

MONITORING OF SYSTEM PERFORMANCES OF A FULL THERMAL ENERGY PLANT – UNCERTAINTY EVALUATIONS

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Abstract: This work proposes the development and characterization of innovative domestic heating system driven by solar assisted heat pump in order to increase the system efficiency. A suitable on-line measurement system of overall observable quantities has been integrated in the plant, to give accurate and updated measurements of all the variables interesting the whole system. A more detailed analysis of quantities that main influence the system performances has been carried out, developing a suitable mathematic model able to describe and control the behaviour of interested phenomena. Finally some information about reliability degree of model has been provided. The use of advanced control and monitoring of several interested quantities has allowed optimising the global system efficiency.

1. Introduction

The Kyoto objectives, like an 8%-reduction of the 1990 values of the greenhouse gas emissions as far as 2012, force for the development of new technologies, innovation and associated accurate measurements of the observable quantities in energy plants.

This work investigates on using solar assisted heat pumps system with high performances to provide the full thermal energy to meet space heating and hot water requirements for domestic houses throughout the year. The project focuses on the domestic housing sector, since this is a major consumer of energy and thus contributor of significant CO₂ emissions.

A new system able to heat domestic space and water has been developed theoretically as a particularly promising application in addition to the generic set of devices known as active solar heaters, or solar assisted heat pumps. It is expected that its widespread application to a variety of sectors over a broad geographical areas would considerably alleviate the greenhouse effect providing at the same time economical space and water heating.

2. Proposed system and methodology

The proposed system uses a solar-assisted heat pump system to provide an efficient method for supplying the thermal energy for space heating and hot water production in buildings.

Heat pumps work by extracting thermal energy from a low temperature (T_L) source and upgrading it to a higher temperature (T_H) for space or water heating. For this aim it is necessary that a certain amount of work be done on the system.

The parameter normally used to compare heat pumps efficiency is the coefficient of performance (COP_{HP}) that measures the ratio between the heat output and the energy used to drive the machine:

$$COP_{HP} = \frac{Q_{out}}{E_m} \quad (1)$$

The COP_{HP} may also be expressed by means of the following theoretical expression, based on Carnot cycle

$$(COP_{HP})_{Carnot} = \frac{T_H}{(T_H - T_L)} \quad (2)$$

It shows that, for a fixed temperature T_H , the value of the COP_{HP} increases as the lower temperature increases. For real machines, the relevant technical I/O curves characteristic curves, factory provided, show the relationship among the evaporator inlet temperature, the condenser inlet temperature and the value of COP , as reported in Fig.1.

The choice of the heating system, as fan coil, radiator or radiant panels, determines the temperature of water supplied by heat pump. The amount of energy consumption can be evaluated through the value of the *COP* established by the evaporator inlet temperature as reported in Eq. (1).

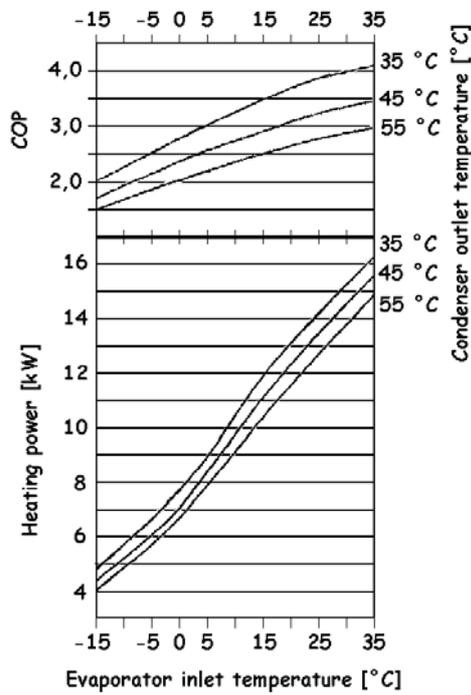


Fig.1 – I/O characteristic curves of *COP* and heating power against evaporator inlet temperature, for a real heat pump

In order to increase the effectiveness of the heat pump, the thermal system under study uses a solar collector to supply thermal energy to cold the tank of the plant cooled by the evaporator of the heat pump. In this way, the inlet temperature of evaporator and the heating power increases and so the system effectiveness (*COP*) improves.

Fig.2 shows the scheme of the whole thermal plant, with the indication of the sensors, the controllers and the valves necessary composing the system too.

Many parameters must be accurately designed to achieve the target, as the water mass flowing through the solar collector in the cold tank, the volume and the shape of tank. The first parameter must be modulated so that the flow mass increases with high solar radiation; on the contrary, with low solar radiation, it is necessary to reduce the flow mass in order to obtain the highest temperature on the top of the tank.

The heat-transfer fluid is pumped through the collectors and a heat exchanger is used to transfer heat from the collector loop to the water in the tank, as shown in Fig.2. Closed loop glycol system must be used for freeze protection.

The flow rate through the solar collector is linked to solar radiation to obtain the wanted temperature of the water to send to thermal plant. A high flow rate is used in solar collector circulation systems when high solar radiation occurs, because heat transfer within the collector improves with flow rate increasing. The major disadvantage of high collector loop flow rates is that thermal stratification in the storage tank may be disturbed by the high flow, even when a heat exchanger is used between the collector and the tank.

In order to evaluating the effectiveness of the plant it is necessary to define and to measure the most relevant parameters, evidenced into the plant scheme shown in Fig.2. These parameters are listed in Table I, where also the relevant formulae for indirectly measuring them, are reported.

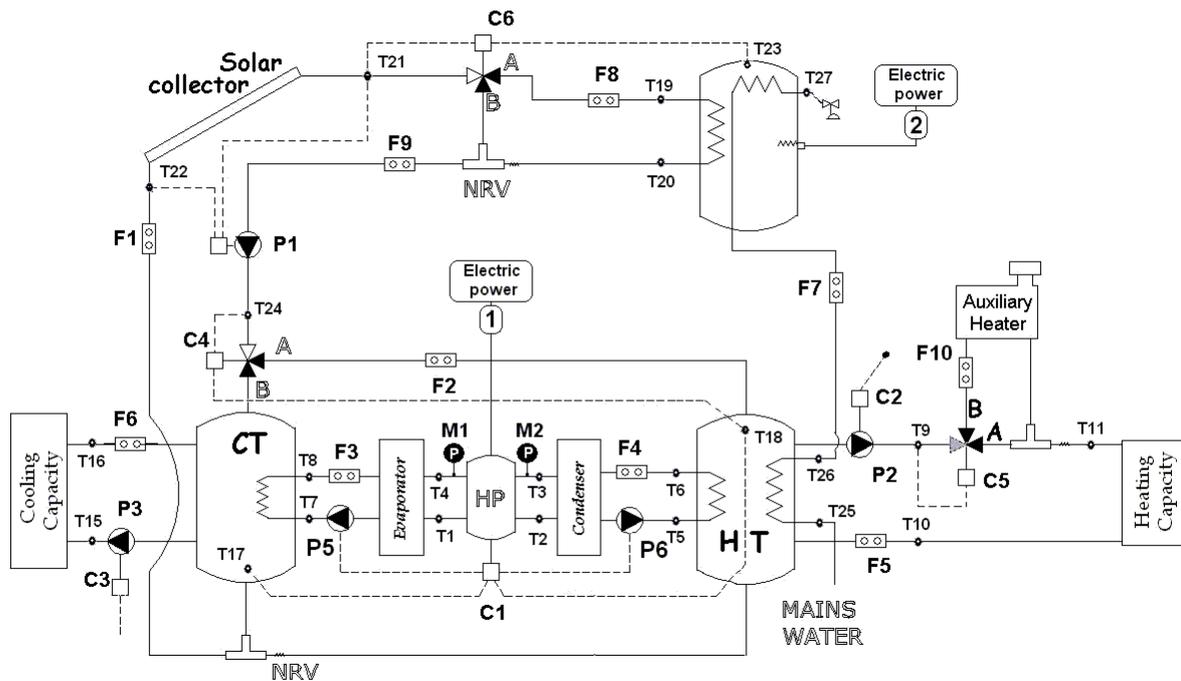


Fig. 2 – Scheme of the thermal plant with the control instruments to evaluating the system performance.

The quantity symbols are defined as follows:

- F_i is the flow measurement carried out by the i -th flowmeter [kg/s];
- c_p is the specific heat of water, that equals 4.187 kJ/(kg·°C);
- T_i is the water's temperature (fan coil outlet or inlet), measured by the specific i -th thermocouple [°C];
- V_i is the input rms voltage relevant to the load 1 or 2 [V];
- I_i is the input rms current relevant to the load 1 or 2 [A].

Tab. I - List of the most significant parameters of the thermal plant of Fig.3.

Name	Symbol	Formulation
Cooling Capacity	CC	$F_6 \cdot c_p \cdot (T_{15} - T_{16})$
Heating Capacity	HC	$F_5 \cdot c_p \cdot [(T_9 - T_{10}) + (T_9 - T_{11})]$
Cooling Power	CP	$F_3 \cdot c_p \cdot (T_7 - T_8)$
Heating Power	HP	$F_4 \cdot c_p \cdot (T_5 - T_6)$
Roof Capacity	RC	$F_1 \cdot c_p \cdot (T_{21} - T_{22})$
Solar power to Domestic Hot Water	RDW	$F_8 \cdot c_p \cdot (T_{19} - T_{20})$
Hot tank to Domestic hot Water	HTDW	$F_7 \cdot c_p \cdot (T_{26} - T_{25})$
Actual Domestic hot Water	ADW	$F_7 \cdot c_p \cdot (T_{27} - T_{26})$
Energy Consumption (Electric active power supplied)	EC	$EC = W = V \cdot I \cdot PF$ (power factor)

The benefit of low flow operation is the promotion of thermal stratification in the storage tank. However, low flow rate is only one factor influencing stratification; so the improving of performances will only be achieved if all factors influencing stratification are considered. High flow systems can have different degrees of stratification, depending on whether there are heat exchangers in the collector loop or the load flow stream. Heat exchangers such as internal coils, full height mantles or external spiral tubing on the wall of the tank, all minimize mixing in the tank and give some stratification, even for high collector loop circulation rates. Maximum performance benefits can only be gained through a fully integrated low flow system design. The most obvious impact is that a smaller low power pump can be used. Smaller tubes lower the thickness and the cost of pipe insulation because the thermal resistance value depends on the ratio of outer diameter to inner diameter and not the absolute thickness of the insulation. Maximum benefit will be achieved in a low flow system if the following load matching principles are incorporated.

The collector outlet temperature drives the rotation speed of the solar collector circulation pump, P1. If the temperature is less than the temperature of the top section of the hot tank, the water flow is driven in cold tank to increase its temperature and to improve the *COP* of the heat pump and the effectiveness of the heating plant. This is obtained by driving the three-way valve, C4 controlled. The algorithm to control this flow must be analysed, but low flow in pumped circulation systems works well if attention is addressed to minimize mixing in the tanks.

Solar heat is collected by means of a roof-shaped solar collector and supplied to hot tank if the temperature is sufficiently high for heating; otherwise it is supplied to cold tank to increase the *COP* heat pump.

The system performance is evaluated through the calculation of heat exchanged between heat pump and the tanks, both the cold tank and the hot one. Moreover it is necessary to evaluate the heat power supplied from the hot tank to users. This energy amount is the actual energy supplied to users so that must be used in effectiveness calculation.

According to the plant scheme of Fig. 2 and to the defined quantities of Table I, we can calculate the *COP* increased against of the temperature of the cold tank as follows:

$$(COP_{HP})_{machine} = \frac{F_4 \cdot c_p \cdot (T_5 - T_6)}{EC_1} \quad (3)$$

where EC_1 is the electric power supplying the compressor.

The actual *COP* for users is:

$$(COP_{HP})_{user} = \frac{HC}{EC_1} \quad (4)$$

for the heating load.

When we consider the domestic hot water, the energy supplied to mains water by hot tank, *HTDW*, and the energy supplied by solar collector, *ADW*, we must evaluate a new value of *COP*:

$$(COP_{HP})_{global} = \frac{(ADW + HTDW) + HC}{EC_1 + EC_2} \quad (5)$$

The regulation rig has the scope to store the heat from the time the energy is collected to the time it is needed without incurring an unacceptably high loss together with a decrease in temperature. Unfortunately, the technology was not able to be used for providing primary heating/hot water systems. In fact, although the system performs reasonably well for sunny periods during the heating season, it could not give a reliable solution for all year round use, as it would be done by an optimal conditioning.

The indirect measurements of Table I suffer of the measurement uncertainty of each directly measured quantity on which they depend, according to the well known theory of error propagation [8]. Under the hypothesis that the errors relevant to the directly measured quantities are statistically independent and uniformly distributed, it is easy to write the analytical expressions of the absolute standard uncertainty in all the indirect measurements as listed in Table II.

Tab. II – Typical values and measurement uncertainty of thermal parameters of Tab.I

Symbol	Operating range [kW]	Analytical formulation of standard measurement uncertainty
CC	0,0 ÷ 7,0	$U_{CC, std} = \frac{CC}{\sqrt{3}} \sqrt{\frac{U_{F_6}^2}{F_6^2} + \frac{U_{T_{15}}^2}{T_{15}^2} + \frac{U_{T_{16}}^2}{T_{16}^2}}$
HC	0,0 ÷ 7,0	$U_{HC, std} = \frac{HC}{\sqrt{3}} \sqrt{\frac{U_{F_5}^2}{F_5^2} + \frac{4U_{T_9}^2}{T_9^2} + \frac{U_{T_{10}}^2}{T_{10}^2} + \frac{U_{T_{11}}^2}{T_{11}^2}}$
CP	0,0 ÷ 4,0	$U_{CP, std} = \frac{CP}{\sqrt{3}} \sqrt{\frac{U_{F_3}^2}{F_3^2} + \frac{U_{T_7}^2}{T_7^2} + \frac{U_{T_8}^2}{T_8^2}}$
HP	0,0 ÷ 7,0	$U_{HP, std} = \frac{HP}{\sqrt{3}} \sqrt{\frac{U_{F_4}^2}{F_4^2} + \frac{U_{T_5}^2}{T_5^2} + \frac{U_{T_6}^2}{T_6^2}}$
RC	0,0 ÷ 7,0	$U_{RC, std} = \frac{RC}{\sqrt{3}} \sqrt{\frac{U_{F_1}^2}{F_1^2} + \frac{U_{T_{21}}^2}{T_{21}^2} + \frac{U_{T_{22}}^2}{T_{22}^2}}$
RDW	0,0 ÷ 7,0	$U_{RDW, std} = \frac{RDW}{\sqrt{3}} \sqrt{\frac{U_{F_8}^2}{F_8^2} + \frac{U_{T_{19}}^2}{T_{19}^2} + \frac{U_{T_{20}}^2}{T_{20}^2}}$
HTDW	0,0 ÷ 7,0	$U_{HTDW, std} = \frac{HDTW}{\sqrt{3}} \sqrt{\frac{U_{F_7}^2}{F_7^2} + \frac{U_{T_{26}}^2}{T_{26}^2} + \frac{U_{T_{25}}^2}{T_{25}^2}}$
ADW	0,0 ÷ 7,0	$U_{ADW, std} = \frac{ADW}{\sqrt{3}} \sqrt{\frac{U_{F_7}^2}{F_7^2} + \frac{U_{T_{27}}^2}{T_{27}^2} + \frac{U_{T_{26}}^2}{T_{26}^2}}$
EC	0,0 ÷ 4,0	$U_{EC, std} = \frac{U_{W, EC}}{\sqrt{3}}$

Two auxiliary heaters are available for heating domestic hot water ant heating fluid. The auxiliary inputs should be provided so those not interfere with the operation of the solar part of the tank.

The auxiliary heaters can be used to provide a delivery capacity that varies across the day to match the demand pattern of the user. In winter, the auxiliary controller could be switched to provide a greater volume to match higher hot water demand. In summer, the boost volume could be reduced to allow greater solar contribution. A programmable controller could be used to maximize solar contribution while it is maintaining a delivery capacity

across the day that matches a specified pattern. The load pattern could be set by the user or 'learned' by an intelligent controller.

The project requires an overall management and quality control package, modelling techniques to allow detailed studies of the whole energy system and its optimising.

The work will also involve a complex measurement system (consisting of more than one hundred thermocouples, several flow-meters and a weather station with solar-meter) to monitor in real time and in an extensive period, including the heating and cooling seasons, all quantities influencing the efficiency system.

The performances of the energy supply plant will be calculated on a weekly/monthly basis as well as seasonally and annually.

Besides suitable control strategies will be investigated and developed to optimise the management of various elements of the overall system, i.e. energy collection, energy upgrading and energy delivery.

3. Simulation and experimental evaluations

In order to design the test systems that will be set up and monitored, several extensive simulation studies (over a full year using average and extreme weather data) have been carried out.

The performances of the energy supply plant have been investigated by means of a dynamic simulation code, realised with the software TRNSYS. It simulates the hourly performances by means of several FORTRAN subroutines, which are linked together in order to model a thermal system. Each subroutine calculates the heat and the mass flow interactions. Simulations performed using average climatic data relevant to Taranto area. Particularly, in the figures 3 and 4 we report the behaviour of the temperatures of the water in the cold tank with two volumes, 2 and 2.5 m³, respectively, during the heating season (from 1st of november to 31th of march), in the second case the extreme temperatures are closer and the lowest temperature is greater, but increasing the volume of the plant and the thermal insulation and the heat losses

An experimental validation of the developed model has been carried out by building up and monitoring a full thermal (heating and cooling) energy plant operating under normal occupied conditions. A first validation has been performed by carrying out the results of a high enough number of runs, whose input variables (like eat-pump thermodynamic cycle pressure, hot water boiler electric power, heating rig, cooling rig, roof hot water heating, dry temperature, wind speed, etc.) assumed values into the ranges

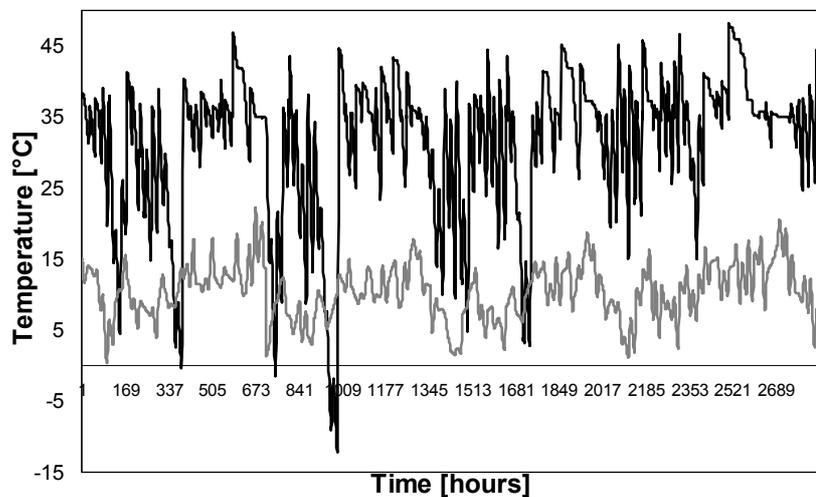


Fig. 3 – Behaviour of external air temperature (grey curve) and temperatures of the water in a 2 m³ cold tank (dark curve) in the heating season (November- March)

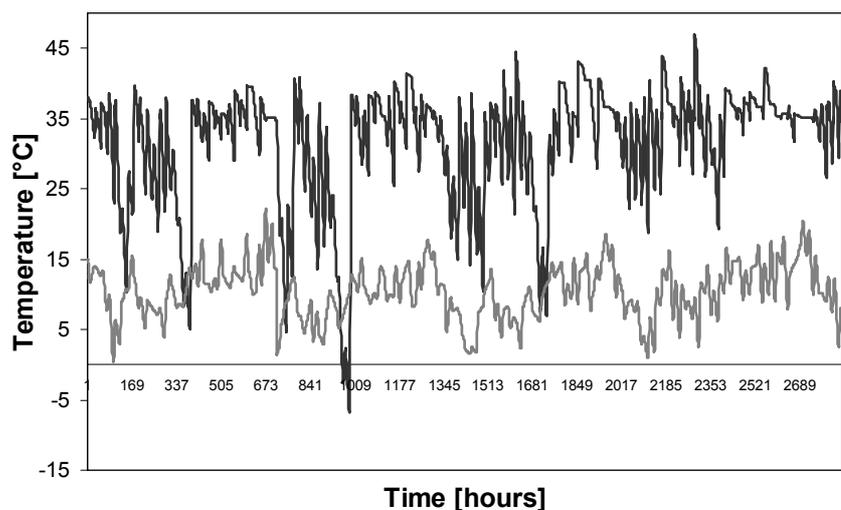


Fig. 4 – Behaviour of external air temperature (grey curve) and temperatures of the water in a 2,5 m³ cold tank (dark curve) in the heating season (November- March)

defined by the relevant measurement uncertainties (prevalently due to noise and/or to degradation of characteristics of devices), on the basis of the metrological characteristics of the used sensors.

Once the noisy input data are collected, as returned from the simulated system, they have to be statistically analysed, so to extract important information about their variance, in order to establish the variance of the simulation results. Finally, the evaluation of the final uncertainty, on the bases of both this information and the knowledge of the model variance has been calculated. Then, the results of these simulations could support the selection and the design of suitable components that will be used in real plant.

Particularly, the greatest attention was devoted to quantities that main influence the COP system and that play leading rule in the control plant as temperatures and flow masses. Then, the measurement of these quantities could be characterized by an uncertainty extremely low.

4. Conclusion

The development and the characterization of an innovative heating system with high performances in terms of efficiency, has been proposed. For this aim complex measurement system has been implemented in order to manage and control all quantities relevant to the plant. The main parameters influencing the efficiency of the system have been identified and for each of them the relevant measurement uncertainty has been evaluated.

The carrying out of several simulations allowed quantifying the dimensions of a lot of components of the full dimension rig, now under construction near the seat of the Engineering Faculty in Taranto.

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