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PARAMETRIC OPTIMIZATION OF PULSATING HEAT PIPE BY TAGUCHI METHOD

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ABSTRACT

Pulsating Heat Pipe (PHP) has become one of the most promising options for passive heat transfer due to its excellent heat transfer capability, high thermal efficiency and structural simplicity. The paper presents an experimental study on the operational limit of closed-loop pulsating heat pipe (CLPHP) charged with ammonia which is consists of total 14 turns of aluminum tube with 3 mm inner and 4 mm outer diameter. A constant electric power supply of 36 W was provided to run the pulsation mechanism and experiment was carried out for three filling ratios of 0.4, 0.6 and 0.8 as well as inclination angle of 0°, 30°, 45°, 60°, 90° and 180°. Here, the heat transfer rate, thermal resistance and heat transfer co-efficient is measured to determine the performance of the PHP. Then Taguchi method is applied to analyze the effect of working parameters of the pulsating heat pipe to predict the optimum design parameters. In Taguchi method, L18 orthogonal array is selected and the best optimum parameters are identified based on main effect plot for means and signal to noise ratio plot under the characteristic of smaller and larger is the better respectively. The analysis of the Taguchi method reveals that, 60% filling ratio at 30° inclination angle, performance of the PHP is maximum.

KEYWORDS: Pulsating Heat Pipe, Taguchi Method, Filling Ratio, Inclination Angle, Thermal Resistance, Heat Transfer Coefficient.

INTRODUCTION

The emergence of nanotechnology and the increase of production of large-scale integrated circuits have attracted strong interests in modeling of micro heat transfer devices, and the heat management of micro components has become increasingly important for next generation electronics and miniaturization.[1] Among other cooling techniques, pulsating heat pipes (PHP) have emerged as a convenient and cost effective thermal design solution due to its remarkable heat transfer capability, high thermal efficiency and structural simplicity. The Pulsating heat pipe (PHP) is a two phase heat transfer device which can efficiently transport thermal energy by using an intermediate heat transfer fluid. It consists of sealed capillary tubes having three zones (i.e. evaporator zone, condenser zone and adiabatic zone) with a small amount of a working fluid.

In PHP, The heat is transferred as latent heat energy by evaporating the working fluid in the evaporator zone and condensing the vapour in a cooling zone, the circulation is completed by the return flow of the condensate to the evaporator zone. By suitable design, pulsating heat pipes are being constructed to serve diverse functions such as precise temperature control, one- way transmission of heat (thermal diode) and heat flux amplification and reduction. The heat pipes are more advantageous in heat recovery systems, solar energy conversion, cooling of electronic components, Geothermal and Ocean thermal energy conversion, and air craft engine cooling.[2]

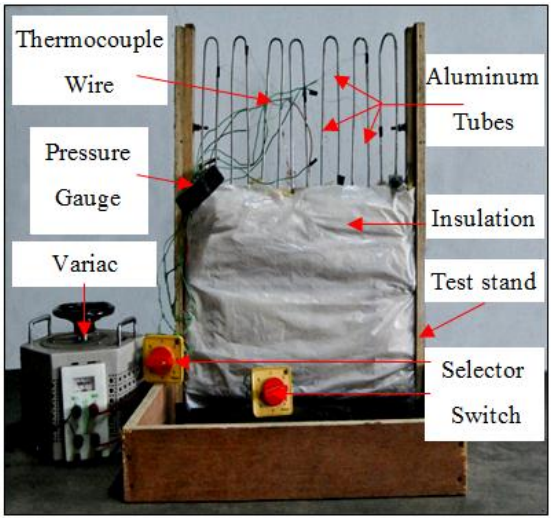
A PHP system may often looks simple, but its working mechanisms are relatively complex, as such systems involve multiphasic processes such as thermo-hydrodynamics, two-phase flow, capillary actions, phase changes and others. Therefore, many challenging issues still remain unsolved. There are quite a few attempts in the literature to model a PHP system with various degrees of approximation and success. However, research persons have presented their experimental results for optimum filling ratio, tube diameters, orientation and maximum heat load of PHP.

W. Qu, et al.[3] has done a theoretical analysis to determine the primary factors affecting the startup characteristics of a pulsating heat pipe. It is found that the wall surface condition, evaporation in the heating section, superheat, bubble growth, and vapor bubbles trapped in cavities at the capillary inner wall affect the startup of oscillating motion in the pulsating heat pipe. X.-S. Yang, et al.[1] has used the firefly algorithm to obtain good estimates of key parameters using very limited experimental data. P. Frank, et al.[4] conducted finite element analysis on PHP and stated that heat transfer coefficient increases with increase in amplitudes of oscillation when the difference in temperature between evaporator and condenser increases. S. Haque, et al.[5,6] has formulated an empirical correlation between overall heat transfer coefficient and different physical parameters such as heat input, evaporator temperature rise, fill ratios and inclinations and found that the correlation is effective for heat input and filling ratios. Babu, et al.[7] has used Taguchi method and considered the L25 orthogonal array and found that heat input plays a significant role in performance of PHP on thermal resistance and heat transfer coefficient followed by working fluid and filling ratio.

In this paper, working parameters of PHP are analyzed using Taguchi methodology. Taguchi techniques are experimental design optimization techniques 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]

Experimental set up

A closed loop pulsating heat pipe (CLPHP) (inside volume of $6.264\times10^{-5}m^3$) was built using aluminum tube of 4.0 mm Outer Diameter (OD), 3.0 mm Inner Diameter (ID) and of 8.862m length to form 14 parallel channels with 13 bends. The experimental setup is illustrated in Fig. 1 and the detailed dimensions of the CLPHP system are listed in the Table 1.



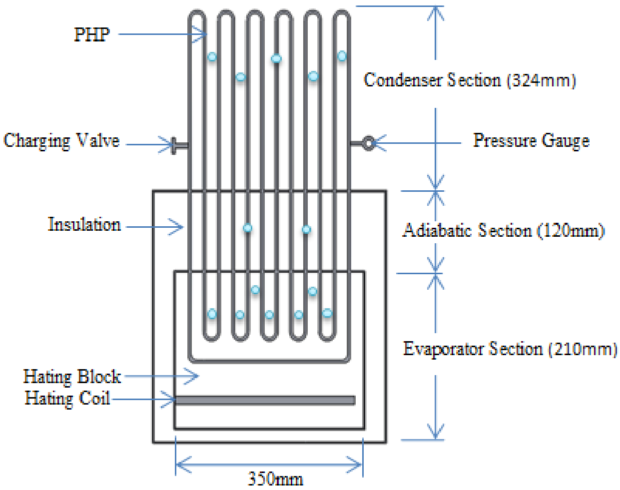


Fig 1: Experimental Set up.

Fig 2: Schematic representation of the CLPHP system.

Fig. 2 represents the schematic diagram of the CLPHP system where it has 3 sections: evaporator, adiabatic and condenser section. The evaporator section is about 210 mm long, the adiabatic section is 120 mm long and the condenser is 324mm long. The evaporator section of the heat pipe was placed inside aluminum block (0.35 m × 0.21 m × 0.035 m) having grooves of same dimension of the heat pipe to avoid any gap between the block and the pipe outside surface to ensure smooth heat flow to the CLPHP. A heating coil fabricated by winding nicrome wire of 0.25 mm diameter on ceramic bead at a constant interval of 1.50 mm was placed inside the slot of Aluminum block which acted as heat source. Heat is supplied to the working fluid directly from AC power supply with the help of a variac. At different locations on the setup, total fourteen K-type thermocouples were attached by insulation tape to monitor the temperature during the tests. A pressure gauge (maximum range: 300 psi) is engaged to the setup for measuring pressure variations at different sections. One gate valve was connected to the heat pipe to remove trapped air as well as to fill the working fluid. The apparatus was placed on a wooden stand which can be rotated at different orientations. Both evaporator and adiabatic sections were insulated by layers glass wool (0.39 m × 0.35 m × 0.075 m), while the condenser section was open to the surrounding to get cooled by natural air flow.

Table 1: Detail dimensions of the CLPHP system.

Parameters	Symbol	Dimensions (m)
Heating block	block	0.35x0.21x0.035
Insulation	ins	0.39x0.35x0.075
Total length of tube	LPHP	8.862
Length of tube in evaporator section	L_e	2.502
Length of tube in condenser section	L_c	4.68
Length of tube in adiabatic section	Lad	1.68
Inner diameter of the tube	d_i	0.003
Outer diameter of the tube	d_o	0.004

Experimental procedure

All the experiments were conducted at room temperature (25 ℃ – 30 ℃). At first, the vacuum was generated inside the pipe through vacuum pump keeping the gate valve closed and monitoring the vacuum pressure on a vacuum gauge. Under vacuum pressure, ammonia was injected to the pipe considering three different fill ratios as 0.4 or 2.506×10^{-5} m^3 (40 % of inside volume), 0.6 or 3.758×10^{-5} m^3 (60 % of inside volume) and 0.8 or $5.011\times10^{-5} m^3$ (80 % of inside volume) and the gate valve was closed immediately to resist air insertion.

The thermocouples were first calibrated using a standard thermometer (range: -40℃ ~1000 ℃). One selector switch was used to monitor the temperature of five and two different points on condenser and adiabatic sections respectively and another selector switch was used to monitor the temperature of seven different points of evaporator section. Knobs were used for selecting desired thermocouples to detect temperature reading on a digital thermometer. The temperature at different sections are monitored and recorded at 20 minutes interval until the system reaches steady state condition. To reach steady state condition, it takes about 260 minutes. The input electric energy was kept constant at 36 W through a variac to the heating coil. Various parameters were measured for different inclinations at 0°, 30°, 45°, 60°, 90° and 180°, three distinct fill ratios of 40 %,60 % and 80 %.

Taguchi Approach (Design of Experiments)

For data analysis, the two parameters and six levels are used for Taguchi method with very careful understanding of the levels taken for the factors. According to Taguchi design concept, L18 orthogonal array is chosen for the experiments as shown in Table 2. Each experimental trail is performed as per L18 table and the optimization of the observed values is determined by comparing the standard method and analysis of variance (ANNOVA) which is based on the Taguchi method. In Taguchi method all the observed values are calculated based on the concept higher the better and smaller the better. In this analysis, the values of thermal resistance is smaller the better, but heat transfer rate and heat transfer coefficient are larger the better.

Table 2: Experimental design for L18 orthogonal array.

Ser No.	Fill Ratio V/V_{max}	Inclination Angle, θ	Heat Transfer Rate, Q_{php}(W)	Thermal Resistance, R (°C/W)	Overall Heat Transfer coefficient, U_{php} (W/m²°C)
1	0.4	0°	34.387	0.083	782.308
2	0.4	30°	34.451	0.078	834.782
3	0.4	45°	33.651	0.091	712.268
4	0.4	60°	33.6441	0.106	614.436
5	0.4	90°	33.012	0.260	250.612
6	0.4	180°	28.5196	0.808	80.652
7	0.6	0°	33.858	0.082	796.091
8	0.6	30°	34.127	0.078	835.796
9	0.6	45°	33.741	0.089	733.575
10	0.6	60°	33.407	0.103	633.702
11	0.6	90°	32.378	0.194	335.155
12	0.6	180°	27.272	0.787	82.760
13	0.8	0°	33.571	0.106	616.425
14	0.8	30°	33.446	0.101	642.327
15	0.8	45°	33.199	0.180	362.793
16	0.8	60°	33.081	0.261	249.660
17	0.8	90°	30.881	0.560	116.359
18	0.8	180°	24.233	1.011	64.429

RESULTS AND DISCUSSIONS

Heat Transfer Rate, Q_{php} (watt)

From the 3D surface plot for the variation of Heat Transfer Rate at different fill ratio and inclination angle shown in the fig. 3, it is found that for all fill ratios the Heat Transfer Rate, Q_{php} at inclinations 0°, 30°, 45°and 60° are very close to each other though it is slightly lower for fill ratio 0.8. It is also observed that for all fill ratios heat transfer rate, Q_{php} at inclinations 90°and 180° is much lower and it is lowest for fill ratio 0.8.

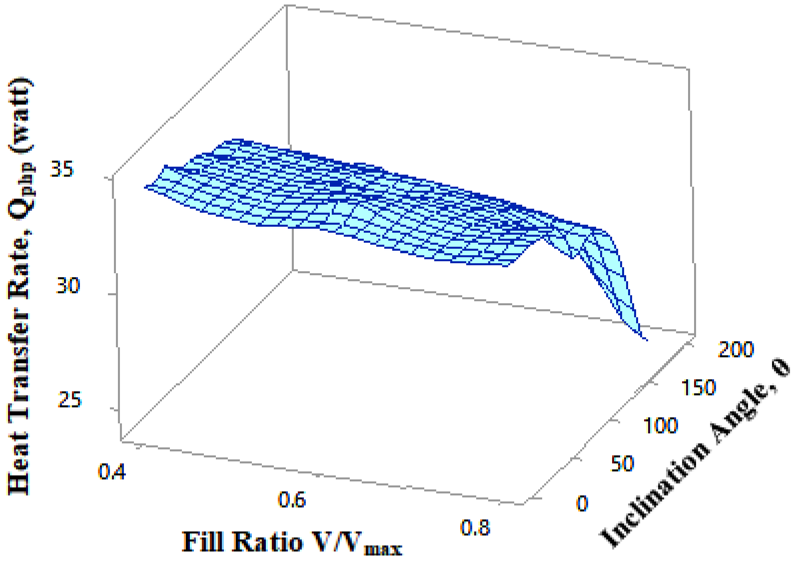


Fig. 3: 3D Surface plot for the variation of Heat Transfer Rate for different Fill Ratio and Inclination Angle.

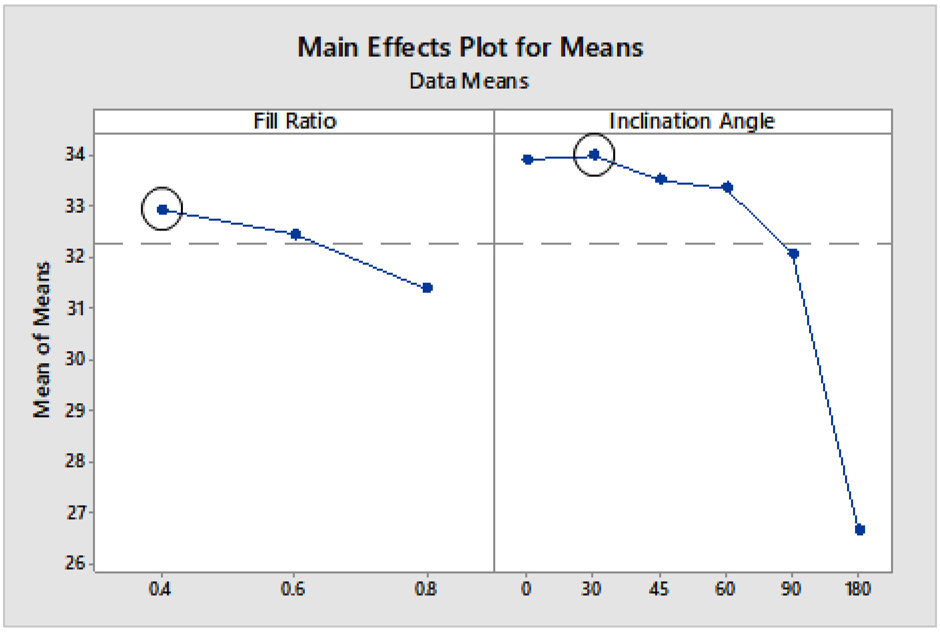


Fig. 4: Main effect plot for heat transfer Rate.

Fig.4 shows the effect of each parameter at different levels for heat transfer rate when analyzed by Taguchi approach. The higher value in each graph specifies the optimum level of that particular parameter. Therefore, the optimum level of each parameter for the better operation of PHP is 40% filling ratio at 30° inclination angle.

Thermal resistance, R (°C/W)

Fig. 4 shows the change in Thermal Resistance, R (°C/W) with Fill Ratio (V/Vmax) at different inclination of CLPHP .From the figure it is clear that, thermal resistances for fill ratios 0.4 and 0.6 show very close values at inclinations below 90°and thermal resistance, R is much higher at inclinations 90ºand above for all fill ratios. At fill ratio 0.8 having 180º inclinations, thermal resistance is the highest. So, it is evident that lowest values of thermal resistance to heat transfer through PHP can be achieved for filling ratio 0.4 and 0.6 having lower values of inclinations as 30º, 60º and 45º.

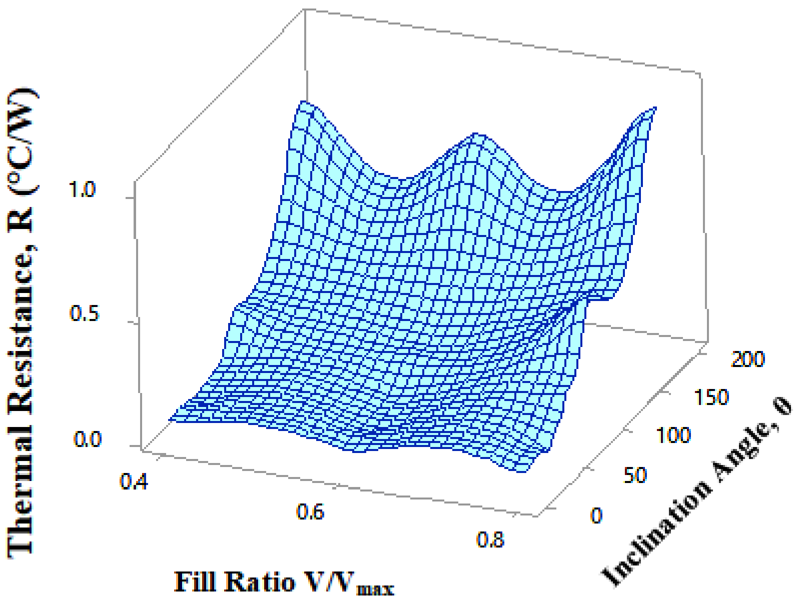


Fig. 5: 3D Surface plot for the variation of Thermal Resistance for Fill Ratio and Inclination Angle.

Fig. 5 shows the variation of thermal resistance of pulsating heat pipe with all the parameters considered when analyzed by Taguchi approach. Here, the lowest value in each graph specifies the optimum level of that particular parameter. From the figure it is observed that among all the parameters considered the thermal resistance is lower at filling ratio of 60% and 30º inclination angles.

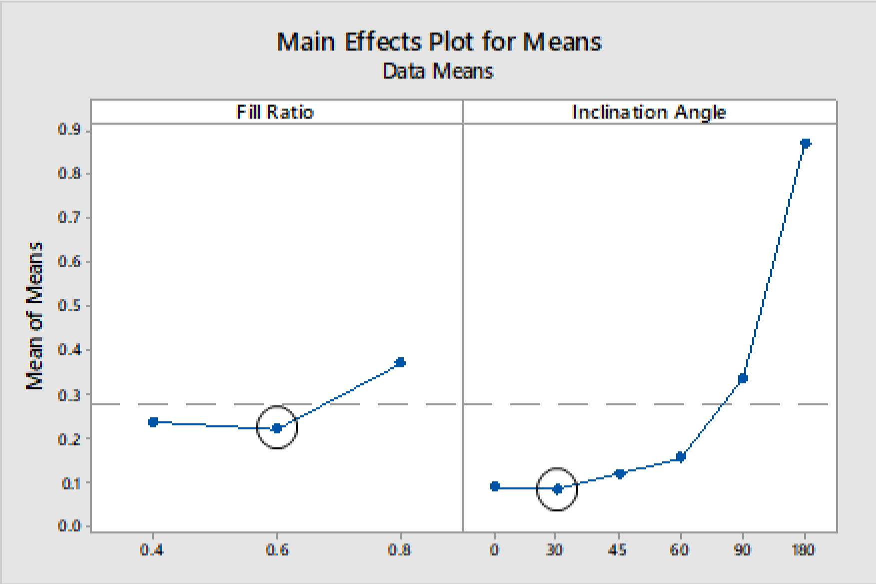


Fig. 6: Main effect plot for Thermal Resistance.

Overall heat transfer coefficient, U (W/m² °C)

From Fig. 7, it is evident that overall heat transfer coefficient, U for a fixed heat input is almost similar for fill ratio 0.4 and 0.6 at all inclinations where it is low for fill ratio 0.8 This is happening because at fill ratio 0.4 and 0.6, CLPHP gets more space to produce bubbles for heat transfer to the condenser section. The value of U, for fill ratio 0.4 and 0.6 are close to each other below 90° inclination.

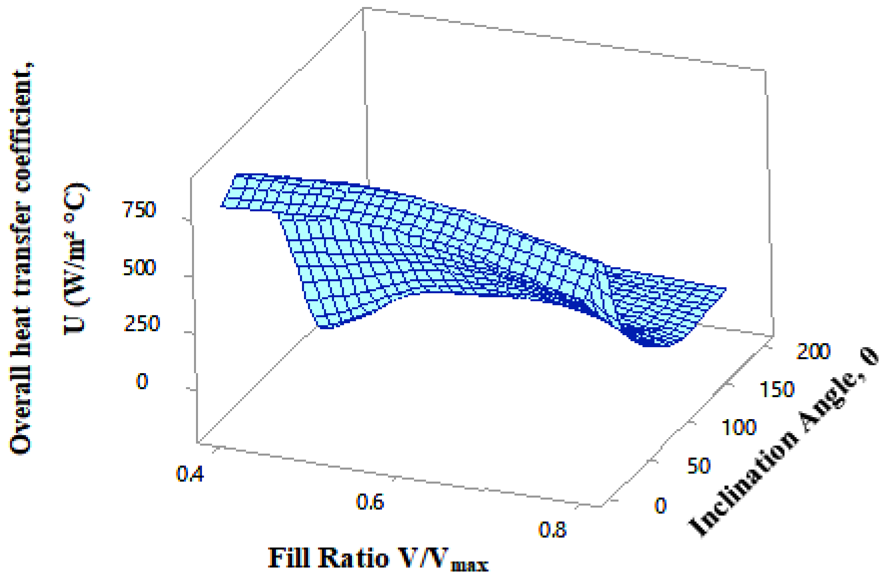


Fig. 7: 3D Surface plot for variation of Heat Transfer Coefficient for Fill Ratio and Inclination Angle.

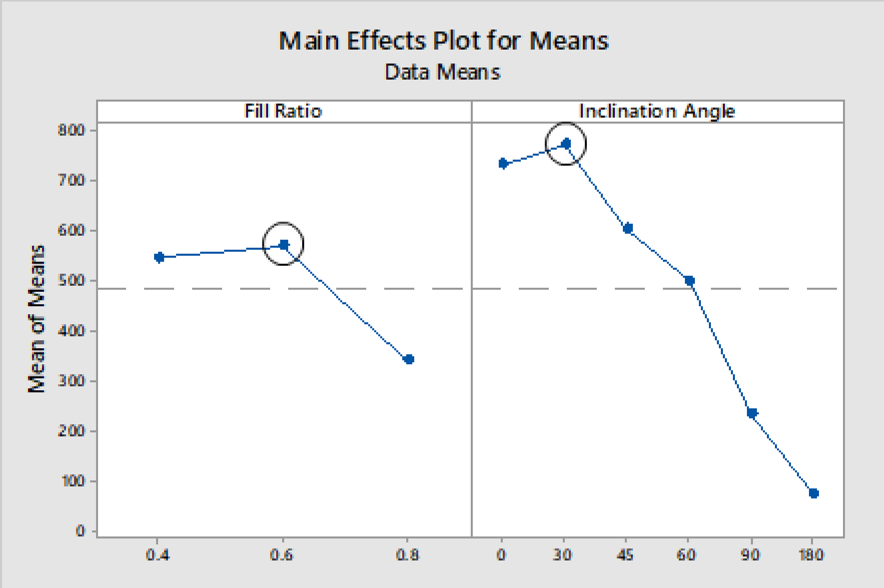


Fig. 8: Main effect plot for heat transfer co-efficient.

For all fill ratios, overall heat transfer coefficient is very low at inclination less than 90°, because at this stage the bubble do not get enough bouncy force to move up for transferring the heat to condenser section. At inclination 180°, the value of heat transfer coefficient is the lowest and approximately same for all fill ratios. This scenario happens due to the lack of bubble production at the evaporator section. So, to achieve higher overall heat transfer coefficient for increased heat transfer through CLPHP, fill ratio of 0.4 and 0.6 along with inclination 30°, will give the best result. Again, Fig.8 depicts that optimum level of each parameter for the better heat transfer co-efficient is 60% filling ratio at 30° inclination angle when analyzed by Taguchi approach. Here, the higher value in each graph specifies the optimum level of that particular parameter.

CONCLUSION

An experimental investigation on thermal analysis of an ammonia filled closed loop pulsating heat pipe was conducted for different filling ratios with different inclination angle. The heat transfer Rate, thermal resistance and heat transfer coefficient in pulsating heat pipe could be predicted successfully with acceptable error by Taguchi method and it has been found that the performance of the PHP is maximum when optimum level of filling ratio is 60% at 30° inclination angle.

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