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Thermal Characteristics of V-Trough Solar Simulator (VTSS) using different Profiles of Heat Pipes

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ABSTRACT

V-Trough solar simulator (VTSS) was designed and constructed at Measurements lab of Annamalai University and its performance was analyzed on indoor test facility. Integrating the heat pipe with V-Trough absorber plate can improve the system performance. VTSS system uses three different heat pipes such as circular, semicircular and Elliptical of same length 900 mm and diameter of 18 mm, 22 mm, 24 mm respectively. The experiment had been conducted by changing the heat pipes of the collector (VTSS). The output responses such as heat output, thermal resistance and overall efficiency has been analyzed with respect to each heat pipe experimentally by using commercial Design of Expert version DX 9 software by using Box- Behnken design of Response Surface Method (RSM). Contour diagram shows the factors effecting and thermal behaviour of the heat output, thermal resistance and overall efficiency has been shown. From the mathematical results and RSM optimization it is concluded that experimental setup integrated with circular heat pipe gives higher heat output and overall efficiency with less thermal resistance.

Introduction

Solar collector technology has become a hot topic with the increasing demand of new generation sustainable energy sources in recent years. The global society is in demand of increasing energy supply and the fossil fuels/sources now in use are exporting vast CO and other harmful emissions at the same time. Both government and industrial sectors are now trying to reduce emissions and improve technological innovations. In search of renewable and clean energy technology, solar collector has been proved to have promising applications in water heating, refrigeration, water desalination, space heating/cooling, heat pumps, combined energy supply, etc. It is reported that both in developed countries and developing countries solar water heating technology can be one economical choice for its simplicity as a renewable source. Flat plate collectors have been in service for a long time without any significant changes in their design and operational principles typically, conventional solar collectors (SC) use water pipes attached to the collecting plate where water circulates either naturally or forcibly and transfers the heat it collects to a storage tank. Some of the shortcomings of this type of solar collector systems include: the additional expense of a pump and the power to operate it; the extra space required for any natural circulation system; the corrosive effect of water; an, the limited quantity of heat transferred by the fluid. Heat pipes are structures of very high thermal conductance. They permit the transport of heat with a temperature drop, which are several orders of magnitude smaller than for any solid conductor of the same size. follow.

Heat pipes consist of a sealed container with a small amount of a working fluid. The heat is transferred as latent heat energy by evaporating the working fluid in a heating zone and condensing the vapour in a cooling zone, the circulation is completed by return flow of the condensate to the heating zone through the capillary structure which lines the inner wall of the container. [1-4]. The heat pipe is suitable for a wide range of applications including solar collector. Thus, solar collectors with heat pipes have a lower thermal mass, resulting in a reduction of start-up time [4].Thermal diode is important in designing of solar collectors, where heat is transferred only from the evaporator to the condenser, but never in the reverse direction. This feature can cut off the heat loss when the absorber temperature is lower than that of the liquid in the heat exchanger [5-9].Several studies on heat pipe solar collectors are reported in the literature. Riffat, [5] studied developing a theoretical model to investigate thermal performance of a thin membrane heat-pipe solar collector. In their work thin membrane heat pipe solar collector was designed and constructed to allow heat from solar radiation to be collected data relatively high efficiency while keeping the capital cost low.

Azad [10] investigated the heat pipe solar collector theoretically and experimentally, and the optimum ratio of heated length-cooled length of the heat pipe. Hull [11] investigated heat transfer factors and thermal efficiency for heat pipe absorber array connected to a common manifold and predicted that array with less than ten heat pipes have significantly less efficiency than conventional flow-through collector. Hussein [12] investigated the different design parameters of the natural circulation two phase closed Thermosyphon flat plate solar water heaters using the verified expanded model.

Saravanan and Karunakaran [13] investigated the V-type absorber plate solar collector with heat pipe shows great potential in terms of higher absorption per unit area as compared to other conventional solar collectors.

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Ramkumar and Ragupathy [14] Response surface methodology (RSM) is a collection of mathematical and statistical techniques for developing, improving and optimizing the process parameters by design of experiments. Senthil kumar [15]. The objective is to optimize the output variable which is influenced by independent input variables. An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response. The objective of present study is to optimize V-Trough solar simulator (collector) with heat pipe operating parameters like heat input, angle of inclination and mass flow rate of cooling water by response surface methodology on the performance of Copper–Deionised water heat pipe with stainless steel wire mesh wicks. This paper analyse the experimental work done and the prediction of empirical relations for heat output, thermal resistance, overall efficiency of simulator using response surface methodology . Therefore in the present study V - Trough solar collector was tested at real conditions in indoor test facility.

Response Surface Methodology

The experimental performance of the V-trough solar collector is analysed by Response surface methodology using Design of Expert software. Box-Behnken design method is employed with three input parameters namely inclination angle (A), heat input (B) and mass flow rate of water (C) with respect to three responses namely heat output (R1), thermal resistance (R2) and overall efficiency (R3) .table 1 shows the process parameter and their coded levels.

Table 1. Process Parameter

Parameter	Level		
	-1	**0**	**1**
A Angle of inclination, deg	30	45	60
B Heat input, W/m^2	450	900	1350
C Flow rate, ml/min	100	110	120

Experimental setup

A prototype of V -Trough solar simulator with three different heat pipes was designed and tested at indoor test facility of Mechanical measurements lab of Annamalai University. V -Trough solar simulator with heat pipe is designed to collect and distribute heat by means of vaporization and condensation of a heat transfer fluid is shown in Figure 1. The specifications of heat pipe and solar simulator are shown in Table 2. It comprised mainly three copper heat pipes with outside diameter of 18 mm for circular, 22 mm for elliptical and 24 mm for semicircular with an evaporator length of 630 mm while the wick consisted of two layers of 100-mesh stainless steel screen fitted to the evaporator section. The evaporator section of the heat pipes are placed in V-trough solar simulator. The experimental setup consists of heat pipe, V-trough solar simulator and Water storage tank. The heat pipe are placed on the grooved absorber plate and tied in a flat plate solar simulator. Working fluid used in the heat pipe was Deionised water. Glass wool insulation was provided below the absorber plate for reducing the conduction losses, the sides of the absorber plate are covered using thermo cool insulator for minimizing the convective losses. The glass plate is used for reducing the radiation losses. By reradiating the heat emitted by the absorber plate in the form infrared rays. Number of glass plates used one or two, if not most of solar radiation will get refracted. Solar power meter was used to measure the solar intensity in W/m^2. The surface temperature of heat pipes, absorber plate and glass plate temperatures was measured using eight K-Type. All the thermocouples were connected to the temperature indicator. The uncertainty in temperature measurement was ± 0.1°C. Flow to condenser section was controlled by rotameter and flow rate was maintained at 100,110 and 120 ml/min.

Table 2. Specifications of Heat pipe and Solar collector

Parameters	**Specifications**
Heat pipe	
Length of heat pipe	900 mm
Evaporator length	630 mm
Adiabatic length	120 mm
Condenser length	180 mm
Outside diameter of heat pipe	19 mm, 22 mm,24 mm
Thickness of the heat pipe, t	1.2mm
Mesh number	50
Wire diameter	0.1 mm = 1 x $(10)^{-4}$ m
No. of layers of wire mesh	2
Container material	Copper
Solar Collector	
Length of solar collector	630 mm
Breadth of solar collector	400 mm
Height of solar collector	150 mm
Insulation	Mineral wool
Artificial Lighting System	
6 Lamps of 300 W	1800 W

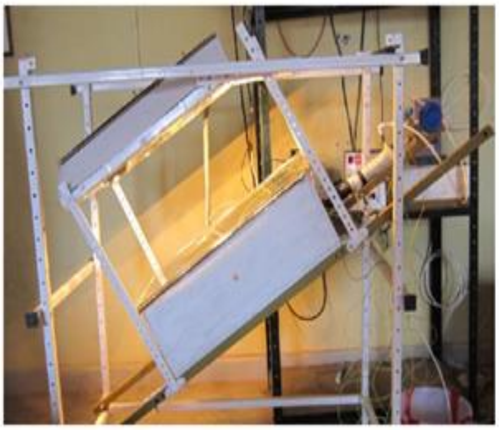

Figure 1. Photographic view of Experimental setup.

Table 3. ANOVA table for response heat output of circular heat pipe.

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	69664.28	9	7740.48	642.91	< 0.0001	significant
A-Angle	7059.94	1	7059.94	586.38	< 0.0001	
B-Heat input	59746.89	1	59746.89	4962.46	< 0.0001	
C- Flow rate	784.44	1	784.44	65.15	< 0.0001	
AB	1568.87	1	1568.87	130.31	< 0.0001	
AC	29.17	1	29.17	2.42	0.1635	
BC	29.17	1	29.17	2.42	0.1635	
A^2	218.37	1	218.37	18.14	0.0038	
B^2	218.37	1	218.37	18.14	0.0038	
C^2	30.71	1	30.71	2.55	0.1543	
Residual	84.28	7	12.04			
Lack of Fit	84.28	3	28.09			
Pure Error	0.000	4	0.000			
Cor Total	69748.56	16				
Std. Dev.	3.47		R-Squared		0.9988	
Mean	137.36		Adj R-Squared		0.9972	
C.V. %	2.53		Pred R-Squared		0.9807	
PRESS	1348.45		Adeq Precision		87.272	

Table 4. ANOVA table for thermal resistance of circular heat pipe.

Source	Sum of Squares	Mean Square	F Value	p-value Prob > F	
Model	0.028957	0.003217	36.84032	< 0.0001	significant
A-Heat input	0.016857	0.016857	193.0194	< 0.0001	
B-Angle	0.003024	0.003024	34.62862	0.0006	
C-Flow rate	0.001201	0.001201	13.74603	0.0076	
AB	0.000107	0.000107	1.226275	0.3047	
AC	0.000915	0.000915	10.4777	0.0143	
BC	6E-06	6E-06	0.06873	0.8007	
A^2	0.001327	0.001327	15.19021	0.0059	
B^2	8.14E-05	8.14E-05	0.931682	0.3666	
C^2	2.84E-05	2.84E-05	0.325108	0.5864	
Residual	0.000611	8.73E-05			
Lack of Fit	8.72E-05	2.91E-05	0.221729	0.8769	not significant
Pure Error	0.000524	0.000131			
Cor Total	0.029568				
Std. Dev.	0.009345	R-Squared	0.979324		
Mean	0.243429	Adj R-Squared	0.952741		
C.V. %	3.839011	Pred R-Squared	0.883531		
PRESS	0.0034444	Adeq Precision	19.49726		

Results and Discussions

The computed values of the heat output, thermal resistance and overall efficiency are entered in the software design matrix. The RSM is used to develop the empirical relationship between experimental variables and the responses are heat output, thermal resistance and overall efficiency. A regression analysis is carried out to develop a best fit model to the experimental data, which are used to generate response surface plots. The Table 3, 4 shows the analysis of variance of variance (ANOVA) for all the three output parameters of V-Trough solar collector with circular heat pipe. For the present work, (A) Angle of inclination and (B) Heat input are producing significant effect than flow rate(C). The square valves 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 effect on heat output than heat input and flow rate (AC) and angle of inclination on the flow rate (BC) on heat output.The predicted Model F-value of 642.91 implies the model is significant. There is only a 0.01% 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, AB, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. Based on ANOVA, the following emprical relation is developed to predict the heat output of heatpipe.

Heat output=138.63157+29.706765×A+86.41×B+9.90× C+19.80× AB+2.70× AC+2.70× BC -7.20×A^2 +7.20× B^2-2.70×C^2.

Similarly, The Model F-value of 28.15 implies the model is significant. model terms are significant.In this case A, B, B^2, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.The "Pred R-Squared" of 0.5698 is not as close to the "Adj R-Squared" of 0.9385 as one might normally expect.A ratio greater than 4 is desirable.your ratio of Your ratio of 18.733 indicates an adequate signal. This model can be used to navigate the design space.

Thermal Resistance = 0.123+0.011×A-0.055×B+0.005×C-0.012× AB + 0.005×AC-0.0121×BC-0.002×A^2+0.017×B^2-0.014 × C^2.

Similarly, The Model F-value of 36.49 implies the model is significant. There is only a 0.01% chance that an 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, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Pred R-Squared" of 0.6661 is not as close to the "Adj R-Squared" of 0.9523 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effectors a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs."Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 21.777 indicates an adequate signal. This model can be used to navigate the design space.

Overall Efficiency = 52.66+10.66×A+8.09×B+3.93 ×C+2.51 ×A×B+1.03×AC-0.68BC-3.70×A^2-1.31×B^2-0.057×C^2.

It is observed from Figs. 2 to 4 that the heat output of heat pipe increases linearly with an increase the heat input and angle of inclination in the evaporator section of V-Trough solar collector. The heat input and thermal resistances not affecting the mass flow rate at condenser section. The heat output of heat pipe increases with the heat flux, due to temperature gradient between the evaporator section of V-Trough solar collector and condenser section. For higher values of heat input in the evaporator section, the heat generated in the surface is more and the working medium which is in the form of vapour moves vigorously in to condenser section. The cooling waters in the condenser absorber this excessive heat and as a result, the efficiency of heat pipe increases. The thermal resistance (R_{th}) of the heat pipe is defined as ratio of temperature difference between the evaporator and condenser to the heat supplied to evaporator.

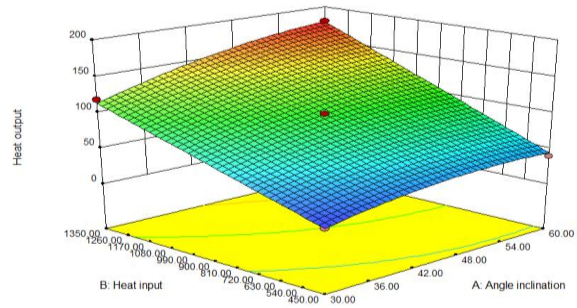

Figure 2. Effect of heat input and angle of inclination to the heat output

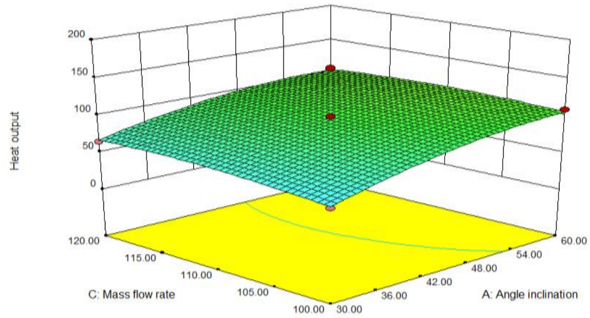

Figure 3. Effect of mass flow rate and angle of inclination to the heat output

From Figs. 5 to 7, thermal resistance of heat pipe decreases with increase with heat input and inclination angle of heat pipe. Mass flow rate is not affecting thermal resistance. Overall efficiency of the collector is the ratio of heat output to the total heat input over the evaporator section of heat pipe. It was found that whenever heat input and angle of inclination increases the overall efficiency of the setup also increases and the mass flow rate not affecting the efficiency.

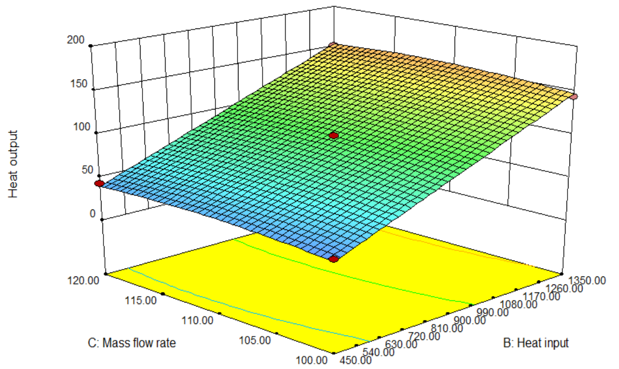

Figure 4. Effect of mass flow rate and heat input to the heat output

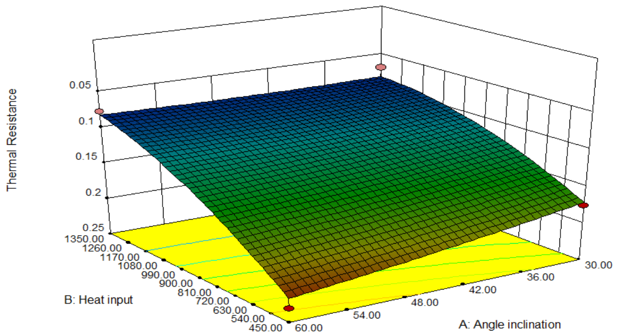

Figure 5. Effect of heat input and angle of inclination to the thermal resistance

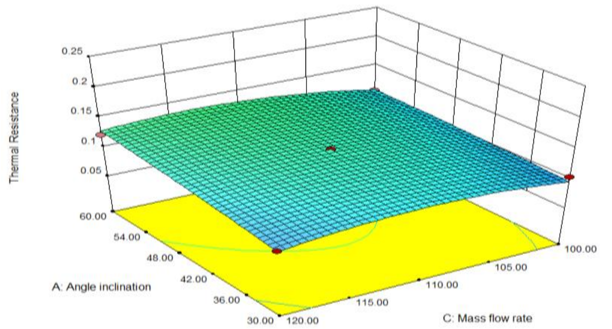

Figure 6. Effect of mass flow rate and angle of inclination to the thermal resistance

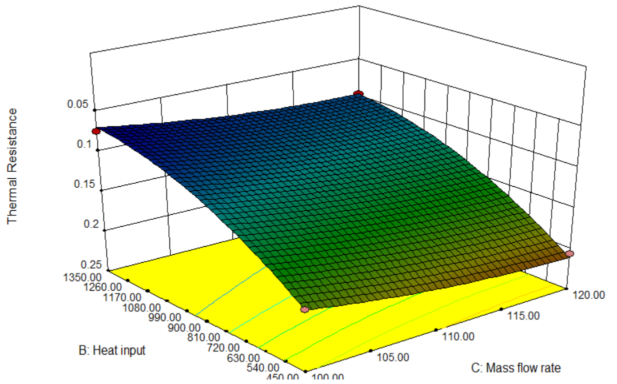

Figure 7. Effect of mass flow rate and heat input to the thermal resistance

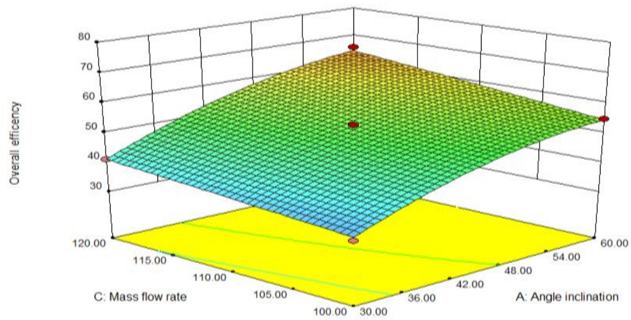

Figure 8. Effect of mass flow rate and angle of inclination to the overall efficiency

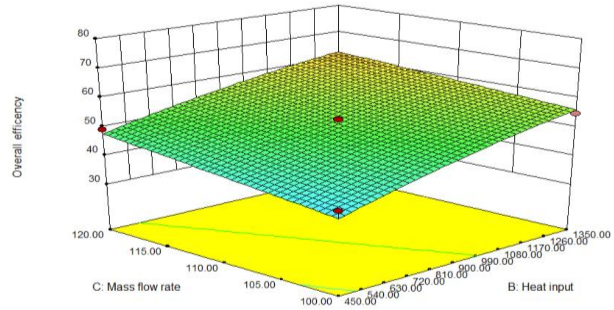

Figure 9. Effect of mass flow rate and heat input to the overall efficiency

Experimental Results

The experimental was conducted on V-Trough simulator using three different heat pipes i.e. Circular, Semi-Circular and Elliptical with respective input parameters has been done. Using observed values results has been calculated by mathematical expressions.

i) Circular heat pipe: When Circular heat pipe is used in the setup maximum heat output of 277.26 W and maximum Overall efficiency of 68.22% is attained with 0.078 $°C/Wm^2$ of Thermal resistance with input parameters of 60° angle of inclination, 1350 w/m^2 heat input and 110 ml/min flow rate.

ii) Semi-Circular heat pipe: When Semi-Circular heat pipe is used in the setup maximum heat output of 178.24 W and maximum Overall efficiency of 45.14% is attained with 0.128 $°C/Wm^2$ of Thermal resistance with input parameters of 60° angle of inclination, 1350 w/m^2 heat input and 110ml/min flow rate.

iii) Elliptical heat pipe: When Elliptical heat pipe is used in the setup maximum heat output of 178.24 W and maximum Overall efficiency of 45.14% is attained with 0.10 $°C/Wm^2$ of Thermal resistance with input parameters of 60˚ angle of inclination, 1350 w/m^2 heat input and 110ml/min flow rate.

Conclusion

Optimization of the input parameters has been done using Box-Behnken design of RSM method with Design of Expert (version 9) software. It concludes that

i) *Circular heat pipe*: Optimum input parameters of the setup integrated with circular heat pipe obtained from RSM method are, 55.23° angle of inclination, 1345.59 W/m^2 Heat input and 102.73 ml/min.

ii) *Semi-Circular heat pipe*: Optimum input parameters of the setup integrated with semi-circular heat pipe obtained from RSM method are, 57.55° angle of inclination, 1269.46 W/m^2 Heat input and 118.26 ml/min.

iii) *Elliptical heat pipe*: Optimum input parameters of the setup integrated with Elliptical heat pipe obtained from RSM method are, 46.53° angle of inclination, 1094.85 W/m^2 Heat input and 105.67 ml/min.

From the above mathematical results and RSM optimization it is concluded that experimental setup integrated with circular heat pipe gives higher heat output and overall efficiency with lesser thermal resistance.

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