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Performance Prediction of Heat Pipe Used in Motor Cooling

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ABSTRACT

With the development of power density in motor, the cooling becomes more and more important. Heat pipe is a method to solve this issue. However, the performance of heat pipe is largely affected by the structure, the operating angle, and the cooling at condensation section. Therefore, this paper experimentally discusses its impact on heat pipe performance. Based on the experimental data, (artificial neural network) ANN model is established to predict the performance. Results showed that, when the operating angle of heat pipe was large than 45°, it can be well adopted for motor cooling; while for other operating angles, the performance would be largely changed. ANN model is suitable method for the prediction the performance of heat pipe. The average relative errors of evaporator temperature, heat load, and effective thermal conductivity 1.0%, 1.7% and 2.9%, respectively.

Keywords: Motor cooling, heat pipe, effective thermal conductivity, artificial neural network

NONMENCLATURE

Abbreviations	
AEA	All-electric aircraft
ANN	Artificial Neural Network
MSE	Mean square error
Symbols	
A	Cross-sectional area (m^2)
D	Diameter of thermal conductive layer (m)
d	Diameter of heat pipe (m)
K_{eff}	Effective thermal conductivity (W/m·K)
L_e	Evaporator length (m)
L_c	Condenser length (m)
L_{eff}	Effective length (m)
T	Temperature (°C)
N	Number of samples
n	Number of nodes in hidden layers
P_0	Electric Power (W)
Q	Heat load (W)
R_{total}	Total thermal resistance (K/W)
U_{air}	Air velocity (m/s)
θ	Angle (°)
λ	Thermal conductivity (W/m·K)

1. INTRODUCTION

Nowadays, the development of all-electric aircraft (AEA) is an indispensable and important part of the electrified transportation process. The traditional cooling of motor cannot meet the requirement of high heat dissipation [1]. Therefore, finding an efficient cooling method becomes more and more urgent.

Heat pipe is a passive heat transfer device to transfer large amount of heat [2, 3], which has been applied in many fields, such as CPU cooling [4], battery thermal management [5], and waste heat recovery [6]. There also have works applying heat pipe into motor cooling. For example, Sun et al. [7] inserted heat pipe into the gap between the winding and the casing. Results showed the maximum temperature of motor was reduced by 22.9 °C. Wan et al. [8] used heat pipe to dissipate heat from motor windings. Compared to conventional cooling, the maximum temperature was reduced by 16.4 °C.

The performance of heat pipe is affected by many factors, such as such as wick structure [9], pressure head of evaporation [10], operating angle [11], and external environment. However, it is usually considered as a material with high thermal conductivity (1×10^4-1×10^5 W/m·K^{-1}) [7, 8], which is not accuracy in motor cooling. Therefore, the performance prediction of heat pipe is needed for motor cooling. Big data/machine learning techniques are a common approach to predict heat pipe performance using operating conditions [12], including artificial neural network (ANN) models [13], corresponding surface analysis models [14], etc. Among them, ANN models are widely used in prediction and calculation of complex systems due to their advantages in nonlinear regression and classification.

Table 1 The parameters of the experiment system

System	Item	Parameter	Value
Heat pipe	Size	d×L (mm)	4×160
	Material	Copper	
	Wick	Pore diameter (μm)	30
		Porosity (%)	27
		Thickness (mm)	1
	Working liquid	Deionized water	/
		Charging ratio	40%
	Bracket	Angle range	0-90°
Heating	Electric heating wire	Resistance (Ω/m)	5.6
	Heat conduction layer	D×d×L (mm)	40×4×50
	24V heating source	Electric power (W)	10-70
Cooling	Air duct	D×L (m)	0.2×2
	Fan	Input voltage (V)	125-225
Data acquisition	Thermo-couples	Accuracy (°C)	±0.1
		Range (°C)	0-200
	Anemometer	Accuracy (m/s)	±0.01
		Range (m/s)	0-35

Therefore, this paper tests heat pipe under different working conditions and established ANN model to predict heat pipe performance by using evaporator temperature (T_e), heat load (Q) and effective thermal conductivity (K_{eff}). This study can provide theoretical and data support for the application of heat pipes in motor heat dissipation.

2. EXPERIMENT DESCRIPTION

2.1 Experiment system introduction

In heat pipe, the working fluid the working fluid evaporates from the evaporator section. The vapor moves towards the condenser section along the axis due to the pressure difference. Then, it is condensed at condensation section. The liquid working fluid moves back to evaporation section due to the capillary force, as shown in Fig. 1.

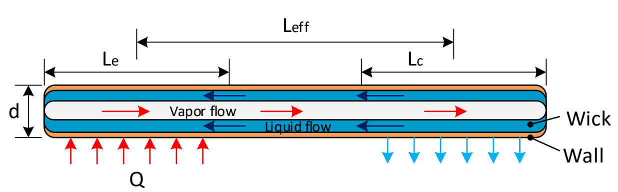
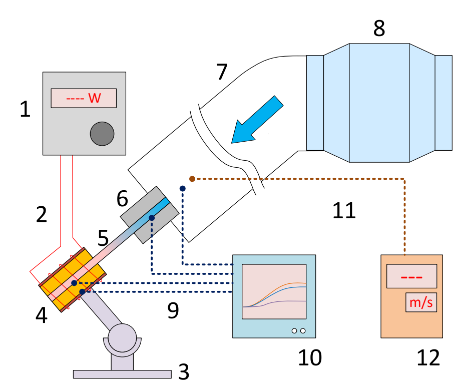


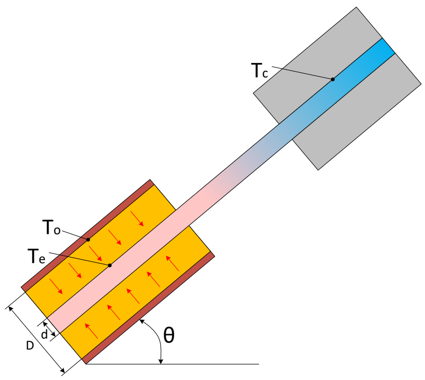
Fig. 1 Heat pipe structure

Experiment system consists of heat pipe, heating system, cooling system, and data acquisition system, as shown in Fig. 2(a). The heat pipe is installed on the bracket, in which the angle could be adjusted from -90° to +90°, the fin is used to enhance the heat transfer at condensation section, as shown in Fig. 2(b). For the heating system, 24 V power source and electric heating wire are used to provide the heat power at evaporator section. For the cooling system, the axial flow fan and air duct simulate different environments. The data acquisition system could record the variation of temperature and air velocity. Thermocouples are arranged at different points: outside of the heat conduction layer of the heating system (operating temperature: T_o), center of the evaporator side wall (T_e), center of the condenser side wall (T_c), and ambient temperature (T_{amb}). The detailed parameter can be found in Table 1.



1- 24V power source; 2- Electric heating wire; 3- Bracket; 4- Heat conduction layer; 5- Heat pipe; 6- Axial fin radiator; 7- Air duct; 8- Axial flow fan; 9- Thermocouples; 10- Temperature data acquisition; 11- Hot-line anemometer; 12- Velocity data acquisition.

(a) Experiment system



(b) Parameter Definition

Fig. 2 The schematic of experiment system

The experimental parameter is shown in Table 2, which is divided into two parts: 1) The experiment cases was determined using the control variable methods, which is used to compare and analyze the heat transfer process; 2) The variables such as air velocity (U_{air}), heat pipe angle (θ) and electrical power (P_0) was set as random in the experiment, which is used to build the ANN model.

Table 2 Experimental parameter

Parts	Variables	Range	Step
1	Air velocity (m/s)	4-8	2
	Angle	-90° - +90°	45
	Electrical power (W)	10-70	10
2	Air velocity (m/s)	4-8	Random
	Angle	-90° - +90°	Random
	Electrical power (W)	10-70	Random

2.2 Performance indicators

For motor windings, the maximum temperature is usually required not to exceed 135 °C [7]. In the experiment system, the operating temperature (T_o) is the highest temperature for the heating system which can decide whether the system is at normal operating temperature.

The electric power (P_0) of heat source is not fully conducted to the heat pipe in the experiment. The heat load (Q) shows how much heat is conducted by the heat pipe, which can be defined as following:

$$Q = 2\pi L_e \lambda_{cu} \frac{(T_o - T_e)}{\ln\frac{D}{d}} \tag{1}$$

where, λ_{cu} is the thermal conductivity of copper.

ΔT is temperature difference between evaporator and condenser, which can be decide whether the heat pipe is working abnormally, which can be defined as following:

$$\Delta T = T_e - T_c \tag{2}$$

The effective thermal conductivity (K_{eff}) represents the amount of heat transfer capability of the heat pipe, which can be solved as following:

$$K_{eff} = \frac{L_{eff}}{R_{total}A} = \frac{L - \frac{1}{2}(L_e + L_c)}{\frac{\Delta T}{Q}A} \tag{3}$$

where, L_{eff}, R_{total}, and A is effective length, total thermal resistance, and the cross-sectional area of heat pipe, respectively.

2.3 Establishment of the ANN model

Based on the experimental data, a fully connected feed-forward ANN model is used to predict the performance of heat pipe. The back propagation learning algorithm is commonly used to construct ANN model due to its excellent adaptability [15]. 200 groups experimental data were randomly employed, 190 groups and 10 groups experimental data were used for training and testing, respectively.

The time and accuracy of the calculation are affected by the number of neurons in the hidden layer. Therefore, the optimal number of neurons is decided by the mean square error (MSE), which defined as shown in Eq. 4 [13].

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(Y_{pre,i} - Y_{exp,i}\right)^2 \tag{4}$$

where, $Y_{pre,\,I}$ and $Y_{exp,\,I}$ are the predicted result by ANN model and experimental data, respectively.

The ANN model construction can be found in Fig. 3.

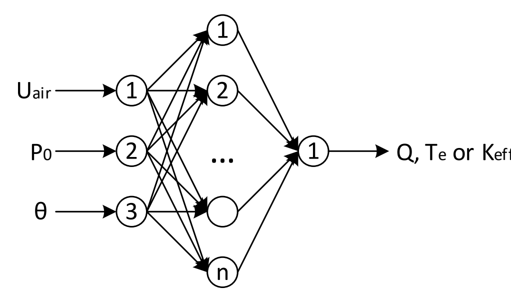


Fig. 3 The ANN model construction

3. RESULT AND DISCUSSION

3.1 Heat pipe performance

Fig. 4 shows the heat pipe performance under different cases when the air velocity is 6m/s. With the increase of heat load, the evaporator temperature and temperature difference increased. It was also clear that, the performance of heat pipe with +45° was always better than those of 0° and -45°, which was mainly caused by the gravity. It should be note that, the performance was slightly changed when the heat load was smaller than 30W, which was mainly due to the suitable working operation. For example, when P_0 was 20W, evaporator temperatures were 36°C, 36.1°C and 38°C for heat pipe with +45°, 0° and -45°, respectively. Moreover, the heat pipe with -45° cannot operated successfully if the heat load was large than 60W. Therefore, the heat pipe performance should be fully considered under different application conditions.

Fig. 5 shows the K_{eff} at different conditions. It can be found that, with the increase of heat electric power, K_{eff} showed a decreasing tendency. It should be note that, K_{eff} of heat pipe with +90° and +45° changed slightly with the variation of both air velocity and P_0, which was within the suitable operating range. However, the impact of angle became more obvious if the angle was smaller than 0°. With the increase of P_0, the K_{eff} first increases and then decreases rapidly when θ=0°, especially the trend is more obvious in the case of high air velocity. This is because when the working fluid condensation is sufficient, the vapor pressure drop will increase with the rise of electric power before reaching the capillary force limitation, which benefits the working fluid mass cycle. Similarly, the capillary force limitation will cause K_{eff} to drop rapidly at θ=-90° and θ=-45° when P_0 is greater than 10W.

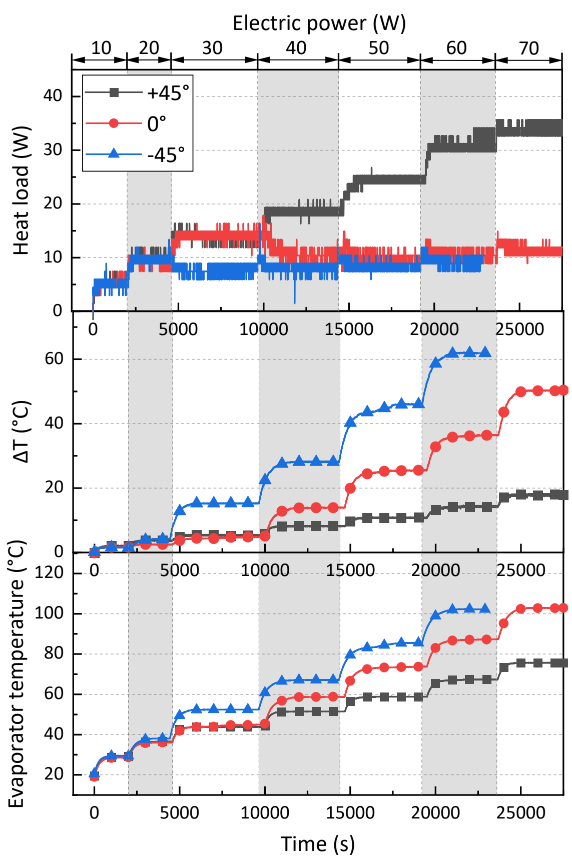


Fig. 4 Heat pipe performance at 6m/s of air velocity

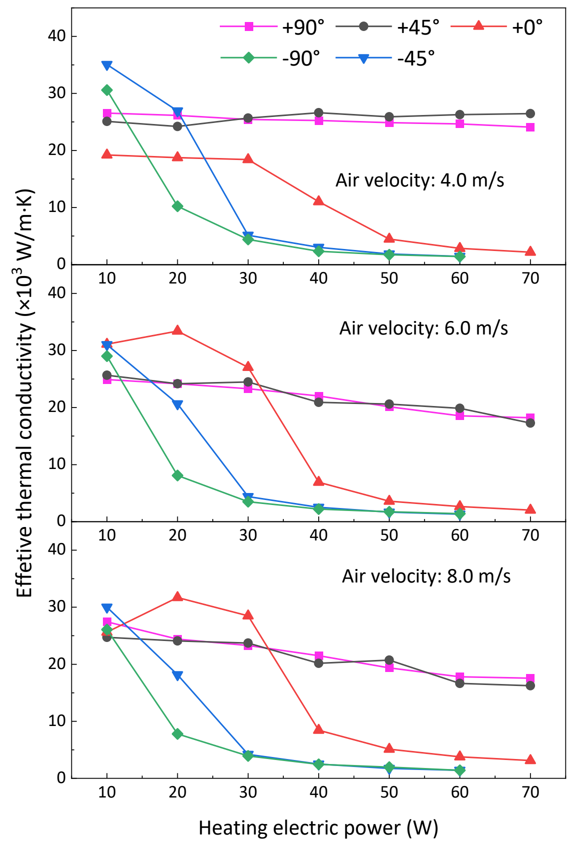


Fig. 5 Variation of K_{eff} at different conditions

3.2 ANN model prediction results

Fig. 6 shows the prediction of ANN model. It can be found that when the number of nodes in the hidden layer is 5, 12, and 7 for T_e, Q, and K_{eff}, the MSE of training data for T_e, Q and K_{eff} possesses the minimum values of 0.004005, 0.004379 and 0.008393, respectively.

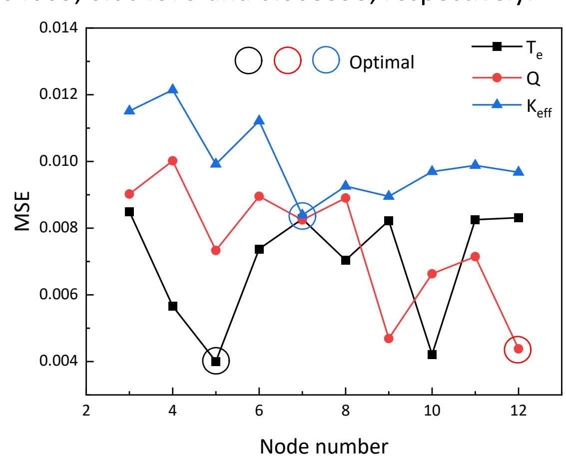


Fig. 6 Prediction of ANN model

Table 3 shows the working condition in 10 cases, which is used to validate the ANN model. T_e, Q, and K_{eff} are used.

Table 3 The cases of Testing Collection

Case	P_0 (W)	θ (°)	U_{air} (m/s)
1	60	90	7.27
2	20	90	6.44
3	60	0	6.71
4	40	45	4.81
5	40	-45	6.66
6	50	45	7.21
7	30	-45	4.42
8	30	0	8.17
9	10	-90	6.99
10	40	-90	4.37

Relative errors of ANN model between experimental data and prediction result are shown in Fig. 7. It was clear that most of the relative errors are less than 4% and the average relative errors of T_e, Q, and K_{eff} are 1.0%, 1.7% and 2.9%, respectively. Combining Table 3, the K_{eff} in Case 9 and 10 showed a large deviation, as well as heat load in Case 8. This phenomenon was mainly caused by the capillary force limitation due to the operation angle.

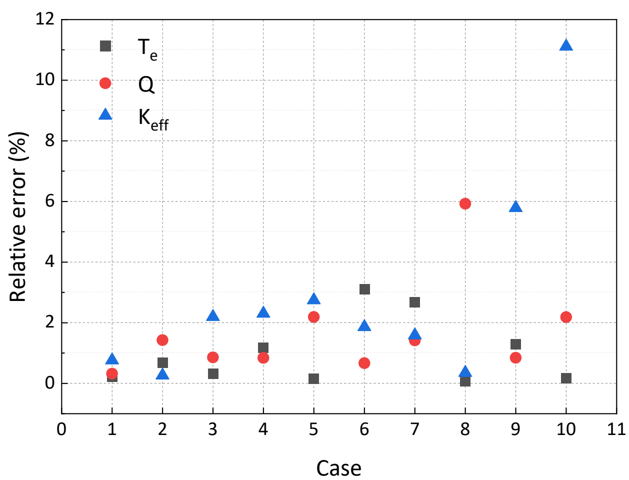


Fig. 7 Relative error of ANN model validation

4. CONCLUSION

Based on the experiment, this paper discusses the impact of operating parameters on heat pipe performance used in motor cooling. ANN model is established to predict the performance. Based on the result, it can be concluded that: (1) When the operating angle of heat pipe was large than 45°, it can be well adopted for motor cooling; while for other operating angles, the performance would be largely changed. (2) ANN model is suitable method for the prediction the performance of heat pipe. The average relative errors of evaporator temperature, heat load, and effective thermal conductivity 1.0%, 1.7% and 2.9%, respectively.

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