THERMAL ANALYSIS OF BLACK LIQUID CYLINDRICAL PARABOLIC COLLECTOR

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Abstract—In the present paper a simple theoretical analysis and an experiment are carried out for a modified concentrating collector which consists of a cylindrical parabolic reflector, a transparent glass tube centered along the focal line, and a highly absorbent black liquid which flows in the glass tube to directly absorb the concentrated solar beam radiation. The analytical results are presented in normalized form and proved to be in very good agreement with the experimental results.

INTRODUCTION

Novel designs of solar energy collectors have been investigated for many years in order to reach high collecting temperatures with high efficiency. The traditional cylindrical parabolic collector appears to be the promising one in many applications. The collector usually consists of a cylindrical parabolic reflector and a metal-tube receiver which is blackened at the outside surface and which carries a working fluid such as clean water to extract heat. The metal tube is centered along the reflector's focal line. To increase the collecting efficiency, some particular designs have been proposed many years ago such as the use of evacuated glass tube to wrap the metal tube to effectively reduce the thermal loss.

The conventional flat-plate collector usually does not give high temperature outputs. A modification was made by Minardi and Chuang[1] who developed a black liquid collector which does not employ a blackened metal tube. In this collector, a highly absorbent black liquid flows in transparent plain channels, and the solar radiation is directly absorbed by the black liquid without the need to heat any other structures within the collector. Thus the liquid is the hottest substance in the collector, and the heat loss can be largely reduced.

Combining above two designs, a further modification is proposed here (Fig. 1). Instead of using the metal tube with blackened surface, the present collector consists of a transparent glass tube which is centered along the focal line, a cylindrical parabolic reflector surface, and a highly absorbent black liquid which flows in the glass tube to directly absorb the focused solar beam radiation. Figure 2 is a cross section view of the collector. To understand the thermal performance of the collector, a simple analytical model is developed in the present paper, and an experiment is carried out to verify the analytical results.

ANALYSIS

To facilitate the analysis, the following assumptions are made:

- (1) The flow is steady, one-dimensional in x -direction.
- (2) The axial heat conduction along the flow direction

is negligible since the Peclet number is not very small in most applications, and no end effects.

(3) Solar beam radiation is constant and incident upon the collector flat cover surface vertically.

(4) The reflector has a perfect geometric parabolic shape.

(5) All thermal and optical properties of the fluid and the structural materials are constant.

From the energy balance to the differential element of the black liquid in length dx within the glass tube, the following equation can be written:

$$mC_p(dT_f/dx) = I_b W \rho \gamma \alpha - U_L \pi D(T_f - T_a) \quad (1)$$

where T_f is the bulk mean temperature of the fluid at x , U_L is the heat loss coefficient from the fluid to the ambient, α represents the overall absorption of the incoming solar radiation by the black liquid inside the glass

Fig. 1. Black liquid cylindrical parabolic collector.

Fig. 2. Collector cross section view.

tube, γ is the intercept factor of the glass tube, τ is the total transmittance of the solar radiation through the glass tube wall and the cover material before the radiation entering the black liquid. Equation (1) can be rewritten in a normalized form:

$$M(d\theta/d\xi) + \theta = 1/R \quad (2)$$

where

M = mass flowrate coefficient = $mC_p/U_L\pi DL$

R = thermal loss ratio = $U_L\pi DL(T_f - T_a)/W\rho\gamma\tau\alpha I_b = U_L\pi DL(T_f - T_a)/I_b WLO_p$

O_p = optical factor = $\rho\gamma\tau\alpha$

$\theta = (T_f - T_a)/(T_f - T_a)$

$\xi = x/L$

The temperature distribution can be solved with the boundary condition, $\theta = 1$ at $\xi = 0$:

$$\theta = 1/R - (1/R - 1) \exp(-\xi/M) \quad (3)$$

and the output temperature θ_L is

$$\theta_L = (1/R - 1)[1 - \exp(-1/M)] \quad (4)$$

the collecting efficiency η is

$$\eta = O_p(1 - R)M[1 - \exp(-1/M)] \quad (5)$$

The above results are plotted in Fig. 3. It is seen that the collector efficiency decreases linearly with the thermal loss ratio R . High efficiency can be reached when the optical factor O_p and the mass flowrate coefficient M are high and the thermal loss ratio R is low. This needs a very careful consideration in selecting the material of reflecting surface, the black liquid and the tracking system.

EXPERIMENT

A black liquid cylindrical parabolic collector was designed for the experiment to verify the above analytical results. Three polished stainless steel (AISI 430) parabolic reflectors, each with 46 cm wide, 180 cm long, 105° rim angle, 8.8 cm focal length, 0.68 reflectance, are connected in series (Fig. 4). An ordinary soda-lime-silica glass tube 1 mm thick and 2.5 cm in diameter is mounted along the focal line of each reflector and carries a black liquid water which is made from Direct Black EX dye made in Holland. The black liquid water is pumped by a circulation pump through three collector glass tubes in which the concentrated solar beam radiation is absorbed.

To investigate the collection efficiency at various inlet temperatures, a constant-temperature bath is used. The black liquid water in the bath is heated by a 550 W electric heater and the temperature is controlled by an automatic temperature controller. The inlet temperatures

Fig. 3. Collecting efficiency and output temperature vs thermal loss ratio.

Fig. 4. Experimental installation.

are controlled up to 80°C in the experiment. The reflectors are tilted above the ground at an angle and can be adjusted east-west by worm gear set so as to face the sun vertically all the time during the experiment. Temperature measurements are made by iron-constantan thermocouples embedded inside the black liquid at the inlet and the outlet of each collector glass tube and at the surface of the reflector. The temperatures are recorded by a 1590 JC DATA LOGGER digital recorder with error of $\pm 0.6^\circ\text{C}$. The mass flowrate of the black liquid is measured in the bath by using a 2000 cm³ graduated cylinder and a stop watch, the associated error is within 6 per cent. The total solar radiation intensity incident on the tilted collector is measured by a R413 STAR PYRANOMETER which is mounted on the same tilted surface nearby the collector. The pyranometer is installed on an adjustable frame which can be adjusted to fully track the sun during the experiment. The solar beam radiation intensity is then obtained by subtracting the diffuse radiation from the total radiation. This gives a maximum error about 2 per cent in determining the beam

radiation. To evaluate the heat loss, the wind speed is also measured during the experiment. The total heat loss coefficient U_L is estimated about $9.5 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$ for all the tests. The dye concentrations of the black liquid water used in the experiment are 1 and 2 per cent in weight. To reduce the heat loss, a transparent plastic cover over the reflector is used. The transmittance of the plastic cover is 95.5 per cent, and the transmittance of the 1 mm thick glass tube wall is 90 per cent. The overall absorptance of the black liquid to the solar radiation spectrum are 0.98 for 2 per cent concentration and 0.95 for 1 per cent concentration by separate measurements. The intercept factor is estimated about 0.98 according to Duffie and Beckman[2].

The energy collecting efficiency and the output temperature of the collector are determined from the measurements, and the results are compared with the theoretical calculations from eqns (4) and (5). The experimental errors in measuring the efficiency and the output temperature are 17 and 14 per cent respectively for 2 per cent black liquid concentration, and 13 and 10

Fig. 5. Collecting efficiency comparison between experiments and theoretical calculations.

Fig. 6. Output temperature comparison between experiments and theoretical calculations.

per cent respectively for 1 per cent concentration. It is seen from Figs. 5 and 6 that the agreement between the theory and the measurement is very good. The consistency is within ± 15 per cent. It also can be seen that the collector efficiency measured in the present experiment ranges from 36 to 50 per cent which are not as high as expected. This is mainly attributed to the poor reflectance of the stainless steel reflector surface. However, this defect can be improved by using highly reflective surface such as mirrors (reflectance higher than 85 per cent), and the collection efficiency will therefore increase considerably.

CONCLUSIONS

A black liquid cylindrical parabolic solar collector is proposed and investigated in the present paper, and a simple analytical model which is in normalized form is developed to predict the thermal performance. It is shown that the experimental results are consistent with the analytical results to within ± 15 per cent. From the collector efficiency measurements, it is also seen that the highly reflective surface of the parabolic reflector plays the most important role in reaching excellent collecting efficiency for black liquid cylindrical parabolic collectors.

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NOMENCLATURE

C_p	specific heat of the black liquid, $\text{Wg}^{-1}\text{C}^{-1}$
D	inside diameter of the glass tube, cm
I_b	solar beam radiation intensity, W cm^{-2}
L	total length of the collector, cm
m	mass flowrate, g sec^{-1}
M	mass flowrate coefficient ($= mC_p/U_L\pi DL$), dimensionless
O_p	optical factor ($= \rho\gamma\alpha$), dimensionless
R	thermal loss ratio ($= U_L\pi DL(T_f - T_a)/I_b WLO_p$), dimensionless
T_a	ambient temperature, $^{\circ}\text{C}$
T_f	bulk mean temperature of the black liquid in the glass tube, $^{\circ}\text{C}$
T_f	inlet fluid temperature, $^{\circ}\text{C}$
T_{fo}	output fluid temperature, $^{\circ}\text{C}$
U_L	total heat loss coefficient, $\text{W cm}^{-2}\text{C}^{-1}$
W	width of the parabolic collector, cm
ρ	reflectance of the reflector, dimensionless
τ	total transmittance of the solar beam radiation before entering the black liquid, dimensionless
α	overall absorptance of the beam radiation by the black liquid within the glass tube, dimensionless
ξ	dimensionless tube length ($= x/L$)
θ	dimensionless temperature $= (T_f - T_a)/(T_f - T_a)$
γ	intercept factor of the glass tube, dimensionless
θ_L	dimensionless output temperature difference $= (T_{fo} - T_f)/(T_f - T_a)$
η	thermal collection efficiency, dimensionless

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