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THEORETICAL AND EXPERIMENTAL HEAT TRANSFER ANALYSIS OF A FLAT PLATE COLLECTOR FOR A SOLAR THERMAL WATER PUMP

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ABSTRACT

A solar thermal water pump using a flat-plate collector is described. Two working fluids, Ether and *Chloroform, which* have low boiling points, are used in this pump. Heat-transfer analysis has been carried out for this system taking the majority of all heat losses into account. Variations in temperature and pressure of working fluids in the collection system with time are predicted. The temperature and pressure of working fluids as well as the temperature of collector plate are measured and compared with the predicted values. Variations in collector efficiency with time are discussed.

من بين إستخدامات الطاقة الشمسية التى ركز عليها فى الآونة الأخيرة استخدامها فى ضخ المياه. مما يساعد على ضخ المياه القريبة من السطح لإستخدامها فى رى الأراضى الزراعة فى الأماكن التى تكون بعيدة عن مصدر التيار الكهربى، كما يساعد فى تقليل استخدام المضخات البديلة التى تستخدم مصادر الطاقة التقليدية فى إدارتها مما يساعد فى تقليل تلوث البيئة الناتج عن مصادر الطاقة التقليدية. المضخة الشمسية المستخدمة فى هذا البحث ليس بها أى أجزاء متحركة ومتصلة بمجمع شمسى مساحته المعرضة للشمس ١ متر مربع وتعتمد فى تشغيلها على إستخدام وسط عامل ذو درجة غليان منخفضة ولايذوب فى الماء.

الهدف من هذا البحث هو تحليل انتقال الحرارة نظريا وعمليا للمجمع الشمسى المستخدم فى هذه المضخة فى حالة استخدام الإثير أو الكلوروفورم كوسط عامل مع الاخذ فى الإعتبار المفاقيد الحرارية المختلفة وذلك بهدف معرفة الضغط ودرجة الحرارة للوسط العامل فى المجمع الشمسى وكذلك فى الخزانات الملحقة به على مدار اليوم. يهدف البحث أيضا إلى حساب درجة الحرارة لنقاط مختلفة فى المجمع الشمسى وكذلك حساب المفاقيد الحرارية المختلفة.

ومن أهم نتائج هذا البحث مايلى:

وجد أن درجة حرارة الوسط العامل وكذلك درجة حرارة السطح السفلى للمجمع تزداد مع زيادة زمن اليوم حتى الظهر تقريبا ثم تأخذ بعد ذلك فى التناقص، ويحدث هذا أيضا بالنسبة لشدة الإشعاع الشمسى الساقط على المجمع.

وجد أيضا أنه مع زيادة درجة حرارة الوسط العامل أو زيادة شدة الإشعاع الشمسى الساقط على المجمع فإن المفاقيد الحرارية وكذلك كمية الحرارة المنتقلة إلى الوسط العامل تزدادان.

بالنسبة لكفاية هذا النظام فوجد أنها تزداد بصورة حادة عند بداية التسخين ثم تقل قليلا بعد ذلك، وأقصى كفاية نظرية متوقعة لهذا النظام هى حوالى ٢٧%.

المقارنة بين الإثير والكلوروفورم أثبتت أنه عند نفس درجة الحرارة فإن ضغط الإثير يكون أكبر بكثير من ضغط الكلوروفورم، مما يجعل الإثير أكثر مناسبة للاستخدام فى هذا النوع من المضخات.

أظهرت القياسات العملية التى أجريت على هذه المضخة أن الاختلاف بين النتائج العملية والنظرية معقول.

Keywords Renewable energy, Solar energy, Solar pump, Flat plate collector, Water pumping.

INTRODUCTION

The pump discussed in this work is an unconventional one, which operates using the vapour of a low boiling point liquid (Diethyl Ether or Chloroform) generated by a flat plate collector. These types of pumps have attracted considerable attention since the beginning of the Twentieth century. This unconventional pump can be used particularly in rural areas for irrigation purposes.

Various types of small solar thermal water pumps are discussed in [1]. The performance of some different types of solar thermal water pumps is studied experimentally and theoretically at different discharge heads and for different working fluids in [2], [3], [4], [5], [6], and [7].

Figure 1 shows the schematic of solar thermal water pump considered in this work. The pump consists of the following components: (i) flat plate solar collector having an exposed area of 1 m^2 coupled to an insulated tank S, both containing working fluid in liquid condition; (ii) insulated storage tank N, which stores working fluid vapour; (iii) insulated vessel A, completely filled with water initially; (iv) uninsulated vessel B, initially containing air and (v) vessel C, immersed in the well water.

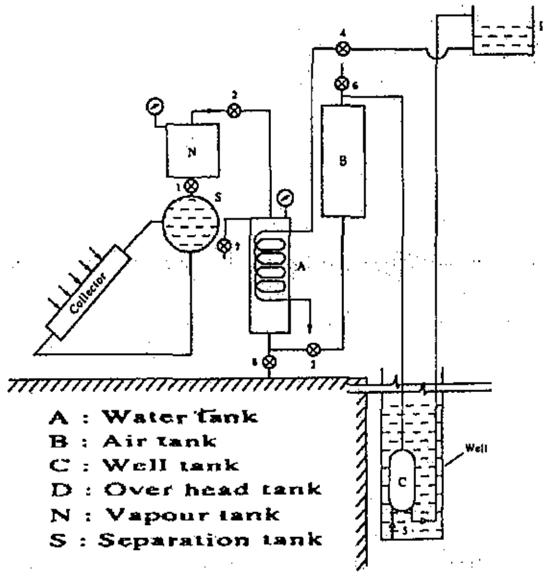


Figure 1 Schematic of the solar thermal water pump

The choice of the working fluid depends to a great extent on the boiling point and its miscibility with water. Diethyl Ether and Chloroform are chosen as two working fluids in this work. They are immiscible with water and have low boiling points, 34.43 and 61.13 °C respectively. Their chemical formulas are $C_4H_{10}O$ and $CHCl_3$ respectively [8].

Liquid Ether or Chloroform is sited in motion by thermosiphon action through solar heating in the flat-plate collector. The saturated vapour separating in tank S is stored in the vapour-storage tank N. When the pressure in tank N reaches a predetermined value, it is isolated from tank S by closing valve 1. Valves 2 and 3 are simultaneously opened so that some vapour from N travels quickly to vessel A, which initially contains water at atmospheric conditions. As a consequence, water in tank A is displaced into tank B, which initially contains air at atmospheric conditions. The rising column of water in B compresses the air in it and the compressed air in turn pushes the water in vessel C (which is immersed in the well) to the overhead tank D. At the end of pumping, valve 2 is closed, valve 1 is opened and water from the overhead tank D is allowed to flow through the cooling coils in vessel A to accelerate the condensation of working fluid vapour in tank A. Because of condensation, the pressure in vessel A decreases, as a result of which the water in vessel B returns to vessel A. During this period, the pressure of air in vessel B returns to its initial value. Consequently, the well water is sucked into vessel C through the one-way valve 5. During the condensation and suction stroke the working fluid in the collection system is heated up until the vapour is required for the next pumping operation. One cycle of operation is thus complete and the pump is now ready for the next cycle.

In this work, heat transfer analysis of a flat plate collector in the above described solar thermal water pump is carried out theoretically and experimentally. Two different situations were considered: one with Ether as working fluid and the other when Choloroform is used instead.

HEAT TRANSFER ANALYSIS

Initially, the system is filled with m kg working fluid at the ambient temperature t_a. Valve 1 is kept open so that the vapour in N and the liquid in the collector are in equilibrium. Thus, the system considered is a mixture of liquid and vapour at a dryness fraction, which can be calculated at any instant.

The collector analysis is aimed at predicting the temperature and pressure of working fluid as a function of time for different days.

Evaluation of Energy Available from the Collector

The total radiation intensity on a horizontal plane is assumed to vary sinusoidally from sunrise to sunset according to

$$I_h = I_{\max} \sin[\pi\theta/l] \tag{1}$$

Where I_{max} is the maximum intensity of solar radiation occurring at solar noon, l the length of the day in hours and θ the difference between time of day at a given instant and the sunrise time in hours. Assuming that the diffuse radiation intensity on the horizontal I_d is 15% of the total radiation intensity, then the total intensity of radiation on an inclined surface I_t is obtained from

$$I_i = (I_h - I_d)(\cos\theta_i / \cos\theta_h) + I_d(1+\cos\beta)/2 \qquad (2)$$

where θ_i is the incident angle on the inclined collector, θ_h is the incident angle on the horizontal surface and β is the inclination of the collector to the horizontal.

$$\theta_i = \cos^{-1}[\cos(L-\beta)\cos\delta\cos h + \sin L\ \sin\delta]$$

$$\theta_h = \cos^{-1}[\cos L\cos\delta\cos h + \sin L\ \sin\delta]$$

where L is altitude, δ is declination and h is the hour angle.

The overall heat loss coefficient, in W/m^2K, of a single glazed collector can be obtained from the following relation [6]

$$U_l = 5.5 + 0.024\, t_p \qquad (3)$$

where t_p is the plate temperature in °C. The absorbed energy per unit area of the collector can be estimated as

$$dQ = [I_i(\tau\alpha) - U_l(t_p - t_a)]d\theta \qquad (4)$$

where α is the absorptivity of the black painted absorber plate, taken as 0.9. τ is the transmissivity of the collector glazing, taken as 0.88 [6] and $d\theta$ is the time interval.

The heat transfer to the fluid from the wall during a small interval $d\theta$ is

$$dQ_s = h_i A_t (t_w - t_s) d\theta / A_c \qquad (5)$$

where h_i is the convective heat coefficient between tube wall and the liquid, A_t is the inside area of the collector tubes, t_w is the wall temperature of the collector tubes, t_s is working fluid temperature in the collector and A_c is the collector area.

For natural convection horizontal tube with a wall temperature increasing at a uniform rate

$$Nu = 1.181\,(Gr\,\Pr)^{0.214}$$

The absorbed energy per unit area of the collector can be estimated also as

$$dQ = C_1 dt_p + C_2 dt_w + dQ_s \qquad (6)$$

where $C_1 dt_p$ is the increase in energy of the flat plate and $C_2 dt_w$ is the increase in energy of the risers, headers, insulation and glazing in the collector.

The heat conducted from the plate to the riser-tube wall through the bond between them is equal to the sum of the increase in energy of the collector components and the heat transfer to working fluid in the collection system. Therefore,

$$[(t_p + dt_p) - (t_w + dt_w)]C_b\, d\theta = C_2\, dt_w + dQ_s \qquad (7)$$

where C_b is the bond conductance.

For assumed initial values of t_p, t_w and t_s the above equations can be solved together to determine the values of dt_p, dt_w and dQ_s

Evaluation of Working Fluid Temperature and Pressure

The heat transfer to the fluid from the wall dQ_s during a small interval $d\theta$ is equal to the difference in internal energy of working fluid, the increase in the heat capacitances of tanks S and N along with their insulations and heat losses dQ_l through tanks S and N. It is assumed that the wall of tanks S and N are at the same temperature of working fluid, whereas the insulation is at the average of wall temperature and the outside temperature t_o. Therefore the rise in temperature of working fluid in interval $d\theta$ can be obtained from the following relation

$$dQ_s = (U_f - U_i) + C_{3w}(t_{sf} - t_s) + C_{3i}[(t_{sf} + t_{of})/2 - (t_s + t_o)/2] + dQ_l \qquad (8)$$

where C_{3w} and C_{3i} are the capacitances of tanks S and N and their insulation respectively, whereas t_s and t_{sf} are the temperatures of working fluid at the beginning and end of interval $d\theta$ respectively. The conduction and convection losses from tanks S and N are calculated according to the technique used in [6]. Equation 8 is solved by trial and error to obtain the value of t_{sf} with an accepted error less than 10^{-7}. The rise in working fluid temperature is then

$$dt_s = t_{sf} - t_s$$

For the next interval $d\theta$, t_s, t_w and t_p are all reset after accounting for their changes during the previous time interval $d\theta$. This evaluation is continued for the entire period of heating. The analysis has been done for two different cases, namely, (i) when Diethyl Ether is used as working fluid and (ii) by using Chloroform as working fluid.

The saturation pressure of Diethyl Ether at any temperature is

$$P = 15.339 + 3.275t - 0.015t^2 + 4.856\times10^{-4}\, t^3 \qquad (9\text{-a})$$

whereas for Chloroform it is

$$P = -74.386 + 3.536t - 0.033t^2 + 3.7\times10^{-4}\, t^3 \qquad (9\text{-b})$$

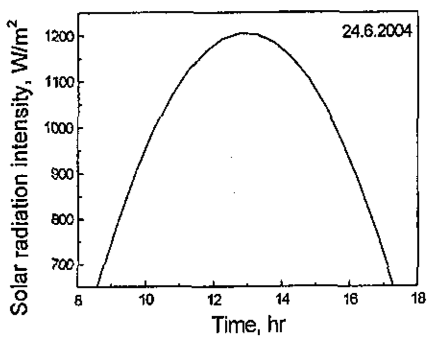
where t is in °C and P in kPa.

EXPERIMENTAL STUDIES

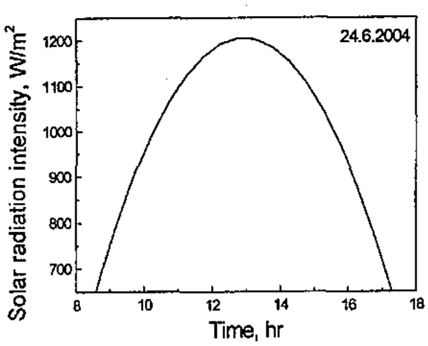
A solar thermal water pump was designed, manufactured and tested in the energy laboratory. The pump was coupled to a flat plate collector with an exposed area of 1 m^2. A calibrated Bourdon pressure gauge was mounted on the vapour storage tank N to measure the pressure of working fluid at any instant. Four calibrated copper-constantan thermocouples are used for measuring the temperatures at collector inlet, collector outlet and collector plate as well as for measuring the temperature of working fluid in tank N at any instant. The collector and the separation tank S are initially filled with working fluid in liquid phase. The vapour storage tank N is then brought in communication with the tank S so that the working fluid vapour separating from tank S is stored in tank N. The working fluid in the system was just heated continuously by thermosiphon action. The temperature and pressure at the above indicated locations in the systems were measured for different days from 9 to 16 o'clock for the two working fluids.

RESULTS AND DISCUSSION

Figure 2 shows the predicted variation of solar radiation intensity with time in the location of this study for different summer days. The solar radiation intensity varies sinusoidal with time and takes its maximum value at solar noon.



(a)



(b)

Figure 2 Variation of solar radiation intensity with time

Figure 3 illustrates the predicted change in working fluid (Ether) and collector plate temperatures with time. The temperature of Ether in the collecting system as well as the temperature of collector plate varies sinusoidal with time. The maximum values occur at about 13 o'clock. Values of 55 and 84 °c are predicted for Ether and collector plate temperatures respectively for this day.

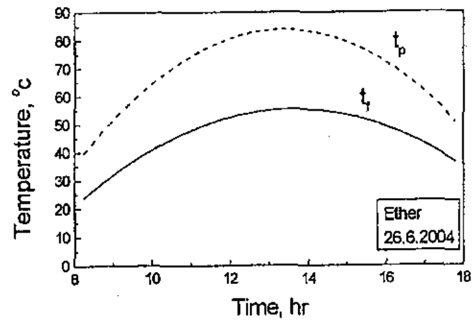


Figure 3 Variation of working fluid and collector plate temperatures with time

The variation of heat absorbed per unit area of collector, heat losses from tanks S, N and heat transferred to working fluid with time is shown in Fig. 4. The behavior of these parameters before solar noon differs from their behavior after solar noon. They increase till solar noon then they decrease. It is also found that heat absorbed per unit area of collector is at the top of other two parameters before solar noon. After solar noon, heat losses from tanks S, N and heat transferred to working fluid are found to be greater than heat absorbed per unit area of collector. This is because a heat conserved in tube walls, walls of tanks S, N as well as heat conserved in insulation will flow to working fluid and to the surroundings.

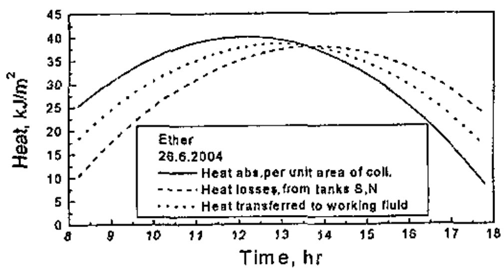


Figure 4 Predicted values of heat absorbed per unit area of collector, heat losses from tanks S,N and heat transferred to working fluid

Figure 5 presents the change of heat losses from tanks S and N with the working fluid temperature. The heat losses increase with the rise in working fluid temperature. This is because of the rise in the temperature difference between the working fluid and the surrounding.

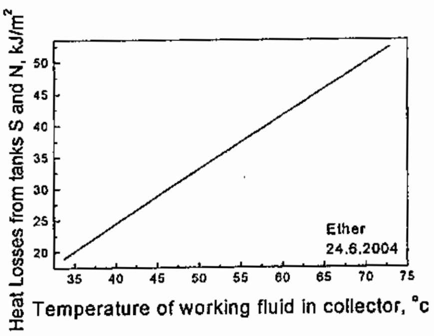


Figure 5 Change of heat losses from tanks S, N with temp. of working fluid

Figures 6 and 7 show the effect of solar radiation intensity on heat losses from tanks S, N and heat transferred to working fluid respectively for each of the two working fluids, Ether and Chloroform. There is a rise in each of these parameters with the increase in solar radiation intensity. The heat losses from tanks S, N and heat transferred to working fluid for Ether are found to be little higher than the corresponding values for Chloroform at the same solar radiation intensity. The rise in solar radiation intensity results in an increase in working fluid temperature.

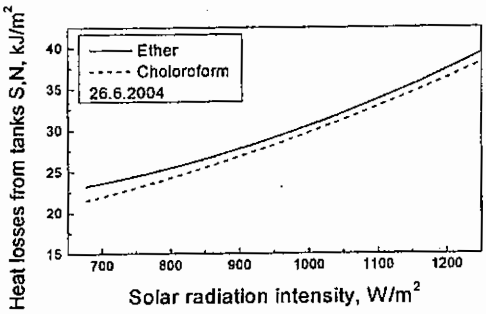


Figure 6 Effect of solar radiation intensity on heat losses from heat tanks S.N.

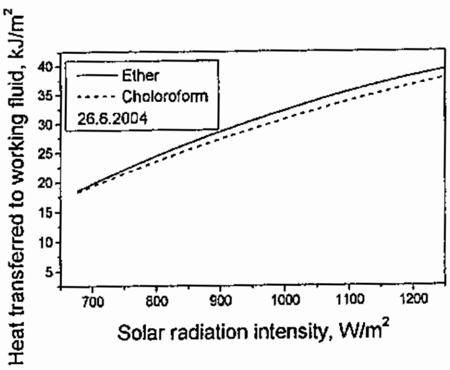


Figure 7 Effect of solar radiation intensity on heat transferred to working fluid

Figure 8 presents the variation of working fluid pressure with temperature for both Ether and Chloroform. One can see that, at the same working fluid temperature the pressure of Ether in the collection system is higher than the pressure of Chloroform. This will make Ether more suitable than Chloroform as working fluid in solar thermal pumps.

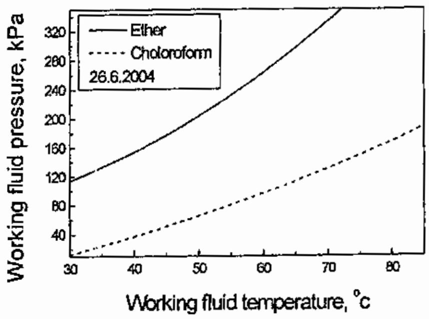


Figure 8 Variation of working fluid pressure with temperature

The variation of instantaneous system efficiency with time of the day is shown in Fig. 9. The instantaneous system efficiency is defined as the ratio of heat transferred to working fluid during certain interval $d\theta$ to the total solar radiation intensity during the same period, as follows.

$$\eta = dQ_s / I_t \, d\theta \tag{10}$$

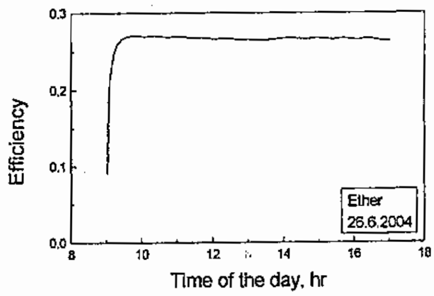


Figure 9 Variation of system efficiency with time of the day

From Fig. 9 one can see that, there is a sharp increase in system efficiency at the beginning of the day then the efficiency slightly decreases with time. At the beginning of the day, the temperature of working fluid and the heat transferred to working fluid increase sharply. This is the main reason for the sharp improvement in efficiency. With outflow of time the losses from the collection system and the decay in solar radiation intensity cause the efficiency to go down slightly.

The above-predicted results were compared with some of the measured data. Figures 10 and 11 show the variation of both predicted and measured working fluid temperature and pressure with time respectively for Ether on 26 June. Both predicted and measured data having the same trend of change with time and the deviation between them is considerable.

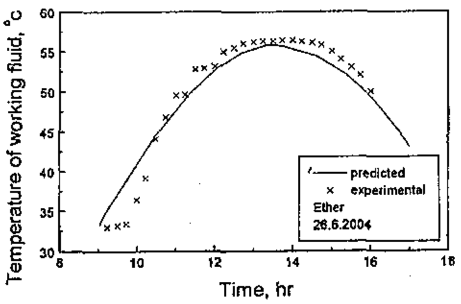


Figure 10 Calculated and measured working fluid temperature

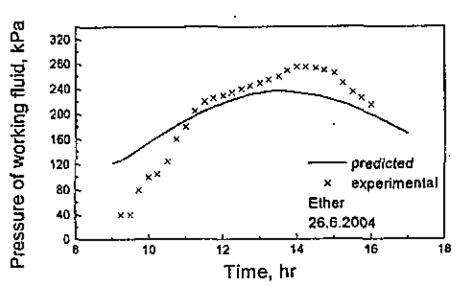


Figure 11 Calculated and measured working fluid pressure

CONCLUSIONS

In this work, a heat transfer analysis of solar thermal water pump using flat plate collector was carried out taking into consideration all heat losses in the collection system. Variations in temperature and pressure of working fluids with time as well as the variation of temperature at different points in collection system are predicted. The temperature and pressure of working fluids as well as the temperature at different points in the collection systems are measured and compared with the predicted values. Variations in collector efficiency with time are discussed.

It was found that, the working fluid and collector plate temperatures are increased with time of day till about solar noon then they decrease. There is also a rise in heat losses and heat transferred to working fluid with the rise in working fluid temperature or the rise in solar radiation intensity. A maximum theoretical efficiency for this system is expected to be 27% and is reached at the beginning of operation. It was also found that, at the same working fluid temperature the working fluid pressure for Ether is higher than the pressure for Chloroform. This gives the indication that Ether will be more suitable than Chloroform for the operation of this pump.

The comparison between theoretical and measured data shows that, both theoretical and measured data have the same trend of change and the deviation between them is considerable.

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NOMENCLATURE

A_c	collector area, m^2
C_1	Capacitance of the absorber plate, $J/m^2 K$.
C_2	Capacitance of the collector tubes, insulation and glass cover, $J/m^2 K$.
C_3	Capacitance of tank S and N, $J/m^2 K$.
dQ	absorbed energy per unit area of the collector, J/m^2.
dQ_l	heat losses through tanks S and N, J/m^2.
dQ_s	heat transfer to the fluid from the wall, J/m^2.
Gr	Grashof number, ---

I_d diffuse radiation intensity, W/m^2.
I_h total radiation intensity on a horizontal plane, W/m^2.
I_i total intensity of radiation on an inclined surface, W/m^2.
Nu Nusselt number, ---.
P pressure of working fluid, kPa.
Pr Prandtl number, ---.
t_a ambient temperature, °C
t_f working fluid temperature at the end of period $d\theta$, °C
t_p plate temperature , °C
t_s initial working fluid temperature, °C
t_w wall temperature of the collector tubes, °C
U_l overall heat loss coefficient, W/m^2K.
H instantaneous system efficiency,-