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Kohei NAKASHIMA
Masao YOSHIDA
Kento NISHII
Ayanari YOSHIDA
Nobuyuki OKURA

Combustion Engines
Polish Scientific Society of Combustion Engines

Improving heat transfer of air-cooled cylinders with fins with slits

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In finned cylinders with slits around the cooling fin circumference, thermocouples were attached at three positions in the radial direction on the surface of the fin, and fin surface temperatures were measured by rotating the cylinders relative to the flow direction in a wind tunnel to change the angular position of the attached thermocouples. The temperature distribution around the fin circumference and the average heat transfer coefficient were then investigated at air velocities from 20 km/h (5.6 m/s) to 60 km/h (16.7 m/s). Results indicated that, compared with fins without slits, fins with slits, either aligned or offset, decreased fin surface temperatures and increased the heat transfer coefficient. The fins with slits also resulted in a more uniform circumferential temperature at the fin root at a lower air velocity, but not at a higher air velocity, compared to fins without slits.

Key words: *air-cooled cylinder, cooling fin, slit, heat transfer, fin surface temperature*

1. Introduction

Air-cooled motorcycle engines are cooled by transferring waste heat from the cylinder through the cooling fins to the surrounding air. Therefore, increasing total fin surface area is generally effective in increasing cylinder cooling. Several studies have reported on the effect of fin dimensions and number of fins on cooling performance in conventional finned cylinders, in order to increase fin surface area [2, 5, 9–14]. For example, Biermann and Pinkel [2] investigated the surface heat transfer coefficient around the fin circumference under forced convection, using vertical steel cylinders with fins with various pitches, lengths, and thicknesses. They found that the space between the fins significantly affected the heat transfer coefficient. Thornhill and May [11] examined the surface heat transfer coefficient around the fin circumference under forced convection, utilizing vertical aluminium alloy cylinders with fins with various pitches and lengths. They also indicated that fin separation has a great effect on the heat transfer coefficient. Thornhill et al. [12, 13] also investigated the heat transfer coefficient around the fin root under forced convection, using vertical aluminium alloy cylinders with fins with various pitches and lengths. They clarified that there is a limit to the heat transfer coefficient for a given fin length, even with increased fin separation. The authors [14] used vertical aluminium alloy cylinders with different fin pitches and numbers of fins to investigate the heat transfer rate from the cylinder and the fin temperature under both natural convection and forced convection, and determined the optimal fin pitch for cooling. In addition to the above-mentioned studies, the numerical analysis by Mishra et al. [5] also revealed that, as more fins are mounted on the cylinder at too narrow a pitch in an effort to increase the total fin surface area, thermal boundary layers overlap between the upper and lower fins, reducing cylinder cooling [9].

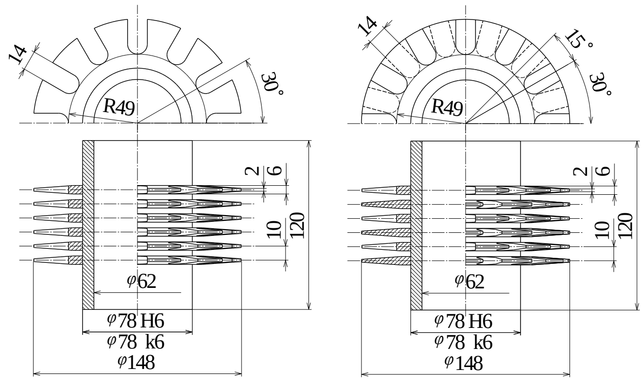
Besides increasing total fin surface area, there have been practical examples of finned cylinders with slits [4]. However, even though 40 years had passed since the finned cylinder with slits was put into practical use, less research had been done on its cooling performance. Over the past 10 years or so, under natural convection, there have been some reports on the cooling performance of finned cylinders with slits where the slits promote a natural convection air flow. That is, for vertical aluminium alloy cylinders, the experiment in our previous study [6] or the numerical analysis by Dubey et al. [3] showed that there are optimal slit widths for cooling, while for a horizontal aluminium alloy cylinder, the numerical analysis by Angamuthu et al. [1] revealed that cooling is improved with a narrower slit width. On the other hand, under forced convection, there have been only our reports on the cooling performance of finned cylinders with slits [7, 8], where the slits disrupt the air flow between the fins, increasing cooling. In our previous studies [7, 8], using the vertical aluminium alloy cylinders with various slit widths around the circumference of the fins, both with slits set in line with cylinder axis, and with slits offset to the slits immediately above, the heat transfer rate from the cylinder was determined by measuring the temperature drop of the heat storage liquid in the cylinder. In addition, the air flow between the fins was observed with the smoke wire method and the air flow on the fin surface with the oil film method. Thus, the optimum slit width was identified for each slit arrangement. In general, it is important for an engine cylinder to be cooled uniformly around its circumference. However, the temperature distribution around the circumference of the finned cylinders with slits has not been clarified. This study set thermocouples to the fin surfaces of finned cylinders with slits around the fin circumference, and then investigated the temperature distribution around its circumference and average heat transfer coefficient under forced convection.

2. Experimental apparatus and method

Figure 1 shows the experimental finned cylinder with slits. For these finned cylinders, the cylinder bore diameter, the cylinder length, and the fin length were designed to approximate most actual single-cylinder motorcycle engines with displacement volumes of 150 cm^3 to 187 cm^3. The fins and cylinder were made of aluminium alloy (JIS A5052). In the fins, the slits were arranged in an equiangular 30° spiral around the circumference. The slit width was 14 mm, which achieved the greatest cooling when all the slits were set in line with the cylinder axis, in our previous study [7]. Six fins were fitted tightly in the cylinder at a fin pitch of 10 mm, either with slits set in line with cylinder axis, or with slits offset at a phase difference of 15° to the slits immediately above. These finned cylinders with slits were compared to a conventional finned cylinder without slits.

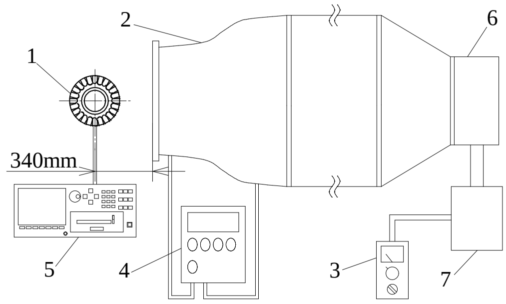
Figure 2 shows the experimental facilities, including an Eiffel-type wind tunnel, with a nozzle of height 680 mm and width 400 mm. The experimental cylinder was mounted on a support table, at a distance of 340 mm from the nozzle of the wind tunnel, with the cylinder axis perpendicular to the air flow.

Figure 3 shows the experimental apparatus. As shown in Fig. 3, a 300 W heater, a stirrer, and a K type thermocouple of 50 μm diameter wire were installed into the cylinder. The cylinder was filled with 290 cm^3 of ethylene glycol as heat storage liquid. On the upper surface of the fourth fin from the top, three K type thermocouples with a wire diameter of 50 μm were attached at positions 5 mm, 20 mm, and 33 mm radially from the fin root, as shown in Fig. 4.



(a) Finned cylinder with aligned slits (b) Finned cylinder with offset slits

Fig. 1. Experimental finned cylinder with slits



1 : Cylinder
2 : Wind tunnel
3 : Speed controller
4 : Manometer
5 : Data logger
6 : Blower
7 : Motor

Fig. 2. Experimental facilities

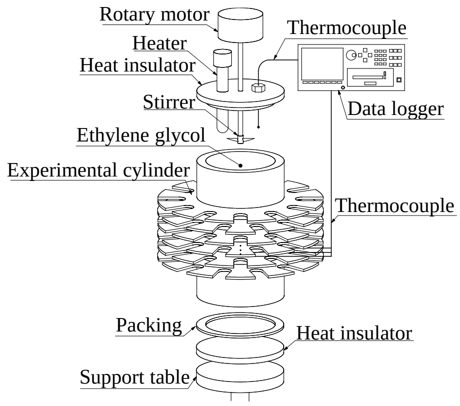


Fig. 3. Experimental apparatus

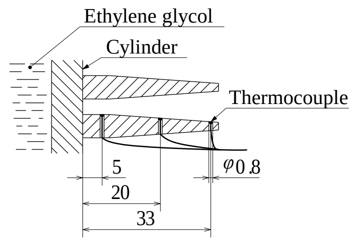
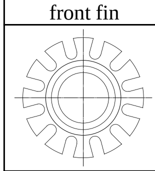
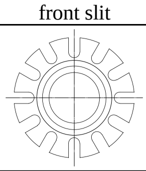
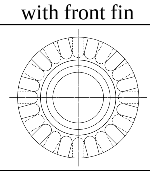
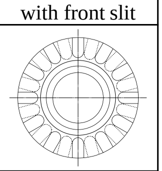


Fig. 4. Installation positions of thermocouples

In the experiment, the stirrer was run, the heat storage liquid was heated with the heater, and the wind tunnel was started. After the temperature of the heat storage liquid became constant, the temperatures of the fin surface and the heat storage liquid were recorded. Here, the cylinder was rotated so that the installation positions of the thermocouples in Fig. 4 were set at 15° intervals from 0° on the windward side (in front of the air flow) to 180° on the leeward side, and the temperatures were recorded for 5 minutes at each angular position of the thermocouple installation. In this case, the fins were located directly in front of the air flow, at 30° intervals from 0° to 180° in the angle position of the thermocouple installation, and the slits were located directly in front of air flow, at 30° intervals from 15° to 165° in the angle position (Table 1). Experiments were carried out at air velocities of 20 km/h (5.6 m/s), 40 km/h (11.1 m/s), and 60 km/h (16.7 m/s), and at an ambient temperature of 22.4 ±1.2°C. The measured temperature was accurate to within ±0.2°C.

Table 1. Slit arrangements

Aligned slits with front fin	Aligned slits with front slit	Offset slits with front fin	Offset slits with front slit
			

The heat rate used to calculate the average heat transfer coefficient was obtained by heating the heat storage liquid with the heater. Here, an insulated vessel (a double-layered stainless steel vacuum vessel wrapped with glass wool on the outside) was equipped with a 300 W heater, a stirrer, and a K type thermocouple with a wire diameter of 50 μm, and then filled with 290 cm^3 of heat storage liquid. The heat storage liquid in the insulated vessel was heated by a heater, while the stirrer ran, and the temperature of the heat storage liquid was measured without air blowing. The heat rate was determined from Eq. (1).

$$Q = \frac{c_m \cdot m \cdot (T_1 - T_2)}{t} \qquad (1)$$

where Q is the heat rate [W], T_1 is 100°C (the approximate temperature of the heat storage liquid at an air velocity of 20 km/h (5.6 m/s)), T_2 is 70°C (the approximate temperature of the heat storage liquid at an air velocity of 60 km/h (16.7 m/s)), t is the time taken for the heat storage liquid to heat from 70°C to 100°C [s], c_m is the average specific heat of the heat storage liquid from 70°C to 100°C [J/(kg °C)], and m is the mass of the heat storage liquid [kg].

Here, the heat rate obtained in this experiment is the increased heat rate of both the heat storage liquid and the vessel from 70°C to 100°C. However, only the increased heat rate of the heat storage liquid was considered.

The average heat transfer coefficient was determined from Eq. (2).

$$h = \frac{Q}{(T_3 - T_4) \cdot A} \qquad (2)$$

where h is the average heat transfer coefficient [W/(m^2 °C)], T_3 is the average fin surface temperature [°C], T_4 is the ambient temperature [°C], and A is the total surface area of the cylinder [m^2]. Here the fluctuation range of the heat transfer coefficient was within ±3%.

3. Results and discussion

Figures 5 and 6 show the fin surface temperatures at each angle position for the finned cylinder, without slits, with aligned slits, and with offset slits, at air velocities of 20 km/h (5.6 m/s) and 60 km/h (16.7 m/s), respectively. As shown in Table 1, in the slit arrangements in our previous studies [7, 8, 15], Figs. 5 and 6 also show the fin surface temperatures both in the aligned slits and in the offset slits, both separately with the front fin and with the front slit.

For all fins, the temperature difference from the windward side to the leeward side tended to decrease as air velocities increased. At all air velocities, the temperatures at each angle and radial position were lower for fins with slits aligned both with the front fin and with the front slit, and for slits offset both with the front fin and with the front slit, than for those without slits. The temperature drop in the fins with the aligned slits and the offset slits at each angle and radial position was greater when the air velocity was slower and smaller when the air velocity was faster. It appears that the air flow disturbance between the fins caused by the slits has a great effect at a lower air velocity. At all air velocities, the temperature differences between the fin root and the fin edge, at angle positions of 0° to 90° in the slits aligned and the slits offset with front fins, were larger than those without slits. The temperature differences between the fin root and the fin edge at angle positions of 15° to 105° in the aligned slits and the offset slits with front slits were also larger than those without slits. Thus, cooling is enhanced by slits, especially at angle positions of 0° to 105°.

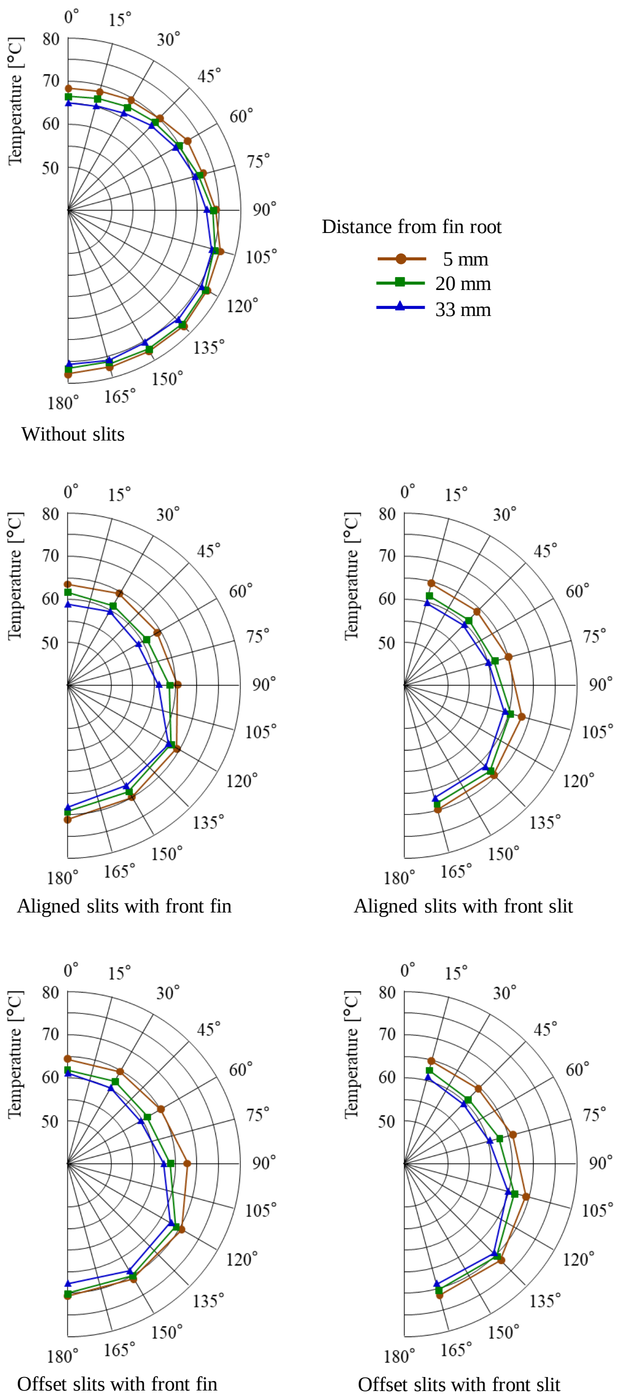


Fig. 5. Fin surface temperatures at an air velocity of 20 km/h (5.6 m/s)

Compared to the slits offset with the front fin, in the slits aligned with the front fin, the temperature at an angle of 90° was lower at a lower air velocity, but the temperatures at all angles were similar at a higher air velocity. Compared to the slits offset with the front slit, in the slits aligned with the front slit, the temperatures at angles of 135° and 165° were also lower at a lower air velocity, but the temperatures at all angles were almost the same at a higher air velocity.

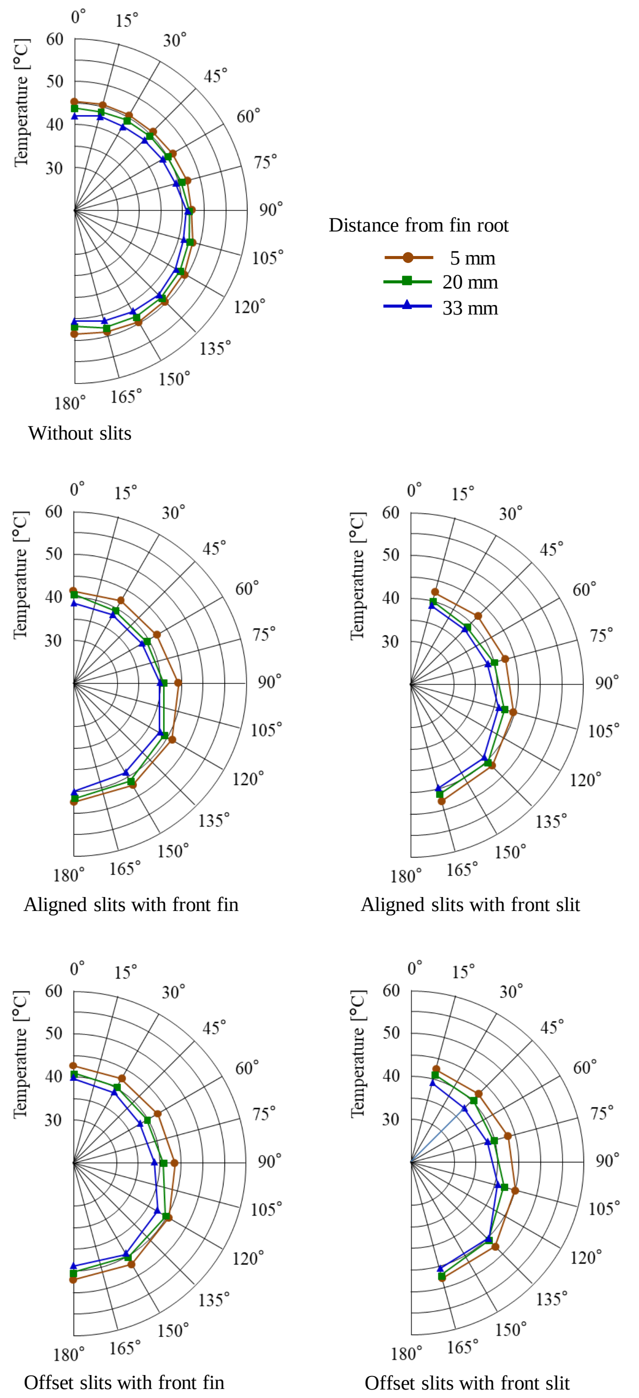


Fig. 6. Fin surface temperatures at an air velocity of 60 km/h (16.7 m/s)

In the fins without slits, the differences between the maximum and the minimum temperatures at the fin root were Δ10.0°C at an air velocity of 20 km/h (5.6 m/s), Δ6.6°C at an air velocity of 40 km/h (11.1 m/s) and Δ4.6°C at an air velocity of 60 km/h (16.7 m/s). Compared to the fins without slits, the differences between the maximum and the minimum temperatures at the fin root, with the slits aligned with the front fin and with the front slit, and with the slits offset with the front fin and with the front slit, were smaller at a lower air velocity, but tended to be almost the same or slightly larger at a higher air velocity. It seems that, at a lower air velocity, in all slit arrangements, air flow is disturbed between the fins, and the flow separation position moves to the rear side, decreasing the differences between the maximum and the minimum temperatures at the fin root. Figure 7 shows the flow pattern on the surface of the second fin from the top, at an air velocity of 60 km/h (16.7 m/s), observed using the oil film method in our previous study [15].

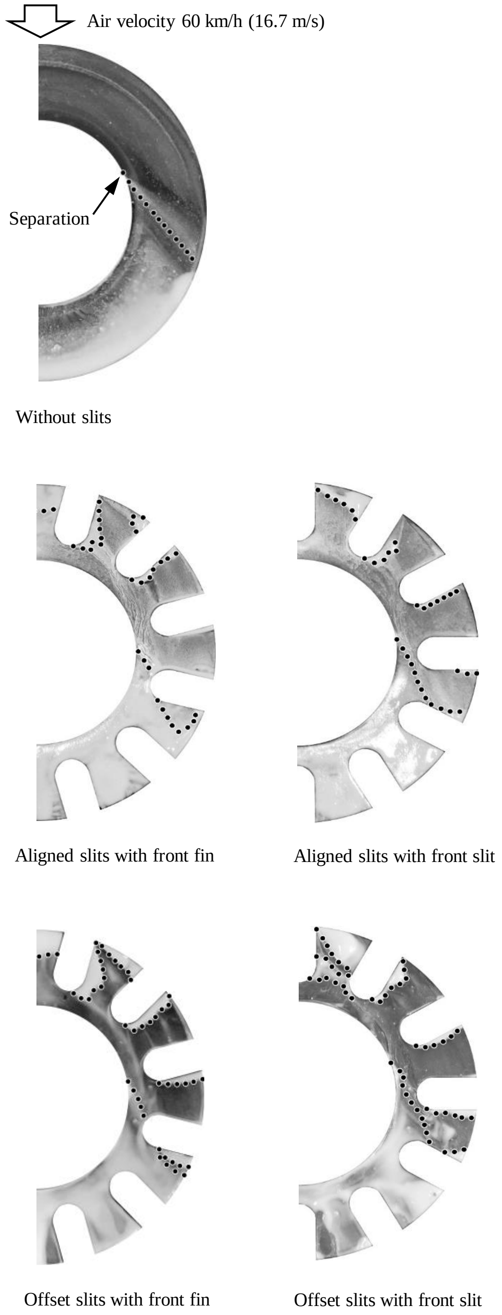


Fig. 7. Observed flow pattern on fin surface between fins at an air velocity of 60 km/h (16.7 m/s) [15]

As shown in Fig. 7, at a higher air velocity, the flow separation position is located at the rear side, even in fins without slits. The flow separation position moves further to the rear side, both in the slits aligned with the front fin and the front slit, and in the slits offset with the front fin and the front slit. These flow separation positions observed with the oil film method did not coincide with the angle positions where the temperature drop was smaller in the slits aligned with the front fin and the front slit, and in the slits offset with the front fin and the front slit, compared to the fins without slits. However, from our fin surface temperature measurements, compared to the fins without slits, the effect of the slits was greater at angle positions of 0° to 150°, but smaller at angle positions of 165° to 180°. As a result, at a higher air velocity, the differences between the maximum and the minimum temperatures at the fin root in all slit arrangements tended to be roughly the same or slightly larger than without slits.

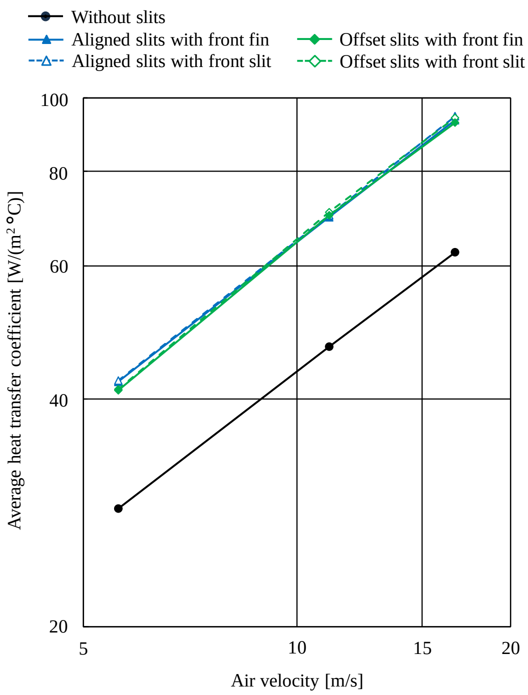


Fig. 8. Average heat transfer coefficient vs. air velocity

Figure 8 shows the average heat transfer coefficient versus air velocity for all slit arrangements and without slits. In all air velocities, the heat transfer coefficients for all slit arrangements were higher than those without slits. For example, the heat transfer coefficient with the slits aligned with the front fin was 47% to 49% higher than that without slits. However, there was no significant difference in the heat transfer coefficient between slits aligned with the front fin and with the front slit, and slits offset with the front fin and with the front slit.

The heat transfer rates from the cylinders with slits and without slits have been investigated by measuring the temperature drop of the heat storage liquid in the cylinder, in our previous study [15]. The result indicated that the heat transfer rate is in descending order of slits aligned with the front fin > slits offset > slits aligned with the front slit > without slits. The reasons why there was no significant difference in the heat transfer coefficient depending on the slit arrangements in this study, are thought to be as follows: First, the ambient temperature was higher than that in our previous study [15], second, the surface temperature on the root side of the slit was not measured, and third, the temperatures on the circumference were examined by attaching thermocouples to only three points on the surface of the fin and rotating the cylinder at 15° intervals from 0° on the windward side to 180° on the leeward side. Our future work will attach thermocouples on the circumferential surfaces of the root side of both the fins and the slits from the windward to leeward sides, in all slit arrangements, simultaneously measure the temperatures around the fin circumference, and then examine the heat transfer coefficient.

4. Conclusions

Using finned cylinders with slits around the fin circumference, the fin surface temperature distribution and the heat transfer coefficient were examined under forced convection. Results show the fin surface temperatures at each angle and radial position were lower, and the heat transfer coefficient was higher, for both fins with aligned slits and with offset slits, than for fins without slits. Compared to fins without slits, the fins both with aligned slits and with offset slits also had more uniform circumferential temperatures at the fin root at a lower air velocity, but not at a higher air velocity.

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Prof. Kohei Nakashima, DEng. – Department of Vehicle and Mechanical Engineering, Meijo University, Nagoya, Japan.
e-mail: *nakasima@meijo-u.ac.jp*

Ayanari Yoshida, BEng. – Department of Vehicle and Mechanical Engineering, Meijo University Graduate School, Nagoya, Japan.
e-mail: *253431022@ccmailg.meijo-u.ac.jp*

Ass. Prof. Masao Yoshida, DEng. – Department of Vehicle and Mechanical Engineering, Meijo University, Nagoya, Japan.
e-mail: *yosida@meijo-u.ac.jp*

Prof. Nobuyuki Okura, DEng. – Department of Vehicle and Mechanical Engineering, Meijo University, Nagoya, Japan.
e-mail: *ohkura@meijo-u.ac.jp*

Kento Nishii, MEng. – Department of Vehicle and Mechanical Engineering, Meijo University Graduate School, Japan.
e-mail: *23343106@ccalumni.meijo-u.ac.jp*