Thermal Performance of a Heat Pipe with Different Working Fluids

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ABSTRACT

The use of Heat pipes, for a variety of applications, has increased worldwide due to them achieving high thermal efficiencies. Heat pipes in evacuated tube solar collector systems, in modern domestic water heating, comprise of a sealed envelope of a copper pipe, which contain a small quantity of working fluid. The Heat pipe transfers energy by the latent heat of the evaporation of the working fluid in a heating section. This vapor travels to the cold portion of the heat pipe and condenses. The circulation is completed with the condensate flowing back through the container's inner wall to the heating section by gravity. Tests were conducted using a test apparatus specifically made for the purpose of comparing the relevant attribute of thermal performance of Heat pipes containing different working fluids. A commercially available heat pipe, with its proprietary working fluid, was used as a reference in comparing its thermal performance efficiency (57.1%) with those of identical heat pipes containing distilled water, methanol, acetone and ethanol as working fluids. The results from the experiments achieved thermal efficiencies of 63.1%, 60.5%, 57.6%, and 42.1% respectively.

Keywords: Heat pipe technology; working fluid; efficiency; solar energy; evacuated glass heat pipe collector

1. Introduction

The evacuated tube consists of an outer and inner glass tube with a vacuum trapped between these glass sections. This allows for radiation to penetrate into a centrally located heat pipe, but prevents heat loss via dissipation. The heat pipe is located centrally inside the inner tube. The heat pipe normally consists of a long copper tube containing a very small quantity of the working fluid (e.g., water, acetone, methanol, ethanol, etc.) which forms the vehicle for moving heat to the cooler section of the copper tube. Each collector is made up of a frame, a manifold and a set of tubes –either 8, 12, 18 or 24 tubes, depending upon the geyser size.

There are various forms of heat pipes, which are commercially used in the solar collector panels. As shown in Figure 1, the structure is basically very similar with variations in the shape and size of the (upper portion) condenser [1, 2].

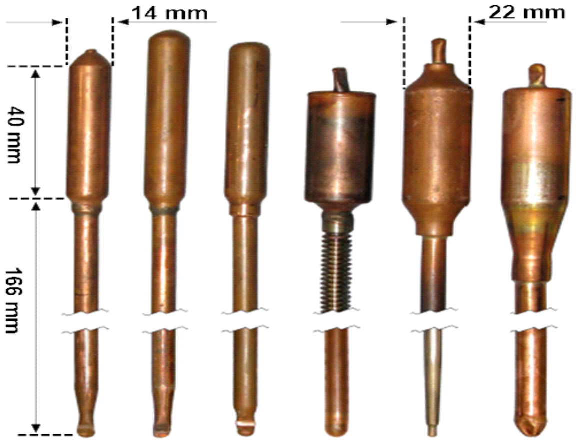

Figure 1: *Various geometrical forms of heat pipes* [1]

2. Heat Pipe Structure and Operation

The design of the heat pipe includes a long copper pipe with a larger diameter condenser at the top and welded at the other end. A small amount of working fluid is added into the heat pipe and then heated to high temperature, or a vacuum pump is used to remove the air from within the space. The result of either method is a vacuum in the copper pipe [3].

The vacuum inside the heat pipe allows the phase change of the fluid to a gas to occur at a lower temperature. The reason for this is to expedite the heat transfer process and create the continuous heat transfer cycle [4, 5&6]

The evacuated tube heat pipes typically found in solar collectors containing a small amount of working fluid have a boiling point of around 25 degrees Celsius as a result of the induced vacuum, so when heating the heat pipe above this temperature the working fluid begins to evaporate. The vapour rises to the condenser at the top of the heat pipe, where it condenses (giving off heat to the desired spot) and returns to the evaporation section at the bottom of the heat pipe. This process is repeated as a cycle [4, 5&7].

2.1 The Working Fluid

As stated before, the heat pipes can utilise various liquids as a working medium. Table 1 refers to the relevant properties of typical fluids that could be used.

Table 1: *Physical properties of Some Heat pipe working fluids* [8, 9].

Fluid	NBP (ºC)	ϱ(kg/m3)	Psat*(kPa)	µ**(kg/ms)	σ**(N/m)	λ (kJ/kg)
Water	100	1000	2.33	1.79 x10^{-3}	7.56 x10^{-2}	2256
Ethanol	78	789	5.95	1.77 x10^{-3}	2.41 x10^{-2}	846
Methanol	65	792	13.02	8.17 x10^{-3}	2.45x10^{-3}	1100
Acetone	56	784	30	4.1 x10^{-4}	2.4 x10^{-2}	518

* *The vapor pressure data are at 293 ºK., 20 ºC*
** *Surface tension and viscosity data are at 273 ºK., 0 ºC*

Some working fluids need a compatible vessel material to prevent and avoid chemical reactions or corrosion between the fluid used and the vessel. Chemical effects such as corrosion reduce the efficiency of the vessel, as a non-condensable gas can be produced by chemical reactions. For example, using ammonia as a working fluid in the heat pipe provides a temperature range from –70 to +60 ºC and is compatible with several vessel materials such as aluminum, nickel and stainless steel, but not copper [10]. In selecting a working fluid for use in a heat pipe application, the prime requirements are as follows, [11].

- Good thermal stability.
- Vapor pressures not too high or low over the operating temperature range.
- High latent heat.
- High thermal conductivity.
- Low liquid and vapor viscosities.
- Acceptable freezing or pour point.

The viscosity, sonic, capillary, entrainment and nucleate boiling limitations play important roles when selecting the working fluid [4, 5&6]. However, in the context of this research, the choice of the working fluid in the heat pipe will rest solely on the level of temperature achieved in the condenser part of the heat pipe. The reason adopted here is that this factor will govern the amount of heat that the heat pipe could transfer. In other words, the higher temperatures at the condenser will inherently be able to transfer more heat (comparatively speaking among heat pipes containing different working fluids) to the bulk of the fluid that is being heated. Therefore, internal heat pipe criteria such as the viscous limit, the sonic limit, the entrainment limit affecting the maximum heat flux, the capillary limit, etc., will be ignored and, the recommendation of which working fluid will best enhance the performance of the commercial evacuated heat pipe solar collector will depend entirely on calorific results [11, 12&13].

2.2 Energy Performance Analysis in the Heat Pipe Testing Apparatus

The energy performance indices to be obtained using a specially designed and constructed apparatus in this part of the study, will entail the energy collected from the sun simulator via the heat (using different working fluids) to equal the energy transferred by the heat pipe to the water in the apparatus's tank. In other words the efficiency of the heat pipe can be calculated in terms of heat transfer associated with the change of the internal energy of the water in the system. The heat input will be controlled using a solar simulator and the ambient temperature is not expected to change appreciably since the testing will be done in a laboratory.

2.3 Efficiency of Heat Pipe in Terms of Heat Transfer to Tank's Water

The efficiency of the heat pipe is calculated using the following formula, which involves the change of the internal energy of the water contained in the system's tank.

$$\eta_{hp} = \frac{(\Delta Q_u)/t}{I} m \times 100\%$$

Where η_{hp} is the heat pipe's efficiency (%) in terms of heat transfer to the tank's water, ΔQ_u is the change in the internal energy of the water in kJ/kg which is dependent on the temperature T and pressure P of the system, t is the solar irradiance time in hours, m is the mass in kg of water in the tank and I is the actual total solar radiation on the surface of the evacuated tube heat pipe, which is the irradiance kW/m^2 from the solar simulator multiplied by the heat pipe's actual receiving area of (0.08084 m^2).

3. A Rig for Testing the Performance of the Heat Pipe with Various Working Fluids

In order to test the performance of the heat pipe with various working fluids, an apparatus was designed and constructed consisting of a small geyser tank mounted on a frame. A heat pipe with its evacuated glass tube could easily be inserted and removed in a short turnaround time (see Figures 2 and 3). A single evacuated heat pipe assembly could be inserted in a dry bay attached to a tank which could accommodate four litters of water. Halogen floodlights mounted on a frame over the heat pipe assembly provided the heat source.

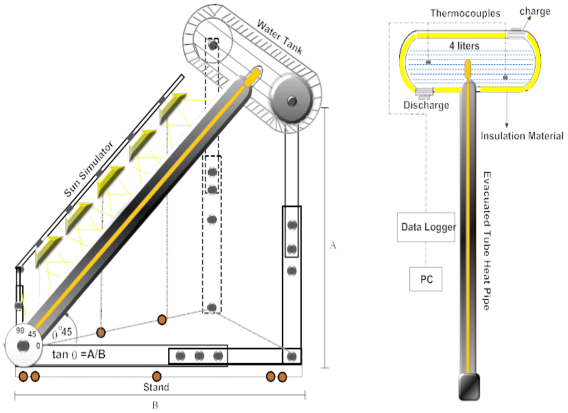

Figure 2: *Schematic diagram of the testing apparatus for the heat pipes.*

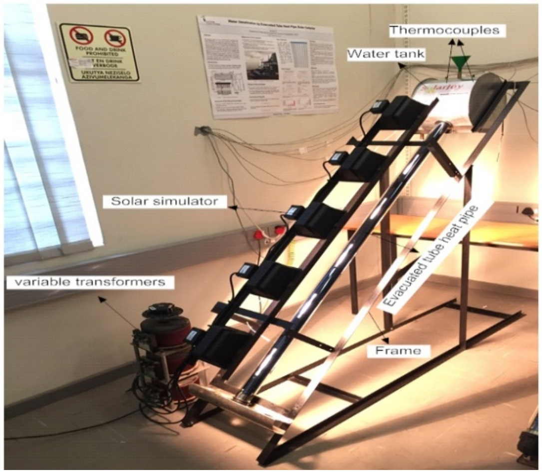

Figure 3: *The heat pipe's testing apparatus*

3.1 Tank Description

The cylindrical tank was made of 1.2 mm thick stainless steel sheet; with dimensions of 200 dia. and 150 mm long. An outer casing was built around the tank to cover the polyurethane insulation.

A brass heat pipe sleeve (14 mm internal diameter) was welded into the tank at a 45 degree angle to line up with the mounting frame of the heat pipe, tank and simulator.

In addition, two wells were built into the top of the tank to place thermo-couple sensors in order to record the temperature of the top and bottom fluid levels in the tank respectively. On the side of the tank a valve drain pipe was fitted with a 15 mm filling pipe fitted at the top. The halogen lights were controlled via a variable transformer thus regulating the simulated radiation on the heat pipe.

3.2 The Sun Simulator for the Heat Pipe Tester

The solar radiation simulator was used to heat the evacuated heat pipe. It consisted of an array of five halogen floodlights of 500 W each. The halogen lamps were distributed evenly over the length of the evacuated tube heat pipe, at a distance of 225 mm above it. The solar simulator's irradiance level was set to a level consistent with an average 800 watts per square metre, as measured over the evacuated heat pipe surface. The output of the sun simulator could be controlled by means of a variac (variable transformer) which controlled voltage supplied to the array of halogen lamps.

3.3 Frame

The frame was built using L shape mild carbon steel sections set for testing at a fixed angle of 45 degree.

4. Instrumentation for the Heat Pipe Tests

Two J-type thermocouples, one of them at the bottom and another at the top of the "geyser", were fitted to measure the water temperature in the storage tank, and, together with the ambient temperature, were recorded during the test period. A digital display data logger (Agilent-34972A) was used to record the temperature scale. All experiments were carried out for seven hours.

5. Testing the Heat Pipe Performance with Different Working Fluids.

The relatively elevated temperatures which are obtainable when using evacuated tube heat pipes in the field of water heating is the reason for the attempt to use them in the desalination of seawater.

The method followed in testing a set of working fluids in the heat pipe is described below:

Testing of the heat pipe's performance with various working fluids required a benchmark. This benchmark was obtained by first testing the commercial heat pipe (as it came from the manufacturer) with the original working fluid. Attempts to obtain information about the constitution of the working fluid, from the manufacturer in China, were unsuccessful. It was assumed that the liquid was water, but it had an orange/yellowish colour possibly because of some kind of additive. The fluid was drained and the heat pipe was charged with new fluid, after which the performance test was undertaken over the seven-hour period. It is worth mentioning here that the quantity of working fluid encountered in the commercial heat pipes varied considerably in the range of 5 to 10 ml; however this did not seem to affect their performance.

The raw data that was collected during each heat pipe experiment with the four working fluids consisted of recording the temperatures of the water at two locations in the tank's water, the irradiance from the solar simulator and the ambient temperature Ta. The duration of the individual tests was seven consecutive hours daily. The data displayed in Appendix A is a typical sample, where T_1 & T_2 are the tank's water temperatures (in degrees centigrade) recorded every 15 minutes via two thermocouples located at the top and bottom levels in the tank's water, using a data-logger. T_{a1}, T_{a2} and T_{a3} (Ambient temperature readings): these temperature readings, represented with their average value $T_{a\,avg.}$, were also recorded each 15 minutes via three thermocouples located around the heat pipe testing apparatus.

5.1 Results of the Heat Pipe Performance with Different Working Fluids

The purpose made testing apparatus was used in testing the performance of the heat pipes with four different working fluids. As already mentioned, the results from a test using one of the commercially available heat pipes was used as a benchmark in comparing their performance. The working fluids chosen were distilled water, methanol, acetone and ethanol. The experiments were conducted for the purpose of improving or better discovering the effect on the thermal performance and efficiency of the heat pipe, which was recharged with various working fluids at the same filling ratio by infusing always the same amount of working fluid (10 ml).

5.1.1 Results from the Experiments with the Testing Apparatus for the Heat Pipes

A summary of the results from testing the performance of the heat pipes with different working fluids appears in Table 2.

Figure 4 displays the behaviour of the temperature rise of the water in the tank of the heat pipe testing apparatus when testing each individual heat pipe, each containing a different fluid. Thus a direct comparison of their performance can be made.

Table 2: *The initial and final temperatures of the water, ambient temperature and the efficiency% of each heat pipe containing a particular working fluid*

	Description of the test	Initial& final temp. °C	Ambient temp. avg. °C	Efficiency%
1	Original heat pipe (Commercial)	16.2-71.8	21.8	57.1
2	Heat pipe with Pure water (Working fluid)	16.3-77.7	19.3	63.1
3	Heat pipe with Methanol (Working fluid)	16.4-75.3	19.3	60.5
4	Heat pipe with Acetone (Working fluid)	16.4-72.5	19.3	57.6
5	Heat pipe with Ethanol (Working fluid)	16.5-57.7	21.9	42.1

The efficiency of each heat pipe, characterised by the working fluid that it contains, is presented for comparison purposes in Figure 5. The addition of the average ambient temperature data during each test enables an enhanced or more informed comparison on the performance of the heat pipes. The ambient temperature plays a major role in the heat loss from the tank of the testing apparatus. This fact affects the heat loss from the water tank and hence affects the water's peak average temperature, reflecting in the heat pipe's efficiency calculation.

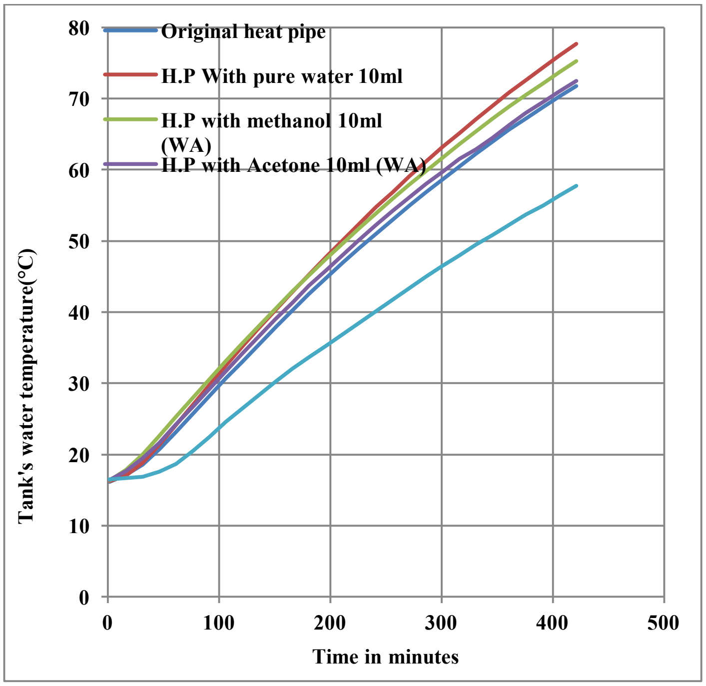

Figure 4: *Average water temperature in the tank of the testing apparatus for each heat pipe tested containing a different working fluid*

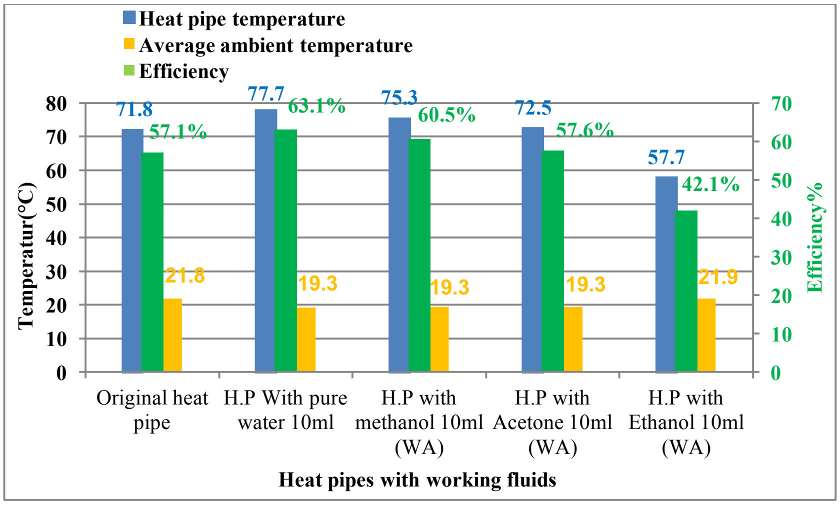

Figure 5: *Efficiencies of the heat pipe, bulk water temperatures in the heat pipe testing apparatus tank and average ambient temperatures*

5.1.2 Discussion of results with the testing apparatus for the heat pipes

The results of the experiments on different working fluids used in the evacuated tube heat pipe have shown that, of all the working fluids chosen in this study, i.e. pure water, methanol, acetone and ethanol, the former three performed well compared to the commercial working fluid.

In terms of ranking their performance, the pure water appeared superior to the others, with a thermal efficiency of 63.1%, followed by Methanol 60.5%, Acetone 57.6%, commercial working fluid 57.1% and Ethanol 42.1%. For a sample calculation of the heat pipe's efficiency in terms of heat transfer to the tank's water see Appendix B.

The averages of ambient temperatures during the tests when using methanol, water and acetone, as working fluids, were equal (19.3 ℃), which was colder/.lower than the average of ambient temperatures when testing with the commercial working fluid and ethanol in the heat pipe (21.8 ℃), as shown in figure 5.

It is not expected that such a small change in the ambient temperature would have affected the results significantly because the heat pipe's testing apparatus had a well-insulated tank. The additional heat losses to the environment (had all experiments been performed at the lower ambient temperature of 19.3 ℃), would be minimal and would have resulted in slightly lowering the efficiencies of the two heat pipes containing the commercial fluid and acetone respectively.

6. Conclusions

A totally separate, newly designed and constructed apparatus was used to test the performance of a heat pipe with various "working" fluids. The "commercial working fluid" inside the heat pipe was replaced each time with a different "working" fluid and individual experiments were performed. The results of these experiments in terms of the thermal efficiency of the heat pipe were compared as follows:

The heat pipe containing the:

- "Commercial" working fluid – thermal efficiency 57.1%
- "Pure water" – thermal efficiency 63.1%
- "Methanol" – thermal efficiency 60.5%
- "Acetone" – thermal efficiency 57.6%
- "Ethanol" – thermal efficiency 42.1%

From these experiments it is concluded that the thermal efficiency of the heat pipe was improved by 6% when distilled water was used, as opposed to the commercial working fluid. In the context of the heat pipe being used in an evacuated tube solar energy collector it is expected that such a system will improve its thermal efficiency (compared to the currently commercially available units), with heat pipes containing pure water, methanol or acetone (in this order) as working fluids.

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Appendixes

Appendix A

Typical data collected during the heat pipe tests for the various working fluids.

Testing the heat pipe containing pure water as a working fluid

	Date &Time	T_1 at top of the tank	T_2 at Bottom of the tank	Tavg.	Ta_1	Ta_2	Ta_3	Ta avg.
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
1	09/09/2015 09:01:20:061	16.4	16.1	16.3	17.6	18.1	17.9	17.9
2	09/09/2015 09:16:20:046	17.9	16.2	17.1	23.4	19.7	19.0	20.7
3	09/09/2015 09:31:20:046	20.5	17.3	18.9	24.0	20.3	19.6	21.3
4	09/09/2015 09:46:20:046	23.3	19.4	21.3	24.4	20.6	19.9	21.7
5	09/09/2015 10:01:20:046	26.3	22.0	24.1	24.8	20.9	20.2	22.0
6	09/09/2015 10:16:20:046	29.1	24.8	27.0	24.9	21.1	20.4	22.1
7	09/09/2015 10:31:20:046	31.9	27.7	29.8	24.8	21.1	20.4	22.1
8	09/09/2015 10:46:20:046	34.5	30.4	32.5	24.9	21.1	20.4	22.2
9	09/09/2015 11:01:20:046	37.2	33.2	35.2	24.8	21.1	20.5	22.1
10	09/09/2015 11:16:20:046	39.8	35.9	37.8	24.8	21.2	20.4	22.2
11	09/09/2015 11:31:20:046	42.3	38.5	40.4	24.8	21.2	20.4	22.2
12	09/09/2015 11:46:20:046	44.8	41.0	42.9	24.8	21.2	20.4	22.1
13	09/09/2015 12:01:20:046	47.2	43.4	45.3	24.7	21.1	20.4	22.1
14	09/09/2015 12:16:20:046	49.7	45.9	47.8	24.7	21.1	20.3	22.1
15	09/09/2015 12:31:20:046	52.1	48.2	50.1	24.7	21.1	20.3	22.0
16	09/09/2015 12:46:20:046	54.4	50.5	52.4	24.9	21.0	20.3	22.1
17	09/09/2015 13:01:20:046	56.8	52.7	54.8	25.0	21.0	20.2	22.1
18	09/09/2015 13:16:20:046	58.8	54.9	56.9	25.0	21.0	20.2	22.1
19	09/09/2015 13:31:20:046	61.2	57.0	59.1	24.9	20.9	20.2	22.0
20	09/09/2015 13:46:20:046	63.2	59.1	61.1	25.0	20.9	20.2	22.0
21	09/09/2015 14:01:20:046	65.3	61.1	63.2	24.9	20.9	20.2	22.0
22	09/09/2015 14:16:20:046	67.2	63.1	65.2	25.0	20.9	20.2	22.1
23	09/09/2015 14:31:20:046	69.2	64.9	67.1	25.2	21.0	20.3	22.2
24	09/09/2015 14:46:20:046	71.2	66.8	69.0	25.5	21.0	20.3	22.3
25	09/09/2015 15:01:20:046	73.1	68.6	70.8	25.4	21.1	20.3	22.3
26	09/09/2015 15:16:20:046	74.9	70.4	72.6	25.4	21.1	20.4	22.3
27	09/09/2015 15:31:20:046	76.7	72.1	74.4	25.5	21.1	20.4	22.3
28	09/09/2015 15:46:20:046	78.4	73.7	76.1	25.4	21.1	20.4	22.3
29	09/09/2015 16:01:20:046	80.1	75.4	77.7	25.4	21.1	20.4	22.3

Appendix B

Sample calculation of the heat pipe efficiency in terms of heat transfer to the tank's water when the heat pipe containing pure water as the working fluid

The efficiency of the heat pipe is calculated using the following formula, which involves the change of the internal energy of the water contained in the system's tank.

$$\mathbf{Efficiency} = \frac{\mathbf{Output}}{\mathbf{Input}} \times \mathbf{100\%}$$

$$\eta_{hp} = \frac{(\Delta Q_u)}{I \times t} m \times 100\%$$

Where η_{hp} is the heat pipe's efficiency (%) in terms of heat transfer to the tank's water.

ΔQ_u (kJ/kg), is the change in the internal energy of the water in the tester's tank that depends on the temperature *T* and pressure *P* of the system.

t is the duration of the time for the test (7 h x 3600 h/s); $m(kg)$, is the mass of the water in the tank and $I(kW)$, is the total solar radiation on the evacuated tube heat pipe, which is the irradiance R, kW/m^2 from the solar simulator multiplied by the heat pipe's receiving area of (0.08084 m^2).

1. Output

$$\Delta E(kJ) = \Delta Q_u \times m$$

$$\Delta E(kJ) = (Q_2 - Q_1)(kj/\mathrm{kg}) \times m(kg)$$

This sample calculation refers to the case of the heat pipe containing pure water as the working fluid; the initial and final temperatures obtained were 16.3 and 77.7 $^\circ C$ respectively.

$\Delta E = (Q_{77.7} - Q_{16.3}) \times m$

Linear interpolation was used to find the energy transferred between the temperatures from a standard table of saturated water.

$\boldsymbol{\Delta E(J)} = (325.3192 - 68.42258) \times 1000 \times 4 = \mathbf{1027586.48}\,\boldsymbol{J}$

2. Input

$R = 800\ W/m^2$

Assumed surface area of the evacuated tube heat pipe

$= 1.72m\ (length) \times 0.047m\ (dia) = 0.08084\ m^2$

$$I = 800W/m^2 \times 0.068\ m^2 = \mathbf{64.672}\ \boldsymbol{W}$$

$$\boldsymbol{t = 7h \times 3600s = 25200\ s}$$

$$\boldsymbol{I \times t = 64.672\ w \times 25200\ s\ = 1629734.4J}$$

$\eta\% = (\mathbf{1027586.48}\boldsymbol{J}/\mathbf{1629734.4}\boldsymbol{J}) \times 100 = \mathbf{63.1}\%$