PARAMETER OPTIMIZATION FOR FLAT MICRO-GROOVE HEAT PIPE BY GAS-LIQUID TWO-PHASE FLOW ANALYSIS

Xibing LI [1], Weixiang LI [2], Jixiang LI [3], Liduan HUANG [4], Tengyue ZOU [5,*]

Micro-groove heat pipe is a good choice for heat dissipation of large CNC lathes. Its thermal conductivity is limited by a variety of heat transfer limits, which mainly depend on the geometrical parameters, the status of working fluid, the structure of the wick and the working temperature. Through mathematical modeling the optimized geometric parameters are chosen as 9.38 mm inner hole diameter and 55 grooves with 0.32 mm top side width, 0.31 mm groove depth, 0.31458 mm bottom width. Analysis of gas-liquid two-phase flow is taken to find out that the best filling rate is 22.62% for the working fluid. An orthogonal experiment is also carried out to get the suitable length, working temperature and inclination angle for the micro-groove heat pipe. From the experimental results, the heating temperature is found to have the largest impact on the heat transfer rate, followed by the heat pipe length, and the inclination angle has the least impact. Moreover, 50°C bath temperature, 160 mm heat pipe length and 90° inclination angle are the most suitable environmental parameters for the flat micro-groove heat pipe under the experimental circumstance.

Keywords: heat pipe; micro groove; two-phase flow; filling rate; thermal conductivity

1. Introduction

With the development of energy, shipbuilding, metallurgical industry, aerospace and transportation, the manufacturing requirements for the CNC lathes become higher. Rotation speed is an important factor that affects these two aspects of the lathe, and it is limited by the increase in oil film temperature [1]. Studies have shown that large-scale lathes tend to cause the temperature of the oil film to rise sharply when the bearing friction is severe, and then the film thickness becomes thinner, which causes the bearing load to increase [2, 3]. Thus, the oil film thermal control of hydrostatic thrust bearings for large-scale lathes is a key issue. The ultra-thin aluminum flat heat pipe has good performances on weight

[1] Professor, College of Mechanical and Electronic Engineering, Fujian Agriculture and Forestry University, Fuzhou 350002, China, e-mail: lxbwjj@163.com.
[2] Master Candidate, College of Mechanical and Electronic Engineering, Fujian Agriculture and Forestry University, Fuzhou 350002, China, e-mail: 630502910@qq.com.
[3] Bachelor Candidate, Jinshan College, Fujian Agriculture and Forestry University, Fuzhou 350002, China, e-mail: 531605727@qq.com.
[4] Master Candidate, College of Mechanical and Electronic Engineering, Fujian Agriculture and Forestry University, Fuzhou 350002, China, e-mail: 1220552443@qq.com.
[5] Corresponding Author, Associate Professor, College of Mechanical and Electronic Engineering, Fujian Agriculture and Forestry University, Fuzhou 350002, China, e-mail: zouty@fafu.edu.cn.

and heat transfer ability, but it cannot afford high-load [4]. The micro-groove heat pipes made on copper plate can be a better choice to take away heat efficiently and avoid dry friction phenomenon [5]. The thermal conductivity of heat pipes is limited by a variety of heat transfer limits [6, 7], which mainly depend on the geometrical parameters of heat pipe, the status of working fluid, the structure of the wick and the working temperature. The liquid filling rate and the two-phase flow effect of evaporation and condensation determines the characteristics of the heat pipe [8, 9]. Experimental results showed that the filling rate had a significant impact on the thermal performance [10]. The closed-loop pulsating heat pipes with different filling rates were also found to have different performances [11]. The selection of the filling rate is closely related to the design and geometry of the heat pipe. The optimal water filling rate of the elliptical cross-section coreless solar heat pipe collector was found to be about 10%, while the optimal water filling rate of the circular cross-section coreless heat pipe collector is very close to 20% [12].

Therefore, how to select the appropriate heat pipe geometrical size and working fluid parameters is a problem that needs to be paid attention to. In this research, through the mathematical modeling, the suitable geometrical parameters of the micro-groove heat pipe for large hydrostatic thrust bearings are selected to achieve the optimal performance. Furthermore, the gas-liquid two-phase flow analysis is adopted to find the best liquid filling rate and heat pipe working temperature.

2. Mathematical modeling and parameters optimization

The thermal conductivity of heat pipes is limited by a variety of heat transfer limits, including: capillary limit, sound velocity limit, carrying limit, boiling limit, freezing start limit, continuous flow limit, viscosity limit, and condensation limit [6, 7]. These limits can be calculated following the formulas in literatures [13]. Parameter optimization procedure is to achieve the best heat transferring performance through modeling analysis based on the eight heat transfer limits. The parameter optimization procedure in this paper is carried out in an environment in which the water is boiling at 40 ℃ under the standard vacuum negative pressure. The material of the flat micro-groove heat pipe is copper, the temperature of the evaporation section is set to 40 ℃ constantly, the condensation section is cooled to 20 ℃ below by water, and the flat heat pipe is laid flat. The effective length of the heat pipe is 110 mm, the evaporation section length is 60 mm, the adiabatic section length is 20 mm, and the condensation section length is 120 mm.

Because the heat pipe is under normal operation at about 40 degrees and the working medium is water, the cold start limit and continuous flow limit are not taken in consideration. If the tooth width of the tool is set too small, tooth root fracture will be easy to be caused. Considering the strength requirements of the tool design, the number of teeth of a multi-tooth tool is limited to a maximum of 55 teeth and the aspect ratio setting range should be within the range of 1:1. The geometrical structure of the flat micro-groove heat pipe can be designed and the results are shown in Table 1. The data were obtained by Computational Fluid Dynamics (CFD) simulation in ANSYS Fluent software which set the sum of the inner hole diameter and the groove depth to 10 mm and intended to achieve the best heat transfer performance.

Table 1

Optimized groove parameters

Groove number [n]	Top side width W [m]	Groove depth δ [m]	Bottom width W_b [m]	Inner hole diameter d_v [m]	Maximum heat transfer q [W]
55	0.00032	0.00031	0.00031458	0.00938	338.283
54	0.00032	0.00031	0.00031458	0.00938	332.403
53	0.00032	0.00031	0.00031458	0.00938	326.514
52	0.00032	0.00031	0.00031458	0.00938	320.616
55	0.00030	0.00029	0.00029493	0.00942	285.311
54	0.00030	0.00029	0.00029493	0.00942	280.299
53	0.00030	0.00029	0.00029493	0.00942	275.280
52	0.00030	0.00029	0.00029493	0.00942	270.255
55	0.00029	0.00028	0.00028511	0.00944	260.479
54	0.00029	0.00028	0.00028511	0.00944	255.882
53	0.00029	0.00028	0.00028511	0.00944	251.280
52	0.00029	0.00028	0.00028511	0.00944	246.673
55	0.00028	0.00027	0.00027528	0.00946	236.809
54	0.00028	0.00027	0.00027528	0.00946	232.612
53	0.00028	0.00027	0.00027528	0.00946	228.412
52	0.00028	0.00027	0.00027528	0.00946	224.207
55	0.00032	0.00031	0.00031458	0.00938	338.283
54	0.00032	0.00031	0.00031458	0.00938	332.403
53	0.00032	0.00031	0.00031458	0.00938	326.514

It can be seen from the above table that the higher the number of grooves the better the maximum heat transfer performance of the heat pipe. After optimization procedure, the optimal geometrical parameters of the micro-groove heat pipe are chosen as 9.38 mm inner hole diameter and 55 grooves with 0.32 mm top side width, 0.31 mm groove depth, 0.31458 mm bottom width.

4. Gas-liquid two-phase flow analysis and filling rate optimization

4.1 Modeling for a single trapezoidal groove

The flow channel of a hole from a flat micro-groove heat pipe is studied to explore the phase change of water and steam during heat transfer process. The changes of steam speed and temperature inside heat pipe were also studied. After size optimization, Re_v=2298<2300 and M_v=0.1<0.2 are calculated, which are the steam Reynolds number and the Mach number. Thus, the steam flow is considered to be incompressible laminar flow and the Viscous-Laminar model is adopted. The Gambit software is used to model a three-dimensional groove of heat pipe and separate it into three equal parts: the evaporation section, the adiabatic section and the condensation section. The model is meshed to 0.1mm*0.1mm*0.1mm grids uniformly and the number of grids is set to 874180. The effective grid is 874180, and the efficiency is 100%.

4.2 Parameter Setting for Two-phase Flow Analysis

Because the steady-state analysis may not be able to obtain the true heat conduction process related to time, the transient calculation method is selected. The heat pipe is divided into three sections, the evaporation section, the adiabatic section, and the condensation section, with steam as the primary phase and water as the second phase. Using the two-phase flow Euler equation VOF, the gravity is set to -9.81m/s^2, the wall temperature of the condensation section is set to 300 K, the heat flux of the adiabatic section is set to 0, the wall temperature of the evaporation section is set to 314 K, and the contact angle of water and steam is designed as 10°. For the corresponding area of the evaporation section, the following settings are done: (1) patch water with a volume fraction of 100%; (2) turn on the heat-ranz marshall and wall adhesion items in the surface tension setting; (3) set the phase transition temperature to 313.15 K; (4) set the relevant parameters according to the 40℃ water. Then set the variable step size to 1e-8, the maximum step size to 0.001, and the colon number to 0.01. Slowly adjust the appropriate colon number according to the results of the later calculations.

5. Simulation results and experiments

The simulation is executed by ANSYS R15.0 software on a PC. After a period of simulation, a cross-sectional view of x=0 is created and the liquid volume fraction diagrams at different time are intercepted. Then the changes in liquid volume fraction with time are shown in Fig.1. It can be found that at the beginning the liquid in the evaporation section slowly tilted due to gravity, and the addition of evaporation makes the liquid decrease. With the passage of time, the liquid volume fraction in the condensation section increases. The liquid volume in the condensation section reaches the maximum at 0.59 s, and the liquid volume in the evaporation section decreases significantly. At 2.25 s, due to the limitation of the filling rate and the longer time, the volume of the liquid in the condensation section is relatively reduced, and the volume of the steam inside the groove increases. Thus, the process is observed to follow the physical principle of two-phase flow. Fig.2 shows the steam motion state at *time*=2.256 s. It can be found that the moving direction of the steam rises from the evaporation section, and then moves in the direction of the condensation section along the axial direction of the groove, disappears in the condensation section and condenses into liquid. The simulation results show that the groove can provide good capillary force, and the steam movement process is consistent with the two-phase flow phenomenon. The transfer mechanism of the micro-groove heat pipe with optimized parameters is verified. Fig.3 shows the temperature distribution of the x=0 section at different times. It can be seen that when *time*=0.028 s, the temperature of the evaporation section is nearly constant. When *time*=0.59 s, the temperature change diffuses to the adiabatic section, because the steam condenses into the condensation section. For water, when *time*=1.15 s, it can be observed that the temperature in the condensation section is significantly reduced where the vapor condenses into liquid, and a certain gradient is formed. At *time*=5.08 s, the temperature of the adiabatic section becomes higher due to the rise of steam. The liquid volume fraction of the condensation section becomes larger. Thus, the designed model conforms to the gas-liquid two-phase flow principle.

Then the temperature changes of different sections in the micro-groove heat pipe with different filling rates were studied. Take the middle point in the evaporation section as the testing point, and monitor the temperature change of it under different filling rates, as shown in Fig.4(A). When the filling rate is 19.29%, the temperature of the evaporation section rises the fastest. The temperature first rises and decreases, and then stabilizes. The temperature of those four filling rates tends to be the same after the time reaches 1.2 s. Among them, the temperature change curve with a filling rate of 12.62% has a relatively slow rise rate and eventually tends to be gentle. For the middle point in the adiabatic section, the temperature change is shown in Fig.4(B). It was found that as the filling rate rises, the start time of the point temperature rise is successively extended, but the slope of the temperature curve with a larger filling rate is smaller in a short period of time. Moreover, the final temperature does not rise and tends to be consistent. As shown in Fig.4(C), for the middle point in the condensation section, the temperature changes under different filling rates are relatively consistent at the beginning. Then as the time increases from 0.2 s to 0.7 s, the temperature rises corresponding to different filling rates. From the simulation, it was found that the best effect is acquired when the liquid filling rate is 22.62%, because of the best heat transfer efficiency and the smoothest changing law. The simulation results are validated by executing the heat transfer experiments using the actual heat pipes with known structural parameters under specific conditions. The resulsts show that the error between the simulation result and the actual experimental value is less than 10%.

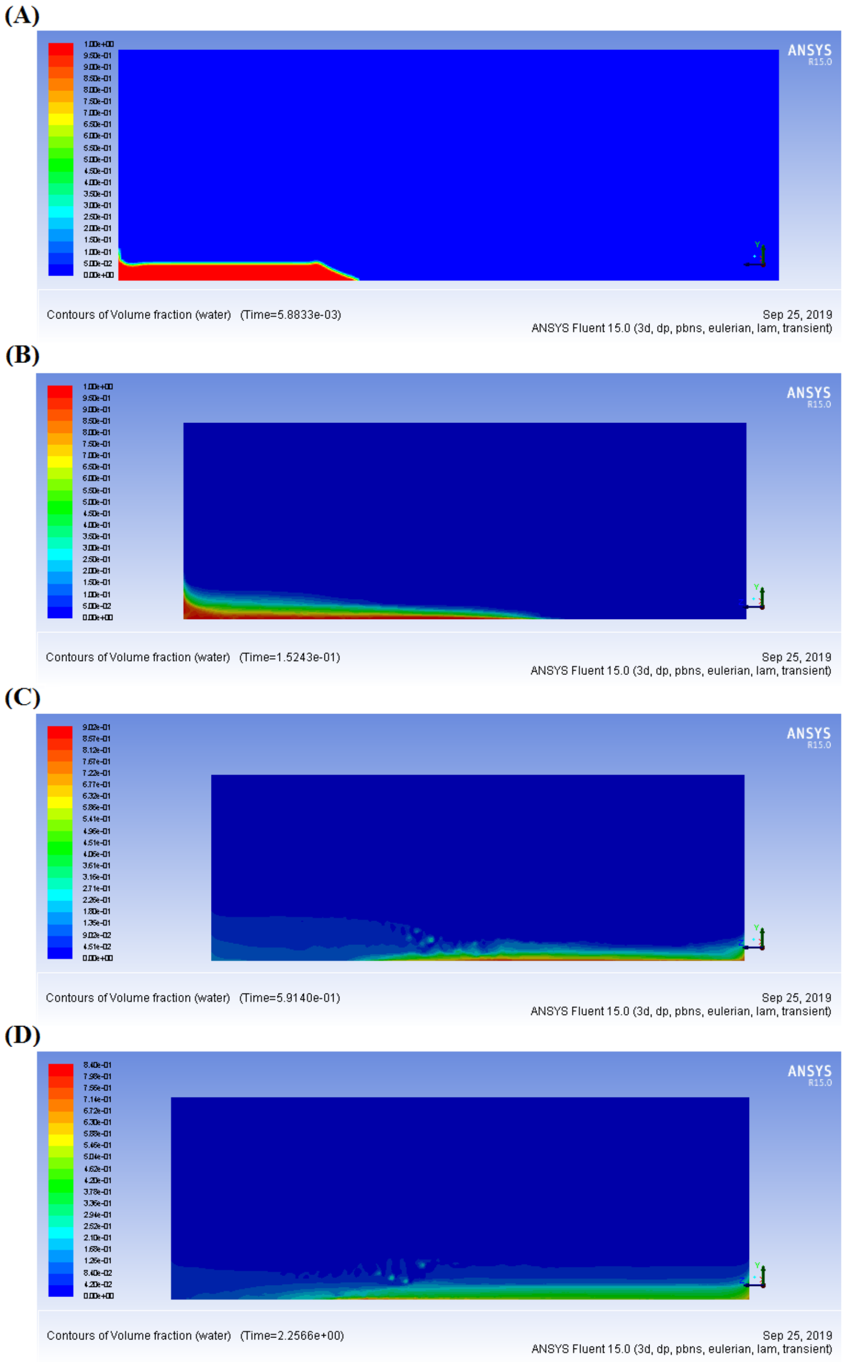

Fig. 1. Liquid volume fraction graph at different times. A: Liquid volume fraction graph at *time*=0.00588 s; B: Liquid volume fraction graph at *time*=0.15 s; C: Liquid volume fraction graph at *time*=0.59 s; D: Liquid volume fraction graph at *time*=2.256 s.

In order to further study the influence of the inclination angle, the length of the heat pipe, and the heating temperature on the performance of the heat pipe, an orthogonal experiment has been carried out based on a heat pipe with a liquid filling rate of 22%-23%, which was chosen to be the best in simulation. The water bath temperature, the length of the heat pipe and the inclination angle were chosen to be the three factors involved in the experiment. Three levels of values were set for each factor, respectively, 40℃, 50℃, 60℃ for the water bath temperature; 120 mm, 160 mm, 200 mm for the length of heat pipe; 30 degrees, 60 degrees, 90 degrees for the inclination angle, as shown in Table 3. The orthogonal table $L_9 3^4$ (4 factors, 3 levels for each factor and 9 items) is selected to be used; the water bath temperature was denoted as factor A, the heat pipe length was set as factor B and the inclination angle was labeled as factor C.

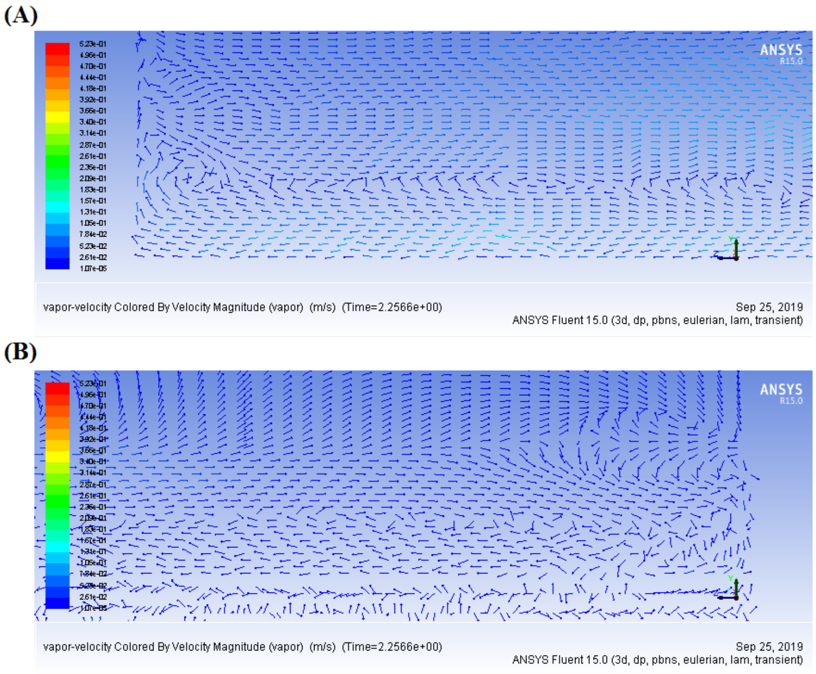

Fig. 2. Steam motion state at *time*=2.256 s. A: Steam speed direction in the evaporation section; B: Steam speed direction in the condensation section.

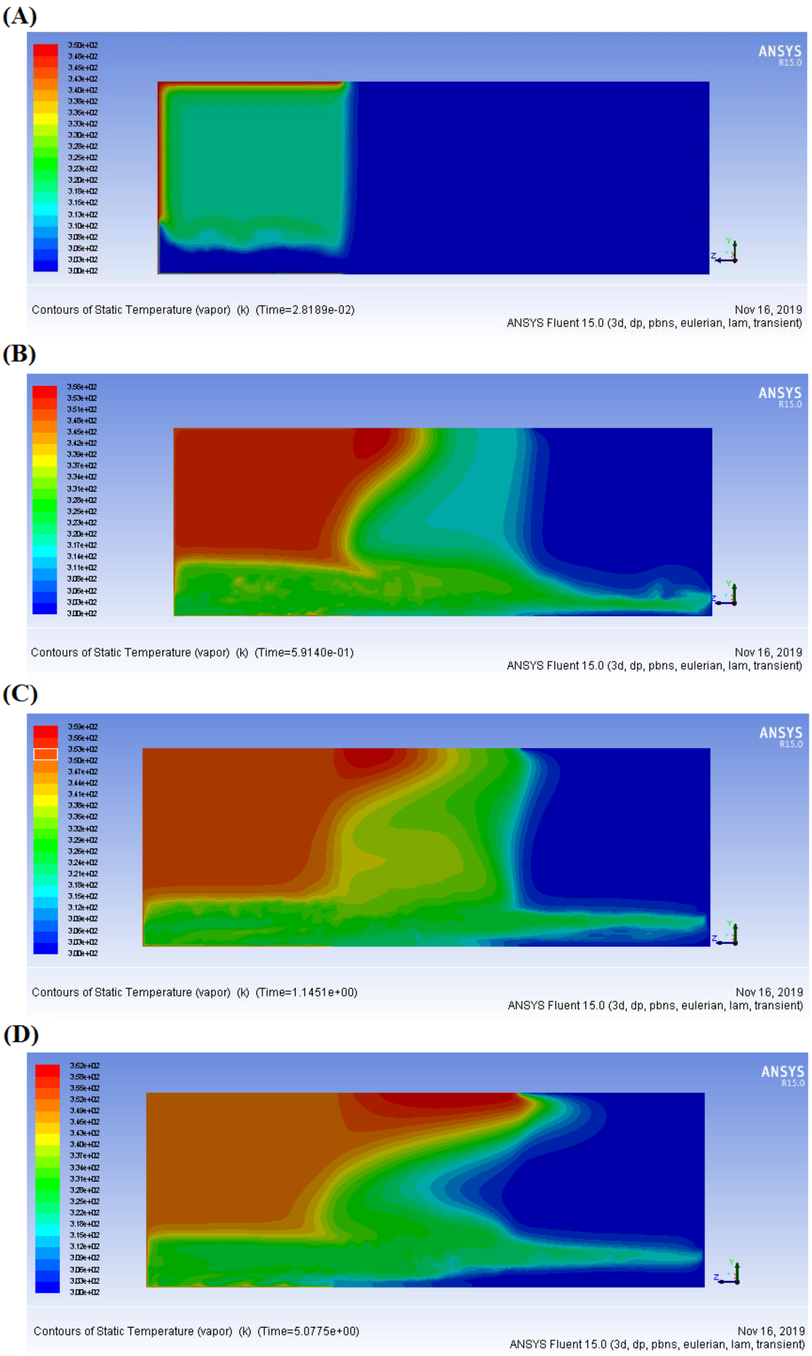

Fig. 3. The temperature status on x=0 section of micro groove at different times. A: The temperature status on x=0 section at *time*=0.028 s; B: The temperature status on x=0 section at *time*=0.59 s; C: The temperature status on x=0 section at *time*=1.15 s; D: The temperature status on x=0 section at *time*=5.08 s.

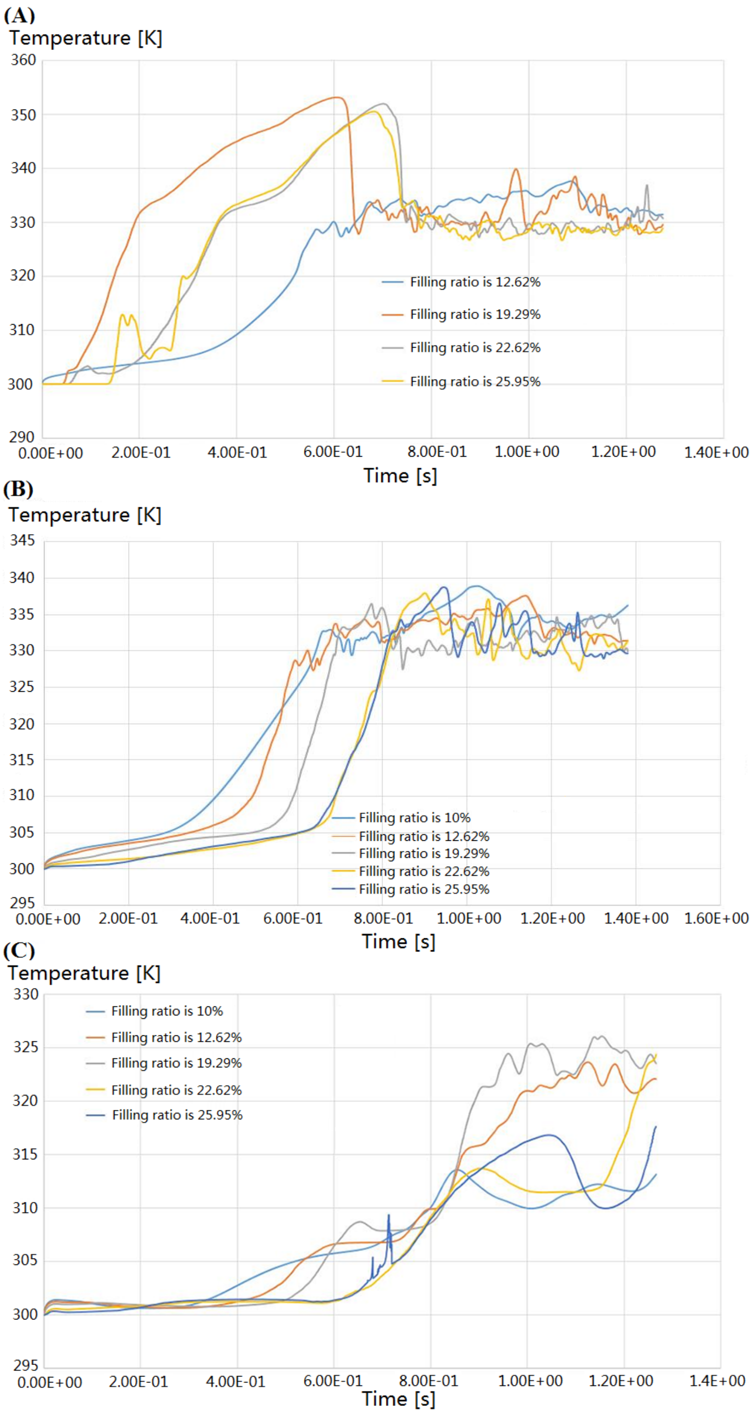

Fig. 4. Temperature change diagrams for various parts of the micro heat pipe with different filling rates. A: The temperature change diagram for the evaporation section; B: The temperature change diagram for the adiabatic section; C: The temperature change diagram for the condensation section.

Fig.5 shows the illustration of the experiment. The temperature sensing system is made of a PT100 surface pasted thermistor, a transducer and an Arduino core board. In the experiment, an electric thermostatic water bath was taken to set the temperature at 350 K, which is 77℃. Then used a PT100 sensor to stick tightly to the condensation section of the heat pipe, and put the evaporation section into 350 K hot water and minimized the tilt angle. The experiment was carried out 10 times, and the average values of heat transfer rates were calculated and recorded in Table 2. The changing situation of heat pipe temperature for each combined item was shown in Fig.6.

Table 2

Heat transfer rate for each combined item

Item	Water bath temperature [°C] A	Length of the heat pipe [mm] B	Inclination angle [°] C	Heat transfer rate [mm/s]
1	40	120	30	1.356
2	40	160	60	1.739
3	40	200	90	1.818
4	50	120	60	7.643
5	50	160	90	9.727
6	50	200	30	6.294
7	60	120	90	3.722
8	60	160	30	3.951
9	60	200	60	4.786

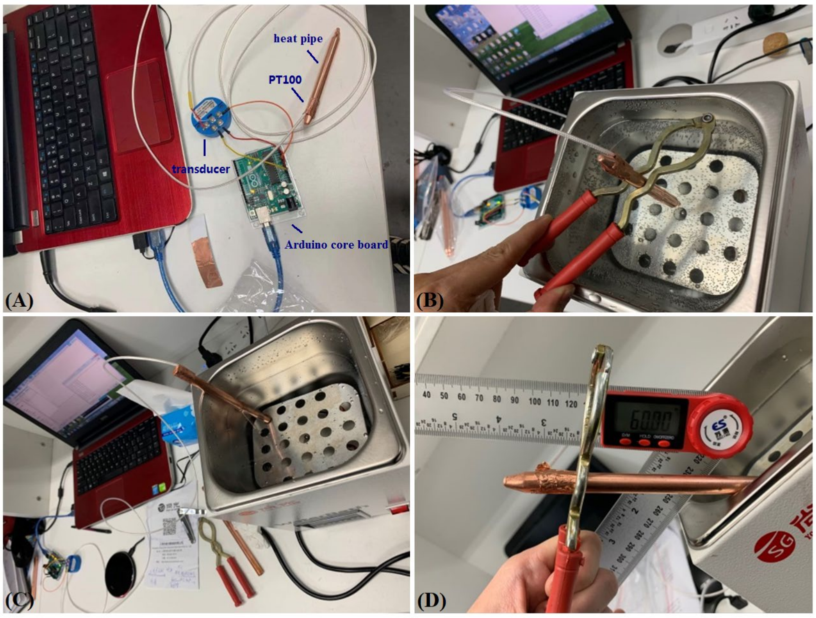

Fig. 5. The illustration of experiments. A: Illustration of temperature sensing system; B: Heat transfer test for the heat pipe when the inclination is 90 degrees; C: Heat transfer test for copper rod; D: Heat transfer test for the heat pipe when the inclination is 60 degrees.

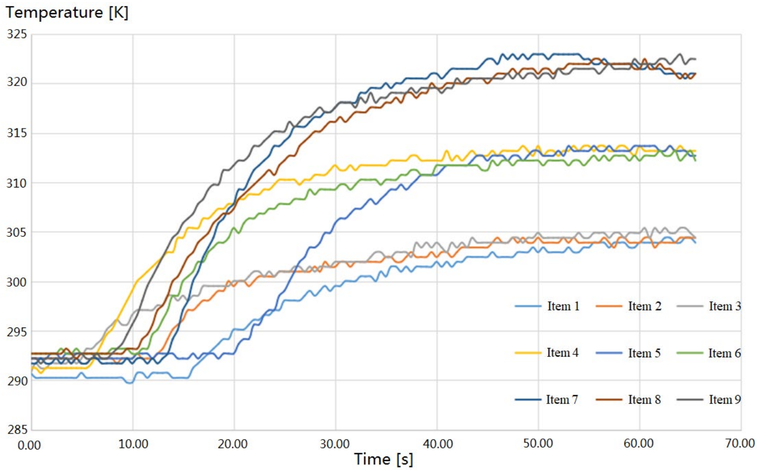

Fig. 6. The changing diagram of heat pipe temperature for each level during experiment.

The range analysis was carried out to obtain K and its average value for the three levels k in Table 3. K_1, K_2 and K_3 denote the heat transfer efficiency for each factor, respectively; k_1, k_2, k_3 were the average values for the three levels calculated by dividing corresponding K_1, K_2, K_3 by 3. R represents the range, $R=k_{max}-k_{min}$.

Table 3

Range Analysis

Level	Water bath temperature [°C] A	Length of the heat pipe [mm] B	Inclination angle [°] C
K_1	4.913	12.721	11.601
K_2	23.664	15.417	14.186
K_3	12.509	12.898	15.267
k_1	1.638	4.240	3.867
k_2	7.888	5.139	4.729
k_3	4.170	4.299	5.089
R	6.25	0.899	1.222
Factor importance		A>C>B	
Optimal combination		$A_2B_2C_3$	

Through the range analysis, we can find that the range values of each column are not the same, which indicate that the change of each factor had a different effect on the result of the orthogonal test. The larger the range value is, the more important impact it shows on the heat transfer rate. Thus, it can be found that the water bath, i.e. working temperature had the largest impact on the heat transfer rate, followed by the length of the heat pipe, and the inclination angle had the least impact. Moreover, the best combination of factors is $A_2B_2C_3$, that is, 50°C bath temperature, 160 mm heat pipe length and 90° inclination angle for this micro-groove heat pipe designed before. These designed parameters and the best working environment can be recommended for producing the micro-groove heat pipe to solve the heat dissipation problem of CNC lathes.

6. Conclusions

The heat transfer performance of micro-groove heat pipes was studied in this research by analysis of gas-liquid two-phase flow. The simulation results showed that the liquid 22.62% filling rate was able to achieve the best performance for the micro-groove heat pipe. Then an orthogonal experiment was arranged to find out the best parameters for heat pipe design. The heating temperature had been found to be the most important factor for the heating transfer of the heat pipe followed by length and inclination angle. The best parameter setting for the heat pipe in experiment is 50°C bath temperature, 160 mm heat pipe length and 90° inclination angle.

Acknowledgments

This project is supported by the Natural Science Foundation of Fujian Province in China (2022J01609), the Outstanding Youth Fund of Fujian Agriculture and Forestry University (XJQ201820) and the Science and Technology Innovation Special Fund of Fujian Agriculture and Forestry University (CXZX2020132B).

REFERENCES

[1]. *M. Mares, O. Horejs, and L. Havlik*, "Thermal error compensation of a 5-axis machine tool using indigenous temperature sensors and CNC integrated Python code validated with a machined test piece", Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology, **vol 66**, 2020, pp. 21-30.

[2]. *P.L. Liu, X.D. Yao, G.Y. Ge, Z.C. Du, X.B. Feng, and J.G. Yang*, "A Dynamic Linearization Modeling of Thermally Induced Error Based on Data-Driven Control for CNC Machine Tools", International Journal of Precision Engineering and Manufacturing, **vol 22**, no.2, 2021, pp. 241-258.

[3]. *M. Yu, X. Yu, X. Zheng, and H. Jiang*, "Thermal-fluid-solid coupling deformation of hydrostatic thrust bearing friction pairs", Industrial Lubrication & Tribology, **vol 71**, no.3, 2019, pp. 467-473.

[4]. *G. Chen, Y. Tang, Z. Wan, G. Zhong, H. Tang, and J. Zeng*, "Heat transfer characteristic of an ultra-thin flat plate heat pipe with surface-functional wicks for cooling electronics", International Communications in Heat and Mass Transfer, **vol 100**, 2019, pp. 12-19.

[5]. *X. Li, W. Li, X. Chen, M. Li, H. Chen, and X. Yue*, "Design and performance analysis on heat pipe hydrostatic thrust bearings based on rectangular oil pad", Industrial Lubrication & Tribology, **vol 70**, no.7, 2018, pp. 1251-1257.

[6]. *X.T. Chen, C. Qi, W. Wang, J.Y. Miao, and H.X. Zhang*, "Heat transfer limit resulting from heat leak in a cryogenic loop heat pipe", Applied Thermal Engineering, **vol 184**, 2021, pp. 12.

[7]. *Q.F. Li, Z. Lan, J. Chun, S.J. Lian, R.F. Wen, and X.H. Ma*, "Fabrication and capillary characterization of multi-scale micro-grooved wicks with sintered copper powder", International Communications in Heat and Mass Transfer, **vol 121**, 2021, pp. 12.

[8]. *C.S. Dong, R.H. Qi, and L.Z. Zhang*, "Flow and heat transfer for a two-phase slug flow in horizontal pipes: A mechanistic model", Physics of Fluids, **vol 33**, no.3, 2021, pp. 11.

[9]. *L. Liu, J.R. Zhang, S. Liu, K. Wang, and H.Y. Gu*, "Decay law and swirl length of swirling gas-liquid flow in a vertical pipe", International Journal of Multiphase Flow, **vol 137**, 2021, pp. 17.

[10]. *G. Wang, Z. Quan, Y. Zhao, and H. Wang*, "Performance of a flat-plate micro heat pipe at different filling ratios and working fluids", Applied Thermal Engineering, **vol 146**, no.5, 2018, pp. 459-468.

[11]. *H. Barua, M. Ali, M. Nuruzzaman, M.Q. Islam, and C.M. Feroz*, "Effect of Filling Ratio on Heat Transfer Characteristics and Performance of a Closed Loop Pulsating Heat Pipe", Procedia Engineering, **vol 56**, 2013, pp. 88-95.

[12]. *H. Hussein, H.H. El-Ghetany, and S.A. Nada*, "Performance of wickless heat pipe flat plate solar collectors having different pipes cross sections geometries and filling ratios", Energy Conversion & Management, **vol 47**, no.11/12, 2006, pp. 1539-1549.

[13]. *X. Li, Z. Yu, X. Li, W. Li, and T. Zou*, "Plough-extrusion Forming for Making Micro-groove Heat Pipes on Hydrostatic Thrust Bearings of Heavy Machinery", Strojniški vestnik - Journal of Mechanical Engineering, **vol 66**, no.12, 2020, pp. 724-735.