

Development of Variable Cooling System Aimed at Fuel Economy Improvement of Air-cooled Engine for Scooters

Tomokazu KOBAYASHI*

Kazuyuki KOSEI*

Satoshi IJIMA*

ABSTRACT

A variable cooling system was developed for a scooter equipped with an air-cooled, four-stroke, and single-cylinder gasoline engine. In this system, slats of the louver, located at the inlet of cooling air, are opened or closed by an oil-temperature-sensitive actuator. These slats shut off the supply of cooling air when the engine is in cold state or is driven with a low load. These operations of the slats help the engine oil temperature increase and the workload of the cooling fan decrease when the vehicle is running with a low load. With those effects, reduction of the mechanical loss is made possible. In addition, shortened warm-up time enables reduction of the injection fuel amount. As a result, fuel economy improvement of 3.3%, when driven in Urban Driving Cycle, was realized.

1. Introduction

Due to the body structure of scooters, driving wind never comes into direct contact with scooter engines. Thus, in forced air-cooled scooter engines, the cylinder head area is cooled by a fan connected directly to the crankshaft: across all temperatures, whether cold or hot, the engine is fed a constant supply of cooling air in proportion to engine speed. Further, engine cooling capacity is set such that the vehicle can be driven without issue even in the hottest and harshest of conditions. For these reasons, the engine is frequently supercooled after cold engine start-up and during low load driving, and driving in this supercooled state decreases fuel economy. This phenomenon is caused by the relationship between engine oil temperature and viscosity: viscosity resistance increases as the driving temperature decreases, in turn increasing the mechanical loss. One solution to this issue is a variable cooling system, in which cooling capacity changes with engine temperature. Such systems are already common in water-cooled engines. Some typical systems use a thermostat to switch the path of circulation for coolant or intermittently use a motor-driven radiator fan. Also, one system specific to four-wheeled vehicles uses openable slats to control the heat released by the radiator⁽¹⁾⁻⁽³⁾. However, to date, no variable cooling systems exist for forced air-cooled engines on two-wheeled vehicles.

In recent years, scooters are rapidly seeing more widespread use in the Asian region which is the major market of smaller two-wheeled vehicles. With the world now looking

to reduce overall CO₂ emissions, the demand is increasing for improved fuel economy in forced air-cooled scooter engines. Given the above background, the authors first studied the losses resulting from constant forced cooling. Then, based on the results, they have proposed a variable cooling system that controls the cooling air volume according to engine oil temperature. The proposed system opens and closes slats installed on the cooling air inlet using a temperature-sensitive actuator that operates when the engine oil temperature reaches a set value. The authors' intention with the system was to prevent engine supercooling for improved fuel economy.

2. Cooling Configuration of the Air-cooled Scooter

Figure 1 shows an external view and the engine mounting position for a motorcycle with an air-cooled engine (hereafter the "air-cooled motorcycle"), and Fig. 2 shows the same for a scooter with an air-cooled engine (hereafter the "air-cooled scooter").

The air-cooled motorcycle is configured such that driving wind will directly hit the cylinder head and cylinder, which are located at the front of the engine and colored red. This structure allows for cooling with driving wind only. Meanwhile, with the air-cooled scooter, the cowl and luggage box cover most of the engine, again colored red. As such, driving wind cannot be expected to cool the cylinder head and cylinder at the front of the engine. To supplement this cooling insufficiency, the scooter air-cooled engine

* Motorcycle R&D Center

is equipped with a fan attached directly to one side of the crankshaft for forced cooling with the generated blown air. This cooling air is continuously blown over the cylinder head and cylinder. The blown air volume depends on the engine speed. Figure 3 shows the mounted location and construction of the cooling fan.



Fig. 1 Air-cooled motorcycle



Fig. 2 Air-cooled scooter

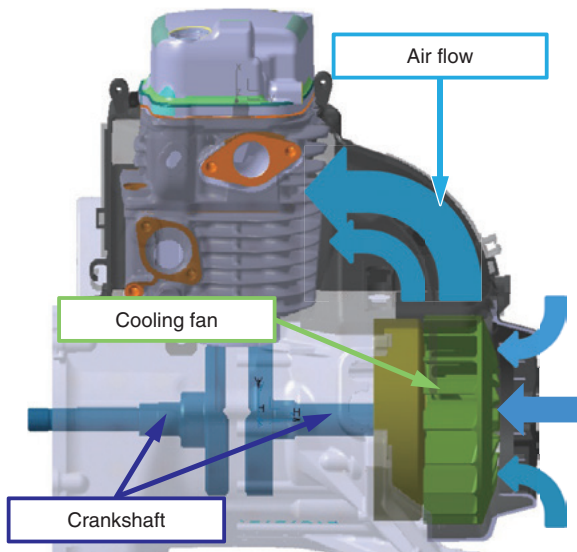


Fig. 3 Location and construction of cooling fan

3. Issues Created by a Forced Cooling Structure

With the cooling air continuously blowing, air-cooled scooters run at lower oil temperatures than air-cooled motorcycles. Thus, air-cooled scooters are assumed to have even greater driving energy loss than air-cooled motorcycles. This section will explore exactly what kind of loss occur due to forced cooling.

3.1. Test Vehicles

Table 1 shows the specifications for the air-cooled scooter used in this study, as well as the air-cooled motorcycle presented in the following clause used for comparison purposes. Both vehicles possess roughly the same displacement, output, and vehicle mass.

3.2. Oil Temperatures while Driving for Different Cooling Methods

The test vehicles described in the previous clause were first put through modal testing before measuring and comparing their oil temperatures. The driving cycle used for testing was the Urban Driving Cycle (UDC) as stipulated in Annex II 2.2.1.1.5 of Chapter 5 in EU Directive 97/24/EC, as amended by Directive 2002/51/EC. UDC is a low load driving cycle which simulates driving in urban and similar other environments. The test drives were performed on a chassis dynamometer with a rolling resistance of ISO 170 kg and a room temperature of $25 \pm 5^\circ\text{C}$.

Upon completion of the UDC test drive, the oil temperature in the oil pan (hereafter T_c) of the air-cooled scooter was approximately 65°C . In comparison, that of the air-cooled motorcycle was approximately 85°C . Therefore, oil temperature was roughly 20°C lower with forced cooling.

This temperature difference is attributed to excessive cooling by the cooling fan and a lack of mechanical heat with no gear shift mechanism or clutch in the oil pan on the air-cooled scooter.

3.3. Issues Created by Forced Cooling

In order to clarify the issues created by forced cooling, first, operating oil temperatures were confirmed for the air-cooled scooter with and without forced cooling to see how much the temperature difference was. For the experiment, two methods were used to stop forced cooling: removing the cooling fan and shutting off the cooling air. For shutting off the cooling air, a closure was placed over the cooling air inlet. The experimental criteria for the air-cooled scooter are listed in Table 2.

Figure 4 shows the change in oil temperature in the oil pan for UDC driving. In the figure, the black line represents the temperature with the cooling fan, the red line that with the cooling fan removed, and the blue line that with cooling air shut off. When driving continuously in UDC both with the cooling fan mounted and removed, temperature was checked when the oil pan oil temperature had sufficiently leveled off.

Table 1 Specifications of experimental vehicles

Item	Forced air-cooled scooter	Air-cooled motorcycle
Engine type	4-stroke single-cylinder	4-stroke single-cylinder
Cooling system	Forced air-cooled	Naturally air-cooled
Bore × Stroke	50.0 mm × 55.1 mm	50.0 mm × 55.6 mm
Displacement	108.2 cm ³	109 cm ³
Compression ratio	9.5	9.3
Fuel supplying system	Fuel injection	Fuel injection
Transmission type	Belt drive (CVT)	4 MT
Maximum power	6.6 kW at 7500 rpm	6.5 kW at 7500 rpm
Maximum torque	9.2 Nm at 5500 rpm	8.8 Nm at 6000 rpm
Curb weight	99 kg	98 kg

Table 2 Experimental criteria

	With forced cooling	Without forced cooling	
	With cooling fan	Without cooling fan (a)	Shut off cooling air (b)
Fan diameter	130 mm		130 mm
Fan type	Centrifugal turbo fan		Centrifugal turbo fan

Both with the cooling fan removed and the cooling air shut off, the oil temperature at completion of UDC driving was approximately 79°C – approximately 15°C higher than that with the cooling fan. Also, when driving continuously in UDC, oil temperature was nearly stable at approximately 70°C with the cooling fan and approximately 103°C with the cooling fan removed. This illustrates that forced cooling is unnecessary when driving in low load conditions.

Next, Fig. 5 shows temperatures of various engine parts with the cooling fan removed when driven at full load (continuous full load at maximum speed). In the figure, the red line represents the temperature of the spark plug seat, the blue line that of the cylinder, and the brown line that of the oil in the oil pan. Note here that for the experiment, full load driving was stopped once spark plug seat temperature reached the maximum plug seat temperature for the air-

cooled motorcycle, shown here in green.

When driven at full load with the cooling fan removed, spark plug seat temperature reached the maximum temperature for the air-cooled motorcycle in approximately 250 seconds. The findings illustrate that forced cooling is essential when driving at full load.

From the test results above, the presumed causes of fuel economy decrease with forced air-cooling are as follows:

- (1) When driving at low loads, oil temperature is low and mechanical loss is high.
- (2) When the engine is cold, the fuel injection quantity is corrected to be higher than that when the engine is warm. Accordingly, more fuel is consumed if the engine is kept cold for extended periods.
- (3) In low load driving, unnecessary cooling fan driving loss is generated.

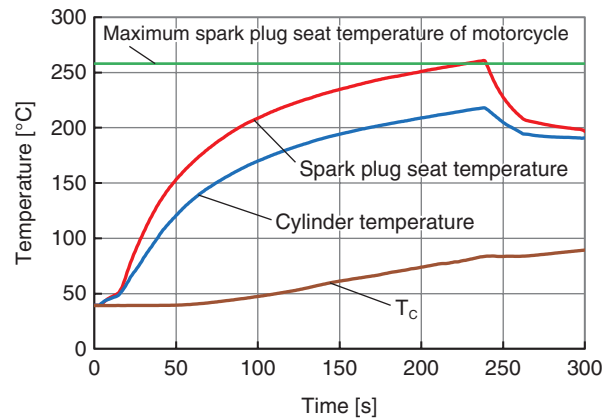


Fig. 5 Temperatures of engine parts when driven at full load without forced cooling

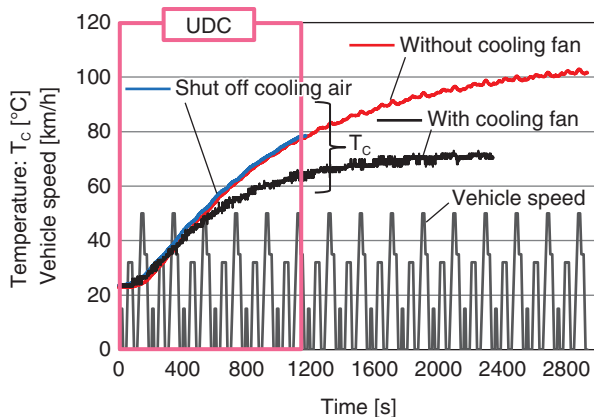
4. Determining Loss due to Forced Cooling

Further testing was performed to determine how much fuel economy decreased due to loss from the presumed causes above. The results for each item are presented below.

4.1. Difference in Engine Mechanical Loss with and without Forced Cooling

The relationship between oil temperature and kinetic viscosity is shown by the red line in Fig. 6. The engine oil used had an SAE viscosity grade of 10W-30 and SJ grade by API standards. In the figure, the green and blue lines represent the relationship between the oil temperature and kinetic viscosity in the oil pan when driven in UDC with the cooling fan removed and with the cooling fan mounted, respectively. With forced cooling stopped, the oil temperature reached 79°C and kinetic viscosity reached 16.8 mm²/s. With forced cooling, the oil temperature reached 65°C and kinetic viscosity reached 26.2 mm²/s.

Next, the difference in engine mechanical loss resulting

Fig. 4 Change in T_c when driving in UDC

from this difference in kinetic viscosity was confirmed. The engine was tested alone using the motoring method. The test results are shown in Fig. 7. At engine speeds of 3500-5500 rpm when driving in UDC, the difference in mechanical loss was 60-110 W.

4.2. Increased Fuel Injection Quantity due to Low Oil Temperature

Next, the impact of difference in oil temperature on fuel injection quantity was confirmed.

The fuel injection systems used in water-cooled engines can generally correct and control the fuel injection quantity based on the parameters of intake air temperature and coolant temperature. In similar fashion, the test vehicles with their air-cooled engines correct and control the fuel injection quantity using the oil temperature parameter. Oil temperature using this control (hereafter T_H) is measured by a sensor mounted to the cylinder head. The changes in T_C and T_H when driving in UDC are shown in Fig. 8. In the figure, the blue line represents the results with forced cooling and the red line those without forced cooling, with bold lines for T_C and thin lines for T_H . As with T_C , there is a difference in the T_H with and without forced cooling: the difference in oil temperature reached upon completion of

driving in UDC is approximately 20°C.

Next, the authors confirmed the difference in the correction coefficient of injected fuel (hereafter K_{TW}) as brought about by the temperature difference for T_H . The relationship between T_H and K_{TW} is shown in Fig. 9. The changes in T_H and K_{TW} when driving in UDC are shown in Fig. 10. Here, the bold lines are with no forced cooling,

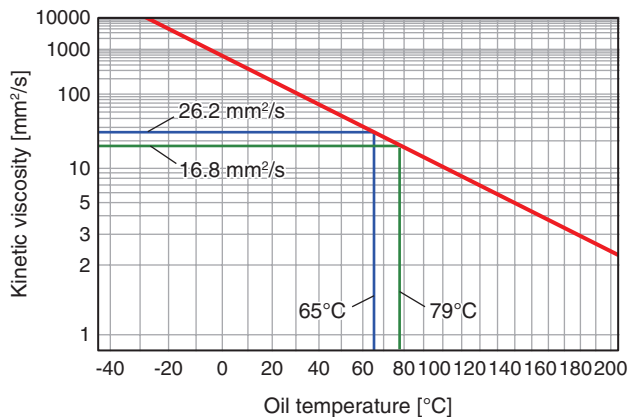


Fig. 6 Kinetic viscosity at various oil temperatures

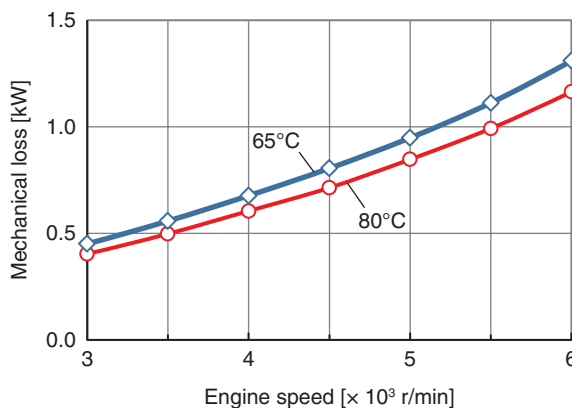


Fig. 7 Engine mechanical loss at various T_C

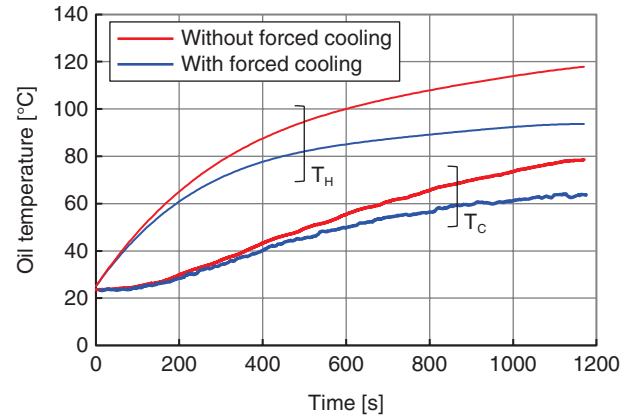


Fig. 8 Change in T_C and T_H when driving in UDC

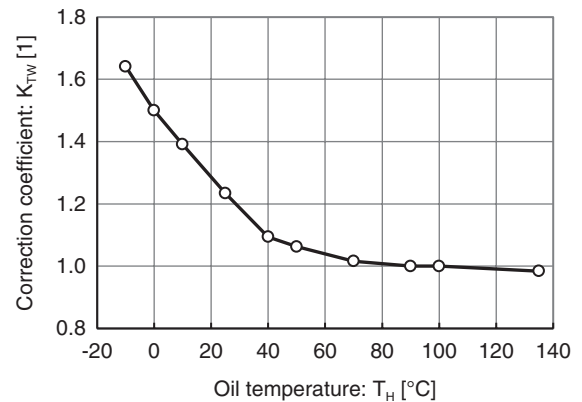


Fig. 9 Relationship between T_H and K_{TW}

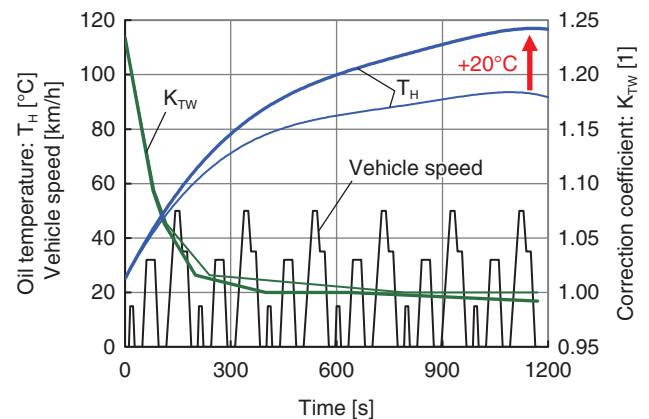


Fig. 10 Changes in T_H and K_{TW} when driving in UDC

and the thin lines are with forced cooling. K_{TW} is a set value with T_H as a parameter. The correction coefficient of the engine with forced cooling takes longer to reach a value of 1. Put another way, it takes longer for the fuel injected with forced cooling to reach the set value than it does without forced cooling. There was a calculated difference of 0.92 mL in correction for injected fuel between the engine with and without forced cooling when driving in UDC. Thus, supercooling lengthens the time the engine is cold and increases injected fuel by 0.92 mL.

4.3. Cooling Fan Driving Loss

In the last step, drive loss of the cooling fan was evaluated. The evaluation was conducted by measuring the mechanical losses of the engine applying motoring method under the three conditions shown in Table 2. The mechanical loss measured without equipping a cooling fan was set as the base value, and the differences between this base value and the results measured in two other conditions, with equipping the cooling fan, were defined as the cooling fan drive losses. The results are shown in Fig. 11.

In the figure, the black line shows the cooling fan driving loss with forced air-cooling, and the red line shows that with cooling air shut off. At an engine speed of 9500 rpm, the cooling fan generated 450 W of driving loss.

Meanwhile, with cooling air shut off, the cooling fan generated 200 W of driving loss at an engine speed of 9500 rpm. This difference is explained by air being sucked through the gap between the crankcase and fan cover, and by air being sucked out of the cooling air outlet when there is negative pressure within the fan cover. Still, cooling fan driving loss is reduced to less than half that with forced cooling.

4.4. Predicted Improvement to Fuel Economy with Mechanical Loss Reduction

Next, the authors will predict how much fuel economy is improved by reducing the loss as calculated through the

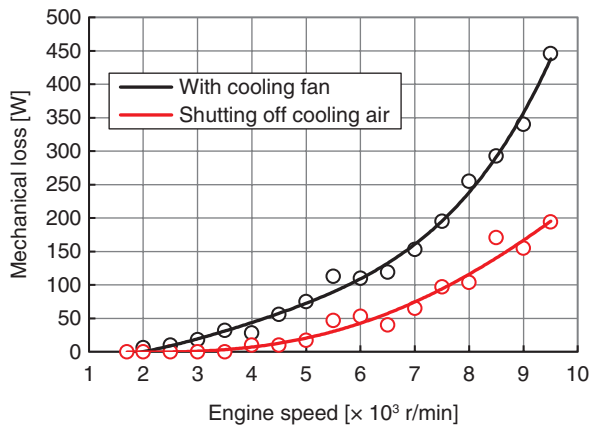


Fig. 11 Cooling fan driving loss at various engine speeds

Table 3 Calculations of fuel economy in UDC

Conditions	Fuel consumption (mL)	Fuel economy (km/L)	Improvement (km/L)
With cooling fan	103.20	57.80	-
Without cooling fan	99.28	60.10	2.30
Shutting off cooling air	99.75	59.80	2.00

preceding section. These predictions were made by finding the cumulative fuel consumption for UDC driving using the engine speed, output, and fuel consumption data from the engine test. The reduction in engine mechanical loss from the increased oil temperature reduced fuel consumption by 1.07 mL. As already mentioned, fuel injection is enriched by 0.92 mL due to the correction coefficient. With the cooling fan removed, fuel consumption reduced by 1.93 mL. With cooling air shut off, consumption reduced by 1.46 mL.

Fuel economy improvement for UDC driving was estimated based on these results. The estimates are summarized in Table 3.

First, for the reference, the engine with cooling fan consumed 103.20 mL in fuel for a fuel economy of 57.8 km/L.

Next, with the cooling fan removed, fuel consumption was 99.28 mL and fuel economy improved 4.0% to 60.1 km/L. Finally, with the cooling air shut off, fuel consumption was 99.75 mL and fuel economy improved 3.5% to 59.8 km/L. Figure 12 shows the breakdown of the fuel economy improvements both with the cooling fan removed and with the cooling air shut off.

Thus, the results from the basic experiments for this study illustrate that forced cooling, while not essential when driving at low loads, is needed when driving at full load. Further, the energy loss from forced cooling for UDC driving was successfully estimated.

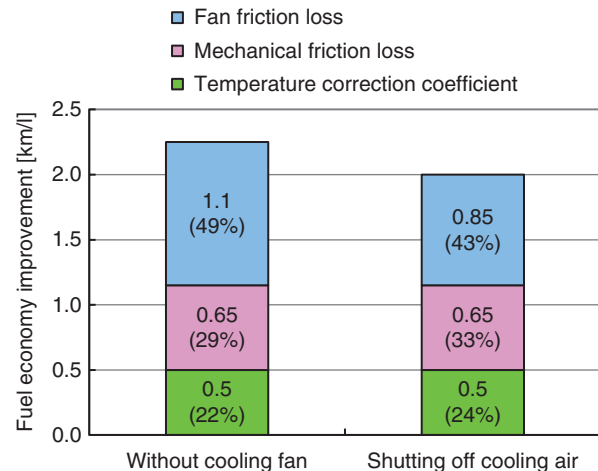


Fig. 12 Detailed fuel economy improvements

5. Investigation of Variable Cooling Systems

Based on the results presented in the previous section, the authors investigated the possibilities of a variable system capable of forced cooling only when needed. Such a system is expected to improve fuel economy when forced cooling is unnecessary.

5.1. Selection of a Variable Method

Two methods were investigated: the first involves using an interrupting mechanism to separate the cooling fan from the crankshaft, and the other uses movable slats to shut off cooling air. The conceivable options for interrupting the cooling fan driving force are application of a motor, electromagnetic clutch, or fluid clutch. Each of these options is used to interrupt the driving force of the radiator cooling fan in water-cooled engines. Applying any of these mechanisms to a scooter engine, however, would require structural changes to the engine that would increase body width and restrict the lean angle when driving. Meanwhile, the air inlet can basically be used to shut off cooling air with structural modifications to the engine side cover components. While this will increase body width, it will not restrict the lean angle. Therefore, in consideration of mountability on the completed vehicle, shutting off cooling air was the method selected in this study.

For shutting off cooling air, there are three conceivable options for the power source to make the slats movable: a thermal actuator, a motor, or a solenoid. Thermal actuators are heat sensitive and require no power. Further, actuators are relatively compact and offer layout advantages for the completed vehicle. This power source is also the most inexpensive option. For motors and solenoids, while relatively lower cost on/off-type units are also available, the requirement of a control CPU still makes them more expensive than thermal actuators. Thus, given the low price demands, motors and solenoids are not suited to use in compact scooters. From the above, a movable louver mechanism using a thermal actuator was selected as the variable cooling system.

5.2. Overview of the Variable Cooling System

The construction of the thermal actuator is shown in Fig. 13.

When in use, the temperature probing point of the thermal actuator is immersed in the engine oil. The thermal actuator is constructed such that wax (shown in purple in the figure) sealed in the temperature probing point expands as the oil in the oil pan rises in temperature to extrude the shaft (blue).

The construction of the variable cooling system is shown in Fig. 14.

The thermal actuator (yellow) is installed on the side of the crankcase. The extruded shaft then operates slats positioned on the cooling air inlet via a linkage mechanism

(within the pink border). Lost motion springs are installed to synchronize the operating angle of the slats. The linkage mechanism is made of PP-GF20.

In this system, the most critical point to ensuring the fuel economy improvements is to maintain the seal when fully closed with no gap between the slats. However, cumulative dimensional errors in the forming of the plastic slats and their driving components could prevent the system from staying airtight. Therefore, the cooling fan driving loss was investigated at various slat clearances (Fig. 15).

No difference in driving loss was observed with no gap and with 0.5 mm gaps between slats. With 1.0 mm gaps, however, a driving loss of approximately 23 W occurred at an engine speed of 9500 rpm. The impact to fuel economy was also estimated using the previously presented method. Fuel economy was unaffected with 0.5 mm gaps but was lowered by 0.02 km/L with 1.0 mm gaps. These results confirmed that the clearance between slats in their fully closed position must be kept to 0.5 mm or lower.

To resolve this issue, the system was structured with lost motion springs fitted to each of the slats so that each slat

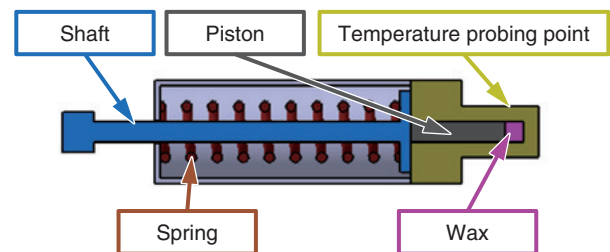


Fig. 13 Construction of thermal actuator

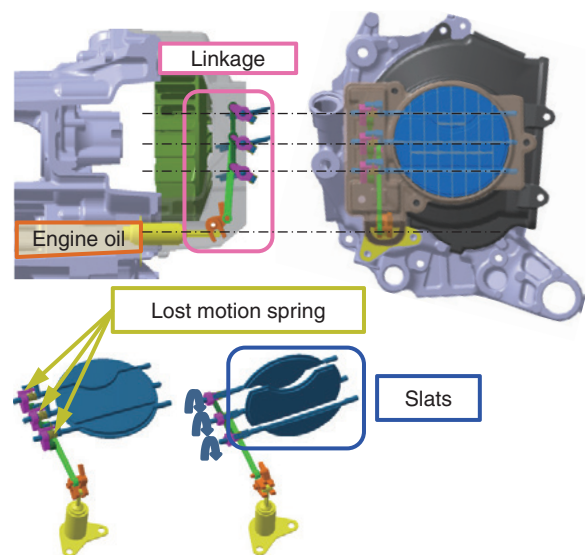


Fig. 14 Construction of variable cooling system

can be closed independently. With this, the three slats can be synchronized without an adjuster mechanism.

Figure 16 shows the relationship between the oil temperature, slat operating angles and generated air flow volume. In the figure, the red line represents the slat operating angles, the blue line the generated air flow volume, and the green line the target air flow volume. The thermal actuator actuates at 97°C . The actuation temperature was set with tolerance for the thermal actuator response delay at the speed with which oil temperature increases when driving at full load. At an oil pan oil temperature of 110°C , the slat angles were set to 73° to ensure the target air flow volume.

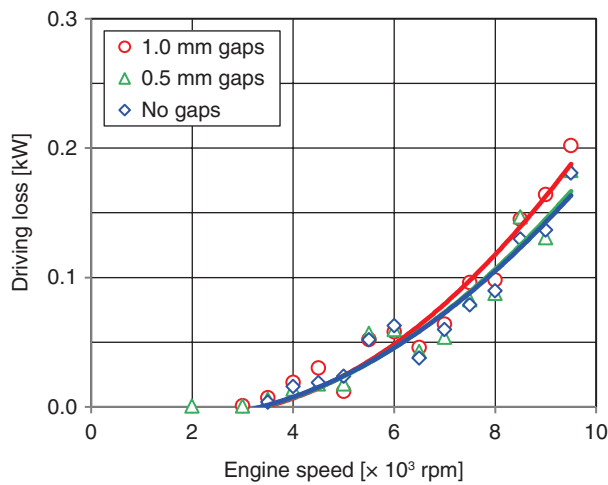


Fig. 15 Cooling fan driving loss at various slat clearances

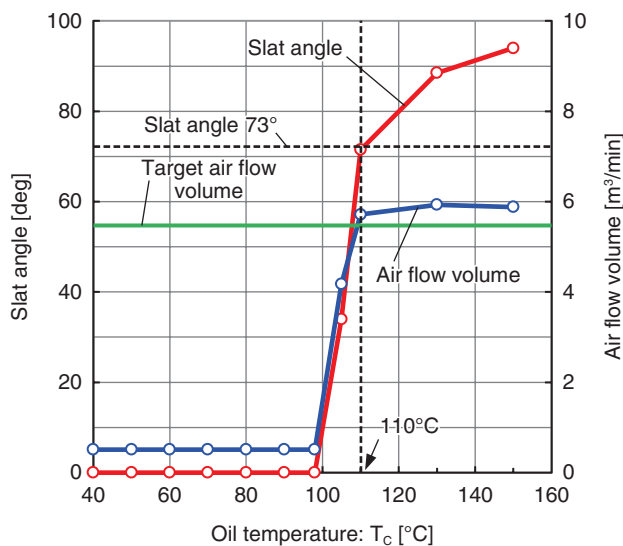


Fig. 16 Relationship among T_c , slat angles, and generated air flow volume at 7500 rpm

6. Verification of Fuel Economy Improvements for the Variable Cooling System

A vehicle equipped with the variable cooling system was driven in UDC to measure oil temperatures in the oil pan and fuel economy. The changes in oil temperature in the oil pan are as shown in Fig. 17. In the figure, the black line represents the base scooter, and the red line represents the scooter with the variable cooling system. The oil temperature of the scooter with the variable cooling system reached the same 79°C at completion of UDC driving as shown in Fig. 4. This confirms that the slat mechanism functions to shut off cooling air as intended.

The objective of this study – fuel economy improvement – was 2.1 km/L, or 3.3%. This result roughly matches with the previously presented estimates.

In addition, the fuel economy improvements of the variable cooling system when driving in WMTC (class 1) were also confirmed. The results were the same as in UDC: fuel economy improved by 2.1 km/L, or 3.4%. The changes in oil temperature when driving in WMTC are as shown in Fig. 18.

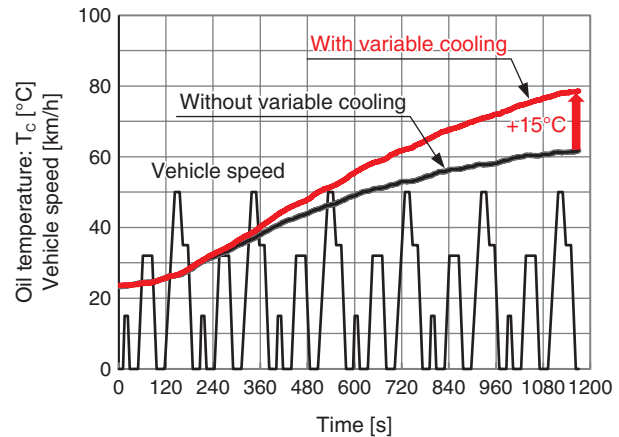


Fig. 17 Change in T_c with variable cooling system when driving in UDC

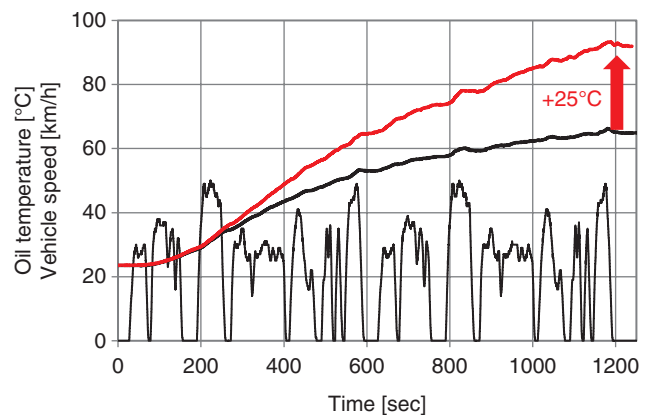


Fig. 18 Change in T_c with variable cooling system when driving in WMTC (class 1)

Table 4 Outline of in-house urban driving cycle

Distance [km/cycle]	1.0
Vehicle speed [km/h]	0-40
Engine speed [r/min]	1700-5500
Throttle opening [%]	0-50

In both UDC and WMTC, the variable cooling system louvers remained closed as engine oil temperatures did not reach the actuation temperature of the thermal actuator. With this, the vehicle was driven assuming urban conditions until the actuator was actuated, measuring fuel economy for each cycle. The driving cycle used for this test was an in-house driving cycle estimating urban driving in ASEAN countries and India (hereafter IUDC). An overview of IUDC is shown in Table 4. The tests room temperature was kept at $25\pm5^{\circ}\text{C}$ during measurement.

The vehicle was driven with a cold engine for 30 cycles (30 km) of IUDC, measuring the changes in oil temperature and fuel economy over time for each cycle. The changes in oil temperature are as shown in Fig. 19, and the changes in fuel economy are as shown in Fig. 20.

After nine cycles, the louvers started to open and oil

temperature started to drop. After driving 30 cycles with and without the variable cooling system, the oil temperature difference was 23°C . Thus, the fuel economy effects were maintained on the vehicle with the variable cooling system. Average fuel economy for the 30 cycles with and without the variable cooling system was 58.6 km/L and 56.7 km/L, respectively, giving the edge to the vehicle with the variable cooling system. Fuel economy improved by 1.9 km/L, or 3.4%. These results show that the variable cooling system has a great impact on fuel economy even in low load, low speed urban driving.

7. Conclusion

In this study, the authors quantitatively determined the loss generated by the cooling fan of forced air-cooled scooter engines. Based on the results, they proposed a variable cooling system that controls the cooling air volume based on engine oil temperature with the objective of improving fuel economy. Upon verifications on an actual vehicle, the proposed system achieved the intended results, functioning to shut off cooling air and improving fuel economy by 2.1 km/L (3.3%) in UDC and 2.1 km/L (3.4%) in WMTC (class 1).

References

- (1) JP, 60-066824 (1985)
- (2) JP, 1760870 (1992)
- (3) JP, 62-501864 (1987)

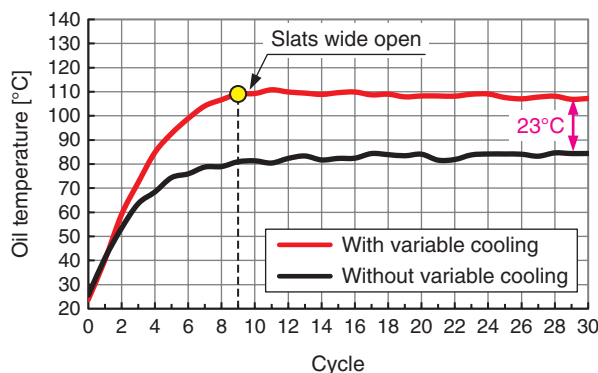


Fig. 19 Changes in oil temperature in oil pan in IUDC

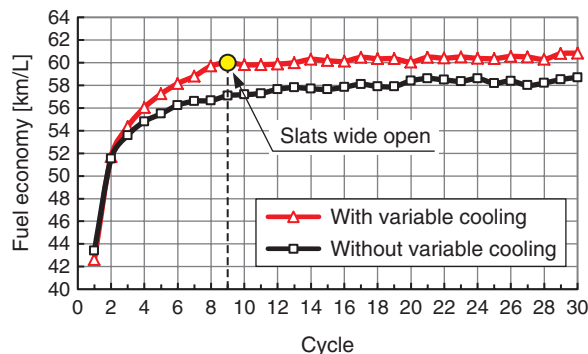


Fig. 20 Changes in fuel economy in IUDC

■ Author ■



Tomokazu KOBAYASHI



Kazuyuki KOSEI



Satoshi IJIMA