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# Newly Developed Motor Cooling Method Using Refrigerant

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**Abstract:** One of the greatest issues for electric vehicles such as an electric vehicle (EV), a hybrid vehicle (HV), a plug-in hybrid electric vehicle (PHEV) and a fuel cell vehicle (FCV) is further improvement of effective motor cooling, since higher rated torque is achieved with higher cooling performance. In this paper, we introduce and propose a newly developed motor cooling method we tested using refrigerant, comparing with conventional water cooling. Test results show higher cooling performance of refrigerant cooling, which achieved the rated torque 60% higher than that of water cooling.

**Keywords:** refrigerant; motor cooling; electric vehicle

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## 1. Introduction

The experience of rally competitions with Outlander PHEV has made us aware that the enhancement of motor cooling performance is essential to win the race. Rallies require driving of high speed, high torque, long period and long range. Such driving generates serious motor heating. To protect the motor materials, such as magnets or the insulation of copper coil windings, torque limitation is required at the upper limit of coil temperature. Once coil temperature exceeds the upper limit, torque is inhibited at limitation level, which results in deterioration of acceleration performance. This is why higher motor cooling performance plays the key role for the faster driving.

Beyond rally cars, higher motor cooling performance contributes greatly to mass-produced vehicles by the following two aspects:

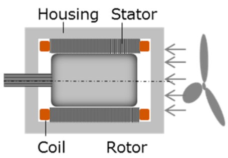
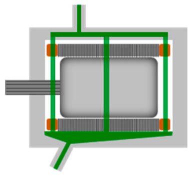
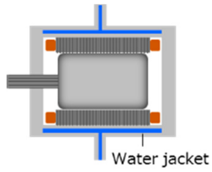
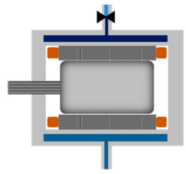
- Rated torque increase
- Downsizing

First contribution is rated torque, which should be increased without negotiating the motor size. The rated torque is generally defined as the torque where motor cooling maintains thermal equilibrium so that a motor can operate continuously. Higher cooling performance enhances motor's rated torque. Second is downsizing of a motor with realizing higher rated torque. Diameter of copper coil windings defines a motor size. Thinner windings increase its resistance that generates more heat. Enhanced cooling performance should absorb increased heat generated by thinner windings, which should realize downsizing of a motor.

Table 1 shows three methods of conventional motor cooling:

- Air cooling
- Oil cooling
- Water cooling

**Table 1.** Motor cooling methods.

| | Air Cooling | Oil Cooling | Water Cooling | Refrigerant Cooling |
|---|---|---|---|---|
| **Schematic Illustration** |   Heat exchange by wind |  Heat exchange by oil directly flowing into heat source |   Heat exchange by flowing water in a water jacket |  Heat exchange by flowing refrigerant and vaporization heat |
| **Cooling Performance** | Low | High | Average | High |
| **Cooling Uniformity** | Uniform | Non-uniform | Uniform | Uniform |
| **Application Example** | Mainly Train | Outlander PHEV(front) | i-MiEV, Outlander PHEV(Rear) | HERE PROPOSED |

First is air cooling, which is mainly utilized in train motors, not in the driving motors of electric vehicles except for some in-wheel motor cars [1,2]. Air cooling is superior to other methods in terms of the cost and the cooling uniformity; however its performance is the lowest among the three conventional cooling methods. Second is oil cooling, which has the best cooling performance since oil flowing into a motor housing cools a heat source directly [3,4]. Mitsubishi motors apply the oil cooling to the front motor of Outlander PHEV [1,5]; however, oil cooling compromises the cooling uniformity and the system cost. Moreover, it requires a water cooling system separately to cool an inverter. The final conventional method is water cooling, which is the most common method among electric vehicles [6]. Mitsubishi motors apply water cooling to the driving motor of i-MiEV and the rear motor of Outlander PHEV [1,5]. In this method, water flows into a jacket installed in the housing and exchanges generated heat. It achieves better cooling uniformity and less system cost than oil cooling; however, its cooling performance is not effective as much as that of oil cooling.

## 2. Refrigerant Cooling

### *2.1. Concept*

To enhance the conventional cooling performance, we have developed a new cooling method: refrigerant cooling. The refrigerant cooling system is connected with a car air conditioning (A/C) system in parallel as shown in Figure 1. It uses a jacket for water cooling as refrigerant path that is installed in a motor housing. A thermal expansion valve (TXV) is attached at an inlet of the motor housing, at which liquid refrigerant evaporates to some extent. The rest of liquid refrigerant evaporates in the path absorbing heat from the motor. A compressor regulates its operation rate to control the cooling performance.

### *2.2. Expected Benefits*

Three expected benefits from replacing water cooling system by refrigerant cooling are:

- Fewer components for PHEV
- Greater cooling uniformity
- Higher cooling performance

First of all, integration of cooling systems with the A/C system should reduce components. Figure 2a shows the current cooling system of Outlander PHEV. Four heat exchangers are located in the front of a vehicle: Two radiators (one for an engine not illustrated in Figure 2 and another for water cooling of EV system); one oil cooler for oil cooling of the front motor and the generator; and one condenser for the A/C. If inverters and converter are integrated into the refrigerant cooling system referring to previous researches [7,8], refrigerant cooling should reduce these four heat exchangers into two: A radiator for the engine cooling and a condenser for the refrigerant cooling as shown in Figure 2b. The essentials to realize this ideal system are: The greater cooling ability of the compressor; the distribution control of refrigerant; and the compressor control to minimize the power consumption. Second is that the refrigerant cooling achieves greater cooling uniformity than oil cooling by letting refrigerant flow through the water jacket. The final benefit of the refrigerant cooling is higher cooling performance than that of water cooling. The study in this paper aims to verify the fact that the refrigerant cooling performance is higher than the water cooling through two approaches: simulation and experiment.

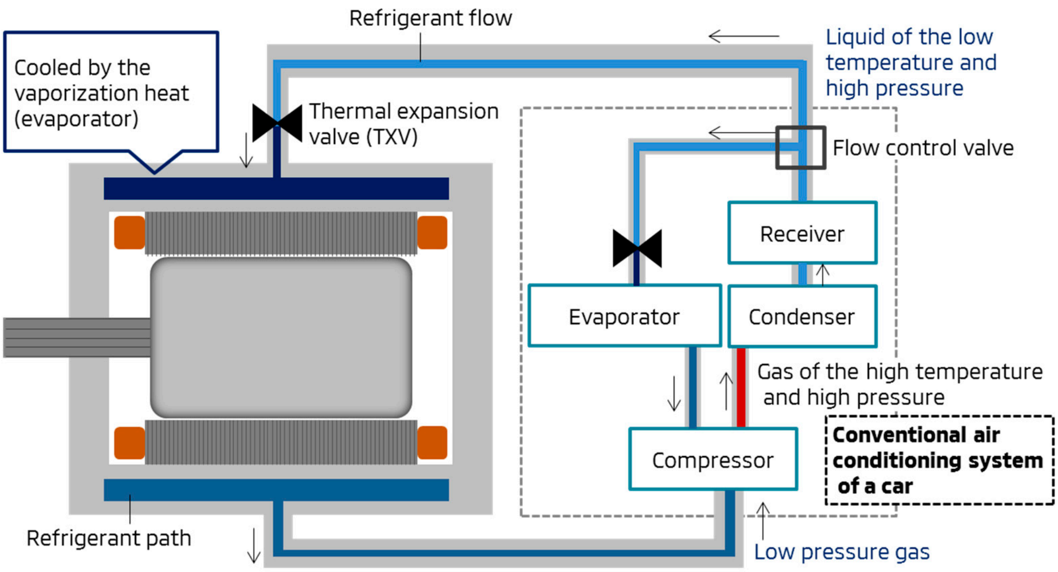



**Figure 1.** Proposed refrigerant cooling system.

(a)

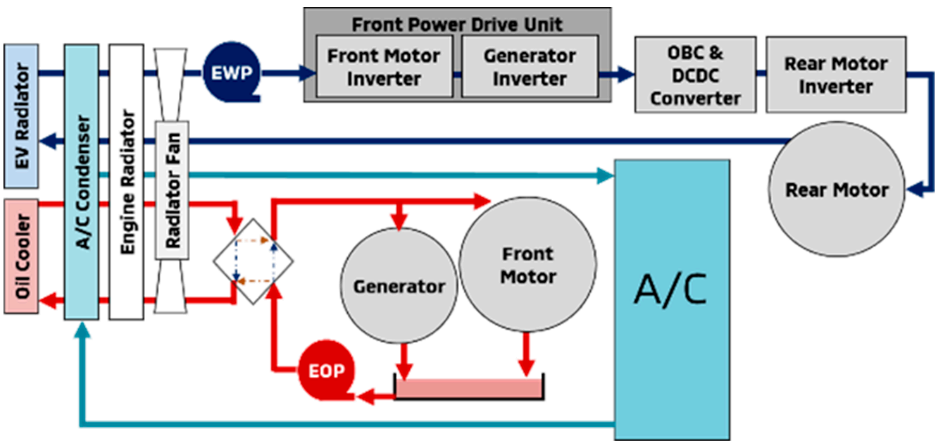



**Figure 2.** *Cont.*

(**b**)

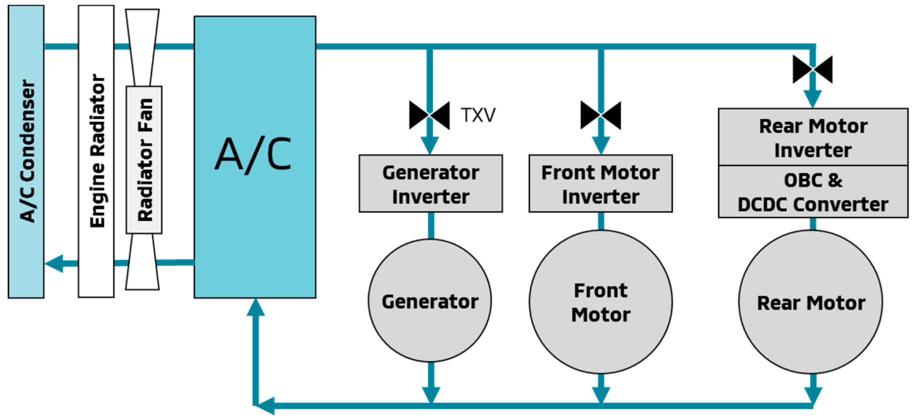



**Figure 2.** (**a**) Current cooling system of PHEV; (**b**) one example of ideal cooling systems using refrigerant cooling.

## 3. Simulation

Simulation shows that refrigerant cooling kept the coil temperature lower than water cooling. This simulation was performed on a one-dimensional model [9,10]. The simulation used the same model for water cooling and refrigerant cooling. The model describes a motor cooling structure without an AC circuit. We introduced a cylindrical-shaped water jacket as shown in Figure 3 to simulate the complicated water/refrigerant path. Heat generated by electrical current through copper coil windings is transferred to water/refrigerant path across the steal stator core and the aluminum housing. For refrigerant cooling, a TXV was attached at the inlet of the refrigerant path to let liquid refrigerant evaporate effectively. Based on the initial experimental conditions Table 2 shows, we calculated the maximum temperatures at thermal equilibrium for water, refrigerant and copper coil windings. As a result, the coil temperature of refrigerant cooling was lower than that of water cooling by 48°C as shown in Table 3.

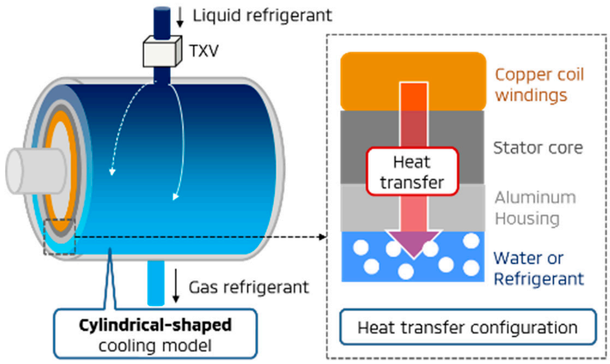



**Figure 3.** Simulation model.

**Table 2.** Initial conditions.

| | | | |
|---|---|---|---|
| **Initial Motor Temperature** | | °C | 25 |
| **Maximum Motor Heat Loss** | | kW | 3 |
| **Water Cooling** | **Water Temperature** | °C | 40 |
| | **Water Flow Rate** | L/min | 10 |
| | **Pressure at Outlet** | kPa | 104 |
| **Refrigerant Cooling** | **Refrigerant** | - | HFC-134a |
| | **Refrigerant Flow Rate** | kg/s | 0.0024 |
| | **Gas Phase Ratio at Inlet** | - | 0.3 |
| | **Pressure at Outlet** | MPa | 0.3 |

**Table 3.** Simulation results.

| | Max. Temperature of Water or Refrigerant [°C] | Max. Temperature of Copper Coil Windings [°C] |
|---|---|---|
| **Water Cooling** | 62 | 81 |
| **Refrigerant Cooling** | 21 | 33 |

## 4. Experiment

### *4.1. Procedure*

The cooling performance was compared between water and refrigerant by using the same motor of the specification in Table 4. All experiments started with water cooling as shown in Figure 4a. A TXV was installed at the inlet of the water jacket as shown in Figure 4b before experimenting refrigerant cooling. The refrigerant cooling experiment used the same motor as the water cooling experiment. The water jacket worked as the refrigerant path. In addition, the water circulation system was replaced by an A/C system. Compressor regulated its operation rate to control the refrigerant cooling performance. The compressor kept operating until the motor surface temperature declined to a target temperature. Note that the target temperatures for refrigerant cooling were set at 0, 10, and 20 °C. The compressor stopped its operation when the motor surface temperature was lowered below the target temperature. Three experiments were performed as shown in Table 5.

**Table 4.** Motor specification.

| Type | - | PMSM |
|---|---|---|
| Max. output | kW | 47 |
| Max. torque | Nm | 180 |
| Max. speed | rpm | 8500 |
| Max. system efficiency* | % | More than 90 |
| Mass | kg | About 45 |
| Cooling method | - | Water cooling |

* Total efficiency of motor and inverter.

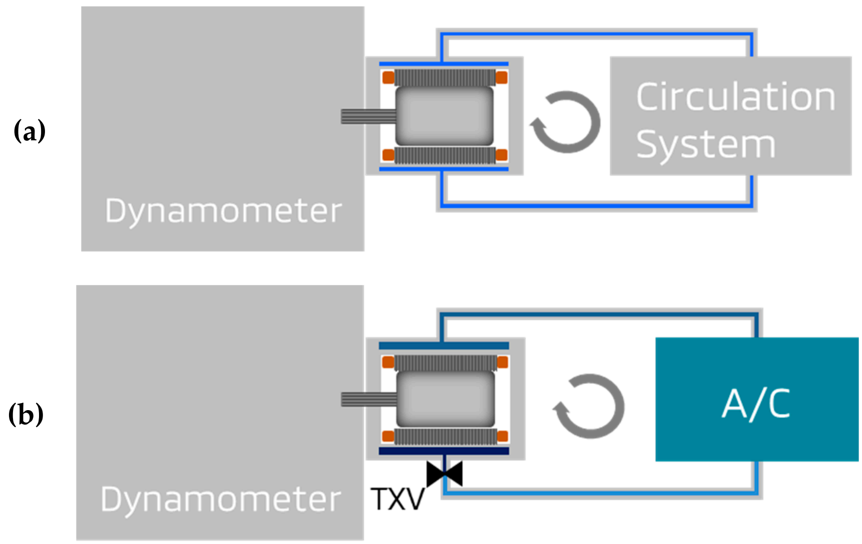



**Figure 4.** Experimental setup: (**a**) Water cooling; (**b**) refrigerant cooling.

In experiment 1, the motor temperature, which was operated at rated torque for 30 min, was measured.

In experiment 2, new rated torque was estimated when water cooling was replaced by refrigerant cooling.

In experiment 3, operation time at the maximum torque was measured.

**Table 5.** Experimental conditions.

| Item | | Unit | Exp.1 | Exp.2 | Exp.3 |
|---|---|---|---|---|---|
| Room temperature | | °C | | 25 | |
| Motor speed | | rpm | 1000 | 1000 | 2500 |
| Motor torque | | Nm | 65 (Rated) | 65~180 | 180 (Maximum) |
| Motor power | | kW | 7 | 7~19 | 47 |
| Water temperature for inverter cooling | | °C | | 40 | |
| Water cooling | Water temperature | °C | | 20, 40, 60 | |
| | Water flow rate | L/min | | 10 | |
| | Initial coil temperature | °C | | Dependent on water temperature | |
| Refrigerant cooling | Refrigerant | - | | HFC-134a | |
| | Target temperature | °C | | 0, 10, 20 | |
| | Initial coil temperature | °C | | 25 | |

### *4.2. Results and Discussion*

#### 4.2.1. Experiment 1

Figure 5 shows that refrigerant cooling kept the coil temperature lower than water cooling. Comparing water cooling of 60 °C and refrigerant cooling of 0 °C, the difference of the coil temperatures extended up to 53 °C after 30 minutes of motor operation at rated torque. The water cooling of 60 °C was the highest water temperature allowed in the specification. The refrigerant cooling of 0 °C was the lowest refrigerant temperature, which was determined by compressor ability. When the water temperature was set at 20 °C to adjust the initial coil temperature, refrigerant cooling even showed the higher cooling performance by 12 °C than water cooling.

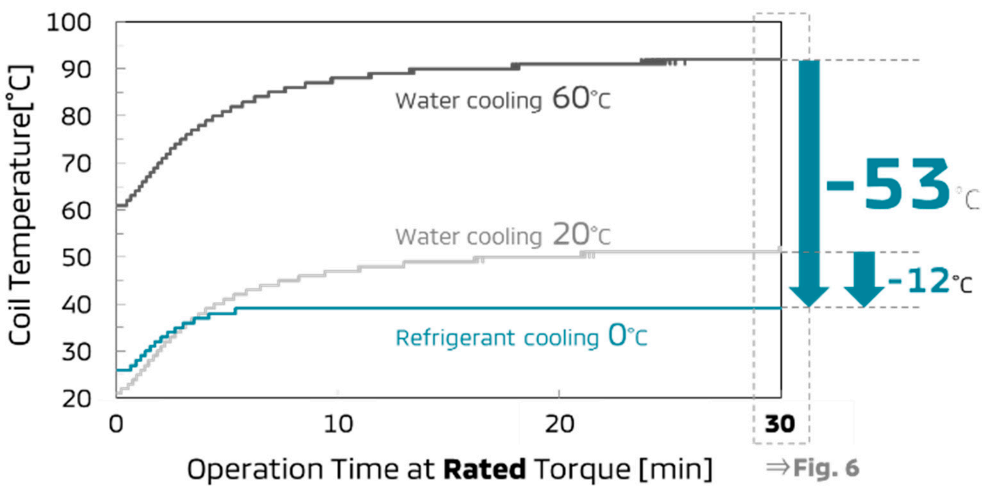



**Figure 5.** Operation time at rated torque vs coil temperature.

The coil temperature was proportional to the temperature of fluid through the water jacket as shown in Figure 6, which shows the higher cooling performance of the refrigerant cooling. The compressor achieved this result by keeping the refrigerant temperature below the ambient temperature for its phase transition causing an endothermic reaction through the TXV.

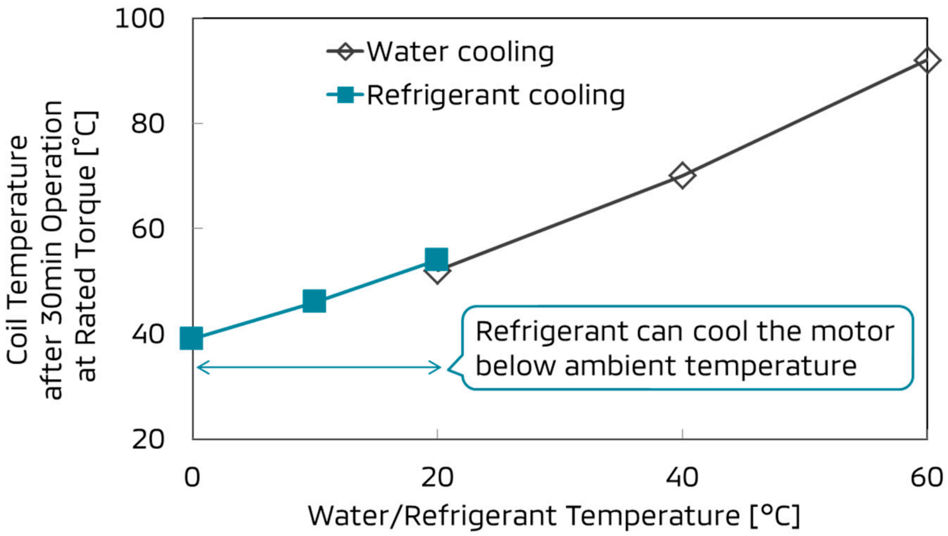



**Figure 6.** Coil temperature after 30 min operation at rated torque vs water temperature or refrigerant temperature.

Figure 7 shows higher cooling performance of refrigerant cooling. The picture was taken after 30 min of motor operation at rated torque. The motor surface was frosted since the refrigerant temperature was set at 0 °C.

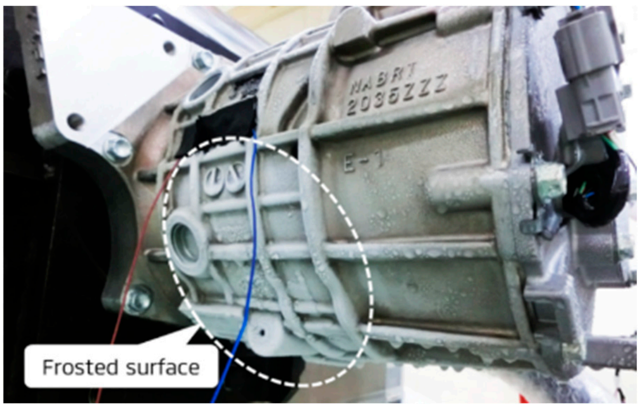



**Figure 7.** Frosted motor surface by refrigerant cooling.

4.2.2. Experiment 2

Figure 8 shows that the rated torque of the refrigerant cooling increased up to 60% more than that of the water cooling. The new rated torque was estimated from the highest coil temperature of the water cooling. After the operation of the water cooling motor with the water temperature of 60 °C operated for 30 min at the rated torque of 65 Nm, the coil temperature reached 92 °C. This result indicates that the rated torque of the refrigerant cooling is allowed to increase until the coil temperature becomes 92 °C. In that case, the motor torque was 105 Nm while the refrigerant cooling was 0 °C. That was a 60% increase of the rated torque of the refrigerant cooling as a result of replacing the cooling substance from water to refrigerant.

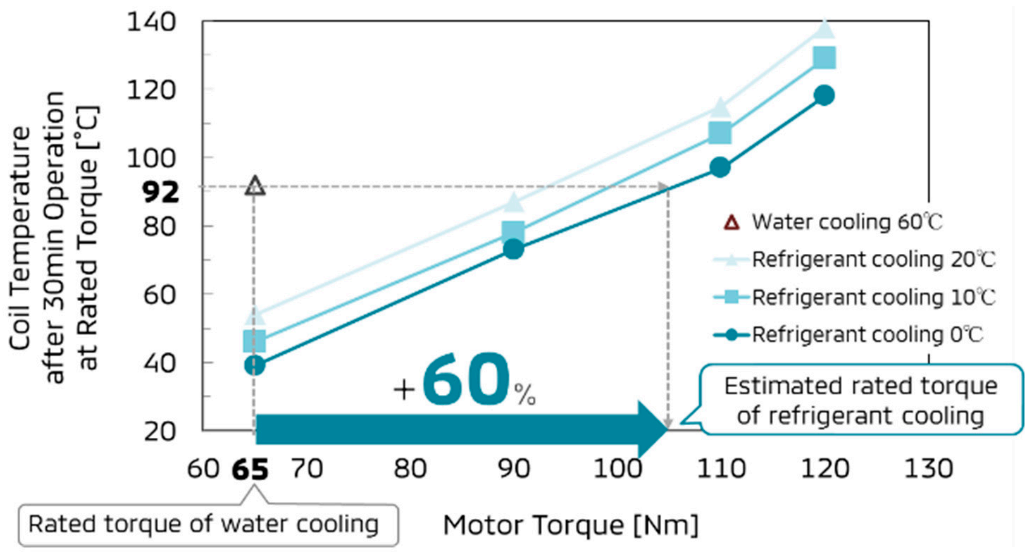



**Figure 8.** Coil temperature after 30 min operation vs motor torque.

4.2.3. Experiment 3

Experiment 3 aims to clarify any impact on the maximum torque of the refrigerant cooling. Note that the inverter performance restricts the maximum torque. What was focused on here was whether refrigerant cooling affected the operation time at maximum torque. The results showed two aspects.

First, cooling methods did not affect any operation time if the initial coil temperature was same as shown in Figure 9. The time range of 150 s was too short for refrigerant cooling to show its effect.

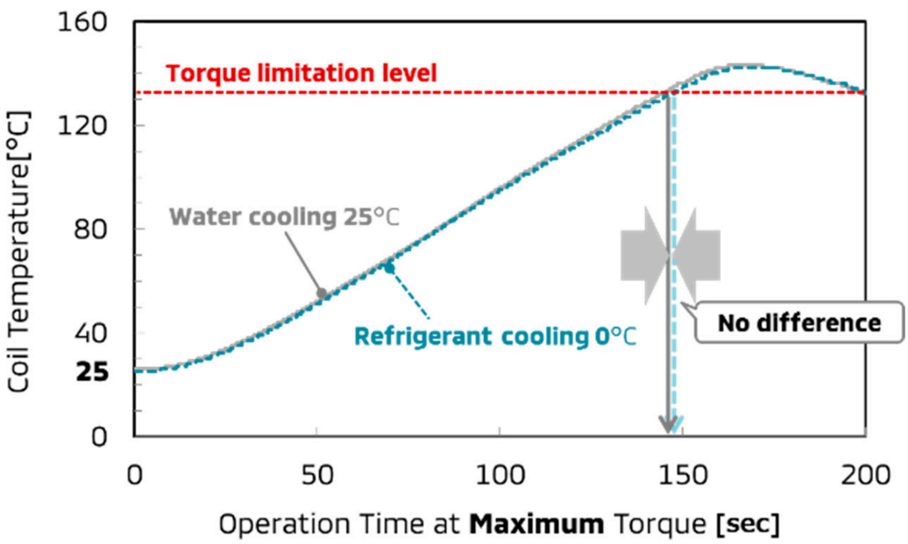



**Figure 9.** Coil temperature vs operation time at maximum torque.

However, when the motor was cooled down to 0 °C in advance of motor operation, the operation time at the maximum torque of the refrigerant cooling was extended by 34% as Figure 10 shows. Figure 11 shows that the lower initial coil temperature led to the longer operation time. In other words, the refrigerant cooling had an advantage over the water cooling since the compressor decreased the initial coil temperature before the motor operation.

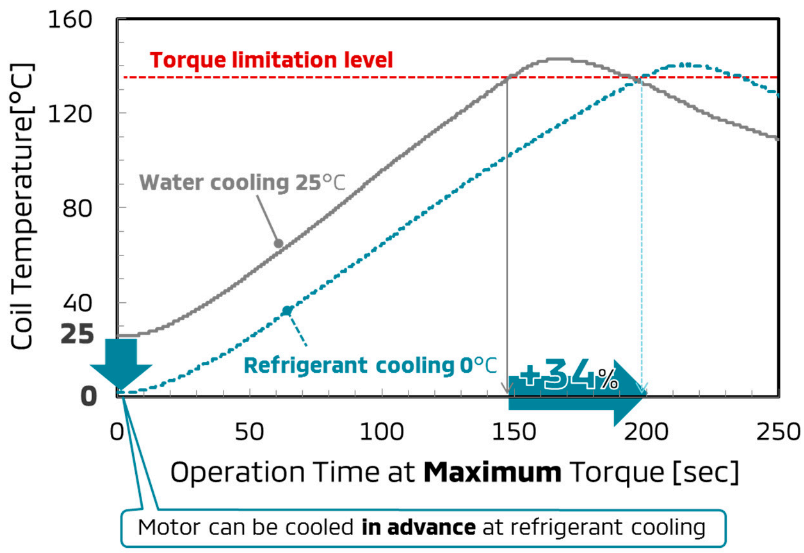



**Figure 10.** Coil temperature vs operation time at the maximum torque in case that refrigerant cooling cooled the motor in advance.

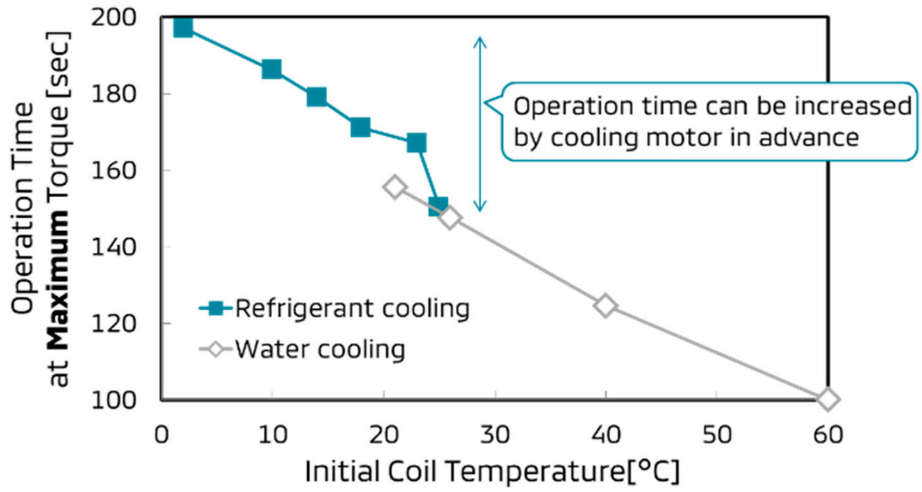



**Figure 11.** Operation time at maximum torque vs initial coil temperature.

## 5. Conclusions

The superiority of the refrigerant cooling has been revealed comparing to the conventional water cooling, because:

- The refrigerant cooling has the coil temperature lower than ambient temperature by the compressor control;
- The rated torque was increased by 60% when the water cooling was replaced by the refrigerant cooling; and
- Cooling the motor in advance of motor operation contributed to extend operation time at the maximum torque by 34%.

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