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Solar assisted heat pump for domestic hot water production

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Abstract

In this article, a R&D project is described involving a prototype solar assisted heat pump (HP) designed for domestic hot water preparation for single family dwellings. This project, developed within the framework of Task 44 of the IEA Solar and Cooling Programme, uses solar energy on the HP evaporator side to maximize the performance level of the system. In cases where solar energy is not enough, the HP under investigation has been designed to extract energy from the heating circuit of the building. This study involves both test bench measurements and dynamic simulations of the solar assisted heat pump system. The overall objectives of the project are summarised as follows:

- Development of solar thermal technology
- Improvement of HP performance for DHW production
- Reduction of non-renewable energy consumption
- Reduction of environmental impacts

This article presents an overview of the project and its current status.

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Keywords: Heat pump ; thermal solar collectors, DHW, COP, measurements, simulation, life cycle analysis

1. Background

In Switzerland, domestic hot water (DHW) represents nearly 13% of the total final energy consumption. This is the second largest consumer of energy in the residential sector after space heating [1]. In order to reduce building's heating requirements, new energy policies have been adopted by the Swiss government to promote optimisation of building envelopes. These measures have led to an increase of the relative share of energy for DHW production. For buildings with high energy performance (type

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Minergie-P), the energy required for DHW heating is now of the same order of magnitude as the energy for space heating. It is therefore important to find ways to reduce the energy used for DHW preparation. The potential of coupling a heat pump and solar collectors as already been demonstrated in a previous study [2].

One of the problems of solar energy is that the source is not in phase with the energy demand (heating and DHW). In this case, the integration of a HP with a solar thermal system could improve the overall performance of the system.

In 2010, a new task of the International Energy Agency (IEA) was defined within the framework of the Solar Heating and Cooling program. Task 44, entitled Solar and Heat Pump Systems, aims to optimize and promote the combination of solar thermal and heat pumps for DHW production and space heating of single family houses [3]. This article concerns the project undertaken by the Laboratory of Solar Energetics and Building Physics (LESBAT) of the School of Business and Engineering Vaud (HEIG-VD), within the framework of Task 44.

Nomenclature

CED	Cumulative energy demand
COP	Coefficient of performance
DHW	Domestic hot water
G	Solar irradiance
GWP	Global warming potential
HP	Heat pump
LCIA	Life cycle impact assessment
NRE	Non-renewable energy
SC	Solar collectors

2. Project description

The objective of this project is to analyse the performance of a brine-to-water HP combined with solar collectors for domestic hot water production. The use of solar energy on the HP evaporator side improves both solar energy use and the performance levels of the system. Fig 1 is a simplified representation of the investigated system.

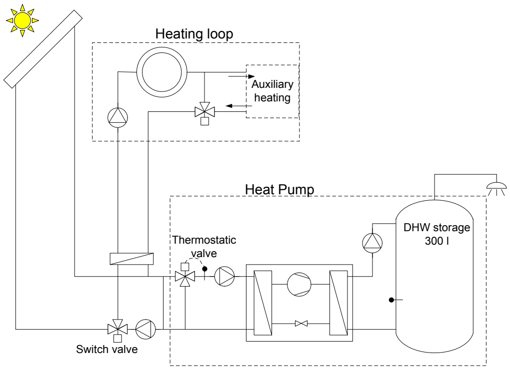


Fig. 1. Working principle of the installation

The HP system under investigation is a prototype and has been designed for DHW production only. It consists of a 2.2 kW brine-to-water HP and a 300 l water storage.

For this study, the following topics have been addressed:

- Development of a solar collector test bench to study the operation of collectors under unusual conditions (night, condensation, rain, frost)
- Development of a test bench to emulate the operation of the HP installation
- Development of a dynamic simulation model of the overall installation (HP, solar collectors, building)
- LCIA of the system and comparison with equivalent facilities
- Active participation in the IEA Task 44 for different working groups

The HP coefficient of performance (COP) presented in this article corresponds to the ratio of the heating capacity to the overall electricity consumption (compressor, internal pumps and regulation), measured under steady-state conditions.

2.1. Collectors test bench

A testing facility comprising four solar thermal collectors (flat plate, evacuated tube, unglazed with rear insulation and unglazed without rear insulation) is operational and equipped with different sorts of sensors for monitoring purposes. The performance of these solar collectors (SC) was experimentally measured and simulated for temperatures below ambient. It was observed that the condensation yield can vary from 25 to 55% of the total collector's yield for these tests depending on the weather conditions.

To characterise the thermal behaviour of the SC coupled as a source to the evaporator of a HP, two testing modes have been defined depending on the incident solar irradiance (G): "day mode" when solar irradiance is above 150W/m^2 and a "night mode" when solar irradiance is below 150W/m^2. Fig 2 shows the output power of the solar collectors for the two conditions. It can be seen that for temperatures below ambient, the unglazed collectors are more efficient than the flat plate or the evacuated tube collector. For these conditions, heat gains have been found to be primarily influenced by two parameters: air temperature and long-wave radiation. This, as expected, bears greater impact on collectors having no glass shield.

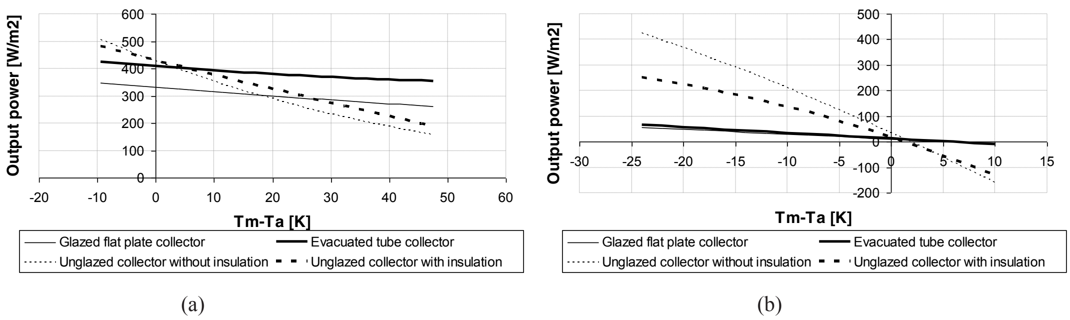


Fig. 2. (a) Output power of solar collectors under “day mode” conditions (~950 W/m^2); (b) Output power of solar collectors under “night mode” conditions (Output power is related to the absorber surface area).

The influence of several other parameters (e.g. collector inlet temperature, air temperature, humidity) was further investigated under the two testing modes Two TRNSYS [4] collector models including condensation heat gains were also evaluated and results compared to experimental measurements. A mathematical model has also been developed to include, in addition to the condensation phenomena, the frost, the rain and the long-wave radiation gains/losses on the rear of the solar collector. Further details and results for these parametric and simulation studies can be found in [6].

2.2. HP test bench

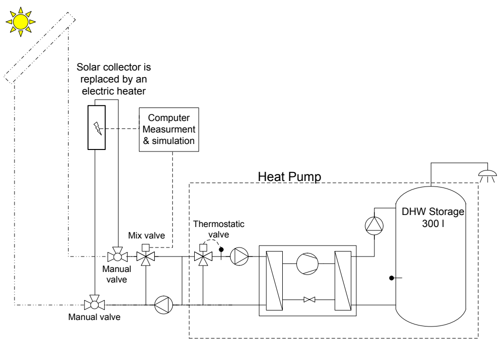


Fig. 3. Simplified representation of the HP test bench

The HP test bench is used to operate the HP system and to characterise its performance. This facility incorporates no real solar collectors or the "heating loop". To emulate the solar collectors, a system has been included to allow characterisation of the operation of the HP for a range of configurations and hydraulic conditions, in a reproducible manner. Fig 3 presents a simplified representation of the HP test bench.

The solar collectors are emulated and controlled by a numerical model based on measurements obtained on the Collectors test bench. Fig 4 is a schematic representation of the acquisition and control system of the installation.

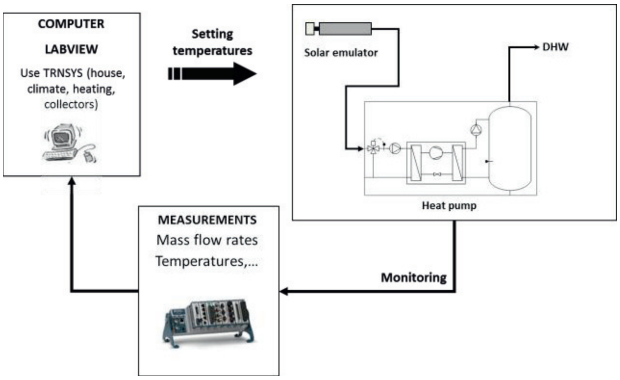


Fig. 4. Schematic representation of the acquisition and control system of the HP test bench

The HP facility is equipped with sensors and controls devices. A 2 seconds acquisition loop reads all measurements and performs various calculations (e.g. energy balances, heat loss calculations, control emulator/heat exchanger). These measurements and calculations are subsequently written to a file every 30 seconds. In parallel to this loop, a dynamic simulation is launched every 30 seconds using the information received from the acquisition system. At the end of the simulation, different instructions are sent to the HP test bench which will change its state to meet the new set point values.

Fig 5 presents a typical monitoring test of the HP facility for the following configuration: Strasbourg climate (summer day), collector surface area is 2 m^2, HP operating hours: 8 am to 7 pm, DHW set point temperature (SPT) is 55°C and DHW draw off: 8 times per day. Fig 5(a) presents the solar irradiance, the simulated collector temperature and the HP operating slots. For this specific test day, the solar irradiance varies from a normal clear day peak value of 900 W/m^2 to 400 W/m^2 due most probably to appearance of clouds. For these conditions, a HP COP of 2.2 was measured.

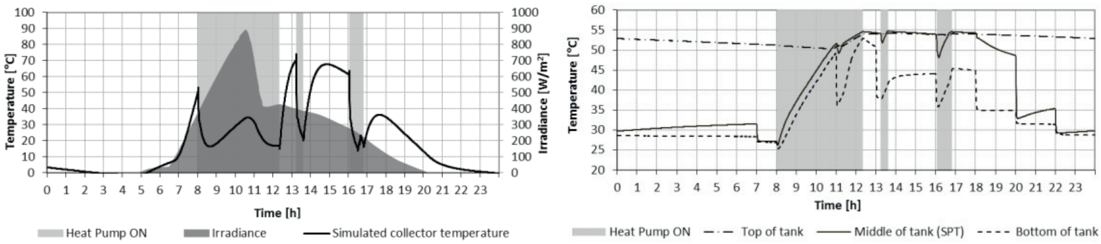


Fig. 5. Strasbourg: (a) Solar irradiance, simulated collector temperature and HP operating period; (b) Evolution of the water storage temperatures

It can be seen that when the HP starts to work, the temperature of the collectors drops dramatically, see for example Fig 5(a) at times 8 am, 1 pm and 4 pm. At the two first start-on times, solar irradiance is significant and the HP operates on collectors' mode i.e. extracting energy from the SC to the evaporator. At 4 pm, the amount of solar irradiance is reduced and the HP changes its operation mode to building i.e. extracting energy from the heating circuit. In any case, the HP will remain on until the SPT of 55 °C is attained in the middle of the storage. Fig 5(b) shows the temperature evolution in the water storage for three levels (top, middle and bottom). The middle temperature corresponds to the temperature control setting on/off the HP.

In order to characterise the performances of the HP system, a number of tests are being conducted. These are mainly of two kinds:

- HP nominal performance testing under stable temperature conditions (evaporator inlet temperature and condenser outlet temperature)
- HP operation testing under realistic conditions and validation of the numerical simulation

Fig 6 shows the first results concerning the HP nominal performances tests. This set of curves shows the evolution of the heat pump COP for a range of temperature levels of the hot source (condenser) and the cold source (evaporator). As defined by the Carnot efficiency, for a given evaporator inlet temperature, the COP decreases with increasing temperature of the outlet of the condenser. Similarly, for the same condenser outlet temperature, the COP is improved when the temperature at the inlet of the evaporator increases. These operating curves form the basis of the performance file required to describe the HP system in the dynamic simulation model.

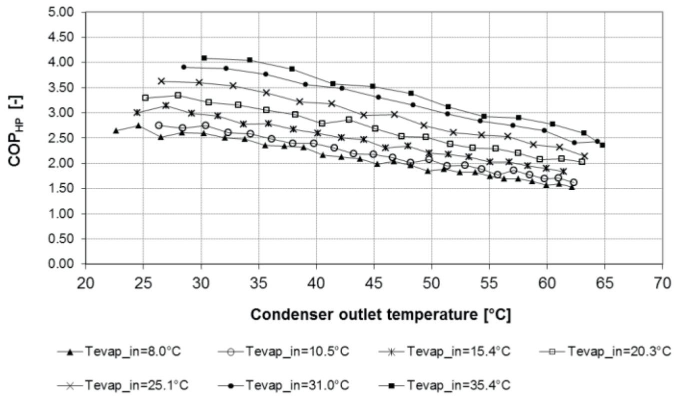


Fig. 6. Coefficient of performance (COP_{HP}) of the HP system under quasi steady-state conditions (constant evaporator inlet temperature and variable condenser outlet temperature)

2.3. Simulation of the installation

A dynamic model is under development to simulate the annual performance of the overall system under different climates and configurations. In this study, TRNSYS 16 was used to simulate the transient behaviour of the installation. The numerical model includes:

- Reference building: corresponding to the single family house adopted in Task 44. The heating area is 140 m² [7].
- DHW load: The annual energy for hot water draw off was fixed at 2133 kWh as proposed by Task 44 [8]. This corresponds to an average draw off of 140 litre per day at 45 °C (cold water temperature of 10°C), and an average daily energy with drawn of 5.845 kWh.
- Heat pump: the brine-to-water HP is simulated by Type 668, a component of the TESS library of TRNSYS. In this model, the HP performance data is based on the measured operating curves of the HP (see Fig 6). In our case, a temperature range of 8 to 40 ° C for the evaporator circuit and 25 to 70 ° C for the condenser circuit was considered.

The simulations take into account the characteristics of the four different types of collectors already described in 2.1. Two types of collectors' models are also considered:

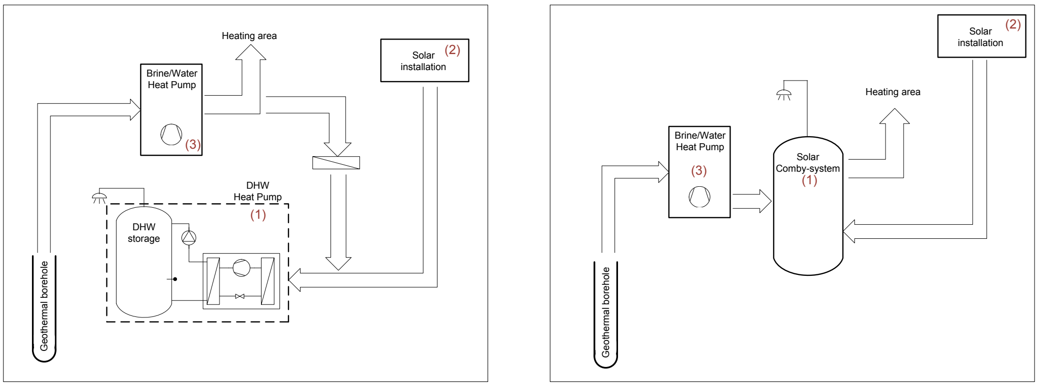
- Type 136, developed by Perers and Bales [8], is applicable to glazed, unglazed flat plate and evacuated tube and takes into account the effect of condensation.
- Type 202, developed by Bertram *et al.* [9] is applicable to unglazed collectors and includes condensation.

The use of two energy sources by the HP defines two main operating modes based on the energy input to the evaporator: a) solar mode uses solar energy b) building mode using energy from the heating circuit of the building. The solar mode has priority over the building mode. The overall numerical model is currently being validated against measurements obtained by the HP test bench. This work will be followed by the annual simulations:

- For three different climates: Strasbourg, Helsinki and Athens
- For optimisation of the control system for improved performance of the system
- For simulating new system concepts

2.4. Life cycle impact analysis (LCIA)

An environmental analyse of the HP system will be undertaken and comparisons will be made against more conventional DHW production systems, see Fig 7.



(a) (b)

Fig. 7. (a) Schematic representation of the tested installation; (b) Schematic representation of the reference installation.

This system includes, (1) the brine-to-water HP for DHW production, (2) the solar collectors, (3) a ground-to-water HP serving as backup for space heating.

The reference installation consists of (1) a combi-system using (2) solar collectors and (3) ground-to-water HP serving as backup for space heating and DHW production.

An environmental assessment will be conducted taking into account the environmental impacts of the energy consumed and the materials used in the two installations. The methodology applied in this study is conforming to standards ISO 14'040 series [10]. The functional unit considered the impacts generated by the overall system including the energy and materials consumption over 20 years. The system boundaries includes the mass of the materials used for each system components, component transport from the supplier to the assembly site of the installation, energy consumption for heating and for DHW throughout the period of use and disposal of materials. All impact values were taken from the Ecoinvent database v2.2 [11].

The indicators considered in this study are:

- Global Warming Potential (GWP) in kg CO_2-eq
- Cumulative Energy Demand Total (CED_{TOTAL}) in MJ-eq. This indicator is the total of primary energy used (renewable and non-renewable).
- Cumulative Energy Demand NRE (CED_{NRE}) in MJ-eq considers non-renewable energy only. This indicator includes fossil, nuclear and biomass from primary forests (i.e. biomass consumption that contributes to deforestation or forest/woodland degradation).

3. Conclusions

A R&D project involving a prototype solar assisted HP designed for DHW preparation for single family dwellings is described. A number of tools have already been developed and implemented to achieve the aims of this project. Two test benches, one testing solar collectors under unusual conditions and another used to test the performance of the prototyped HP, were constructed and are operational. Measurements from the collector test bench provide new data concerning so far neglected collectors operating conditions: night, condensation, rain and frost. First results have showed that for these conditions, important heat gains can be obtained with unglazed collectors. For the HP test bench, SC and the building are emulated and controlled by a numerical model based on measurements obtained on the Collectors facility. A simulation model of the HP system was also developed and is currently under validation with measurements performed on HP testing facility. The validation process will allow optimisation of the installation by performing annual simulations under different configurations. Participation in Task 44 is an opportunity to disseminate new findings and to compare results with other research teams.

Acknowledgements

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