PERFORMANCE OF A SOLAR SYSTEM USED FOR HEATING, COOLING AND HOT WATER PRODUCTION EMPLOYING COLORED COLLECTORS

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ABSTRACT

To avoid the monotony of the black colored flat plate solar collectors, color absorbers can be used which have lower thermal efficiency than that of the usual black type collectors. In this paper a solar heating, cooling and hot water application with colored-absorber collectors of high (usual type) and low (selective) emissivity is presented. The house considered is 196 m^2 insulated construction. The solar system consists of 20 m^2 solar collectors and a 1000 lt storage tank. For the cooling system a LiBr absorption unit was used. The solar system provides part of the heating, cooling and hot water load for a 4-persons family. The system is simulated with TRNSYS on an annual basis at three different locations, Nicosia, Cyprus; Athens, Greece and Madison, Wisconsin. The results show that for a medium value of the coefficient of absorptance, the colored collectors give satisfactory results compared to collectors with black absorbers. This implies the use of slightly larger collector aperture area to have the same energy output as that of typical black colored collectors, which is acceptable.

Keywords: Color solar collectors, space heating, cooling, hot water production

1. INTRODUCTION

Flat plate solar collectors are generally of black appearance because of the color of the absorber which is employed to maximize the absorption of the solar spectrum. The black view of the solar collectors on building roofs and facades is not usually aesthetically attractive and in some applications, they are not compatible with the color and architecture of the buildings. In most of these installations the black color of the collectors is not effectively combined with the white color of buildings, the blue color of the sea and sky and the color of the doors and windows. Considering that the aesthetic view is of priority for buildings of traditional and modern architecture we estimate that solar collectors with absorbers of different color than black could be an interesting solution for the building integration of solar energy systems. To avoid the monotony of the black color, collectors with absorbers of blue, red-brown, green or other color can be used. These collectors are of lower thermal efficiency than that of the usual black type collectors, because of the lower collector absorptance, but they are of more interest to architects for applications on traditional or modern buildings. The application of solar collectors with colored absorbers is a new concept and regarding the complete solar system, we notice that the increase in cost (by using a larger collector area) is balanced by the achieved aesthetic harmony with the building architecture.

An extensive study, including prototype testing and modeling, has been carried out and has shown that colored collectors can be of satisfactory efficiency, especially if a dark color absorber is used which has a better performance than a light tone one [1]. The constructed and tested flat plate collector prototypes were of blue and red-brown absorbers.

In this paper the application of solar collectors with colored absorbers in the heating, cooling and domestic hot water application of a typical house is presented. The collectors are analyzed with respect to their performance, aiming to give guidelines for their wider use on buildings. These systems are simulated on an annual basis at three different locations at different latitudes, Nicosia, Cyprus (35°), Athens, Greece (38°) and Madison, Wisconsin (43°).

2. ABSORPTION COOLING

Absorption systems are similar to vapour-compression air conditioning systems but differ in the pressurisation stage. In general an absorbent, on the low-pressure side, absorbs an evaporating refrigerant. The most usual combinations of fluids include lithium bromide-water (LiBr-H_2O) where water vapour is the refrigerant and ammonia-water (NH_3-H_2O) systems where ammonia is the refrigerant. The NH_3-H_2O system is more complicated than the LiBr-H_2O system, since it needs a rectifying column that assures that no water vapour enters the evaporator where it could freeze. The NH_3-H_2O system requires generator temperatures in the range of 125-170°C with air-cooled absorber and condenser and 95-120°C when water-cooling is used. The coefficient of performance (COP), which is defined as the ratio of the cooling effect to the heat input, is between 0.6 to 0.7.

The LiBr-H_2O system operates at a generator temperature in the range of 70-95°C with water used as a coolant in the absorber and condenser. The COP of this system is between 0.6 and 0.8 [2]. A disadvantage of the LiBr-H_2O systems is that their evaporator cannot operate at temperatures much below 5°C since the refrigerant is water vapour.

3. MODELING OF THE SYSTEM

The present system is modeled and simulated with TRNSYS program [3]. The system consists of a number of solar collectors, a thermally insulated vertical storage tank, an absorption refrigerator, a conventional boiler and interconnecting piping. A schematic of the system showing also the simulation program information flow is shown in Fig. 1. The type number of every TRNSYS subroutine used to model each component is also shown in Fig. 1. The LiBr-H_2O absorption air conditioner (TRNSYS Type 7) is a single-effect unit, based on Arkla model WF-36. Its nominal capacity is 65,000 kJ/hr and working in energy rate control.

The building considered is a typical house of 196m^2 floor area. Its load is calculated using TRNSYS Type 19 component. The typical house consists of four identical external walls. Every wall is 14m in length by 3m in height and has a double glazing window of 5.2m^2. The typical house is constructed with double-walls made of 0.1m hollow brick and 0.02m plaster on each side and a layer of 0.05m insulation in between. The roof is constructed from fair-face 15cm heavy concrete, 5cm polystyrene insulation, 7cm screed and 0.4cm asphalt, covered with aluminum paint of 0.55 solar absorptivity. The model house is further divided into four identical zones and the partition walls are considered as walls separating the four zones. Details of the input parameters required to model the typical house are given in [4].

During winter the solar system is used for space heating. The load is this case is the building heating load. An active solar space heating system is considered in which solar collectors are used to heat water, a storage tank to store solar energy until needed, and distribution equipment to provide the solar energy to the heated spaces in a controlled manner. It should be noted that in combination with conventional heating equipment solar heating provides the same levels of comfort and reliability as conventional systems [5].

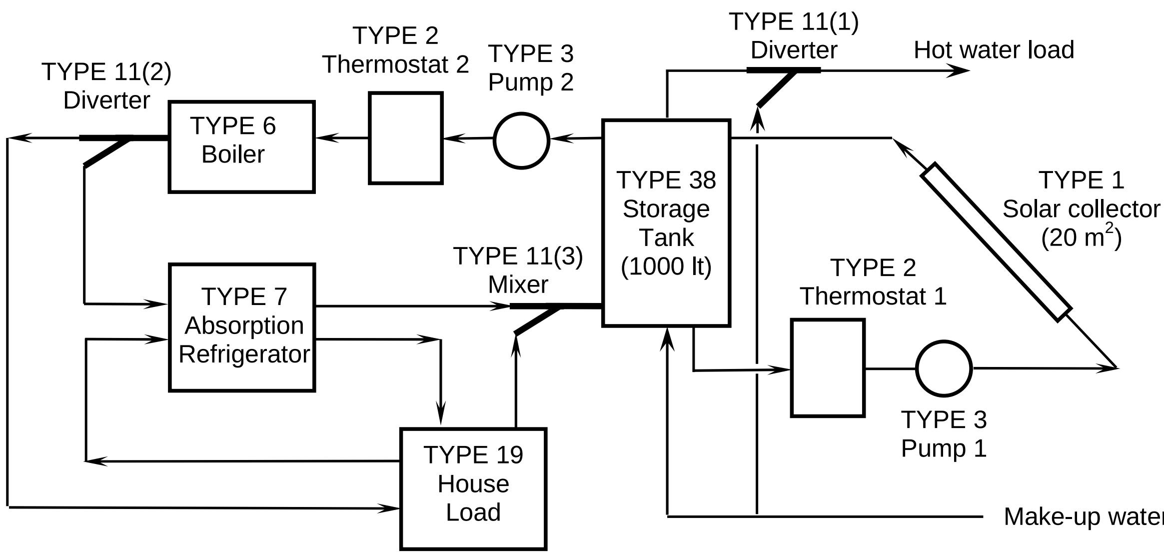

Fig. 1 Circuit diagram and TRNSYS types used for modelling the system.

During daytime the solar system absorbs solar radiation with collectors and conveys it to storage tank. When the building requires heat this is obtained from the storage tank. Control of this solar system is exercised by differential temperature controllers. To protect the system from freezing, a low-temperature sensor is installed on the collector which controls the collector pump when a pre-set temperature is reached (not shown in Fig. 1). This process wastes some stored heat, but it prevents costly damages to the solar collectors.

Auxiliary energy for heating is added so as to "top off" that available from the solar energy system. The auxiliary considered in this system is diesel. The same boiler is used as back-up of the heating and cooling system [5]. The domestic hot water required is drawn directly for the storage tank as shown in Fig. 1. A variable water consumption profile of a total of 120 liters of hot water per day is considered in simulations which is the consumption required for a four-person family. The hot water is mixed with water from the mains in order to obtain the required supply temperature of 50°C.

The various systems investigated were simulated with TRNSYS using the Typical Meteorological Year (TMY) data for Nicosia, Cyprus, Athens, Greece and Madison, Wisconsin. The annual total values of global radiation on a horizontal surface and direct normal radiation as well as the annual mean air temperature of the three locations as obtained from data contained in the three TMYs are shown in Table 1. As can be seen the weather of Nicosia and Athens is very similar whereas both the mean annual air temperature and total annual radiation are much lower in Madison.

Table 1 Annual values of radiation and mean annual temperature for the three locations

Location	Total global horizontal radiation (kWh/m^2)	Total direct normal radiation (kWh/m^2)	Mean ambient temperature (°C)
Nicosia, Cyprus	1691.2	1749.1	18.5
Athens, Greece	1669.6	1519.8	17.9
Madison, Wisconsin	1369.5	1317.2	7.9

4. COLLECTOR CHARACTERISTICS

The performance equations of the collectors that are employed in this work are based on evaluated equations from test results of prototypes [1]. Two types of flat-plate collectors are considered, collectors painted with normal black and color paints with an emittance value of 0.9 and collectors with selective coatings with an emittance value of 0.1. The absorptance of the black collectors considered is equal to 0.95 whereas the values for colored collectors vary from 0.85 to 0.65. These values apply to colored collectors irrespective of the actual color. The performance equations for the collectors considered are [1]:

Type A. Black collector, α=0.95 and ε=0.1: $n=0.8319 - 4.2629\ (\Delta T/G_t)$
Type B. Color collector, α=0.85 and ε=0.1: $n=0.7453 - 4.2648\ (\Delta T/G_t)$
Type C. Color collector α=0.75 and ε=0.1: $n=0.6585 - 4.2642\ (\Delta T/G_t)$
Type D. Color collector α=0.65 and ε=0.1: $n=0.5714 - 4.2604\ (\Delta T/G_t)$
Type E. Black collector, α=0.95 and ε=0.9: $n=0.7937 - 6.7128\ (\Delta T/G_t)$
Type F. Color collector, α=0.85 and ε=0.9: $n=0.7109 - 6.7316\ (\Delta T/G_t)$
Type G. Color collector α=0.75 and ε=0.9: $n=0.6277 - 6.7539\ (\Delta T/G_t)$
Type H. Color collector α=0.65 and ε=0.9: $n=0.5448 - 6.7740\ (\Delta T/G_t)$

5. RESULTS

TRNSYS can give results in an annual, monthly, daily or hourly basis. As the purpose of this work is to show the differences between the black and colored collectors only annual and monthly results are presented. It should be noted that one deck file is used. The parameters changed for each run are the call of the appropriate TMY file for each city considered, the latitude of the city and the characteristics of the collectors considered each time.

Table 2 presents the annual thermal loads of the typical house in the three locations considered. As can be seen the cooling load in Nicosia is the highest, Athens is a little lower whereas in Madison is much lower. The reverse is true for the heating load. This behaviour corresponds to the general weather prevailing in each location as presented in Table 1.

Table 2 Typical building thermal loads.

Location	Cooling load (MJ)	Heating load (MJ)	Hot water load (MJ)
Nicosia	78240	12530	5530
Athens	58600	15560	5530
Madison	25500	135200	5530

Table 3 presents the results of the whole system simulation on an annual basis. As can be seen the better the collector characteristics the higher the useful energy collected from the collector (Q_u) and the lower the energy required by the conventional boiler (Q_{boil}) which represents the energy required by the conventional boiler to cover the heating, cooling and hot water needs of the house. In all cases the cooling load (Q_{cool}) is the energy supplied by the absorption unit to cover the cooling load and is a little higher than the actual cooling load of the house. It should be noted that the same size of system is used for all locations for comparison purposes. Even for Wisconsin, where the system looks undersized, a bigger system would produce unnecessary energy during summertime due to the low cooling energy requirement.

As can be seen from Table 3 the performance of the collectors with absorptivity of 0.85 (B and F) is very near to the respective black collectors (A and D) whereas the performance of lower absorptivity ones is very much less, requiring more conventional energy to cover the lower performance. The relative percentage differences for Madison are much less due to the lower contribution of the solar system to the total annual energy requirement. From the results shown in Table 3 it can be concluded that color collectors with absorptivity of 0.85 (B and F) are acceptable whereas the ones with lower absorptivity are less effective. Therefore these collectors are investigated further and their performance is presented on a monthly basis.

Table 3 Annual results

Collector type	Nicosia, Cyprus			Athens, Greece			Madison, Wisconsin		
	Q_{cool}	Q_{boil}	Q_u	Q_{cool}	Q_{boil}	Q_u	Q_{cool}	Q_{boil}	Q_u
A(black)	**81590**	**69120**	**44370**	**65470**	**45590**	**41530**	**26760**	**162900**	**27480**
B	81210	73130 (5.8)	35840 (19.2)	65290	49140 (7.8)	33900 (18.4)	26610	166200 (2.0)	21660 (21.2)
C	81410	78190 (13.1)	27460 (38.1)	65090	51570 (13.1)	26180 (36.9)	26440	169300 (3.9)	16070 (41.5)
D	81630	84700 (22.5)	19400 (56.3)	64950	55520 (21.8)	18500 (55.5)	26570	173200 (6.3)	11000 (60.0)
E(black)	**81300**	**82630**	**22480**	**65050**	**55380**	**21300**	**26620**	**172700**	**11900**
F	81550	87940 (6.4)	15540 (30.9)	64900	58010 (4.7)	14930 (29.9)	26590	175300 (1.5)	7898 (33.6)
G	82140	95180 (15.2)	9088 (59.6)	64940	61950 (11.9)	8895 (58.2)	26720	177900 (3.0)	4318 (63.7)
H	81540	102600 (24.2)	3742 (83.4)	65090	67810 (22.4)	4021 (81.1)	26860	179900 (4.2)	1642 (86.2)

Notes:1. For collectors A, B, C, and D, ε=0.1 and for collectors E, F, G and H, ε=0.9
2. Number in parenthesis represent percentage difference with respect to black collector

The monthly energy flows of the system for Nicosia are shown in Fig. 2 where only the characteristics of collector types A, B, E and F are plotted. As can be seen selective collectors (A and B) offer much more heat than the non selective ones (E and F). The performance of the black colored collectors (A and E) is better than the colored ones (B and F). However these differences are within acceptable limits not imposing a large increase in area if the same output is required. The boiler heat required to cover the load is also shown in Fig. 2. As can be seen in the summer months the boiler heat in excess of the cooling load is required to cover the cooling load and the hot water load for the non-selective collectors (E and F). It should be noted that due to the similar solar environment a similar behaviour is expected for Athens.

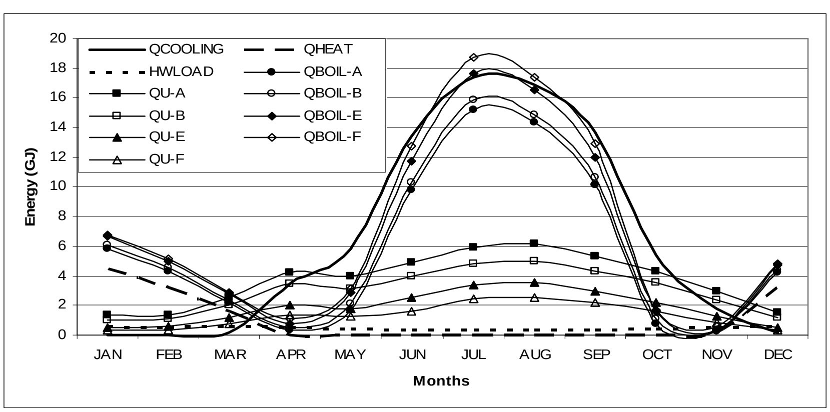

Fig. 2 Monthly energy flows of the system for collectors A,B, E and F for Nicosia

A much different behaviour is presented in Fig. 3 for Madison. Here the main load is the heating load. The solar system covers almost totally the cooling and hot water needs for the summertime but due to the excessive heating load required, the system is very much undersized for wintertime. Here the differences between the various collector types are insignificant due to the fact the solar heat is a very small percentage of the total energy required by the system annually.

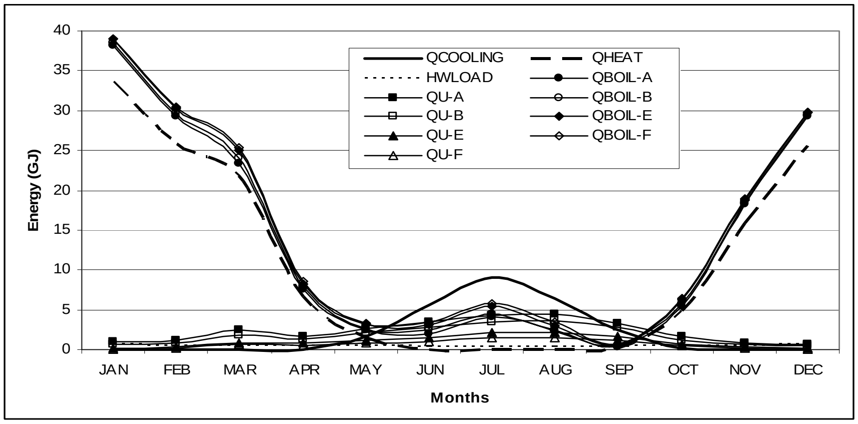

Fig. 3 Monthly energy flows of the system for collectors A,B, E and F for Madison

6. CONCLUSIONS

In this paper the application of solar collectors with colored absorbers in a solar space cooling and heating and domestic hot water system suitable for a typical house with a floor area of 196 m^2 is presented. The system is simulated on an annual basis at three different locations at different latitudes, Nicosia, Cyprus (35°), Athens, Greece (38°) and Madison, Wisconsin (43°). The results show that although the colored collectors present lower efficiency than the typical black type collectors, the difference in energy output is at an acceptable level considering the improvement in aesthetics. For a medium value of the coefficient of absorptance (α=0.85), the colored collectors give satisfactory results regarding the drop of the amount of collected energy for the three locations (about 20% for selective and 30% for non-selective collectors), compared to collectors with black absorbers (α=0.95). This implies the use of proportionate larger collector aperture area to have the same energy output as that of typical black colored collectors. Therefore, systems employing color collectors are feasible for applications on buildings of traditional or modern architecture, contributing to a wider use of solar collectors in the built environment.

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