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Dynamic simulation of solar thermal collectors for domestic hot water production

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Abstract

In this paper a system for the Domestic Hot Water (DHW) production based on solar collectors is analyzed by means of a dynamic approach based on a Simulink model and by using the F-chart method, able to evaluate system performances on a monthly basis. Following the dynamic approach, it is possible to evaluate hour by hour the energy collected by the solar panels and the temperature of the hot water produced by the system, by taking into account the impact of different daily DHW consumption profiles on the percentage of thermal energy produced by the solar collector (Solar Coverage Factor, SCF). The comparison between the prediction made both by using the Simulink model and the F-Chart method in terms of SCF is shown by taking into account the effect on SCF of the typology of solar collector (unglazed, glazed and evacuated collectors), of the storage tank volume connected to the solar panels and of the hourly DHW consumption profile. The results point out that SCF is strongly dependent on the daily DHW consumption profile, which cannot be taken into account in a quasi-static approach like the F-chart method.

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1. Introduction

Nowadays, two complementary approaches are available for the designers of HVAC systems: the first one \textit{(quasi-static approach)} is based on a steady-state analysis of the system in which the seasonal behavior of the HVAC system is reconstructed by a set of monthly static analyses where the main status parameters of the system are freezes. The second approach \textit{(dynamic approach)} is based on a dynamic analysis of the system in which the hourly evolution of the significant status parameters is taken into account by considering the heat storage and discharge capacity of the different HVAC components by means of dynamic codes (i.e. Energy+, ESP-r, TRNSYS). The results obtained by simulating a thermal

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plant by using these two approaches can give different results especially if the thermal loads strongly depend on time and/or if the performance of the HVAC components varies significantly during the day and the season, like for HVAC systems based on renewable sources. In these cases, the dynamic approach must be preferred in order to obtain an accurate evaluation of the performance of HVAC systems.

A thermal plant based on solar thermal collectors for the production of Domestic Hot Water (DHW) is a typical example of HVAC system characterized by a strong variation of the thermal load during the day and during the different seasons, as well as by a significant variation of the performance of the heat generation system, based on solar energy. This kind of HVAC system is very diffuse in Italy where the production of at least 50% of thermal energy consumptions for DHW production must be provided by renewable sources, as imposed by law [1]. The technical UNITS 11300-4 [2] suggest to use the F-chart method [3] in order to estimate the efficiency of a solar hydronic system composed by thermal collectors. This method employs a quasi-static approach that allows to evaluate the performance of the system only on a monthly basis. However, due to the variability of the thermal loads and of the performance of solar collectors, a dynamic simulation of these systems can be recommended, as pointed out by many researchers. For example, Ahmed et al. [4] suggest to use the dynamic approach for the estimation of the performance of solar hydronic system for DHW production after the deep investigation of the effect on the solar coverage factor of different DHW load profiles, by taking into account the change of DHW energy demand during weekend and weekdays in Finnish apartments. The dynamic approach is also recommended when the variation of the performance of the solar components must be taken into account in order to obtain a reliable simulation of the system: Da Silva et al. [5] and Tsai [6] have used MATLAB/Simulink environment to simulate the behavior of a hybrid PV/T plant coupled to residential buildings.

As evidenced by the open literature [5-7], MATLAB/Simulink environment is a powerful instrument to approach dynamically HVAC systems. In fact, thermal plants can be modelled through blocks simulating the behavior of real components by a lumped formulation of the conservation equations. By following the trend indicated by the cited papers, in this work a dynamic model of a hydronic solar system for DHW production based on a series of customized blocks made by using MATLAB/Simulink, is presented. The dynamic model includes all components that constitute the system and its control system. The model is used in order to investigate the influence of the typology of solar collectors (unglazed, evacuated and glazed), of thermal inertia of the storage tank coupled to the collectors and of different DHW profile loads on the global system performance for a typical Italian residential building. A comparison, in terms of monthly and annual solar coverage factors, with the values obtained by means of the F-chart method is presented. The results point out that the solar system efficiency is strongly dependent on the DHW profile load, which cannot be taken into account in a quasi-static approach like the F-chart method.

2. Simulink model description

As shown by Morini and Piva [8-9], Simulink can be proficiently used in order to build a “thermal library” for the modeling of HVAC systems in which any HVAC component is modeled by means of a specific sub-block containing the lumped formulation of the main conservation equations. In Fig. 1 the layout of the solar heating system coupled to a residential building built with MATLAB/Simulink is shown; the HVAC system considered in this paper is composed by a series of sub-blocks: Parameters, Climatic Data, Collector, Pump, Back-up, DHW load and Solar thermal storage.

More in detail, the Climatic Data block is a sub-system, described in [10], that, by using as input the hourly climatic data from a Test Reference Year (TRY), calculates the hourly total solar radiation incident on the thermal collectors as a function of the tilt angle and orientation. Through the Parameters block in
Fig. 1 the user can set all the values of the main physical and geometrical parameters of the HVAC system: for example it is possible to define the collector geometrical properties, the optical efficiency ($\eta_0$) and the characteristic loss coefficients ($a_1, a_2$) linked to the collectors, the storage volume and so on.

![Fig. 1. Layout of the MATLAB/Simulink developed model](image)

The Collector block simulates the solar thermal collectors that compose the heating system. The input data for this sub-system are the total incident solar radiation and the outdoor temperature, both calculated by the Climatic Data block, and the inlet working fluid (brine) temperature. The model of Fig. 1 is able to model a solar heating system realized by using $N_c$ solar collectors connected in parallel; each collector has an inlet brine temperature equal to the outlet fluid temperature from the storage heat exchanger ($T_i$).

In the Pump block, the pump governing equations reported in [7] are solved in order to calculate the brine temperature rise caused by the pump itself and the pump electrical consumption. A customized controller has been implemented in this block in order to turn off the pump when the fluid temperature exceeds the safety range and when the solar system is not able to collect useful energy (i.e. when it is not possible to exchange heat from collectors to tank).

The thermal load needed for DHW production is evaluated by the DHW load block. The hourly values of the DHW energy demand and of the hot water mass flow rate for a residential application can be calculated by following the procedure reported by the standard UNI TS 11300-2 [11] or by selecting a custom daily DHW consumption profile, in order to consider the effect of different load profiles on the performance of the solar system.

The Solar thermal storage block models the hot water storage tank with its inner heat exchanger coil. A completely mixed tank model is considered with a uniform temperature of water stored in the storage ($T_s$).

The Back-up block simulates the electric heater used as a back-up system for the storage. The electric heater is switched on when the solar collectors are not able to ensure the water storage minimum temperature. A controller implemented within the block supervises electric heater operation: the back-up is characterized by an on-off logical control that follows an hysteresis cycle of $\pm 5^\circ$C in which the minimum value of the cycle is the minimum set-point temperature of the water stored in the tank.

3. Case study

The developed model has been used in order to evaluate the performance of the solar system for DHW production described before coupled to a residential building located in Bologna (Italy, 44.47 N; 11.43 E) with a useful floor area of 200 m$^2$, corresponding to a daily energy load for DHW production of 8.72
kWh, following [11]. The TRY provided by CTI for Bologna [12] has been used as climatic input data. Three different solar collectors (evacuated collector (EC), single glazed collector (GC) and unglazed collector (UC)) coupled with storage tanks having different volumes (168, 291, 500 liters) have been considered. The technical and geometrical data of each solar collector and each tank are given in Table 1.

Table 1. Solar collectors technical data and solar tanks geometrical data

<table>
<thead>
<tr>
<th>Solar collector type</th>
<th>EC</th>
<th>GC</th>
<th>UC</th>
<th>Solar thermal storage</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>η₀</td>
<td>0.605</td>
<td>0.72</td>
<td>0.959</td>
<td>Volume (l)</td>
<td>168</td>
<td>291</td>
<td>500</td>
</tr>
<tr>
<td>a₁(W/m²K)</td>
<td>0.85</td>
<td>3.826</td>
<td>8.91</td>
<td>Diameter (m)</td>
<td>0.60</td>
<td>0.60</td>
<td>0.75</td>
</tr>
<tr>
<td>a₂(W/m²K²)</td>
<td>0.01</td>
<td>0.0094</td>
<td>0.047</td>
<td>Height (m)</td>
<td>0.99</td>
<td>1.615</td>
<td>1.69</td>
</tr>
<tr>
<td>A_abs (m²)</td>
<td>2.36</td>
<td>2.31</td>
<td>2.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Simulations have been carried out by evaluating the behavior of the thermal plant for the whole year; in this way one is able to estimate the hourly, daily, monthly and annual solar coverage factor (SCF) of the system, defined as:

\[
\text{SCF} = \frac{E_{\text{Sol}}}{E_{\text{DHW}}}
\]  

in which \( E_{\text{Sol}} \) is the thermal energy provided by solar collectors and \( E_{\text{DHW}} \) is the energy need for DHW production in the same period. The monthly and annual values assumed by SCF can be compared with the corresponding values obtained by applying the F-chart method in order to highlight the difference existing between the "dynamic" and the "quasi-static approach" for this kind of solar systems.

In Fig. 2 the annual SCF trend obtained with the Simulink model and the values calculated by using the F-chart method, by considering the daily DHW consumption profile suggested by [2] for residential buildings, are compared. Annual simulations have been carried out by considering each combination solar collector-storage tank (see Table 1) and by considering an increasing number of solar panels for each combination, from 1 to 3 collectors.

Fig. 2. Annual SCF for the considered collectors and tanks, evaluated for a solar system composed by 1, 2 or 3 solar collectors
The results point out that ECs are characterized by the best annual performance with respect to GCs and UCs typologies. The reason is mainly due to the low values assumed for ECs by the loss coefficients $a_1$ and $a_2$, which enable to obtain a significant contribution of the solar collector to the DHW production also during the colder season. In addition, scaling from the smaller storage tank (tank a) to the bigger one (tank c) the yearly efficiency of the system increases, but the annual SCF weakly depends on the tank size.

On the contrary, the number of solar collectors strongly affects the SCF values. Systems composed by two collectors are characterized by an annual SCF about 50% greater than SCF obtained using a single solar panel, even if it is evident a saturation effects: the addition of the third collector to the system increases the annual SCF value of about 10-20% only. From Fig. 2 it is also evident the tendency of the F-Chart method to underestimate the values of the annual SCF.

Another series of simulations has been carried out by using the Simulink model and by considering the above-mentioned solar collector typologies (EC, GC and UC). Three different DHW profile loads have been simulated: profile A is in agreement with the hourly DHW consumption profile reported by [3], profile B is characterized by a uniform DHW consumption during the night between 23 and 5 and profile C concentrates the DHW consumption during the day between 7 and 19. The daily DHW consumption of these profiles is the same (8.72 kWh) and the solar heating system is composed by 1 glazed collector (GC) coupled to the tank a (168 liters of volume) (see Table 1).

In Table 2 the annual SCF determined by means of the Simulink model and by the F-Chart method are reported as well as the monthly value of SCF associated to February and July.

Table 2 – SCF trend as a function of the DHW daily consumption profile for the Simulink model and the F-chart method.

<table>
<thead>
<tr>
<th>Profile load</th>
<th>Collector typology</th>
<th>Annual SCF</th>
<th>Monthly SCF</th>
<th>Monthly SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Simulink</td>
<td>F-Chart</td>
<td>Simulink</td>
</tr>
<tr>
<td>A</td>
<td>UC</td>
<td>0.270</td>
<td>0.283</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>GC</td>
<td>0.370</td>
<td>0.304</td>
<td>0.115</td>
</tr>
<tr>
<td></td>
<td>EC</td>
<td>0.480</td>
<td>0.321</td>
<td>0.211</td>
</tr>
<tr>
<td></td>
<td>UC</td>
<td>0.234</td>
<td>0.283</td>
<td>0.019</td>
</tr>
<tr>
<td>B</td>
<td>GC</td>
<td>0.335</td>
<td>0.304</td>
<td>0.106</td>
</tr>
<tr>
<td></td>
<td>EC</td>
<td>0.449</td>
<td>0.321</td>
<td>0.198</td>
</tr>
<tr>
<td></td>
<td>UC</td>
<td>0.336</td>
<td>0.283</td>
<td>0.030</td>
</tr>
<tr>
<td>C</td>
<td>GC</td>
<td>0.409</td>
<td>0.304</td>
<td>0.123</td>
</tr>
<tr>
<td></td>
<td>EC</td>
<td>0.501</td>
<td>0.321</td>
<td>0.222</td>
</tr>
</tbody>
</table>

The results of Table 2 emphasize that the annual and monthly solar coverage factor strongly depends on the DHW profile load.

With glazed collectors a DHW energy demand concentrated during the night (profile B) leads to a lower annual performance of 9.5% with respect to profile A (standard profile). On the contrary, it is possible to reach an increase of annual SCF of 10.5% with respect to standard profile if the DHW thermal load is concentrated during the day (profile C).

Results obtained for unglazed collectors confirm this evidence: profile B and profile C are characterized by an annual SCF lower of 13.3% and higher of 24.3% with respect to profile A, respectively. UCs are more influenced by larger $T_i$ because this collector typology is characterized by very high values of loss coefficients $a_1$ and $a_2$, inducing high thermal losses and low instantaneous
efficiency. On the other hand, annual SCF of a system composed by ECs is less dependent on DHW profile load. When DHW load is concentrated during the day the solar system directly provides the thermal energy required for DHW production, avoiding thermal losses from the tank and an excessive increase of the water temperature inside the storage. On the other hand, a request of DHW entirely located during the night leads to an increase of the temperature of the stored water during the day, causing a double negative effect: higher tank temperatures induce higher thermal losses from the storage and a decrease of solar collector instantaneous efficiency. If $T_s$ increases also the inlet brine temperature ($T_i$) becomes higher; climatic abscissa ($\frac{(T_i-T_{ext})}{H}$) increases and solar collectors work with lower instantaneous efficiency.

4. Conclusions

In this work a dynamic model, written in MATLAB/Simulink environment, able to simulate a solar heating system for DHW production composed by solar collectors coupled to a thermal storage is described. The Simulink model calculates hour by hour the thermal energy produced by the solar collectors, the average storage tank temperature and the solar coverage factor of the system (SCF). The results obtained by using the dynamic model have been compared with those obtained by means of the F-chart method. The influence of solar collector typology, of storage tank volume and of the daily DHW consumption profile on SCF has been investigated. On the contrary of the F-chart method, the results obtained with the dynamic model enable to evaluate how much the SCF value is influenced by different DHW consumption profiles.

References

Biography

Matteo Dongellini is a Ph.D. Student in Energy, Nuclear and Environmental Control Engineering at the Department of Industrial Engineering of the University of Bologna. He is author of 3 conference papers and 1 paper published on international journal. His current research interests include heat pumps, energy efficiency and building dynamic simulation.