Heat Pipe Performance Optimization: A Taguchi Approach

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Abstract

Heat pipe performance depends on a number of factors. This study uses Taguchi method to investigate the effects of wick structure, heat pipe diameter, and working fluid on the thermal conductivity of the heat pipe. To study the effect of these factors, orthogonal array "L8" was used. A test rig with the required measuring instruments was designed and assembled to perform the study. Results show that wick structure type is the highest parameter affecting the thermal performance of the heat pipe, followed by the pipe diameter and finally the working fluid. Further, results show that the heat pipe that has the best performance has a thermal conductivity that is about 114.33 times that of copper. Finally, two solar collectors are designed. The first one uses heat pipes with parameters similar to those of the best performing heat pipe, while the second one is a conventional solar heater. Results show that the heat pipe solar collector performs better than the conventional solar collector in many respects. The heat pipe solar collector shows a Coefficient Of Performance (COP) increase of 185% compared to conventional solar collectors under the same conditions.

Keywords

Heat pipes, solar collectors, Taguchi method, experimental design, optimization

I. Introduction

Heat pipes are high thermal conductance devices that have the ability to transport large amounts of heat along the direction of fluid flow with a very small temperature drop. There are number of parameters which govern the heat pipe performance such as powder size, wick thickness, material, working fluid, wick structure, shape, diameter, and length of heat pipe. In order to design a heat pipe for any application, all these parameters must be first identified, then interpretations are made to specify and select the most critical parameters while working on improving heat pipe performance and increasing its thermal conductivity.

Heat pipe is divided into three sections, evaporator, adiabatic, and condenser. Heat is added through the evaporator section, where the working fluid is vaporized. The vapor is then passed through the adiabatic section to the condenser section. The vapor releases its latent heat and gets liquefied. The liquid then flows toward the evaporator section and the cycle continues.

Given the wide range of operating temperatures for working fluids, the high efficiencies, the low relative weights, and the absence of external pumps in heat pipes, these systems are seen as attractive options in a wide range of heat transfer applications [1-4]. Some examples are electronic component production, assembly and storage film drying, processing and storage, drug, chemical and paper manufacturing and storage, candy, chocolate processing and storage, swimming pool enclosures, hospital operating rooms, grocery stores, telephone exchanges, relay stations, clean room, underground silos, nuclear radiators, air conditioning and solar collectors [1-4].

Most of the previous studies focused on optimizing the configuration of heat pipes solar collector rather than optimizing heat pipes themselves [5-6]. Further, this study deals with the very special and exceptional conditions in Gaza Strip due to the imposed siege since 2006. Under the siege, imports are only allowed for very basic humanitarian needs. This situation is further aggravated by the fact that electricity supplies are always interrupted for 5-8 hours daily. Therefore, the challenge in this study is twofold. First, the study had to be performed given all the limitations and thus use only available equipments and instrumentation. This has an impact on the choice of the parameters to be studied and optimized in this study, in addition to the equipment used in designing the prototype application of the heat pipe solar heater. In other words, the equipments used are only those available in local markets. Second, the study would attempt to alleviate the consumption of electricity through obtaining hot water using the freely available sun rays by introducing a more efficient use of sun rays. Therefore, this study is well suited for geographical areas in developing countries where there is mainly no access to high tech. and other resources. The experimental design in this study uses the Taguchi method.

Taguchi experimental design is a design that differentiates between control factors and noise or uncontrollable factors and treats them separately by means of special design matrices called Orthogonal Arrays (OA) [7]. The use of these arrays helps to determine the least number of experiments needed for a given set of factors.

This paper is organized as follows: Section II deals with the design, manufacturing, and assembly of heat pipes, while section III describes the designed test rig used to study the heat pipe performance. Section IV describes the experimental design. Section V shows the experimental procedures. Results and analysis are given in section VI. Section VII details the proposed solar heater using heat pipes and discusses the results. Conclusions are given in section VIII.

II. Heat pipe design, manufacturing and assembly

Copper tubes having outer diameters of 3/8" (0.95 cm) and 5/8" (1.59 cm) and inner diameters of 0.74 cm and 1.31 cm and length of 25cm are selected. Heat pipe dimensions and are shown in fig. (1a and 1b). The steps used to produce the sintered and mesh wick structures are detailed below.

The sintered wick structure was made from pure red copper powder having particle size ranging between 200 and 350 µm grades. 20 mm3 of copper powder was mixed with 20% (4 mm3) of sodium carbonate ($Na_2 Co_3$) that acts as a binder to ensure the adhesion of the wick to the copper pipe wall. A mandrel with an end cap was inserted in the copper pipe in order to leave a central vapor channel open. The powder with the binder was then placed in the annulus between the mandrel and the pipe and compacted to eliminate any gross cavities in the wick. The pipe, the powder and the mandrel were then heated in an electric furnace at 850 °C for ½ hour. Then, the pipe was cooled and the mandrel was removed.

Pipe edges were welded and pipes were evacuated using a vacuum pump until the pressure inside the pipe became approximately 3 Pounds per Square Inch (PSI). The working fluid was then injected into the heat pipe. The pipes with sintered wicks were filled with a working fluid percentage of 50% of the evaporator section volume [2]. Pipes with mesh wicks were filled with a percentage of 70% of the evaporator section volume [4]. Acetone and water were used as working fluids since their operating temperatures are within the temperature range in Gaza Strip (20-50°C). The specifications of the manufactured heat pipes are shown in Table 1. After performing the previous steps, heat pipes were ready for testing using the test rig described in the next section.

Table 1: Working fluid filling ratios and volumes.

Outer diameter (cm)	Inner diameter (cm)	Volume of evaporator (cm³)	Wick structure	Filling ratio (%)	Volume of working fluid (cm³)
0.95	0.7445	2.176	Mesh	70	1.52
			Sintered wick	50	1.09
1.59	1.3075	6.731	Mesh	70	4.69
			Sintered wick	50	3.35

III. Test Rig design

Fig. 2 shows a schematic of the designed test rig that was used in the experiments in which all the heat pipes were fixed to operate in a horizontal position. The test rig includes a water jacket connected to a 13 W water pump. The input current was measured using a clip meter, while two thermometers were used to measure the inlet and outlet water temperatures. Heat was applied to the evaporator using an electrical heater that was connected to a voltage regulator to control the evaporator surface temperature. The condenser section was cooled using a water jacket. Temperature on the surface was measured using two thermocouples located at midpoints of evaporator and condenser and they are 20 centimeters apart.

IV. Design of experiments

The experiments were designed by OAs using L8 with some modifications to fit the condition of the parameters. Table (2) shows the different levels of the factors used. These factors are wick structure, diameter, and working fluid. Eight experiments and eight replicates were performed to study the effect of parameters on the thermal conductivity.

Table 2: Levels of control parameters

Factors	Level 1	Level 2	Level 3	Level 4
Wick structure	Mesh 0.5 mm	Mesh 1 mm	Mesh combination 0.5 mm and 1 mm	Copper Sintered Wick
Diameter	3/8”	5/8”	____	____
Working fluid	Water	Acetone	____	____

V. Experimental procedure

The test rig was turned on for three hours till the difference in temperatures between the evaporator and condenser temperatures was 6 °C or less which approximates a steady state was reached [2]. The evaporator section temperature was maintained at 30 °C. The temperature readings were taken till the difference between condenser and evaporator temperatures reached 0.5 to 0.1 °C. At steady state, the amount of input heat (Watt) from the volt regulator is computed as follows:

$$Q_{input} = V \ \cos\theta$$

Where:
V: Input voltage (Volt).
I: Input current (Ampere).
Cos θ: the power factor.
The amount of output heat transferred to the cooling water is computed using equation

$$Q_{Output} = m^{\bullet}_{c.w} Cp_{c.w} \ (T_{cw,o} - T_{cw,i})$$

Where:

$m^{\bullet}_{c.w}$: Mass flow rate of cooling water (kg/sec)
$Cp_{c.w}$: Specific heat of cooling water which is 4186 J/kg.°C.

$T_{cw,o}$: Cooling water outlet temperature (°C).

$T_{cw,o}$: Cooling water inlet temperature (°C).
The heat flux q (W/m²) was calculated using equation

$$q = Q_{Output} / A_{ev}$$

Where:

A_{ev} : inner surface area of the evaporator section . $A_{ev} = \pi d_i L_{ev}$
Where d_i and L_{ev} are the inner heat pipe diameter (m) and evaporator length (m) respectively.
The heat transfer coefficient U (W/m².°C) was calculated using equation .

$$U = q / (T_{w,ev} - T_{w,c})$$

Where the temperatures represent surface temperatures of the evaporator and condenser respectively.

Finally, thermal conductivity K in (W/m. °C) is calculated using equation

$$K = U \times t$$

Where: $T_{w,ev} and T_{w,c}$ represent the surface temperatures of the evaporator and condenser respectively.
t: The distance between the thermocouples at the condenser and the evaporator which is 0.2 m.

VI. Results and analysis

Table 3 shows the heat pipe thermal conductivities of the experiments and replicates. The last column shows the ratio obtained by dividing the thermal conductivity by that of copper. It is noted that the thermal conductivity of the best performing heat pipe is 114.34 times that of copper thermal conductivity.

Table 3: Thermal conductivity obtained for each experiment

No.	Wick Structure (A)	Diameter (B)	Working Fluid (C)	Thermal Conductivity Experiment (W/m. °C)	Thermal Conductivity Replicate (W/m. °C)	Average (W/m. °C)	Ratio
1	Mesh 0.5 mm (1)	0.95 (1)	Water (1)	2352.72	2334.52	2343.62	5.945
2	Mesh 0.5 mm (1)	1.59 (2)	Acetone (2)	3411.24	3500.11	3455.68	8.77
3	Mesh 1 mm (2)	0.95 (1)	Water (1)	2252.61	2162.5	2207.56	5.60
4	Mesh 1 mm (2)	1.59 (2)	Acetone (2)	2640.28	2656	2648.14	6.72
5	Mesh (1+0.5)mm (3)	0.95 (1)	Acetone (2)	2088.78	2196.29	2142.54	5.44
6	Mesh (1+0.5)mm (3)	1.59 (2)	Water (1)	3575.38	3607.88	3591.63	9.12
7	Copper wick (4)	0.95 (1)	Acetone (2)	2202.55	2402.78	2302.67	5.84
8	Copper wick (4)	1.59 (2)	Water (1)	40759.35	49340.26	45049.81	114.34

A. Average and Main Effect of Factors

Table 4 shows the main effect of factors under study. Since the quality characteristic was the bigger is better, the main effects that present the optimum condition was A4 B2 C1 which represents the condition of sintered copper wick structure, 5/8" diameter and water as a working fluid. This condition is the eighth experiment from the Table 4. Further, the factors can be ranked according to their effect on the thermal conductivity of the heat pipe by noticing the Delta column in Table (4). It is clear that Wick structure has the greatest effect followed by heat pipe diameter and finally working fluid.

Table 4: The main effects of factors

Factors	Level 1	Level 2	Delta	Level 3	Level 4
Wick structure A	$\overline{A}_1 = 2899.64$	$\overline{A}_2 = 2427.85$	21248.38	$\overline{A}_3 = 2867.08$	$\overline{A}_4 = 23676.23$
Diameter B	$\overline{B}_1 = 2249.09$	$\overline{B}_2 = 13686.31$	11437.21	——	——
Working fluid C	$\overline{C}_1 = 13298.15$	$\overline{C}_2 = 2637.25$	10660.9	——	——

B. Signal To Noise Ratio

To analyze the effect of each factor, signal to noise(S/N) ratio which is a log function of desired output. It serves as the objective function for optimization and helps in data analysis and prediction of optimum results was used as a statistical measure of performance.

$$S/n = -10\log_{10}\left[\frac{\sum 1/Y_1^2}{n}\right]$$

Table 6 shows the main effect of S/N ratio.. It is noted that Experiment 8 has the largest S/N ratio, which means that it is the optimal experiment and its levels are the ones that maximize the performance in this study.

Table 5: The S/N ratio of factors

Experiment	S/N ratios
1	67.39
2	70.77
3	66.87
4	68.46
5	66.61
6	71.11
7	67.22
8	92.96

Table 6: S/N ratio mean effect

Factors	Level 1	Level 2	Level 3	Level 4
Wick structure (A)	$A_1 = 69.08$	$A_2 = 67.67$	$A_3 = 68.86$	$A_4 = 80.16$
Diameter (B)	$B_1 = 67.03$	$B_2 = 75.85$	——	——
Working fluid (C)	$C_1 = 74.61$	$C_2 = 68.27$	——	——

It is observed from Table (7) that using the S//N ratio for the mean effect of the parameters would yield that the optimum is A4 B2 C1 which represents sintered copper wick structure, large diameter and water as a working fluid which is the same results obtained earlier.

VII. Heat Pipe Solar Collector Design

Heat pipes with design parameters similar to those of the heat pipe with the highest thermal conductivity were manufactured and used in a heat pipe solar collector as an application. The following paragraphs describe the components and procedure used in making the heat pipe solar collector.

A. Components

The heat pipe solar collector design incorporates main components which are heat pipes, evacuated glass tubes, copper header pipe, insulation, manifold casing and stainless steel frame, water tank, piping system,

Evacuated heat pipes and glass tubes form the heat absorption and transfer portion of the solar collector. The evacuated glass tube consists of two tubes made from a strong borosilicate glass. The outer tube is transparent to allow light rays to pass through with a minimal reflection. The inner tube is coated with a special coating (Al-N/Al) which features excellent solar radiation absorption and minimal reflection properties. The upper ends of the two tubes are fused together and the air trapped in the space between the two layers of glass is pumped out by subjecting the tubes to high temperatures.

A 2" diameter copper that works as a header. The condenser sections of the five heat pipes inserted inside the header.

A manifold casing made of black aluminum sheet with dimensions of 60, 30 and 10 cm.is used to protect the header. Inside the casing, thermal wool acts as an insulator. When the cold water enters the inlet of the copper header and passes around the condenser sections of the five heat pipes its temperature increases as it continues moving towards the outlet, then to the water piping system.

The Assembly procedures were as follows:

Five heat pipes were used in constructing heat pipe solar collector. 7 cm from the heat pipe are inserted inside the manifold casing to act as a condenser of 5 cm length and 2 cm as adiabatic section of the heat pipe. The rest of the pipe acts as an evaporator that is inserted in 18 cm long evacuated copper twin tubes. The diameters of inner and outer copper twin tubes are 2.54 cm and 3.8 cm.

The evacuated heat pipes are installed inside stainless steel frame at the end of the evaporator sections with length of 40 cm, width of 60 cm and height of 10 cm. The frame was tilted an angle of 45 to increase thermal performance of heat pipes to allow the working fluid return to the evaporator section by capillary action and gravity. The heat pipes were covered with a black aluminum sheet to work as an absorber of the sun rays. A schematic of the designed solar collector is shown in fig. 3.

After building the heat pipe solar collector with the predetermined design specifications, A 6 –liters tank was coated internally with thermal wool was installed to the system. In addition, a piping system was installed for the inlet and outlet opening of the solar collector and the water tank.

For testing the performance of heat pipe solar collector, a conventional solar collector with the same specifications was constructed. The heat pipe solar collector and conventional solar collector both were supplied with water of the same laminar flow rate.

The readings were taken on the same day by measuring the temperature of the hot water from the water tank outlet. According to the Palestinian meteorological department, the temperature in Gaza city on Monday 28/6/2010 was 29°C, the measurements were taken from 12:00p.m till 5:05 p.m. fig. 5 shows the heat pipe solar collector used in the study.

As shown in fig. 5 the HP solar collector outperformed the conventional solar collector. It is noted that the temperature of the HP solar collector rises at a higher rate than that of conventional solar collector. The highest reading for the HP solar collector was 44.6°C at 15:35 p.m. while the temperature of the conventional solar collector outlet at the same time was 37.9°C.

It is noticed that the temperature readings for the HP solar collector start declining at 3:35 p.m., on the other hand the conventional starts declining at 3:21 p.m. Further, it is also noticed that the declining rate of conventional solar collector much larger than HP solar collector readings. This adds an extra feature for the HP solar collector than the conventional. The performance of the HP solar collector was 23% better than the conventional at time 5:05 p.m. with a gap of 8 degrees. Further, it is noted that the last four readings in of the HP solar collector seem to be reaching a steady state and not declining.

Calculating the maximum Coefficient of Performance for each of the collectors using the equation

COP= MCp (Twf –Twin)/ Total input power

The improvement would be of the same magnitude as the ratio of the maximum difference in water temperature for both collectors. Thus, the ratio between the COPS equals 1.85. This suggests a 185% improvement.

VIII. Conclusions

In this study heat pipe thermal performance was optimized by conducting experiments using Taguchi approach. The effect of operating parameters on the thermal conductivity of heat pipes was analyzed. Sintered copper wick structure with an outer diameter of 1.58 cm and water as a working fluid was found to give the best performance. Its thermal conductivity was 114.43 times that of solid copper.

In spite of the limitations, a considerable improvement of the designed heat pipe solar collector was obtained compared to the conventional one..

It is recommended to construct HP solar collector with a parabolic configuration instead of flat one in order to increase the concentration of the sun rays that project on the collector surface. It is further suggested that more modern equipments, materials, be used since this one only used equipment and materials available during the siege where no imports are allowed.

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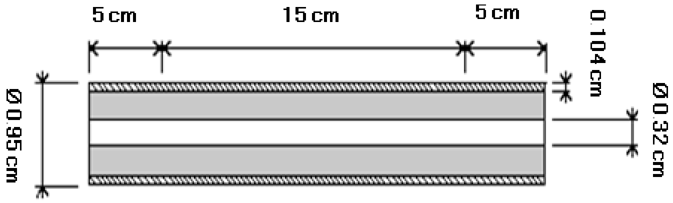

Fig. 1 A : 1st Heat pipe dimensions

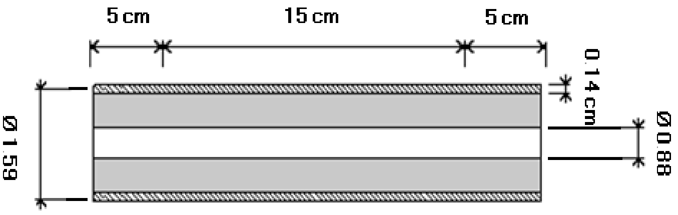

Fig. 1 B : 2nd Heat pipe dimensions

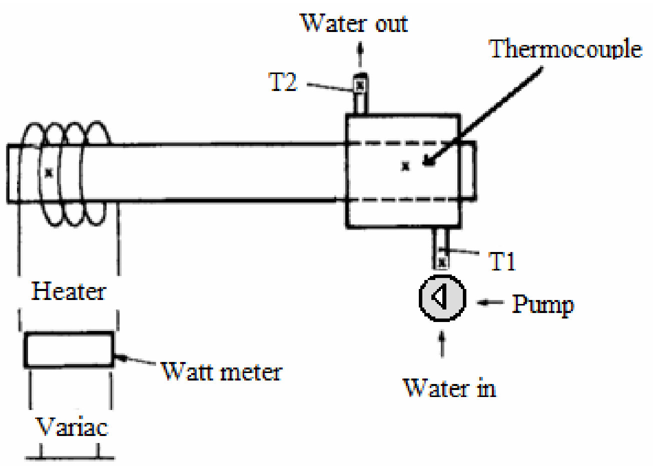

Fig. 2 : A schematic of the test rig

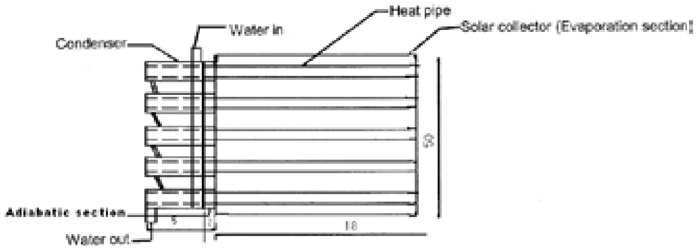

Fig. 3 : A schematic of the designed solar collector

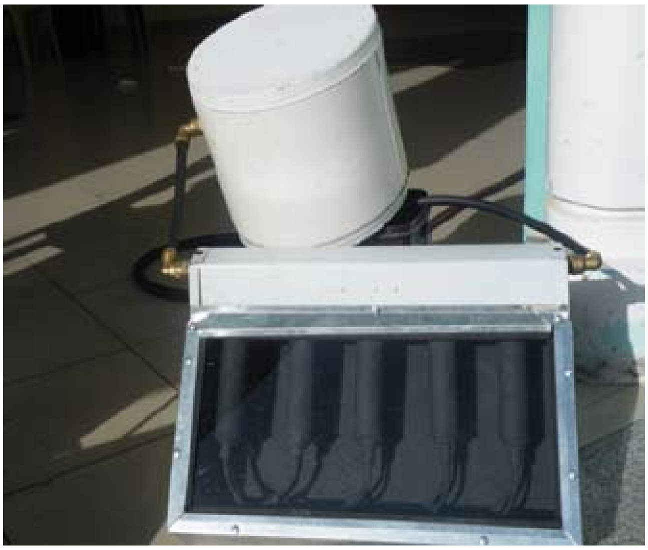

Fig. 4 : Solar Collector Assembled

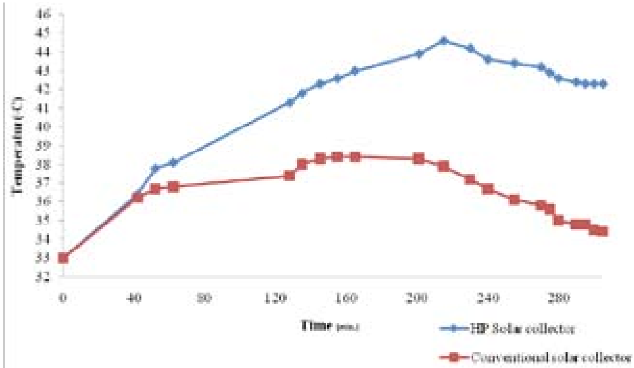

Fig. 5 : Outlet temperature readings of HP solar collector and conventional solar collector