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ANALYSIS OF ENERGY CONSERVATION POTENTIAL OF THE HEAT PIPE USING RESPONSE SURFACE METHODOLOGY

***Senthilkumar, R., Prabakaran, J. and Karthikeyan, M.**

Department of Mechanical Engineering, Annamalai University, India

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ABSTRACT

This paper discusses about the energy conservation potential of the heat pipe using copper nanofluid as a working fluid and the optimizes the working parameters using the response surface methodology (RSM). The parameters considered are heat input, angle of inclination and concentration of the copper nano particles in the copper nanofluid. Box Behnken design is used to conduct the experiments in the heat pipe and the responses are thermal efficiency and the thermal resistance. The influences of the above parameters and the interaction effects are studied by analysis of variance (ANNOVA). The proposed model is the very useful to predict the thermal efficiency and thermal resistance of the heat pipe.

INTRODUCTION

The energy requirement of all the countries is increasing greatly in recent times. The maximum energy consumption occurs in the industrial sector, transport sector, residential applications and commercial sectors (Reay and Kew 2006). In addition, based on the report of World Energy Council (WEC), the world energy demand would increase up to 50–80% in 2020. So the energy efficient tools and efficient heat recovery systems are required to minimize the energy consumption. There are many heat recovery systems which are widely used to recover the waste heat, among which the heat pipe is of great importance. The heat pipe is an effective heat transfer device that can transport heat at high rates with a very small temperature gradient by utilizing the phase change of working fluid. The heat pipe makes use of the highly efficient thermal transport process of evaporation and condensation to maximize the thermal conductance between a heat source and a heat sink. The amount of the heat transported by these devices is normally several orders of magnitude greater than pure conduction through a solid metal (Chi 1976). Some of the applications are electronics cooling, thermal energy recovery, energy conversion system, isothermal furnace, thermal control in spacecraft, solar collector, heat pipe heat exchangers, heat recovery for HVAC Systems, gasification process and thermal storage subsystems (Singha *et al.*, 2011). The operating parameters of the heat pipe depends on the heat source (heat input), type of wick structure, working fluid, angle of inclination, vapour core diameter, heat pipe container material, wick material, properties of the working fluid, etc. The heat transfer properties of heat pipes can be enhanced by increasing either the heat transfer surface or the heat transfer coefficient between the fluid and the surface area.

The use of heat pipes in high-power cooling applications has been limited to conventional applications which require either low thermal resistance or a severely restricted enclosure area. Besides, most of the traditional fluids have poor heat transfer properties compared to most solid, which necessitates the vital need for new and novel coolants with improved performance. The conventional fluids such as water, engine oil and ethylene glycol are generally used as working fluids in the heat transfer equipments. The performance of these conventional heat transfer fluids is often limited by their low thermal conductivities. Thus, there is a strong motivation to develop advanced heat transfer fluids with substantially higher conductivities to enhance the thermal characteristics. The use of solid particles as an additive suspended into the base fluid is a new technique for enhancing the heat transfer performance. Owing to the fact that the solid metal has a superior thermal

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**Corresponding author: Senthilkumar, R., Department of Mechanical Engineering, Annamalai University, India.*

conductivity than the base fluid, suspending metallic solid fine particles into the base fluid is predicted to improve the thermal conductivity of that fluid. The suspension of solid particles such as millimeter or micrometer sized particles in the base fluid paves the way for enhancing the thermal conductivity of the traditional working fluids. But in the practical domain, micronized particles cause the problems such as sedimentation, erosion, fouling and increased pressure drop of the flow channel.

The latest progress in materials technology has made it feasible to generate nanometer-sizes particles that can conquer these problems. The innovative heat transfer fluids suspended by nanometer-sized solid particles are called ‘Nanofluids’. These suspended nanoparticles can change the transport and thermal properties of the base fluid. The term ‘Nanofluids’ is used to indicate a special class of heat transfer fluids that contain nanoparticles (≤100 nm) of metallic/non metallic substances uniformly and stably suspended in a conventional coolant (Choi 1995; Lee *et al.,* 1999; Choi *et al.,* 1999; Xie *et al.,* 2002). The experimental results show that the nanofluids have remarkably higher thermal conductivity and greater heat transfer characteristics than conventional pure fluids (Xuan, and Li 2000; Daungthongsuk, and Wongwises 2007; Xuan and Li 2003). Response surface methodology (RSM) is a collection of mathematical and statistical techniques for developing, improving and optimizing the process parameters by the design of experiments. The objective is to optimize the output variable which is influenced by independent input variables. An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response (Montgomery 2005; Mohammed *et al.,* 2010; Gunaraj and Murugan 1999; Ramkumar, and Ragupathy 2012; Prabakaran *et al.,* 2012). In general the relationship is

$$Y= f (X_1+X_2+X_3+\ldots) \pm\varepsilon.$$

where Y is the response, X_1, X_2, $X_{3,\ldots..}$ are input variables and ε is the measurement error.

The objective of the present study is to optimize the heat pipe operating parameters like heat input, angle of inclination, and the concentration of copper nanofluid in the base fluid by response surface methodology on the performance of copper–water heat pipes with mesh screen wicks. The present work elaborates the experimental work done and the prediction of empirical relations for thermal efficiency and thermal resistance of heat pipe using response surface methodology.

Response Surface Methodology

The experimental performance of the heat pipe is analyzed by response surface methodology (RSM) using Design of Expert software. Box Behnken design method is employed with three input parameters namely heat input (A), angle of inclination (B) and concentration of copper nano particle in the base fluid (C) over the output response of thermal efficiency and thermal resistance. Table 1 shows the process parameters and their levels.

Table 1. Process parameters

Parameter	Level		
	-1	0	+1
A. Heat Input, W	30	50	70
B. Angle of Inclination, deg	0	30	60
C. Concentration, mg/lit	25	75	125

Experimental procedure

The schematic diagram of the experimental setup is shown in Fig.1. The specifications of the heat pipe are given in Table 2. Heat input is applied at the evaporator section using an electric strip attached to it with proper electrical insulation and heater is energized with AC current through a variac. The desired heat input is supplied to evaporator end of heat pipe by adjusting the variac. Water jacket is used at the condenser end to remove the heat from the pipe. The heat pipe has the ability to transfer the heat through the internal structure. As a result, sudden rise in wall temperature occurs which could damage the heat pipe if the heat was not released at the condenser properly. Therefore, before heat is supplied to the evaporator, the cooling water is first circulated through the condenser jacket. The power input is gradually raised to the desired power level. The surface temperatures at seven different locations along the heat pipe are measured using copper constantan thermocouple at a regular time interval of ten minutes until heat pipe reaches steady state condition. Simultaneously the evaporator wall temperature, wick temperature, water inlet and water outlet temperatures are measured using thermocouples. Once 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 experiments. Then the power is increased to the next level and the heat pipe is tested for its performance. The experimental procedure is repeated for different flow rates and different inclinations of pipe to the horizontal and observations are recorded.

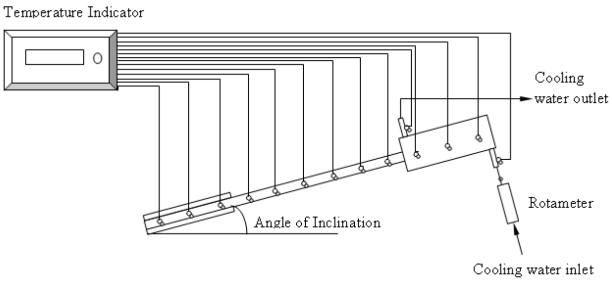

Fig. 1. Experimental setup

Table 2. Specifications of heat pipe

Parameters	Specifications
Heat pipe material	Copper
Wick material	Stainless steel (two layers)
Total length of pipe, m	0.6
Evaporator length, m	0.15
Adiabatic length, m	0.3
Condenser length, m	0.15
Condenser outer dia, m	0.036
Condenser inner dia, m	0.030
Outer diameter of the pipe, m	0.020
Inner diameter of the pipe, m	0.0176
Working fluid	Copper nanofluid, 100 mg/lit

RESULTS AND DISCUSSION

The computed values of the thermal efficiency and thermal efficiency are entered in the software design matrix. The RSM is used to develop the empirical relationship between the experimental variables and the responses that are thermal efficiency and thermal resistance. A regression analysis is carried out to develop a best fit model to the experimental data, which are used to generate response surface plots. The Table 3 and 4 shows the analysis of variance (ANNOVA) for thermal efficiency and thermal resistance. The values of **“**Prob>F” less than 0.05 indicates that the model terms are significant. For the present case, heat input (A) and angle of inclination (B) are producing a significant effect than the concentration (C). The square values of heat input and angle of inclination are also having major effect. The interaction effect between heat input and angle of inclination (AB) has more significant effect on the thermal efficiency than the heat input and concentration (AC) and angle of inclination and the concentration (BC) on the thermal efficiency. The “Pred R-Squared” value of 0.965 is responsible agreement with “Adj R-Squared” of 0.935. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Here the ratio of 17.42 indicates an adequate signal. Based on the ANNOVA, the following empirical relation is developed to predict the thermal efficiency of the heat pipe. Thermal Efficiency = 33.56875 - 0.68875 A + 0.343 B + 0.05245 C + 0.00354167 AB + 0.00025 AC + 0.00033333 BC + 0.0104187 A^2 - 0.0062028 B^2 - 0.000583C^2 Similarly, the “Pred R-Squared” value of 0.935 is in responsible agreement with “Adj R-Squared” of 0.945. The ratio of adequate signal is 11.56. The empirical equation for thermal resistance is given as, Thermal Resistance = 3.959793 - 0.02204 A - 0.02397 B - 0.01897 C + 0.0000281 AB -0.00018 AC + 0.0000233 BC + 0.000114 A^2 + 0.000249B^2 +0.000151 C^2

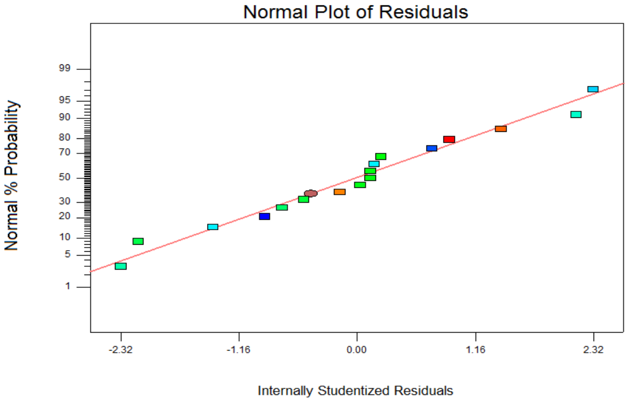

Fig. 2. Variations of experimental and predicted values of thermal efficiency

The Figs. 2 and 3 show the normal plot of residuals, which indicates that errors in the experiments are normally distributed for thermal efficiency and thermal resistance respectively. The thermal efficiency of the heat pipe is calculated as the ratio of heat rejection in the condenser section to the heat input at the evaporator section (Senthilkumar *et al.*, 2011). The working fluid in this analysis is copper nanofluid. The base fluid used in the copper nanofluid is DI water.

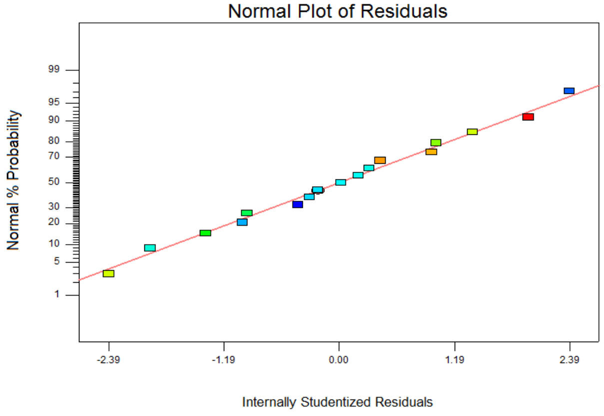

Fig. 3. Variations of experimental and predicted values of thermal resistance

Table 3. Annova for response surface quadratic model - thermal efficiency

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1173.81	9	130.424	26.758	0.0001
A	731.53	1	731.531	150.082	< 0.0001
B	215.28	1	215.281	44.167	0.0003
C	3.12	1	3.125	0.641	0.4496
AB	18.06	1	18.063	3.706	0.0956
AC	0.25	1	0.250	0.051	0.8273
BC	1.00	1	1.000	0.205	0.6643
A^2	73.123	1	73.129	15.003	0.0061
B^2	131.22	1	131.218	26.921	0.0013
C^2	8.94	1	8.944	1.835	0.2176
Residual	34.12	7	4.874		
Lack of Fit	32.69	3	10.896	30.435	0.0033
R-Squared	0.972	Pred R-Squared	0.965		
Adj R-Squared	0.935	Adeq Precision	17.422		

Table 4. Annova for response surface quadratic model - thermal resistance

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	3.383	9	0.376	13.466	0.0012
A	1.714	1	1.714	61.385	0.0001
B	0.251	1	0.251	9.000	0.0199
C	0.405	1	0.405	14.508	0.0066
AB	0.001	1	0.001	0.041	0.8458
AC	0.128	1	0.128	4.568	0.0699
BC	0.005	1	0.005	0.174	0.6888
A^2	0.009	1	0.009	0.316	0.5914
B^2	0.211	1	0.211	7.547	0.0286
C^2	0.603	1	0.603	21.594	0.0024
Residual	0.195	7	0.028		
Lack of Fit	0.189	3	0.063	40.248	0.0019
R-Squared	0.945	Pred R-Squared	0.935		
Adj R-Squared	0.875	Adeq Precision			11.560

It is observed from Figs. 4-6 that the thermal efficiency of heat pipe increases linearly with an increase the heat input in the evaporator section. The thermal efficiency of the heat pipe increases with increase in heat flux, due to the fact that the temperature gradient between the evaporator section and condenser sections increase. For higher values of heat input in the evaporator section, the heat generated in the surface is more and the working medium which is in the form of vapour moves vigorously into the condenser section. The cooling water in the condenser absorbs this excessive heat and as a result, the efficiency of the heat pipe increases.

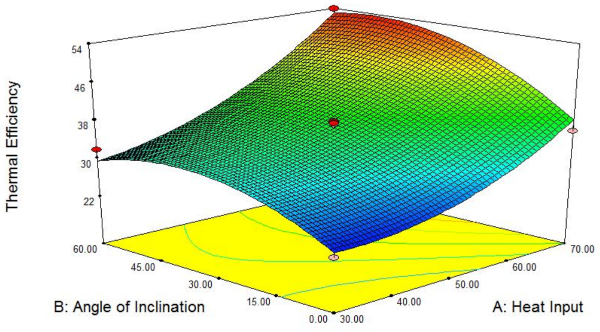

Fig. 4. Effect of heat input and angle of inclination on thermal efficiency

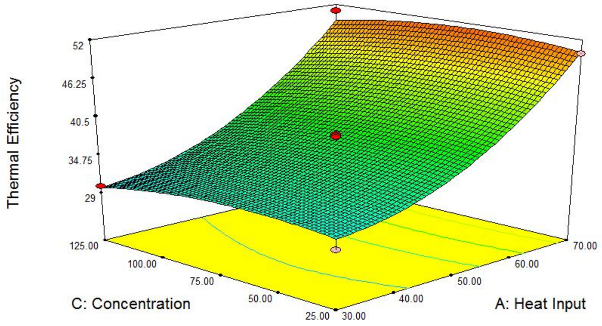

Fig.5. Effect of heat input and concentration on thermal efficiency

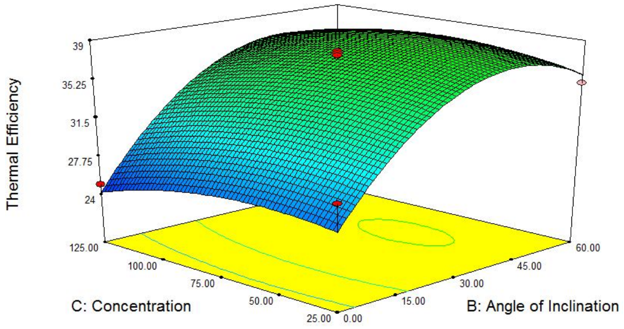

Fig.6. Effect of angle of inclination and concentration on thermal efficiency

The thermal resistance (R) of the heat pipe is defined as ratio of the temperature difference between the evaporator and the condenser to the heat supplied in the evaporator. From the Figs. 7 - 9, it is clear that the thermal resistance of heat pipe decreases with increase with the heat input and inclination angle of the heat pipe. The thermal resistance value is minimum at higher heat input and that value is minimum at 15^{o} to 30^{o} inclination of the heat pipe. The thermal resistances condense quickly to its minimum value when the heat load is increased. The effect of the heat transfer enhancement of a heat pipe using nanofluids is not due to the thermo physical properties of nanofluids but it is owing to the thin porous coating layer formed by nanoparticles in the evaporation region. Besides, the coating layer formed by nanoparticles improves the surface wettability by reducing the contact angle and increasing the surface roughness, which in turn increases the critical heat flux. This not only improves the maximum heat transport rate but also, significantly reduces the thermal resistance of the heat pipe using nanofluids.

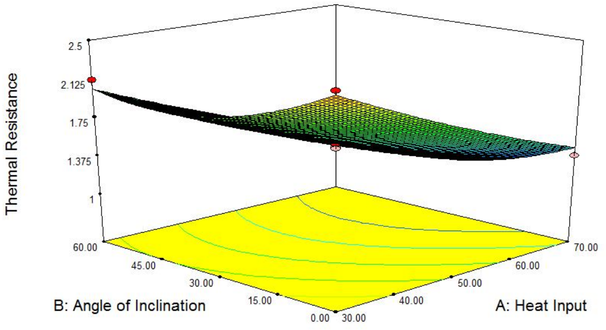

Fig. 7. Effect of heat input and angle of inclination on thermal resistance

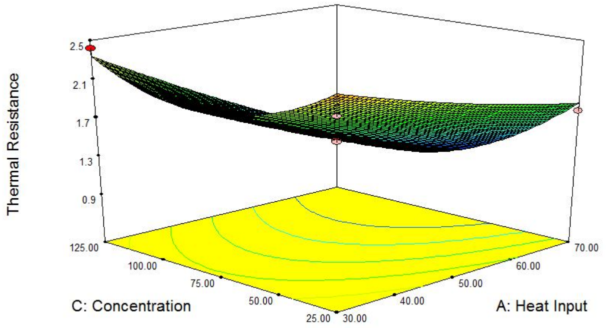

Fig. 8. Effect of heat input and concentration on thermal resistance

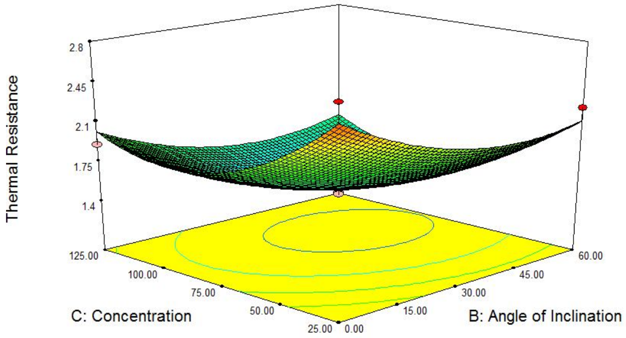

Fig. 9. Effect of angle of inclination and concentration on thermal resistance

Confirmation experiments

The Fig. 10 shows the optimization plot generated by the RSM with a desirability of 0.995. It shows that the optimum value of the thermal efficiency is 53.667% and thermal resistance is 1.08112 when the heat input is 70 W, at 49.59^{o} inclination, and concentration of CUO is 74.29 mg/lit. In order to confirm the optimization results, the experiment is conducted with 70 W heat input at 50^{o} inclination of the heat pipe with a concentration 75 mg/lit. The thermal efficiency of the heat pipe is found as 54.32% and the thermal resistance is 1.12 which is nearer to the optimum value.

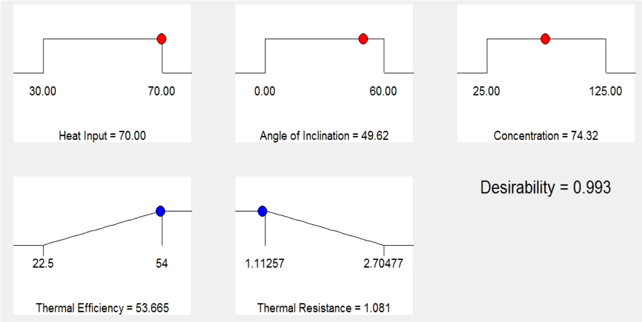

Fig. 10. Optimization plot

Conclusion

In this study, the thermal efficiency and thermal resistance of the heat pipe are optimized by RSM. The proposed model will be useful to predict the thermal efficiency of heat pipe with an error of ±1 %. Based on the RSM results, the optimum value of thermal efficiency is 54.32% and thermal resistance is 1.12 K/W. The heat pipe based passive systems can provide reliable and effective thermal control for energy conservation, energy recovery and renewable energy applications.

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