A STUDY ON THE EFFICIENCY OF HIGH VOLTAGE PTC HEATERS FOR ELECTRIC VEHICLES

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ABSTRACT

The development of electric vehicles has attracted significant international attention due to increasing environmental problems. Therefore, the mileage of electric vehicles becomes an important concern. However, air-conditioning systems have adverse effects on the mileage of electric vehicles. This study conducted a numerical analysis for the optimization of the efficiency of a PTC heater fin and verified the thermal efficiency of the PTC heater through numerical analyses and experiments. The results showed that a fin pitch of 1.3mm yielded the best efficiency, and the PTC heater maintained a minimum efficiency of 93% in the considered ambient temperature range.

Keywords: PTC heater, electric vehicle, mileage, heat rejection rate.

INTRODUCTION

The modern civilization has caused serious environmental problems. According to the 5th IPCC (Intergovernmental Panel on Climate Change) assessment report [1], the average temperature and sea level of the earth will increase by 3.7 K and 63 cm, respectively, by the end of the 21st century if greenhouse gas emission is not reduced. Such increase in the temperature would lead to changes in the seasonal characteristics of countries; increase in the sea level will threaten the existence of the coastal cities.

The major cause of global warming is CO_2. CO_2 concentration within the atmosphere is expected to reach the risk level within a few decades if such emission is not reduced. As a response, WMO(World Meteorological Organization) and UNEP (The United Nations Environment Program) together constituted an IPCC council and agreed to decrease by 2050 the global CO_2 emission to below half of the CO_2 emission of 1990 [1].

Transportation makes up a large portion of CO_2 emission, and regulation of CO_2 emission is necessary. Therefore, the automobile industry is expected to suffer a large impact. The automobile industry has led research on exhaust reduction devices and increases in mileage to reduce CO_2 production. The development of electric vehicles has attracted international attention as the best method to resolve the issue of CO_2 emission [2].

Automobiles with internal combustion engines use engine waste heat for heating. However, an electric vehicle uses a motor instead of an engine, such that it cannot provide sufficient heat for heating. PTC (Positive Temperature coefficient) has attracted much attention to replace the conventional method. Figure-1 shows a PTC heater model [3].

The nature of a PTC heater is that its resistance increases rapidly at a certain temperature. The constant voltage and increasing resistance lead to a decrease in the electric current. This property leads to a constant temperature and eliminates the concern of overheating. Furthermore, heating is promptly conducted. Recently, PTC elements have been actively studied [4-7].

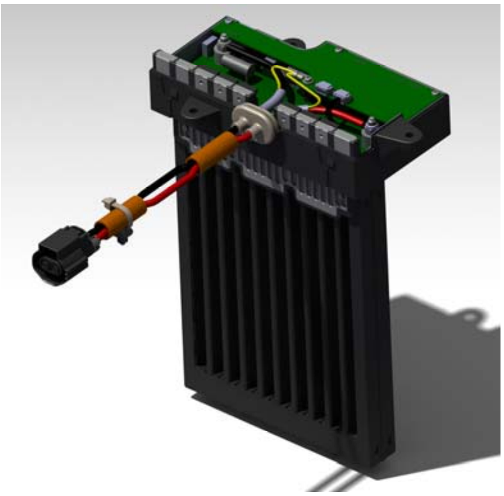

Figure-1. PTC heater model.

The development of electric vehicles has led to a competitive edge for electric vehicles due to improvements in mileage; and the heating system of electric vehicles significantly influences the total mileage. Experiments with an electric vehicle currently sold in the market show that heating reduced the total mileage by approximately 50% [8-10]. This result shows that an excessive amount of the electric power for the motor was used by the heater. This issue calls for the prompt development of PTC heaters. Diverse research has been conducted to improve the fin efficiency [11-14].

This study optimized the fin pitch using CFD to improve the thermal efficiency of the PTC heater. In addition, the thermal efficiency of the PTC heater with respect to the ambient temperature was also analyzed and the analysis was verified with a PTC heater prototype.

ANALYSIS METHOD AND CONDITIONS

Heat rejection rate with respect to the PTC heater fin pitch

Figure-2 illustrates a schematic of a fin model. Since the number of meshes will be too great when the entire PTC heater is analyzed, half of the fin was modeled under symmetry condition. The heat flow considered in the PTC heater exit temperature analysis with respect to the fin pitch used the assumptions of 3-dimensions, normal state, compressibility, and turbulent flow; the radiant heat transfer used the DO (discrete ordinate) model. Table-1 shows the conditions considered in the numerical analysis. BaTiO3 was used as the material for PTC; aluminum was used for the fin. The heat rejection rate of the PTC heater fin was simplified as in equation (1).

$$\begin{aligned} Q_{heat,f} &= \dot{m} C_p \triangle T \\ &= \dot{m} C_p (T_{out} - T_{amb}) \end{aligned} \tag{1}$$

Here, $Q_{heat,f}$, $\dot{m}$, C_p, $T_{out}$and T_{amb} represent fin heat rejection rate, mass flow rate, specific heat of air, and the temperature difference between the outlet and inlet, respectively.

$$Q_{total} = Q_{heat,f} \times EA_{fin} \tag{2}$$

Equation (2) shows the total heat rejection rate of the PTC heater. Q_{total} and EA_{fin} represent the total heat rejection rate of the PTC heater and the number of fins.

$$h_{fin} = \frac{q}{\triangle T} \tag{3}$$

Equation (3) shows the average heat transfer coefficient of the fin surface; h_{fin} represents the average heat transfer coefficient.

Table-1. Boundary conditions.

Factor	Values
Height	7.9mm
Depth	23mm
Pitch	1.1~1.5mm
Ambient temperature	273K
Turbulent intensity	5%
Mass flow rate	300kg/h
Power	5600W

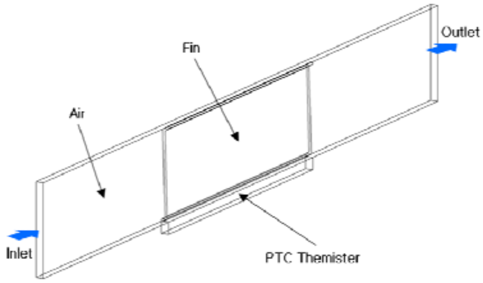

Figure-2. Schematic of the fin model.

PTC heater heat rejection rate with respect to the ambient temperature

The conditions considered for the exit temperature analysis of the PTC heater with respect to the ambient temperature are the same as those used in the fin pitch analysis. The previously optimized and analyzed fin pitch was analyzed according to the temperature variation. Since the resistance of the PTC element varies dramatically with respect to the temperature variation, the electric potential difference was assumed to be 360V, in order to compute the electric power. The temperature change was assumed to be in the range of 253K~293K, and it was analyzed every 10K.

Experimental device and method

The efficiency of the PTC heater with respect to the ambient temperature was verified. A calorimeter was used to measure the outlet temperature. Figure-3 provides a schematic of the calorimeter. The service requirements of the heater were assumed to be electric voltage of 360V and mass flow of 300kg/h. The heating element of the PTC heater had dimensions of (length × height × depth) of 210mm×165mm×25mm; the fin had a thickness of 0.4mm. PTC was made out of $BaTiO_3$ and the fin was made from aluminum. The optimized fin pitch, determined from the heat rejection rate analysis, was 1.3mm; such a fin was made as a prototype. In addition, the outlet temperature was measured with the ambient temperature altered within the range of 253K~293K.

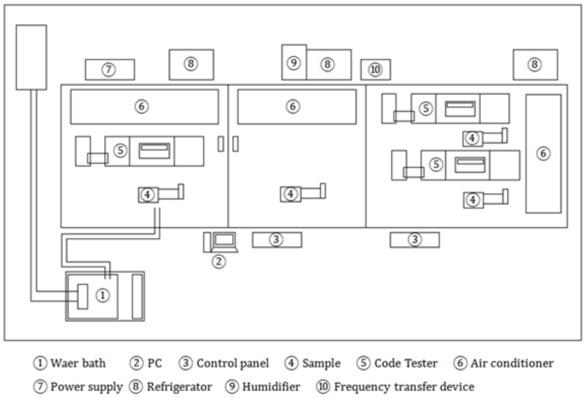

Figure-3. Schematic of the calorimeter.

RESULTS AND DISCUSSIONS

Heat rejection rate according to fin pitch of the fin model

Figure-4 shows the change in the heat rejection rate of the fin model according to the fin pitch. The heat rejection rate of the fin model increased linearly with respect to the increasing fin pitch. The heat rejection rate of the fin model increased from 3.73×10^{-4}W for a fin pitch of 1.1mm to 5.44×10^{-4}W for a fin pitch of 1.5mm. This change resulted from the simple increase in the heating surface area due to the increase in the surface area.

On the other hand, the change in the heat rejection rate of the fin model with respect to the unit area was also studied. Figure-5 shows the change in the heat rejection rate of the outlet with respect to the pitch. The heat rejection rate increased with decreasing pitch and yielded a maximum value of 4.43×10-5 W at the pitch of 1.3mm. A further reduction in the pitch resulted in a decrease of the heat rejection rate.

The total heat rejection rate of the PTC heater according to each pitch value was computed from the heating element size of the PTC heater. Figure-6 shows the change in the total heat rejection rate with respect to the fin pitch. The total heat rejection rate increased with decreasing pitch and yielded a maximum value of 5, 531W at the pitch of 1.3mm. A further decrease in the pitch resulted in a decrease of the total heat rejection rate. Therefore, the optimum fin pitch was 1.3mm.

Figure-7 shows the change in the average heat transfer coefficient of the fin surface according to the fin pitch. The average heat transfer coefficient of the fin surface increased with decreasing pitch and yielded a maximum value of 268.9 W/m^{2}K at the pitch of 1.3mm. Further reduction in the pitch resulted in a rapid decrease in the heat transfer coefficient. This change in the heat transfer coefficient confirms that the optimal fin pitch is 1.3mm.

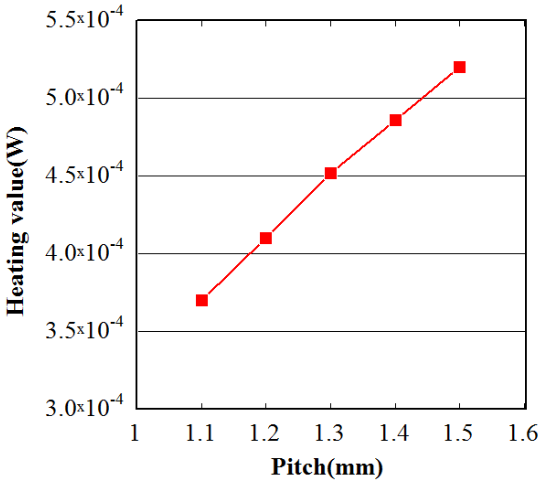

Figure-4. Change in heat rejection rate with respect to pitch.

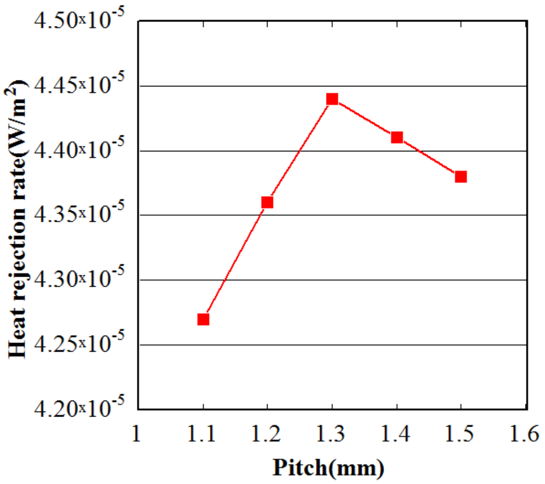

Figure-5. Change in heat rejection rate with respect to pitch.

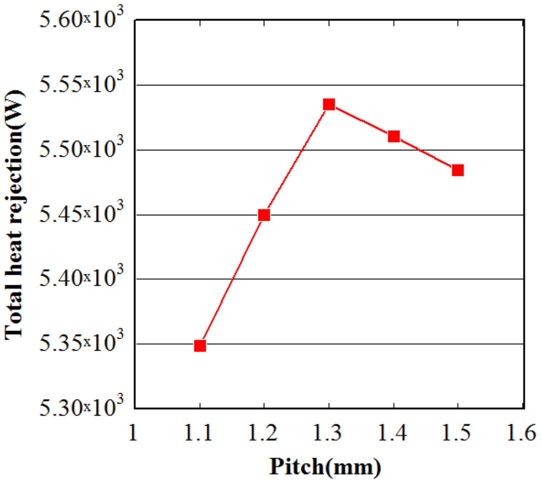

Figure-6. Change in total heat rejection rate of PTC heater with respect to pitch.

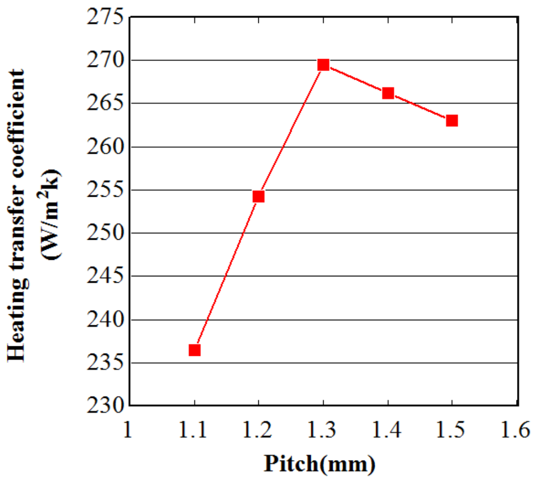

Figure-7. Change in average heat transfer coefficient.

Total heat rejection rate of PTC heater model

Figure-8 shows the heat rejection rate predicted by numerical analysis according to the electric power on the PTC heater. The electric power increases in a relatively linear manner with decreasing ambient temperature, and the heat rejection rate increases accordingly. However, the applied electric power decreased due to the limit of the PTC heater capacity around the ambient temperature of 253K, and the heat rejection rate of PTC heater also decreased. On the other hand, the thermal efficiency of the PTC heater was high, with a value of 95.7% around the considered ambient temperature. However, the efficiency decreased with the decreasing ambient temperature, and a minimum efficiency of approximately 94.5% was observed around the ambient temperature of 253K. Therefore, the PTC heater with a high efficiency predicted from the numerical analysis was produced as a prototype for the verification of the thermal efficiency.

Total heat rejection rate of PTC heater prototype

Figure-9 shows the heat rejection rate measured from the experiment with respect to the electric power applied to the PTC heater. Similar to the results of the numerical analysis, the electric power increased in a relatively linear manner as the ambient temperature decreased, and the corresponding heat rejection rate increased. The errors between the experimentally predicted heat rejection rates and the results of the numerical analyses were in the range of 1~5%. The maximum error occurred at 253K, and the heat rejection rate at that point was less than the heat rejection rate at 263K. The efficiency of the PTC heater according to the experimentally measured heat rejection rate was approximately 94.5% on average, and this is approximately 1% less than the value predicted from the numerical analysis. However, the minimum PTC thermal efficiency was approximately 93.7%, which would still indicate a PTC heater with high efficiency.

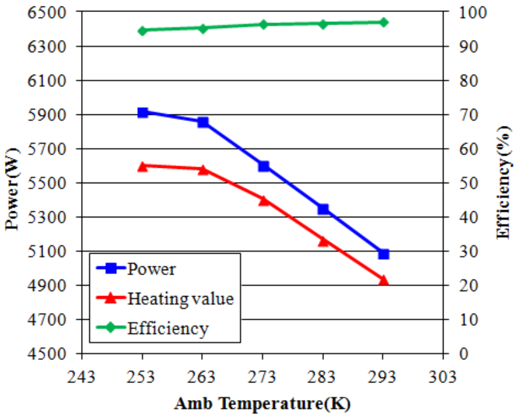

Figure-8. Electric power, heat rejection rate, and efficiency change of PTC heater according to the ambient temperature (Analysis).

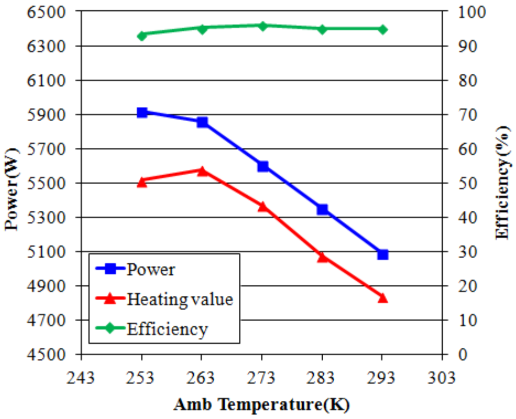

Figure-9. Electric power, heat rejection rate, and efficiency change of PTC heater according to the ambient temperature (Experiment).

CONCLUSIONS

This study conducted a numerical analysis and experiment to optimize the PTC heater performance of an electric vehicle. The conclusions obtained from this study are as follows.

a) According to the numerical analysis results, the heat rejection rate increases with decreasing fin pitch of the PTC heater. When the fin pitch is further reduced from 1.3mm, the heat rejection rate drops due to the decreasing average heat transfer coefficient of the fin. Therefore, fin pitch is most effective when it is 1.3mm.
b) According to the heat rejection rate analysis, the heat rejection rate of the PTC heater linearly increased as the ambient temperature decreased, and the increase rate was reduced at 253K due to the capacity limit. In addition, the average thermal efficiency of the PTC with respect to the ambient temperature was maintained at 95.7%.
c) The performance test with the PTC heater prototype showed that the change in the heat rejection rate of the PTC heater qualitatively and quantitatively agreed with the analysis results. The errors with the analysis result were in the range of approximately 1~5%. The measured minimum PTC efficiency was 93.7% at 253K, which shows that a high efficiency PTC heater has been successfully developed.

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