Experimental investigations and optimization of process parameters of meshed-wick heat pipe

G R Sanjay Krishna*

*Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, KL Deemed to be University, Green Fields, Vaddeswaram, Guntur, 522502, India

Abstract:

Heat pipes are used to transfer heat, which are hollow cylindrical shape device filled with small amount of working fluid, which can change its phase. The rate of heat transfer in heat pipes compared to normal heat exchanging devices is more. Depending on the applications of heat transfer various heat pipes are being designed. Methanol fluid is used with 50% fill ratio. It is madeof copper with outer diameter of 15.88mm and inner diameter of 14.88mm. It consists of a screen mesh made of copper powder inside it with thickness of 0.5mm. Due to heat input methanol changes its phase from liquid to vapor. The vapor loses its heat and changes its phase back to liquid in the condenser. At the condenser section the vapour gives up it heat and changes its phase from vapour to liquid.

The screen mesh assists the flow of condensed working fluid through capillary action. Optimized the results by "Taguchi method" using "Minitab software". The Thermal analysis was done with the optimum conditions, which were obtained as a result from the optimization method by Ansys Fluent software. Then finally compared the thermal parameters obtained from experiments with the Thermal analysis result. It is found the maximum heat transfer rate is optimized using meshed wick heat pipe conditions.

Keywords: Heat Pipe, Taguchi Method, Ansys Fluent Software, Minitab Software

Introduction

The micro-channel heat sink is a simple and compact heat dissipating device well suitable for thermal management of electronics [1]. To cool the machine, heat sinks are utilized to its hot parts (https://www.cdn-inc.com/heatsinks/). Cost minimization and cooling maximization of heat sinks demand appropriate design considerations. Aluminium is mechanically well suited for heat sinks, which has a better conductor of electricity. To have product life with efficiency, access for cleaning should be provided to protect heat sinks from clogging debris (such as dust, loose fibres or hair). Various micro-channel configurations have been proposed to fulfil the demands on cooling of the electronic devices [2-4].

Raghuraman et al. [5] have adopted Taguchi method and carried out grey rational analysis to obtain optimal EDM process parameters (such as current, pulse-on-time and pulse-off-time) on 3 performance indicators (viz., material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR)) for machining mild steel IS2026 using copper electrode. Bhoopathy and Sundaram [6] have performed nanoparticle mixed electrical discharge machining (NPMEDM) of INCONEL718 using brass electrode, and examined the influence of EDM process parameters (viz., current, pulse-on-time, pulse-off-time and titanium carbide nanoparticle mixed dielectric fluid) on MRR and TWR. Improvement in MRR and reduction in TWR are noted. Modi et al. [7] have made a review on the EDM process and recommended cheaper air hardening tool steel as a forming tool for low duty cutting application. They proposed Taguchi’s design of experiments (DOE) and response surface methodology (RSM) for improving MRR and surface finish considering pulse-off-time, pulse-on-time and servo voltage as the machining parameters. Raghav et al. [8] have carried out statistical regression analysis to develop relationships between the EDM process variables and the performance indicators, which are used as the objectives functions to be optimized using the generalized Genetic Algorithms. The results are confirmed with test data on MRR in EDM using mild steel. They claimed that this methodology can be applied to complex mechanical engineering problems. Bahgat et al. [9] have conducted experiments (as per the Taguchi’s DOE) to examine the effect of peak current, pulse-on-time and electrode material on the machining process of H13 die steel. Mohite and Gaikwad [10] have chosen the micro-channel heat sink material AA6061as the work-piece material and the copper as the tool electrode material. AA6061 has good heat absorption ability and also possesses good surface finish.

Usage of Two-Phase Cooling Technology has remarkably improved the Cooling setups of the electronic devices. Heat pipe has working fluid embedded inside the chamber, which take advantage of capillary pressure to transfer the liquid from condenser section to evaporator section. They have low drop of temperature. Investigations had been done on the effect of pore size on the capillary pressure.

Heat pipes provide the cooling solutions to the advance devices developed like multi core processors. Boiling heat transfer limit is more important than capillary limit to find out the limitations of the chamber. Selenic and Catton , conducted many experiments by varying thickness of the wick, powder size to evaluate its performance.

Visual observation provides the insight on the boiling in evaporator chamber at different orientations. This paper describes about the performance of heat pipe with sintered powder mesh wick varying the factors and recording the thermal performance parameters and finding the optimum condition of operation. FMHP consisting of composite fiber wick can transfer the heat load of 3 was effectively up to 100 mm distance with heat pipe thermal resistance ranging 0.25 – 0.45oC/W by handheld device. Dependence of thermal performance on the particle size & thickness of wick was investigated. The minimum evaporative & critical

Design of experiments was done using Taguchi method, which is a statistical method. The influence of factors like heat input, mass flow rate and inclination angle on thermal performance parameters was obtained as the result of data analysis.

Experimental Setup

A total of Nine experiments are conducted using a Copper heat pipe with meshed wick shown in figure 1 with specification shown in table 1, and experimental setup shown in figure 2. By varying orientations, variation of heat input and mass flow rates experiments are conducted shown in Table 2.

Fig 1. Copper heat pipe with meshed wick

Table 1. Specifications of heat pipe

Parameters	**details**
Heat pipe length	565 mm
Evaporator chamber length	200mm
Adiabatic chamber length	165mm 20
Condenser chamber length	200mm 20
Outer Diameter of the heat pipe	15.88mm
Inner Diameter of the heat pipe	14mm
Thickness of the wick	0.5mm
Working Fluid	Methyl alcohol
Fill Ratio	50%

Fig. 2: Experimental Setup

Methodology of Process flow

Heat pipe is fixed in the experimental setup through the funnel. Then switched on the heater connected at the evaporator end and the water pump. The rate of the water is adjusted as desired using the control valve. The required heat input is given using the control panel knob.

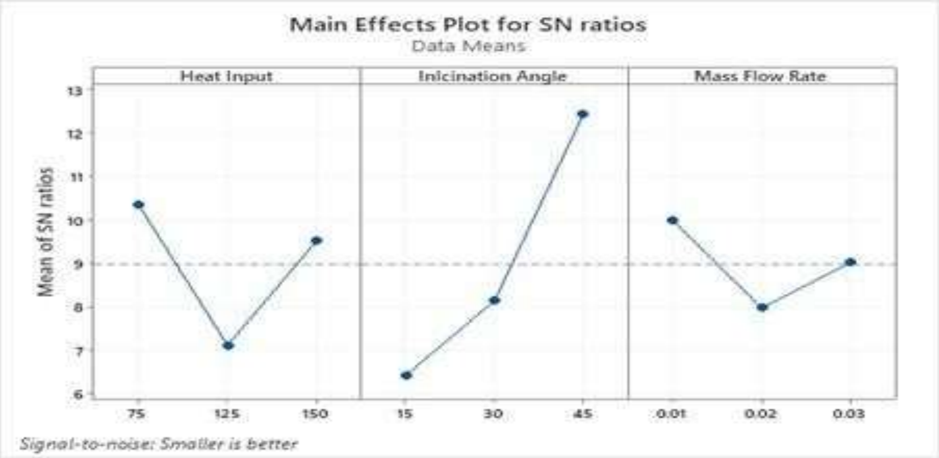

Fig 3. Image of S/N Ratio Plot for Thermal Resistance

It can infer from the above figure 3 that the optimum value of the thermal resistance was obtained at the heat input of 75W, Inclination angle of 450 and flow rate of 0.01 Kg/s.

The inclination angle is set using a magnetic dial indicator. The heat input is increased gradually from 25W to 150W with each increment of 25W. The inclination angles and the mass flow rate are adjusted as per the optimization table. The same procedure is used throughout all nine experiments.

With the given heat input the variation of the values of the thermal performance parameters is calculated with the variation of the mass flow rate and inclination angle.

Following formula were used to calculated given in equation 1 and 2, Heat input at the evaporator (Qin), Thermal Resistance (R)

$$Qin = V*I\ \text{Watt}\ (1)\ \ R = Te-Tc/Qin\ (2)$$

Where

Water inlet temperature (Tin)

Water outlet temperature (Tout)

Evaporator temperature (Te)

Condenser temperature (Tc)

Voltage(V)

Current (I)

THERMAL ANALYSIS

Temperature distribution

Thermal analysis is conducted using ANSYS Fluent to determine the influence of the heat load on the heat pipe fluid flow. Variation of parameters like Temperature and Pressure was studied. Mesh is shown figure 7. Meshing of Heat Pipe. Mesh number = 60

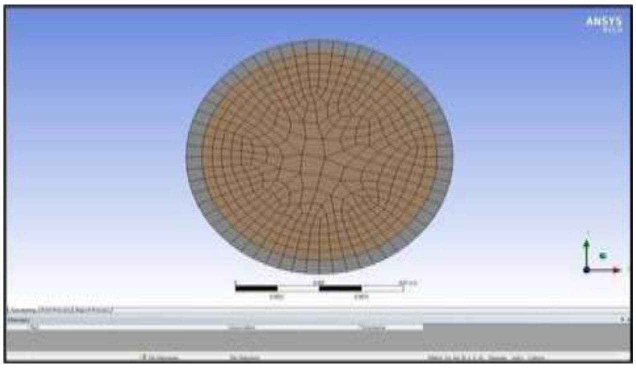

Fig 7. Image of Cross sectional view of Meshed heat pipe

The heat pipe is first designed using design modeler and then meshing of the heat pipe is done with mesh number 60.

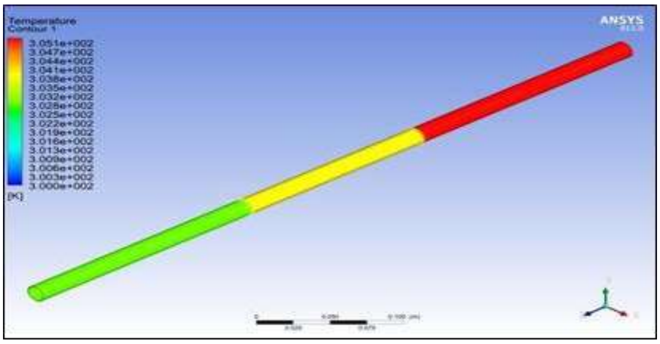

Fig 8. Image of Variation of temperature along axial length of the heat pipe

The above figure 8 shows the variation of the surface temperature along the axial length of the heat pipe.

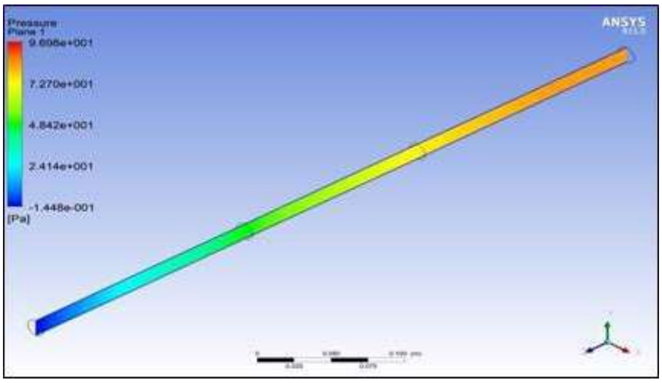

Fig 9. Image of pressure variation along the axial length of the heat pipe

The above figure 9 shows the variation of the pressure due to heat input along the axial length of the heat pipe from evaporator section to the condenser section.

Specifications of heat pipe

Parameters	**Details**
Heat pipe length	565 mm
Evaporator chamber length	200mm
Adiabatic chamber length	165mm 20
Condenser chamber length	200mm 20
Outer Diameter of the heatpipe	15.88mm
Inner Diameter of the heatpipe	14mm
Thickness of the wick	0.5mm
Working Fluid	Methyl alcohol
Fill Ratio	50%

Taguchi approach

As per the Taguchi approach, the number of experiments (NT) for the number of process parameters (np) and the number of levels (nl) assigned to each process parameter, which selects an appropriate orthogonal array to perform experiments, can be found from the formula

$$NT = 1 + np \text{ x } (n\mathit{l} - 1).$$

Table 1: Selected processing parameters and level

S.no	Factors	Level 1	Level 2	Level 3
A	Heat Input	75 (A1)	15 (A2)	0.01 (A3)
B	Angle(deg.)	125 (B1)	30 (B2)	0.02 (B3)
C	Mass Flow Rate(Kg/s)	150 (C1)	45 (C2)	0.03 (C3)
D	fictious	d1	d2	d3

$NT = 1 + np \text{ x } (n\mathit{l} - 1)$ where, NT = number of experiments

$= 1 + 4 \text{ x } (3-1)$ np = number of parameters

$= 9$ nl = number of levels

Table 2: Experimental results of a L9 orthogonal array

Test Run/Sample no.	Heat Input	Angle (deg.)	Mass Flow Rate(Kg/s)	Response
				Thermal Resistance(^{0}C/W)
1	75	15	0.01	0.33
2	75	30	0.02	0.37
3	75	45	0.03	0.23
4	125	15	0.02	0.75
5	125	30	0.03	0.44
6	125	45	0.01	0.26
7	150	15	0.03	0.44
8	150	30	0.01	0.37
9	150	30	0.02	0.23

Test Run/Sample no.	**Heat Input**	**Angle (deg.)**	**Mass Flow Rate (Kg/s)**	**Response**	**xpectedrange**	
				Thermal Resistance (^{0}C/W)	**Upperlimit**	**Lowerlimit**
1	75	15	0.01	0.33	0.44	0.32
2	75	30	0.02	0.37	0.45	0.33
3	75	45	0.03	0.23	0.23	0.11
4	125	15	0.02	0.75	0.72	0.62
5	125	30	0.03	0.44	0.54	0.42
6	125	45	0.01	0.26	0.34	0.22
7	150	15	0.03	0.44	0.52	0.4
8	150	30	0.01	0.37	0.35	0.23
9	150	45	0.02	0.23	0.34	0.22

☐ For Heat Input (A)

$\phi A1 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.33 + 0.37 + 0.23) = 0.31 \phi A2 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.75 + 0.44 + 0.26) = 0.48 \phi A3 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.44 + 0.37 + 0.23) = 0.34$

☐ For Angle(deg.) (B)

$\phi B1 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.33 + 0.75 + 0.44) = 0.50 \phi B2 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.37 + 0.44 + 0.37) = 0.38 \phi B3 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.23 + 0.26 + 0.23) = 0.24$

☐ For Mass Flow Rate(Kg/s) (C)

$\phi C1 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.33 + 0.26 + 0.37) = 0.32 \phi C2 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.37 + 0.75 + 0.23) = 0.45 \phi C3 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.23 + 0.44 + 0.44) = 0.37$

☐ For fictious (D)

$\phi D1 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.33 + 0.44 + 0.23) = 0.33 \phi D2 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.37 + 0.26 + 0.44) = 0.35 \phi D3 = \frac{1}{3} (\phi 1 + \phi 2 + \phi 3) = \frac{1}{3} (0.23 + 0.75 + 0.37) = 0.45$

Grand Mean $= (\phi A1 + \phi A2 + \phi A3 + \phi B1 + \phi B2 + \phi B3 + \phi C1 + \phi C2 + \phi C3 + \phi D1 + \phi D2 + \phi D3)/ 9$

$= (0.31+0.48+0.34+0.50+0.38+0.24+0.32+0.45+0.37+0.33+0.35+0.45)/ 9$

Grand Mean = 0.38

☐ Sum of Squares $(SOS)_A$ = no. of levels [$(A_1$ mean – Grand mean$)^2$ + $(A_2$ mean – Grand mean$)^2$ + $(A_3$ mean – Grand mean$)^2$]

$$= 3\,[(0.31 - 0.38)^2 + (0.48 - 0.38)^2 + (0.34 - 0.38)^2]$$

$(SOS)_A = 0.0474$

☐ Sum of Squares $(SOS)_B$ = no. of levels [$(B_1$ mean – Grand mean$)^2$ + $(B_2$ mean – Grand mean$)^2$ + $(B_3$ mean – Grand mean$)^2$]

$= 3\,[(0.05 - 0.38)^2 + (0.38 - 0.38)^2 + (0.24 - 0.38)^2]$

$(SOS)_B = 0.102$

☐ Sum of Squares $(SOS)_C$ = no. of levels [$(C_1$ mean – Grand mean$)^2$ + $(C_2$ mean – Grand mean$)^2$ + $(C_3$ mean – Grand mean$)^2$]

$= 3\,[(0.32 - 0.38)^2 + (0.45 - 0.38)^2 + (0.37 - 0.38)^2]$

$(SOS)_C = 0.0258$

☐ Sum of Squares $(SOS)_D$ = no. of levels [$(D_1$ mean – Grand mean$)^2$ + $(D_2$ mean – Grand mean$)^2$ + $(D_3$ mean – Grand mean$)^2$]

$= 3\,[(0.33 - 0.38)^2 + (0.37 - 0.38)^2 + (0.45 - 0.38)^2]$

$(SOS)_D = 0.0249$

Total Sum of Squares $(SOS)_{Total} = (SOS)_A + (SOS)_B + (SOS)_C + (SOS)_D$

$= 0.0474 + 0.102 + 0.0258 + 0.0249$

$= 0.2001$

☐ % Contribution of 'A'

$$P_A = (SOS)_A / (SOS)_{Total} \times 100 = (0.0474 / 0.2001) \times 100 = 23.68$$

☐ % Contribution of 'B'

$$P_B = (SOS)_B / (SOS)_{Total} \times 100 = (0.102 / 0.2001) \times 100 = 50.97$$

☐ % Contribution of 'C'

$$P_C = (SOS)_C / (SOS)_{Total} \times 100 = (0.0258 / 0.2001) \times 100 = 12.89$$

☐ % Contribution of 'D'

$$PD = (SOS)D / (SOS)Total \times 100 = (0.0249 / 0.2001) \times 100 = 12.44$$

Table 3: ANOVA for Thermal Resistance(^{0}C/W)

Process Parameter	**Output response: Thermal Resistance(^{0}C/W)**			**Sum of Squares (SOS)**	**% Contribution**
	1- Mean	**2-Mean**	**3-Mean**		
A	0.31	0.48	0.34	0.474	23.68
B	0.50	0.38	0.24	0.102	50.97
C	0.32	0.45	0.37	0.0258	12.89
D	0.33	0.35	0.45	0.0249	12.44
Total				0.2001	100

Concluding Remarks

From the experimental results, the optimum value of thermal resistance at the heat input of 75W, Inclination angle of 30° and mass flow rate of 0.02 Kg/s is 0.124 ^{O}C/W.

The optimum values of thermal Resistance at the heat input of 75W, Inclinationangle of 45° and mass flow rate of 0.01 Kg/s using ANSYS is 0.126 ^{O}C/W. The error percentage is varying from 1% to 2%.

The results also showed that the inclination angle contributes the highest valueto the optimum thermal resistance, the mass flow rate shows a minor contribution to the optimum value. As the inclination angle decreases the thermal resistance increases.

References

1. N.R. Korasikha, T.K. Sharma, G.A.P. Rao and K.M. Murthy, “Recent Advancements in Thermal Performance Enhancement in Microchannel Heatsinks for Electronic Cooling Applications”, In IntechOpen Book Series: Heat transfer – Design, Experimentation and Applications (Editor: Miguel Araiz), ISBN:978-1-83968-438-8 (2015)
2. P. Hazarathaiah, , Y.A.K. Reddy and S. Indumati, “Design of Micro Channel Heat Sink”, International Journal of Research and Analytical Reviews (IJRAR), Vol.4, Issue 3, pp.1-10 (2017).

3. G. Narendran, N. Gnanasekaran and D.A. Perumal, " A Review on Recent Advances in Microchannel Heat Sink Configurations", Recent Patents on Mechanical Engineering, Vol.11, pp.190-215 (2018).
4. W.M.A.A. Japar, N.A.C. Sidik, R. Saidur, Y. Asako, and S.N.A. Yusof, "A review of passive methods in microchannel heat sink application through advanced geometric structure and nanofluids: Current advancements and challenges", Nanotechnology Reviews, Vol.9, pp.1192-1216 (2019). https://doi.org/10.1515/ntrev-2020-0094
5. S. Raghuraman, K. Thiruppathi, T. Panneerselvam and S. Santosh, "Optimization of EDM parameters using Taguchi method and grey relational analysis for mild steel IS2026", International Journal of Innovative Research in Science, Engineering and Technology (IJIRSET), Vol. 2, Issue 7, pp. 3095-3104 (2013).
6. R. Boopathi and S. Sundaram, "Influence of Process Parameters for Electrical Discharge Machine Using Nano Particle and Brass Electrode", International Journal of Research in Advent Technology, Vol.2, No.11, pp.45-49 (2014)
7. T. Modi, S. Sanawada and J. Patel, "A review paper on Optimization of process parameter of EDM for air hardening tool steel", International Journal of Engineering Research and Applications, Vol.5, Issue 1(Part I), pp.32-37 (2015)
8. G. Raghav, B.S. Kadam and M. Kumar, "Optimization of Material Removal Rate in Electric Discharge Machining Using Mild Steel", International Journal of Emerging Science and Engineering (IJESE), Vol.1, Issue 7, pp. 42-49 (2013)
9. M.M. Bahgat, A.Y. Shash, M. Abd-Rabou and I.S. El-Mahallawi, "Influence of process parameters in electrical discharge machining on H13 die steel", Heliyon 5 (2019) e01813 https://doi.org/10.1016/j.heliyon.2019.e01813
10. M.B. Mohite and V.P. Gaikwad, "Development of EDM Tool for Fabrication of Microchannel Heat Sink and Optimization of Single Response Parameter of EDM by Taguchi Method", International Journal for Innovative Research in Science & Technology (IJIRST), Vol.2, Issue 9, pp.63-70 (2016).