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 one 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 cheaper cover, transparent insulation increased of 25% the productivity of the air collectors, and doubled the gain of the Trombe wall. Thanks to passive or active controls, the thermal comfort was not reduced by the solar systems, neither 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 life time, 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 our bondary conditions, concerning energy but 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

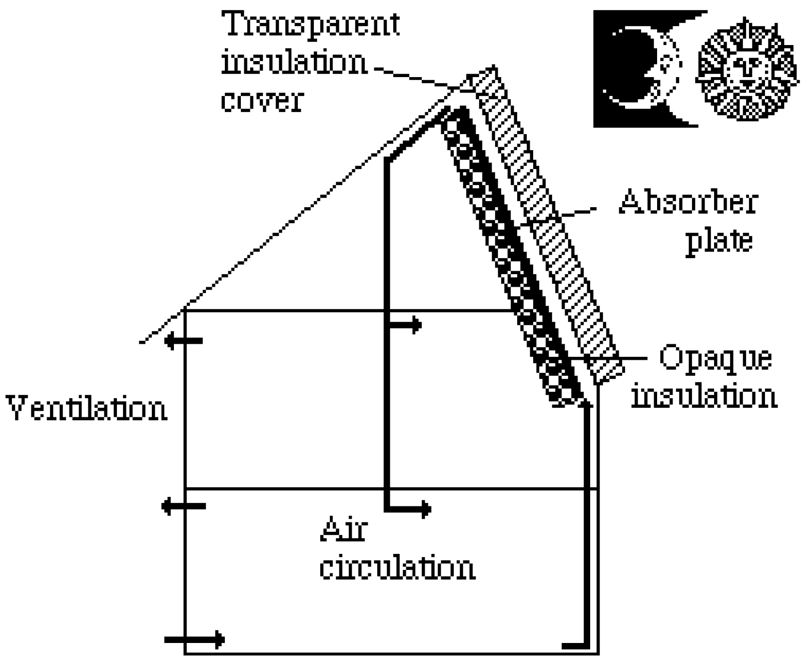
Four houses were already built some years ago on the site by Jacques Michel (1971), with a traditionnal masonry construction. This solar housing estate called "Aurore", situated in Mouzon, acts as a regional demonstration project for solar heating. The owner of the present project is the social housing 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 each 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 and 1992) and Leslie Jesh (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.

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

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.

FIGURE 1. Active system, air collector



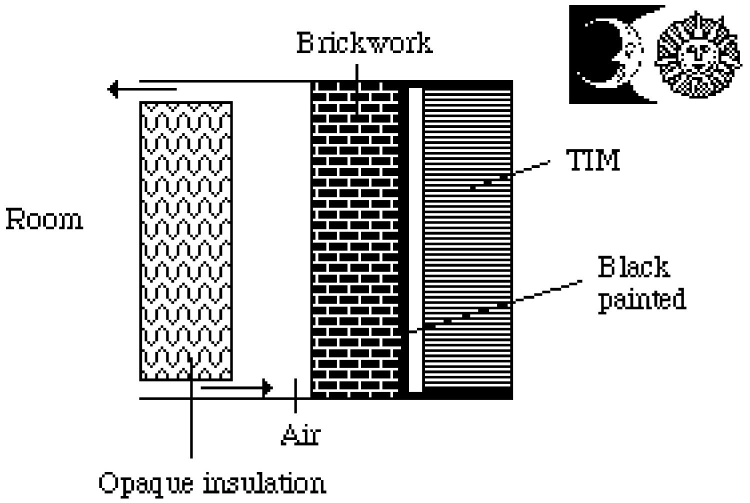
In summer, the fan is off and the collector is ventilated by two openings. The opaque insulation (16 cm rock wool) protects the rooms underneath the collector against overheating.

The passive system is made of "Trombe-Michel" walls (Fig. 2) which are mounted on the south façade of the houses. They comprise 4 layers : a transparent cover, a masonry wall, an air gap and an opaque insulation. 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, rises and circulates towards the room (the louvers are open in 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 storeys). 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 in when the modules arrive on the building site.

FIGURE 2. Passive system, Trombe wall



The social housing company ESPACE HABITAT has been supported by ADEME which financed 50% of the overcost. But the cheapest solar houses, even without financial support, can be built within the cost limit corresponding to social housing, they cost 720$ per m^2 of living area (see table 2).

Table 2 : cost for each system in $ 1992 (*)

configuration (2 x 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

2.2 First predictive simulation results

The simulation tool COMFIE developed by Peuportier and Blanc Sommereux (1988) has been used during the design 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 (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 to 45% according to the system (cf table 3). This avoids to reject 2 tons of CO_2 per year and house (electric heating with fuel or coal power plant during the peak hours).

Table 3 : comparative simulation results for the different systems

configuration (2 x 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

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 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 showed also a risk of discomfort in summer. But 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 a propper management of venitian blinds and night ventilation.

3 MONITORING

The experimental follow-up allows to check the performance predicted and to study the acceptability 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 a technical assistance.

The monitoring system has been working from the end of May 1992 until the beginning of june 1993. The collected data has been used for an evaluation of the summer comfort. We also studied a week in autumn and one during 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°C to 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 not 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 sun-set.

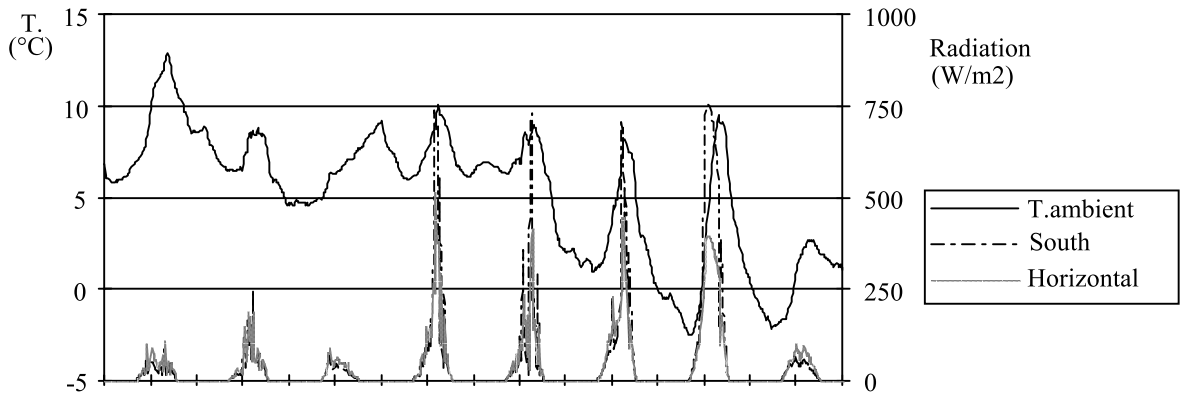
Attention was paid to the highest absorber temperature occurring in the solar systems to be sure that the limit admissible for the polycarbonate (130°C) will not be reached. The measurements showed the highest absorber temperature to be 105°C for the active system and 80°C for the passive one, and the polycarbonate temperature is lower. The polycarbonate materials are guaranteed by manufacturers for 10 years under propper conditions. Previous projects using such materials as transparent cover have shown a satisfying durability, and 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

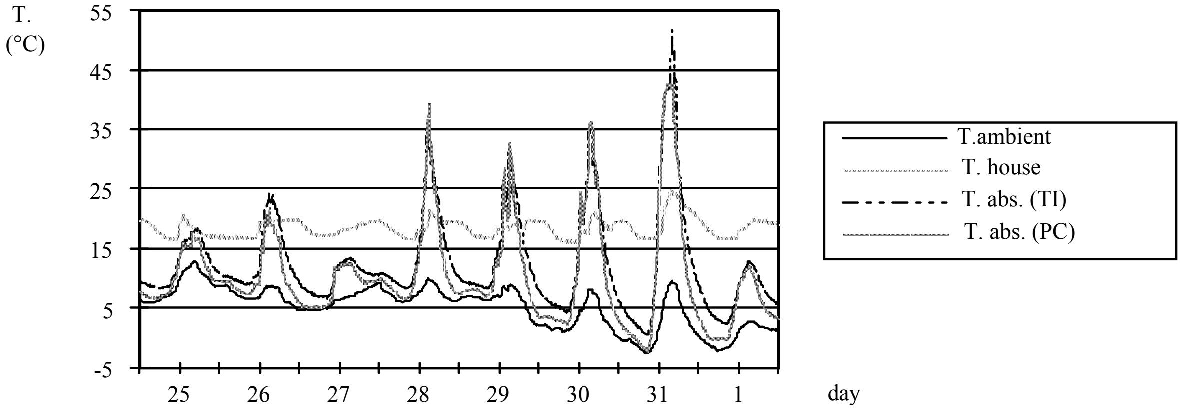
We studied in detail the period from October 25th to November 1st 1992 (Fig. 3). First, there were three cloudy days, followed by 4 sunny days and one overcast day at the end. Therefore, this period is a good representation of the possible weather situations during mid-season. The ambient outside temperatures at the begining 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.

FIGURE 3. Autumn climate conditions in Mouzon, 25/10/92 - 01/11/92



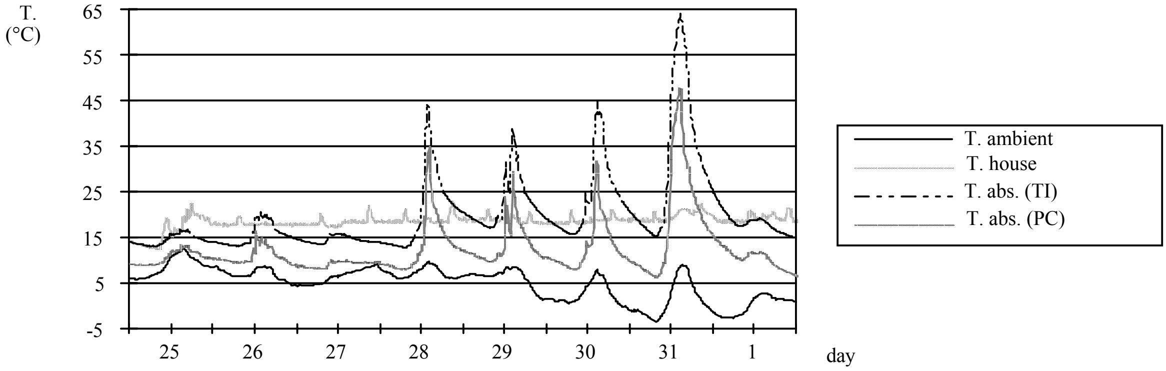
The active system constitutes a real heating system when the weather is good. Then, the absorber temperatures can reach 43°C for the polycarbonate plate (PC) and even 52°C with the transparent insulation (TI) component (Fig. 4). The system does not work during bad weather, because the temperatures are 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.

FIGURE 4. Absorber temperature in the collectors of the active system, 25/10/92 - 01/11/92



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 like 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).

FIGURE 5. Temperatures in the Trombe wall of the passive system, 25/10/92 - 01/11/92



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.

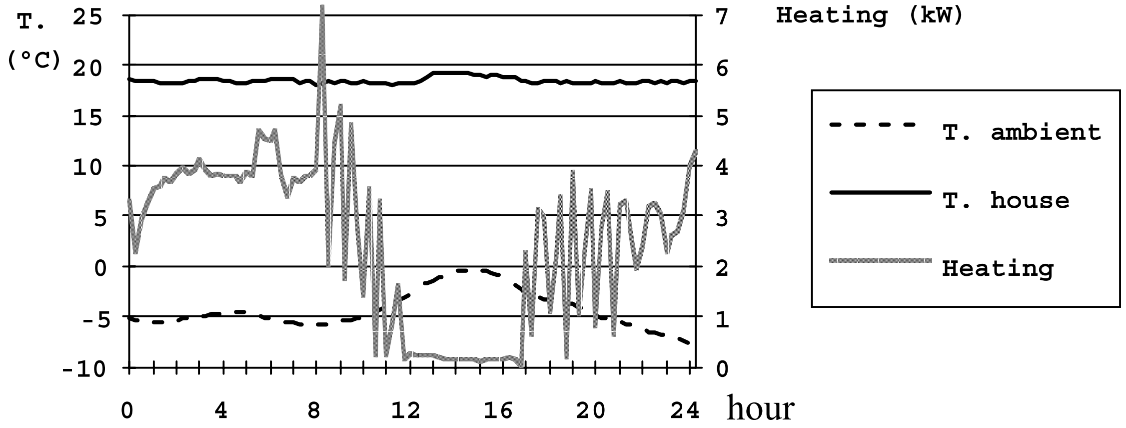
3.3 Results during the coldest period

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

The absorber temperature of the active system rose to 30°C - 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.

Concerning the passive system, the temperature between the brick wall and the transparent cover (at the level of the black painted surface) reaches at the same period 55°C using the capillary structure and 40°C using the polycarbonate plate. An examplary heating load profile is given in Figure 6 below.

FIGURE 6. Reduction of the heating load in a passive house during a cold but sunny winter day (02/01/1993)



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 and predictions are mainly caused by the occupants behaviour. First the simulations were performed assuming a constant 19°C thermostat set point and a SRY (Short Reference Year, see § 2.2) for Nancy (66,540 degree hours). The actual climate was slightly different (65,880 degree hours). In the reality, some people stop the heating while they are working during the day and lower the set point at night and in the bedrooms. This is shown by the actual degree hours column. Some occupants have stopped the mechanical ventilation, which would have provided a constant 0.6 ach air renewal. The corresponding load is 3,500 kWh per year (for a constant 19°C inside temperature). The management of shading devices or Trombe wall louvres as well as the internal gains for lighting etc. may also explain certain discrepancies. Finally, the physical assumptions of the model and the uncertainty on parameters produce supplementary errors.

Table 4. Measured and predicted energy consumption on a heating season

house	measured consumption (kWh)	predicted consumption (19°C)	actual mean temperature	actual degree hours
3 (passive, TIM)	3,560 (1)	7,000	16.32	52,496
3 bis (passive, PC)	8,218	7,700	18.97	65,787
4 (active, PC)	3,050 (1)	6,000	18.51 (2)	(2)
5 (active, TIM)	4,685	5,300	18.64 (2)	(2)
7 (passive, TIM)	7,037	7,000	18.75	65,255
9 (passive, PC)	5,051	7,700	16.74	55,107

(1) The mechanical ventilation was stopped in this house, it would add a 3,500 kWh heating load.

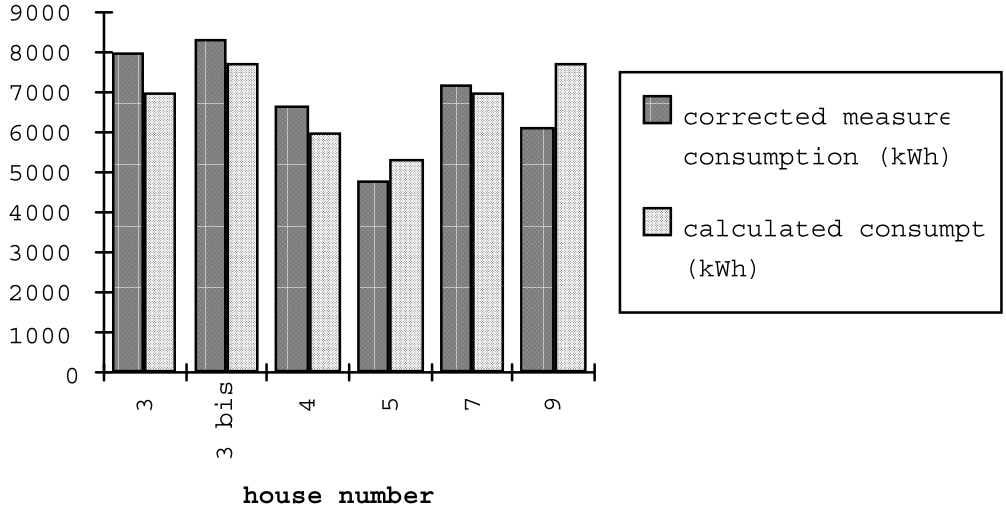
(2) 6 weeks are missing due to technical problems, this does not concern the electricity meters.

In order to compare the different systems, it is necessary to eliminate the effect of different users behaviour. Simulation allows to perform such an analysis, provided that some parameters (e.g. thermal bridges) are identified or corrected. The methodology adopted is the following. We decided to study in detail the coldest week, during which it is assumed that the occupants do not open windows or doors for a long time, air being renewed by the mechanical system. Thermal bridges through collector frames were identified during the cloudy period of this week, when solar gains are negligible. The product of the transmission factors of transparent covers by the absorption factor of the absorber was slightly modified in order to meet the measured temperature profile during sunny days. There remains a temperature difference during clear nights due to insufficient modelling of radiation towards the sky.

This parameter identification was then checked during another week, in mid-season. The agreement was rather good, except for one day during which we suppose that condensation was particularly important.

Using this corrected model, we simulated all systems using the same occupancy pattern as in the predictive calculation : a constant 19°C set point temperature, a constant 0.6 ach air renewal and constant 400 W internal gains. The heating loads obtained on a typical year (SRY) were quite similar to the predicted values. Measured heating consumption were also corrected in terms of the measured degree days, assuming a linear dependence. Also, the load corresponding to mechanical ventilation was added in the houses where occupants had stopped this system. Comparative results are presented in fig. 7. According to the social housing company, the mean heating load in the region for such detached houses is typically 10 to 11,000 kWh.
Concerning active systems, the electricity consumption of the 100 W fan, functionning only during sunny hours of the heating season, is less than 200 kWh.

FIGURE 7 : Comparison between measured and calculated heating consumption after correction



Both calculations and measurements give an advantage to the active systems (houses 4 and 5), for which the solar fraction reaches 40%. But these systems need a maintenance twice a year. In may, the collectors are to be naturally ventilated from outside and the inside air circulation must be stopped. In october, the system must be set in winter position, and the control system must be checked. On the contrary, passive systems need no maintenance.

ACKNOWLEDGEMENTS

The French Agency for Environment and Energy Management (ADEME) supported this project by financing half of the solar overcost and of the monitoring. ESPACE HABITAT, Jacques Michel and HOUOT have kindly taken the risk to test a new technology. The patience of the occupants of the Aurore solar estate was requested during the installation and monitoring of the system. EdF kindly provided electric meters. The technicians of CSTB have shown much expertise and efficiency. CELAIR and OKALUX gave useful advice concerning the application of the materials. At last, we would like to thank Isabelle Grieder (Technology Institute of Longwy) and Bernd Polster for their useful and kind contribution.

CONCLUSIONS AND PERSPECTIVES

The solar systems tested here showed their effectiveness : compared to the cheaper cover, transparent insulation increased of 25% the productivity of the air collectors, and doubled the gain of the Trombe wall. There has not been any particular problem during the installation of transparent insulation on the site, because the components were encapsulated and thus protected from dust and water. Though, we have seen some condensation on both materials, which reduces a little the transmission in the morning. The aesthetical aspect is better than using glazings on Trombe walls, because the façades are not as black.

We are discussing with the French Ministry of dwelling if it is possible to finance a gas heating over the maximum price imposed for social housing. This would allow to choose a more economical and less polluting heating system. The corresponding overcost would be very rapidly recovered. In our active system, a back up heating on the air flow would perhaps be an interesting possibility.

The thermal performance could be improved by increasing the inertia of the houses, but the wooden frame concept would then have to be replaced by a concrete masonry. This could also reduce the overheating problems, which are not due to the solar systems but to the low inertia of the houses. On the other hand, wood is a renewable material which corresponds to the sustainable development approach. The present industrial process allows to produce low cost solar houses with a good thermal performance : in the rather unpromising climate considered, the annual heating load ranges from 45 to 65 $kWh.a^{-1}.m^{-2}$ living area.

This project has shown that solar energy is also accessible to low income families. New technologies allow to achieve high solar fractions (30 to 45%) within the cost limit of social housing. We hope this work will contribute to improve the environmental quality in the building sector.

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