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MEASURED AND CALCULATED PERFORMANCES OF A DUCT HEAT STORAGE FED BY SOLAR PANELS AND COUPLED WITH A GAS HEAT PUMP

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ABSTRACT

This study describes and analyses an active solar system which equips an industrial building. The measured performances of the solar panels, the diffusive duct storage, as well as the heat pump are presented. They do not exhibit the anticipated performances, as the heat pump did not work properly. In order to obtain an evaluation of the active solar system, the performances of the components are recalculated. A global solar efficiency of 27% is assessed. A substitution heat balance is established: one kilowatt-hour extracted from storage or solar panels gives a saving of 0.7 kilowatt-hours of gas. The behaviour of the duct ground heat storage is analysed in detail. The temperature difference between the heat carrier fluid and the average temperature level of the storage shows the limits of utilisation of the duct storage.

1. INTRODUCTION

The industrial building Marcinhès (68'000 m³, 18'400 m²), located near Geneva, was entirely constructed with private funding. The heating design (Matthey and Roulet, 1987) involves 940 m² of flat plate collectors, a seasonal heat storage comprising 20'000 m³ of moraine under the building, a gas powered heat pump of 215 kW, three auxiliary furnaces (gas/oil and wood) totalling 640 kW and 3'400 m² of double skin facades for large passive solar gains.

The building was measured and analysed in detail by the Group of Applied Physics at the University of Geneva, from May 89 to May 93 (Pahud, 1993). The heat demand of the building remained below 140 MJ/m²y, as the building was half occupied and partially heated. (The reference area is the heated floor area). Recalculated with a normal utilization (a mean internal temperature of 18°C), the heat demand of the building is evaluated to 150 MJ/m²y, and represents only one quarter of the average value in Switzerland (with a similar climate). During the heating season of 1990-1991, the energy resources taking part in the heating of the building were composed of; the passives gains (25%), the internal gains (13%), the underground heat storage (21%) and the remainder, the gas consumed by the
heat pump and the furnaces (41%). The gas consumption was only 100 MJ/m²y. We will now concentrate on the analysis of the active solar system.

2. THE ACTIVE SOLAR SYSTEM

The active solar system is formed by the couple "solar panels - duct storage", acting as the cold source of the gas heat pump, and the heat pump itself. The heat produced is distributed in the building via low temperature floor heating (30 - 45°C).

2.1 The solar panels

The roof of the building, constructed in a shed structure, is formed by the solar panels. They are single glazed collectors with selective absorbers. They feed the duct heat storage, mostly in summer time and occasionally during winter, when solar gains exceed the amount of heat extracted by the heat pump.

The solar panels are working properly and as expected. Measurements show that they are characterized by an optical efficiency of 0.74 and by thermal losses (including piping of the array) of 5.1 W/m²K. The first year of operation, a mean annual efficiency of 47% was measured (Mermoud, Pahud, Guisan and Lachal, 1991).

2.2 The underground duct storage

The heat exchanger of the storage is formed by 258 vertical boreholes (11 cm diameter), 15m deep and 2.3m apart. The heat carrier fluid (water) circulates in plastic tube forming a double U-pipe in each borehole. Fine sand assures thermal contact between the tubes and the ground. A thermal insulation layer of 5cm separates the storage from the building.

The storage operates at low temperature (5-30°C). Over the first four years of operation, the storage worked without any serious problems. The heat capacity was measured at 50 GJ/K and the thermal properties of the storage were quite stable (Pahud, 1993).

2.3 The gas heat pump

The heat pump is equipped with a condenser of 12 kW on the gas exhaust and delivers 110, 180 or 215 kW.

The thermal performances of the heat pump are determined by its transformation losses and its performance coefficient (COP). The transformation losses are measured at 20% of the energy entering the heat pump (gas energy according to the lower heating value (LHV) plus heat extracted at the evaporator). The COP varies between 1.4 and 1.8, depending on the temperature level of the condenser and evaporator. It may fall to 1.0 following the deregulation of heat pump components (ie: the expansion valve). Globally, the reliability of the heat pump is disappointing, mostly due to faults in the command or control elements.
3. MEASURED GLOBAL PERFORMANCES

The energy fluxes through the active solar system were all measured for two consecutive years (1990 to 1992), corresponding to the second and third operation years of the system. They are shown in Table 1.

Table 1: Measured heat fluxes through the active solar system and associated temperature level

<table>
<thead>
<tr>
<th>Energy GJ</th>
<th>Period from 7.1.90 to 7.1.91</th>
<th>Period from 7.1.92 to 7.1.92</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar panels production</td>
<td>1'200 41.9°C</td>
<td>1'250 40.8°C</td>
</tr>
<tr>
<td>Duct storage injection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>storage temp. during inj.</td>
<td>1'140 35.5°C</td>
<td>1'200 34.4°C</td>
</tr>
<tr>
<td>storage temp. during ext.</td>
<td>25.6°C</td>
<td>24.3°C</td>
</tr>
<tr>
<td>extraction capacity variation</td>
<td>21.8°C</td>
<td>21.9°C</td>
</tr>
<tr>
<td>losses</td>
<td>-290 16.4°C</td>
<td>560 17.4°C</td>
</tr>
<tr>
<td>recovery factor</td>
<td>690</td>
<td>+60 1690</td>
</tr>
<tr>
<td>Heat pump evaporator</td>
<td>740</td>
<td>580</td>
</tr>
<tr>
<td>gas (LHV) production losses</td>
<td>0.48</td>
<td>0.49</td>
</tr>
<tr>
<td>annual COP</td>
<td>750 14.8°C</td>
<td>610 15.8°C</td>
</tr>
<tr>
<td></td>
<td>870</td>
<td>740</td>
</tr>
<tr>
<td></td>
<td>1'350 38.9°C</td>
<td>1'070 38.4°C</td>
</tr>
<tr>
<td></td>
<td>270</td>
<td>280</td>
</tr>
</tbody>
</table>

As the heat pump failed most of the time, the global performances of the active solar system are disappointing, resulting in a poor utilization of the storage (low value of the recovery factor). As a negative consequence, the solar panels had to be covered in summer 1990, in order not to exceed the temperature limit (≈50°C) of the plastic tubes of the underground heat exchanger.

If the heat pump had worked properly when it was not out of order, its annual COP would have been 1.60 the winter of 1990-1991 and 1.64 the winter of 1991-1992.

The temperature level of a heat flux is defined by the average of the temperature values of the heat carrier fluid, weighted by the corresponding values of the heat flux transferred. They are also indicated in Table 1, from the solar panels to the heat pump production. The mean temperature of the storage is also given during injection and extraction (temperature weighted by injected or extracted heat flux).

The first temperature quality loss occurs in the heat exchanger between the pipes of the solar panel array and the pipes of the underground duct storage (6K). The underground heat exchanger is responsible for the main temperature quality losses, 10K during injection and 4-5K during extraction. The conservation of the energy in the storage is less significant with a decrease of 2 to 4K of the mean storage temperature level. There is still a drop of 1 to 2K between the energy delivered by the storage and the energy extracted at the evaporator of
the heat pump, as the temperature level can not exceed 17°C at the evaporator for technical reasons.

4. CALCULATED GLOBAL PERFORMANCES

Based on the assumption of a normal use of the building and a reliable operation of the heat pump, the global performances of the active solar system are recalculated (Pahud, 1993). Knowing the thermal characteristics of the building, the annual heat demand is calculated at 150 MJ/m²/year or 760 MWh/year. The heat pump production covers 75% of this amount or 560 MWh/year. The rest is produced by the gas furnaces. With a consistent annual COP of 1.6, the heat pump consumes 350 MWh/year of gas and extracts 350 MWh/year at the evaporator.

The storage has to deliver 320 MWh/year, the rest comes directly from the solar panels. The performances of the duct storage are assessed knowing that the temperature of the heat carrier fluid in the storage (water) can not fall below freezing point. Simplified models are used (Hellström, 1989). They allow the recovery factor to be established at 80%. The storage needs to be fed by 390 MWh/year and will work at a mean annual temperature of 18°C.

![Diagram](image)

Figure 1: Heat production by the active solar system and comparison with the gas furnaces' production
The solar pannels have to produce 420 MWh/y. Their mean annual efficiency is expected to be 50%. The required solar panel area corresponds to 650 m².

Figure 1 allow us to assess the active solar system. The efficiencies of the different parts of the active solar system are shown and may be compared to the mean annual efficiency of the gas furnaces (93% including the condensation of the burned gasses).

Fourty gas energy units invested in the gas heat pump produce 64 heat units. With the gas furnaces, 37 heat units are produced. The difference is attributed to the solar system and corresponds to a global solar efficiency of 27%. The heat losses of the heat pump are excessive in relation to those of the gas furnaces. A substitution heat balance shows that one kilowatt-hour extracted from storage or solar panels gives a saving of only 0.7 kilowatt-hours of gas. The price of the energy extracted by the evaporator of the heat pump is devalorized.

5. PERFORMANCES OF THE DUCT STORAGE

The Duct Ground Heat Storage Model (Hellström, 1989) has been used with success. The parameters of the storage and the ground, determined in situ, allow the reproduction of the performances of the storage over three and a half years (Pahud, 1993). A standard loading condition year is constructed using measurements from 1 June 90 to 1 June 91 (hourly values). The energy fluxes are adjusted so that the annual heat demand is satisfied and the solar heat production corresponds to the quantity required.

The standard operation year is repeated ten times. The temperature of the heat carrier fluid cannot drop below 1°C at the entrance of the underground heat exchanger. A slight transient period appears during the first two years. The characteristics of the 10th cycle are shown in table 2.

Table 2: Characteristics of the 10th cycle of the storage, calculated with DST assuming a normal utilisation of the building and a good operation of the heat pump

<table>
<thead>
<tr>
<th>Energies</th>
<th>Solar production</th>
<th>Injected into storage</th>
<th>Extracted from storage</th>
<th>Recovery factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Losses</td>
<td>435 MWh</td>
<td>Top 23 MWh 28% Side 42 MWh 51% Bottom 17 MWh 21% Total 82 MWh 100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat carrier fluid temperature</td>
<td>Average during injection 32.9 °C</td>
<td>Average during extraction 11.6</td>
<td>Maximum 51°C Minimum 1°C</td>
<td></td>
</tr>
<tr>
<td>Mean storage temperature</td>
<td>Annual 19°C Maximum 28.6°C Minimum 9.3 °C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The mean temperature of the storage only varies between 9 and 29°C, but the temperature of the heat carrier fluid may reach 51°C during injection, which is the limit accepted by the plastic tubes of the underground heat exchanger (made of polyethylene). During extraction, the temperature may drop to 1°C and the heat demand cannot be satisfied. However, over the heating season, 99% of the prescribed heat is extracted from the storage. This shows the limit of exploitation of the duct heat storage.

The electrical consumption of the pumps, from the solar loop to the low distribution heating network, is estimated at 25 MWh/y. It represents 4% of the heat produced by the heat pump. Taken into account, the annual COP of the heat pump drop from 1.6 to 1.5.

A monthly heat balance is shown in figure 2 for the 10th cycle of operation of the storage.

![Graph](image)

**Figure 2:** Monthly injected and extracted energies from storage. Mean temperatures of storage, heat carrier fluid during injection and extraction are also shown for the 10th cycle.

The temperature difference between the heat carrier fluid and the mean storage temperature is 2 to 3 times larger during injection than during extraction for comparable monthly transferred energy. This is typically due to solar production, which provides large thermal power over a short period of the day.

The solar panels and the storage constitute a cold source for the heat pump. The temperature level of the cold source is at best given by the temperature of the heat carrier fluid in the underground heat exchanger during extraction. The temperature levels of the cold source are given in monthly values in figure 3.
An average temperature level of 10.6°C is obtained by weighting each monthly value by the heat extracted. The cold source "solar panels - duct storage" competes with other cold sources by its price and its temperature level.

6. CONCLUSION

The solar panels and the duct storage worked properly over the first four years of operation, with stable characteristics. The gas heat pump failed most of the time and penalized drastically the performances of the solar panels and the storage. In comparison to the gas furnaces used in the building, the gas heat pump shows excessive losses. The energy extracted from the duct storage or the solar panels is thus devalorized. This study allow us to analyse and examine the behaviour of the diffusive seasonal duct storage. We were also able to highlight the limit of utilisation of the storage.

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REFERENCES


