THE IMPACT OF OPTICAL PROPERTIES ON THE PERFORMANCE OF FLAT PLATE SOLAR COLLECTORS

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Abstract - The impact of the optical properties of flat plate collectors on the annual performance in a typical Mediterranean climate is estimated with TRNSYS program. For this purpose the detailed collector model has been considered and the simulations were performed by using the TMY file for Nicosia, Cyprus. The factors considered are absorptance and emittance of the absorber and the number of collector glazing. The reference solar collector considered is one were the absorber is painted with ordinary black-mat paint with α=0.9 and ε=0.1. The results show that the increase in performance of collectors employing an absorber with improved properties is considerable. A simple way to obtain somewhat improved properties is by painting the absorber with selective paint (α=0.95, ε=0.1). This is not a very expensive method therefore this modification is expected to be economically viable. However other more high-tech measures like a collector with α=0.97 and ε=0.05, which is out of the manufacturing capabilities of the industry and considered only for comparison purposes, increases more the performance of the collector but their economic viability is questionable unless the collectors are used in high-temperature applications. The use of double-glazing is also questionable because at low temperature applications gives worse performance. However, at higher temperatures double-glazing is superior due to the better insulating properties and the minimization of the thermal top losses. Another point of interest is that at lower temperatures the use of advance coating materials can let to lower performance, as the temperature of the absorber plate is low and thus radiation losses are minimal.

1. INTRODUCTION

The market of solar thermal collector is growing continuously worldwide. In many countries with good solar potential the industry has matured sufficiently and manufacturers seek to improve the performance of their systems in order to satisfy their customers and obtain a market advantage. Solar systems have high initial cost and low running cost, therefore the initial investment required is usually high. As funds to build a solar system are usually obtained through borrowing (from loans), the improvements should affect as little as possible the cost of the solar collectors so as to enable solar energy to compete with conventional sources of energy.

The objective of this work is to investigate the impact of the optical properties on the annual performance of flat plate collectors in a typical Mediterranean climate. This would allow the manufacturers of solar collectors to give priority to the most cost-effective improvements of their products. The factors considered are absorptance and emittance of the absorber and the number of collector glazing. The target is to increase of the absorptance and the decrease of the emittance so as to improve the thermal characteristics of the collectors. These are studied by means of simulating a simple system for one complete year.

A similar study involving a number of measures has been made by Frei and Brunold (2000). This study involves absorber and glazing improvements and treats matters of economy, durability and future development. Simulation results however are presented for only the absorber improvements and antireflective treatment of the cover glass.

Hellstrom *et al.* (2003) also studied the impact of optical and thermal properties on the performance of flat plate solar collectors for the Swedish climate using the MINSUN program. The collector parameters were determined with a theoretically based calculation program. The importance of changes in solar absorptance and thermal emittance of the absorber, the addition of a Teflon film or a Teflon honeycomb antireflection treatment of the cover glazing and combinations of these improvements were investigated.

2. MODEL DESCRIPTION

The impact of the optical properties on the annual performance of flat plate collectors is estimated with TRNSYS program. For this purpose the subroutine for the detailed collector model has been considered and the simulations were performed by using the typical meteorological year (TMY) file for Nicosia, Cyprus, which exhibits a typical Mediterranean climate.

As the objective is to investigate the optical properties of the various components of the collector a fairly simple model has been used in the simulations as shown in Fig. 1. In this a constant inlet temperature is used which varies by the user and a simple controller which switches the solar pump ON whenever the collector outlet temperature is greater than the inlet by 7°C. The input parameters of the program are shown in Table 1.

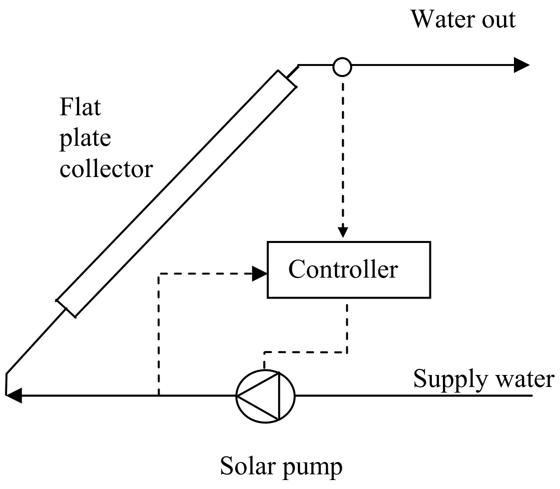

Fig. 1 Schematic diagram of the solar collector system

2.1 TRNSYS program description

TRNSYS is an acronym for a "transient simulation program" and is a quasi-steady simulation model (TRNSYS, 1996). The program consists of many subroutines that model subsystem components. The mathematical models for the subsystem components are given in terms of their ordinary differential or algebraic equations. With a program such as TRNSYS which has the capability of interconnecting system components in any desired manner, solving differential equations and facilitating information output, the entire problem of system simulation reduces to a problem of identifying all the components that comprise the particular system and formulating a general mathematical description of each.

Once all the components of the system have been identified and a mathematical description of each component is available, it is necessary to construct an information flow diagram for the system. The purpose of the information flow diagram is to facilitate identification of the components and the flow of information between them. Each component is represented as a box, which requires a number of constant PARAMETERS and time dependent INPUTS and produces a time dependent OUTPUTS. An information flow diagram shows the manner in which all system components are interconnected. A given OUTPUT may be used as an INPUT to any number of other components. A simplified information flow diagram for the solar system under investigation is shown in Fig. 2.

From the flow diagram shown in Fig. 2 a deck file has to be constructed containing information on all the components of the system, weather data file, and the output format.

TRNSYS type 1 was used for the simulation of the collectors. This type is operated under mode 3 which is more suitable for the theoretical analysis of flat plate collectors.

For this mode the useful energy collected is modelled according to the Hottel-Whillier equation:

$$Q_u = AF_R\left[I(\tau\alpha) - U_L(T_i - T_a)\right] \quad (1)$$

where F_R is the heat removal factor given by:

$$F_R = \frac{\dot{m}c_p}{AU_L}\left(1 - Exp\left[\frac{U_L F' A}{\dot{m}c_p}\right]\right) \quad (2)$$

The collector fin efficiency factor, F′, can be determined according to the analysis given in another paper of the same author in these proceedings (Kalogirou, 2003). The overall heat loss coefficient is a complicated function of the collector construction and its operating conditions and it is given by the following expression:

$$U_L = U_t + U_{be} \quad (3)$$

Table 1. Input parameters used in the simulation

Parameter	Value
Collector efficiency factor (F′)	0.86
Heat losses from bottom and edges of collector (U_{be})	3.24
Absorber plate emittance (ε)	variable
Absorber plate absorptance (α)	variable
Index of refraction of cover material (n_R)	1.526
Product of extinction coefficient and thickness of each cover (kL)	0.0375
Number of glass covers (N_G)	variable

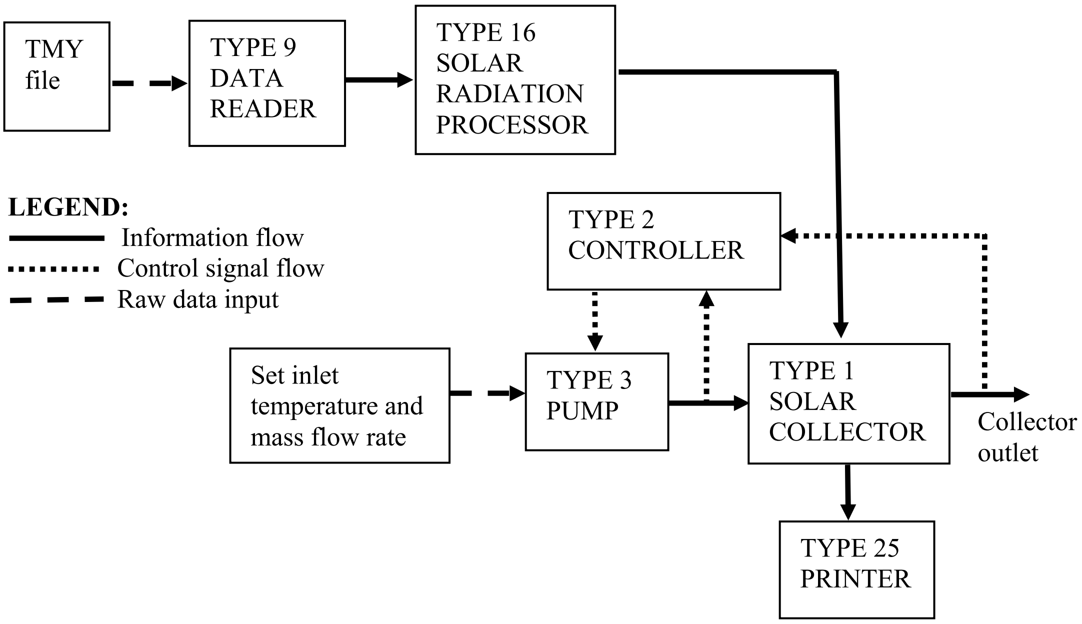

Fig. 2 Information flow diagram for the solar system model.

The top loss coefficient is given by (Klein, 1975):

$$U_t = \frac{1}{\dfrac{N_g}{\dfrac{C}{T_p}\left[\dfrac{(T_{av}-T_a}{N_g+f}\right]^{0.33}+\dfrac{1}{h_w}}} + \frac{\sigma\left(T_{av}^2+T_a^2\right)\left(T_{av}+T_a\right)}{\dfrac{1}{\varepsilon_p+0.05N_g\left(1-\varepsilon_p\right)}+\dfrac{2N_g+f-1}{\varepsilon_g}-N_g} \tag{4}$$

The overall transmittance-absorbtance product (τα) is determined as:

$$(\tau\alpha) = \frac{I_{bT}(\tau\alpha)_b + I_d\left(\dfrac{1+\cos\beta}{2}\right)(\tau\alpha)_s + \rho I\left(\dfrac{1-\cos\beta}{2}\right)(\tau\alpha)_g}{I} \tag{5}$$

where in Eq. (3):

$$h_w = 5.7 + 3.8W \tag{6}$$

$$f = \left(1-0.04h_w+0.0005h_w^2\right)\left(1+0.091N_g\right) \tag{7}$$

$$C = 365.9\left(1-0.00883\beta+0.0001298\beta^2\right) \tag{8}$$

and T_p is the collector stagnation temperature, i.e., the temperature of the absorbing plate when the flow rate is equal to zero, and is obtained from:

$$T_p = \frac{I(\tau\alpha)}{U_L} + T_a \tag{9}$$

As usually good insulation is used in the collector construction the loss coefficient for the bottom and edges of the collector, U_{be}, is considered as constant in Eq. (3) and therefore its estimation is straightforward.

The transmittance absorbtance products (τα) for beam, sky diffuse, and ground diffuse radiation are determined from a subroutine which uses the Fresnel's equations to determine the (τα) of a solar collector for a given angle of incident radiation (TRNSYS, 1996).

Effective incidence angles for the sky diffuse and ground reflected radiation are obtained from:

$$\theta_{sky} = 59.68° - 0.1388\beta + 0.001497\beta^2 \tag{10}$$

and

$$\theta_{gnd} = 90° - 0.05788\beta + 0.002693\beta^2 \tag{11}$$

The total useful energy for the whole year is obtained from:

$$Q_{u,a} = \sum_{d=1}^{365}\sum_{h=1}^{24} Q_u \tag{12}$$

As can be seen from the above equations the energy obtained from the solar collector field depends on the inlet temperature to the collector T_i, which when connected to a complete system depends on the load pattern and the losses from the storage tank and pipes. It should be noted that in this work the inlet temperature was kept constant and related to ambient temperature, thus the systems were simulated using the same weather and operating conditions for comparison purposes. Three different values of T_i were investigated here, T_a+5°C, T_a+15°C and T_a+30°C in order to investigate how the inlet temperature affects the collector performance.

2.2 Typical meteorological year

Cyprus is located at the Eastern Mediterranean at 35° north latitude and has a typical Mediterranean climate. The climatic conditions of Cyprus are predominantly very sunny with daily average solar radiation of about 5.4 kWh/m^2 on a horizontal surface. In the lowlands the daily sunshine duration varies from 5.5 hours in winter to about 12.5 hours in summer. Mean daily global solar radiation varies from about 2.3 kWh/m^2 in the cloudiest months of the year, December and January, to about 7.2 kWh/m^2 in July. The amount of global radiation falling on a horizontal surface with average weather conditions is 1727 kWh/m^2 per year (Kalogirou, 1991).

The systems were simulated with TRNSYS using Typical Meteorological Year (TMY) data for Nicosia, Cyprus. TMY is defined as a year which sums up all the climatic information characterizing a period as long as the mean life of the system. The selection of typical weather conditions for a given location is very crucial in computer simulations for performance predictions and has led various investigators either to run long periods of observational data or to select a particular year, which appears to be typical from several years of data. Klein *et al.* (1976) have constructed the "average year" by selecting the monthly data from an 8-year period, which corresponded most closely to the average monthly insolation and ambient temperature. Petrakis *et al.* (1998) have generated the TMY for Cyprus from hourly measurements, of solar irradiance (global and diffuse on horizontal surface, ambient temperature, wind speed and direction, and humidity ratio), for a seven-year period, from 1986 to 1992 using the Filkenstein – Schafer statistical method. The measurements were recorded by the Cyprus Meteorological Service at the Athalassa region, an area at the suburbs of the town of Nicosia. The TMY is considered as a representative year for the Cypriot and Mediterranean environment. Using this approach the long-term integrated system performance can be evaluated and the dynamic system's behavior can be obtained.

The adequacy of using an average or typical year of meteorological data with a simulation model to provide an estimate of the long-term system performance depends on the sensitivity of system performance to the hourly and daily weather sequences. Regardless of how it is selected, an "average" year cannot be expected to have the same weather sequences as those occurring in the long term. However, the simulated performance of a system for an "average year" may provide a good estimate of the long-term system performance if the weather sequences occurring in the average year are representative of those occurring in the long term or if the system performance is independent of the weather sequences (Klein *et al.* 1976).

3. RESULTS

The impact of the optical properties on the annual performance of flat plate collectors in a typical Mediterranean climate is evaluated. The factors considered are absorptance and emittance of the absorber and the number of collector glazing. Initially a reference solar collector is considered. The absorber of this collector is painted with ordinary black-mat paint with α=0.9 and ε=0.1. The performance of this collector for the three inlet temperatures is shown in Table 2. As can be seen, as expected, the useful energy collected is reduced at higher inlet temperatures.

Table 2. Annual simulated performance for the reference collector

Inlet temperature (°C)	Useful energy (GJ)
T_a+5°C	3.079
T_a+15°C	2.724
T_a+30°C	1.085
Notes: 1. Collector characteristics: α=0.9, ε=0.1 2. Single glazing	

The results for the improved collector characteristics for a single glazing collector are shown in Table 3. The percentage increase in performance of the improved collectors with respect to the reference collector is also shown in Table 3.

Table 3. Annual simulated performance for the use of various combinations of absorber plate optical properties for single glazing collectors

Absorptance (α)	Emittance (ε)	Annual useful energy collected at various inlet temperatures (GJ)		
		T_a+5°C	T_a+15°C	T_a+30°C
0.9	**0.1**	**3.079**	**2.724**	**1.085**
0.95	0.1	3.231 (4.9%)	2.903 (6.6%)	1.287 (18.6%)
0.97	0.1	3.284 (6.7%)	2.943 (8.0%)	1.366 (25.9%)
0.95	0.05	3.138 (1.9%)	2.881 (5.8%)	1.499 (38.2%)
0.97	0.05	3.173 (3.1%)	2.955 (8.5%)	1.579 (45.5%)

Notes: 1. Performance values shown are in GJ
2. Numbers in bold represent the reference collector
3. Numbers in parenthesis represent the percentage increase in performance with respect to the reference collector characteristics

As can be seen from Table 3 the percentage increase is more when the collector is operating at higher temperatures and this is so because at these higher temperatures the improved characteristics are really needed.

The results for the improved collector characteristics for a double-glazed collector are shown in Table 4. Here both the reference single-glazed and double-glazed collectors are shown for comparison purposes. The percentage differences in performance of the improved collectors, shown in Table 4, are with respect to the reference double-glazed collector.

By comparing the results shown in Tables 3 and 4 it can be concluded that there is a substantial increase in the percentage differences for collectors operating at higher temperatures although the absolute values of the useful energy collected between the single and double-glazed collectors are lower.

4. DISCUSSION

Generally the results show that the increase in performance of the collectors employing an absorber with improved properties is considerable. High-technology measures like a collector with α=0.97 and ε=0.05, which is out of the manufacturing capabilities of the industry and considered only for comparison purposes, increase more the performance of the collector but their economic viability is questionable unless the collectors are used for high-temperature applications. The same is true for the use of double-glazing of the collector, which at low temperature applications gives even worse performance because some of the incoming solar radiation is blocked from entering the collector aperture due to double reflection on the surfaces of the two glasses. However, at higher temperatures double-glazing is superior due to the better insulating properties and the minimization of the thermal top losses.

Table 4. Annual simulated performance for the use of various combinations of absorber plate optical properties for double-glazed collectors

Absorptance (α)	Emittance (ε)	Annual useful energy collected at various inlet temperatures (GJ)		
		T_a+5°C	T_a+15°C	T_a+30°C
0.9	***0.1***	***3.079***	***2.724***	***1.085***
0.9	**0.1**	**2.254**	**2.523**	**1.504**
0.95	0.1	2.649 (17.5%)	2.661(5.5%)	1.674 (11.3%)
0.97	0.1	2.681 (18.9%)	2.718 (7.7%)	1.741 (15.8%)
0.95	0.05	2.482 (10.1%)	2.723 (7.9%)	1.808 (20.2%)
0.97	0.05	2.500 (10.9%)	2.783 (10.3%)	1.875 (24.7%)

Notes: 1. Performance values shown are in GJ
2. Numbers in bold and *italic* represent the reference single-glazed collector
2. Numbers in bold represent the reference double-glazed collector
3. Numbers in parenthesis represent the percentage increase in performance with respect to the reference double-glazed collector characteristics

Another point of interest is that at lower temperatures the use of advance coating materials can let to lower performance, as the temperature of the absorber plate is low and thus radiation losses are minimal. For example the performance at low temperature of a collector with α=0.95 and ε=0.1 can be compared with a collector with α=0.95 and ε=0.05. According to the figures shown in Table 3 the latter shows a 3% lower performance (single-glazing) irrespective of the fact that this is also a more expensive material.

The improvements considered should be examined in relation to the investment cost required to build the collector with the improved characteristics. The extra cost required to build a superior collector may be compared with the extra energy collected from the collector in say 20-years period (life of the system) in order to evaluate its economic benefit. This analysis is beyond the scope of this paper, it is believed however that some improved optical properties which can be obtained by inexpensive methods, such as the painting of the absorber with selective paint, which gives α=0.95 and ε=0.1, are expected to be economically viable.

NOMENCLATURE

A	Collector area, m^2
c_p	Specific heat capacity, J/kgK
F'	Collector efficiency factor
F_R	Heat removal factor
I	Total horizontal solar radiation per unit area, W/m^2
I_{bT}	Incident beam solar radiation per unit area, W/m^2
I_d	Horizontal diffuse solar radiation per unit area, W/m^2
m	Mass flow rate, kg/s
N_g	Number of glass covers
Q_u	Rate of useful energy collected, W
T_a	Ambient temperature, K
T_{av}	Average collector fluid temperature, K
T_i	Collector inlet temperature, K
T_p	Stagnation temperature, K
U_{be}	Bottom and edges heat loss coefficient, W/m^{2}K
U_L	Overall heat loss coefficient, W/m^{2}K
U_t	Top heat loss coefficient, W/m^{2}K

Greek

α	Absorptance
β	Collector slope (degrees)
ε_g	Emissivity of glass covers
ε_p	Absorber plate emittance
θ_{sky}	Effective incidence angle for evaluating the incidence angle modifier of flat - plate collector for sky diffuse radiation
θ_{gnd}	Effective incidence angle for evaluating the incidence angle modifier of flat - plate collector for ground reflected radiation
ρ	Reflectance
σ	Stefan-Boltzmann constant (=5.67x10^{-8} W/m^{2}K^4)
τ	Transmittance
$(\tau\alpha)_b$	Transmittance - absorptance product for estimating incidence angle modifier for beam radiation
$(\tau\alpha)_s$	Transmittance - absorptance product for estimating incidence angle modifier for sky radiation
$(\tau\alpha)_g$	Transmittance - absorptance product for estimating incidence angle modifier for ground reflected radiation

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