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Research Article

Thermal performance analysis of heat pipe using response surface methdology

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ABSTRACT

Heat pipes are the specific class of heat exchangers. They are used in thermal management of electronic components. Research community is continuously working to obtain the optimum heat transfer performance. In present work, parametric study of heat pipe using nano- fluid has been carried out. The operating parameters of heat pipe like power supply, orientation (gravity assisted angle), filling- ratio, and nano-fluids concentration are being investigated to find the optimum thermal performance of heat pipe. Response surface method (RSM) is used to analyze the effect of operating parameters on thermal performance. The optimum value of thermal resistance and thermal efficiency are 0.3994 °C/Watt and 68.44% respectively. Most suitable power supply, inclination angle, filling ratio and nanofluid concentration are 185.85 W, 60.09°, 50.7% and 1.05 % respectively. The experimental results confirm and validate the RSM predicted results.

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INTRODUCTION

Heat Pipes (HPs) are the specific class of the heat exchangers. They are widely used in electronics cooling, spacecrafts, energy conservation, snow melting-deicing, energy storage, solar-thermal applications, cooling of gas turbine blades and domestic warm air heaters (USA). HP works on phase change phenomenon. Heat supplied to the evaporator section is used to vaporize the working fluid. Vapors of the working fluid move towards condenser section (due to pressure difference) and finally gets condensed after rejecting heat to the cooling media of the condenser section. Now condensed liquid comes back towards the evaporator section through mesh wick structure [1] There are various operating limitations of heat pipes like sonic limit, entrainment limit, capillary limit, boiling limit and viscous limit [1]. Operating limitations are considered in design stage for the successful working of HP in varying and prolonged working conditions. Selection of operating parameters like heat load, orientation, volume, type of

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working fluid and vacuum pressure, depend on operating limitations.

Figure 1 shows the various design/operating parameters considered by researchers in last 10 years. Researchers are already working on design parameters like shapes of HP [2] and mesh type [3][4][5] from last many years. Researchers noticed the superior thermophysical properties of nanofluids [6]. Superior thermo-physical properties make them futuristic class of thermofluids. Choi et al [7] introduced nano-fluid as the suspension of nanoparticles (size<100nm) in base fluids. He presented the NFs as the potential thermo-fluids for future endeavors. Thermal performance of heat pipe (TPHP) depends on the thermo-physical properties of working fluid like density, wettability, dynamic viscosity, thermal diffusivity etc. [8]. Superior thermo-physical properties of working fluids enhance the TPHP. Poplaski et al. [9] studied the TPHP using nanofluids (like Al_2O_3, CuO and TiO_2) as working fluid. Authors claimed that higher concentration of NFs reduced the convection currents, therefore, deteriorated the TPHP. In the era of nanotechnology, researchers used nanoparticles of highly conductive materials in various thermal applications in order to obtain the desired results [10]. Thermal diffusivity is the most important characteristic of NFs which plays an important role in heat transfer processes [11]. Therefore, nanoparticles of highly diffusive metals are considered to prepare NFs. Other properties like density, specific heat, surface characteristic etc. also have their own impact on thermal characteristics. Researchers have both positive and negative opinion regarding the application of NFs as working fluids in HPs. Some researchers claimed that NFs enhance the TPHP [11,12,13,14]. Qu et al [11] studied the oscillating heat pipe (OHP) using Al_2O_3-water NF.

Researchers showed that alumina NF enhanced the thermal performance of OHP. Deposited nanoparticles create convection current and improve the wettability of the evaporator surface. Qu and Wu [15] analyzed the TPHP using SiO_2/water and Al_2O_3/water NF respectively. Results showed that Al_2O_3/water NF increased the TPHP while SiO_2/water NF decreased the same. The main cause of the enhancement was the improved surface condition of HP.

Xue et al. [16] conducted an experimental study on the TPHP using carbon nanotube suspension and found significant deterioration in thermal performance. Addition of carbon nanotube, changes the solid-liquid-vapor interfacial properties, and deteriorate the boiling heat transfer rate. Das et al. [17] investigated the variation in thermal conductivity with temperature. Authors claimed that thermal conductivity of NFs depends on the size of nanoparticles. Thermal conductivity of NF increases with the decrease in size of nanoparticles. Mahdavi et al [18] studied the heat transfer characteristics of HP. Authors performed numerical as well as experimental investigations and found good agreement between the results.

Authors concluded that superior thermal conductivity of NF is the major cause of the enhancement in TPHP. The other major causes are extended surface area, reduction in bubble formations, enhanced wettability, higher conductivity of interfacial layer etc. Gupta et al [19] studied the application of CeO_2/H_2O nanofluid in HP. Authors observed good agreements between experimental and numerical data. Researchers [20] presented the review on nanofluids application in heat pipes and concluded that maximum thermal performance of heat pipe is obtained for suitable value of nanoparticles concentration.

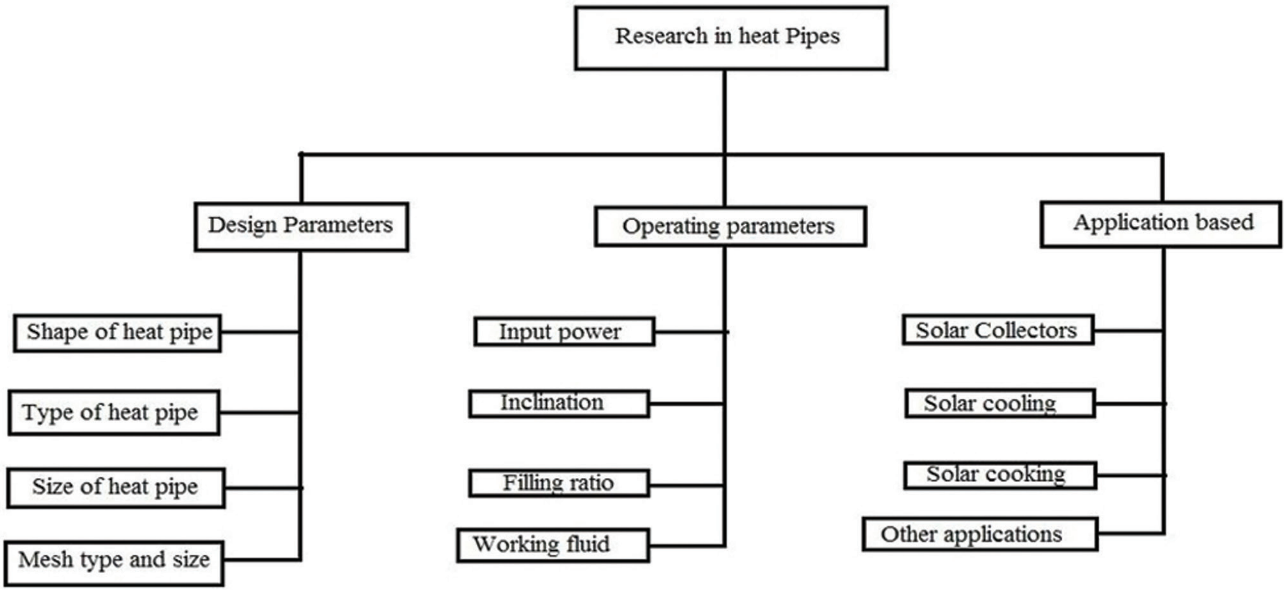


Figure 1. Progress of research on heat pipes.

Enhancement in thermal performance is obtained due to the increment in number of nucleation sites and superior thermal conductivity of nanofluids. Ahmadi et al [21] presented model for pulsating heat pipe, by applying GMDH (group method of data handling) neural network. Model predicted the value of thermal resistance and effective thermal conductivity with good accuracy. Maddah et al [22] presented numerical investigation for boiler efficiency. Researchers used response surface method to optimize the thermal efficiency for the variable mass flow rates and steam temperatures.

In recent years research is going on the effect of nanoparticles coated mesh surface on thermal performance of HP. Researchers [23] used Al_2O_3 and TiO_2 nanoparticles coated wick surface in their experimental study.

In nanofluid applications, stability plays an important role. Due to sedimentation and agglomeration of nanoparticles, thermophysical properties of nanofluids deteriorate in prolonged working conditions. Therefore, TPHP also changes [24]. In nanoparticles coating, detachment of nanoparticles from the parent surface also causes deterioration in TPHP. But this deterioration is negligible as compared to the deterioration in case of nanofluids (due to sedimentation and agglomeration of nanoparticles)[25].

In last 20 years, researchers noticed that NF applications enhance the TPHP [26],[27]. Suspended nanoparticles reduced the bubble generation rate at the solid-liquid surface and leading to the reduction in thermal resistance. In available research articles, limited research on parametric optimization has been done [28]. The Optimization work on HP using nanofluids is available in very limited cases [29].

Limited research articles focus on the basic mechanisms and physics of NF application on TPHP. Therefore, in present work authors made an attempt to analyze the thermal performance of heat pipe using Al_2O_3/water. Authors identified and highlighted the mechanism responsible for the change in thermal performance. RSM is an effective tool for optimization purpose.

METHOD AND MATERIALS

Al_2O_3 nanoparticles were purchased from Nano Research Lab (Jharkhand, India). Nanoparticles were stirred into D.I water as per the requirement. D.I water was prepared by distillation-based water purification system in chemistry lab of GLA University, Mathura (India). Mixture of D.I. water and nanoparticles were stirred for 4 hours. Table 1 show the description of nanoparticles.

There are two types of methods to prepare the NFs: single step and double step. In present study double step method was chosen to prepare the NFs. To ensure the good stability of NF, it was sonicated for 5 hours and allowed to

Table 1. Description of nanoparticles

S.N.	Nanoparticles	Description
1	Name	Aluminum Oxide Nanoparticles / Nano powder
2	Molecular formula	Al_2O_3
3	Purity	99.9%
4	Average particle size	30-50 nm
5	Color	White
6	Morphology	Spherical
7	Specific surface	> 10 m²/g,
8	Density	3970 Kg/m3
9	Specific heat capacity	525J/KgK
10	Thermal Conductivity	17.65W/mK

Figure 2. Sedimentation test for Al_2O_3/H_2O nanofluid, before and after 10 days.

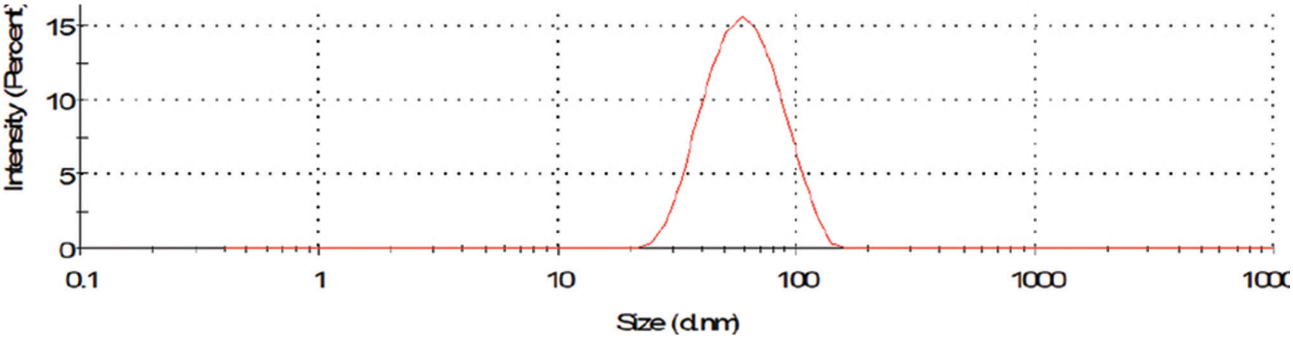


Figure 3. Size distribution of nanoparticles in nanofluid by DLS technique.

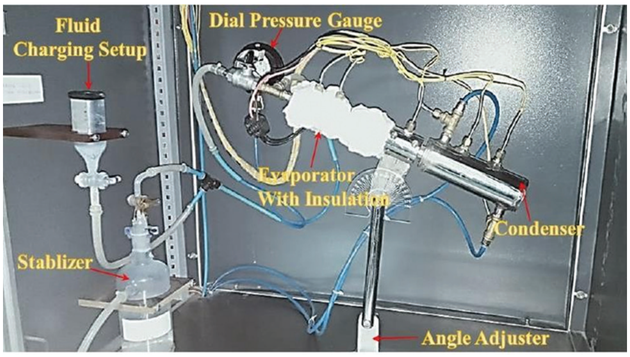


Figure 4. Experimental set-up.

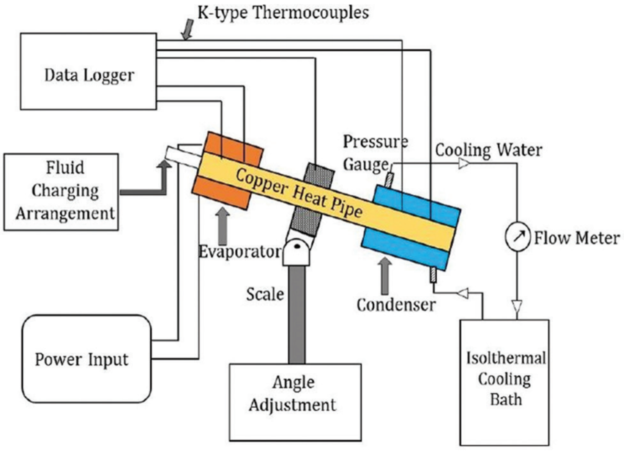


Figure 5. Schematic of the experimental setup.

settle down. Figure 2 shows the sedimentation test of nanofluid for 10 days. After 10 days no sedimentation or agglomeration was noticed. To ensure the stability, diffraction light scattering (DLS) test was performed. Figure 3 shows the DLS analysis of NF. DLS analysis shows the slight agglomeration of nanoparticles. The agglomerated size is known as secondary size of nanoparticles. Generally secondary size (Size of nanoparticle in liquid form) is higher as compared to primary size (size of nanoparticle in powdered form) due to slight agglomeration.

Experimental Setup

In present work, authors investigated the TPHP using Al_2O_3/water NF as working fluid. Figure 4 shows the experimental set up. Figure 5 shows the schematic of the experimental set up. At evaporator section, circumferential heater is used. Control switch is used to regulate the power supply. Cooling water jacket is attached at the condenser section. K-type thermocouples are attached to the wall surface of HP. For recording the temperatures, all the thermocouples are attached to data logger. Vacuum pump with stabilizer is attached to the HP. Fluid filling arrangement is also attached to the HP. Evaporator section is wrapped with glass wool to reduce the heat loss. An orientation adjustment stand is also attached to the HP. The temperature of cooling water is maintained with the help of an isothermal cooling bath. All the temperatures were recorded after achieving the steady state of the set- up. The HP details and the uncertainties involved in experimentation are shown in Table 2 & Table 3 respectively.

Uncertainty Analysis

Uncertainty analysis is an inevitable step of the experimental studies and it provides the assurance of experimental results. Assessment of uncertainty involve the systematic analysis of all kinds of errors related to measuring instruments and procedures also. Moffat R.J. [30] described the detailed and structured procedure to analyze the uncertainty. The uncertainties concerned to heat supply, thermal resistance and thermal efficiency were evaluated according to the following relations.

$$\frac{\Delta Q}{Q}=\left[\left(\frac{\Delta V}{V}\right)^2+\left(\frac{\Delta I}{I}\right)^2\right]^{1/2} \tag{1}$$

$$\frac{\Delta q}{q}=\left[\left(\frac{\Delta Q}{Q}\right)^2+\left(\frac{\Delta A}{A}\right)^2\right]^{1/2} \tag{2}$$

$$\frac{\Delta R}{R}=\left[\left(\frac{\Delta Q}{Q}\right)^2+\left(\frac{\Delta T}{T}\right)^2\right]^{1/2} \tag{3}$$

The uncertainty associated with evaporator section was 3.7%. The uncertainty present in the measurement of heat loss was 4.1%. Uncertainty in heat supply, TRHP and TEHP were 3.5%, 3.87% and 4.1% respectively.

Governing Equations

For evaporator and condenser sections, thermal resistance is evaluated by the following expressions [31]:

$$\text{The total TRHP (R)} = (TE - TC)/Qout \tag{4}$$

The Overall thermal conductivity (effective) of HP is evaluated by the following relation:

$$Keff = Leff / (AxR) \tag{5}$$

$$Leff = Le/2 + La + Lc / 2 \tag{6}$$

Table 2. Details of Heat pipe

S.N.	Component Name	Material (Dimensions in mm)
1	Wick material	Copper
2	Wick type	Wire mesh
3	Mesh per inch	40
4	Number of strands/ inches	250
5	Number of multiple layers of similar screen mesh	4
6	Porosity	0.46
8	Wire diameter (mm)	0.036
9	Heat Pipe	Length=550, ID=18, OD=21
10	Material	Copper
10	Evaporator section	100
11	Condenser Section	200
12	Adiabatic Section	250
13	Thermocouples	12 K- type and 4T-type

The thermal efficiency of HP is expressed as:

$$\eta = MC(T2-T1)/VI \tag{7}$$

RSM Methdology

RSM mathematical modelling is used to determine the optimum results of any real-life application. RSM is used to find the most suitable combination of operating parameters to obtain the optimum results after performing minimum number of experiments. In present work, RSM architecture has four factors and five level for each. Heating power, orientation, filling ratio and nano fluid concentrations are treated as input parameters. The thermal resistance and thermal efficiency of HP are considered as the system responses. Table 4 shows the values of various factors and their levels considered in present study. Table 5 show the experimental results according to the CCRD structure.

According to architecture matrix, experiments were conducted. Analysis of variance (ANOVA) for the above experimentation work provided the quantitative results for the p-value. Null hypothesis was rejected on the basis of p-value. The maximum acceptable p-value was 0.05. S values ensure the feasibility of the RSM model. For the above case S values were 0.565 and 3.451 respectively. R2 values were 97.35% and 96.35% respectively. R2 (adj) values were 96.23% and 96.6%.

RESULT AND DISCUSSION

Effects of Operating Parameters on Thermal Resistance

The effects of operating parameters on thermal resistance of heat pipe (TRHP) are shown in Figure 6 (a-h). The

Table 3. Measurements related uncertainties

S.N.	Parameters	Uncertainties
1	Mass flow rate of cooling water	0.97%
2	Voltage supply	0.81%
3	Current supply	0.38%
4	Vacuum pressure	0.87%
5	Wall temperature of HP	1.1°C
6	Volume of working fluid	1.7%
7	Orientation of HP	0.45%

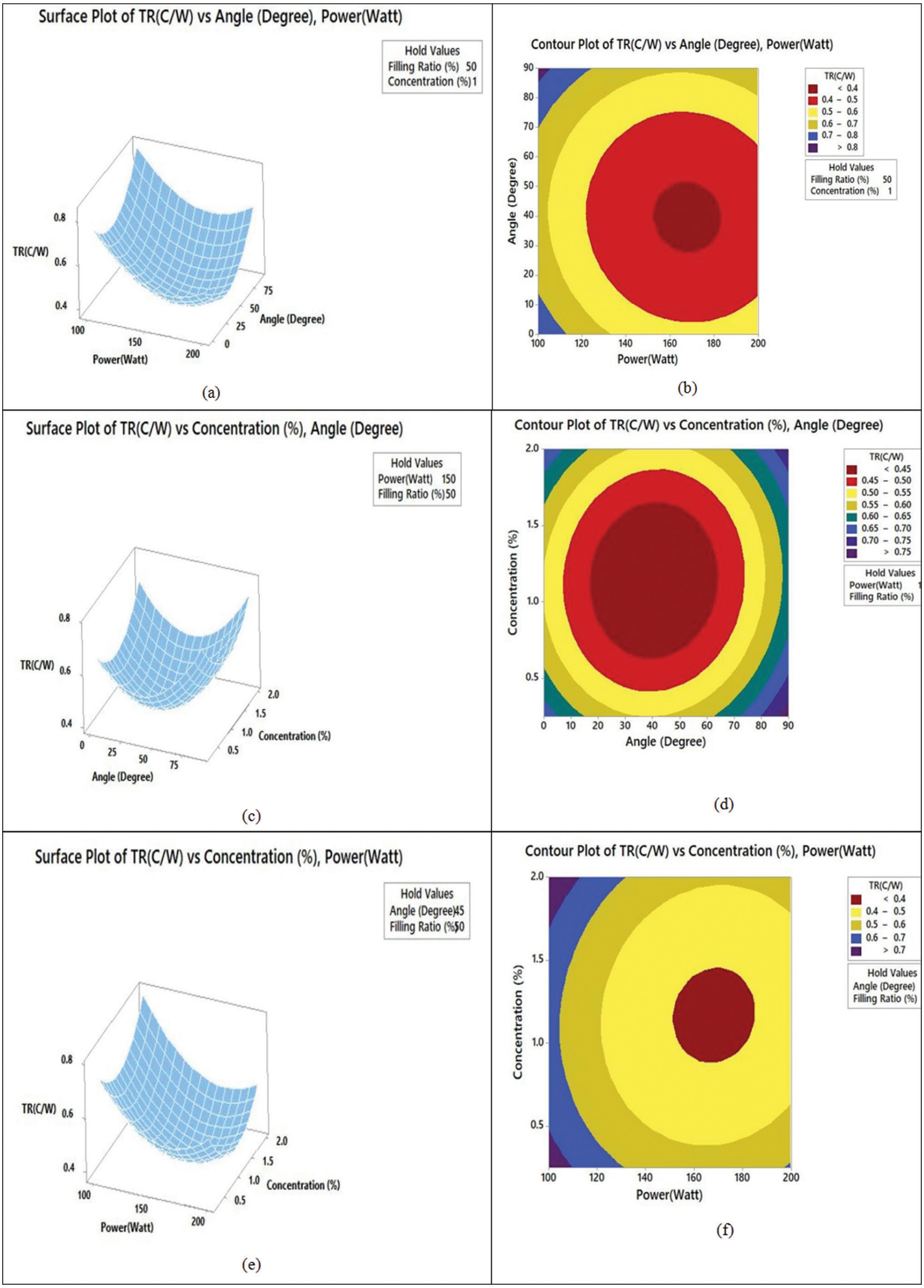
Table 4. Coded stages

System inputs	Coded Stages				
	-2	-1	0	1	2
Power Input (W)	100	125	150	175	200
Inclination angle (°)	0	30	45	60	90
Filling ratio (%)	40	45	50	55	60
Nanofluid concentration (wt.%)	0.25	0.50	1.0	1.50	2.0

Table 5. Experimental design matrix

S.N.	Power (Watt)	Angle (°)	Filling ratio (%)	Concentration (%)	TR (°C/Watt)	TE (%)
1	175	60	55	1.50	0.46	61.5
2	200	45	50	1.0	0.45	60
3	200	45	50	1.0	0.455	60.5
4	200	45	60	1.0	0.42	57
5	175	30	55	0.50	0.465	59
6	125	30	55	0.50	0.58	60
7	175	60	55	0.50	0.50	58.5
8	125	30	45	1.50	0.53	57
9	125	30	55	0.50	0.57	65
10	200	45	50	0.25	0.45	63.3
11	200	45	50	1.0	0.46	60
12	200	45	40	1.0	0.50	65
13	125	60	45	1.50	0.47	62.5
14	200	45	50	1.0	0.41	60
15	200	45	50	2.0	0.44	59
16	175	60	45	0.50	0.48	64
17	125	60	55	1.50	0.47	61.5
18	100	45	50	1.0	0.46	62
19	125	60	55	0.50	0.48	60
20	200	0	50	1.0	0.47	64
21	200	90	50	1.0	0.46	65
22	125	30	55	1.50	0.44	62.4
23	200	45	50	1.0	0.45	61.8
24	200	45	50	1.0	0.46	62.5
25	175	30	45	1.50	0.43	61
26	175	60	45	1.50	0.425	63.5
27	175	30	55	1.50	0.41	62
28	125	60	45	0.50	0.47	63.5
29	200	45	50	1.0	0.46	60.8
30	175	30	45	0.50	0.47	63.5
31	200	45	50	1.0	0.40	64

TRHP depends on evaporator and conduction thermal resistances. Figure 6 (a) shows the dependence of TRHP on the increase in power and inclination angle (other parameters remain constant). Fig. 6(a) shows that the TR is inversely proportional to the power from 100Watt to 185 Watt, after that it depends directly on the power supply (up to 200 Watt). The Brownian motion of the suspended nanoparticles depend directly on the power input. The thermal conductivity of NF is the function of temperature. The TRHP decreases up to the most favorable inclination angle (i.e. 60° angle) after that it increases. TRHP is determined on the basis of the wall temperature.


Surface Plot of TR(C/W) vs Angle (Degree), Power(Watt)
Hold Values
Filling Ratio (%) 50
Concentration (%) 1
TR(C/W)
0.8
0.6
0.4
100
150
200
Power(Watt)
0
25
50
75
Angle (Degree)
(a)
Contour Plot of TR(C/W) vs Angle (Degree), Power(Watt)
Angle (Degree)
0
10
20
30
40
50
60
70
80
90
100
120
140
160
180
200
Power(Watt)
TR(C/W)
< 0.4
0.4 – 0.5
0.5 – 0.6
0.6 – 0.7
0.7 – 0.8
> 0.8
Hold Values
Filling Ratio (%) 50
Concentration (%) 1
(b)
Surface Plot of TR(C/W) vs Concentration (%), Angle (Degree)
Hold Values
Power(Watt) 150
Filling Ratio (%) 50
TR(C/W)
0.8
0.6
0.4
0
25
50
75
Angle (Degree)
0.5
1.0
1.5
2.0
Concentration (%)
(c)
Contour Plot of TR(C/W) vs Concentration (%), Angle (Degree)
Concentration (%)
0.5
1.0
1.5
2.0
0
10
20
30
40
50
60
70
80
90
Angle (Degree)
TR(C/W)
< 0.45
0.45 – 0.50
0.50 – 0.55
0.55 – 0.60
0.60 – 0.65
0.65 – 0.70
0.70 – 0.75
> 0.75
Hold Values
Power(Watt)
Filling Ratio (%)
(d)
Surface Plot of TR(C/W) vs Concentration (%), Power(Watt)
Hold Values
Angle (Degree) 45
Filling Ratio (%) 50
TR(C/W)
0.8
0.6
0.4
100
150
200
Power(Watt)
0.5
1.0
1.5
2.0
Concentration (%)
(e)
Contour Plot of TR(C/W) vs Concentration (%), Power(Watt)
Concentration (%)
0.5
1.0
1.5
2.0
100
120
140
160
180
200
Power(Watt)
TR(C/W)
< 0.4
0.4 – 0.5
0.5 – 0.6
0.6 – 0.7
> 0.7
Hold Values
Angle (Degree)
Filling Ratio (%)
(f)

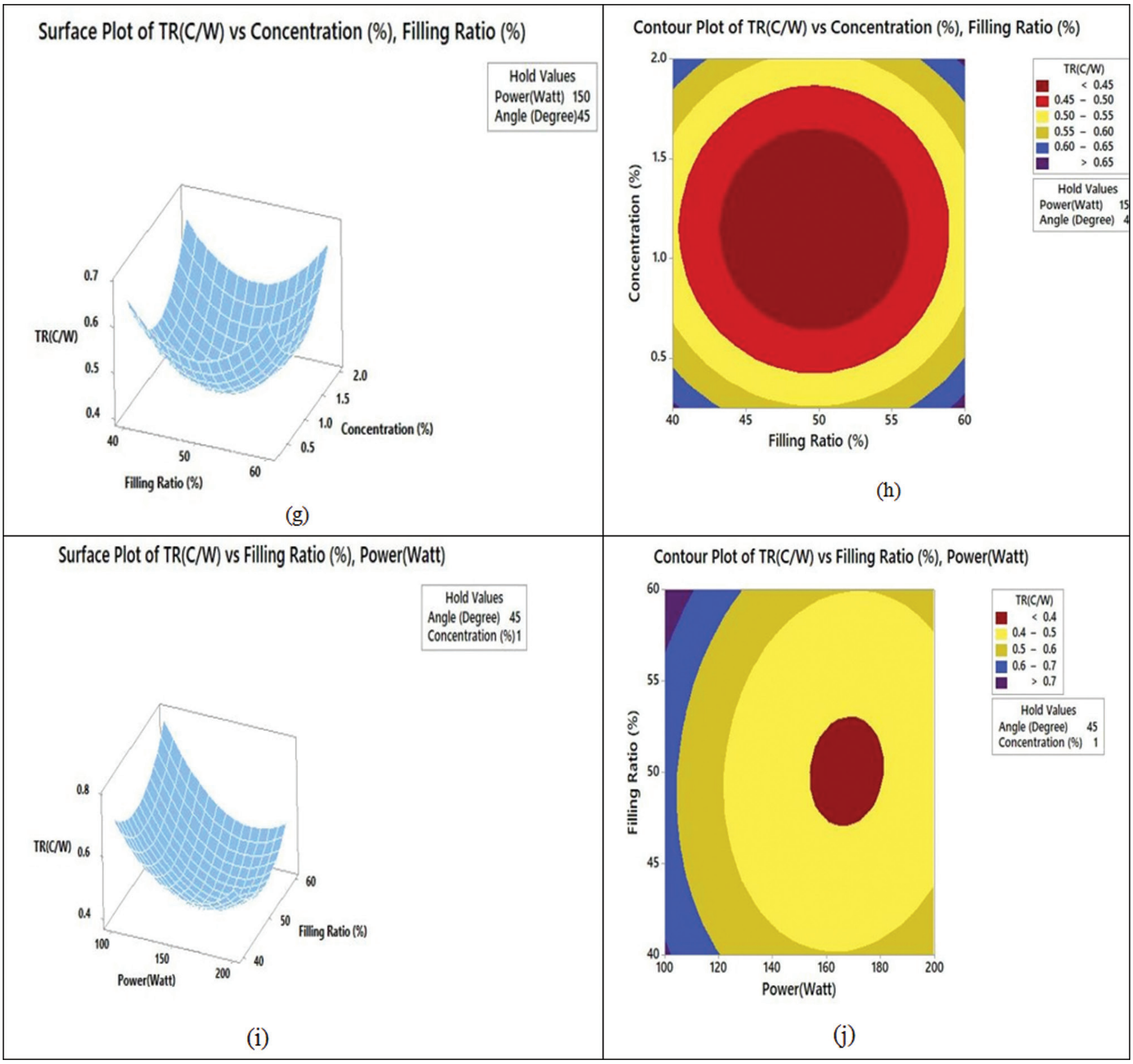


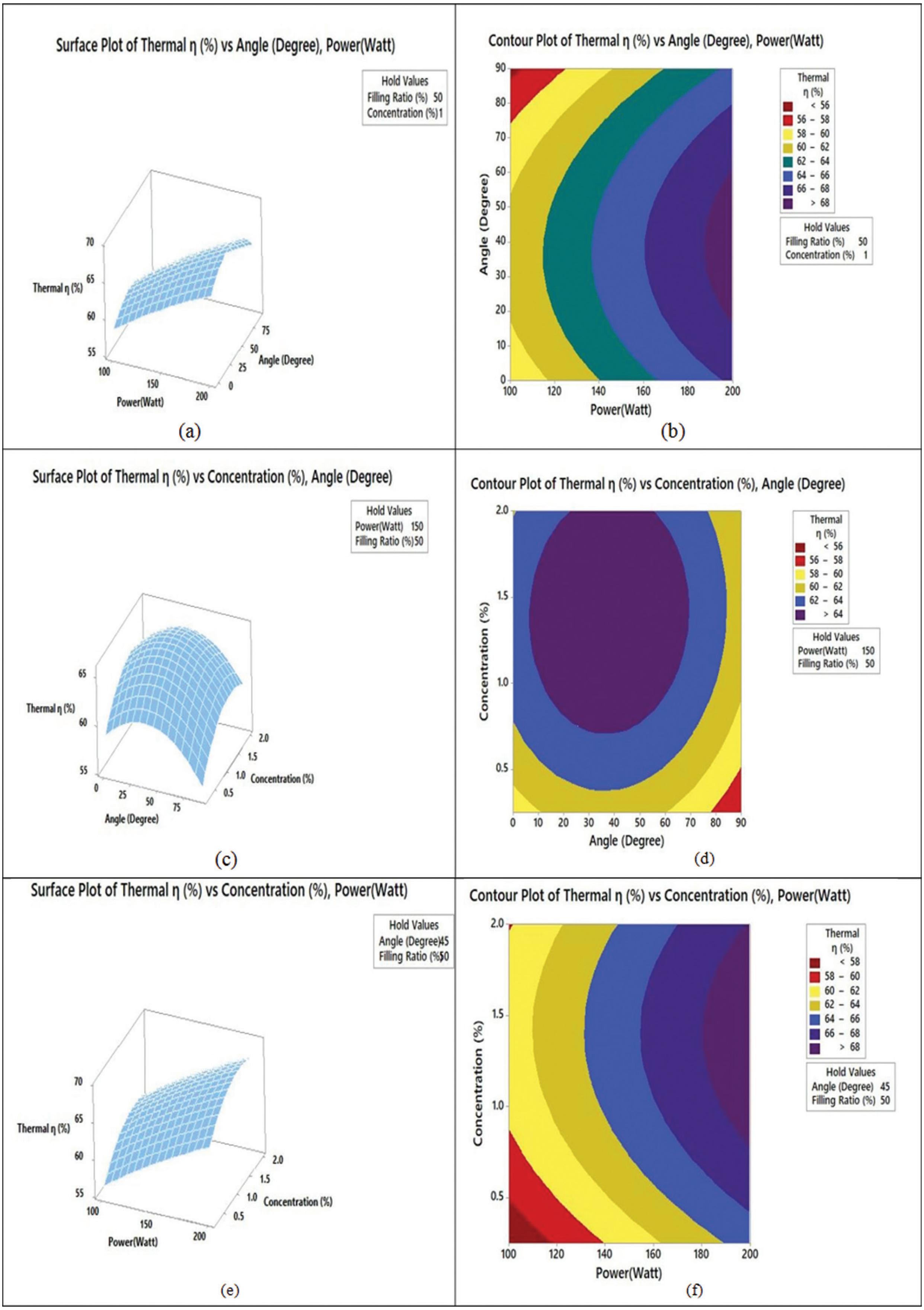
Figure 6. Parametric analysis for thermal resistance.

Figure 6 (b) shows that the most favorable power supply and inclination angle are 185 Watt and 60° respectively for the minimum TR (less than 0.4°C/Watt). Figure 6 (c) displays the trend of TR for various inclination angles and concentrations. Orientation of HP has more impact on TR, minimum TR was found at 60° angle. TR continuously decreased initially with concentration and after 1.0%, increased slightly. Figure 6(d) shows that minimum TR (less than 0.4°C/Watt) was noticed at inclination angle of 60o and nanofluid concentration of 1.0 %. Figure 6(e) and 6(f) shows the change in TR with the change in concentration and power. TRHP decreases with the increase in power and concentration. Most suitable power and concentration depend on various parameters like thermophysical properties of NF, deposition of nanoparticles, interfacial layers, micro convection currents etc.

Figure 6(g) and 6(h) shows the change in TR with the change in concentration and filling ratio. Filling ratio of HP is also an important operating parameter. Filling ratio of HP decides the effective length of HP. Excess filling ratio reduces the effective length while lower filling ratio reduces the heat transfer rate. Figure 6(i) and 6(j) shows the change in TR with the change in filling ratio and power.

Effects of Operating Parameters on Thermal Efficiency

Figure 7 (a-h) shows the variation in thermal efficiency (TE) with the increase in all four operating parameters. Figure 7 (a) shows the variation in TEHP with the increase in power and inclination angle (filling ratio and


Surface Plot of Thermal η (%) vs Angle (Degree), Power(Watt)
Hold Values
Filling Ratio (%) 50
Concentration (%) 1
Thermal η (%)
55
60
65
70
Power(Watt)
100
150
200
Angle (Degree)
0
25
50
75
Contour Plot of Thermal η (%) vs Angle (Degree), Power(Watt)
Angle (Degree)
Power(Watt)
Thermal η (%)
< 56
56 – 58
58 – 60
60 – 62
62 – 64
64 – 66
66 – 68
> 68
Hold Values
Filling Ratio (%) 50
Concentration (%) 1
Surface Plot of Thermal η (%) vs Concentration (%), Angle (Degree)
Hold Values
Power(Watt) 150
Filling Ratio (%) 50
Thermal η (%)
Angle (Degree)
Concentration (%)
Contour Plot of Thermal η (%) vs Concentration (%), Angle (Degree)
Concentration (%)
Angle (Degree)
Thermal η (%)
< 56
56 – 58
58 – 60
60 – 62
62 – 64
> 64
Hold Values
Power(Watt) 150
Filling Ratio (%) 50
Surface Plot of Thermal η (%) vs Concentration (%), Power(Watt)
Hold Values
Angle (Degree) 45
Filling Ratio (%) 50
Thermal η (%)
Power(Watt)
Concentration (%)
Contour Plot of Thermal η (%) vs Concentration (%), Power(Watt)
Concentration (%)
Power(Watt)
Thermal η (%)
< 58
58 – 60
60 – 62
62 – 64
64 – 66
66 – 68
> 68
Hold Values
Angle (Degree) 45
Filling Ratio (%) 50

(a) (b)

(c) (d)

(e) (f)

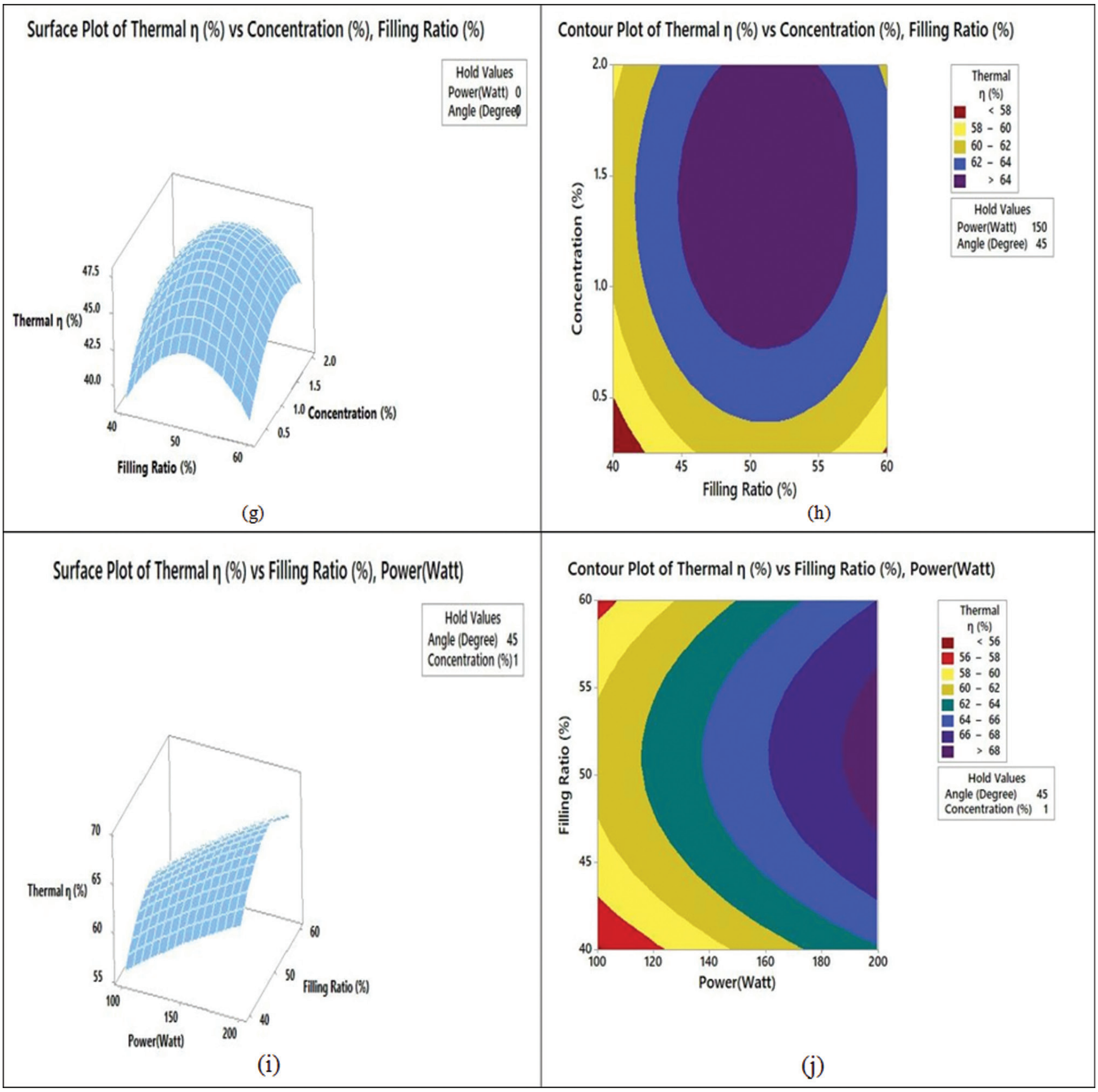


Figure 7. Parametric analysis for thermal efficiency.

concentration remains constant). Figure 7(a) shows that the TEHP increased with power from 100- 185 Watt after that it is decreased slightly up to 200-Watt. It can also be noticed that TE increases up to 60° inclination angle and beyond that TEHP decreases. The reason for variation in TE with the change in power, filling ratio, NF concentration and orientation of HP is almost similar as in the case of thermal resistance. Figure 7 (b) shows contour plot between the power and inclination angle. It was observed that maximum TE (approximately 68%) occurs at 185-Watt power and 60o inclination angle. Figure 7 (c) shows the trend of TE with inclination angle and concentration (Power and filling ratio remains constant). Inclination angles have more impact on TE. Maximum thermal efficiency was found at 60° inclination angle. TE continuously increased with the increase in concentration and after 1.0 %, it decreased. Figure 7(d) shows that maximum TE was obtained at inclination angle of 60° and with 1.0% concentration.

Figure 7 (e) and 7 (f) shows the variation in TE with the increase in concentration and power. TEHP increases with the increase in concentration. Increase in concentration of NF enhances the thermal conductivity of the entire HP. Increase in power reduces the thermal resistance of HP. Figure 7(g) and 7(h) shows the change in TEHP with the increase in concentration and filling ratio. Maximum TE was obtained at 1.0 % concentration and 50 % filling

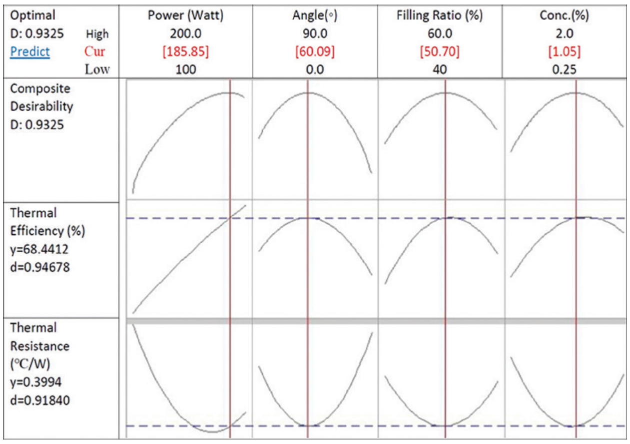


Figure 8. Optimization plots.

ratio. Figure 7(i) and 7(j) shows the change in TE with the increase in filling ratio and power.

The TPHP depends on the thermophysical properties of working fluid like thermal conductivity, viscosity, specific heat, density etc. Thermophysical properties of NFs depend on the type of nanoparticles, base fluid, concentration, temperature etc. The viscosity and density of NF increases with the increase in nanoparticles concentration. Nanoparticles deposit on the mesh surface, due to which capillary force and wettability changes. Nanoparticles also deposit on the inner surface of the heat pipe. Deposition of nanoparticles changes the wettability of the surface. The wettability of solid surface depends upon the solid-liquid contact angle, surface temperature, inclination angle and thermophysical properties of the working fluid.

RSM Optimiation

RSM tool is used to find the most suitable operating parameters to obtain the maximum TPHP. Figure 8 shows the optimization plot. In this multi-objective optimization process TE and TRHP have been maximized and minimized respectively. Figure 8 depicts the following conclusions:

- Most suitable operating parameters are as: 185.85Watt power supply, 60.09° inclination angle, 50.7% filling ratio and 1.05% nanofluid concentration.
- Maximum value of thermal efficiency which can be achieved is 68.4% with most suitable operating parameters.
- Minimum value of thermal resistance which can be achieved is 0.3994 °C/Watt with most suitable operating parameters.

Experimental Validation

Experiments were conducted to validate the RSM results. Table 6 shows the RSM predicted and experimental values for the specific working condition.

Table 6. Validation test

Response at 185.85 W Power, 60.09° inclination angle, 50.7% filling ratio and 1.05 % nanofluid concentration.			
Response	**Predicted**	**Actual**	**% Error**
TR (°C/Watt)	0.3994	0.4125	3.27
TE (%)	68.44	66.54	2.77

The % error in TR and TE are 3.27 and 2.77 respectively. The error % is within the acceptable range. Experimental results are compared with the published results [32]. Experimental results of the present work are in good agreements with the published results.

Therefore, RSM results may be considered as the optimization results of the thermal performance of heat pipe.

CONCLUSION

After conducting the experimental investigation, authors have drawn the following conclusions:

- Nanofluids have the potential to enhance the thermal performance of heat pipe. Although stability issues restricted their use in prolonged working conditions.
- The optimum value of thermal resistance and thermal efficiency are 0.3994 °C/Watt and 68.44% respectively.
- Most suitable operating parameters for the maximum thermal performance in present investigation are as: 185.85 W Power, 60.09° inclination angle, 50.7% filling ratio and 1.05 % nanofluid concentration.
- The predicted values by RSM model and experimental results validate each other.

The nanofluids application in heat pipe improves the thermal performance. It involves more numbers of factors at mini, micro and nano level. Controlling of parameters simultaneously in order to obtain the maximum possible thermal performance at the aforesaid level is a challenging task. To explore the analysis at higher level of precision, advanced statistical tools and precise equipment are need to be developed.

NOMENCLATURE

NF	Nanofluid
TR	Thermal Resistance
CCRD	Central composite rotating design
T	Wall temperature in °C
Q	Heat supplied
I	Current supply
V	Voltage
q	Heat flux
l_e	Length of evaporator section
l_a	Length of adiabatic section
l_c	Length of condenser section
HP	Heat Pipe
RSM	Response surface methodology

W	Watt
TR	Thermal Resistance (°C/W)
TPHP	Thermal performance of heat pipe
A	Surface area
K_{eff}	Effective thermal conductivity of the heat pipe
L_{eff}	Effective length of the heat pipe
A_{cs}	Cross-sectional (inner) area of heat pipe
R	Thermal resistance of heat pipe
r	Filling ratio (%)
c	Concentration of nanofluid (vol. %)
P	Input power (Watts)

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Zohuri B. Heat Pipe Design and Technology, Modern Applications for Practical Thermal Management. 2nd ed. Berlin: Springer; 2016.

[2] Alijani A, Cetin B, Akkus Y, Dursunkaya Z. Effect of design and operating parameters on the thermal performance of aluminum flat grooved heat pipes. Appl Therm Eng 2018;132:174–187.

[3] Nizam AR, Gupta NK, Alam P. Experimental investigation of thermal performance of mesh wick heat pipe using nanofluid. In: editors. 3rd International Congress on Advances in Mechanical Sciences; 2020 Aug 27-28; Hyderabad, India: IOP Science; 2020. Article 012034.

[4] Kilic F, Menlik T, Sozen A. Effect of titanium dioxide/water nano fluid use on thermal performance of the flat plate solar collector. Sol Energy 2018;164:101–108.

[5] Wang G, Quan Z, Zhao Y, Wang H. Performance of a flat-plate micro heat pipe at different filling ratios and working fluids. Appl Therm Eng 2018;146:459–468.

[6] Gupta NK, Mishra S, Tiwari AK, Ghosh SK. A review of thermo physical properties of nanofluids. Mater Today Proc 2019;18:968–978.

[7] Choi SUS. Enhancing thermal conductivity of fluids with nanoparticles, developments and application of non-newtonian flows. ASME J Heat Transf 1995;231:99–105.

[8] Gupta NK, Tiwari AK, Ghosh SK. Experimental investigation of the thermal performance of mesh wick heat pipe. Heat Transf Res 2018;49:1793–1811.

[9] Poplaski LM, Benn SP, Faghri A. Thermal performance of heat pipes using nanofluids. Int J Heat Mass Transf 2017;107:358–371.

[10] Abdulshaheed AA, Wang P, Huang G, Li C. High performance copper-water heat pipes with nano engineered evaporator sections. Int J Heat Mass Transf 2019;133:474– 486.

[11] Qu J, Wu HY, Cheng P. Thermal performance of an oscillating heat pipe with Al2O3 water nanofluids. Int Commun Heat Mass Transf 2010;37:111–115.

[12] Nookaraju BC, Kurmarao PSV, Nagasarada S, Karthikeyan R, Vinay A. Optimization of process parameters of helical grooved heat pipe using response surface methodology. Mater Today Proc 2018;5:5262–5271.

[13] Dehaj MS, Mohiabadi MZ. Experimental investigation of heat pipe solar collector using MgO nano fluids. Sol Energy Mater Sol Cells 2019;191:91–99.

[14] Gupta NK, Verma SK, Rathore PKS, Sharma A. Effects of CuO/water nanofluid application on thermal performance of mesh wick heat pipe. Heat Transf Res 2020;51:837–850.

[15] Qu J, Wu H. Thermal performance comparison of oscillating heat pipes with SiO2/water and Al2O3/water nanofluids. Int J Therm Sci 2011;50:1954–1962.

[16] Xue HS, Fan RJ, Hu YC, Hong RH, Cen KF. The interface effect of carbon nanotube suspension on the thermal performance of a two-phase closed thermosyphon. J Appl Phys 2006;100:104909.

[17] Das SK, Putra N, Thiesen P, Roetzel W. Temperature dependence of thermal conductivity enhancement for nanofluids. J Heat Transf 2003;125:567–574.

[18] Mahdavi M, Tiari S, De Schampheleire S, Qiu S. Experimental study of the thermal characteristics of a heat pipe. Exp Therm Fluid Sci 2018;93:292–304.

[19] Gupta NK, Barua A, Mishra S, Singh SK, Tiwari AK, Ghosh SK. Numerical study of CeO2/H2 O nanofluid application on thermal performance of heat pipe. Mater Today Proc 2019;18:1006–1016.

[19] Nazari MA, Ahmadi MH, Sadeghzadeh M, Shafii MB, Goodarzi M. A review on application of nanofluids in various types of heat pipes. J Cent South Univ 2019;26:1021–1041.

[20] Ahmadi MH, Sadeghzadeh M, Rafiee AH, Chau KW. Applying GMDH neural network to estimate the thermal resistance and thermal conductivity of pulsating heat pipes.

[21] Maddah M, Sadeghzadeh M, Ahmadi MH, Kumar R, Shamshirband S. Modelling and efficiency optimization of steam boilers by employing neural networks and response surface method. Mathematics 2019;7:629.

[22] Maddah H, Aghayari R, Mirzaee M, Ahmadi MH, Sadeghzadeh M, Chamkha AJ. Factorial experimental design for the thermal performance of a double pipe heat exchanger using Al2O3-TiO2 hybrid nanofluid. Int Commun Heat Mass Transf 2018;97:92–102.

[23] Gupta NK, Tiwari AK, Verma SK, Rathore PKSR, Ghosh SK. A comparative study of thermal performance of a heat pipe using water and nanofluid, and a nanoparticle-coated wick heat pipe using water. Heat Transf Res 2019;50:1767–1779.

[24] Gupta NK, Tiwari AK, Ghosh SK. Experimental study of thermal performance of nanofluid-filled and nanoparticles-coated mesh wick heat pipes. J Heat Transf ASME 2018;140:102403.

[25] Sajid MU, Ali HM. Recent advances in application of nanofluids in heat transfer devices: A critical review. Renew Sustain Energy Rev 2018;103:556–592.

[26] Monroe JG, Kumari S, Fairley JD, Walters KB, Berg MJ, Thompson SM. Energy harvesting and heat transfer ability of a ferro-nanofluid oscillating heat pipe. Int J Heat Mass Transf 2019;132:162–171.

[27] Gupta NK, Sharma A, Rathore PKS, Verma SK. Thermal performance optimization of heat pipe using nanofluid: response surface methodology. J Brazilian Soc Mech Sci Eng 2020;42:590.

[28] Maddah H, Ghazvini M, Ahmadi MH. Predicting the efficiency of CuO /water nanofluid in heat pipe heat exchanger using neural network. Int Commun Heat Mass Transf 2019;104,:33–40.

[29] Moffat RJ. Describing the uncertainties in experimental results. Exp Therm Fluid Sci 1988;1:3–17.

[30] Gupta NK. Thermal performance optimization of heat pipe using nanofluids. in *Lecture Notes in Mechanical Engineering*, 2021, pp. 499–508.

[31] Bullar BS, Dasaroju G, Das SK. Augmented thermal performance of straight heat pipe employing annular screen mesh wick and surfactant free stable aqueous nanofluids. Heat Transf Eng 2017;38:217–226.