Active solar heating system with concrete plate heating analysed with dynamical thermal simulations

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Abstract

A single family house is planned on the south side of the Alps with the objective of integrating renewable energies in the heating design. Several ways of decreasing the thermal needs of the house are analysed. They involve the building envelope, ventilation system with heat recovery and an active solar heating system coupled to the active concrete plates of the house.

The dynamic simulation programme TRNSYS is used to simulate the house, the active concrete plates and the solar heating system together. Dynamic simulations are used to confirm the technical feasibility of the studied concept, to check the thermal comfort and to establish the thermal potential of the solar heating system.

The effective over-cost associated with each measure is assessed, which also takes into account the increase in price of auxiliary heat. From the economic point of view, a “solar heating system” measure is equivalent to a “solar passive” measure.

Introduction

A single family house is planned in Tenero (south side of the Alps, Tessin, Switzerland), with the objective of integrating renewable energies into the heating design. The strategy is to decrease the thermal needs of the house, so that its concrete plates can be “activated” for heating purposes. A prerequisite is that the structure of the house is heavy. In particular the floors should be made of concrete plates whose thickness is about 20 cm. This is often the case in Tessin. An “active plate” is a concrete plate in which pipes have been fixed for the circulation of a heat carrier fluid. It is a heat emitter with a very large heat capacity, much greater than that of a floor heating system. Active concrete plates can serve as heat storage for a solar heating system. They are connected directly to the solar collectors (via a heat exchanger). The water tank storage used for hot water does not need to be enlarged, thus saving space and investment costs. This is an advantage when the space available in the house is a problem for technical utilities. A significant solar fraction of space heating and hot water demands can be reached without the need for a large water tank.

Such a solution requires dynamic thermal simulations of the whole system, house included, in order to assess the feasibility of the system concept and learn about its thermal behaviour. In particular, heating is characterised by a very large thermal inertia and a low specific thermal power. It conditions the house design and its heating requirement. Dynamic system simulations are also indispensable to check thermal comfort conditions and assess system thermal performances. They also help for the system sizing and control.

Based on the house project and site climate, the main objectives of the study are to:

- develop a simulation tool of the solar heating system coupled to the house;
- establish a list of prerequisites to make active concrete plate heating possible;
- assess the active solar heating potential of solar collectors coupled to active concrete plates (in a climate characterised by dry and sunny weather conditions in winter);
- assess and compare the economic aspect of several measures devised to decrease the auxiliary energy requirements of the house.

Simulation tool

The dynamic TRNSYS simulation programme (Klein and al., 2000) is used to construct a thermal calculation tool. It simulates the house, the concrete active plates and the solar heating system together (Pahud and Travaglini, 2000). A simple system control concept is developed to ensure that the house temperature remains within limits for satisfactory thermal comfort (which corresponds to a maximum predicted percentage of dissatisfaction of 10%). Provided that the house can be entirely heated with active concrete plates, simulations confirmed the technical feasibility of the system concept. They showed the importance to controlling independently the active solar system from the auxiliary heater. The task of the auxiliary heater is to maintain the house temperature just above the lowest permissible values. With the solar heating system, the system control has to prevent the house temperature from exceeding the maximum tolerated values. A simplified drawing of the system design is shown in figure 1.

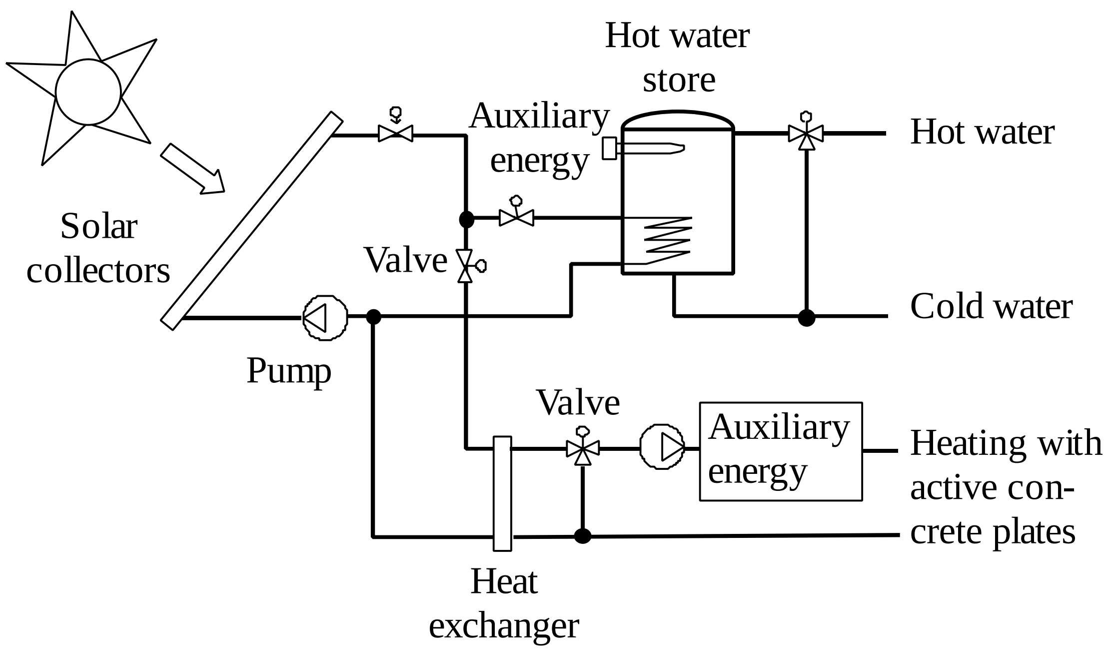

Figure 1 Drawing of the active solar heating system layout.

Thermal characteristics of the house

The house is built on two storeys that totalise a heated floor area of 240 m^2 (external dimensions). The main façade, oriented south-southeast, has an area of 100 m^2, of which 20 m^2 are windows. The ratio between the total window area over the heated floor area is 0.14. The house lies at the bottom of a wide east-west orientated valley at an altitude of 220 m. The situation is open from the point of view of solar radiation. The annual global solar radiation on a horizontal plane is measured at 1'200 kWh/m^2. The monthly average outdoor air temperature varies between 2 and 21 °C, with an average annual value of 11°C.

Heating with active concrete plates differs from floor heating in the fact that pipes are fixed directly in the concrete plate and not in the light-weight concrete layer that covers it. Heat emission takes place mostly through the ceiling rather than the floor. A previous study has shown that an optimal solution is a concrete plate thickness of about 20 cm with pipes positioned in the middle (Fromentin et Sujevs, 1996). The heat transfer coefficient between the heat carrier fluid and the heated zone is in practice about 4 W/m^2K (pipe spacing of 20 cm in the concrete). In order to make concrete plate heating possible, building envelope and active concrete plate area have to be designed so that heating is ensured with a specific thermal power of 20 – 30 W per square meter of active concrete plate. As a result, heating can be achieved with fluid temperatures lower than 30°C. The advantage is the "auto regulation" property: heat emission can be stopped or even inversed when heat gains are generated in a room. When possible, there is one more level of active concrete plate than storeys, so that every storey can be "sandwiched" between the active concrete plates. In the case of this house, this is not possible for the first floor. The alternative is to activate concrete walls.

Thermal needs of the house can be calculated once the house envelope, the air change rate, the internal gains and the weather conditions are defined. Type 56 of the TRNSYS programme, configured to simulate the house, is used to both calculate the annual heating energy demand and the design thermal power of the heating system (the design outdoor air temperature is -2°C for heating). Thermal insulation is placed on the outside of the building envelope, in order to make the reduction of thermal bridges easier and keep the thermal mass inside.

Two cases are defined; the first one, called "*standard*", corresponds to the level of insulation which conforms to the 1988 Swiss building code[1] (SIA 380/1, 1988). The "*active concrete plate*" case is defined to make heating with active concrete plate possible. The total area of active concrete plate is, in the case of the house studied, limited to a maximum of 220 m^2. Contrary to the standard variant, a two-flow ventilation system with heat recovery is foreseen. This is also an advantage in controlling humidity problems and pollutant concentrations that arise from the air-tight envelope of a low energy house. The characteristics of the house are shown in table 1 for both cases.

[1] Requirements of the building code changed in 2001. The trend is toward improved building envelopes, improved thermal comfort and lower heating energy demand.

Parameter	"*Standard*" case	"*Active concrete plate*" case
Insulation thickness: roof / external walls / walls and floors in contact with ground	10 cm / 10 cm / 5 cm	20 cm / 15 cm / 10 cm
Window U-values	2.8 W/m^2K	1.3 W/m^2K^*
Ventilation system with heat recovery	No (0.4 h^{-1})	Yes (0.2 h^{-1} **)
Annual energy demand for space heating	72 kWh/m^2an	28 kWh/m^2an
Heating power	8 kW	5 kW
per m^2 heated area	33 W/m^2	20 W/m^2
per m^2 active concrete plate (160 m^2)	50 W/m^2	31 W/m^2
per m^2 active concrete plate (220 m^2)	36 W/m^2	23 W/m^2

* selective double pane window with Argon filling ; U-value including frame.

** the equivalent air change rate for ventilation heat losses is decreased by a factor of 2 relative to the case without ventilation system. One assumes a heat recovery factor of 2/3 with the ventilation system, and an air change rate of 0.1 h^{-1} caused by air infiltrations through the house envelope (0.1 h^{-1} + (1-2/3) x 0.3 h^{-1} = 0.2 h^{-1}).

Table 1 Thermal characteristics of the house for the two cases and corresponding annual heating demand and heating power.

Dynamic system simulations

In figure 2, the thermal behaviour of active concrete plate is best illustrated. The house with the "active concrete plate" characteristics is simulated with a solar collector area of 15 m^2 for hot water and space heating. The window area in the south-southeast façade is, as previously mentioned, fixed at 20 m^2. Passive solar gains generated in the house are shown with the dashed line. The dotted line shows the heating thermal power injected in the concrete plates which results from the circulation and cooling of the heat carrier fluid. During the last day shown in the graph (the 18th of February), the auxiliary heater is switched on as solar gains are not sufficient to keep the house indoor air temperature high enough. Although active solar gains are injected in the concrete plates at the same time as passive solar gains are collected, the concrete plate heat emission is stopped and even inversed by these latter. It means that passive solar gains are also stored in the concrete plates although active solar gains are injected in them. This illustrates the auto-regulating thermal behaviour of active concrete plates. It should be noted that the forward fluid temperature in the concrete plate flow circuit did not exceed 30°C, whereas the return fluid temperature remained below 24°C. Another advantage of the large heat capacity of concrete plates is that injection of large active solar gains during a short period of time results in a low and constant thermal power emitted in the house.

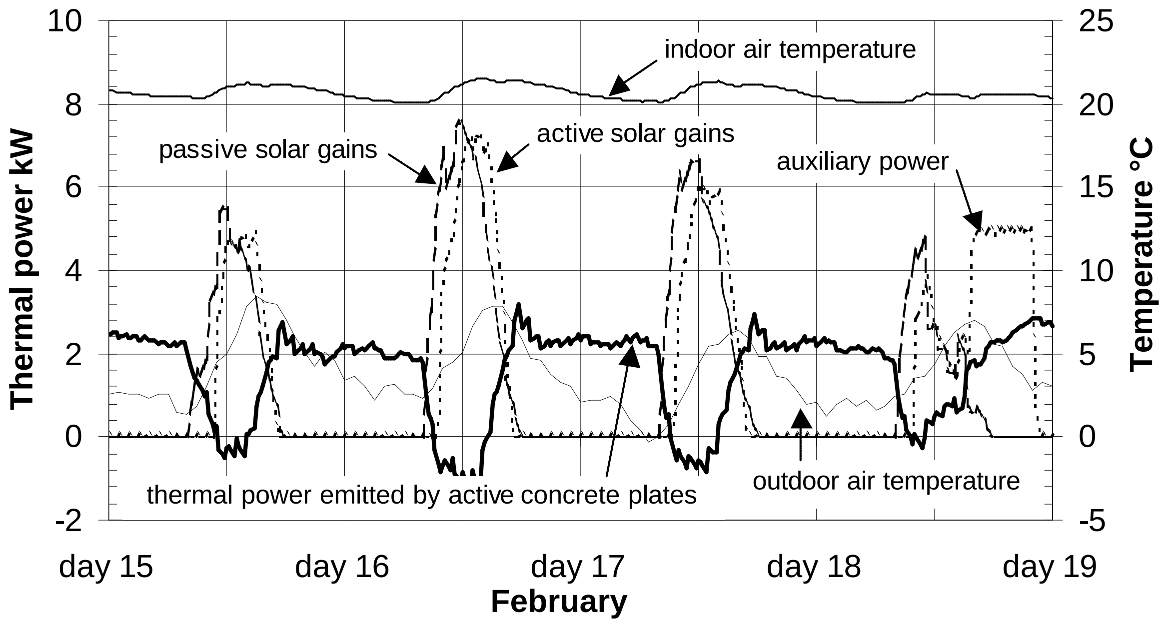

Figure 2 *Dynamic thermal behaviour of active concrete plates. Passive solar gains can stop and even inverse heat emission from active concrete plates. Active solar gains injected inside the plates are emitted in the house throughout the day.*

Reduction of the auxiliary heating energy

The case "active concrete plate" (see table 1) is taken as a reference for simulations. The lowest active concrete plate area (160 m^2) is selected. Thermal performances of the solar heating system with the greater area (220 m^2) barely improve. It shows that active concrete plates have to be sized primarily for space heating. In figure 3, the reduction potential of auxiliary energy for space heating is shown for both active solar heating and passive solar gains. The space heating solar fraction is defined in terms of auxiliary energy reduction. The "zero" solar fraction is set by the reference case. This latter is characterised by 20 m^2 of window area in the south-southeast façade and 5 m^2 of solar collector solely used for hot water.

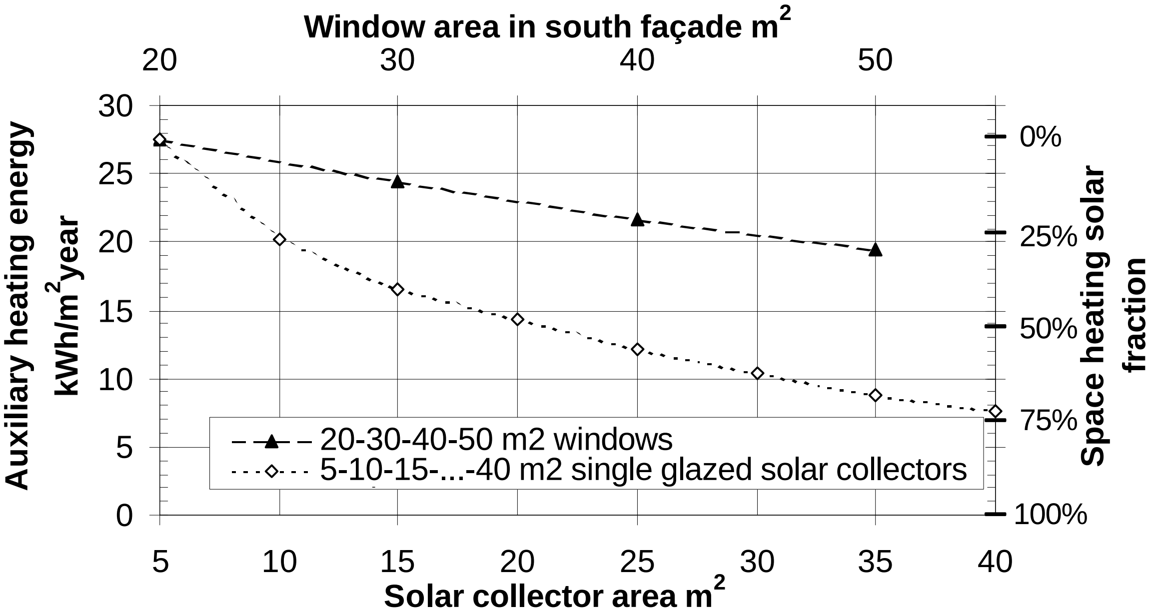

Figure 3 *Active and passive solar potential assessed in terms of space heating auxiliary energy reduction.*

The hot water solar fraction is about 65% up to a collector area of 20 m^2, and tends to increase up to 80% with a collector area of 40 m^2. Without space heating, the solar hot water system is sized for 5 people (1 m^2 per person).

It can be seen from figure 3 that 5 m^2 of additional solar collectors is equivalent to 25 – 30 m^2 of additional windows in the south façade. Simulations with unglazed solar collectors show the same equivalence with 10 m^2 of additional solar absorbers. These equivalences allow us to select the most advantageous option in relation to its respective cost. However the economic criterion is not the only one and the final choice is conditioned by factors such as architecture, durability, maintenance, etc. Nevertheless, the auxiliary heat reduction potential is greater with an active solar heating system.

Over-cost estimation

Over-cost, or more precisely additional investment estimation for each measure is required for an economical analysis. Considering the great variability of cost estimation, results presented in this study have to be considered with prudence. Lifetime associated to each measure is based on indications given in the Swiss Ravel programme (Ravel, 1997).

The starting point for evaluating a combination of measures is the “standard” case (see table 1), whose annual heating demand is calculated to 72 kWh/m^{2}year. The heating energy demand is covered by an oil burner whose annual mean efficiency if fixed to 85%. Hot water demand is covered by an electric boiler . The electric energy consumed by the electric hot water boiler amounts to 18 kWh/m^{2}an. The space heating and hot water energy index of the “standard” house is calculated to 103 kWh/m^{2}an.

The auxiliary energy saving measures are evaluated in the following order:

A. Improved building envelope and ventilation system. The ventilation system is without heat recovery. The main functions of the ventilation system are to guarantee a good indoor air quality and control humidity related problems.

B. Heat recovery on the ventilation system. The measures A + B correspond to the "active concrete plate" house (see table 1).

C. "Solar Kit" for hot water heating. Hot water is heated with 5 m^2 of single glazed solar collectors.

D1. Solar collectors coupled to active concrete plates. The collector area is increased from 5 m^2 to 15 m^2 to satisfy space heating requirements as well (see system layout in figure 1).

D2. Additional windows. Instead of increasing the solar collector area (D1 measure), the window area in the south-southeast façade is increased from 20 to 40 m^2.

According to practical experience, the cost of active concrete plates is equivalent to that of a floor heating system (Cornu, 2000). In consequence, no over-cost is counted for active concrete plates. In figure 4, additional investment for each measure is shown in relation to the energy index of the house.

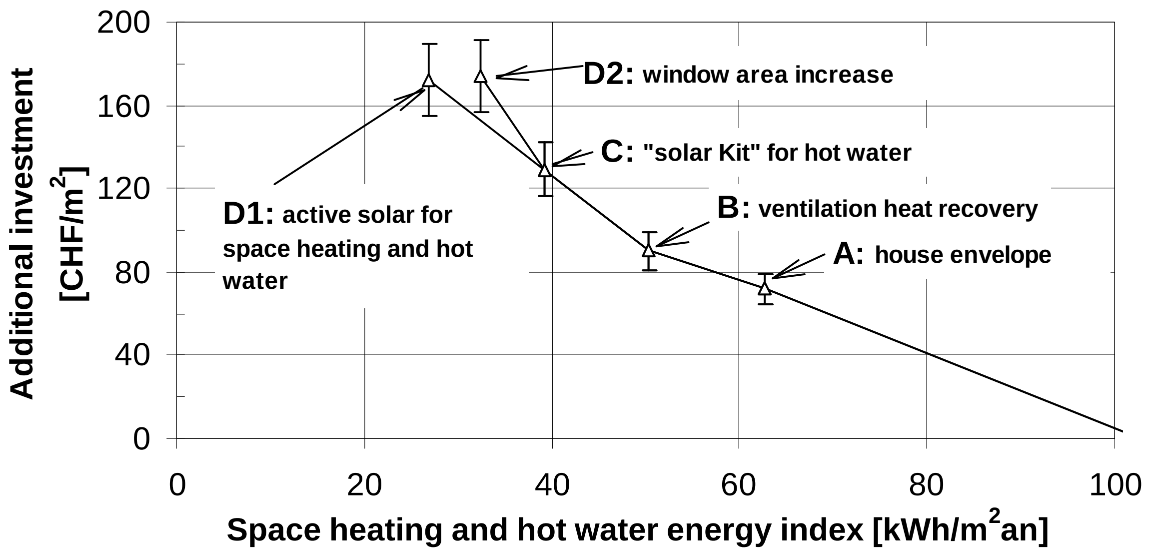

Figure 4 Additional investment per square meter of heated floor area for each measure in relation to space heating and hot water energy index.

The total construction cost of a house is about 2'000 CHF/m^2 (CHF is Swiss francs). The sum of the additional investments, performed up to the two variants D1 and D2, remains inferior to 10% of the total construction cost. The over-cost associated to the active solar heating system (hot water and heating) is less than 5%.

Effective over-cost

Each measure leads to a reduction of auxiliary energy, and thus decreases the energy that has to be purchased every year. The effective over-cost takes into account auxiliary energy savings during the lifetime of a measure. It is formed by the annual capital cost of the corresponding additional investment (annuity), from which is subtracted the annual cost of the auxiliary energy saved. It should also contain the maintenance cost, but is not taken in consideration in this study. As the price of auxiliary energy is increasing with time, the annual saving is also increasing. The mean annual saving becomes more important if the lifetime of a measure is longer. Inflation rate, interest rate and increases in the cost of energy were taken according to recommendations given in the Swiss Ravel programme (Ravel, 1997). The mean effective over-cost is shown in table 2 for each measure. It is calculated according to three scenarios, depending on energy cost increase (electricity and oil). The "maximum" scenario corresponds to the largest increase rates, which, of course, tends to make the measures economically more favourable. No subvention, tax reduction or CO_2 tax were taken into account in the calculations.

Measure / variant effective over-cost in CHF/an	Minimum scenario	Average scenario	Maximum scenario
A : envelope	470	200	-170
B : ventilation heat recovery	260	230	190
C : glazed solar kit (hot water)	60	-50	-160
D1 : active solar heating	720	680	620
D2 : additional windows	730	690	650
Total variant 1 (A+B+C+D1)	1'510	1'060	480
Total variant 2 (A+B+C+D2)	1'520	1'070	510

NB : these numbers have to be considered with prudence. They were obtained with constant inflation, interest and energy increase rates, and thus calculated with exponential functions during time periods up to 30 years (house envelope measure).

Table 2 *Effective over-cost for each measure, taking into account three possible scenarios for the increase in the cost of energy.*

Calculated values in table 2 have to be considered with prudence. In particular, they only show the economic aspect. They do not reflect advantages such as improvement of thermal comfort with better house envelopes, indoor air quality and humidity problem reduction with a ventilation system, the higher mean indoor air temperature with an active solar system, etc. Auxiliary energy should further be reduced with a more sophisticated system control, which would, for example, take into account weather forecast.

Conclusion

The window area enlargement measure (D2) has an additional investment cost which is about the same as the active solar heating measure (D1). Although the auxiliary energy reduction of measure D2 is significantly lower than measure D1, their respective effective over-cost is about the same. This results comes from the lifetime of windows (25 years) which is assumed to be longer than solar collectors (20 years). These measures (D1 and D2) are also the most expensive as they come last on the list of interventions. However, the sum of the effective over-cost for each of the two variants is reasonable, and amounts to about 100 CHF per month. The solar collector measure gives a greater flexibility to the architecture in the sense that the constraint on the window area to be inserted in the south façade is removed.

The most advantageous measure is the “solar kit” for hot water. It also has the advantage of not depending on the realisation of another measure, such as for example the improvement of the house envelope. This is not the case for an active solar heating system coupled to active concrete plates, although this solution significantly reduces the auxiliary heat demand of a low energy house (from 30 to 60%).

Acknowledgements

The Swiss Federal Office of Energy is acknowledged for its financial support. Mr. Cornu is also cordially acknowledged for his interest in this study and his constructive discussions.

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