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Modeling of Direct Cooling Method with Forced Convection Boiling Phenomena considering Liquid Phase Behavior of Liquid Gas Two-Phase Refrigerant for Vehicle Traction Application PMSM

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ABSTRACT: A direct cooling with boiling phenomena for motor stator winding is expected to be one of output capability improvement methods of Electric Vehicle (EV) traction applications due to its high heat dissipation capability. However, the behavior of refrigerant under boiling phenomena in such narrow space like stator slot is not studied very well. So, a model to obtain heat transfer coefficient of the method is proposed. The model includes capillary force effect to fill the gap in the stator winding with refrigerant liquid under convection boiling by pump system. A case of winding temperature under the phenomena is calculated using a stator slot model, and the calculated result reasonably agree with the experimental result. The result shows non-linear sensitivity to slot fill factor and winding temperature, and it suggests importance of slot fill factor for maximizing cooling performance of the method.

KEY WORDS: refrigerant, forced convection boiling, motor cooling, direct cooling

1. INTRODUCTION

As the performance requirements of in-vehicle units increase, downsizing, especially for traction motors will be more important. However, the heat generation density increases as unit size decreases, so the cooling performance is expected to be higher not to exceed the allowable stator winding and magnet temperature.

With the conventional water-cooling method, because of the high thermal resistance in the stator slot due to insulation material between winding and stator core, the winding temperature tends to be higher in case continuous rated output is increased. So, new cooling method application is preferred for this purpose.

There are two major approaches. The first, it makes low temperature and high heat transfer cooling by air conditioner refrigerant instead of water in water jacket[1]. The second, it makes reduction of thermal resistance by water into the slot of coil[2] or by oil direct cooling [3]. In particular, the oil direct cooling is highly effective because the structure is simple compared with other method. However, the high viscosity of oil increases mechanical friction when it fills the air gap, so effective of direct oil cooling is possibly limited in some cases. Therefore, some papers discuss a low mechanical friction and high heat transfer by using a refrigerant instead of oil. The cooling method is pump-less system by structure which have two rooms, it’s named "Boiling Immersion Cooling System”[4][5]. But the amount of heat transport is limited with pump-less system because the condensing capacity make be down without pressure by pump, so this cooling method could not be satisfied with required high power motors such as in-big size vehicle motors. This paper presents a method of modeling includes capillary force effect to fill the gap in the stator winding with refrigerant liquid under convection boiling by pump system.

2. MODEL and CULCULATION

Assuming a cooling method that supplies refrigerant directly to the coils in the motor slot, we studied the case where the refrigerant flows only through a small gap between the coils, such as inside the slot.

To predict the coil temperature, two things need to be considered. The first is the heat transfer coefficient between the coils and the refrigerant. Therefore, we conducted basic

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experiments to measure the heat transfer coefficient using a general-purpose copper pin-fin heat exchanger that closely resembles the round wire shape of the coils. Second, since the heat transfer coefficient differs greatly between cooling with liquid and gaseous refrigerants, and cooling performance drops significantly when the dryout phenomenon occurs, we considered it necessary to include the effects of gravity and surface tension in the prediction of the coil temperature. Therefore, we modeled the attraction force due to gravity and capillary force generated in the refrigerant between coils as shown in Figure 1 and calculated how the relationship changed with the winding filling ratio. As shown in Figure 2, at a low winding fill factor, the weight of the refrigerant exceeds the capillary force, and the liquid is predicted to fall, so the dryout phenomenon for different winding fill factors. In the case of a low winding fill factor, the gravity force is higher than the capillary force between coils, so this effectively makes a low level of the liquid surface and high temperature of coil in dryout region. For this graph, an image of the state of the refrigerant between the coils is shown in Figure 3. It is presumed that a low winding fill factor causes the upper part to become a gas, resulting in a dryout region and higher temperatures. Therefore, we mention designing a higher winding fill factor with this cooling method

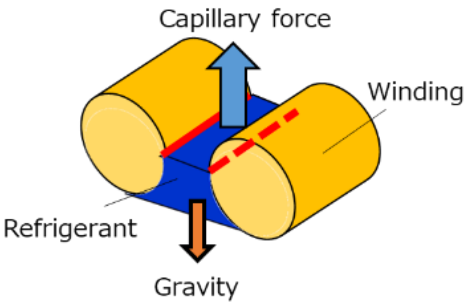

Figure 1. Image of capillary force in coils

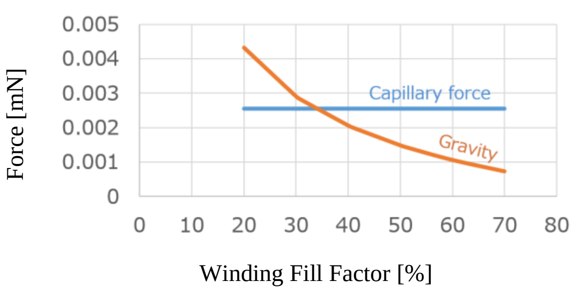

Figure 2. Winding fill factor vs Calculated Capillary Force and Gravity Force

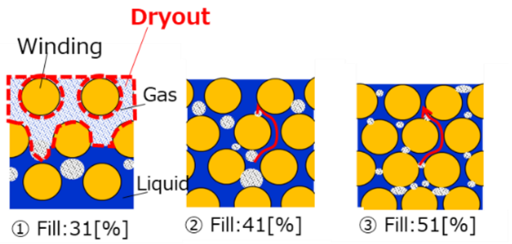

Figure 3. Dryout image each winding fill factor

Figure 4 shows the coil temperature results for each winding fill factor calculated from the heat transfer coefficient obtained from the aforementioned basic experiments on pin-fin heat exchangers and the relationship between surface tension and gravity in Figure 2. It can be seen that a lower winding fill factor results in higher coil temperatures due to the dryout phenomenon.

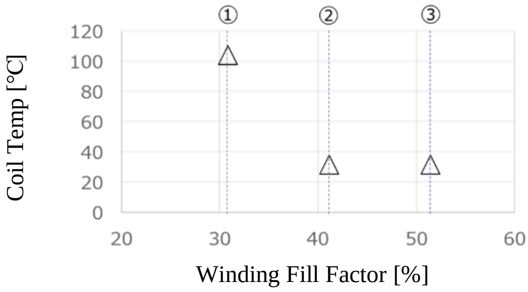

Figure 4. Winding fill factor vs Calculated Coil Temperature

3. EXPERIMENT

Figure 5 shows the test model. The test piece is a stator 1/12 cut model of the IPMSM for electric vehicle "LEAF". To measure the thermal performance of the coil and refrigerant, the stator core was fabricated from PPS resin. Transparent polycarbonate is used to observe boiling conditions. Liquid refrigerant flowed in one direction and DC current was applied to the coil to measure Joule loss and coil temperature. Table 1 shows the elemental test specifications and experimental conditions.

Figure 6 shows the cooling system: to supply liquid refrigerant of the specified temperature to the test setup, the refrigerant vaporized in the test setup is condensed and liquefied in a heat exchanger and circulated by a pump. Heaters were used to regulate the temperature.

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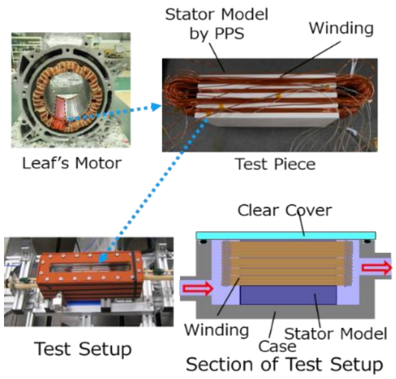

Figure 5. Test model

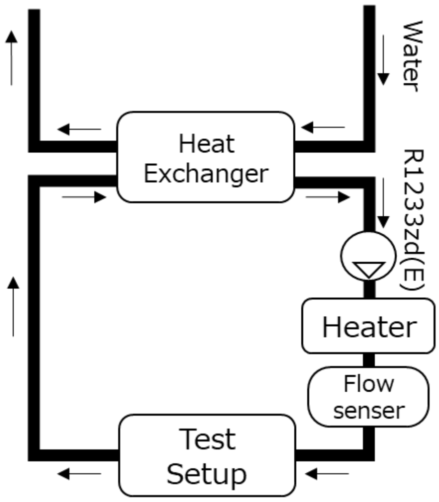

Figure 6. Cooling System

Table1. Test System Specification

Quantity	Value	Unit
Coil diameter	0.75	mm
Number of coil turns per slot	108	
Number of slot	4	
Active length	140	mm
Tooth width	5	mm
Flow Rate	0.5	L/min
Liquid Inlet Temp.	20	℃
Refrigerant	R-1233zd(E)	

Figure 7 shows a photograph of boiling phenomena on the test piece. As the heat flux increases, small bubbles begin to form, and the small bubbles merge to form a large bubble state.

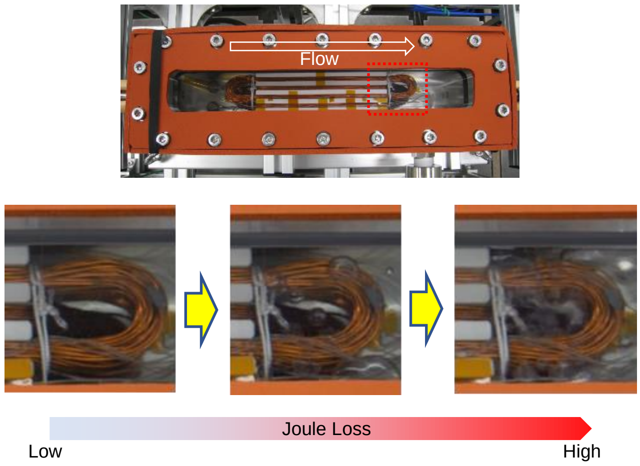

Figure7. Photograph of Boiling Phenomena

Figures 8 to 10. show the changing joule loss and temperature of the winding with winding fill factor 31% and 51%. The temperature of coil in case of winding fill factor 31% higher than that of 51%. Figure 9 shows the inside of the coil at the highest temperature reached, and it can be seen that the liquid level drops significantly on both the upstream and downstream sides, and the dryout region spreads over the entire area, indicating that this is the cause of the higher temperature. On the other hand, at winding fill factor 51% shown in Figure 10, a liquid surface exists high level, so the liquid touches polycarbonate at the upstream side, and a liquid flow can be seen on the coil-end at the downstream side in spite of dryout region. The above shows that a coil of temperature is higher at a low winding fill factor (31%), as expected in the previous section.

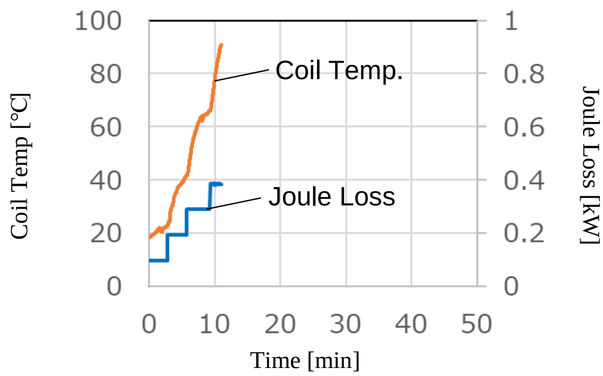

Figure.8. Experimental Result of Coil Temp. and Coil Joule Loss(Winding Fill Factor 31[%])

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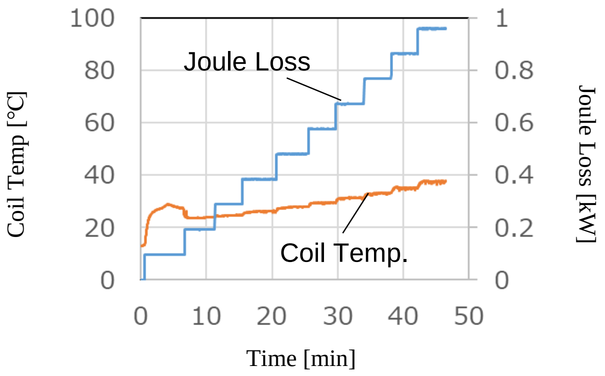

Figure.9. Experimental Result of Coil Temp. and Coil Joule Loss(Winding Fill Factor 41[%])

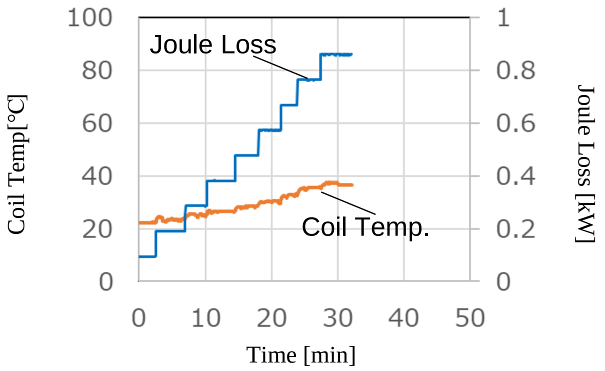

Figure.10. Experimental Result of Coil Temp. and Coil Joule Loss(Winding Fill Factor 51[%])

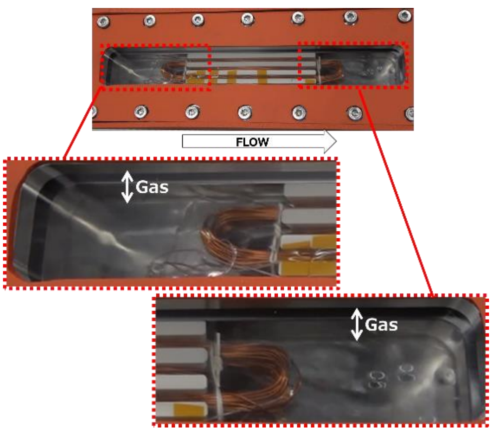

Figure 11. Photograph of Test Piece at maximum Coil Temp. Winding Fill Factor 31[%]

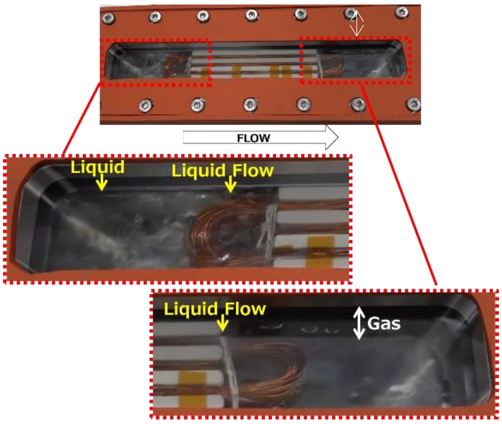

Figure 12. Photograph of Test Piece at maximum Coil Temp. Winding Fill Factor 41[%]

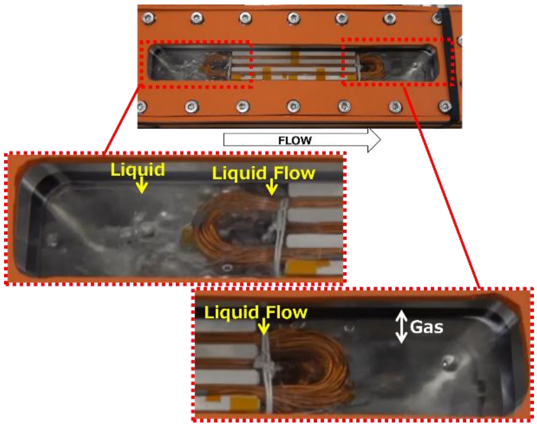

Figure 12. Photograph of Test Piece at maximum Coil Temp. Winding Fill Factor 51[%]

5. CONCLUSION

The conclusions and contributions of this paper are summarized as the following

- This paper presents a direct cooling method with forced convection boiling phenomena considering liquid phase behavior of liquid gas two-phase refrigerant
- The calculation model was constructed to simulate the temperature rise due to dryout occurrence caused by differences in winding fill factors
- In the case of a low winding fill factor, the gravity force is higher than the capillary force between coils, so this effectively makes a low level of the liquid surface and high temperature of coil in dryout region. Therefore, we mention designing higher winding fill factor with this cooling method

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