Thermal solar energy systems for space heating of buildings

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ABSTRACT

In this study, the simulation and the analysis of a solar flat plate collectors combined with a compression heat pump is carried out. The system suggested must ensure the heating of a building without the recourse to an auxiliary energy source in complement of this heating 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.

The performances of this system were compared to the performances of the traditional solar heating system using solar collectors and an auxiliary heating load to compensate the deficit. In this case a traditional solar heating system having the same characteristics with regard to the solar collecting area and the volume of storage tank is used.

It can be concluded that the space heating system using a solar energy combined with heat pump improve the thermal performance of the heat pump and the global system. The performances of the heating system combining heat pump and solar collectors are higher than that of solar heating system with solar collectors and storage tank. 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.

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 daily and yearly variation, 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. 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 the evaporator.

Hawlader et al [Hawlader, 2001] presented an Analytical and experimental studies 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 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 [Badescu, 2003] 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 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. [Kuang, 2003]. 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. [Huang, 2004]. The prototype has been running continuously for more than 13,000 hours with total running time more than 20,000 hours during 5 years. The measured energy consumption is 0.019 kWh/l of

hot water at 57°C. In the study of Chyng et al. [Chyng, 2003] a modelling and system simulation of an integral-type solar assisted heat pump water heater (ISAHP) was carried out. The 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 [Ozgener, 2005] investigates the performance characteristics of a solar-assisted ground-source (geothermal) heat pump system (SAGSHPS) for greenhouse heating with a 50m vertical 32mm nominal diameter U-bend ground heat-exchanger. The study of Berdal et al. [Berdal, 2007] 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 180m^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 [Georgiev, 2008] 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. [Chow, 2010] 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 thermal systems. Thus a system of more powerful heating resulting from the coupling of the two thermal systems 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.

DESCRIPTION OF THE SYSTEM

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.

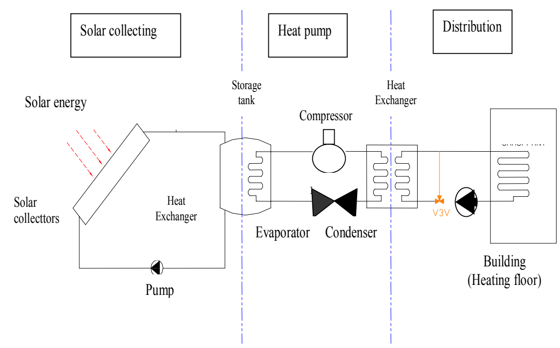


Figure 1. Schematic diagram of solar assisted heat pump system

The heat pump is "water - water" type, it transfer heat between the solar system (solar collectors) and the system of distribution by the means of a heat exchanger. 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.

MODELLING OF THE SYSTEM

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 [Frederick, 1976], [Kalogirou 2004], [Uca et al., 2007], [Karatasou, 2006], [Akhtara, 2007], [Sartori 2006]
The energy balance equation of the solar collector can be written as follows [F. S. Frederick, 1976]:

$$I_G.A_c = Q_u + Q_{loss} + Q_{stg} \qquad (1)$$

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:

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

Where A_C is the collector area, F_R is the collector heat removal factor, $(\tau.\alpha)$ is the transmittance-absorptance 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.

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

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, bottom U_B and 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:

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

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 [Kalogirou 2004], [Uca et al., 2007], [Karatasou, 2006], [Akhtara, 2007], [Sartori 2006]. 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 [Bugler, 1977].

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 transfer to the surroundings [W/°C]
U: the global coefficient of heat transfer 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 of the water storage tank can be expressed as:

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

M: Mass of fluid in the storage tank [kg]
Cp: Specific heat at constant pressure [kJ/Kg.°C]
Q_S: Energy lost to the surroundings of the storage tank
Q_L: Energy extracted from the storage tank (energy absorbed by the evaporator of the heat pump, Q_{ev})
t: time [s]

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

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

The heating system is designed to work between time of day 8 and 17. The temperature of the fluid in the storage tank must be evaluated throughout all the working hours and during the stop period 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 using 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 (Q_{cd}) is:

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

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

Heating load

The thermal load ($Q_{Heat\text{-}L}$) is the quantity of heat required to the building to ensure its heating and to reach the consigned temperature of comfort.

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

$(\dot{m}C_p)_L$: Flow rate of the heating load [kW/°C]

$\dot{m}$: Mass flow rate of the heating fluid [kg/s]
T_{inH}: The inlet temperature of the heating fluid [°C]
T_{ouH}: The outlet temperature of the heating fluid [°C]

This energy (Q_{Heat-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.

TRADITIONAL SOLAR HEATING SYSTEM

In order to better appreciate the contribution of the combination of solar collectors and compression heat pump the performances of the solar collectors/compression heat pump system will be compared to the performances of the traditional solar heating system using solar collectors and an auxiliary heating load to compensate the deficit. In this case a traditional solar heating system having the same characteristics with regard to the solar collecting area and the volume of storage tank is used (figure 2).

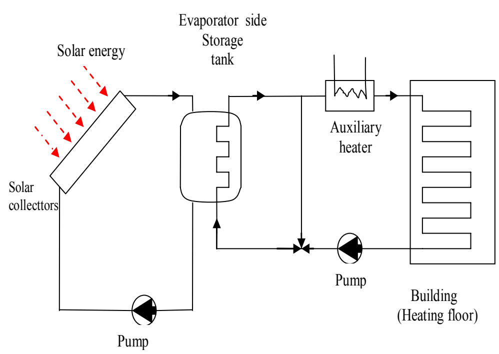


Figure 2. Schematic diagram of traditional solar heating system

The system was modelled and simulated in the same way that for the combined solar collectors/compression heat pump.
In order to compare the two heating systems the daily solar collectors efficiency and the daily solar fraction are introduced as follow:

Daily solar collectors efficiency

$$\varepsilon_D = \frac{\sum Q_U}{\sum I_T.A_C} \quad (12)$$

Daily solar fraction:

$$F_D = \frac{\sum Q_U}{\sum Q_L} \quad (13)$$

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
- Total solar collector Area=160 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 : $(UA)_S = 10 W/°C$
- Storage tank volume=3.5 m^3

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 tank, 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 n=47 days. (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 17h 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 3 shows the variation of the storage tank temperature T_S versus time of day. It is clear that the temperature of the storage tank is fluctuating during the day, it increases in the beginning (from 7 to 8h) because the system is off then there is no heat extracted from the storage tank. (Q_L=0). Storage tank temperature decreases from 8 to 9h since the solar heat collected is lower than the quantity of extracted heat from the storage tank. From 9h until 14h, T_S increases 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 decreases since ($Q_U > Q_L$).

After 17h the heating system is stopped and T_S decreases 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.

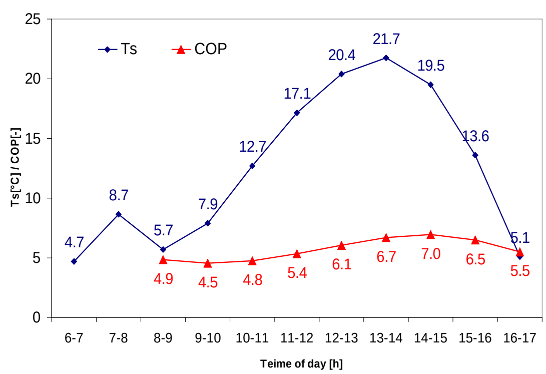


Figure 3. Variation of the Storage tank temperature and the COP versus time of day

Figure 3 represents also the variation of the coefficient of performance of the compression heat pump (COP) according to the time of day. It is clear that the COP is maximum between 13 and 14h. This is due to the fact that the storage tank temperature T_S is maximum during this period. This figure 3 shows that the variation of the COP follow in a similar way and in the same direction the variation of the storage tank temperature. The COP is directly related to the temperature of storage tank.

Figure 4 shows the variation of the storage tank temperature and the thermal efficiency of the solar collectors versus time of day.

It can be seen that 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 the storage tank then it is possible to say that the temperature of storage tank 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.

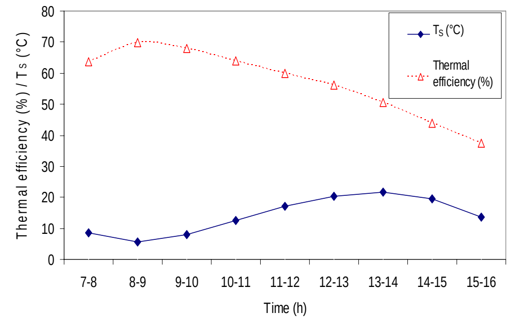


Figure 4. Variation of the storage tank temperature and thermal efficiency of solar collectors versus time of day

Figure 5 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.

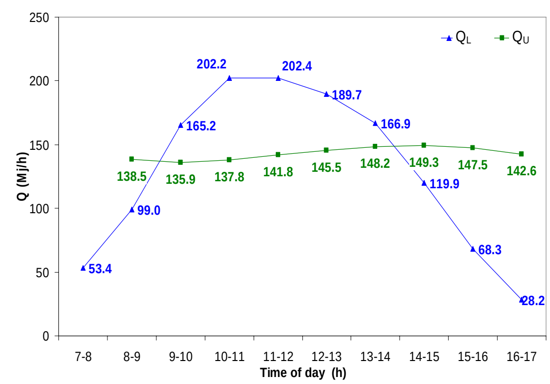


Figure 5. Variation of Q_U and Q_L versus time of day

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

During the period 9 to 14h the quantity of collected heat is higher than the quantity of heat extracted from storage tank (Q_U>Q_L).

During the period 14 to 17h, Q_U decreases (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 14h. 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.
Figure 6 represents the variation of the thermal efficiency of the solar collectors and the variation of solar fraction. It is clear that the thermal efficiency of the solar collectors is maximum between 9 and 10 hour (corresponding to the minimum value of T_S) and decrease hour by hour to reach its minimal value at the end of the day (17h), because during this period the temperature of storage tank is increasing and more T_S is high and less heat is collected compared to the total quantity of heat available.
On the other hand the solar fraction is relatively increasing and directly related to T_S because more is high the temperature of the storage tank and more significant is the heat available in the storage tank i.e. heat available which can be extracted.

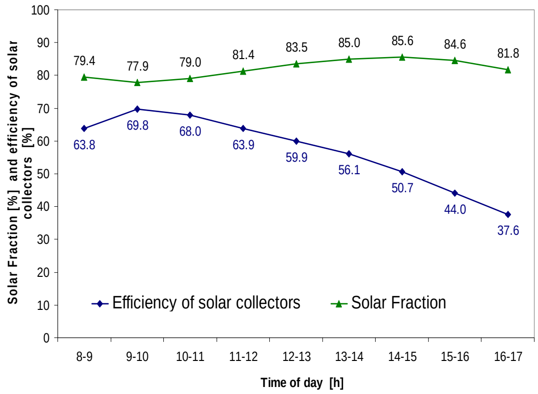
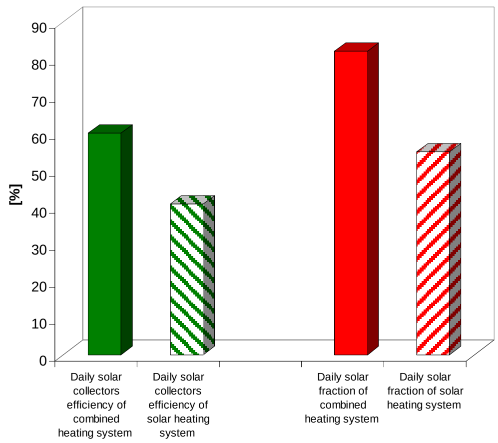


Figure 6. Variation of the thermal efficiency of the solar collectors and the solar fraction.

The performances of this system were compared to the performances of the traditional solar heating system using solar collectors and an auxiliary heating load to compensate the deficit. In this case a traditional solar heating system having the same characteristics with regard to the solar collecting area and the volume of storage tank is used in order to better appreciate the contribution of the combination of solar collectors and compression heat pump.
The daily efficiency of the solar collectors in the traditional solar heating system is about 41% but this efficiency is about 60% for the combined heating system (solar collectors /heat pump system). The daily solar fraction is about 55% and 82 % for solar heating system and for the combined heating system (solar collectors /heat pump system) respectively, this can be explained by the fact that in the case of the combined system solar collectors works at low temperatures (temperatures of the storage tank)



La figure 7. Values of the daily efficiency of the solar collectors and the daily solar fraction.

CONCLUSION

The following conclusion can be drawn:

- Because of the low temperatures of the storage tank, high values of thermal efficiency of the solar collectors and solar fraction were obtained and the mean values of one day for the heat pump assisted by solar energy heating 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.

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