Mobile Solar Assisted Heat Pump with Direct Expansion

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Abstract

This paper presents development of direct-expansion solar assisted heat pump system (DX-SAHP) along with the results of the trial testing. The main purpose of the developed unit with 300 l water tank is to heat up the water by 45 to 55°C. The unit is designed as a test rig enabling all necessary measurements to evaluate potential of solar irradiation for domestic water heating on various locations. A mobile and compact-in-form-and-size device has been developed representing a gradual step towards the commercial application. First set of measurements has been carried out explaining procedures in examination of the working parameters. The evaporation dynamics of the refrigerant in the collector/evaporator has been examined by means of quantitative infra-red thermography method. Computational fluid dynamics simulation has been carried out providing temperature distribution in the water tank. It was compared with the results obtained by temperature measurements by means of thermocouples that were placed in the water tank.

1. Introduction

Building sector is the largest energy consumer in Croatia. Taking into account its share of 42,3 % in the final energy consumption in 2010 [1], it becomes obvious that every progress in minimizing the energy amount that is spent for this purpose could significantly lower the overall figures. As Croatia will join the EU by July 2013, it also contributes to the efforts to meet the requirements set by EU Directive 2009/28/EC, i.e. it has to increase the share of renewable energy sources in energy production. Taking into consideration that domestic water heating is among four largest energy consumers in commercial buildings sector [2]; it increases the importance of practical solutions. The developed unit that is described in this paper enables *in situ* testing on different locations.

A potential of using DX_SAHP systems for water heating has been recognized by many researchers worldwide. Hawlader *et al.* [3] developed simulation model of a solar assisted heat pump water heating system, where unglazed, flat plate solar collectors acted as an evaporator for the refrigerant R-134 a. Experiments were conducted to validate simulation model. It was found that the thermal performance of the system is affected by compressor speed, solar irradiation, collector area and storage volume. Proper matching between the collector load and speed of the compressor is of great importance in order to achieve higher system COP.

Chaturvedi *et. al* [4] analyzed thermal performance of a direct expansion solar assisted heat pump with variable capacity (unglazed flat plate solar collector, R12 as a refrigerant). Experimental results indicate that significant improvement in system COP can be achieved by modulating the compressor capacity with seasonal changes in ambient temperature. System COP ranged from 2,5 to 4 during measurements.

Soldo *et al*. [5] carried out analytical and experimental studies on a solar assisted heat pump using refrigerant R-134 a. Results showed that increase in solar irradiation and/or ambient temperature or decrease of the compressor speed increase system's COP. On the other hand, increase of the condensing or water temperature decreases system COP.

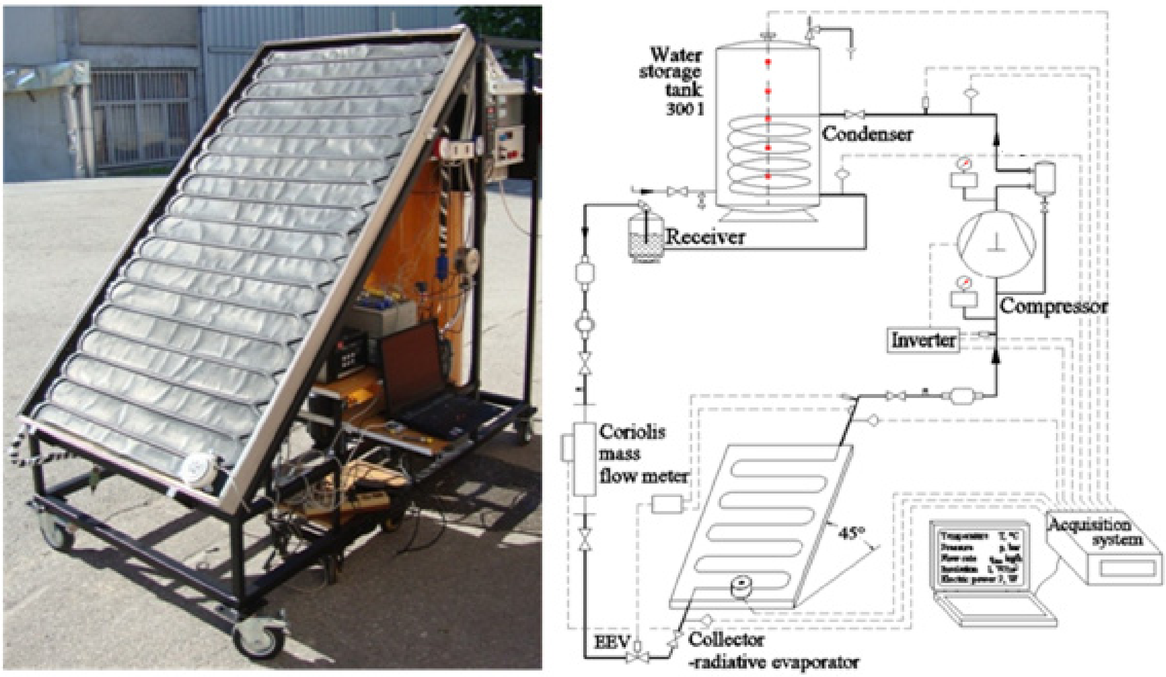
A test rig has been developed at the Laboratory for Applied Thermodynamics, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb representing the next stage in the investigation of using renewable energy sources in heat pump technology. Outcomes of the previously conducted research and simulation results published earlier [5-7] have shown large potential for implementation of solar assisted heat pumps for water heating as well as its advantages in comparison with conventional solar heating systems [6].

This paper presents mobile direct-expansion solar assisted heat pump (DX-SAHP) water heater. The developed unit is described and trial testing results are presented. Condenser and evaporator heat rates are calculated and compressor electric power is measured to obtain the data needed for coefficient of performance (COP). A comparison of experimentally obtained set of values and numerical simulation results is given for a temperature distribution in a water tank. The quantitative infra-red thermography method is used to examine evaporation dynamics of a refrigerant in the collector. The aim of this work is to develop a mobile and compact-in-form-and-size unit designed as a test rig enabling all necessary measurements to asses DX-SAHP water heater performance on various locations.

2. Test rig

Fig. 1. shows a schematic diagram of the developed unit. It consists of four main components enabling a Rankine refrigeration cycle: collector/evaporator, compressor, condenser (in a water tank) and expansion valve as well as other auxiliary components required for successful system performance and measurements. The refrigerant (R134a) evaporates in unglazed solar collector at the evaporating temperature and pressure by simultaneously absorbing solar irradiation and ambient heat. The absorber plate (thickness 1 mm) is made of copper (absorption coefficient 0,92) as well as the collector tube (ϕ12x1 mm). The heat pump compressor (displacement volume 15,28 cm^3) suitable for high back pressure and consequently high evaporating temperatures operation is used. The speed of compressor is controlled by a variable frequency drive. The refrigerant vapour condenses in a helical coil heat exchanger immersed in the water tank providing condensation heat for water heating. A receiver is installed downstream from the condenser, followed by a filter and a sight glass. An electronic expansion valve (EEV) controls the superheat and the refrigerant mass flow measured by Coriolis-type flow meter located in the liquid line between the sight glass and the EEV. Temperatures and pressures of the refrigerant in the process are measured by means of copper-constantan thermocouples (T-type) and pressure transducers respectively. A pyranometer is used for the measurement of solar irradiation on the inclined collector surface.

A 300 l tank is used for hot water storage. Polyurethane foam thermal insulation (thickness 50 mm) decreases heat losses preserving high water temperature which is measured by means of five Ni-Cr-Ni thermocouples (K-type) positioned at different heights in the water tank.



a) b)

Fig. 1. Mobile DX-SAHP: a) unit in operation; b) schematic diagram of the developed unit

3. Analysis

In order to calculate the COP of the heating process, temperatures and pressures are measured at various locations in the system. Additionally, as could be seen in Fig. 2, a set of five NiCr-Ni thermocouples is positioned in the tank with the aim of examining temperature distribution of the water due to the height. The same figure also shows characteristic points of the process during the operation.

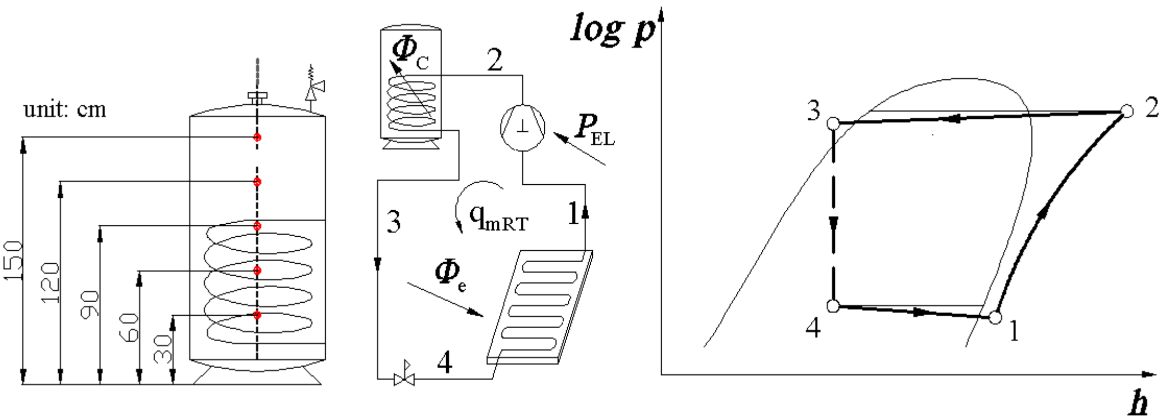


Fig. 2. Positions of thermocouples in the water tank and heat pump cycle in the log p,h diagram

Refrigerant temperatures are measured at all four characteristic points. Evaporating and condensing pressures are measured by pressure transducers at points 1 and 2 respectively. Moreover, mass flow rate of refrigerant, solar irradiation, ambient temperature and electric power use of the compressor are also obtained. All mentioned data are collected by means of acquisition system every 30 sec. Both thermodynamic and transport properties of refrigerant are evaluated using a computer program REFPROP, version 6.01[8].

A simple mathematical model based on the first law of thermodynamics is used to calculate COP [5].

The condenser heat rate is given for the refrigerant side:

$$\Phi_C = q_{mRT}\left(h_2 - h_3\right) \qquad \text{[W]} \qquad (1)$$

where q_{mRT} is the refrigerant mass flow in kg/s and h_2 and h_3 are enthalpies at points 2 and 3 in J/kg:

$$h_2 = h\left(\vartheta_2, p_2\right) \qquad \text{[J/kg]} \qquad (2)$$

$$h_3 \approx h'\left(\vartheta_3\right) \qquad \text{[J/kg]} \qquad (3)$$

where ϑ_2 and ϑ_3 are temperatures at characteristic points 2 and 3, p_2 is the pressure at the condenser inlet, h' is specific enthalpy of the refrigerant at the saturated liquid state (water vapour content $x = 0$ kg/kg) and $(h_2 - h_3)$ represents specific heat rejected from refrigerant to the water.

The condenser heat rate can also be given as:

$$\Phi_C = UA\left(\vartheta_C - \vartheta_w\right) \qquad \text{[W]} \qquad (4)$$

where U [W/(m^{2}K)] is overall heat transfer coefficient from the condensing refrigerant to the water in a tank, A [m^2] is heat exchange area and ϑ_{C} and ϑ_{w} [°C] are temperatures of the refrigerant and water.

Coefficient of performance (COP) for heating is defined as the heat gain at the condenser in relation to the power of electrical motor (P_{EL}) that runs the compressor:

$$COP = \frac{\Phi_C}{P_{EL}} \qquad \text{[-]} \qquad (5)$$

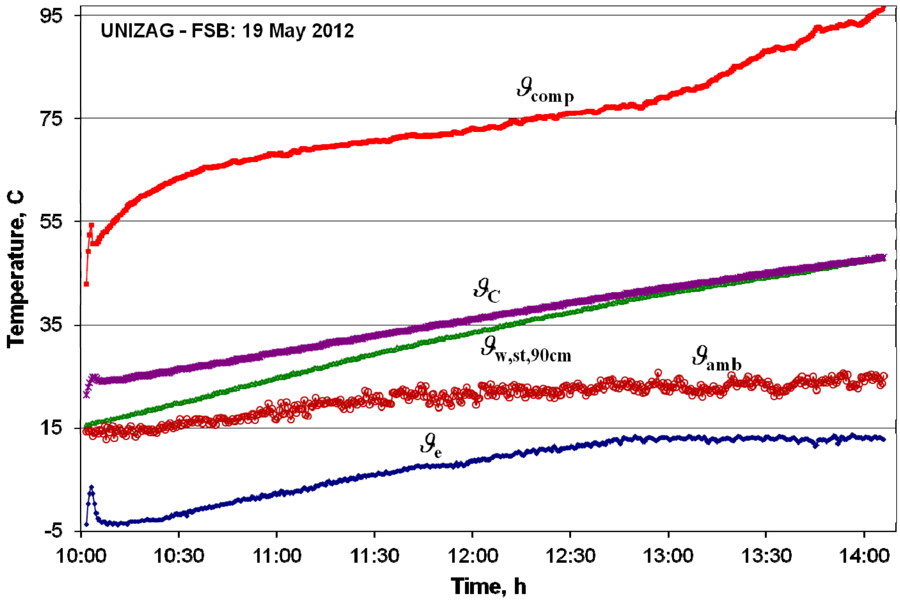
As the refrigerant evaporates by absorbing the heat in the collector not only by means of radiation (solar irradiation), but also by means of the convection heat transfer mechanism (from ambient air through the absorber plate and tube to the refrigerant), evaporating heat rate Φ_{e} is influenced by both the solar radiation intensity I_{sol} on the one hand and an ambient conditions (ambient temperature ϑ_{amb}, wind speed and direction) on the other. Electronic expansion valve controls the degree of superheat by changing the refrigerant mass flow in the collector. Consequently, the condensing heat rate Φ_{C} and electric power use of the compressor P_{EL} vary in time as well as COP.

4. Results

4.1. *In situ* testing: results and discussion

The trial testing of developed DX-SAHP unit was carried out on 19th May 2012 at the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture with the aim of heating the water in a tank up to the temperature of approximately 50°C. As the main goal of this work is to develop a commercial version and conduct a research in a real-life conditions, at the beginning of testing water was pumped into the tank from the public water supply system at the temperature of 15,5°C. Measurements were performed with a collector facing south and with a constant compressor speed at the frequency of 50 Hz.

Fig. 3. shows the results of measured temperatures, heat rates, coefficient of performance, electric power use and solar irradiation.



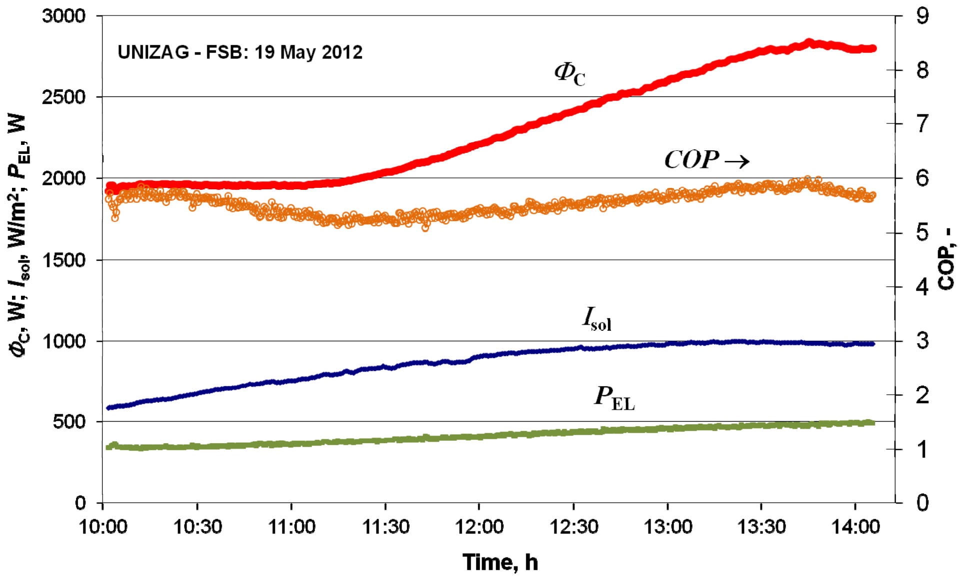


Fig. 3. Experimental data obtained during the trial testing

Measurements were carried out from 10 a.m. to 2:15 p.m. in a total duration of 4 hours and 15 minutes. An average ambient temperature ϑ_{amb} was 20,6°C ranging from 13 to 25,7°C. Solar irradiation was in the range from 587 to 998 W/m^2 with an average of 865 W/m^2 at the measurement points.

Previously described changes of evaporating temperature ϑ_e (i.e. ϑ_4 in the Fig. 2.) caused by varying weather conditions are clearly presented in Fig. 3. Temperature at the height of 90 cm $\vartheta_{w,st,90cm}$ is chosen to present the water temperature rise because it is the highest of all measured values in the water tank. This is due to the fact that condenser coil inlet is located at approximately that height. Therefore, the highest temperature difference between the refrigerant and the heated water appears ($\vartheta_{comp} - \vartheta_w$) so it is the "highest heated" point in the water tank.

At the beginning of the measurement COP is very high (near 6) due to the small temperature difference between the condensing temperature ϑ_C and the evaporating temperature ϑ_e.

After transition period as water is heated, COP starts to rise along with the condenser heat rate Φ_C from the point at which the increase in solar irradiation and ambient temperature becomes more influential compared with rising electric power use P_{EL}.

Analysis of the presented diagrams shows the largest influence of solar irradiation on the Φ_C and COP, especially in the period of time starting at approximately 11:15 onwards. It has to be noticed that solar irradiation I_{sol} is shown in W/m^2 as it was measured by means of pyranometer while the other curves represent the values calculated in W. So, with the increase in I_{sol} until approx. 13:30 h, the COP rises up to near 6 again and about 13:45 h the COP starts to drop due to the expected decrease in solar irradiation and high compression ratio at that time.

4.2. Numerical simulation

Computational fluid dynamics (CFD) simulation using modelling software Fluent was performed to examine the temperature distribution in a water tank. The laminar flow inside the water tank due to the temperature difference was examined as 2-D problem in which the centre line of the water tank was defined as the axis of symmetry (boundary condition type: axis). Due to the polyurethane foam thermal insulation of the water tank and condensation within the tubes, boundary conditions at the tank walls and at the tubes were set as adiabatic and isothermal respectively. Fig. 4. shows a mesh that consists of 60 968 cells.

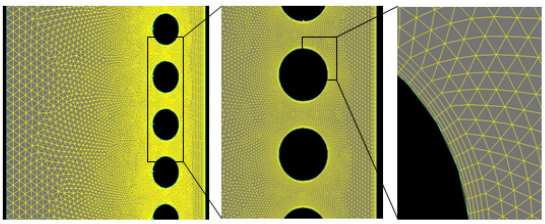


Fig. 4. Numerical simulation in Fluent – mesh

Isothermal boundary was changed every time the condensing temperature increased. Obtained temperatures are compared with the values measured by thermocouples. This kind of simplified two dimensional model provides values that fit measured temperatures within the first 8,5 minutes of measurement. After 13,5 minutes, temperature differences increase in time significantly up to more than 1°C at the height of 90 cm after 21 minutes. Additionally, simulation results do not fit measured values for the higher points (120 and 150 cm) in the tank from the start point of measurement. The temperature differences occur due to the simplification in a model used (adiabatic and isothermal boundaries and 2-D instead of 3-D model). A comparison is shown in Table 1.

Table 1. Comparison of water temperatures obtained by thermocouples (TC) and numerical simulation (CFD)

	Water temperature ϑ_w, °C					
	30 cm		**60 cm**		**90 cm**	
	TC	**CFD**	**TC**	**CFD**	**TC**	**CFD**
after 8 minutes	16,00	15,86	16,48	16,46	16,73	16,74
after 21 minutes	17,56	17,57	18,40	17,78	18,63	17,69

4.3. Infrared thermography

Evaporation of the refrigerant in the collector is a dynamic process influenced by previously explained various parameters. In order to analyse the evaporation dynamics, an infrared camera is used. The same method enables a comparison between the temperatures measured by thermocouples and infrared camera (Table 2. shows slight differences between the values).

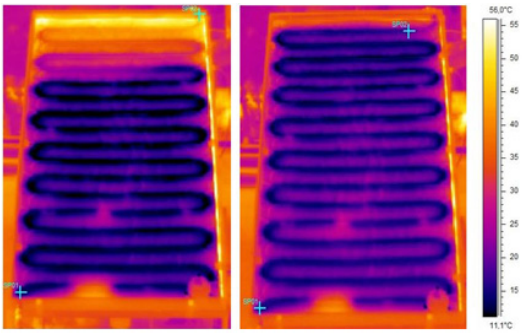


Fig. 5. Thermographs of the absorber plate

Fig. 5. shows two thermographs captured in different weather conditions after adjusting all necessary parameters. Dark blue coloured part of the tube presents liquid and lighter red and yellow colours indicate refrigerant vapour. Solar irradiation suddenly increased significantly when the thermograph on the left was captured because a wind moved clouds away very fast. Therefore, an existing amount of liquid refrigerant in a collector evaporated rapidly which increased the amount of vapour and consequently a temperature ϑ_1 at the collector outlet (superheat). Taking into account that the higher ϑ_1 decrease evaporating temperature and increase compressor discharge temperature it is necessary to control the evaporating process in the collector. Thermograph on the right shows the same collector after EEV released more liquid in a collector due to the increased irradiation. Ambient temperature remained the same between the captures.

Table 2 Comparison of temperatures measured by means of thermocouples and infrared camera

	Collector inlet temperature ϑ_4, °C		Collector outlet temperature ϑ_1, °C	
	Thermocouple	**Infrared camera**	**Thermocouple**	**Infrared camera**
Thermograph (left)	11,23	11,90	42,90	42,10
Thermograph (right)	15,37	15,70	17,87	17,90

5. Conclusion

A mobile DX-SAHP unit is described in this paper. After conducting the trial testing, promising experimental results were obtained. With a 300 l of water heated from an average temperature of 15,5°C up to 50°C in 4 hours and 15 minutes and a COP ranging between 5,1 and 5,9, a developed unit showed high potential for a future commercial version. Moreover, an influence of solar irradiation, ambient and evaporative temperatures and electric power on a condensing heat rate is analysed. Solar irradiation has the most significant impact on a COP. The fact that evaporating temperature is lower than the ambient temperature enables absorbing the heat from the ambient air by convection.

The following stage in a development of mobile DX-SAHP unit consists of conducting the long term field testing on a daily basis. Moreover, a DX-SAHP Matlab simulation model will be develop in order to compare all the values to be measured during the field testing with the results of the simulation.

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Nomenclature

Latin letters

A	- heat exchange area	(m^2)
COP	- coefficient of performance	(-)
h	- specific enthalpy	(kJ/kg)
h_2	- specific enthalpy at condenser inlet	(kJ/kg)
h_3	- specific enthalpy at condenser outlet	(kJ/kg)
h'	- specific enthalpy of the refrigerant at the saturated liquid state	(kJ/kg)
I_{sol}	- solar irradiation on collector	(W/m^2)
P_{EL}	- electric power of compressor	(W)
p	- pressure	(bar)
p_2	- pressure at condenser inlet	(bar)
q_{mRT}	- mass flow rate of refrigerant	(kg/s)
U	- overall heat transfer coefficient from the condensing refrigerant to the water in a tank	($W/(m^2K)$)
x	- water vapour content	(kg/kg)

Greek letters

ϑ	- temperature	(^oC)
ϑ_1	- temperature at evaporator outlet	(^oC)
ϑ_2	- temperature at condenser inlet	(^oC)
ϑ_3	- temperature at condenser outlet	(^oC)
ϑ_4	- temperature at evaporator inlet	(^oC)
ϑ_{amb}	- ambient temperature	(^oC)
ϑ_C	- condensing temperature	(^oC)
ϑ_{comp}	- temperature after compression	(^oC)
ϑ_e	- evaporating temperature	(^oC)
ϑ_w	- temperature of the heated water in a tank	(^oC)
$\vartheta_{w,st,90cm}$	- temperature of the water in a tank at the height of 90 cm	(^oC)
Φ_C	- condenser heat rate	(W)
Φ_e	- evaporator heat rate	(W)

CFD	Computational Fluid Dynamics
DX-SAHP	Direct-Expansion Solar Assisted Heat Pump
EEV	Electronic Expansion Valve