THERMAL PERFORMANCE PREDICTION OF HEAT PIPE WITH TiO_2 NANOFLUIDS USING RSM

by

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Heat pipe is a two-phase heat transfer device with high effective thermal conductivity and transfer huge amount of heat with minimum temperature gradient in between evaporator and condenser section. This paper objective is to predict the thermal performance in terms of thermal resistance, R, and heat transfer coefficient, h, of screen mesh wick heat pipe with deionized water-TiO_2 as working fluid. The input process parameters of heat pipe such as heat load, Q, tilt angle, θ, and concentration of nanofluid, ϕ, were modeled and optimized by utilizing response surface methodology with MINITAB-17 software to attain minimum thermal resistance and maximum heat transfer coefficient. The minimum thermal resistance of 0.1764 °C per W and maximum heat transfer coefficient of 1411.52 W/m^2 °C was obtained under the optimized conditions of 200 W heat load, 57.2° tilt angle, and 0.159 vol.% concentration of nanofluid.

Key words*: heat pipe, reponse surface methodology, thermal resistance, heat transfer coefficient, tilt angle, nanofluid*

Introduction

Heat pipe is throwing a light on the recent generation in industrial applications like power generations, chemical processes, cooling of electronics and aerospace due to its two-phase heat transfer. Due to vaporization and condensation of operational fluid with minimum temperature gradient hefty amount of heat is transferred and the condensed fluid is re-circulated in the evaporator section using the capillary force. Heat pipe has comparatively high thermal conductivity with normal thermal conductors (like fins, metal rods). It uses conventional fluids like alcohols and water as working fluids for heat transfer and these fluids were limited due to its meager thermal properties which results as a dominant hitch. Thus nanofluids are developed and are emerging as heat transfer fluids in heat transfer applications.

Naphon *et al.* [1] fabricated heat pipe with copper material and experimentally studied about the input parameters of a heat pipe by considering heat load (HL), tilt angle (TA) and different concentrations of T_iO_2 nanofluids to augment the thermal efficiency. The results showed that the optimum performance of a heat pipe was obtained at a concentration of 1.0 vol.% and at a TA of 45°. Veerasamy *et al.* [2] utilized graphene nanofluids to improve the thermal performance of a circular grooved heat pipe with the orientation of

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90°, constant flow rate of coolant as 100 mL per minute and the concentrations of 0.6 vol.% and 0.75 vol.%. Author observed that the thermal resistance had been decreased when increasing concentration of nanofluids, also the surface temperatures of a heat pipe were reduced as compared to deionized water as the base working fluid of a heat pipe and Torii [3] performed experiments using graphene oxide nanofluids at constant heat flux on copper heat pipe with varying concentrations and stated the heat transfer coefficient was increased when mass concentration of nanofluids increases. Jang and Choi [4] analyzed parameters that influenced nanofluids thermal conductivity and showed that they were affected by the size of nanoparticles, the temperature range and the volume fraction of the nanofluids. Teng *et al.* [5] tested heat pipe with water and various concentrations of Al_2O_3-water as the working fluid and measured the effects of alumina concentration and inclination angle on heat pipe thermal efficiency and concluded that the efficiency was increased from 62.5-79% while charged 1.0 vol.% of alumina concentration and Hassan *et al.* [6] prepared water based alumina nanofluids by considering 20-70 nm particle size with the 1 and 3 vol.% concentrations and presented that the thermal performance increased by 26% as compared to base fluid. Das *et al.* [7] reported from the experiments the nanofluids thermal conductivity had been increased with temperature. Somasundaram *et al.* [8] prepared and investigated the thermal performance of a copper flat heat pipe with metal foam wick with 0.77 porosity. The considered factors of a heat pipe were the heat flux, flow rate of cooling water, fill ratio and different temperatures at condenser zone to improve the thermal efficiency of a heat pipe. Finally stated that the thermal resistance decreased 2.1% and 3.1%, respectively, when used one and two layers of wick scrolled inside of the heat pipe. Liu *et al.* [9] discussed experimentations of a miniature-flat-heat pipe to find the effects of different concentrations of CuO/H_2O nanofluids and decreasing the operating pressure on critical heat flux and the heat transfer coefficient of a heat pipe. The results revealed that significantly increases the responses and found better mass concentration was about 1.0 wt.%. Do *et al.* [10] conducted experiments on screen mesh wick heat pipe using Al_2O_3-water nanofluids. The results revealed that the thermal performance of heat pipe has been increased up to 40%. Kang *et al.* [11] considered 10 nm and 35 nm size Ag nanoparticles to prepare various concentrations with deionized water and performed experiments on deep-grooved heat pipe to estimate its thermal performance in terms of thermal resistance. As compared to deionized water smaller and bigger size nanoparticles nanofluids decreased their thermal resistance 50% and 80%, respectively. Raghuram *et al.* [12] made a copper-heat pipe with the specifications of length 30 cm, diameter 12 mm, and thickness of 1 mm. The experiments were conducted with and with-out by using water and acetone as operating fluids and compared each other to quantify the thermal performance in the form of over-all heat transfer coefficient and also validated the experimental results with CFD simulation results. The optimum results were obtained when heat pipe operated with acetone as the working fluid. Khalili and Shatii [13] used water and acetone as the working fluids to investigate the thermal performance of a partly sintered wick heat pipe. Researcher studied about fill ratio, HL and orientation of heat pipe and also studied at which conditions dry out has been obtained. Moldoveanu *et al.* [14] evaluated the thermo physical properties density, specific heat, viscosity and thermal conductivity of different metallic oxides (Al_2O_3, TiO_2, and CuO) nanofluids by conducting experiments and concluded these nanofluids can replace with water for specific applications. SanthiSree *et al.* [15] analyzed closed loop pulsating heat pipe by adopting a statistical tool (Taguchi technique) to optimize the input parameters and also improve the quality of heat pipe in terms of thermal resistance. The optimization process shows that HL was the most significant factor which improved performance followed by fill ratio and TA. Nookaraju *et al.* [16] considered input factors of a test heat pipe were TA, HL and coolant mass-flow rate and developed an empirical relationship to predict better thermal performance (heat transfer coefficient) of a helical grooved heat pipe using response surface methodology. Khoobbakht *et al.* [17] designed experiments on a Diesel engine with their independent factors (engine load, speed, blended levels of biodiesel and ethanol) using a statistical tool known as design of experiments (DoE) based on central composite rotatable design of a response surface methodology (RSM). The effects of the number of screen mesh layers and fluid loading on the screen mesh wick heat pipes were examined by Kempers *et al.* [18]. They concluded that there were much less efficient thermal resistances in the heat pipe with slightly less working fluid, but that the overall heat transfer rate was significantly reduced.

The main objective of this work is to study the effects of individual operating parameters of mesh wick heat pipe such as HL, TA and concentration of nanofluid. The RSM was used to model the process parameter and to design the optimum operating conditions to minimize the thermal resistance and maximize the heat transfer coefficient of heat pipe. The relationship between input variables on the responses was also developed using the RSM in this study. The error between the experimental and modeled was observed to be less than 5%.

Experimentation

Nanofluid preparation

The water based TiO_2 nanoparticles (99.8% pure, <50 nm) were purchased from Sigma-Aldrich, Germany. Using a two step method different volume percentage (0.05, 0.15, and 0.25 vol.%) concentrations of TiO_2-water nanofluids were prepared by dissolving nanoparticles in water and fig. 1(b) illustrates the prepared nanofluid with 0.25 vol.% concentration. To achieve a good stability of TiO_2-water nanofluid concentrations the prepared mixture is kept in an ultra-sonicator [UP400S, Hielscher] at 50 kHz frequency at a duration of one hour. Figure 2 shows the crystalline pattern of TiO_2 nanoparticles observed by the X-ray diffraction (Shimadzu LabX-6000) analysis. The evaluated average size of the particle is found to be 32.5 nm by using Scherrer formula [19] and from XRD pattern full width half mean is observed as 0.29 from data process sheet at 2θ is equals to 25.2°.

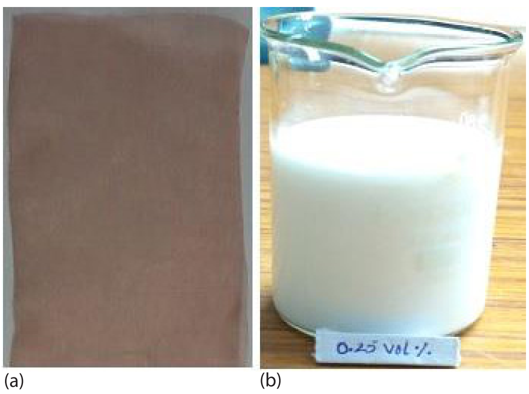

Figure 1. (a) The 100 mesh size screen wire mesh and (b) prepared 0.25 vol.% nanofluid

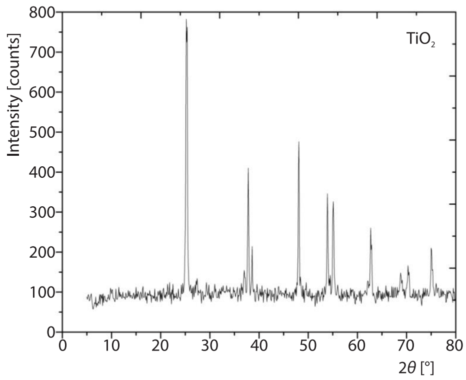

Figure 2. The XRD pattern of TiO_2 nanoparticles

Experimental set-up and procedure

Figures 3(a) and 3(b) shows the experimental apparatus (at Karunya University, Coimbatore, India) and the schematic diagram of heat pipe test set up, mainly it consists data acquisition system, water storage tank, thermostatic bath, personal computer, transformer, flow meter, and digital multi-meter. The fabricated copper material cylindrical screen mesh wick heat pipe with different sections (evaporator, adiabatic and condenser) with the lengths of 100 mm, 50 mm, and 150 mm is shown in fig. 4 and having 12.7 mm and 11.5 mm as outer and inner diameters. Inside of heat pipe by using a spring mechanism three layers of copper mesh with a mesh size of 100/inch and wire diameter of 0.15 mm is wrapped. The working fluid was loaded in heat pipe with a fill ratio of 30% of the total volume of heat pipe to completely saturate the wick at lower pressure. The condenser zone of the heat pipe was enclosed with acrylic material pipe and acts as heat exchanger. To absorb heat from condenser section water is used as a coolant and it flows at a rate of 15 Lph.

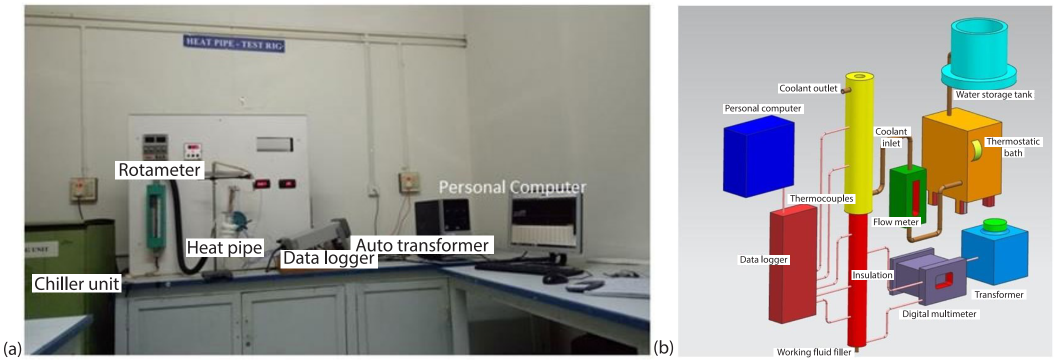

Figure 3. (a) Experimental apparatus and (b) schematic diagram of heat pipe test facility

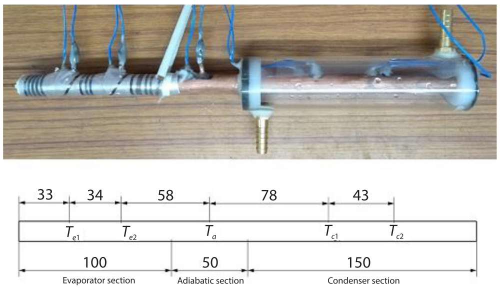

Figure 4. Thermocouple locations on the test section

For all the tests to maintain a constant coolant inlet temperature of 20 °C, a thermostatic bath unit was used. A total of five *T*-type thermocouples (two in evaporator, one in adiabatic and two in condenser section) were fixed on wall surface of heat pipe and shown the lengths of thermocouples (accuracy ±0.5 °C) from evaporator to measure the surface temperatures of the heat pipe. A 230 V AC supply is used to energize the electric heater which is wounded on the evaporator section and measured by a digital multi meter with an uncertainty of ±0.5 W. In order to minimize the heat loss to ambient, the evaporator and adiabatic sections completely insulated by glass wool material. The surface temperatures of the test section are recorded by the data logger until the steady-state is reached and it is connected to personal computer to store the data for analysis purpose.

Figure 1(b) shows the copper screen wire mesh which was used in the present study and three layers of mesh inserted inside of the heat pipe. The multi layer wick structure porosity, ε, and permeability, k, were calculated using the formulae from [20] and found to be 0.76 and 3.98×10^{-10} m^2, respectively.

Data reduction

The thermal resistance, R [°CW^{-1}], and the overall heat transfer co-efficient, h [Wm^{-2}°C^{-1}], of cylindrical screen mesh wick heat pipe can be evaluated from [19]:

$$R = \frac{T_e - T_c}{Q} \tag{1}$$

$$h = \frac{Q}{A\left(T_e - T_c\right)} \tag{2}$$

where T_e and T_c are the evaporator and condenser average temperature, Q – the evaporator HL at evaporator, and A – the evaporator heat transfer surface area.

Results and discussion

The present study considered three input factors namely HL, TA and nanofluid concentration. The nanofluid concentrations are considered in order to evaluate the thermal performance of the heat pipe. While considering the limits of the nanofluids, it was noted that the increase in the nanofluid concentration, increased the density of the fluids, therby higher pumping power is required to pump the nanofluid into the heat pipe. Increasing the nanofluid concentration leads to the increasing the density thereby inefficient results arrived. Keeping these points in mind, the levels of nanofluids are kept with in the limits so that the feasibility of the work can take place with positive results. The considered input factors and their lower and upper boundaries are shown in tab. 1. The lower limits and upper limits of each factor is considered as per the feasibility of the study. The application of each factors in the industries are also being taken care while considering the limits. The total of 15 experiments was conducted as per box-behnken design (BBD) of RSM using MINITAB 17 since it is efficient to predict the responses. The R and h were considered as the output responses in the present work.

Table 1. Process parameters and its levels

Factors	Parameters	Units	Lower bound	Upper bound
HL	HL	[W]	100	200
TA	TA	[°]	0	90
C	Concentration	[Vol.%]	0.05	0.25

The RSM methodology

The BBD are a class of rotatable second order designs with incomplete three level factorial designs. The BBD is a part of response surface method design, which is very efficient when compared to central composite design for three level full factorial designs [21, 22]. The goal of the present work is to minimize the R and maximize the h. The total experimental design along with their responses is shown in tab. 2. The thermal performance of a HP was calculated for pure water at 200 W, 45°, and 30% fill ratio and observed to be 0.2054 °C per W and 413.28 W/mK for thermal resistance and heat transfer coefficient, respectively. The present obtained results are observed to be higher when compared to pure water due to the addition of nanofiller (TiO_2).

The experiments were conducted and the responses were evaluated for all the tests. The ANOVA was performed on the obtained response values to know the significance of the

Table 2. Experimental run conditions and their responses

Test number	HL [W]	TA [°]	Concentration [vol.%]	Thermal resistance [°CW^{-1}]	Heat transfer coefficient [Wm^{-2}°C]
1	200	90	0.15	0.1791	1399.279
2	200	45	0.25	0.1851	1354.006
3	150	45	0.15	0.1900	1318.836
4	100	45	0.25	0.2036	1231.030
5	150	90	0.05	0.2050	1222.751
6	150	45	0.15	0.1900	1318.836
7	100	45	0.05	0.2098	1194.649
8	100	90	0.15	0.1989	1260.121
9	200	0	0.15	0.1840	1362.018
10	100	0	0.15	0.2049	1223.219
11	150	0	0.05	0.2093	1197.435
12	150	45	0.15	0.1900	1318.836
13	200	45	0.05	0.1886	1328.800
14	150	0	0.25	0.2053	1220.765
15	150	90	0.25	0.2001	1252.489

parameters and judged weather the model is significant or not with the help of *P*-value (probability). The *P*-value can clearly explains weather the model is significantly important for the predicting the responses. The *P*-value of more than 0.05 is considered as the insignificant where as less than 0.05 is significant and are considered to have a significant effect on the response variables. The feasibility of the RSM is ensured by observing the S (statistical) value of both *R* and *h* and was observed to be 0.000298 and 4.4711, respectively. Likewise, coefficient of determination, R^2, values was observed to be 99.97% and 99.84% for *R* and *h*. The R^2 (adj) values of both *R* and *h* are 99.91% and 99.54%. The R^2 value of both the responses was satisfactory as it was observed to be above 95%.

Optimized responses

The RSM optimizer was used to find the optimum heat pipe input parameters for the best possible heat pipe responses (*R* and *h*) as shown in figs. 5 and 6.

Figure 5 shows the optimization plot for the *R*. The optimization limits of the three input factors are observed that HL 200 W, TA is 55.45° and nanofluid concentration of 0.159 vol.%. The thermal resistance was predicted at the optimized parameter settings levels and the response value was observed to be 0.1764 °C per W. The thermal resistance is decreasing with increasing the HL as it can be observed from the fig. 5 whereas for TA and nanofluid concentration the thermal resistance decreased up to TA of 55.45° and concentration of 0.159 vol.% and further increase in these two factors increased the response.

Figure 6 shows the optimization plot for the *h*. The optimization limits of the three input factors are observed that HL is 200 W, TA is 57.27° and nanofluid concentration of 0.159 vol.%. The heat transfer coefficient was predicted at the optimized parameter settings levels and the response value was observed to be 1411.52 W/m^2 °C. The heat transfer coefficient is increasing with increasing the HL as it can be observed from the fig. 6 whereas for TA and nanofluid

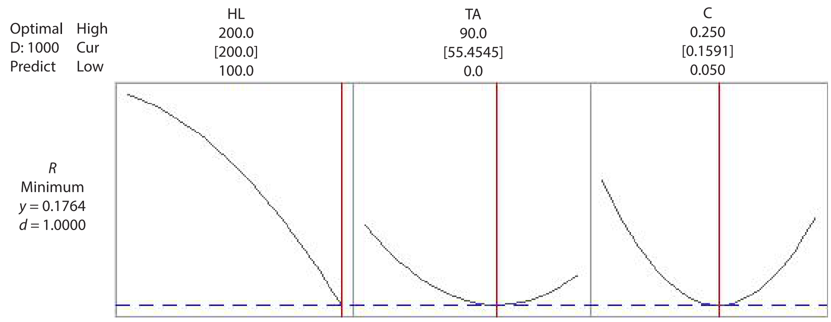

Figure 5. Response optimization of thermal resistance

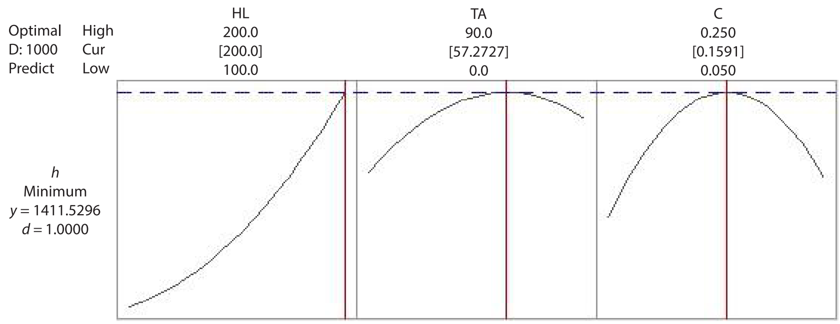

Figure 6. Response optimization of heat transfer coefficient

concentration the heat transfer coefficient increased up to certain limit and decreased further again after increasing the input factor levels.

The ANOVA of the responses

Table 3 shows the ANOVA of the *R*. The predictive capability of the thermal resistance is significant since the R^2 value of the *R* was observed to be 99.97%. From the tab. 3, it was noticed that the factors A, B, and C was significantly affecting the response since *P*-value was less than 0.05. Even the interactions of B and C are also significantly affecting the response. From the tab. 3, it was also noted that HL has more impact on *R* followed by nanofluid concentration and TA. Figure 7 shows the scatter plot of *R* between predicted and experimental values. Figure 7 concludes that the predictive capability is high since the points are almost in line with the regression-line. The developed model can be successfully utilized for predicting the responses for various parameter combinations within the selected limits of the input factors.

Table 4 shows the ANOVA of the *h*. The predictive capability of the thermal resistance is significant since the R^2 value of the *R* was observed to be 99.84%. From the tab. 4, it was noticed that the factors A, B, and C was significantly affecting the response since *P*-value was less than 0.05. Even the interactions of B and C are also significantly affecting the response. From tab. 4, it was observed that HL has more impact on *h* followed by nanofluid concentration and TA similarly like *R*. Figure 8 shows the scatter plot of *h* between predicted and experimental values. Figure 8 concludes that the predictive capability is high since the points are almost in line with the regression-line.

Table 3. The ANOVA of *R*

Source	DF	Adj SS	Adj MS	*F*-Value	*P*-Value
Model	9	0.001404	0.000156	1753.03	0
Linear	3	0.000902	0.000301	3379.29	0
HL	1	0.000807	0.000807	9066.32	0
TA	1	0.000052	0.000052	586.62	0
C	1	0.000043	0.000043	484.92	0
Square	3	0.000499	0.000166	1871.21	0
HL*HL	1	0.000038	0.000038	432.48	0
TA*TA	1	0.000089	0.000089	1003.81	0
C*C	1	0.000367	0.000367	4121.36	0
2-Way interaction	3	0.000002	0.000001	8.61	0.02
HL*TA	1	0	0	3.4	0.125
HL*C	1	0.000002	0.000002	20.31	0.006
TA*C	1	0	0	2.11	0.206
Error	5	0	0		
Lack-of-fit	3	0	0	–	–
Pure error	2	0	0		
Total	14	0.001404			
Model summary					
S	R^2	R^2 (*adj*)	R^2 (pred)		
0.000298	99.97%	99.91%	99.49%		

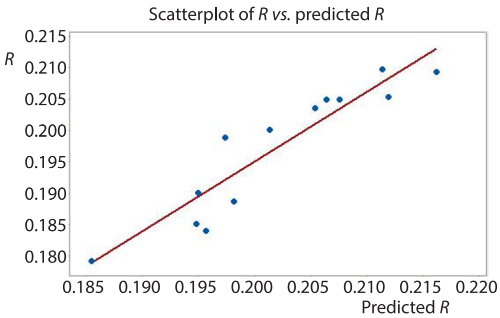

Figure 7. Scatter plot of thermal resistance

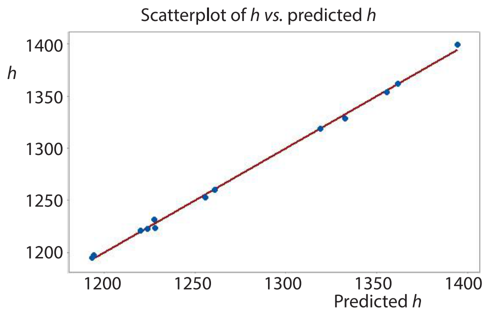

Figure 8. Scatter plot of heat transfer coefficient

Validation of experiments

The validation of the experiments was carried out by using the regression eqs. (3) and (4). The experiments were carried out for three different input parameters combinations and the same combinations was predicted using regression equation as shown in eqs. (3) and (4). The error between the predicted and experimental values was observed to be around 4%. The predictive capability of the developed model is significantly high due to the less error percentage between experimental and predicted results, tab. 5.

Table 4. The ANOVA of *h*

Source	DF	Adj SS	Adj MS	*F*-Value	*P*-Value
Model	9	60898.9	6766.5	338.47	0
Linear	3	39584.2	13194.7	660.02	0
HL	1	35789.2	35789.2	1790.23	0
TA	1	2151.7	2151.7	107.63	0
C	1	1643.2	1643.2	82.2	0
Square	3	21273.2	7091.1	354.7	0
HL*HL	1	1960.4	1960.4	98.06	0
TA*TA	1	3484.3	3484.3	174.29	0
C*C	1	15483.6	15483.6	774.51	0
2-Way interaction	3	41.5	13.8	0.69	0.595
HL*TA	1	0	0	0	0.969
HL*C	1	31.2	31.2	1.56	0.267
TA*C	1	10.3	10.3	0.51	0.506
Error	5	100	20		
Lack-of-fit	3	100	33.3	–	–
Pure error	2	0	0		
Total	14	60998.9			
Model summary					
S	R^2	R^2 (adj)	R^2 (pred)		
4.47118	99.84%	99.54%	97.38%		

$$R = 0.22801 + 0.000161\, HL - 0.000286\, TA - 0.34018\, C - 0.000001 HL*HL + 0.000002 TA*TA + 0.9965 C*C + 0.000000\, HL*TA + 0.000134\, HL*C - 0.000048\, TA*C \quad (3)$$

$$h = 1101.3 - 1.345\, HL + 1.670\, TA + 2154\, C + 0.009217\, HL*HL - 0.01517\, TA*TA - 6476\, C*C + 0.000040\, HL*TA - 0.559\, HL*C + 0.356\, TA*C \quad (4)$$

Table 5. Validation experiments

Parameter settings			R [°CW^{-1}]			h [wm^{-2-} °C]		
HL [W]	*TA* [°]	*C* [vol.%]	Predicted	Expt.	Error [%]	Predicted	Expt.	Error [%]
200	50	0.17	0.181026	0.184	1.9	1409.999	1455	3.1
200	60	0.20	0.179658	0.186	3.4	1400.720	1425	1.7
200	55	0.15	0.179498	0.176	2.0	1410.938	1450	2.7

The SEM analysis of wick structures

The SEM images of the screen wire mesh at evaporator section of operated heat pipe without and with TiO_2-water nanofluids depicted in fig. 9 and these images were performed with the help of JSM 6300 model microscope, JEOL USA. It was observed from the SEM picture that a thin porous layer was formed due to the substantial deposition of nanoparticles over the surface of the wick. Due to this, surface wettability was increased such that it minimized the contact angle between the solid-liquid surfaces thereby it increased the boiling heat flux and also the capillary action of the wick [23] and large amount of liquid is drawn from the condenser section which in turn improved the thermal performance of the heat pipe.

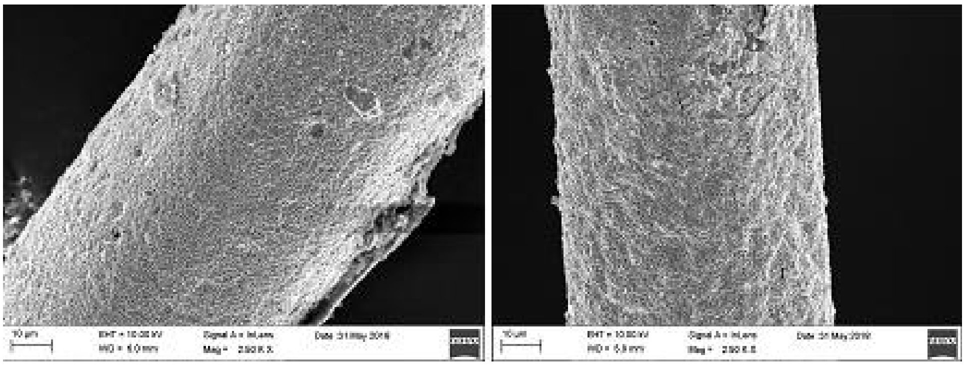

Figure 9. The SEM images of the wick surface without and with TiO_2 nanofluid

Conclusions

The effect on the heat pipe output responses (*R* and *h*) of heat pipe input parameter including HL, TA and concentration of TiO_2 nanofluids was examined in the present work. According to the study, the following conclusions were made.

- In a mesh wick heat pipe at the evaporation section addition of TiO_2 nanoparticles provides more area for liquid boiling and thus enhances the thermal performance of heat pipe.
- The optimum operating conditions of the heat pipe to improve the thermal performance from TiO_2 concentrations are found to be at 200 W HL, 57.20 TA and TiO_2 concentration of 0.159 vol.%.
- Responses such as *R* and *h* at optimized parameters are found to be 0.1764 °C per W and 1411.52 W/m^2°C, respectively.
- The ANOVA was performed on both the responses and observed that all the three considered parameters were significantly affecting the responses.
- From the ANOVA it was concluded that HL followed by *C* and TA has more impact on both the responses.
- This work will help to develop the knowledge base reliable and robust, best performance HP inputs with the prior prediction at which better heat pipe *R* and *h* can obtain, for water based TiO_2 nanofluids

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