, the temperature of the central piston head area of an ICE piston was reduced by 39 K, and ΔT was also reduced from 140 K to 75 K.

The above results indicate effectiveness in reducing the thermal stress on the piston. In addition, structural modification was also found to effectively increase the amount of heat transfer. However, various issues are of course anticipated, such as the impact of heat pipe installation on strength, development of a structure that can withstand long-term use, and increased weight due to increased wall thickness in the skirt area where heat pipes are incorporated.

Nevertheless, it is thought to be potentially feasible in principle to develop this approach into an extremely advantageous engine cooling system through creative efforts in the future⁽²⁹⁾⁻⁽⁴³⁾.

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