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COMPARATIVE ANALYSIS OF ACTIVE AND PASSIVE SOLAR HEATING SYSTEMS WITH TRANSPARENT INSULATION

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Abstract—The objective of this research is to achieve a high solar fraction in social housing, for which investment costs are strictly limited. Six houses have been built in the east of France: two with active (solar collectors) and four with passive (Trombe walls) solar heating systems. Two types of transparent covers are compared: a capillary structure and a simpler polycarbonate plate. The project was monitored during 1 year. Experimental measurements as well as simulation results are presented in this article. The use of simulation allowed a comparison of the various systems on a common basis, i.e., minimizing the effect of different occupants behaviour. Compared to the less expensive cover, transparent insulation increased the productivity of the air collectors 25% and doubled the gain of the Trombe wall. Thanks to passive or active controls, the thermal comfort was not reduced by the solar systems in summer nor in mid-season.

1. INTRODUCTION

In a long-term approach to design eco-friendly buildings, transparent insulation seems a promising technology. Life cycle analysis of buildings shows that, due to a long lifetime, the utilization phase has a larger environmental impact than construction and demolition. During this phase, energy plays an essential role and the corresponding impact can be greatly reduced by the use of solar gains. Furthermore, transparent insulation gives interesting possibilities for architectural integration, concerning both opaque walls and glazings, for both heating and daylighting applications.

The objectives of this study are to evaluate the interest and potential of transparent insulation in the local bondary conditions. Evaluation criteria concern energy and also comfort, cost, building technique, aesthetics, or any other architectural aspect. In the frame of this social housing project, an industrial production has been chosen in order to reduce the construction time and the cost.

2. DESIGN OF THE PROJECT

2.1 *Description*

Four houses were already built some years ago on the site by Jacques Michel (1971) with a traditional masonry construction. This solar housing estate called "Aurore," situated in Mouzon, acts as a regional demonstration project for solar heating. The owner of the present project is the social housing company Espace Habitat in Charleville Mézières. The manufacturer is Houot (wooden frame buildings). Four houses are equipped with passive systems, two with active air collectors. Transparent insulation and polycarbonate plates were used in three houses (two passive and one active).

The transparent insulation being considered is produced by the German firm Okalux, after the research works of the Fraunhofer-Institut Freiburg by A. Goetzberger *et al.* (1984, 1992) and Leslie Jesch (1986). It consists of a capillary structure where the capillaries are mounted perpendicular to an absorber surface, and encapsulated between two glazings. This advanced technology will be compared to less expensive transparent covers produced by the French firm Celair. These are extruded polycarbonate plates having the form of a triple glazing with connection joints. The corresponding physical properties are given in Table 1, the solar transmission values were measured by CSTB on the OPTORA test facility as explained by Soler and Chevalier (1993). Both materials improve the efficiency of Trombe walls, covered until now with simple or double glazings.

In the active system, a transparent cover forms a solar air collector on the roof (Fig. 1), either with a 5 cm Okalux capillary structure or with 16 mm of triple-wall polycarbonate plates produced by Celair. The warm air is inducted into the dwelling by a controlled fan. The air circulation is also shown in Fig. 1. The flow rate can be varied between 1 and 2.5 ACH. In practice, and after predictive calculations, a flow rate of 1.5 ACH, corresponding to 480 m^3/h, was adopted. A higher value does not significantly increase the performance, but leads to draught and noise. The control system allows the air to flow if the collector temperature is higher than the dwelling temperature plus a differential (which can be set between 0 and 20 K). A thermostat switches the fan off if the inside temperature becomes too high. In summer, the fan is off and the collector is ventilated by two openings. The opaque insulation (16 cm rock wool) protects the rooms underneath the collector against overheating.

The passive system is made of "Trombe–Michel" walls (Fig. 2) which are mounted on the south façade of the houses. They comprise four layers: a transparent cover, a masonry wall, an air gap, and an opaque in-

Table 1. Physical values for the two types of transparent covers considered

Material	Heat loss factor $W\ m^{-2}\ K^{-1}$	Transmission of solar radiation (diffuse-hemispherical)
10 cm encapsulated capillary structure	0.8	0.67
16 mm polycarbonate plate	2.4	0.64

sulation. The external transparent cover transmits solar radiation in, but holds back heat. The brick wall is 11 cm thick and painted black at its outer surface to act as an absorber. It stores heat from the day and releases it with a time delay to the air layer between this wall and the opaque insulation. The air is heated in contact with the brick wall and rises and circulates toward the room (the louvers are open in the winter during good weather periods).

In summer, the louvers are closed by the inhabitants. The internal opaque insulation layer prevents overheating as the air circulation is stopped when the louvers are closed. This is an alternative to sophisticated shading devices.

All houses are wooden framed, with a good insulation (20 cm of glass wool in the loft and 10 cm in the walls). The cost of a reference house is \$67000 (for two 50 m^2 stories). The solar overcost (see Table 2) ranges from \$5000 (passive system, Celair cover) to \$9000 and \$16000 (active system, Celair, and Okalux components). The houses are constituted by modules, produced in a fabric, and transported by truck: The wallpaper, sanitaries, convectors, etc, are already installed when the modules arrive on the building site.

The social housing company Espace Habitat has been supported by ADEME which financed 50% of the overcost. The most inexpensive solar houses, even without financial support, can be built within the cost limit corresponding to social housing; usually \$720 per m^2 of living area (see Table 2).

2.2 *First predictive simulation results*

The simulation tool Comfie developed by Peuportier and Blanc-Sommereux (1988) has been used in order to compare various possibilities during the design:

- transparent cover (single or double glazings, polycarbonate plate, 5 or 10 cm capillaries);
- thickness of masonry wall (concrete, brickwork of 5, 11, 16 cm);
- wall colour (light or dark brick, black);
- control of the active system, air flow-rate.

Simulations were performed over a heating season, the climate considered is the Short Reference Year (SRY; Lund, 1985) of Nancy (SRY): 8 typical weeks, 2 per season. It is assumed that there is no air leakage in the air collector and that the control system functions correctly. The first measurements showed that, in fact, the air collector is not airtight, though the construction was carefully done. Further simulations will be performed to study this effect, which corresponds to a preheating of ventilation air. According to these predictive simulation results, the annual heating consumption is reduced and the solar fraction can reach 30–45% according to the system (cf Table 3). The electricity saved would have been produced partly by nuclear plants, but also by coal power plants during the peak hours, with a low efficiency and high CO_2 emissions. Under these local conditions, the solar contribution avoids the emission of 2 tons of CO_2 per year and house (average value for the six houses).

The performance of the passive system is partly reduced because the radiative heat transfer is stopped by the internal double wall, but the advantage is that overheating can be avoided without a shading device. Also, the very low inertia of the houses reduces the utilizability of solar gains. Masonry walls, particularly in the active system, could improve the thermal performance, concerning both the heating season (increased utilizability of solar gains) and the summer (damping of overheating). But thermal inertia is difficult to achieve with industrial wooden construction.

The simulation also showed a risk of discomfort in summer. This risk is due to the very low inertia of these wooden houses and not to the solar heating itself. Inhabitants can solve this problem by proper management of venitian blinds and night ventilation.

3. MONITORING

The experimental follow-up allows one to check the predicted performance and to study the accept-

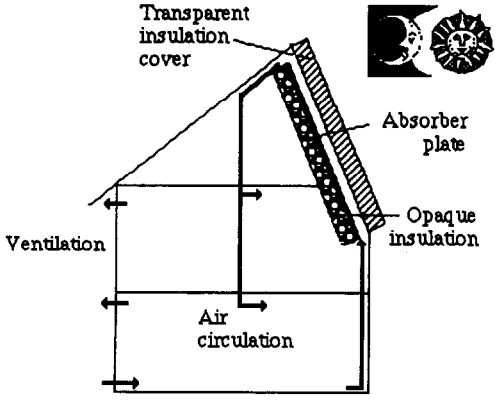

Fig. 1. Active system, air collector.

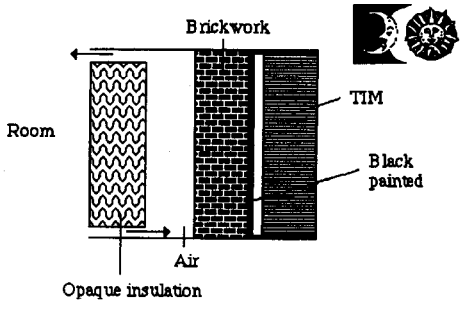

Fig. 2. Passive system, Trombe wall.

Table 2. Cost for each system in 1992 dollars*

Configuration (2×50 m^2 living area)	Solar overcost	Total cost	Cost per m^2 of living area
Trombe wall, polycarbonate	5,000	72,000	720
Trombe wall, 10 cm OKALUX	12,000	79,000	790
Active system, polycarbonate	9,000	76,000	760
Active system, 5 cm OKALUX	16,000	83,000	830

* 1$ 1992 was 6 FF and around 0.9 ECU.

ability and management of the systems by inhabitants. The data acquisition was connected to the phone and the measurements were accessible by Ecole des Mines and the Technological University Institute of Longwy. The CSTB provided technical assistance.

The monitoring system has been working from the end of May 1992 to the beginning of June 1993. The collected data has been used for an evaluation of the summer comfort. We also studied a week in the autumn and another week in the winter. Finally, a global performance assessment was obtained by the analysis of the whole heating season.

3.1 *Summer results*

The comfort temperature limit is often reached during normal hot periods (30°C outside, 27–28°C inside). This is due to the very light construction (wooden walls, wooden floors) and not to the solar systems: The temperature difference between the north and south rooms is lower than 1 K. The comfort can no longer be guaranteed during exceptional days (with outside temperatures above 30°C). On the other hand, the advantage of this very low inertia is that the houses can be quickly refreshed after sunset.

Attention was paid to the highest absorber temperature occurring in the solar systems to be sure that the limit admissible for the polycarbonate (130°C) would not be reached. The measurements showed the highest absorber temperature to be 105°C for the active system and 80°C for the passive. The polycarbonate temperature is lower. The polycarbonate materials are guaranteed by manufacturers for 10 years under proper conditions. Previous projects using such materials as transparent covers have shown a satisfying durability. In addition, the quality of products is improving, particularly concerning U.V. protection. Previous experience with Trombe walls shows that the brick wall can also stand the temperature fluctuations without damage.

3.2 *Autumn results*

We studied in detail the period from October 25 to November 1, 1992 (Fig. 3). There were 3 cloudy days, followed by 4 sunny days and one overcast day at the end. Therefore, this period is a good representation of the possible mid-season weather situation. The ambient outside temperatures at the beginning of the period ranged from 5°C (night minimum) to 12°C (day maximum). They then dropped to −2°C and +3°C during the last day.

The active system constitutes a real heating system when the weather is good. Then, the absorber temperatures can reach 43°C for the polycarbonate plate (PC) and even 52°C with the transparent insulation (TI) component (Fig. 4). The system does not work during bad weather, because the temperatures are not higher than 25°C. They drop at night to 3°C, even dropping to freezing the last two nights. The inside temperatures of the houses oscillate between 15°C and 25°C, depending on the solar irradiation and on the heating thermostat set point, which is chosen by the inhabitants.

The solar contribution is not so obvious for the passive systems, because the walls stock the solar gains from the day to the night. Therefore, there does not exist a significant flow rate of heated air such as in the active systems. The temperature at the absorbing surface of the collector can reach 47°C and even 64°C with transparent insulation components (Fig. 5). The heat is stored in the brickwork and, therefore, the temperature in the air gap remains temperate, between 15°C and 25°C. Energy savings are thus achieved as the heating losses are reduced. When the temperature is higher in the Trombe wall than in the room, a natural air circulation is established (if the louvers are open). When the louvers are closed, the maximum temperature in the inner air gap of the Trombe wall was 45°C in summer, and the opaque insulation protected the dwelling from a high heat flux.

3.3 *Results during the coldest period*

We analysed the week from December 31 to January 7 1993. The first 4 days of this period were sunny and the temperature dropped to −12°C. The next 2 days were unsettled and the last 2 were very cloudy with increased temperatures (between 5°C and 7°C).

Table 3. Comparative simulation results for the different systems

Configuration (2×50 m^2 living area)	Heating load (kWh/a)	Load per m^2 (kWh.m^{-2}/a)	Solar fraction
Trombe wall, polycarbonate	7,700	64	31
Trombe wall, 10 cm OKALUX	7,000	58	35
Active system, polycarbonate	6,000	50	40
Active system, 5 cm OKALUX	5,300	44	44

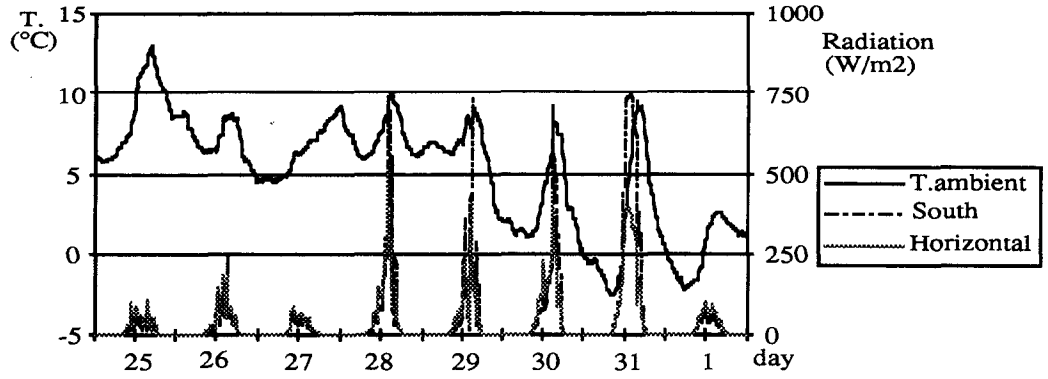

Fig. 3. Autumn climate conditions in Mouzon, October 25–November 1, 1992.

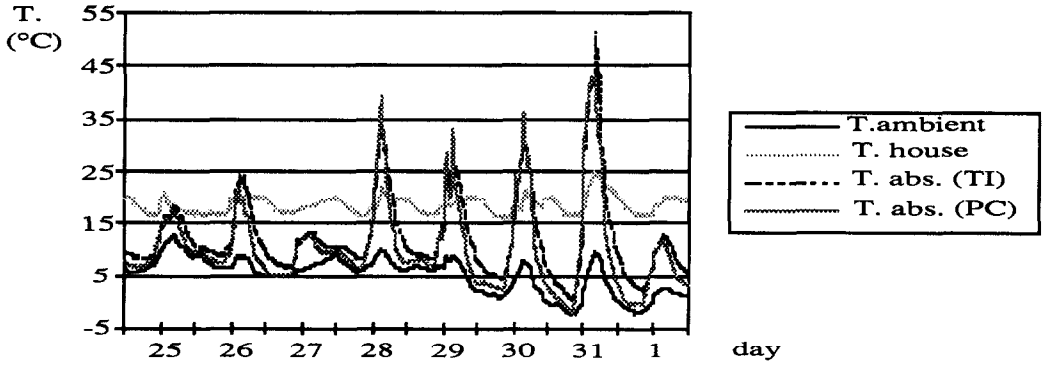

Fig. 4. Absorber temperature in the collectors of the active system, October 25–November 1, 1992.

The absorber temperature of the active system rose to 30–35°C during the first 4 days (when the fan was on), to 25°C during the fifth day, to 20°C at the sixth, and then it stayed at about 10°C during the two cloudy days (the fan remained off). The room temperatures varied, depending on the control chosen by the inhabitants. The fan was on between 12 o'clock and 18 o'clock during the sunny days. Even during this cold period, the energy used for heating purpose was greatly reduced. On the contrary, the fan did not work during the cloudy days because the air temperature was too low in the collectors.

the level of the black painted surface) at the same period reaches 55°C using the capillary structure and 40°C using the polycarbonate plate. An examplary heating load profile is given in Fig. 6 below.

4. COMPARISON BETWEEN MEASUREMENTS AND PREDICTIONS

The heating loads, measured by electricity meters, have been integrated over a whole heating season. They are compared in Table 4 with the predictions obtained by simulation. The discrepancies between measures