MODELLING OF A PARABOLIC TROUGH COLLECTOR SYSTEM FOR HOT WATER PRODUCTION

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ABSTRACT

The modelling of a Parabolic Trough Collector System for hot water production is presented. This is followed by an experimental verification of the model and analysis of the experimental results. The difference between the predicted and actual results is about 7%. This variation is attributed to the difference of the actual weather during the tests compared to standard data taken from a "reference year" and the convection losses from the collector receiver which were not constant as accounted by the program.

INTRODUCTION

Cyprus began manufacturing solar water heaters in the early sixties. It is estimated that about 130,000 such heaters are in operation today which correspond to one heater for every 5 people on the island. These systems are almost exclusively of the flat-plate type. Opportunities still exist on the island for large scale hot water production for which the parabolic trough collector can be used more economically [1].

Cyprus enjoys an abundance of solar radiation which for a year with average weather conditions reaches 1725 kWh/m^2 (global), of which 69% (1188 kWh/m^2) is direct and the rest 31% (537 kWh/m^2) is diffuse radiation. All values apply for radiation falling to a horizontal surface.

Parabolic Trough Collectors (PTC) are generally employed for a variety of applications such as industrial steam production [2] and hot water production [1]. It has been shown that the use of PTC for hot water production can be more viable than the flat-plate type owing to its higher operating efficiency [1].

The scope of the modelling presented here is to investigate the performance of a PTC system and compare the results with the actual system performance.

THE REFERENCE YEAR

The operation of solar collectors and systems depends on the solar radiation input and the ambient air temperature. A typical year, called a Reference Year, is defined as a year which sums up all the climatic information characterising a period equivalent to the mean life of the system. In this way the long term performance of a system can be calculated by simulating its performance over the reference year.

The reference year for the town of Nicosia, Cyprus was developed [3]. The actual reference year is a table of the hourly solar beam radiation and ambient air temperatures. The beam radiation is used here as PTCs with concentration ratios above 10, can only utilise this type of radiation [4].

SYSTEM MODELLING

The PTC system modelled here includes components as shown in Fig. 1 i.e. a PTC, a hot water storage tank, a circulating pump and a differential thermostat. The PTC system specifications are shown in Table 1.

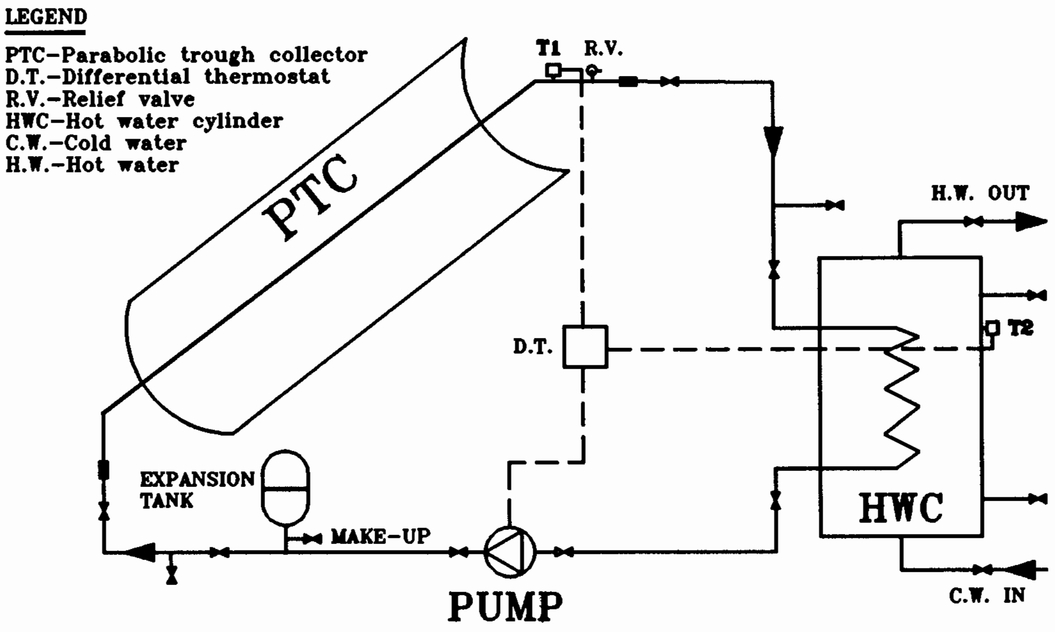

FIGURE 1. The PTC system

Table 1. Parabolic trough collector system specification

ITEM	VALUE
Collector aperture area	1 m^2
Collector aperture	0.8 m
Aperture to length ratio	0.64
Rim angle	90°
Glass to receiver dia. ratio	2.17
Concentration ratio	21.2
Optimum water flow rate	0.012 kg/s
Differential thermostat setting	5°C
Storage capacity	90 l

A BASIC program was developed which used the data from the reference year and, the thermal and optical characteristics of the PTC system. These characteristics are determined from first principles, by the specifications given in Table 1. The hourly solar radiation values are modified by the program to account for the collector inclination. For simplicity, it is assumed that no hot water is used. Also, the initial storage temperature is considered equal to the ambient temperature at the first hour of the day. The program calculations are performed for each minute throughout of the day, whilst the output from the program is given for every hour. The program flow chart is shown in Fig. 2.

Standard relations are used in the program for the calculation of the heat transfer coefficients. The useful power delivered by the collector is estimated by:

$$q_u = A_a\, F_R \left[n_o\, I - \frac{U_L(T_i - T_a)}{CR} \right] \tag{1}$$

The thermal efficiency can be obtained by dividing q_u by I A_a. The optical efficiency is given by:

$$n_o = \rho\ \tau\ \alpha\ \gamma[(1 - A_f \tan(\theta))\cos(\theta)] \tag{2}$$

where A_f is the geometric factor determining the loss of area due to abnormal incidence effects and is given by:

$$A_f = \frac{\frac{2}{3} W_a\, h_p + f\, W_a \left(1 + \frac{W_a^2}{48\, f^2}\right)}{A_a} \tag{3}$$

For the evaluation of the intercept factor, γ, the method presented by Guven *et al.*[5] was used. The method requires the estimation of the random and nonrandom errors of the system which are then combined with the collector geometric parameters, concentration ratio and receiver diameter, to give the universal error parameters. These are then used for the estimation of γ.

For the heat loss coefficient, U_L, of the glazed tube receiver the formulation presented by Mullick *et al.* [6] was adopted.

A fully mixed storage tank is assumed. For submerged coils which is the case of the heat exchanger in the storage tank, the heat transfer coefficient, for the outside diameter of the heat exchanger pipe, can be obtained from [7]:

$$Nu_D = 0.53\ (Gr\ Pr)^{0.25} \tag{4}$$

The overall heat transfer coefficient in this case based on the outside pipe diameter is given by [7]:

$$U = \left[\frac{D_o}{D_i} \frac{1}{h_f} + \frac{D_o \ln(D_o / D_i)}{2\,k} + \frac{1}{h_o} \right]^{-1} \tag{5}$$

The computed output from the program for the months April to June inclusive is shown in Table 2 whereas the mean daily energy collected for each month is shown in Table 3.

EXPERIMENTATION

A prototype model was constructed and tested over four months. Hence the accuracy with which the simulation program predicts performance can be assessed. From the standard collector performance testing [8], some differences were observed between the theoretical values of the slope and intercept, and the experimental values. The results are shown in Table 4. A small difference is seen between the theoretical and experimental values with respect to the test intercept, whereas there is a large variation in test slope. Therefore the optical efficiency, n_o, which is deduced from the graph intercept is accurately predicted. The large variation of the test slope is due to a difference in the heat loss coefficient, U_L, which may be accounted for by the conduction/convection losses through the receiver support brackets. This difference is reduced from 24.9% to 5.7% when these losses are accounted for.

The results from the experiments carried out with the PTC system are presented in Table 5. The values shown are the mean values of the tests performed over a five day period during each month. As can be seen from this table the difference in the predicted and actual energy gain for all the months investigated is below 7% which may be considered reasonable.

Some of this difference may be accounted for by the following reasons:

1. The amount of cloud to sunshine hours. The amount of direct to diffuse radiation and the ambient air temperature may be different from those which are taken from reference year. This is strengthened by the fact that for the two Spring months of May and June, the difference is much smaller because the possibility of cloud is less.

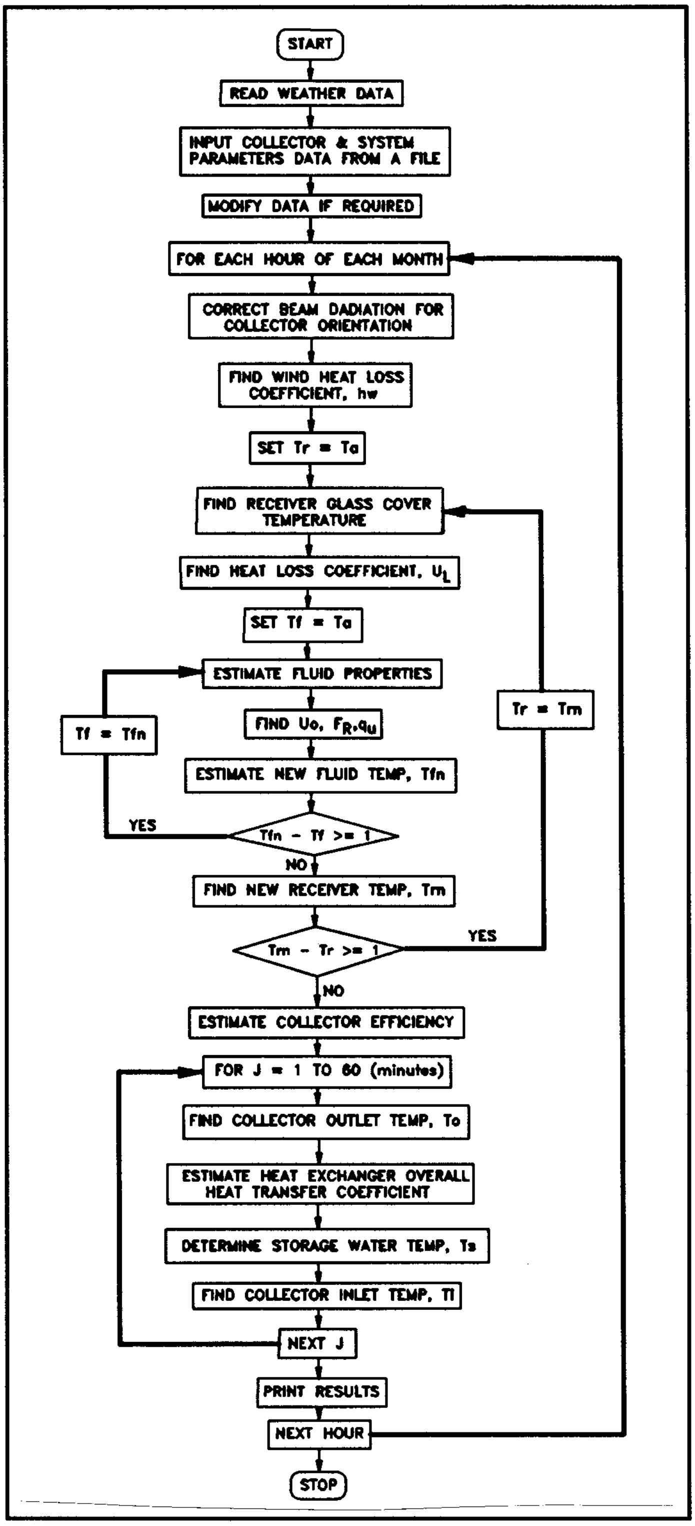

FIGURE 2. Program flow chart

2.Convective losses. There was light wind in all test cases but its velocity varied. In the program a wind velocity of 1 m/s was considered as being constant.

Table 2. Simulation program output for months March to June

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MONTH =MARCH
   TIME  COL. OUT.    THERM.   USEFUL    STORAGE
           TEMP.      EFFIC.    POWER     TEMP.
   8.00    14.43      64.83    112.53     12.17
   9.00    18.37      64.89    213.66     14.19
  10.00    22.41      64.85    283.90     16.88
  11.00    26.10      64.76    321.02     19.92
  12.00    29.68      64.65    340.80     23.15
  13.00    32.55      64.51    328.78     26.26
  14.00    35.45      64.36    321.81     29.31
  15.00    38.62      64.15    326.09     32.40
  16.00    41.29      63.88    311.63     35.35

MONTH =APRIL
   TIME  COL. OUT.    THERM.   USEFUL    STORAGE
           TEMP.      EFFIC.    POWER     TEMP.
   8.00    21.58      61.45    164.75     18.36
   9.00    25.79      61.44    256.55     20.79
  10.00    29.72      61.37    311.77     23.74
  11.00    33.71      61.28    346.96     27.03
  12.00    36.44      61.14    329.52     30.15
  13.00    39.38      60.97    323.36     33.21
  14.00    42.15      60.80    313.36     36.18
  15.00    44.57      60.52    293.93     38.96
  16.00    45.89      60.08    241.11     41.25

MONTH =MAY
   TIME  COL. OUT.    THERM.   USEFUL    STORAGE
           TEMP.      EFFIC.    POWER     TEMP.
   8.00    26.95      55.48    174.12     23.55
   9.00    30.46      55.50    240.79     25.83
  10.00    34.26      55.44    292.92     28.61
  11.00    37.48      55.36    308.93     31.53
  12.00    40.24      55.27    303.63     34.41
  13.00    42.16      55.10    271.37     36.98
  14.00    44.28      54.93    255.71     39.40
  15.00    46.33      54.66    242.70     41.70
  16.00    47.80      54.33    212.06     43.70

MONTH =JUNE
   TIME  COL. OUT.    THERM.   USEFUL    STORAGE
           TEMP.      EFFIC.    POWER     TEMP.
   8.00    32.76      52.23    225.04     28.43
   9.00    36.69      52.21    287.31     31.15
  10.00    40.40      52.16    323.94     34.22
  11.00    43.92      52.08    340.22     37.44
  12.00    47.31      51.98    346.47     40.73
  13.00    50.34      51.83    337.97     43.93
  14.00    53.08      51.68    321.40     46.97
  15.00    55.47      51.42    296.40     49.78
  16.00    57.62      51.15    274.88     52.38
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Table 3. Mean daily energy collected

MONTH	ENERGY (Wh)
JAN	1544
FEB	1941
MAR	2587
APR	2577
MAY	2307
JUN	2755
JUL	3051
AUG	3406
SEP	3730
OCT	3221
NOV	2026
DEC	2006

Table 4. Collector performance

ITEM	TEST SLOPE	TEST INTERCEPT
Predicted performance	0.353	0.656
Actual performance	0.441	0.642
% difference	24.9	2.1

Table 5. Comparison of actual and predicted system performance

MONTH	PREDICTED PERFORMANCE (using actual optical efficiency)	ACTUAL PERFORMANCE	ENERGY GAIN % DIFFERENCE
MARCH	2506 Wh	2403 Wh	-4.1
APRIL	2527 Wh	2351 Wh	-6.9
MAY	2254 Wh	2241 Wh	-0.6
JUNE	2696 Wh	2713 Wh	+0.6

CONCLUSIONS

The simulation program can predict the PTC system performance to an accuracy of 7% and therefore the model can be successfully used for long term parabolic trough collector system performance prediction.

NOMENCLATURE

A_a	Aperture area, m^2
A_f	Geometric factor
A_r	Receiver area, m^2
CR	Concentration ratio
D	Receiver diameter, m
D_i	Inside receiver diameter, m
D_o	Outside receiver diameter, m
f	Focal distance, m
F_R	Heat removal factor
Gr	Grashof number, dimensionless
h	Loss coefficient, W/m^2K
h_f	Heat transfer coefficient inside tube, W/m^2K
h_o	Heat transfer coefficient outside tube, W/m^2K
h_p	Parabola height, m
k	Thermal conductivity, W/mK
I	Beam solar radiation, W/m^2
Nu	Nuselt number, dimensionless
Pr	Prandtl number, dimensionless
q_u	Useful power, W
U_L	Heat loss coefficient, W/m^2K
T_i	Collector inlet temperature, K
T_a	Ambient temperature, K
W_a	Collector aperture, m

Greek letters:

α – Absorptance of receiver coating
ρ – Mirror reflectivity
τ – Transmittance of receiver cover
γ – Intercept factor
Θ – Angle of incidence, deg.
n – Thermal efficiency
n_o – Optical efficiency

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