Solar assisted heat pump pilot plant management and troubleshooting by means of numerical modelling: a case study

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Abstract. A solar assisted heat pump integrated with fossil burners provides the space heating and Domestic Hot Water (DHW) demand of the sport palace Palacus, Genoa. The plant complexity requires a Data Acquisition System (DAS) to perform diagnoses for problem troubleshooting. A DAS with a set of sensors able to measure every key parameter of the plant loses economic feasibility as the installation complexity increases. This compulsory lack of information can be handled with numerical modelling calibrated on the collected data. In the case study, a net variation in the thermal losses during night (where all the plant is off and the facility is closed) within the DHW storage tanks has been measured. Without any apparent reason, the temperatures reached within the tank at 8.00 a.m. can be either 33 °C or 50 °C. According to the approach of inverse heat transfer problems, a numerical simulation in TRNSYS17 is used to enquire the most likely causes of failure and to establish new regulation criteria. Thermal stratification and its destruction are studied to better understand the temperature trend in the DHW tanks.

1. Introduction
Complex plant schemes such as Solar Assisted Heat Pumps (SAHPs) require an extended Data Acquisition System (DAS), already for very simple, prototypal schemes [1] to make the SAHPs competitive. Indeed, a complete grid of sensors influences the cost-effectiveness of the plant. So, the analyses in technical plants with incomplete data pose further challenges to cope with [2], [3]. The missing information can be determined through stationary/transient simulations of the numerical models validated on the measured parameters. Namely, a validated numerical model of the plant reduces the required sensors without information losses by means of. This issue is part of the Inverse Heat Transfer Problem (IHTP) which relies on temperature measurements to estimate the unknown properties within the context of thermal engineering problems [4]. In particular, thermophysical properties and boundary conditions are inferred from the comparison among the measured and calculated temperatures.

2. Description of the plant
A SAHP integrated with solar hybrid panels (PVT) interacts with the traditional gas burners to satisfy the requirements of the sport palace Palacus (Domestic Hot Water, DHW and Space Heating, SH). The solar field produces 50 kW_T and 20 kW_E under peak conditions with 140 m² of total capturing surface. The thermal field increases the COP of the Heat Pump (HP) up to 6-7 (62 kW_T against 12 kW_E consumption under peak conditions) while the PV field supplies the electric needs of the plant (Figure 1). A DAS manages a grid of 50 measurement sensors and over 15 regulation points over the plant. A specific insight on the DHW production subsystem is provided below with the help of Figure 2. Each DHW tank (DHW1 and DHW2, Figure 2) has a capacity of 1500 l with 4 cm of thick insulation. The
DHW is sent to a controlled mixing regulator valve V8 that keeps the supply temperature at the set point value T20*. On the other hand, T20 is the temperature measured downstream of V8 while T14 and T19 represent the temperatures in the tanks DHW1 and DHW2 respectively.

Figure 1. Simplified schematic representation of the Palacus pilot plant, University of Genoa.

The connection between the top of tank DHW1 and the lower part of DHW2 works independently by means of the pump P10, designed to recirculate internally the two boilers and to heat DHW2. The water supply can enter either DHW1 or V8 (side A) by means of a “T” diverter. The water supply before entering V8 is eventually mixed with the DHW coming from the recirculation system, granted by the twin pumps P9. Only DHW1 is directly heated following specific priorities to maximise the renewable sources exploitation. Cold water is drawn from the lower part of DHW1 by means of the twin pumps P8 and sent to a first exchanger interfaced with the HP. During summer, the HP is off and a bypass directly connects the solar thermal field to the exchanger. Then, if the inlet temperature T16 is lower than the required set point (e.g. 52 °C), valve V7 switches from A-AB to B-BA to send the water to a second exchanger interfaced with a 35kW gas burner. The DAS acquires almost continuously the temperatures in Figure 2 and the working period of the pumps. No flow rate meters or data on the valves are available, so the information collected results incomplete.

3. Case study
The data collected over the year 2019 has revealed untypical trends in the tank temperatures (T14 and T19) during about 150 nights from June to August and from October to November. The differences between standard and non-standard trends of the DHW during night are analysed and showed below.
3.1 Standard day (Figure 3a, left side)

Figure 3a shows the trend of the temperatures recorded in the two tanks (DHW1 – T14, blue line and DHW2 – T19, orange line) during a standard day (September, 29-30). An initial increase in temperature occurs from 8.00 a.m. to 8.35 a.m. when the plant starts heating the DHW after thermal losses in the night. Reached the set point temperature in about 30 minutes, the plant switches to stand-by mode.

![Figure 3a: Temperatures trend of T14, T19 and T20 from September, 29th to October, 1st 2019 correspond respectively to a standard (a) and an untypical day (b). T14 DHW1 – T19 DHW 2 – T20 Controlled DHW supply temperature (set point: T*20 = 52°C).](image)

The following oscillating trends are the DHW cycles to supply the end users’ needs during the day. Coherently, T14 is always lower than T19 and its oscillations are pronounced, due to the presence of the cold water supply. At about 23.00, the plant turns off and the temperatures within the two boilers cool down almost linearly of about 3°C until about 8.00 a.m.. The steep and sudden decrease in temperature recorded at the end of the night-time is due to the activation of the pumps. The measured values for T20 have been overlaid (in yellow) in Figures 3a and 3b. During the day the temperature is almost constant and equal to 52°C (the set point value) unless minimal instrumental fluctuations. When the plant is turned off, T20 cools down to the asymptote of 28-29°C (early in the morning) following a negative exponential curve while T14 and T19 have a linear cooling phase. This difference is due to the high thermal inertia associated to the tanks which determines a large time constant (about 40 hours) with a longer time to cool down (about 200 hours). So, the negative exponential cooling trend of the tanks during night can be linearly approximated with very little error while the low time constant for V8 (about 1 hour) requires a negative exponential approximation.

3.2 Untypical day (Figure 3b, right side)

The trend of T14, T19 and T20 during the day (September, 30th) is comparable with the one recorded in September, 29th and no significative differences can be identified. A very large deviation in the temperature-time profiles has been detected overnight (October, 1st). In particular:

- T19 (orange lines - temperature in DHW2) shows a lower slope with a decrease of about 1°C during the night, while during a typical night a decrease of 3°C is appreciated over the same time-period.
- T14 (blue lines- temperature in DHW1) shows an almost linear initial decrease, followed by a strongly non-linear trend. An additional decrease of 20°C is lost each night (Figure 3b) with respect to the 3°C decrease (Figure 3a).
- T20 (yellow line – DHW set point control): the negative exponential trend of the temperature variation due to the overnight cooling reduces from 25°C (Figure 3a) to 15°C (Figure 3b).
No apparent change occurred within the Palacus facility to justify these different trends in temperature. Indeed, in the morning, the temperature in the boilers is lower and more power is required to re-heat it up to the set point value. The choice of the days in Figure 3a and 3b is representative of most of the “standard” days as well as the “untypical” ones.

4. Numerical modelling
The absence of mass flow rate measures inhibits any possible balance on the DHW subsystem. A numerical simulation by means of TRNSYS17 is carried out to obtain a reliable estimation of the water flow rates which cause the “untypical” trends in temperature by means of transient problem resolution.

4.1. Model assembly
Basing on Figure 2, during night the following components shall be inactive: recirculation pumps (P9), the pump P10 between DHW1 and DHW2 and the heat exchange circuit with the gas burner (pumps P8). Figure 4 shows the simplified DHW subsystem and the correspondent TRNSYS model.

![Figure 4. Simplified scheme of the DHW subsystem for numerical overnight modelling (on the left) and corresponding TRNSYS model (on the right). In night mode the T20 control is off.](image)

A single boiler of 3000 l capacity and a total height of 4.20 m equal to the double of a single boiler height is employed. Indeed, the connection between the top of DHW1 with the lower part of DHW2 makes the two tanks work as if they were stacked one on the other. The implementation of a model with two distinct boilers is under study to validate this assumption. The specific TRNSYS thermal storage Type 4 with stratification [5] has been chosen with ten internal nodes equally spaced both to grant a mesh fine enough and to have a node at the same height of each temperature sensor (T14 and T19). The thermal properties have been validated on the records of a standard day (Figure 3a). The initial thermal inertia of the boiler is assigned by means of the temperatures of each node at the initial time following a linear trend, based on the measured values (T14 and T19).

The modelling of V8 is performed with the attribution of regulation to the T diverter while the mixing and the inertia have been modelled with a small additional tank (TYPE60b). A “control signal” of the T diverter regulates in real time the percentage of water flowing inside the DHW tanks while the remaining part is directly sent to the valve V8. This value is fixed since during night the valves are not controlled. About 80 cm of bare pipe divide the mixing valve from the temperature sensor. The additional masses of steel and water have been accounted in the parameters of V8 with equivalent properties by means of weighted averages. Figure 4 on the right shows the related TRNSYS model. The load profile represents a forcing function linked to any DHW water draw. The temperature of the inlet water from the underground supply line is set equal to 14.7 °C (the local average seasonal air temperature for Genoa).

4.2. Calibration and validation of the model
The convergence results obtained from the model calibration with the values recorded during a standard night (Figure 3a) are shown below. A constant water flow rate of 7 kg/h (about 0.12 l/min) is adopted.
Any conductive heat transfer along the walls of the pipeline is negligible due to their length (over 4 m in length).

4.3. Temperature at valve V8 – T20

The equivalent volume of valve V8 and of the pipe connecting V8 to T20 has been set to 1.2 l, with a density of 7000 kg/m\(^3\) and an equivalent specific heat of 1.1 kJ/kg K. The properties derive from weighted averages between the steel and water (\(c_{p,\text{water}} = 4.186 \text{ kJ/kg K}\); \(\rho_{\text{water}} = 1000 \text{ kg/m}^3\); \(c_{p,\text{steel}} = 0.4 \text{ kJ/kg K}\); \(\rho_{\text{steel}} = 7800 \text{ kg/m}^3\)). The tank loss coefficient is set to 17 W/m\(^2\) K which is representative of the thermal losses of a bare pipe, in accordance with the predictions of [6]. Moreover, it can be obtained from the well-known formulation reported in Eq.1 which already neglects the thermal resistance of the bare steel. So, the transmittance depends on the internal (water-pipe walls) and external (pipe walls – air) heat transfer coefficients (\(h_{\text{int}} \approx 100 \text{ W/m}^2\text{K}\) and \(h_{\text{ext}} \approx 20 \text{ W/m}^2\text{K}\):

\[
U_{V8} = \left( \frac{1}{h_{\text{ext}}} + \frac{1}{h_{\text{int}}} \right)^{-1} = 16.7 \text{ W/m}^2\text{K}
\]  

The validation of V8 is shown in Figure 5. A maximum difference of 1.7 °C between the measured and simulated lines can be noticed while a variation of 0.5 °C is appreciated at the asymptote of about 28-29 °C. The result is acceptable considering the precision of ±0.5 °C for the temperature sensors. The ambient temperature inside the boiler room during that nights was about 17 °C and the only way to grant an asymptote for V8 of about 28-29 °C is by means of a hot water flow inside V8.

![Figure 5. Plot of the numerical and measured time-temperature profile of T20 (assumed minimum water flow rate \(m = 7 \text{ kg/h}\) with variable temperatures in the range 57-53°C).](image)

4.4. Water storage tank (DHW1 + DHW2) – T14 and T19

The 3000 l water storage tank has a thermal loss coefficient of 2.6 W/m\(^2\) K, in accordance with the preliminary calculations shown in Table 1. The transmittances of each tank component have been computed considering the lateral surface as plane, thanks to its negligible curvature. The transmittance for the lower basis of the tank considers only the steel, since no insulation is present. The global thermal loss coefficient has been determined by means of an average weighted on the different areas (Table 1b). Figure 6 shows the overlapped plot between the measured values for T14 and T19 (dotted red lines) and the TRNSYS simulated T14 (lower line) and T19 (upper line). The maximum difference between the...
measured and recorded data is of 0.5 °C and it can be obtained only with a very low water flow rate (e.g. a small leakage within the plant).

Table 1. Additional information (a) and estimation of the global thermal loss coefficient for DHW tanks (b).

| Properties | λ (W/mK) | s (m) |
|------------|----------|------|
| Steel      | 80       | 0.002|
| Insulation | 0.028    | 0.04 |

\[ h_{int} = 100 \text{ W/m}^2\text{K} \quad h_{est} = 25 \text{ W/m}^2\text{K} \]

Otherwise, the simulated trend would become strongly non-linear and representative of a mixing instead of a cooling process. In the following section, the assumption of a constant flow rate is removed and a constant step approximation is adopted. Using the thermal properties validated before, the water load profile that best suits the trends for T14, T19 and T20 during an “untypical” day is searched.

**Figure 6.** Plot of the numerical and measured overnight trends for T14 (DHW1) and T19 (DHW2) (in between the on-off status of the plant).

4.5. Unexpected measured data analysis and simulation

Figure 7 provides the temperatures inside the DHW tanks (T14 – DHW1 – yellow line, T19 – DHW2 – red line) and for the valve V8 (T20 – blue line) referred to water profile in the lower part of the graph, (right axis). The measured values are dotted while the numerical ones from TRNSYS are continuous. The following observations and conclusions can be drawn:

- **T19 – temperature in DHW2 (red line in Figure 7):** the initial trend is well approximated. Then the difference increases up to 2.4 °C at the end of the simulation. At first look, the trends of the two lines are different, although the error is small. No influence of the boundary conditions (e.g. ambient temperature) occurs since they are the same for the typical and untypical days. Even decreasing the flow rate up to the case limit of still water inside the boilers (omitted in this work), the trend for T14 and T19 is very similar to the one reported in Figure 6, but still different from the one measured in Figure 7. On the other hand, an increase of the flow rate only reduces the simulated T19 with a pronounced non-linear trend (with shapes that resemble T14). The different behavior can be imputed to local mixing effects as the hot water coming from the top of DHW1 enters DHW2. Moreover, the connection between the two boilers (Figure 4) is about 7 cm lower than the
temperature sensor T19 and it is not on the bottom of DHW2 as in the numerical model. Physically, the water entering DHW2 from DHW1 is not so cold to destroy completely the stratification in the lower part of DHW2, but it is still low enough to rise a mixing. So, the recorded trend can be read as half-way between the two case limits of stratification and full mixing [7] which cannot be performed with the numerical model.

![Figure 7. Measured (dotted lines) and the numerically simulated data (continuous lines). T19: tank 2 (DHW2) temperature, T14 tank 1 (DHW1) temperature, T20 DHW delivery temperature (just after the 3-way regulation valve V8), associated water flow rate in blue (ref. right axis).](image)

- **T14 – temperature in DHW1 (yellow line in Figure 7):** the approximation obtained is very good, with a maximum difference of about 1 °C. This parameter is highly sensible to the water flow rate entering the tank. Indeed, the load profile in Figure 7 consists in different steps to follow the several slopes of the measured T14 with a piecewise linear approximation. Differently from T19, the behavior of T14 can be reconstructed with the numerical model, even if in both cases the inlet is near the temperature sensors (Figure 4). Actually, this difference is due to the lower temperature level of the inlet water in DHW1 which causes the local destruction of the thermal stratification. Indeed, the results of the numerical model compare well to the recorded data because an almost complete mixing process takes place in the lower region of DHW1.

- **T20 – temperature at the exit of valve V8:** the transient in the first two hours of the process has maximum differences of 5 °C (4 °C on average). After the transient, the difference between the two lines becomes negligible (lower than 0.2 °C). The leap between the two regions is due to the forced instantaneous passage from 50 kg/h to 195 kg/h at the end of the first two hours. The jump becomes more evident as the step in the water draw profile becomes more pronounced and vice-versa.

The water load profile referred to the untypical days is associated to the cleaning activities after the sport palace closure. Indeed, the nearly 600 l of water consumed each night over three hours are comparable to the total water and time needed to wash about 2000 m² of floor. The average thermal loss of the boiler doubles in the untypical nights as well as the power required in the morning, since the plant is turned on always half an hour before the opening. So, the plant can start one hour before the opening whenever the temperature T14 (DHW1) lowers a fixed set point (e.g. 45 °C) during night.

5. Conclusions and future developments

The issue of data acquisition systems (DAS) is becoming a widespread problem as technologically advanced plants take place over the market. The information collected has very different and useful applications, such as the study on the plant efficiency and of new regulation criteria to increase it. Moreover, the DAS provides real time plant status (e.g. ruptures, unusual working). Nevertheless, the
cost of each sensor makes a complete DAS economically unfeasible, so numerical models can be employed to integrate the missing data. In this paper, the DAS associated to a DHW production system by means of traditional fossil burners integrated with a SAHP has been presented. No flow rate measurement is available, only the temperature levels have been recorded over the plant (e.g. tanks). This missing information has been determined by means of a simple, but still reliable numerical model built with TRNSYS commercial code and validated with the measured data. This work is put in the wider context of Inverse Heat Transfer Problem for thermophysical properties and boundary conditions. Two case studies highlighted by the DAS have been numerically simulated:

- **Typical nights**: the trend in temperature inside the DHW tanks is representative of the cooling within inactive plants. The results of the numerical model highlight the presence of a low, constant water flow rate, representative perhaps of a leakage (e.g. ruptures). 

- **Untypical nights**: the trend occurs often along the year and it is apparently unjustified, since no variations in the plant scheme or operative modes are introduced. The TRNSYS numerical simulations lead to an approximate water load profile that can be compatible for duration and entity with the cleaning of the sport palace. This usage of DHW roughly doubles the energy and the power required in the morning to reach the set temperature in the tanks. So, the plant can be turned on 1 hour before the opening (instead of 30 minutes) each time temperature in the DHW tanks lowers a set point value (about 45 °C) to solve this issue.

In addition, the validation of the model has involved the issue of thermal stratification which has been enquired as well. The results obtained shall be compared with a TRNSYS simulation modelling separately the two boilers. The so-built model can be integrated with all the components neglected over nights to simulate the plant during the day. This model shall have multiple applications, from data integration (especially on the water flow rates) to analyses of efficiency under transient regime.

**References**

[1] Scarpa F, Tagliafico L.A, Reverberi A.P and Fabiano B 2015, “An Experimental Approach for the Dynamic Investigation on Solar Assisted Direct Expansion Heat Pumps”, C.Eng. Trans., pp. 2485-2490.

[2] Zengkai L, Yonghong L, Dawei Z, Baoping C and Chao Z 2015, “Fault diagnosis for a solar assisted heat pump system under incomplete data and expert knowledge”, Energy 87, pp.41-48.

[3] Tagliafico L.A, Scarpa F and Carrea E 2006, “Performance analysis of integrated solar-assisted heat pumps for water heating”, 61st ATI Congress, International session on solar heating and cooling.

[4] Woodbury K.A., 2002 “Inverse engineering handbook”, CRC press, pp. 20-60.

[5] Banister C.J, Wagar W.R and Collins M.R 2014 “Validation of a single tank, multi-mode solar-assisted heat pump TRNSYS model”, En. Proc., pp. 499-504.

[6] UNI EN 12831:2018, Energy performance of buildings – Method for calculation of the design heat load – Part1: Space heating load, model M3-3: Evaluation of primary energy need and of system efficiencies for space heating, domestic hot water production, ventilation and lighting for non-residential buildings 2019.

[7] Han Y.M, Wang R.Z and Dai Y.J 2009 “Thermal stratification within the water tank”, Renewable and Sustainable En. Rev. 13, pp. 1014-1026.

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