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Effect of the Storage Capacity and Solar Collectors Area on the Performance of Space Heating System using a Solar Heat Pump

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Abstract

The purpose of this work is the study, the simulation, and the analysis of a solar flat plate collector combined with a compression heat pump. The system suggested must ensure the heating of a building without the recourse to an auxiliary energy source in complement of this heating system. A numerical model is developed to study the influence of the volume of storage tank and the area of the solar collectors on the performance of the system. The system is used to heat a building using heating floor. The building considered is located in Constantine-East of Algeria (Latitude 36.28°N, Longitude 6.62°E, Altitude 689m). For the calculation, the month of February was chosen, which is considered as the coldest month according to the weather data of Constantine.

Keywords: *Heat pump, Flat plate solar collectors, Storage Tank, Space heating.*

1. Introduction

Nowadays, provide clean energy in sufficient quantity and at a handsome price, constitutes a major requirement for the development of any nation. Indeed, the increase in demand in energy, the accelerated deterioration of the environment related to the residues of the energy resources used, pose serious problems on a global scale. The socio-economic impact of these problems can only be intensified in the short and medium term. Due to the forecasts of inescapable exhaustion of the world energy supplies (oil, gas, coal…), due to the multiple oil and economic crises, and due to the climatic changes due to the effect of greenhouse, science quite naturally was interested in the resources known as "renewable" and in particular towards oldest, the sun. However there are a certain factors making the exploitation of solar energy difficult, mainly the intermittency of the solar radiation and its variation day and even according to the year, indeed solar energy remains dependent on the weather conditions moreover there is a dephasing between the requirements in energy (heat) and the contributions generated by solar energy and considering this unavailability it is always necessary to envisage a supplement in energy for each use, the solar systems are often assisted with auxiliary heat source.

The heat pumps are machines that transfer heat from area at low temperature to another at high temperature. This is usually carried out through the refrigeration cycle by vapour compression, taking advantage of the heat given off by the condenser instead of the heat absorbed by evaporator.

Hawlader et al [1] presented an Analytical and experimental studies were performed on a solar assisted heat pump water heating system, where unglazed, flat plate solar collectors acted as an evaporator for the refrigerant R-134a.The system was designed and fabricated locally, and operated under meteorological conditions of Singapore. The results obtained from simulation are used for the optimum design of the system and enable determination of compressor work, solar fraction and auxiliary energy required for a particular application. Badescu [2] presented details about modelling a sensible heat thermal energy storage (TES) device integrated into a space heating system. Solar air heaters provide thermal energy for driving a vapor compression heat pump. The TES operation is modeled by using two non-linear coupled partial differential equations for the temperature of the storage medium and heat transfer fluid, respectively. A simple and cost effective solar assisted heat pump system (SAHP) with flat plate collectors, a hot water storage tank and a water source heat pump has been proposed by Kuang et al. [3]. The thermal performances of the whole system and its major components have been investigated experimentally during the 2000–2001 heating season in north China. A long-term reliability test of an integral-type solar-assisted heat pump water heater (ISAHP) was carried out by Huang et al. [4]. The prototype has been running continuously for more than 13,000 hours with total running time >20,000 hours during the past 5 years. The measured energy consumption is 0.019 kWh/l of hot water at 57^{o}C that is much less than the backup electric energy consumption of the conventional solar water heater. In the study of Chyng et al. [5] a modelling and system simulation of an integral-type solar assisted heat pump water heater (ISAHP) was carried out. The

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modelling and simulation assume a quasi-steady process for all the components in the ISAHP except the storage tank. The simulation results for instantaneous performance agreed very well with experiment. The simulation technique was used to analyze the daily performance of an ISAHP for 1 year. The study of Ozgener [6] investigates the performance characteristics of a solar-assisted ground-source (geothermal) heat pump system (SAGSHPS) for greenhouse heating with a 50 m vertical 32 mm nominal diameter U-bend ground heat-exchanger. The study of Berdal et al. [7] relates the design and the development of a process consisting of combining a reversible geothermal heat pump with thermal solar collectors for building heating and cooling and the production of domestic hot water. The proposed process, called GEOSOL, has been installed in a 180 m^2 private residence in 2004. This installation is the subject of long-term experimental follow-up to analyse the energy-related behaviour of the installation at all times of the year. Georgiev [8] presents the experimental study of a heat pump possessing solar collectors as an energy source. A method to test the combined work of collectors delivering heat to the evaporator of a heat pump was devised. The layout of the test facility is shown and the system construction with the measurement equipment is described. Chow et al. [9] presented the modelling and application of direct-expansion solar-assisted heat pump for water heating in subtropical Hong Kong.

The purpose of this work is the contribution to the study, the simulation and the analysis of the heat pumps assisted by solar energy. In space heating, heat pumps and solar collectors taken separately have insufficiencies and deficiencies. The objective of the coupling of these two systems is to avoid the imperfections of each system and to cumulate the advantages suitable for each of the two systems. Thus a system of more powerful heating resulting from the coupling of the two heat engines is obtained.

For the execution of this work the heating system proposed is used to heat a building located in Constantine-Algeria. The area of the building is 650 m² and the heating load is evaluated to 40 kW.

2. System description

The system proposed consists of 3 parts (figure 1):

- Solar collectors and storage tank
- Heat pump
- Heat distribution.

The solar loop consist of a solar collectors and a storage tank connected to each other by pipes, the coolant (water glycol) was put in circulation between solar collectors and storage tank by a pump.

The solar collectors collect solar energy and transform it into thermal energy which is transmitted to the coolant (water glycol); this thermal energy is stored in the form of sensible heat in a storage tank until it can be used. When it is necessary heat is pumped from the storage tank to supply with thermal energy the building to be heated by the mean of a heat pump.
The heat pump is "water - water" type, it transfer heat between the solar system (solar collector) and the system of distribution by the means of a heat exchanger of heat. The coolant which transports the heat of the solar system is antifreeze (water glycol) and the system of distribution of heat uses water like coolant.

The energy transmitted to the building is composed of the collected solar energy plus the equivalent thermal of the work of the compressor of the heat pump. Thus the heat pump concentrates and increases the level of temperature of this free heat coming from the sun, before distributing it in the building (space to be heated) using a floor heating.

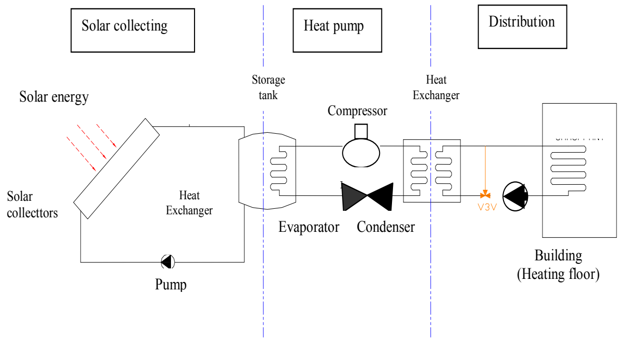

Fig.1. Schematic diagram of solar assisted heat pump system

2.1. Solar Collector System

The various relations that are required in order to determine the useful energy collected and interaction of the various constructural parameters on the performance of a collector are taken from [10-15]

The energy balance equation of the solar collector can be written as follows [10]:

$$I_G.A_c = Q_u + Q_{loss} + Q_{stg} \tag{1}$$

Where I_G is the instantaneous solar radiation incident on the collector per unit area, A_C is the collector surface area, Q_{loss} is the heat loss from the collector and Q_u is the useful energy transferred from the absorber to the fluid flowing through the tubes of the collector. Q_{stg} is the energy stored in the collector (Q_{stg}=0: the solar thermal system is considered at steady state conditions).

The useful energy gain of the flat plate collectors is calculated by:

$$Q_u = A_c.F_R.[(\tau.\alpha).I_G - U_L.(T_{fi} - T_a)] \tag{2}$$

Where A_C is the collector area, F_R is the collector heat removal factor, $(\tau.\alpha)$ is the transmittance-absorbance products, U_L is the collector overall loss coefficient, T_a is the ambient air temperature and T_{fi} is the fluid temperature at the inlet to the collector.

The Collector heat removal factor (F_R) is the ratio of useful heat obtained in collector to the heat collected by collector when the absorber surface temperature is equal to fluid entire temperature on every point of the collector surface.

$$F_R = \frac{m.C_p}{A_c.U_L}\left[1 - e^{-\frac{(A_c.U_L.F')}{m.C_p}}\right] \tag{3}$$

Where m is the mass flow rate of water, C_p is the specific heat of water and F' is the collector efficiency factor. F' represents the ratio of the actual useful energy gain to the useful energy gain that would result if the collector absorbing surface had been at local fluid temperature.

The collector overall heat loss coefficient (U_L) is the sum of the top U_T, the bottom U_B and the edge U_E heat loss coefficient. It means that:

$$U_L = U_T + U_B + U_E \quad (4)$$

The first law efficiency (thermal efficiency) of the solar collectors is the ratio of useful energy obtained in collector to solar radiation incoming to collector. It can be formulated as:

$$\eta_{th\text{-}FPC} = \frac{Q_u}{I_G . A_c} \quad (5)$$

The prediction of collector performance requires knowledge of the absorbed solar energy by collector absorber plate. The solar energy incident on a tilted collector consists of three different distributions: beam radiation, diffuse radiation, and ground – reflected radiation. The details of the calculation depend on which diffuse sky model is used. For estimating sky diffuse solar radiations several models have been developed [11-15]. They vary mainly in the way that treats the three components of the sky diffuse radiation, i.e. the isotropic, circumsolar and horizon radiation streams.
In this study the absorbed radiation on the absorber plate is calculated by Perez's model [16].

2.2. Collecting Surface

The area suggested of the solar collectors depends on the needs for energy, the type of system and the type of solar collector. For the heating of water with storage the needs for energy include, the load of heating plus the losses (pipes, storage tank, and energy loss during the night).

2.3. Storage Tank and Heat Pump

Thermal losses Q_S of storage tank are given by:

$$Q_S = (UA)_S (T_S - T_a) \quad (6)$$

$(UA)_S$: Energy lost to the surroundings [W/°C]
U: Total coefficient of loss of the storage tank [W/m²°C]
A: Storage tank area [m²]
T_a : Ambient temperature [°C]
T_S : Temperature of water in the storage tank [°C]

The energy balance for the water storage tank can be expressed as:

$$(MC_p)_s \left(\frac{dT_s}{dt}\right) = Q_U - Q_L - Q_S \quad (7)$$

M : Mass of fluid in the storage tank [kg]
Q_L : Energy extracted from the storage tank (energy absorbed by the evaporator of the heat pump)

$$Q_L = Q_{ev} \quad (8)$$

2.4. Variation of the temperature of the storage tank during the stop of the system

The heating system being designed to be to the stop after the working hours, the temperature of the fluid on the level of the storage tank must be evaluated throughout all that and this stop to be able to appreciate the starting temperature of the system the following day. After the stop of the system Q_U=0 and Q_L=0, the final temperature of storage tank can be evaluated starting from the equation (7).

The coefficient of performance of heat pump (COP) is given by the following relation:

$$COP = \frac{Q_{cd}}{W} \quad (9)$$

The heat transferred to the condenser is:

$$Q_{cd} = Q_{ev} + W \quad (10)$$

Q_{ev} : Energy absorbed in the evaporator [kW]
W : Mechanical work of the compressor [kW]

2.5. Heating Load

The thermal load (Q_L) is the quantity of heat required to the building to ensure its heating and to reach the consigned temperature of comfort.

$$Q_L = (\dot{m}C_p)_L (T_{inH} - T_{outH}) \quad (11)$$

$(\dot{m}C_p)_L$: Flow rate of the heating load [kW/°C]
$\dot{m}$: Mass flow rate of heating fluid [kg/s]
T_{inH} : The inlet hot water temperature of the heating loop [°C]
T_{outH} : The outlet hot water temperature of the heating loop [°C]

This energy (Q_L) is provided to the floor heating of the building by the condenser of the heat pump through a heat exchanger, taking account of the effectiveness of the heat transfer between the condenser and the heat exchanger, the heat delivered by the condenser must be higher than the heat necessary for the heating of the building.

3. Parameters of Calculation and Assumptions

In order to simulate the behaviour of the system, all components must have all their characteristics defined and specified.

- A Compression heat pump (Refrigerant : R134a)
- The flow rate in the solar loop is constant
- Pipeline between the solar collectors and the storage tank and between the heat pump and the system of distribution are perfectly insulated, therefore the thermal losses are negligible.
- Pressure loss in the heat pump are negligible
- Isentropic efficiency of the compressor: 0,8
- The difference between the temperature of storage and the temperature of evaporation is : T_S-T_{ev}=5°C
- The temperature of condensation is: T_{cd}=50°C
- The superheating of the refrigerant on the outlet side of the evaporator is: 7°C
- Under cooling of the refrigerant on the outlet side of the condenser is: 5°C
- Solar flat plate collectors: Model Alternate Energy AE-21 (coolant: water glycol)
- Solar collector Area : Ac=1,783 m²

- Coefficient of transmittance - absorbency: $F_R(\tau\alpha) = 0{,}706$
- Total coefficient of loss of the solar collector : $F_R U_L = 4{,}9099 W/m^2 °C$
- The heating system operates between time of day 8 and 17.
- Indoor air temperature : 18°C.
- The inlet hot water temperature of the heating loop : $T_{inH} = 45°C$
- The outlet hot water temperature of the heating loop : $T_{outH} = 40°C$
- Energy lost to the surroundings of the storage tank : $(UA)_S = 10$ W/°C

4. Results and Discussion

A detailed simulation of the whole system was carried out in order to study the operation and the behaviour of the global heating system and to simulate the diurnal temperature variations of the storage fluid and energy fluxes exchanged of each part in the solar heating system: collecting, storage, heat pump and distribution. In the present study the simulation is carried out for the average day of February which is the 16th day corresponding to the number of the n=47 day. **(**For the calculation, the month of February was chosen, which is considered as the coldest month according to the weather data of Constantine**)**.

The system was designed to function from 8 to 17 hour and since the operation of the system over one day depends on the previous day, the temperature of storage tank during the stop of the system must be evaluated. The Results obtained are discussed below.

Figure 2 presents the variation of the daily average COP of the heat pump versus the volume of storage tank (Vs) for fixed values of solar collectors area (Ac). It can be seen that the COP is maximum for lowest value of Vs. With an increase in the volume of storage tank the COP decreases then remains relatively constant and finally decrease again, this can be explained by the fact that the COP is directly related to the temperature of water in the storage tank (T_S) which is the temperature of the cold source of the heat pump.

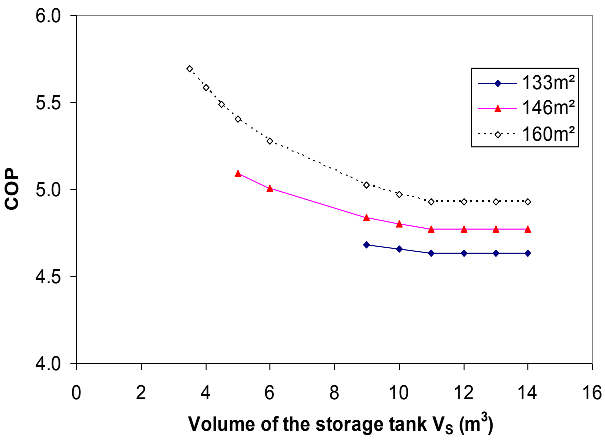

Fig. 2. Variation of the COP versus to the volume of the storage tank (V_S)

Figure 3 presents the variation of the COP according to time for various values of A_C/V_S. It is clear that the COP is maximum between times of day 14-15. This is can be explained by the fact that the temperature T_S is maximum during this period.

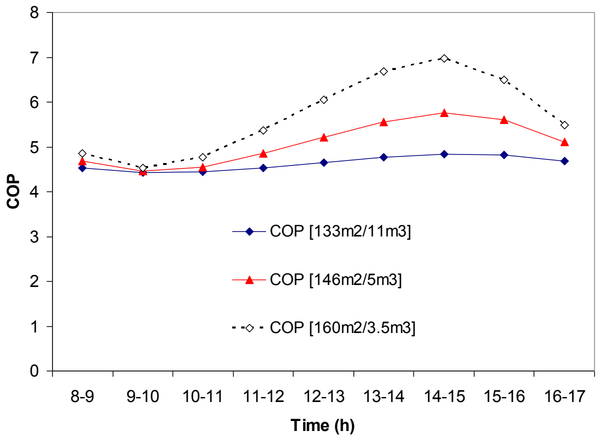

Fig. 3. Variation of the COP versus time of day for various values of the couple A_C/V_S

Figure 4 presents the variation of the quantity of collected heat Q_U versus the time of day for the optimal values of the couple A_C/V_S.

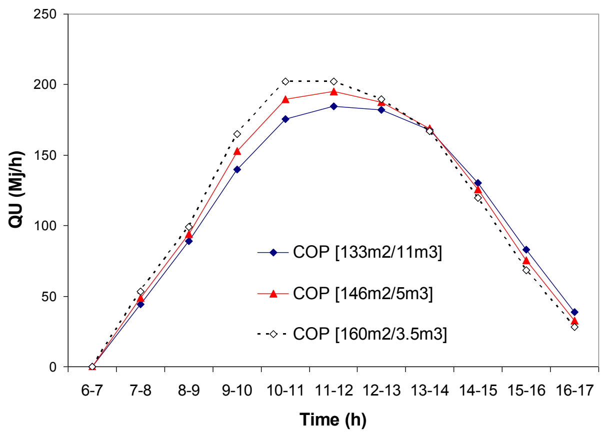

Fig. 4. Variation of the of collected heat versus time of day for various values of the couple A_C/V_S

It can be seen that the quantity of collected heat Q_U increases in the morning and becomes maximum at 11-12 hour to decrease again after midday. Collected heat Q_U depends on two parameters the intensity of the solar radiation and the temperature of entry to the solar collectors which is in our case the temperature of storage tank T_S. In the morning with the starting of the system the temperature of storage tank is low but progresses slowly whereas the intensity of the radiation is growing what supports the increase in collected heat.

After midday collected heat allows the increase in T_S and owing to the fact that the intensity of the solar radiation is in regression, collected heat decreases. One can notice that the profit of heat is not proportional to the increase in the solar collectors area, this profit is larger for the greatest value of A_C in the morning, maximum at midday to decrease and becomes again smaller for the smallest value of A_C, i.e. the profit of collected heat is larger after midday for the smallest value of collecting solar energy area.

Figure 5 shows the variation of the storage temperature T_S versus time of day for the optimal values of the couple A_C/V_S. It is clear that the temperature of storage tank is fluctuating during the day, it increases in the beginning (7-8h) because de system is off then there is no heat extracted from the storage tank. (Q_L=0). Storage tank temperature decreases from (8-9h) since the solar heat collected is lower than the quantity of extracted heat from the storage tank. From 9 hour until (13-14h) T_S increase since during this period the quantity of solar heat collected is higher than the quantity of heat extracted from the storage tank ($Q_U > Q_L$).

During the period 14 to 17h, T_S decrease since (Q_U>Q_L).

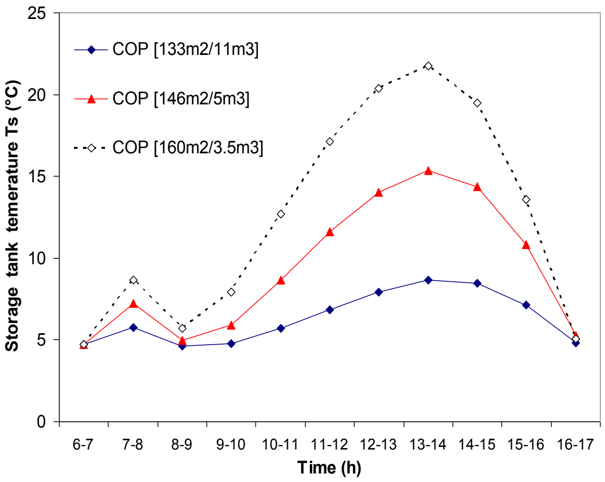

Fig. 5. Variation of the Storage tank temperature versus time of day for various values of the couple A_C/V_S

From 17 hour the system is stopped and T_S decrease continuously and gradually, the variation of the temperature of the storage tank and the ambient temperature are small and the losses of heat are relatively small. It is noticed that the temperature of storage tank T_S is higher in the case of higher value of the solar collecting area A_C and the smallest value of the volume of the storage tank V_S.

Figure 6 shows the variation of the storage tank temperature and the thermal efficiency of the solar collectors versus time of day.

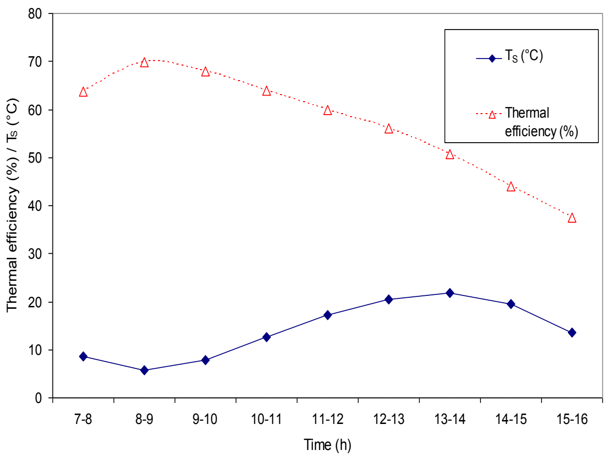

Fig. 6. Variation of the Storage tank temperature and thermal efficiency of solar collectors versus time of day

It can be seen that the effectiveness of the thermal efficiency of the solar collectors is maximum when the temperature of storage tank is low and decreases with the increase in the temperature of storage then it is possible to say that the temperature of storage T_S which is the inlet temperature of the fluid to the solar collectors is an important parameter in the evolution of the thermal efficiency of the solar collectors.

Figure 7 shows the variation of the collected solar energy Q_U and heating load Q_L versus time of day. It is clear that the energy extracted from the storage tank Q_L is almost constant whereas the energy collected Q_U is variable.

At the beginning (7-8h), since the system is off thus there is no heat extracted from the storage tank (Q_U>Q_L=0), from (8-9h) the collected heat Q_U is lower than the quantity of extracted heat (Q_U<Q_L).

During the period 9 to 13h the quantity of collected heat is higher than the quantity of heat extracted from storage (Q_U>Q_L).

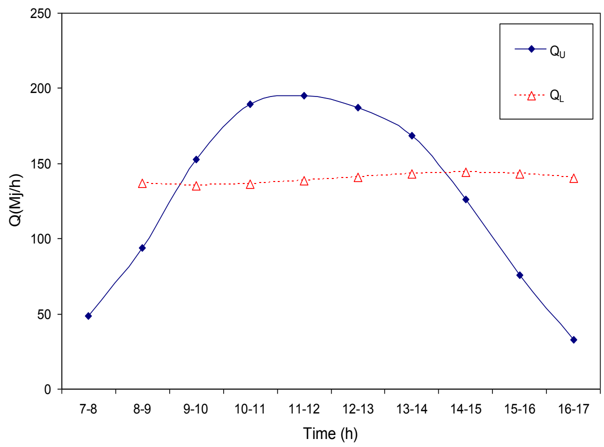

Fig.7. Variation of Q_U and Q_L versus time of day

During the period 14 to 17h, Q_U decrease (Q_U<Q_L). The surplus of heat collected during the period where Q_U>Q_L allows to make up the deficit during the period where Q_U<Q_L at the starting of the system and after 14 hour. This surplus also makes it possible to compensate the losses of heat in period when the system is off.

We notice the significant role which plays the thermal storage tank in the modulation and the regulation of the collected energy and energy required by the heating system.

5. Conclusion

The following conclusion can be drawn:

- Collected heat is not proportional to the increase in the solar collectors area. For a given heating load there is a required minimum solar collectors area. At this area corresponds an optimal storage tank volume. For a given storage tank volume the temperature of storage increases with the increase in the solar collectors area.
- The COP increases with the increase in the temperature of storage tank. But, more the temperature of storage increases less solar heat is collected thus, the efficiency of the solar collectors decreases.

- The thermal storage tank is a component of major importance for the solar heating systems, which can modulate the variation of the evolution between solar radiations (solar contributions) and the heating load.
- Because of the low temperatures of storage tank, high thermal efficiency of the solar collectors and solar fraction were obtained and the mean values of one day for this system are respectively 60% and 82%.
- Space heating system (in particular heating floor) using a solar energy assisted heat pump can strongly improve the thermal performance of the heat pump and the global system.
- The heat pump assisted by solar energy can contribute to the conservation of conventional energy and can be competitive with the traditional systems of heating.

Nomenclature

A_C	Collector surface area, m^2
COP	Thermal efficiency (coefficient of performance) of the absorption cooling system
C_p	Specific heat of water, kJ/kg.K
F'	Collector efficiency factor.
F_R	Collector heat removal factor
H	Enthalpy, kJ/kg
I_G	Instantaneous solar radiation incident, kW/m^2
M	Mass flow rate of the fluid stream,
Q	Heat (Energy), kW
T	Temperature, K
U	Heat loss coefficient, $kW/m^2.K$
W	Mechanical work transfer to or from the system, kW
T	Temperature of the jet, K

Greek Symbols

$(\tau.\alpha)$	is the transmittance-absorptance products

Subscripts

0	Reference value
A	Ambient
B	Bottom
Cd	Condenser
E	Edge
Ev	Evaporator
Fi	The fluid at the inlet to the collector.
FPC	Flat plate collectors
inH	Inlet hot water temperature of the heating loop
outH	Outlet hot water temperature of the heating loop
L	Energy extracted from the storage tank
S	Storage
T	Top

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