



ANALYSIS ON THE EFFECT OF NANO PARTICLES IN WASTE HEAT RECOVERY SYSTEM USING HEAT PIPES BY RSM

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ABSTRACT

Waste heat recovery systems are used to recover the waste heat in all possible ways. It saves the energy and reduces the man power and materials. Heat pipes have the ability to improve the effectiveness of waste heat recovery system. The present investigation focuses to recover the heat from Heating, Ventilation, and Air Condition system (HVAC) with two different working fluids refrigerant(R410a) and nano refrigerant (R410a+Al₂O₃). Design of experiment was employed, to fix the number of trials. Fresh air temperature, flow rate of air, filling ratio and volume of nano particles are considered as factors. The effectiveness is considered as response. The results were analyzed using Response Surface Methodology.

Key Words: Heat pipe, waste heat recovery system, Nano refrigerants and RSM.

1. Introduction

Growth in population and global warming has increased the energy demand for heating ventilation and air conditioning [HVAC] systems. HVAC ensures the indoor air quality which is very essential. The recent investigations are focused on to reduce the energy consumption for HVAC as major portion of being consumed by HVAC. Waste heat recovery is one of method to reduce the energy required for HVAC systems. Air to air heat exchangers are needed for recover the heat from HVAC systems. To improve the efficiency, heat pipes have been found more suitable. Heat pipe is a heat conducting device that would transfer/recover heat without any additional energy and with minimum loss. Heat pipe design is flexible according to its application and it can be designed. Initial investigations are focused on the material of wick, angle of the inclination, filling ratios and shape. Investigations on working fluids are gaining more attention on now days. The working fluids have been selected based on the operating temperature range of heat pipe. Some of investigations on waste heat recovery system using heat pipes are reviewed. Seshan and Vijayalakshmi [1] suggested using a heat pipe in Waste Heat Recovery System (WHRS) to improve the effectiveness. Littwin and McCurley [2] recovered the waste heat from fire tube boiler by adopting heat pipe technology. The advantages are compact design,

reduction in thermal induced stress, improved efficiency and easy to clean. Peretz and Bendescu [3] reported that the heat transfer rate depends on number of rows and heat capacity of working fluid. Azad and Geoola [4] simulated the thermal performance of heat pipe heat exchanger. Copper – water heat pipes were investigated by the many investigators like Chi [5] Dunn and Ray [6] for its compatibility within the temperature range 100 °C to 150 °C. Akyurt et al. [7] simulated to recover waste heat from gas turbine using steel – water heat pipe at minimum temperature range. After their investigation they positively reported for recovery system using heat pipe. Riffat and Gan [8] investigated self finned heat pipe exchanger for natural ventilated building for cooling purpose. The heat pipes were arranged in four rows. Habeebullah et al. [9] experimentally tested recovery system from exhaust gases using heat pipe .It was able to recover the heat up to 93 %. Noie et al. [10] designed heat pipe using methanol as working fluid for waste heat recovery system to recover the cooling from surgery room. After experimental investigation they recommended for finned tube, number of rows and proper insulation. Feng yang et al. [11] recovered the heat from engine exhaust and proved heat pipes (steel – water thermosyphon) were more effective in recovery system and the heat transfer rate also increased between the air to air. Francisco Javier et al. [12] tried to improve the indoor air quality by means of recovery system by adopting heat pipe technology and considered parameters like temperature, flow rate of air and relative

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humidity. Best results were obtained in heat pipe assisted recovery system. Soylemez [13] optimized the heat recovery system for finding effective temperature. Design optimization was done by Tao et al. [14] using NTU methods. Song lin et al [15] implanted and tested the heat pipe heat exchanger for indoor dehumidification process. The study recommended the CFD analysis to predict the thermal performance of heat pipe heat exchanger. Looped heat pipe was developed by Di Liu et al., [16] and tested with water and methanol as working fluid. Effects of power throughput, evaporator length and hydraulic diameters were considered as factors. Mostafa and Mohamed [17] designed and tested the heat pipe heat recovery system to recover the heat from air conditioning using R11 as working fluid. Mass flow rate of air, fresh air temperature were considered as parameters. Yau [18] evaluated the effect of inclination angle in HVAC system, the vertical position resulted in best performances over other tilt in recovery system. Efficiency of fins were computationally analyzed by Tao et al [19] in heat exchanger. The fins had good agreement with the efficiency. The performance of air conditioner was increased by Paisarn naphon [20] by using refrigeration R134a charged heat pipe and proved that performance increase due to heat pipe. Hussam Jouhara and Richard [21] investigated looped heat pipe for energy saving purposes in air condition and installed heat pipe in recirculation. They recommended the looped heat pipe for energy saving applications. The parameter filling ratio and operating temperatures for different working fluids were considered for the performance analysis of thermosyphon assisted waste heat recovery system by Kannan and Natarajan [22]. The operating temperature was found to have a considerable effect on performance more than other factors. Ahmadzadehatalepeh and Yau [23] simulated the heat pipe heat recovery system in air condition plant for hospital and recommended the eight row heat pipe heat exchanger for air heat exchanger. In 1980's Freon gases were used in heat pipe for air conditioning application. R22, R134a and R410a gas refrigerants were introduced because of ozone depletion. Than et al [24] conducted a study on solar collector using thermosyphon charged with R22. Ong and Haidar [25] tested the performance of R134a filled thermosyphon. Dalkilic et al [26] experimentally investigated the heat transfer coefficient of smooth vertical tube filled with R134a. These investigations recorded the performance of heat pipe with R134a. Esen and Esen [27] conducted a investigation on thermosyphon assisted solar water heater using three refrigerant R134a, R407e and 410a . To make the working fluid more effective, presently nano fluids have been used. Nano fluid is liquid having a suspended nano metal particle within it. The nano metal

particle increases the thermal conductivity of fluid. The compatibility of nano fluids for the heat pipe applications in waste heat recovery systems to improve the efficiency have been reported in few literatures. This concept was developed by Maxwell. Nano fluids were prepared using nano particles and were named so by Choi et al [28] in 1995. The thermal conductivity was measured by Lee et al., [29]. The nano-fluids have been put under numerous investigations for thermal conductivity and it was evident that the thermal conductivity of nano particles did not affect the thermal conductivity of the base fluids thermal conductivity. Fluid thermal conductivity depends upon the size of the particle surfactant dispersion of particle. Maximum investigations are focused on the effect of nano particle in base fluids. Change in character of base fluid like thermal resistance and thermal conductivity of base fluid are considered. Suresh Kumar et al.[30] reviewed numerous investigations for preparing the nano fluid and applications of nano fluids in the heat pipes. The survey indicates a two step process for preparation of nano fluid in heat pipes. It was concluded that addition of surfactant reduces the heat transfer. In this investigation finned gravitational heat pipes are used. Refrigerant and nano refrigerators have been tested with different inlet air temperature, air flow rate, filling ratio, and volume concentration of nano particles. The experiment has been conducted based on the design of experiments. Design of Experiments (DoE) is a technique used to understand the experimental phenomena within minimum duration of time and less cost. Many factors are involved in experiments. All the input parameters are called as factors and the outputs are as response. DoE helps the researchers to determine the factors which have significant effect on the output. The linear, squared and interactive effects of factors can be easily identified. The process of arriving at a set of operating conditions for the process variables that will result in the best process performance is termed as process. Response Surface Methodology is one such tool for optimization and was developed as early as 1950s. DoE is an important aspect of RSM. Though originally developed for the model fitting of physical experiments, it can also be extended to numerical experiments. Selection of the points where the response should be evaluated is the objective of DoE. Mathematical models, generally polynomials, account for most of the criteria for optimal design of experiments. The accuracy of the approximation and the cost are greatly influenced by choice of design of experiments. A factorial experiment is an experimental strategy in which allows the design variables to be varied simultaneously instead of one at a time. The lower and upper bounds of each of N design variables in the optimization problem needs to be

defined. The allowable range is then discretized at different levels. If each of the variables is defined at only the lower and upper bounds (two levels), the experimental design is called 2N full factorial. Similarly, if the midpoints are included, the design is called 3N full factorial. A 3X3 full factorial design Factorial designs can be used for fitting second-order models. A second-order model can significantly improve the optimization process when a first-order model suffers lack of fit due to interaction between variables and surface curvature.

In this work four input factors variable and three responses are considered. Experiment run was discussed using design of experiment It allows twenty nine run for this experiment. In order to optimize the media components and the precursor addition for enhanced GSH production, a three level Box-Behnken design (-1, 0 and +1) was used. For statistical calculations, the relation between the coded values and actual values were used. The optimizations were done by RSM. The optimized values of both working fluids were compared. The nano refrigerant is more effective than the refrigerant.

2. Experimental Set-Up

The experimental setup is shown in Fig.1. In this study, air-to- air heat exchanger using heat pipes was investigated. The air duct of size 0.45 x 0.45 m cross section were constructed with a galvanized steel sheet of 1mm thickness. The length of duct is 1m. Air entry sides have been designed like a chamber to step up the air velocity. The air ducts were fixed one above the other with 0.1 m gap. The return air from air conditioning system flows in upper duct and fresh air through bottom duct. The ducts were connected by the test section without mixing of air. The exchanger was designed for cross flow. The advantage of cross flow heat exchanger lies in its ability to achieve up to 90 % of heat transfer.

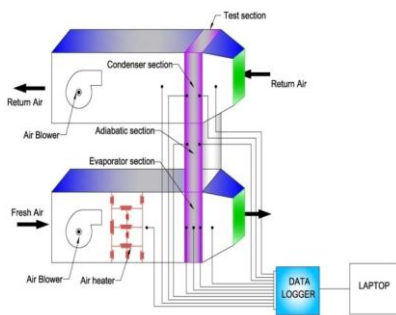


Fig. 1 Circuit diagram of the heat exchanger.

The ducts were well insulated using 5 mm thick insulations to minimize the heat loss. Two blowers have been engaged to maintain the air flow rate inside the duct. The blower speed has been controlled by the regulators. The return air velocity has been kept constant at 3 m/s. The fresh air velocity has been varied in the ratio of 1.1, 1.2, 1.4, 1.6 and 1.8 with the return air. The flow rate has been measured using vane type anemometer.

The temperature of return air has been kept constant. The laboratory air conditioning system was used to supply return air. For the testing purpose, the fresh air temperature has been varied using air heater. The air heater is able to heat up to 100 ° C. The temperature has been controlled by auto transformer. Totally 11 T type thermocouples have been used to measure the temperatures.

The advantages of T type thermocouples are that it is more accurate, quick to respond, possible to measure small changes and less cost. The thermocouples have been provided four in the inlet and outlet of both the air ducts, three in evaporator section, two in adiabatic section and two in condenser section. The thermocouples were connected to the data acquisition system of Agilent Technologies make.

3. Test Section

The two air ducts were connected by the test section of cross section 0.16 x0. 90 m. In this section, looped heat pipe heat exchanger was installed. The heat exchanger consists of 60 copper tubes looped and having outer diameter 0.01 m, inner diameter 0.008 m and a length of 1m. The length of evaporator and the condenser sections have been kept as 0.45 m and the adiabatic section is 0.1 m. One layer of 100 mesh stainless steel wire mesh with wire diameter of 0.00125 m was used as a wick.



Fig. 2 Experimental setup.

The heat pipes were arranged in 4 rows in a zigzag manner in the space of 0.01 m gap. Two valves were placed for charging and discharging the heat pipe. The 0.0005 m aluminum sheets with an area 0.16 x0.4 m were used as fins. In evaporator and condenser section 220 fins were installed in each section. The refrigerants were charged as an working fluid for heat pipe

4. Test Procedure

Design of experiments (DoE) was employed for fixing the number of runs and to study the linear squared and interactive effect of the parameter. Box-Behnken method was selected. Four factors inlet fresh air temperature, mass flow rate of air, filling ratio and volume of nano particles were considered. The condenser side return air temperature from air conditioning room (26 °C) and the air flow rate (3 m/sec) were kept constant.

Effectiveness, thermal resistances and thermal conductivity at evaporator side were considered as response. Four factor and there response was analyzed using DoE Box-Behnken’s method. Twenty nine trials were designed by DoE per working fluid. According to the DoE, factors were set and corresponding readings were taken. The repeatable readings were taken in certain time interval of 15 days. The readings were analyzed using Response Surface Methodology (RSM). From RSM results, optimum equations were obtained.

The study was to find out the enhancement in effectiveness of the heat pipe heat exchanger by waste heat recovery system. The flow rate of air was controlled by blowers. The fresh air temperature was varied using electrical heating coil by adjusting the autotransformer while the return air temperature was maintained as a constant.

The heat rejected from the air stream in the evaporator section can be calculated as

$$Q = m c_p (T_{fi} - T_{fo})$$

The effectiveness (ϵ) of heat pipe heat exchanger at evaporator side is given by

$$\epsilon = \frac{T_{fo} - T_{ri}}{T_{fi} - T_{ri}}$$

where, m is the mass flow rate of air in m/s, c_p is the specific heat of air in J/kgK, T_{fi} is the inlet

temperature of fresh air in K, T_{fo} is the exit temperature of the fresh air in K and T_{ri} is the return air temperature in K.

5. Nano Fluids

Fluids with suspended nano particles are called as nano fluids. Base fluids are conventional heat transfer fluids. The thermal conductivity of base fluids increases by the addition of nano fluids without any pressure drop. The nano particle reduces the size of nucleation bubbles and increases their numbers.

6. Preparation of Nano Refrigerant

The nano refrigerant is prepared in two steps. In the first step 100 mg of nano particle was mixed in the one liter de-ionized water. The suspended nano particles quickly settle down in the water. For avoiding the deposits, electronic ultra sonic homogenizer was employed. When the suspended fluid was exposed to continuous oscillation, the settlement will be delayed. Since refrigerant cannot be exposed, they are mixed with the above preparation while charging.

7. Result and Discussion

The refrigerant R410a and nano refrigerant (R410a+ Al₂O₃) are considered as working fluids for heat pipe. Experiments were conducted as per the Box-Behnkin design matrix. The linear and interactive effects of inlet air temperature, flow rate of air, filling ratio and volume of nano particles on effectiveness was observed. The results of both fluids were compared to find effect of nano particle.

Table 1 Process Parameters

Parameters	Level		
	-1	0	1
A. Inlet air temperature, °C	30	38	46
B. Flow rate of air, m/s	3.0	4.2	5.4
C. Filling ratio, %	20	30	40
D. Concentration of Nano particles, ml *	50	100	150

*for only nano refrigerant

Table 2 ANOVA Table for Fluid R410a

ANOVA for Response Surface Quadratic Model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of	df	Mean	F	p-value	
Source	Squares		Square	Value	Prob > F	significant
Model	0.027024	9	0.003003	10.01577	0.0031	
A-Inlet air temperature	0.005762	1	0.005762	19.21959	0.0032	
B-Flow rate of air	0.002201	1	0.002201	7.342125	0.0302	
C- Filling ratio	0.000459	1	0.000459	1.531176	0.2558	
AB	0.000219	1	0.000219	0.730623	0.4210	
AC	0.002347	1	0.002347	7.829923	0.0266	
BC	0.009149	1	0.009149	30.51686	0.0009	
A ²	0.000304	1	0.000304	1.014715	0.3473	
B ²	2.63E-05	1	2.63E-05	0.087778	0.7756	
C ²	0.006712	1	0.006712	22.38701	0.0021	
Residual	0.002099	7	0.0003			
Lack of Fit	0.001979	3	0.00066	21.98436	0.0060	significant
Pure Error	0.00012	4	0.00003			
Cor Total	0.029123	16				
Std. Dev.	0.017315		R-Squared	0.927941		
Mean	0.723588		Adj R-Squared	0.835293		
C.V. %	2.392894		Pred R-Squared	-0.09346		
PRESS	0.031845		Adeq Precision	10.6393		

From the above ANOVA table it is seen that The Model F-value of 10.02 implies the model is significant. There is only a 0.31% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, AC, BC, C² are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Final Equation in Terms of Coded Factors are as follows

$$\text{Effectiveness} = +0.74 + 0.027 * A + 0.017 * B + 7.575E-003 * C - 7.400E-003 * A * B + 0.024 * A * C + 0.048 * B * C + 8.500E-003 * A^2 + 2.500E-003 * B^2 - 0.040 * C^2$$

From the above ANOVA table it is seen that The Model F-value of 6.90 implies the model is significant. There is only a 0.04% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, D are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Final Equation in Terms of Coded Factors are as follows

$$\text{Effectiveness} = +0.72 + 0.034 * A + 0.013 * B + 0.019 * C + 0.023 * D + 0.012 * A * B - 9.250E-003 * A * C - 0.013 * A * D - 2.950E-003 * B * C + 2.820E-003 * B * D - 3.975E-003 * C * D - 0.014 * A^2 + 7.386E-003 * B^2 - 8.393E-003 * C^2 + 0.013 * D^2$$

The linear, squared and interaction effects of the three factors on effectiveness are studied using ANOVA table 1 for R410a and wire mesh plot of the run. It was found that the linear effects of the two factors namely inlet air temperature and flow rate of air impacts the effectiveness significantly. The linear effect of filling ratio is less significant on effectiveness. The R410a is a high pressurized gas; the filling ratio is not affecting the effectiveness. But the interaction effect of filling ratio combinations with inlet air temperature and flow rate of air has more significant effect. The mesh diagram Fig.2 depicts the interactive effects of the three factors. The interactive effect of inlet air temperature and flow rate of air increases the effectiveness.

Table 3 ANOVA Table for Fluid R410a + Al₂O₃

Response	1	Effectiveness				
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	0.032168	14	0.002298	6.904453	0.0004	significant
A-Inlet air Temp.	0.013688	1	0.013688	41.13254	< 0.0001	
B-Flow rate of air	0.001908	1	0.001908	5.733093	0.0312	
C-Filling ratio	0.004428	1	0.004428	13.30441	0.0026	
D-Concentration of nano	0.006362	1	0.006362	19.11681	0.0006	
AB	0.00062	1	0.00062	1.862341	0.1939	
AC	0.000342	1	0.000342	1.028439	0.3277	
AD	0.000633	1	0.000633	1.900688	0.1896	
BC	3.48E-05	1	3.48E-05	0.104602	0.7512	
BD	3.18E-05	1	3.18E-05	0.095586	0.7617	
CD	6.32E-05	1	6.32E-05	0.189919	0.6696	
A ²	0.00132	1	0.00132	3.967249	0.0663	
B ²	0.000354	1	0.000354	1.06327	0.3200	
C ²	0.000457	1	0.000457	1.372999	0.2609	
D ²	0.001162	1	0.001162	3.491839	0.0827	
Residual	0.004659	14	0.000333			
Lack of Fit	0.004659	10	0.000466			
Pure Error	0	4	0			
Cor Total	0.036827	28				
Std. Dev.	0.018242		R-Squared	0.873489		
Mean	0.719718		Adj R-Squared	0.746978		
C.V. %	2.534662		Pred R-Squared	0.271297		
PRESS	0.026836		Adeq Precision	10.98462		

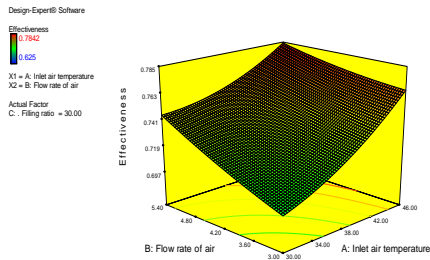


Fig.2 R410a

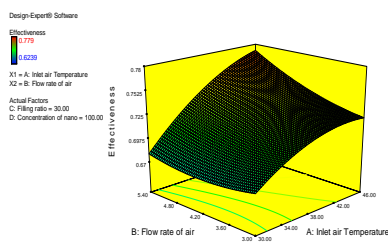


Fig.3 R410a+ Al₂O₃

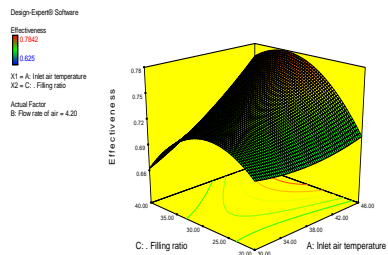


Fig.4 R410a

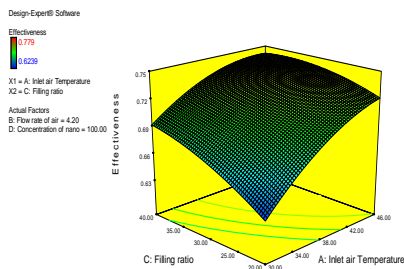


Fig.5 R410a+ Al₂O₃

The effectiveness increases as the inlet air temperature increases even at low air flow rates. The flow rate of air though, at lower temperatures has a minimal effect; there is a significant rise in effectiveness

at higher inlet temperatures. The effectiveness increases with increase in both inlet temperature and flow rate of air. From the ANNOVA table 2 for R410a+Al₂O₃, it is clear that the linear effect of the entire four factors have a trilling impact on effectiveness. The surface plots Fig.3 show the interactive effects of these factors on the output parameters. The interactive effect of inlet air temperature and the flow rate of air are found to have significant effect on effectiveness. Increase in both the factors increases the effectiveness and a maximum effectiveness has been attained at higher temperature and flow rate. The interactive effect of inlet air temperature and filling has been shown in the plot Fig. 4. There is a minimal rise in effectiveness with rise in inlet air temperature at low filling ratio and the effect increased at high filling ratio. The effectiveness increases with increase of filling ratio at low temperature and at the mid value of filling ratio effectiveness reaches the maximum and after that it gets reduced. Same effect has been found for filling ratio at high temperature. But there is significant rise in effectiveness at higher inlet air temperature and mid values of filling ratio. In R410a+ Al₂O₃, Increase in filling ratio increases the effectiveness at low temperatures from Fig.5. At higher temperatures, there is slight increase in effectiveness with increase in filling ratio. Increase in temperature increases the effectiveness significantly. Simultaneous increase in filling ratio and inlet air temperature to higher levels maximize the effectiveness.

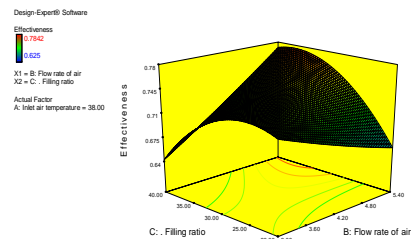


Fig.6 R410a

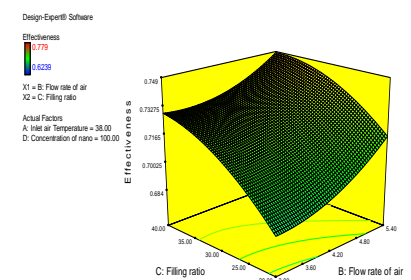


Fig.7 R410a+ Al₂O₃

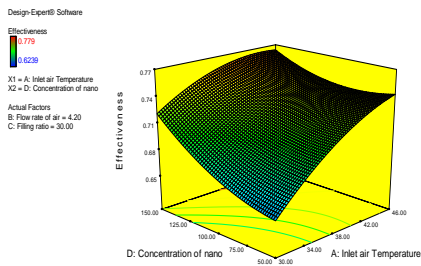


Fig.8 R410a+ Al₂O₃

While observing from Fig.6, the interactive effect of filling ratio and flow rate of air, it has been found that the effectiveness decreases with both filling ratio and flow rates. At low flow rate of air, the filling ratio increases the effectiveness up to certain values and reduces the effectiveness with further increase in filling ratio. The effectiveness gradually increases with increase of filling ratio at high flow rate. The impact of flow rate on effectiveness is less but effectiveness shows a huge increase with increase in air flow rate at high filling ratio. In the case of R410a+ Al₂O₃ increase in filling ratio with respect to the flow rate of air shows the gradual increase in effectiveness. But increase in flow rate shows a steeper increase in effectiveness with respect to filling ratio. Increase in both these factors result in maximized effectiveness indicated in Fig.7. The interactive effect is more effective than the linear effects. Increase in filling ratio with respect to the flow rate of air shows the gradual increase in effectiveness. But increase in flow rate shows a steeper increase in effectiveness with respect to filling ratio. Increase in both these factors result in maximized effectiveness.

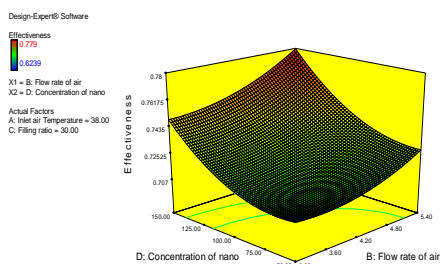


Fig.9 R410a+ Al₂O₃

Increase in concentration of nano particle pushes the effectiveness to the higher side steeply at low temperature and slightly at higher temperatures shown in Fig.8. The effectiveness increase with increase of temperature at low and high range of concentration of

nano particles but the values are higher at high range of concentration of nano particles. Effectiveness increases slightly with increase in flow rate at lower concentration but steeper at higher concentrations. A maximum effectiveness is achieved with simultaneous increase in both factors.

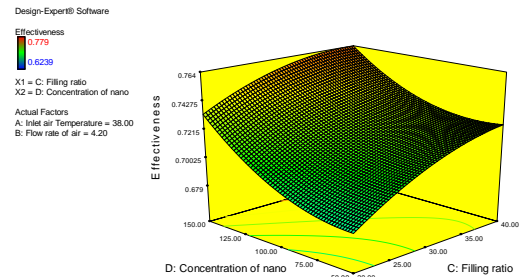


Fig.10 R410a+ Al₂O₃

The effectiveness increases in higher rate with respect to concentration of nano particle compare to filling ratio. In interaction effect of both factors slightly increases the effectiveness.

8. Conclusions

In this experiment, effectiveness of the heat pipe heat exchanger for two different working fluids were analyzed by RSM. Now a day's energy conservation is very important. This system saves energy by 10% and also predicts the optimum effectiveness for each working fluid under varies filling ratio and inlet temperature. Addition of nano particle improves the effectiveness and also saves energy. Refrigerant filled heat pipes behave like a gas operated heat pipe. Even in minimum filling ratio it shows better performance. Inlet air velocity increases the effectiveness with the combination of increase in temperature. It gives maximum effectiveness at minimum filling ratio, maximum temperature and maximum air velocity. Less amount of Al₂O₃ (54.41ml) required to maximize the effectiveness. The nano refrigerant having better performance compare to refrigerant.

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