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Thermal Analysis of Heat Pipe Using Taguchi Method

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Abstract

Experiment was carried out to study the working parameters of heat pipe. In this paper effect of optimum values of heat pipe working parameters namely heat input, flow rate of cooling water and angle of inclination with horizontal on thermal resistance and overall heat transfer coefficient is analyzed using Taguchi method. The Taguchi method is used to formulate the design of experiment, analyse the effect of working parameters and predict the optimal parameters of heat pipe. It is found that these parameters have a significant influence on heat pipe performance. The analysis of the Taguchi method reveals that, all the parameters mentioned above have equal contributions in the performance of heat pipe. Experimental observations and results are provided to validate the proposed approach.

Keywords: *Heat pipe; taguchi method; thermal analysis.*

1. Introduction

The heat pipe is a thermal device which affords efficient transport of thermal energy by using a heat transfer fluid. Heat pipes are one of the most effective procedures to transport thermal energy from one point to another, mostly used for cooling. A heat pipe is essentially a passive heat transfer device with an extremely high effective thermal conductivity. The two-phase heat transfer mechanism results in heat transfer capabilities from one hundred to several thousand times that of an equivalent piece of copper [4]. Heat pipes consist of a sealed container with a small amount of a working fluid. The heat is transferred as latent heat energy by evaporating the working fluid in the evaporator zone and condensing the vapor in a cooling zone, the circulation is completed by the return flow of the condensate to the evaporator zone through the wrapped screen capillary structure which lines the inner wall of the container [2]. Nowadays heat pipes are used in several applications, where one has limited space and the necessity of a high heat flux. The common sections of the vapor space are circular, rectangular and annular and are chosen based on the application of heat pipe. Heat pipes are being used very often in particular applications when conventional cooling methods are not suitable. Once the need for heat pipe arises, the most appropriate heat pipe needs to be selected. For this study copper heat pipe with water as a working fluid is used. Taguchi techniques are experimental design optimization techniques [2] which use standard 'Orthogonal Arrays' for forming a matrix of experiments in such a way to extract the maximum important information with minimum number of experiments. Using Taguchi techniques, the number of parameters can be tested at a time with probably least number of experiments as compared to any of the other experimental optimization techniques. Moreover, the technique provides all the necessary information required for optimizing the problem. The main advantage of Taguchi Techniques is not only the smallest number of experiments required but also the best level of each parameter can be found and each parameter can be shared towards the problem separately. The main steps of Taguchi Method are determining the quality characteristics and design parameters necessary for the product/process, designing and conducting the experiments, analyzing the results to determine the optimum conditions and carrying out a confirmatory test using the optimum conditions [2].

2. Experimental Setup

2.1 Components

Heat Pipe
Heaters
Water jacket
Thermocouples
Temperature Indicator
Variac
Rotameter
Water Jacket
Wattmeter

Heat Pipe

Heat pipe is a heat transfer device with an extremely high effective thermal conductivity. Heat pipes are evacuated vessels which are partially back filled with a small quantity of working fluid. They are used to transfer heat from a heat source to a heat sink with minimal temperature gradient [3]. Heat pipe is a heat transfer device which transports large quantities of heat with minimum temperature gradient without any additional power between the two temperature limits. It consists of three different sections namely evaporator, adiabatic section and condenser section. These three parts have equal importance and can significantly affect the performance of a heat pipe. The heat input is added to the evaporator section of the container, the working fluid present in the wicking structure which is kept in the container is heated until it vaporizes. Since the latent heat of evaporation is large, considerable quantities of heat can be transported with a very small temperature difference from end to end. Thus, the structure will also have a high effective thermal conductance. The high temperature and corresponding high pressure in the evaporator section cause the vapour to flow to the cooler condenser section, where the vapour condenses and releases its latent heat of vaporization. The capillary forces existing in the wicking structure then pump the liquid back to the evaporator. The evaporator and condenser sections of a heat pipe function independently, needing only common liquid and vapour streams [1].

Table 1: Heat Pipe Specification

Sr. No.	**Heat pipe specifications**	
	Specification	***Dimension***
1	Outside diameter , m	0.254
2	Inside diameter, m	0.220
3	Evaporator length, m	0.400
4	Condenser length, m	0.400
5	Adiabatic length, m	0.200
6	Total length, m	1
7	Working fluid	Water
8	Material	Copper

2.2 Procedure

The schematic diagram of the experimental setup is shown in Fig.1. The specifications of heat pipe are tabulated in Table 1 . Heat input was given at the evaporator section using an electric strip attached to it with proper electrical insulation and heater was energized with an AC supply through a variac. The desired heat input was supplied to the evaporator end of the heat pipe by adjusting the variac. Thermocouples are used to measure temperatures of heat pipe surface at heater section and adiabatic section. The cooling water is circulated in the cooling jacket attached to the condenser section which is located at the end of heat pipe to remove the heat of the working fluid. The heat pipe has the ability to transfer the heat through the internal structure. As a result, a sudden rise in wall temperature occurs which could damage the heat pipe if the heat is not released at the condenser properly. Therefore, the cooling water is circulated first through the condenser jacket, before the heat is supplied to the evaporator [2]. The condenser section of the heat pipe is cooled using water and its flow rate is measured by a floating Rotameter. The inlet and outlet temperatures of the cooling water are measured using two thermocouples. The adiabatic section of the heat pipe is completely insulated with the glass wool. The amount of heat loss from the evaporator and condenser surface is negligible. The power input to the heat pipe is gradually raised to the desired power level. The surface temperatures of the heat pipe are measured at regular time intervals until the heat pipe reaches the steady state condition. Simultaneously the evaporator wall temperatures, condenser wall temperatures, water inlet and outlet temperatures in the condenser zone are measured. Once the steady state is reached, the input power is turned off and cooling water is allowed to flow through the condenser to cool the heat pipe and to make it ready for further experimental purpose. The steady state is defined as the variation in temperature less than ±0.1°C for 10 minutes [1] (This takes 30-45 minutes). Then the power is increased to the next level and the heat pipe is tested for its performance. Experimental procedure is repeated for different combinations of heat inputs, inclinations of pipe to the horizontal, flow rates and observations are recorded.

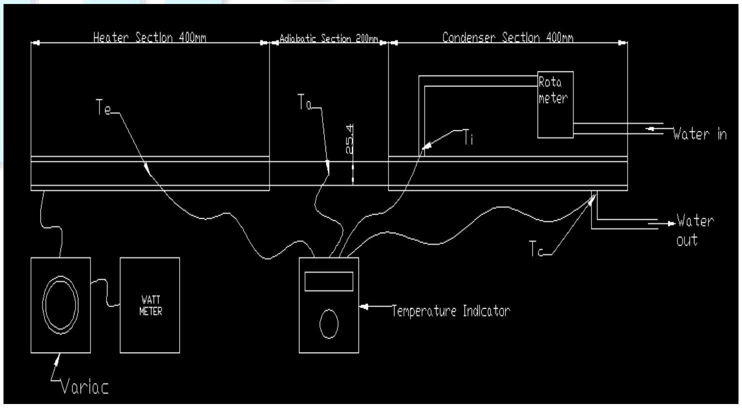

Fig.1 Experimental Setup.

3. Design of Experiment

For the experimental purpose, the three parameters and three levels are used for Taguchi method with very careful understanding of the levels taken for the factors. The factors to be studied are mentioned in table 2. Before selecting an orthogonal array, the minimum number of experiments to be conducted can be fixed by using the following relation,

$$N_{taguchi} = 1 + NV(L - 1)$$

Where N Taguchi is the number of experiments to be conducted, NV is the number of variables and L is the number of levels [2]. In this analysis, NV = 3 and L = 3. Hence a minimum of seven experiments are to be conducted. The standard orthogonal arrays available are L4, L8, L9, L12, L16, L18 etc. According to the Taguchi design concept L9 orthogonal array is chosen for the experiments as shown in table 3. In this study, the observed values of heat input, inclination angle and flow rate are set at maximum level. Each experimental trail is performed as per L9 table and the optimization of the observed values is determined by comparing the standard method and analysis of variance (ANOVA) which is based on the Taguchi method. Table 3 shows the experimental design for L9 orthogonal array. In the Taguchi method, all the observed values are calculated based on the concept higher the better and smaller the better. In this analysis, the observed values of thermal resistance and overall heat transfer coefficient are smaller the better and higher the better respectively.

Table 2: Control Parameters and Levels

Control Parameters	*Level 1*	*Level2*	*Level 3*
Heat Input (W)	80	100	120
Inclination Angle (°)	0	70	90
Flow Rate (kg/min)	0.06	0.08	0.1

Table 3: L9 Orthogonal Array

L_9	*Level 1*	*Level 2*	*Level 3*
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3.1 Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) is used to analyse the experimental data as follows

$$(S/N) = -10 \log [y_i^{\,2}] \quad \ldots\ldots \text{(For smallest the best)}$$

$$(S/N) = -10 \log [1/ y_i^{\,2}] \ \ldots\ldots \text{(For largest the best)}$$

$$\text{Correction Factor (C.F)} = (\Sigma(S/N)^2 / N)$$

$$\text{Sum of Squares (SS)} = ½ \{(\Sigma S/N \text{ ratio I level})^2 + (\Sigma S/N \text{ ratio II level})^2 + (\Sigma S/N \text{ ratio III level})^2 - \text{C.F}\}$$

$$\text{Percentage of Contribution} = \text{SS} / \text{total sum of squares}$$

Where y_i is output of performance characteristics
N is the total number of experiments.

4. Observations

Table 4: Observation Table

Test	*Heat Input (W)*	*Angle of inclination (°)*	*Flow rate (L/min)*	*Te ,°C (Heater Temp)*	*Ta,°C (Adiabatic)*	*Ti,°C (Water inlet)*	*Tc ,°C (Water outlet)*
1	80	0	0.06	53	44	25	40
2	80	70	0.08	48	41	25	41
3	80	90	0.1	49	44	26	43
4	100	0	0.08	58	46	24	43
5	100	70	0.1	57	41	24	40
6	100	90	0.06	56	48	25	48
7	120	0	0.1	58	45	26	44
8	120	70	0.06	64	53	24	52
9	120	90	0.08	55	47	25	47

5. Taguchi Analysis

In this study, the objective is to determine the main effects of the working parameters of heat pipe, to perform the analysis of variance (ANOVA) and to establish the optimum conditions based on the Taguchi method. The main effects of heat pipe analysis are used to study the effects of each of the factors, as shown in figures 2 and 3. The performances of the heat pipe (ANOVA-significant factor) can be calculated for each experiment of the L9 by using the observed values of the thermal resistance and overall heat transfer coefficient from table 4. Table 5, 6 and 7 lists the ANOVA test results for efficiency, thermal resistance and overall heat transfer coefficient respectively. The optimum operating conditions of heat pipe (ANOVA-optimum condition) for each of the observed values are illustrated in tables 8, 9 and 10.

5.1 Sample Calculations

For 1st Reading

- Thermal resistance

$$R = \frac{Te - Tc}{Q}$$

$$= \frac{53-40}{80}$$

$$= 0.1625\ ^0C/W$$

[1]

- (S/N) = -10 log [y_i^2] ……..(for smallest the best)
  = -10 log [0.1625^2]
  = 15.78

For 1st Reading

- Overall Heat Transfer Coefficient

$$U = \frac{Q}{A \times (Te - Tc)}$$

$$\text{Where, } A = 2 \times \pi \times r \times L = 2 \times \pi \times 0.0127 \times 1$$

$$= 0.0797\ m^2$$

$$U = \frac{80}{0.797 \times (53-40)}$$

$$= 77.2126\ W/m^2k$$

[3]

- (S/N) = -10 log [1/ y_i^2]
  = -10 log [1/ 77.2126^2]
  = 37.75

5.2 Result Table

Table 5: Result Table

N O	***Heat input (W)***	***Angle (°)***	***Flow rate (L/min)***	***Thermal resistance Yi (°C/W)***	***S/N ratio***	***Overall heat transfer coefficient, Yi (W/m2k)***	***S/N ratio***
1	80	0	0.06	0.1625	15.7	77.21	37.7
2	80	70	0.08	0.0875	21.1	143.394	43.1
3	80	90	0.1	0.075	22.4	167.29	44.4
4	100	0	0.08	0.15	16.4	83.647	38.4
5	100	70	0.1	0.17	15.3	73.8061	37.3
6	100	90	0.06	0.08	21.9	156.838	43.9
7	120	0	0.1	0.1166	18.6	107.546	40.6
8	120	70	0.06	0.1	20	125.47	41.9
9	120	90	0.08	0.06	24.4	188.205	45.4

Table 6: ANOVA for Thermal Resistance

Parameter	***I Mean***	***II Mean***	***III Mean***	***SS***	***%contribution***
Heat input	17.35	17.93	21.03	3206.714	33.33
Angle of inclination	16.97	18.84	20.5	3199.64	33.25
Flow rate	19.23	18.84	16.39	3214.37	33.41

Table 7: ANOVA for Overall Heat Transfer Coefficient

Parameter	***I Mean***	***II Mean***	***III Mean***	***SS***	***% contribution***
Heat input	41.78	39.9	42.69	15489.405	33.32
Angle of inclination	38.94	40.82	44.52	15515.91	33.38
Flow rate	41.21	42.35	40.81	15476.97	33.29

Table 8: Optimum Working Parameters

Working Parameter	***Level 1***	***Level 2***	***Level 3***	***Validation***
Thermal resistance	120 W	90°	0.06 L/min	0.05 °C/W
Overall Heat Transfer Coefficient	120 W	90°	0.06 L/min	250.9 W/m2k

6. Results and Discussion

Figure 2 depicts the variations of thermal resistance of heat pipe with all the three working parameters. The thermal resistance of heat pipe decreases for increasing values of heat input and angle of inclination. But in the case of flow rate, thermal resistance decreases up to the level II and afterwards its value increases from level II to level III. The flow is disturbed inside the heat pipe between the evaporator and condensate which is coming from the condenser. This may be the reason for an increase in the thermal resistance of the heat pipe [2]. The variations of thermal resistance in all the levels are less than 10%.

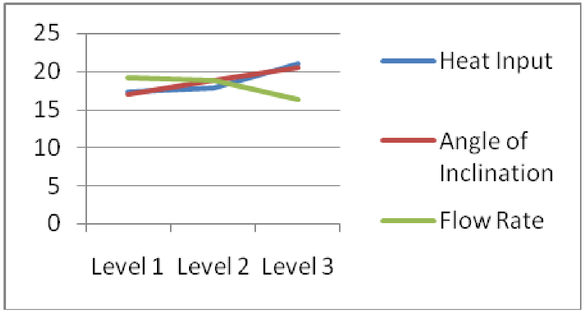

Fig. 2 Effect of each factor on Thermal Resistance

Figure 3 displays the variations of overall heat transfer coefficient for all the parameters. But the variations are very less or almost same for all the conditions. These variations are within the range of 1%. It indicates that the overall heat transfer coefficient plays an important role in heat transfer characteristics of heat pipe and its value is almost constant.

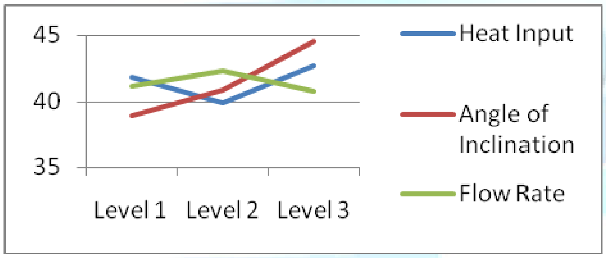

Fig. 3 Effect of each factor on Thermal Resistance

The percentage contributions of all the working parameters of heat pipe are almost same in all the levels as seen in table 6, 7. The variations are quite less than 0.2% only. The optimum working conditions and validation of experimental analysis of heat pipe by adopting Taguchi method is tabulated in table 8.

Table 8: Optimum Working Parameters

Working Parameter	***Level 1***	***Level 2***	***Level 3***	***Validation***
Thermal resistance	120 W	90°	0.06 L/min	0.05 °C/W
Overall Heat Transfer Coefficient	120 W	90°	0.06 L/min	250.9 W/m2k

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