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Research Paper

AN EXPERIMENTAL ANALYSIS ON THERMAL PERFORMANCE OF CYLINDRICAL SCREEN MESH WICK HEAT PIPE WITH CUO NANO FLUID USING RESPONSE SURFACE METHODOLOGY

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In general, the heat transfer enhancement techniques can be classified into two methods including active method (requires external power source) and passive method (not requires external power source). Heat pipes are passive devices and can provide reliable and effective thermal control for energy conservation, energy recovery and renewable energy applications like Electronics cooling in CPU and Laptops, Nuclear power production, and Solar flat plate collectors, etc. Now a day's recent trends are the nano fluids and hybrid nano fluids to enhance the increased performance of heat pipes, heat exchangers, heat engines, etc. In this work an experimental setup is constructed to study the thermal performance of cylindrical screen mesh wick heat pipe using Cuo nano fluid as the working medium and optimizes the working parameters using the Response Surface Methodology (RSM). The working parameters considered are heat input, angle of inclination and concentration of the copper nano particles in the copper nano fluid. Box Behnken design is used in the RSM to conduct the experiments in the heat pipe and the responses are thermal efficiency, HT Coefficient and thermal resistance. The influences of the above parameters and the interaction effects are studied by analysis of variance (ANNOVA) in the RSM.

Keywords: Heat pipe, Cuo Nano fluid, Screen mesh wick, Response Surface Methodology, Thermal resistance, Thermal efficiency, HT Coefficient, Heat input, Angle of inclination

INTRODUCTION

As the story goes, it was in 1963 when a Los Alamos National Research Laboratory engineer named George Grover demonstrated the first heat pipe. Heat pipe is a high heat transfer device and is one of the most effective procedures to transport thermal energy from one place to another mostly used for cooling. It combines the principles of both thermal conductivity and phase transition to efficiently manage the transfer of heat between two solid interfaces. Here the phase change of working fluid leads to increase heat

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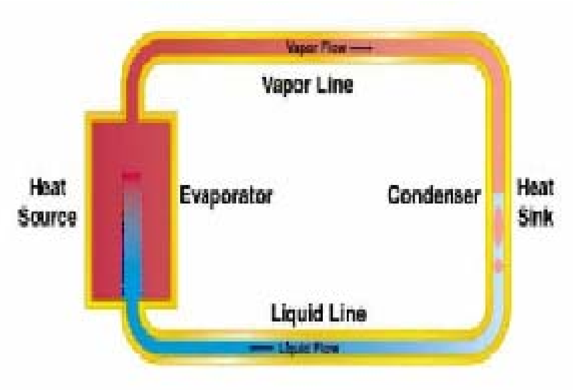
transport efficiency of heat pipe, since convective heat transfer has high heat transfer coefficient. Conventional heat pipes have Heat source and Heat sink and structures which consists of evaporation, adiabatic(transport) and condensation section as shown in Figure 4. The heat is transferred from the heat source to the evaporation zone by conduction through the pipe wall and wick structure and vaporizes the working fluid. The vapor pressure then drives the vapor through the adiabatic zone to the condenser zone. At condenser the vapor condenses and releases its latent heat of vaporization to the heat sink. The liquid then returns to the hot interface through capillary action, centrifugal force or gravity.

In this heat pipe the capillary pressure created by the wick structure pumps the condensed fluid back to evaporator and the cycle repeats as shown in Figure 1. Thus the heat pipe can continuously transport the latent of vaporization from the evaporator to the condenser without the use of mechanical components. This process will continue as long as there is sufficient capillary pressure to drive the condensate back to the evaporator. The heat pipes are tubular cross sections which are mostly cylindrical, oval and rectangular.

Figure 1: Cyclic Process of a Heat Pipe



Parameters Affecting Thermal Performance of Heat Pipe

1. Pipe diameter, length and material of construction.
2. Wick structure or capillary structure.
3. Heat input.
4. Type of working fluid and its viscosity.
5. Position of heat pipe (Horizontal, inclined or vertical)
6. Fluid fill ratio.
7. Source of heat sink.

Working Fluid Selection

Selection of working fluid is directly linked to the properties of the fluid. The properties of working fluid affect the ability to transfer heat and the comparability with the case and wick material. Below is the list to consider when we choose the working fluid.

- Compatibility with wick and wall materials.
- Good thermal stability.
- Wettability of wick and wall materials.
- Vapor pressures not too high or low over the.
- Operating temperature range.
- High latent heat.
- High thermal conductivity.
- Low liquid and vapor viscosities.
- High surface tension.

Nano Fluid

Nano fluids are stable suspensions of nanometer-sized materials (nano particles, nano fibers, nano tubes, nano wires, nano rods, nano sheet, or droplets) ranging from 1-100 nm in base fluids that show many interesting properties, and their distinctive features offer unprecedented potential for many applications Like nuclear reactors, transportation, electrical energy, mechanical, magnetic, solar absorption, and biomedical fields. Common base fluids include water, organic liquids (e.g., ethylene, tri-ethylene-glycols, refrigerants, etc.), oils and lubricants, bio-fluids, polymeric solutions and other common liquids. Materials commonly used as nano particles include chemically stable metals (e.g., gold, copper), metal oxides (e.g., alumina, silica, zirconia, titania), oxide ceramics (e.g., Al_2O_3, CuO), metal carbides (e.g., Sic), carbon in various forms (e.g., diamond, graphite, carbon nano tubes, fullerene) and functionalized nano particles. The idea of suspending these nano particles in a base liquid for improving thermal conductivity has been proposed recently. Such suspension of nano particles in a base fluid is called a nano fluid. Due to their small size, nano particles fluidize easily inside the base fluid, and as a consequence, clogging of channels and erosion in channel walls are no longer a problem. In this experiment Cuo nano fluid is prepared with two step method and suspended by Ultrasonic homogenization as shown in Figure 2.

Figure 2: Preparation Cuo Nano Fluid

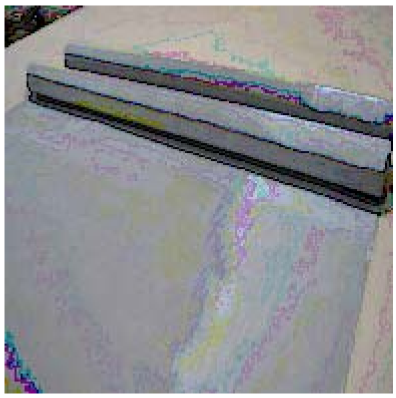
Advantages of Heat Pipe

1. Large quantities of heat can be moved with a small temperature drop.
2. The heat pipe is relatively light in weight.
3. It is mechanically simple and has no moving parts.
4. It does not require any power source to perform its function.

Capillary Wick Structure

The wick provides a means for the flow of liquid from the condenser to the evaporator section of the heat pipe. It also provides surface pores that are required at the liquid-vapor interface for development of the required capillary pressure. The wick structure as shown in Figure 3 also has an impact on the radial temperature drop at the evaporator end between the inner heat pipe surface and the liquid-vapor surface. Thus, an effective wick requires large internal pores in a direction normal to the heat flow path. This will minimize liquid flow resistance. In addition, small surface pores are required for the development of high capillary pressure and a highly conductive heat flow path for minimization of the radial surface to liquid-vapor surface temperature drop.

Figure 3: Screen Mesh Wick



Applications of Heat Pipe

1. Electronics cooling like CPU, Laptop, etc.
2. Die casting and injection molding.
3. Ventilation heat recovery and other energy conserving uses.
4. Nuclear power conversion.
5. Solar thermal conversion used to cool the solar collectors.
6. Medical field, Cooking and space craft's, etc.

Response Surface Methodology

According to Myers and Montgomery RSM is a "collection of stastical and mathematical techniques useful for developing and optimizing processes". Response Surface Methodology is useful for developing, improving, and optimizing the response variable.

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 nano fluid 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, HT Coefficient and thermal resistance of heat pipe using response surface methodology. Table 1 shows the process parameters and their levels.

Table 1: Process Parameters of Heat pipe

Parameters	Level		
	-1	0	1
A. Heat Input, W	30	60	90
B. Angle of Inclination, deg	0	30	60
C. Concentration of Nano particle, mg/lit	30	80	130

EXPERIMENTAL STUDIES AND PROCEDURE

The schematic diagram and photographic view of the experimental setup is shown in Figures 4 and 5 respectively. The brief description of various measuring instruments and the specifications of the heat pipe are given in Table 2 and 3 respectively.

Below procedure is followed to conduct experiments.

1. The cylindrical heat pipe is charged with 20 mL of working fluid, which approximately corresponds to the amount, required filling the evaporator. The distance between the evaporator and the condenser is normally called as the adiabatic section
2. The wall temperature distribution of the cylindrical heat pipe in adiabatic zone is measured using two thermocouples.
3. The adiabatic section of the heat pipe is completely insulated with the glass wool and asbestos rope. The amount of heat loss from the evaporator and condenser surface is negligible.
4. The electrical power input is applied at the evaporator section using resistance wire heater wounded to it with proper electrical insulation and the heater is energized with 230 V AC supply and measured using a voltmeter and ammeter connected in parallel and series connections respectively. Variac is connected to the resistance wire heater to control and vary the AC supply according to our required input power.
5. In order to measure the average temperature of the evaporator one thermocouple is placed along the length of evaporator.

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Figure 4: Schematic Diagram of Heat Pipe

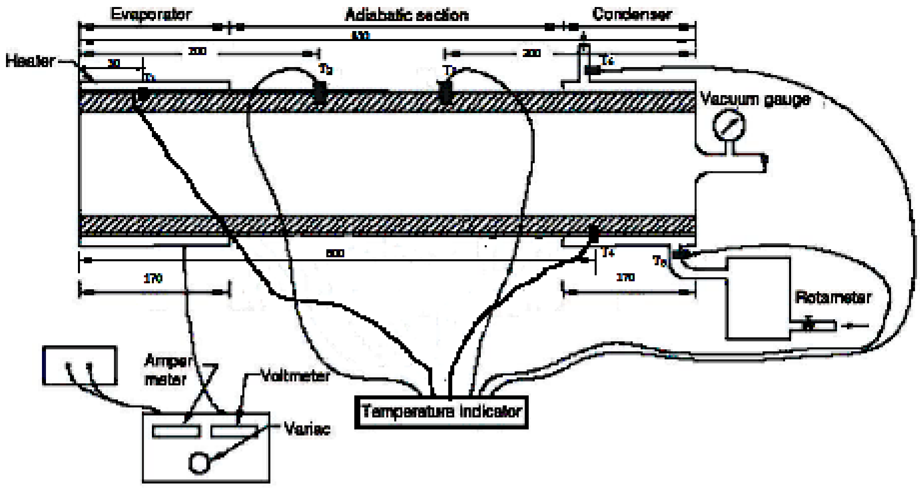


Figure 5: Photographic View of Heat Pipe

6. Water jacket has been 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, 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.

7. The condenser section of the heat pipe is cooled using water flow through a jacket made with UPVC. The water flow rate is measured using a rotameter on the inlet line to the jacket, the flow rate is kept constant

at 0.231 lpm, to measure the average temperature of the condenser, and one thermocouple is placed along the length of condenser.

8. The inlet and outlet temperatures of the cooling water are measured using two thermocouples. Totally 27 experiments are conducted using three identical heat pipes which are manufactured as per mentioned dimensions. One of the heat pipes is filled with 30 mg/L concentration of CuO nano particles, second one with 80 mg/L Cuo nano fluid, third one with 130 mg/L Cuo nano fluid.

9. The power input to the heat pipe is gradually raised to the desired power level. The surface temperatures at different locations along the adiabatic section of heat pipe are measured at regular time intervals until the heat pipe reaches the steady state condition. Simultaneously the evaporator wall temperature, condenser wall temperature, water inlet and outlet temperatures in the condenser zone are measured.

10. 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.

11. The steady state condition is defined as a state in which the variation of temperature is within 1p C for 10 min. Then the power is increased to the next level and the heat pipe is tested for its performance.

12. The same Experimental procedure is repeated for next 26 experiments obtained according to the RSM three factorial method employed.

RESULTS AND DISCUSSION

The computed values of the thermal resistance, heat transfer coefficient 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, heat transfer coefficient 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 Tables 4, 5 and 6 shows the analysis of variance

Table 2: The Brief Description of Various Measuring Instruments

S.No.	Instruments	Capacity	Quantity
1	Resistance wire heater	300 W	1
2	Ammeter	0-2 A	1
3	Voltmeter	0-250 V	1
4	Digital Temp. indicator	400 ^{o}c	1
5	Variable Auto transformer	8 A	1
6	Thermocouple(K-Type)	700 ^{o}c	6

Table 3: Technical Specifications of Heat Pipe

S.No	Parameters	Specifications
1	Heat pipe material	Copper
2	Total length of pipe, mm	650
3	Outer diameter of the pipe, mm	12.5
4	Inner diameter of the pipe, mm	11.06
5	Thickness of Copper tube, mm	0.72
6	Evaporator length, mm	170
7	Adiabatic length, mm	310
8	Condenser length, mm	170
9	Condenser outer diameter, mm	32
10	Condenser inner diameter, mm	28
11	Cooling Jacket	U-PVC pipe
12	Working fluid	Copper Oxide nano fluid
13	Color and appearance of nano particle	Black powder
14	Cuo Nano particle size, nm	20-50
15	Quantity of working fluid, ml	16.5
16	Wick material	Stainless steel
17	No of layers of Wick	2
18	Screen Mesh Size 1st layer	200
19	Screen Mesh Size 2nd layer	300
20	Screen Mesh Wire diameter, mm	0.08
21	Quantity of cooling water lpm	0.231
22	Insulating material	Glass wool

(ANNOVA) for thermal resistance, heat transfer coefficient 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 0.9682 is reasonable agreement with "Adj R-Squared" of 0.9819. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Here the ratio of 44.748 indicates an adequate

Table 4: The ANNOVA Analysis for Thermal Resistance

Use your mouse to right click on individual cells for definitions.

Response 1 thermal resistance

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	12.79	9	1.42	71.33	< 0.0001
A-heat input	10.24	1	10.24	513.94	< 0.0001
B-angle of inclination	1.20	1	1.20	59.99	< 0.0001
C-concentration of nano particle	[illegible]	1	0.57	28.64	< 0.0001
AB	0.26	1	0.26	13.21	0.0020
AC	0.11	1	0.11	5.56	0.0303
BC	0.073	1	0.073	3.64	0.0735
A²	0.26	1	0.26	13.11	0.0021
B²	1.372E-003	1	1.372E-003	0.069	0.7961
C²	0.076	1	0.076	3.82	0.0672
Residual	0.34	17	0.020		
Cor Total	13.13	26			

R- Squared	0.972	Pred R- Squrd	0.9328
Adj R-Squrd	0.9605	Adeq Precision	27.7051

Table 5: The ANNOVA Analysis for H T Coefficient

Use your mouse to right click on individual cells for definitions.

Response 2 evaporator h.t coefficient

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.538E+006	9	1.709E+005	287.24	<0.0001	significant
A-heat input	3.985E+005	1	3.985E+005	668.75	<0.0001	
B-angle of inclination	34294.58	1	34294.58	57.64	<0.0001	
C-concentration of nano particle	[illegible]	1	8.644E+005	1452.69	<0.0001	
AB	1094.66	1	1094.66	1.84	0.1927	
AC	1.038E+005	1	1.038E+005	174.55	<0.0001	
BC	3915.44	1	3915.44	6.58	0.0201	
A²	185.76	1	185.76	0.31	0.5836	
B²	350.56	1	350.56	0.59	0.4532	
C²	1.314E+005	1	1.314E+005	220.93	<0.0001	
Residual	10113.94	17	594.94			
Cor Total	1.548E+006	26				

R Squrd	0.99436	Pred R squrd	0.98334
Adj R Squrd	0.99008	Adeq Precision	58.1443

signal. Based on the ANNOVA, the following empirical relation is developed to predict the thermal efficiency of the heat pipe.

Thermal Efficiency = 34.68993 + 11.476A + 5.3015 B - 3.35989 C - 0.5635 AB - 0.78902 AC – 0.8575 BC - 0.77178 A^2 + 0.721389 B^2 + 0.570222 C^2.

Table 6: The ANNOVA Analysis for Thermal Efficiency

Use your mouse to right click on individual cells for definitions.

Response 3 efficiency

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3108.28	9	345.36	157.90	<0.0001	significant
A-heat input	2370.57	1	2370.57	1083.43	<0.0001	
B-angle of inclination	505.91	1	505.91	231.30	<0.0001	
C-concentration of nano particle	[illegible]	1	203.34	92.90	<0.0001	
AB	3.81	1	3.81	1.74	0.2044	
AC	7.32	1	7.32	3.35	0.0850	
BC	8.82	1	8.82	4.03	0.0607	
A²	3.57	1	3.57	1.63	0.2183	
B²	3.12	1	3.12	1.43	0.2486	
C²	1.95	1	1.95	0.89	0.3592	
Residual	37.18	17	2.19			
Cor Total	3145.46	26				

R Squrd	0.98817	Pred R Squrd	0.968205
Adj R Squrd	0.98192	Adeq Precision	44.7473

Similarly, the "Pred R Squared" value of 0.9328 is in reasonable agreement with "Adj. R-Squared" of 0.9605. The ratio of adequate signal is 27.705. The empirical equation for thermal resistance is given as,

Thermal Resistance = 1.879809 - 0.75433 A - 0.25771 B +0.17807 C + 0.148142 AB + 0.096283 AC - 0.07775 BC + 0.208646 A^2 + 0.015124 B^2 - 0.11268C^2.

Similarly, the "Pred R Squared" value of 0.9833 is in reasonable agreement with "Adj R-Squared" of 0.9900. The ratio of adequate signal is 58.145. The empirical equation for H.T. Coefficient is given as, H.T. Coefficient = 238.8046 + 148.7837 A + 43.64922 B - 219.145 C + 9.551 AB – 93.0265 AC – 18.0634 BC – 5.56422 A^2 + 7.643778 B^2 + 148.0073 C^2.

The Figures 6, 7 and 8 show the normal plot of residuals, which indicates that errors in the experiments are normally distributed for thermal efficiency, thermal resistance and HT Coefficient

Figure 6: Variations of Experimental and Predicted Values of Thermal Efficiency

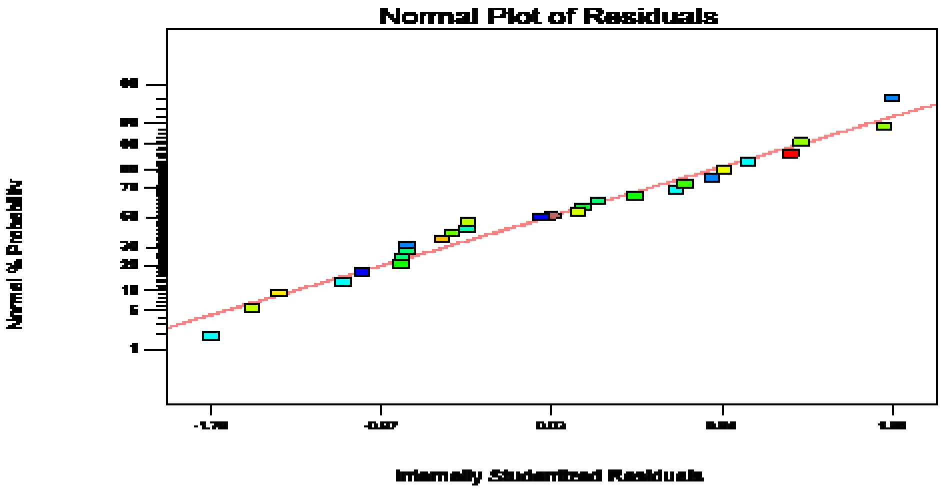


Figure 7: Variations of Experimental and Predicted Values of Thermal Resistance

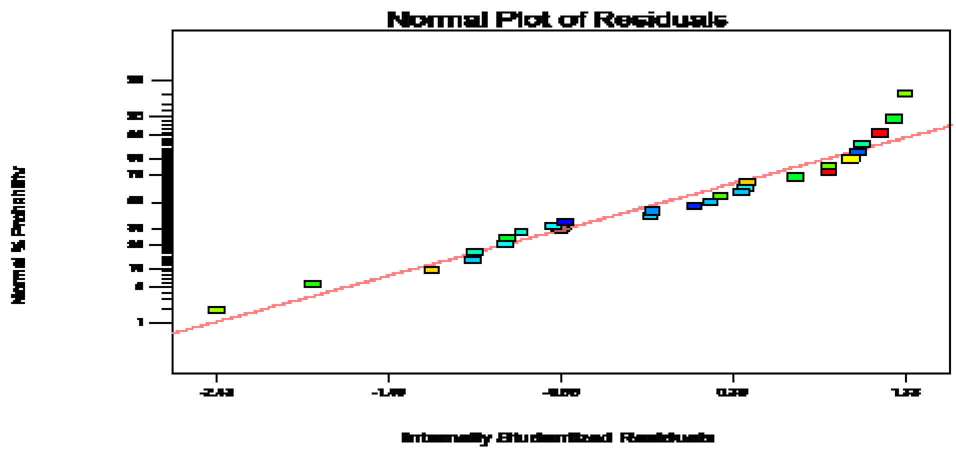
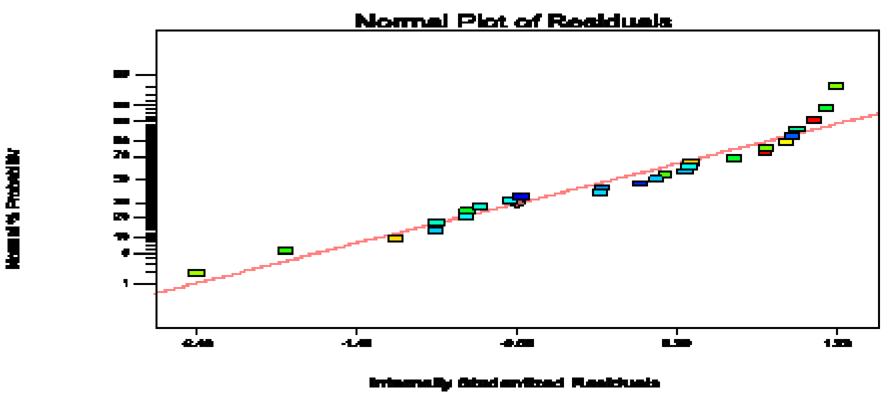


Figure 8: Variations of Experimental and Predicted Values of H T Coefficient



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. The working fluid in this analysis is copper nano fluid. The base fluid used in the copper nano fluid is DI water.

It is observed from Figures 9 to 11 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 vapor moves vigorosly 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.

Figure 9: Effect of Concentration and Angle of Inclination on Thermal Efficiency

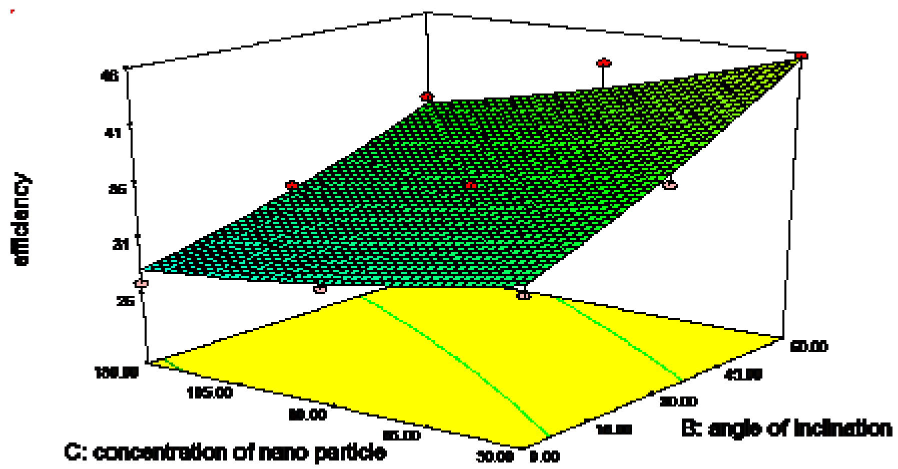


Figure 10: Effect of Heat Input And Angle of Inclination on Thermal Efficiency

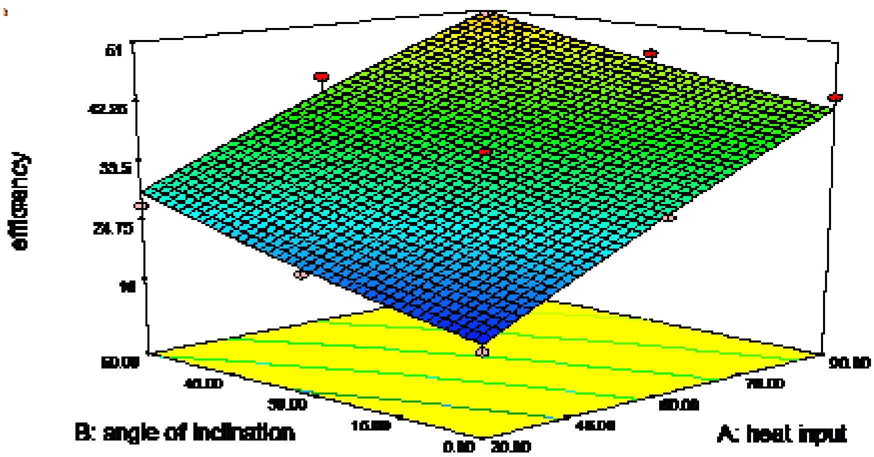
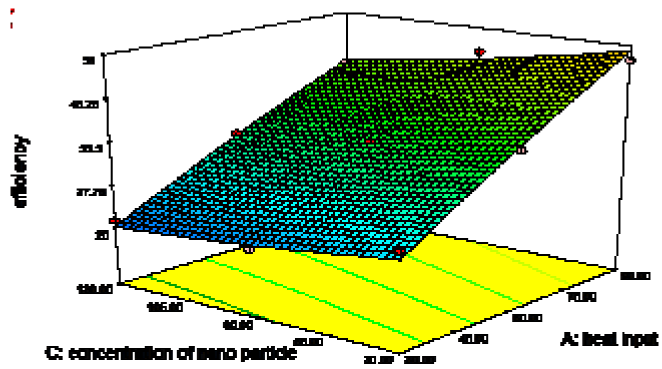


Figure 11: Effect of Concentration and Heat Input on Thermal Efficiency



It is observed from Figures 12 to 14 that the H.T. coefficient of heat pipe increases linearly with an increase the heat input in the evaporator section and angle of inclination. The H.T. Coefficient 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 vapor moves vigorously into the condenser section.

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 Figures 15-17, 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 30^o to 60^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 nano fluids is not due to the thermo physical properties of nano fluids but it is owing to the thin porous coating layer formed by nano particles in the evaporation region. Besides, the coating layer formed by nano particles improves the surface wettability by reducing the contact angle and increasing the surface

Figure 12: Effect of Concentration and Heat Input on H T Coefficient

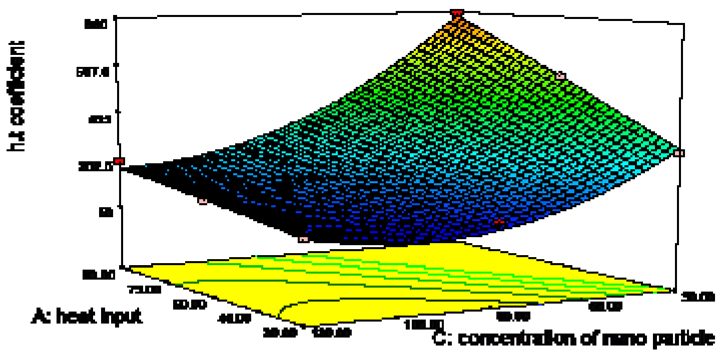


Figure 13: Effect of Concentration and Angle of Inclination on H T Coefficient

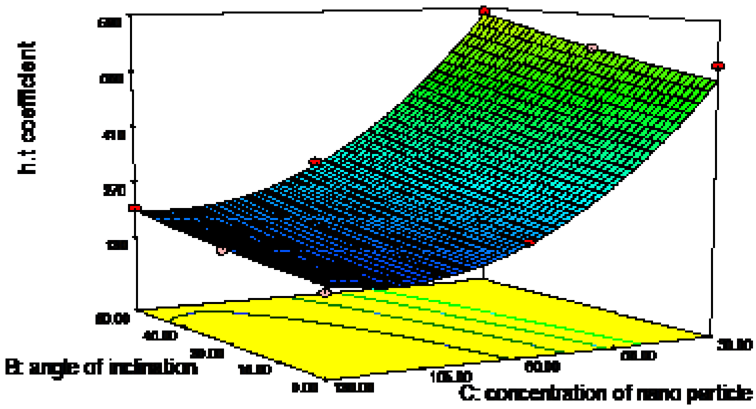


Figure 14: Effect of Angle of Inclination and Heat Input on H T Coefficient

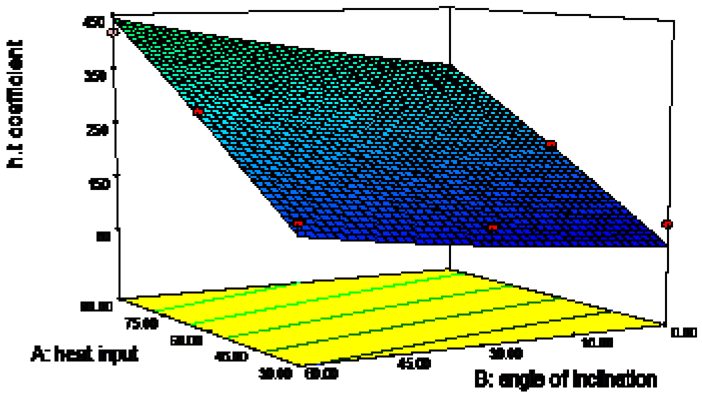


Figure 15: Effect of Heat Input and Concentration on Thermal Resistance

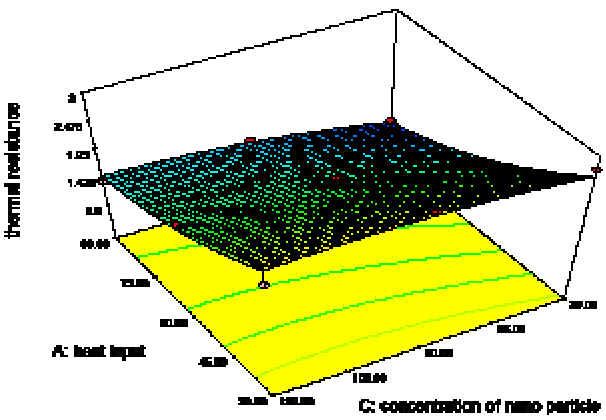


Figure 16: Effect of Heat Input and Angle of Inclination on Thermal Resistance

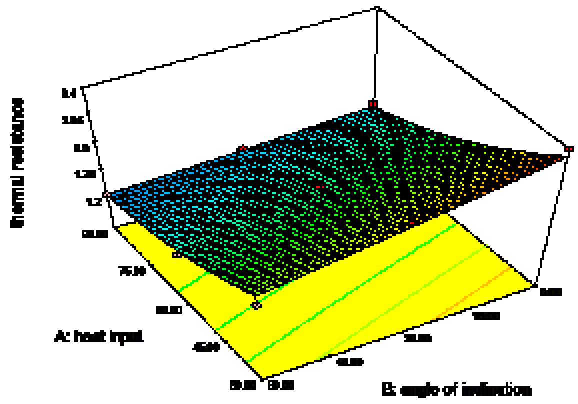
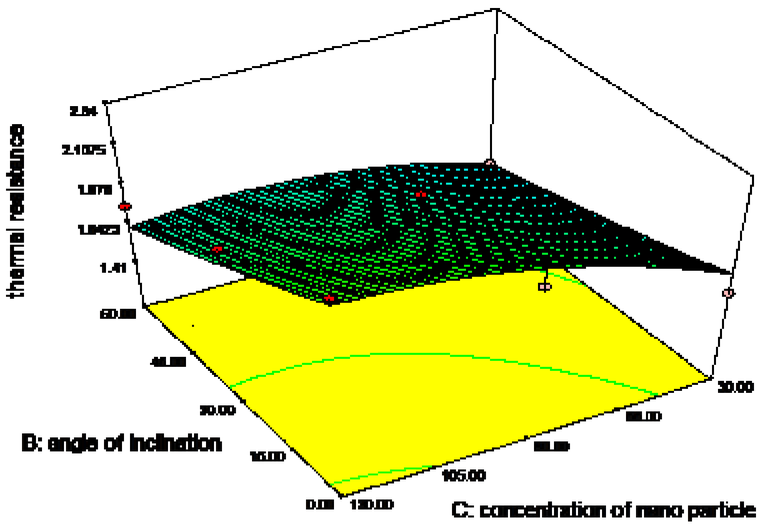


Figure 17: Effect of Concentration and Angle of Inclination on Thermal Resistance



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 nano fluids.

Confirmation Experiments

The Figure 18 shows the optimization plot generated by the RSM with a desirability of 0.978. It shows that the optimum value of the thermal efficiency is 56.4221%, H.T. Coefficient is 921.11 W/m^2k and thermal resistance is 0.930393 K/W when the heat input is 90 W, at 60^o inclination, and concentration of CuO is 30 mg/L. In order to confirm the optimization results, the experiment is conducted with 90 W heat input at 60^o inclination of the heat pipe with a concentration 30 mg/L. The thermal efficiency of the heat pipe is found as 56.7956%, H.T. Coefficient is 928.0565 W/m^2k the thermal resistance is 0.940651 K/W which is nearer to the optimum value.

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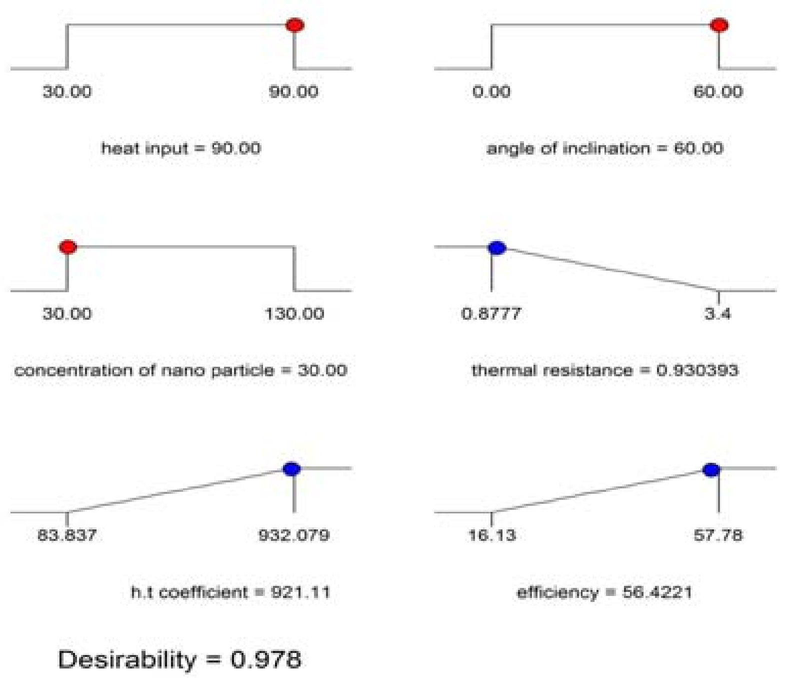
Figure 18: Optimization Plot



CONCLUSION

In this study, the thermal efficiency, H.T. Coefficient and thermal resistance of the heat pipe are optimized by Response Surface Methodology. 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 56.7956%, H.T. Coefficient is 928.0565 W/m^{2}k and thermal resistance is 0.940651 K/W.

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