技術論文

# Study on appropriate cooling systems according to output of motor for small EV's

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要旨

小型EVにとって、小型軽量モータは非常に重要であり、出力に応じて適切な電動コンポーネント冷却方式（液冷、空冷）を選定することは必須となる。

液冷を選定する場合、液冷システムの体積、重量も考慮する必要があり、上記システムを含んだ状態でも小型軽量化が可能となる出力の切り替わり点があると考えた。

概算した結果、10kW以上の出力域で液冷を適応することにより重量低減可能であることがわかった。

本研究では、モータと冷却システム両方を含んだ状態での体積・重量に着目し、モータ出力ごとに適切な冷却方式の明確化を試みた。

Abstract

It is important to make small and light weight motor for small EV.

It is necessary to select appropriate cooling system (liquid cool or air cool) according to motor output. We thought that there is a threshold output that makes the volume smaller and the weight lighter including the liquid cooling system.

As a result of the rough calculation, it was found that the weight can be reduced by adopting the liquid cooling for at about 10kW or more.

In this study we focused on motor and cooling system volume and weight and tried to clarify appropriate cooling system according to motor output.

## 1 INTRODUCTION

In recent years, the development of electric vehicles (EV) has been actively pursued in response to environmental issues such as the reduction of carbon dioxide emissions. It is also thought that electric drive technology will be increasingly applied to motorcycles in the future.

However, as motorcycles generally have less space available and are light-weight, there is a requirement for a reduction in the size and weight particularly of the high-level EV components and overall systems used.

The means used for reducing the size and weight of the motor include higher motor rotation, adoption of flat wire, and improvements in cooling efficiency. However, in this paper, we intend to focus mainly on cooling methods. The output of compact personal mobility such as motorcycles ranges from several kW to several tens of kW.

When converting them to electric vehicles, it is necessary to select the appropriate cooling method according to a model's output level.

To date, there have been many research reports on the size and weight reduction of motors and cooling methods[1], but few reports that focus on the appropriate cooling method (air- or water-cooling options) depending on a model's output level.

Fig.1 plots output/voltage/cooling method of YMC and other manufacturer motors which are adopted for EV or HEV.

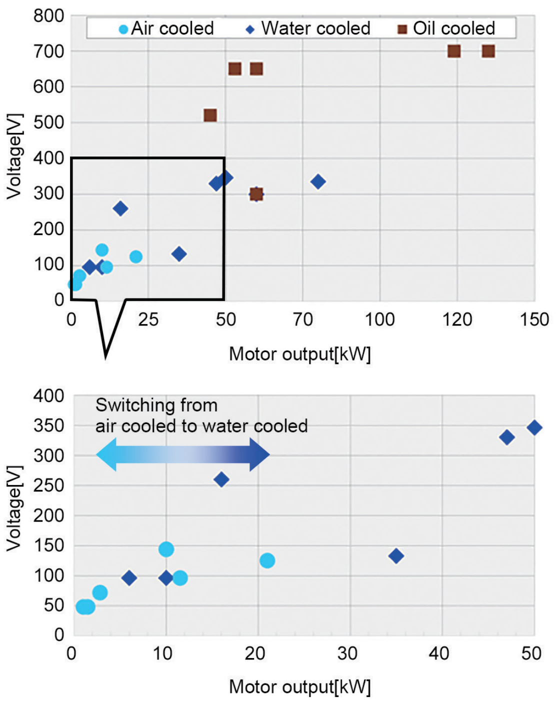



Fig. 1 Output/Voltage/Cooling method of Electric Motor

From Fig 1, it can be seen that switching from air cooled to water cooled is performed with a motor output of about 10 kW.

In this paper, with a focus on the motor, we derived output that makes it possible to reduce the volume and weight of the motor even if it includes a water-cooling system (radiator, pump, etc).

## 2 TEST RESULT OF AIR-COOLED MOTER DESIGNED FOR ELECTRIC MOTERCYCLES

To date, Yamaha Motor has continued to promote the development and commercialization of electric motorcycles.

Even though the output of its commercialized model is only in the 1kW class, development is also in progress for more high-powered options in the future (Fig. 2).

First, in this session, we will explain the motor structure which is the basis of the air-cooled and water-cooled motor of this study.

Fig. 2 Prototype Model (2015 Tokyo Motor Show)

### 2-1. Basic Structure of Motor

The key components of an electric motor using permanent magnets are a component with a coil wound on an iron core called a stator, and a rotating component called a rotor that has a magnet fitted to an iron core.

Current is supplied to the coil of the stator to create a rotating magnetic field, and the rotor receives the rotating magnetic field and rotates to create the shaft output.

In order to use a compact high-efficiency motor which prevents the magnet scattering at high RPM, an Interior Permanent Magnet Synchronous Motor (IPMSM) was adopted for this study.

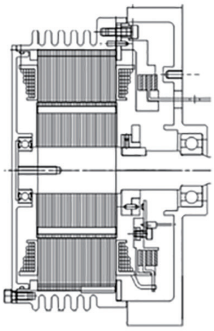
A requirement for downsizing an air-cooled motor designed for a motorcycle is achieving both durability and cooling performance.

In order to ensure durability, it is necessary to seal the interior of the motor room with a case.

In order to cool the coil held inside, a structure was adopted that the iron core with the coil wound on it is shrink-fitted to the aluminum case and cooled by using the outside air.

The motor is including concentrated winding, flat wiring, and a divided iron core to achieve downsizing.

We selected a form of inserting the wound wire toothed part into the outer diameter portion of the stator iron core, which achieved a reliable pressurized fitting on an aluminum case and ensured a narrow air gap with the rotor. (Fig.3, Fig.4)



| | Specifications |
|---|---|
| Type | IPMSM |
| Number of poles | 8 |
| Number of stator slots | 12 |
| Cooling system | Air cooling |
| System voltage[V] | 100 |
| Maximum motor power[kW] | 11.5 |
| Rated motor power[kW] | 10 |
| Maximum motor torque[Nm] | 32 |
| Volume[ℓ]※ | 1.7 |
| Air gap[mm] | 0.5 |
| Winding Type | Concentrated Winding |
| Coil resistance[mΩ] | 5.75/Phase |
| Connection | Y |

※volume of stator outer diameter part and coil end outermost part

Fig. 3 Drawing of Motor Assembly and its Specifications

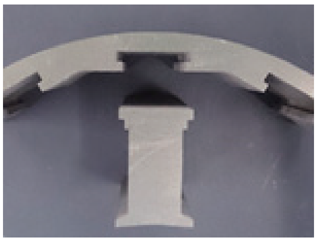


Fig. 4 Structure of Divided Core

The measuring devices used for this motor are shown below (Fig. 5).

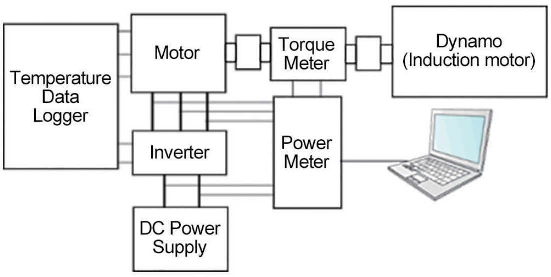



Fig. 5 Motor Test System

The graph below shows the torque characteristics for this motor (Fig. 6).

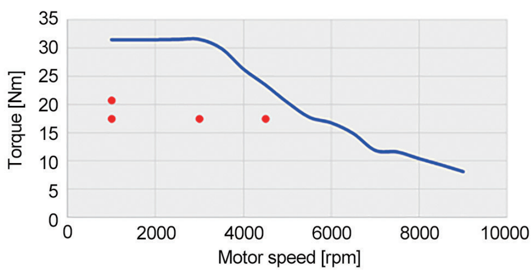



Fig. 6 Torque Characteristics

At the red points shown in Fig6, continuous operation for 60 minutes was carried out to measure the temperature of each material in the stator. The thermal resistance toward the outside air was then calculated from the obtained results.

The thermal resistance was calculated assuming that heat radiated only in the direction of the cooling fins.

In actual fact, although heat radiation works not only in the direction of the cooling fins, from a systematic calculation perspective, the above was used as the basis for consideration. The validity of this approach will be explained later.

In terms of copper loss, the calculation was carried out using the resistance value calculated from the temperature of the coil at end of the 60-minutes of operation.

With respect to the stator iron loss, from the motor loss measured by the power meter, mechanical loss measured beforehand by the rotor without magnet inserted, and the loss of magnet and the rotor core derived by analysis were deducted, and the result is adopted as the basis of our thermal resistance calculations.

The below data shows the temperature rise during air cooling based on a wind speed of 6m/s and a motor current of 130 Ap & 1000 RPM. (Fig.7)

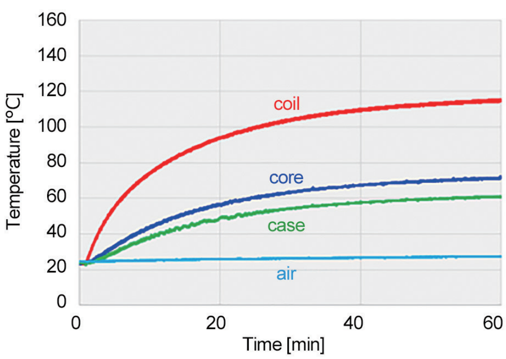
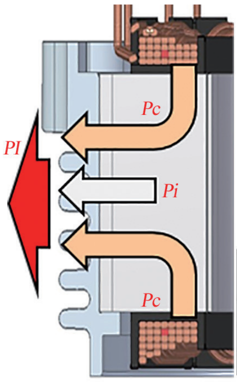



Fig. 7 Temperature Data at a Motor Current of 130Ap & 1000 RPM stem

The thermal resistance calculated from the temperature measurement result is shown as follows. (Fig.8)




| | |
|---|---|
| Coil Temp at 60min [°C] | 109.5 |
| Coil Resistance at 60min [mΩ] | 7.7 |
| *Pc* : Cupper Loss [W] | 258.3 |
| Iron & mechanical Loss [W] | 148.8 |
| Rotor Loss Estimate [W] | 13.8 |
| *Pi* : Stator Iron Loss [W] | 135.0 |
| *PI* : Stator Loss [W] | 337.3 |

| Passing Route | ⊿T[°C] | Passing Heat[W] | Thermal Resistance[K/W] |
|---|---|---|---|
| Coil ⇒ Core | 44.2 | 202.3 | 0.218 |
| Core ⇒ Case | 11.7 | 337.3 | 0.035 |
| Case ⇒ Air | 34.4 | 337.3 | 0.102 |

Fig. 8 Thermal Resistance Calculations from Test Results of Air-Cooled Motor

Similar calculations were carried out at other temperature measurement points, but the results were almost the same. Table 1 below shows the average values.

Table 1 Average Thermal Resistance Calculations from Test Results

| Passing Route | Thermal Resistance[K/W] |
|---|---|
| Coil ⇒ Core | 0.210 |
| Core ⇒ Case | 0.037 |
| Case ⇒ Air | 0.114 |

Using the above thermal resistance, the calculated value and the test results for the temperature rise of the coil at 5000 RPM and when powered at 130Ap were compared (Table 2).

Table 2 Comparison of Calculations and Test Results

| 5000rpm 130Ap | Calculation Result | Test Result |
|---|---|---|
| Coil Temp [℃] | 129.8 | 132.4 |

For air-cooled motors, it is assumed that sufficient accuracy is ensured with respect to temperature prediction, and, based on this, the above thermal resistance is used to estimate the temperature limit when the output changes.

Further details of how the size and weight of the air-cooled motor changes according to the output will be explained in Section 4.

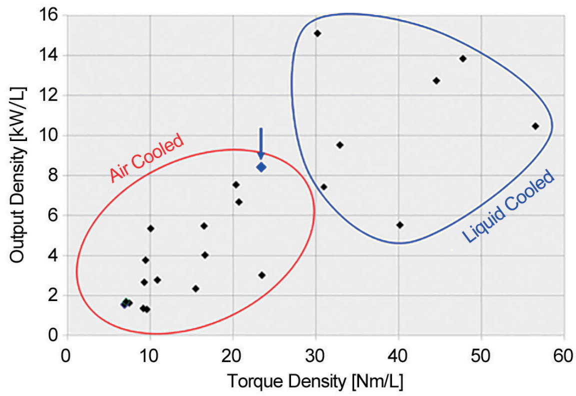



Fig. 9 Torque-Output Density of Motor

With a contribution from our own divided stator core, etc., we confirmed that a high level of downsizing was achieved in the air-cooling region.

## 3 TEST RESULT OF WATER-COOLED MOTER DESIGNED FOR ELECTRIC MOTERCYCLES

### 3-1. Basic Structure of Motor

The flow path was cut in the case portion of the air-cooled motor described in Section 2, and the motor was water-cooled and evaluated. Using this motor, water cooling and air cooling was compared, and the thermal resistance was calculated.

Detailed specifications have not been included here as the design of the magnetic circuit of the motor is the same as with the air cooling.
The water-cooling system is shown below in Fig. 10.

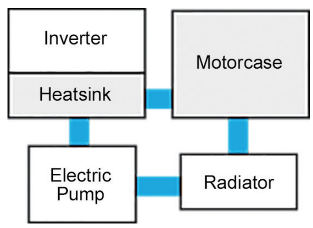



Fig.10 Water-Cooling System

For the radiator, the model that has been adopted for a 125cc ICE-motorcycle was chosen, and for the electric pump, we used that has been used for a 4-wheel EV component cooling application with an output of 12W.

## 3-2. Test Results

These were not included as the motor characteristic test results were the same as the specification of the air-cooling motor.

Temperature measurements were carried out at the same points as with the air-cooled motor to calculate the thermal resistance. The temperature rise data compared with the air-cooled motor under the same conditions is shown in Fig.11 below. (Room temperature was at an almost identical level)

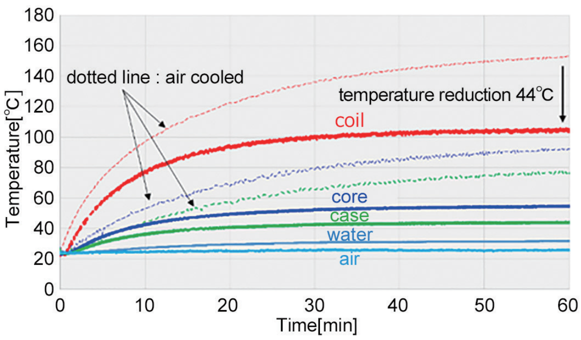


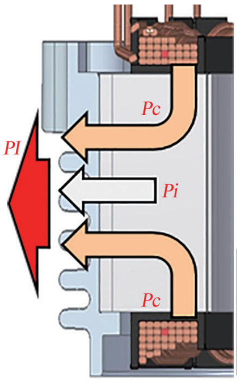

Fig. 11 Temperature Data at Motor Current 150Ap & 1000 RPM (Comparison with water-cooled & air-cooled motor)

The air-cooling level to the radiator at the front area was set to 6m/s similar to the air-cooling motor cooled air, and the evaluation was carried out without directly blowing towards the motor.

As the above temperature measurement was carried out to calculate the thermal resistance of the motor, an inverter was used installed outside the water-cooling system.

Although the dotted line on the graph represents the result of the air-cooled motor, it can be seen that the coil temperature reduction (44°C) is achieved by water cooling.

The thermal resistance calculated from the temperature measurement result is shown as follows. (Fig.12)




| | |
|---|---|
| Coil Temp at 60min [°C] | 110.2 |
| Coil Resistance at 60min [mΩ] | 7.7 |
| Pc : Cupper Loss [W] | 258.9 |
| Iron & mechanical Loss [W] | 188.6 |
| Rotor Loss Estimate [W] | 17.3 |
| Pi : Stator Iron Loss [W] | 171.3 |
| Pl : Stator Loss [W] | 430.2 |

| Passing Route | ⊿T[°C] | Passing Heat[W] | Thermal Resistance[K/W] |
|---|---|---|---|
| Coil ⇒ Core | 57.53 | 258.9 | 0.222 |
| Core ⇒ Case | 11.2 | 430.2 | 0.026 |
| Case ⇒ Water | 12.8 | 430.2 | 0.030 |

Fig. 12 Thermal Resistance Calculation from Test Results of Water-Cooled Motor

Similar calculations were carried out at other temperature measurement points, but the results were almost the same.

Table 3 below shows the average values.

Table 3 Average Thermal Resistance of Water-Cooled Motor

| Passing Route | Thermal Resistance[K/W] |
|---|---|
| Coil ⇒ Core | 0.218 |
| Core ⇒ Case | 0.028 |
| Case ⇒ Air | 0.025 |

In terms of the coil, iron core, and the case, the thermal resistance is almost the same because of the same configuration.

As with the air-cooling example, but for the thermal resistance between the case and the cooling water, it is less compared to the air-cooling example.

Using the above thermal resistance, the calculated value and the test results for the temperature rise of the coil at 5000 RPM and when powered at 130Ap were compared. (Table 4)

Table 4 Comparison of Calculations and Test Results

| 5000rpm 130Ap | Calculation Result | Test Result |
|---|---|---|
| Coil Temp [℃] | 103.4 | 99.4 |

For the water-cooled motor, the above thermal resistance is used for the calculation, assuming that sufficient accuracy is ensured with regard to temperature prediction. In terms of the water-cooled motor, the water temperature changes depending on the capacity of the radiator.

## 4 CONSIDERATIONS OF APPROPRIATE COOLING SYSTEMS ACCORDING TO MOTOR OUTPUT

Comparative evaluation with air cooling of the volume/ weight of the motor and cooling system as a whole is as in Section.

In terms of water cooling, it is possible to reduce the motor temperature by improving the heat transfer coefficient between the case and the refrigerant.

However, as additional parts such as the radiator and pump, etc., are required, it is necessary to correctly select water cooling and air cooling according to the output of the motor.

### 4-1. Design Requirements of Motor

In this section, firstly, the design requirements of the motor applicable for the motorcycle are derived from the characteristics of the ICE motorcycle sold by Yamaha Motor in the following way.

The graph below (Fig.13) shows the maximum driving force and the highest speed of the ICE motorcycle, arranged by vehicle output.

The motor RPM when driven at the highest speed is set to 9,000 RPM, the tire diameter is appropriately selected corresponding to the ICE motorcycle according to the output, the reduction ratio is derived according to the output, and from the reduction ratio, the torque required at the time of maximum drive is obtained.

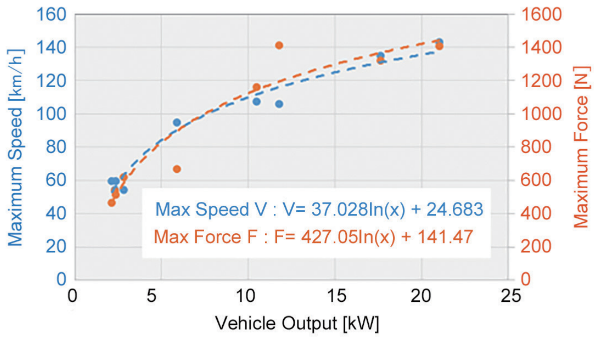



Fig. 13 ICE motorcycle Maximum speed, Maximum driving force, Maximum output

The motor torque was calculated considering the tire loss (20N) and the efficiency of the single speed two-stage gearing (assumed to be 93%). (Fig.14)

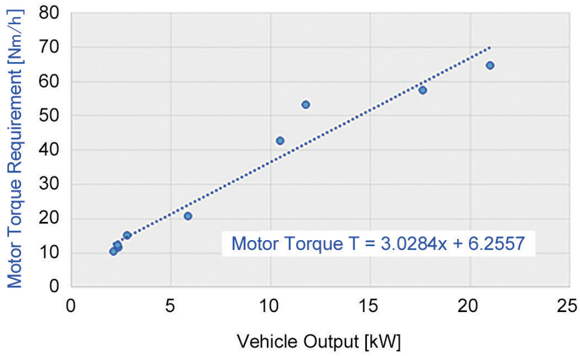



Fig. 14 Torque Requirement According to Vehicle output

In terms of motor output, this has been converted into the motor axle output considering the loss of the gearing and the tires.

In the next section, we have examined the combination of the motor output and torque requirement when adapting it to motorcycles using the method described above.

### 4-2. Calculation Results for Volume and Weight Reduction of Water-Cooled Motors on Each Output Level

The volume and weight of the air cooled and water -cooled motors for each output level was calculated, and the most appropriate cooling methods were determined according to output.

We carried out studies on the 35kW upper limit which can be ridden on a European A2 license.

The studies progressed under the following conditions in order to organize them systematically.

[Motor]
- The outer diameter of the motor is the same as that in the second and third sections, with a broadened axle direction for when output is increased.

- When the size changes based on the values calculated in the second and the third sections, the thermal resistance is calculated by proportional calculations where an increase/decrease of the heat radiation area is used.

- Rather than actual travel data, the conditions required for seeing heat resistance are assumed to be the conditions at medium to high speed and at high output.

For an output level when the torque reaches the specified output at 6500 RPM, an approximation for both air and water cooling was carried out to determine the size when the coil temperature reaches 180°C in an environment of 40°C.

- Regarding the heat resistance of magnets, this was not taken into our considerations as it is sufficient to adopt a split magnet or use a high-coercivity material.

- An approximate calculation was made on the assumption that the voltage changes according to the change in output with reference to the prototype motor (10kW/100V).

[Water-Cooling System]
- Assuming that all output is for 12W products, based on the evaluation result, the electric pump is judged to be adequate with a 12W output. (Flow Rate: 8 ℓ /min, Volume: 251cc, Weight: 0.4 kg)

- The cooling hose volume is assumed to be a $\phi$22 hose 400 mm

- The radiator from an ICE 125cc motorcycle that was used in the evaluation is adopted as a base, and the volume of the cooling fin part was changed to be used as a parameter of this size and weight reduction study.

Even though air-speed varies according to vehicle layout and its travel speed, it is assumed to be 6m/s equivalent at the time of evaluation in order to organize the data systematically.

(The volume of the tank part is 387cc / The fin part is a parameter)

-The overall weight and volume are calculated according to the following formula *.

*Water-Cooling System Weight/Volume
=Water Pump (0.4kg/0.251 ℓ) + Hose (0.02kg/0.152 ℓ) + Radiator Tank (0.21kg/0.387 ℓ) + Radiator Fins (Variable) + Water (Variable (Weight))

If cooling water temperature is lowered, the cooling performance of the motor improves, and the size and weight reduction of the motor progresses. On the other hand, the volume of the radiator increases and the weight increases. We have to consider about their balance.

In order to estimate the optimum point of volume/weight, the volume of the radiator was changed, the radiator inflow water temperature was adjusted, and the relationship between the size and weight of the motor and cooling system was calculated.

(The inverter was not considered as part of this study.)

The following shows the results of our 10kW study.
(Output10kW and Maximum torque32Nm)

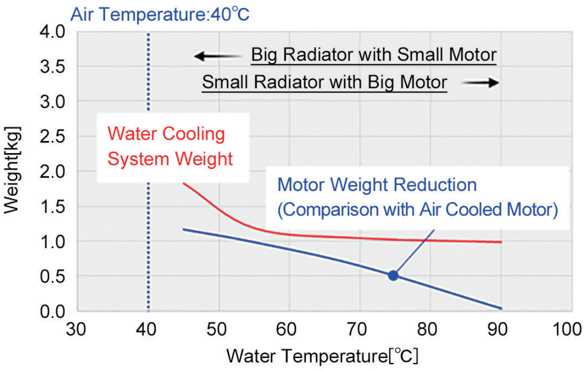



Fig.15 Calculation result of Weight (10kW motor)

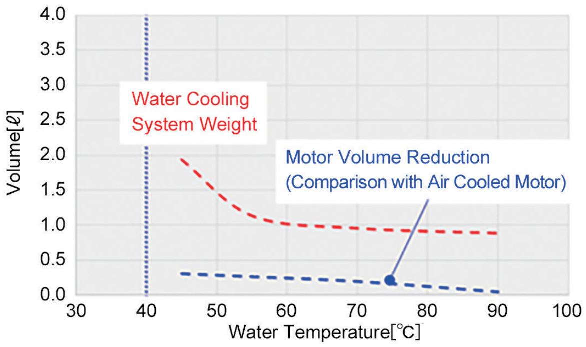



Fig.16 Calculation result of Volume (10kW motor)

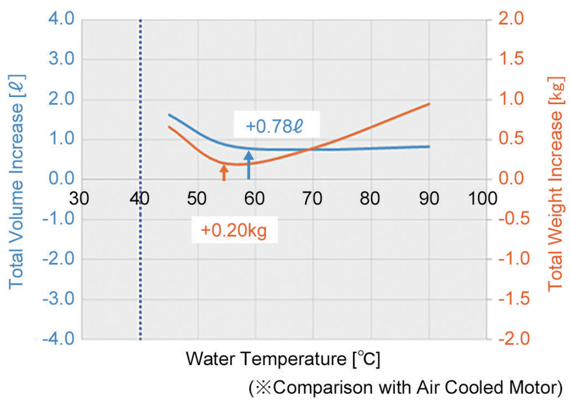



Fig.17 Calculation result of total volume/weight increase (comparison with air cooling) (10kW motor)

In case motor output 10kW

- Volume reduction :unable
  Weight reduction :unable
- Appropriate water temperature :55 to 60°C (From the viewpoint of small volume and light weight)

At the 10kW, it was not found that the advantage of volume and weight reduction.

When cooling the motor with water, at least we have to set the pump, hose and radiator tank and cooling water, and they have base volume and base weight.

・water-cooling system base volume : 0.792 ℓ
・water-cooling system base weight : 0.910kg

In addition, it is necessary to add radiator fin portion. Its volume and weight depend on cooling capacity requirement.

At 10kW level, the volume and weight reduction of the motor can't exceed the volume and weight increase of the water-cooling system (water pump, hose, radiator, water).

The following shows the results of our 15kW study. (Output15kW and Maximum torque42.6Nm)

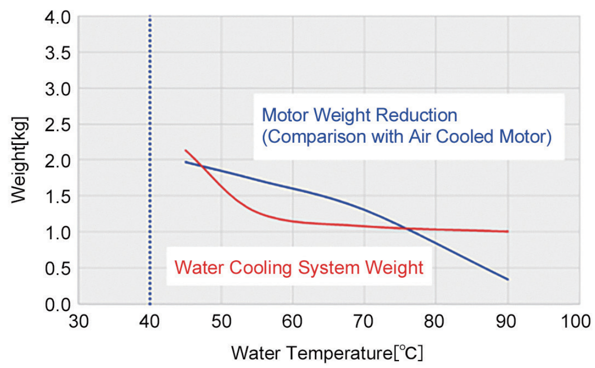



Fig.18 Calculation result of Weight (15kW motor)

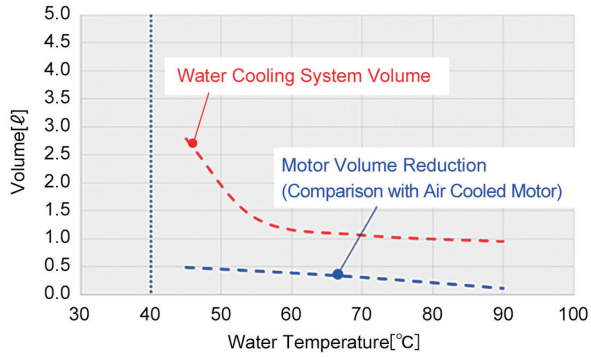



Fig.19 Calculation result of Volume (15kW motor)

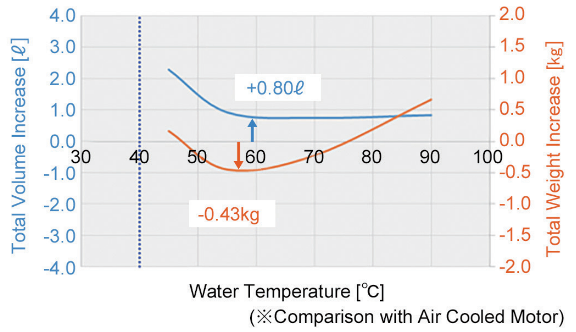



Fig.20 Calculation result of total volume/weight increase (comparison with air cooling) (15kW motor)

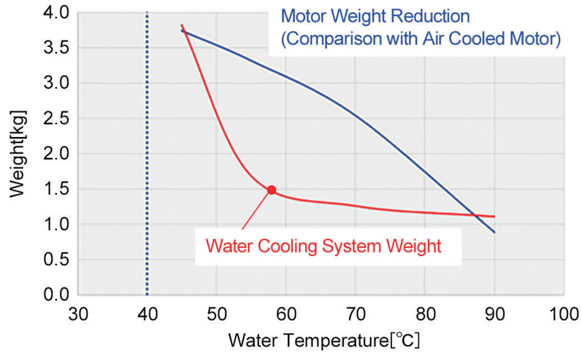



Fig.21 Calculation result of Weight (35kW motor)

In case motor output15kW

- Volume reduction ：unable(+0.80 ℓ )
  Weight reduction ：able (-0.43kg)
- Appropriate water temperature：55 to 60°C
  (From the view point of small volume and light weight)

We saw benefit of changing to a water-cooling method from the standpoint for weight reduction from the 15kW model.

Regarding overall downsizing, the results compared to the 10kW studies were not significantly different in terms of the volume increase.

As the output rises, the amount of heat that is generated from electric motor also increases, and therefore a larger radiator is needed.

This result was obtained because the radiator volume was increased in volume to counteract the downsizing of the motor.

This study was carried out to see if there are benefits available for downsizing at the upper limit output at the 35kW level.

The following shows the results of our 35kW study.
(Output35kW and Maximum torque91.1Nm)

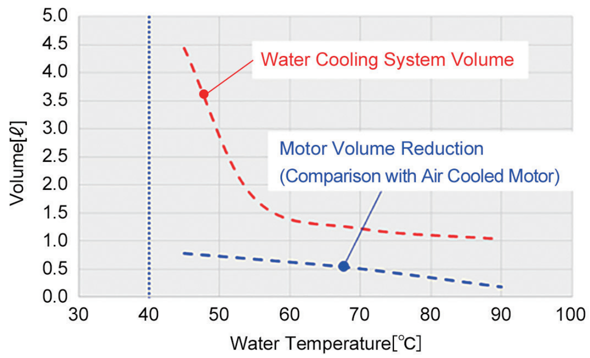



Fig.22 Calculation result of Volume (35kW motor)

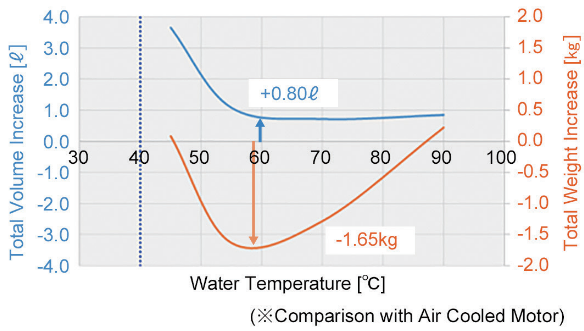



Fig.23 Calculation result of total volume/weight increase (comparison with air cooling) (35kW motor)

In case motor output 35kW

- Volume reduction ：unable
  Weight reduction ：able (1.63 kg)
- Appropriate water temperature ：55 to 60°C
  (From the viewpoint of small size and light weight)

Even at 35kW, downsizing did not proceed as the volume increase was not significantly different from the results of study at the 10kW level.

From the results of this study, it was found that the advantage of weight reduction comes from about the 15kW level due to water cooling of only the motor.

At the 10kW or less, it was not found that the advantage of weight reduction. Because the weight reduction of the motor can't exceed the weight increase of the water-cooling system (water pump, hose, radiator, water).

In terms of downsizing, we found from our study that there was not much benefit obtained.

In addition, it was found that the water temperature is about 55 to 60°C at its optimum temperature from the viewpoint of volume reduction and weight reduction at any output.

## 5 SUMMARY/CONCLUSIONS

- When using the above air-cooled motor as a base, when cooling only the motor with water, there is a benefit for weight reduction as in from a 15kW level type compared with the air-cooled motor.
  ※Including Water-cooling system weight

- Even if you only try to increase the output power by only cooling the motor with water, it is not possible to see the benefits of downsizing.
  ※ Including Water-cooling system volume

- The water temperature which is beneficial from the viewpoint of small size and light weight is between 55 to 60 degrees (When the air temperature is 40 degrees).

In terms of weight reduction at the 15kW level, as it is beneficial to water cool only the motor, water-cooling is effective for high-powered models when personal mobility options including motorcycles are electrically driven.

On the other hand, it is now found that downsizing cannot be achieved as a whole only by cooling the motor with water.

However, as downsizing of the motor alone has been achieved, there is more benefit for laying out the motor into the vehicle.

In terms of the adoption or non-adoption of water-cooling, multifaceted investigation including of motorcycle layouts in practice is required in addition to the results of this study.

In future, we will continue studies that include inverters as well as improving motor cooling performance and strive to enhance the appeal of electric personal mobility.

## REFERENCES

[1] Matsuda Y. "A Study of Electric Motorcycle", SAE Technical Paper 2014-32-0012, 2014, doi:10.4271/2014-32-0012.

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