Parametric optimization for better thermal performance on Heat Pipe using Taguchi method

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Abstract:

Heat pipes are hollow cylindrical form devices filled with a small amount of operational fluid and are used to transfer heat, which alters its phase. In contrast to standard heat exchange systems, the heat transfer rate in heat pipes is higher. Different heat pipes are being built depending on the heat transfer applications. The aim of the current work is to optimize the process parameters of heat pipe using Taguchi technique. The control factors like heat input (Q), inclination angle (θ), fill ratio (ϕ) and mass flow rate (M) were considered to evaluate the thermal performance in terms of thermal resistance and thermal conductivity. Using a L9 orthogonal array, a total of nine experimental runs were performed and the optimal combination of control parameter levels for the responses was calculated. The Taguchi technique is utilized by using MiniTab-17 software to find the level of importance and optimal independent parameter for the cylindrical mesh wick heat pipe using DI-water as the working fluid.

Key words: Heat pipe, Taguchi technique, Screen mesh, Inclination, Thermal conductivity.

1. Introduction

For the cooling application of high power electronic devices, heat pipes have been used as a two phase heat transfer system. The heat pipe is a successful heat transfer device due to its versatility and high effective thermal performance as compared with common thermal conductors such as metal rods and fins. Heat pipe consists parameters, such as wick type and its material type,
porosity and permeability, working fluid, filling ratio and operating conditions such as tilt angle and heat input which affect the thermal performance of a heat pipe.

Huminic et al. [1] evaluated the thermal performance of a thermosyphon heat pipe using water-iron oxide as the nanofluid and noted that thermal resistance was reduced at a tilt angle of 90 degree with an enhancement of 42% in heat transfer rate. Do et al. [2] reviewed the thermal performance of circular mesh wick heat pipes by considering 0.3 and 0.1% of the volume fractions of Al_2O_3 nanofluids. The thermal resistance and the surface temperature distributions are measured between adiabatic and the evaporator sections and correlated with heat pipe which uses working fluid as de-ionized water. The Al_2O_3/H_2O nanofluid evaporator surface temperatures are much lower the water heat pipe wall temperatures and resulted the lowest thermal resistance at 0.3 Vol% concentration and this significantly reduced by 40%. Reddy et al. [3] fabricated samples by aluminum alloy Al 6063 with three different reinforcement weight percentages like 5, 10 and 15% by adding TiC particles with stir casting process. To analyze the results (hardness and tensile values) and also to conduct the experimentation Box–Behnken design has been utilized. Process variables as load, reinforcement weight percent and sliding speed for three levels and specific wear rate as response are considered. By using ANOVA, it was evident that sliding speed and reinforcement weight percent has govern the parameters on the response. Peyghambarzadeh et al. [4] evaluated heat transfer performance of a copper heat pipe with a length of 40 cm and the dia at evaporator section is large and smaller the diameter in remaining two sections. Author observed that the heat transfer coefficient is high for ethanol and water as compared to methanol when they acted as heat pipe operating fluids. Quadri et al. [5] conducted a series of experiments to achieve curtailed emissions, greater performance and a good combustion in the IC engines. In order to find out the best parameters, trial and error method is used. Based on Taguchi statistical method an orthogonal array of L9 was formulated and a set of experiments were performed on compression ratios and injection operating pressures in the range of 18.5, 17.5, 16.5 and 240, 220, 200 bar respectively. Senthilkumar et al. [6] was used Taguchi technique to conduct experiments and to observe the effect of control factors and to predict heat pipe optimal factors such as flow rate of water, tilt angle and heat supplied. It was found that all the three factors were influenced on the performance of a heat pipe. The operational limitation of a copper oscillating heat pipe with alumina-water nanofluid for filling ratios of 30 to 70%, inclination angles of 0-90 degree and a volume fraction of 0.5 was
investigated by Ji et al. [7]. The experimental results showed that when substituted with nanofluid, the increased in operating limit and decreased in thermal resistance was observed. Pang et al. [8] evaluated the thermal conductivity of a DI water-alumina and water- SiO$_2$ nanofluids at 22$^\circ$ C with the volume fraction of 0.5% concentration. They observed 10.73% and 14.28% enhancement in conductivity respectively. Naphon et al. [9] observed that heat transfer devices can enhance their heat transfer capability by changing the operating fluids and their transport properties. The heat pipe efficiency had been increased by substituting the water with TiO$_2$ nanofluids. Nanofluids prepared with the help of ultrasonicator and commercially available titanium nanoparticles (21 nm). Sarfaraz et al. [10] used an eco-friendly method to synthesize Ag nanoparticles and used them to prepare silver-water nanofluid. These nanofluids utilized to decrease the temperatures of the heat pipe wall and at 0.4 Wt. % of nanofluid the best output (thermal performance) was obtained.

From the literature review, it was found that the Taguchi technique is very useful to study process parameters effect on the responses with reduced number of experimental trails. So, in the present study, the effect of operating factors such as heat load (HL), orientation (TA), fill ratio of heat pipe (FR) and mass flow rate (MFR) on the responses like thermal resistance and thermal conductivity. In this present work, orthogonal array (OA) was used to establish the experimental trails and finally the responses were analyzed using Taguchi method to obtain optimum process parameters combination for minimizing the overall thermal resistance ($R_o$) and to maximize the effective thermal conductivity of the heat pipe ($k_e$).

2. Experimental setup and procedure:
Fig.1 indicates the experimental test facility setup and it consists of a thermostat (chiller) unit, a power supplier, a rotameter, a data logger and a variable angle test zone. The hollow circular copper heat pipe with a total length of 30 cm and the wall thickness is 0.06 cm. The copper screen wire mesh is spread on the inner tube with three layers (100 holes per inch) with a mesh diameter of 150 $\mu$m and its porosity was 0.76 which has been evaluated based on literature [11].

The heat pipe was prepared (fabricated), evacuated, filled with different percentages and conducted experiments at Karunya University, Coimbatore, India. The condenser, evaporator and adiabatic sections of the heat pipe were 15 cm, 10 cm and 5 cm long is shown in Fig. 2. At the evaporator section, a nichrome wire electrical heater gives uniform heat flux to the surface of the
The evaporator and adiabatic zones covered with insulation (glass wool) material to minimize the heat loss to the surrounding. The condenser zone was enclosed with acrylic material pipe by providing inlet to enter the constant temperature (293 K) coolant (water) and outlet was used to leave the coolant after absorbing heat from the condenser surface. The heat pipe surface temperatures of different sections were recorded using T-type thermocouples by providing two in condenser zone, one in the middle of adiabatic section and two in evaporator zone. During experimentation the heat load increased and then decreased manually and after 20 minutes attained the steady state.

2.1 Data reduction:

The overall thermal resistance and the effective thermal conductivity [12] of a heat pipe are calculated from:
\[ R_o = \frac{T_{er} - T_{cr}}{Q} \]  
(1)

Where \( Q, T_{cr}, T_{er} \) are heat input, condenser and evaporator wall temperatures of a heat pipe.

\[ k_e = \frac{L_e}{A \Delta T_{ec}} \frac{Q}{\Delta T_{ec}} \]  
(2)

Where \( A \) is the cross sectional area, \( \Delta T_{ec} \) is the temperature difference between the evaporator and condenser zone and \( L_e \) is the effective length of the heat pipe and it is denoted as

\[ L_e = L_{ac} + \left( \frac{L_{er} + L_{cr}}{2} \right) \]  
(3)

Where \( L_{ac}, L_{er} \) and \( L_{cr} \) are the lengths of adiabatic, evaporator and condenser zones of the heat pipe.

**Experimental Design**

The current work is to achieve minimum thermal resistance and maximum thermal conductivity for the designed input factors of the heat pipe. The experiments were planned on the basis of the Taguchis’ \( L_9 \) orthogonal array. The impact of process parameters on the responses was calculated. The considered parameters of the input processes and levels are shown in Table 1.

| Parameters         | Symbol | Units | Level 1 | Level 2 | Level 3 |
|--------------------|--------|-------|---------|---------|---------|
| Heat Input         | \( Q \) | W     | 100     | 150     | 200     |
| Tilt Angle         | \( \theta \) | Deg. | 0       | 45      | 90      |
| Fill Ratio         | \( \phi \) | %    | 20      | 30      | 40      |
| Mass Flow Rate     | \( M \) | ltr./hr | 10      | 15      | 20      |

**Results and Discussion**

The experimental trials were conducted as per the Taguchis’ \( L_9 \) OA and the obtained results are tabulated in Table 2.

| Test No. | HL  | TA  | FR  | MFR | \( R_o \)  | \( k_e \)  |
|----------|-----|-----|-----|-----|------------|------------|
|          | 100 | 0   | 20  | 10  | 0.2525     | 5648.49    |
The obtained experimental results of both thermal resistance and thermal conductivity were analyzed using Taguchi method and the optimization plots of both the results are shown in Fig. 3 and Fig. 4 respectively.

![Main Effects Plot for Means](image)

Fig. 3 Control factors effect on thermal resistance

|   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
|   | 100 | 100 | 150 | 150 | 150 | 200 | 200 | 200 |
|   | 45  | 90  | 0   | 45  | 90  | 0   | 45  | 90  |
|   | 30  | 40  | 30  | 40  | 20  | 40  | 20  | 30  |
|   | 15  | 20  | 15  | 10  | 15  | 15  | 20  | 10  |
|   | 0.2153 | 0.2713 | 0.2270 | 0.2476 | 0.2309 | 0.2381 | 0.2111 | 0.2060 |
|   | 6624.44 | 5257.07 | 6283.85 | 5760.27 | 6175.99 | 5990.10 | 6757.84 | 6921.83 |
From the figure 3 and 4, it is finalized that the desirable thermal conductivity and thermal resistance can be obtained at the parameters combination of heat load of 200 W, tilt angle of 45 deg, fill ratio of 30 % and finally mass flow rate of 15 ltr/hr. From the figures (3 and 4), it was also observed that desirable thermal performance was obtained for second level (middle) for tilt angle, fill ratio and mass flow rate. Table 3 and 4 shows the response values of both thermal resistance and thermal conductivity respectively. From the tables (3 and 4), it is observed that factor 3 and 1 has more significance on the output responses where has factor 4 has least significance. Fill ratio has the least significance on the response variables and the results obtained in the present study are similar with the literature work results [13].

Table 3 Response table for means of thermal resistance

| Level | HL   | TA   | FR   | MFR  |
|-------|------|------|------|------|
| 1     | 5843 | 5974 | 6194 | 6110 |
| 2     | 6073 | 6381 | 6610 | 6264 |
| 3     | 6557 | 6118 | 5669 | 6100 |
| Delta | 713  | 407  | 941  | 164  |
| Rank  | 2    | 3    | 1    | 4    |

Table 4 Response table for means of thermal conductivity
Validation of results

The experiments were performed at Taguchi optimum parameter combinations and the results were compared with the predicted results. Table 5 shows the experimental results at optimum combination along with the predicted results. The mean error percentage of the predicted results with the experimental results is below 5%.

Table 5 Validation of the optimum combination results

| Test No | HL  | TA  | FR  | MFR  | Expt. R₀ | Pred. R₀ | Error % | Expt. kₑ | Pred. kₑ | Error % |
|---------|-----|-----|-----|------|----------|----------|---------|----------|----------|---------|
| 1       | 200 | 45  | 30  | 15   | 0.1854   | 0.1916   | 3.34    | 7489     | 7337     | 2.02    |
| 2       | 200 | 45  | 30  | 15   | 0.1952   | 0.1916   | 1.84    | 7124     | 7337     | 2.98    |
| 3       | 200 | 45  | 30  | 15   | 0.1947   | 0.1916   | 1.59    | 7224     | 7337     | 1.56    |

Conclusions

Taguchi technique employed to optimize the parameters in screen wire mesh wick heat pipe on thermal resistance and thermal conductivity for water as the operational working fluid. Optimum values are identified in order to minimize the “R₀” and maximize the “kₑ”.

1. The fill ratio is observed to be most significant factor, followed by least contributions to heat load, tilt angle and flow rate for minimum thermal resistance for water as a working fluid.
2. The experimental results are validated with the confirmation tests used by the Taguchi method for optimizing the cylindrical mesh wick heat pipe.
3. For parameter optimization the Taguchi method provides a systematic, simple and efficient methodology.
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