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CONTROL OF PASSIVE SOLAR SYSTEM

State of the art

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ABSTRACT. Without control high solar fractions are difficult to obtain from Trombe walls, direct solar gains, and rock bins. Integration of all these techniques by control is absolutely necessary. A short review is given of the available sensors, actuators, and control systems. The control of individual solar techniques as well as several combinations are discussed; for instance, the control strategy for the combination of direct solar gains and Trombe Wall. Based on literature general conclusions are given about the energy efficiency of these systems in relation with the control strategy. A more detailed analysis is made of a costeffective simple passive solar system with adjustable window devices such as insulating rolling shutters, shading devices and vent windows. The benefits of modern control such as predictive control are compared with respect to simple and straightforward control strategies. Emphasis is put on the application of controlled ventilation for the maintenance of comfort in summer. Natural ventilation is strongly recommended here because of its passive character. In this paper special attention is given to the various digital control systems designed in a concerted action of the project PASTOR of the commission of the European Communities.

1. INTRODUCTION

High solar fractions are difficult to obtain from Trombe walls, direct gains and rock bins. Moreover their contributions have different dynamics, so that maximum values occur at different moments and do not always coincide with the need for heating.
A successful application can only be obtained when their complementary contributions are synchronized by a control system. For a conventional control system this is a difficult task, because of the complex nature and interactions of the passive solar techniques. Therefore preference should be given to computer based control systems with more advanced control algorithms. In this paper conventional as well as computer control systems are described.

Collecting solar energy is not always advantageous. Problems encountered in passive solar buildings with poor control include overheating. In summer the solar energy system during a succession of hot days forms a big danger for overheating. This problem can be eliminated by cooling with night air. Of course mechanical ventilation can be used for this purpose, but it is more in harmony with the passive solar philosophy to apply natural ventilation by motorized windows. In this paper special attention is paid to natural ventilation and the way it can be controlled.

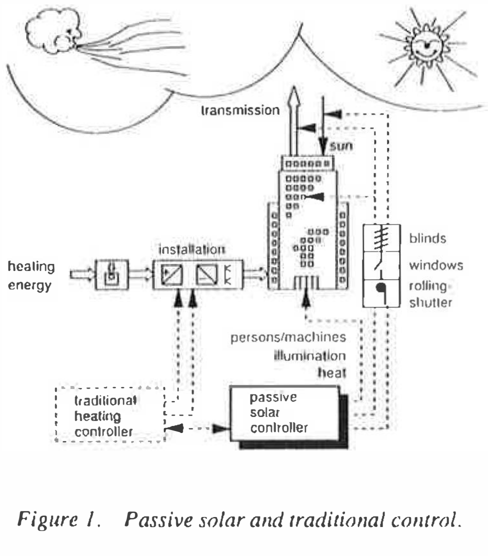

Figure 1. Passive solar and traditional control.

From the above discussion it is obvious that the widespread idea that passive solar systems are self regulating and do not require automatic control is completely wrong. It must be kept in mind that the window is an important factor in the psychological sensation of comfort and that automatic control of window devices is not always accepted by the occupants. Therefore automatic control systems should always have provisions for manual takeover.

In this paper will be discussed: sensors, actuators, control strategies and digital control systems for optimal control. An indication is given of the energy saving and comfort of the various passive solar configurations and their control systems.

2. CONTROL ELEMENTS

2.1 SENSORS

Comfort is the main objective. Consequently comfort should be measured. There are comfort sensors available, but they are too expensive for control applications. An economical solution is the use of the effective temperature in which both the air temperature and the radiant temperature are equally weighed. In passive solar control systems the following sensors are of vital importance:

- temperature sensors for the indoor and outdoor temperature,
- solar flux sensors.

For optimization sensors for the energy consumption and windspeed are very useful. For detailed information the reader is referred to the cataloques of the manufacturers of control equipment for heating, ventilation and airconditioning (HVAC).

2.2 CONTROLLERS

The control system can be realized with components that are standard practice in HVAC. A controller characteristic for solar applications is the temperature difference controller. It compares two temperatures in order to detect when transport of solar energy gains is advantageous, for instance to determine the moment of discharge of a rock bin. Preference should be given to digital control systems, such as Building Managment Systems (BMS) with which the best integration can only be realized without compromises.

Of course, in that case, strategies and algorithms giving this optimal integration should be known. In paragraph 5 several control systems are proposed, which are designed in a concerted action of project PASTOR of the commission of European Communities.

2.3 ACTUATORS

Control of passive solar gains can be carried out by the following essential actions:

- adjusting the position of insulating shutters, Venetian blinds, awnings, etc. by a tube motor,
- adjusting the position of an air damper through an electric or pneumatic motor.

Examples are: control of the convective air flow in Trombe walls, the airflow control through a vent window opening.

3. CONTROL OF INDIVIDUAL PASSIVE SOLAR TECHNIQUES

3.1 CONTROL OF SHADING DEVICES

Shading devices can be used for the following purposes:

- control of direct solar gains,
- control of daylighting
- prevent inconvenient glare.

The shading devices can be controlled in a closed loop configuration or by feedforward. In the first case a temperature, respectively lighting controller adjusts the position of the shading device in order to keep the indoor temperature just below a specific threshold or to keep the illumination at a comfortable level. Feedforward is applied when it is desired to adjust the position only as a function of the sun and the amount of solar radiation, for instance to avoid glare. Both types of control can overrule each other, for instance, in the morning shading is being controlled by feedforward to avoid glare while lateron the temperature controller takes it over by feedback control action in order to avoid overheating.
The window is an important factor for occupants. Therefore automatic window devices always should have provisions to be overruled by the inhabitants by manual control.
Glare generated by direct solar radiation is preceived by people as the strongest factor for sunshading actions. Glare can be controlled automatically by outside or inside Venetian blinds or by awnings. More information about glare is given by Inoue [2]. The best policy is to adjust the slats in such a way that no direct solar radiation can reach the occupants. Proper slat angles can be calculated from the profile angle of the sun.

3.2 CONTROL OF VENTILATION

Ventilation is necessary for fresh air supply and cooling in hot periods to avoid overheating. Mechanical ventilation is a well known technique and it can be controlled by adjusting the speed of the fan motor or by on/off operation. Control of natural ventilation by adjusting vent window openings is much more complicated. A simple control strategy for cooling is the start and stop ventilation by means of the threshold values of the indoor temperature (24°C and 20°C). It will be clear that in this case solar gains can be wasted. Control of the minimum supply of fresh air needs more research. The equations found by Gids and Pfaff [3] may be useful for this purpose.

4. CONTROL OF DIRECT GAINS AND TROMBE WALLS

Control of Trombe walls cannot be discussed without taking the influence of the direct gains into consideration. The same applies for rock bins. The Trombe wall's heat delivery can be controlled by an air damper and/or by switching on the fan in case forced ventilation is applied. The direct gains can be controlled by shading (overhand, awning, outside Venetian blinds).
Control strategies as proposed by Sebold [1]:

1. Night setback 11 PM to 7 AM at 15°C,
   otherwise night insulation on.
2. Trombe wall and direct gain windows.
   Too hot:
   - if $T_{air} > 24$°C, vent to the outside air;
   - if still $T_{air} > 24.5$°C, cancel vent and shade instead.

   Too cold:
   - if $T_{air} < T_{set}$, turn on Trombe wall fan or open air dampers, if the space air temperature of the Trombe wall exceeds T_{air} by 10°C;
   - if still $T_{air} < T_{set}$, use auxiliary energy.

Sebold tested this strategy by computer simulation for various weather zones of the U.S. (Albuquerque, Madison, Santa Maria). From his results the following general conclusions could be drawn:

- The control system reduces auxiliary heat requirements considerably and provides a slightly more comfortable building;
- Night insulation on both the direct gains windows and the Trombe walls is the most useful control (40 - 60% reduction in auxiliary heating).
- The Trombe wall fan control saves only 3 - 8% due to the presence of competing direct gains and is therefore marginal and not cost effective.
- In hot climate zones controls can also be very useful in providing much better comfort.
- Night air cooling was not considered by Sebold. However, other research results showed that it is very useful to improve comfort. The number of hours with too high temperatures can be reduced substantially, as will be demonstrated furtheron in this paper.

Sebold's simulation studies show that adding a passive rock bin does not significantly reduce backup requirements [1]. They are of the same magnitude as the auxiliary energy consumed by the charging fan. When a fan is used to increase the air flow through the rock bin the auxiliary heating energy consumption is reduced more efficiently (twice as great) as the passive case, which showes only a small reduction.

5. CONTROL OF A SIMPLE PASSIVE SOLAR SYSTEM

In a concerted action of the program PASTOR of the Commission of European Communities control systems are designed for a simple passive solar system, which can manage the passive solar gains, natural or mechanical ventilation, auxiliary heating and lighting. For the analyses of the control systems no insulation window shutter was considered. From the calculation results of Sebold [1] it may be concluded that Trombe walls and rock bins are not cost effective and therefore omitted in the EC- project.
Three different control systems were designed for this simple passive solar system. Advanced techniques have been applied such as adaptive modelling, optimization, weather predicition, and adaptive control. Participants of this project were: Delft University of Technology, Ecole des Mines de Paris, Centre Scientifique et Technique des Batiments, and a French Company: NAPAC in Paris. In a series of publications these systems are described in detail [4,5,6]. Here, only a global description will be given.

5.1 OPTIMAL CONTROL SYSTEM

The internal structure of the controllers is represented schematically in figure 2. It functions in the following way. The outdoor climate W (horizontal global radiation, outdoor temperature, windspeed and wind direction) and the indoor temperatures (θ_i) are measured. In the preprocessor these values are transformed into relevant parameters for the model; for instance the measured horizontal solar radiation is transferred into solar radiation upon a vertical or inclined surface. These preprocessed data are used to identify the parameters of the model relating the temperatures θ_i to the outdoor climate variables W and the control actions U (position of the blinds, etc.). The parameters are found by a recursive least square parameter estimation method (Iserman, 1977). The weather data W are also used to identify a weather model, which can predict the weather for the next 24 hours. A weather report can be added to improve prediction. This weather predictor W_H and the building model are used to determine the optimal control strategy U (setpoints for room controllers and/or the positions of the actuators.). With feedback control these desired values are realized in each room.

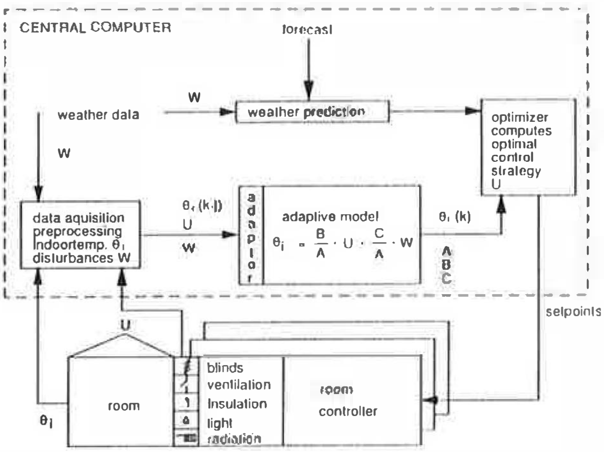

Figure 2. Structure of controllers.

5.2 SIMULATION TESTS.

The control systems have been tested with a simulator that contains a simplified model of the thermal behaviour of the building and its passive components [4]. A one room building is considered with well insulated walls and one window facing south. The calculations are carried out for window areas which are 40 and 80% of the front wall respectively.
Some general conclusions could be drawn:

- The predictive control systems of the Delft University of Technology and Centre Scientifique et Technique des Bâtiments show to be very effective for switching on the heating installation at the best moment in the morning. The number of hours with indoor temperatures lower than 20°C are much lower than the control system, which does not apply weather prediction (NAPAC).
- Although the simulation shows that the control systems are stable, a field test is felt to be necessary. Especially the model identification method, used in each control system may cause problems under real conditions.
- High thermal inertia is the first requirement for getting an acceptable indoor climate in summer.
- Only in colder climates comfort can be realized in summer. In figure 3 hystograms of the indoor temperature in summer are given for Uccle and Carpentras. It showns 69 hours with temperatures exceeding 26°C for Uccle and 607 for Carpentras.
- The heat losses through the windows outweight the advantages of the solar gains, so that night insulation of the windows is essential for passive solar systems. In paragraph 5.4 more details are given.

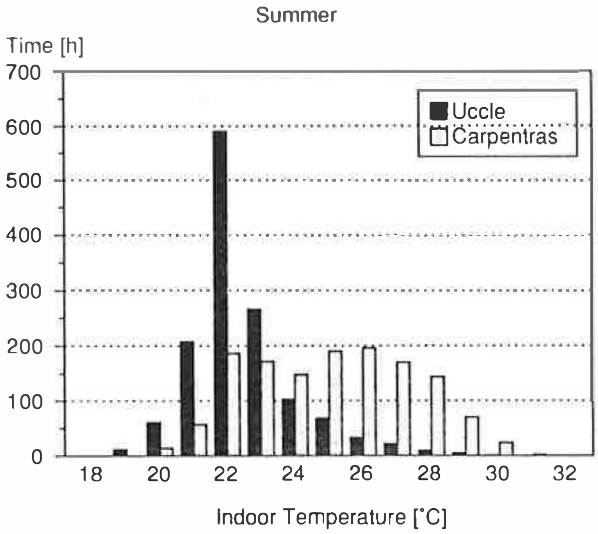

Figure 3. Temperature exceeding for Uccle (Belgium) and Carpentras (South of France). Heavy building and 80% window area.

5.3 COMPARISON WITH A SIMPLE CONTROL STRATEGY

The TU Delft design has been compared with the following simple and straight forward control strategy:

- Starting up and control of the heating installation are carried out in the same way as applied in conventional radiator heating systems;
- Natural ventilation: $T_{inside} > 22°C$, then:
  vent windows open if $T_{outside} > 15°C$
  vent windows closed if $T_{outside} > 24°C$
  vent windows halfway if $5°C < T_{outside} < 15°C$
  vent windows at minimum position if $T_{outside} < 5°C$.
  (The maximum ventilation flow is 600 m^3/h in case mechanical ventilation is applied).
- The minimum ventilation (fresh air control) opening of a high positioned ventwindow is 5 degrees (in case of mechanical ventilation 30 m^3/h is delivered).
- The horizontal awning is put in maximum position if solar radiation on a vertical surface > 400 W and $T_{inside} > 22°C$.

The following conclusions could be drawn:

- For the summer period there is no need for an advanced control system. The rule: "Cool the building by ventilation as soon as the indoor temperature exceeds 22°C" gives results equivalent with the advanced control system.
- In the heating period the advanced control system saves 20% energy with respect to the simple control system.

5.4 INSULATING SHUTTER

As said before an insulating shutter is necessary. With the simulator its effect on the heating requirement is calculated. For example, for heavy buildings with a 80% window surface the insulating shutter gives a reduction in heating requirements of 50%.
Table 1 shows that when a shutter is applied preference should be given to large windows. That does not count when no shutter is applied.

Window surface	40%	80%
Without shutter	1780	2400
With shutter	1576	1200

Table 1. Heating requirement (kWh).

5.5 NATURAL AND MECHANICAL VENTILATION

In the simulator it is assumed that 600 m^3/h outside air can be supplied to the room by the mechanical ventilation system. The natural ventilation Φ is simulated by:

$\Phi = f$ (windspeed, $T_{out} - T_{in}$)

The coefficients of this equation are such that the maximum ventilation rate equals that of mechanical ventilation. It is emphasized that this rate can only be obtained when a window system with low and high positioned vent openings is applied.
The simulation results showed that natural ventilation can compete with mechanical ventilation. The number of exceedings (> 26°C) for the heavy building in Uccle with 80% window area were 75 and 69 hours respectively.

6. CONCLUSIONS

- Trombe walls are not cost effective.
  The same yields for rock bins.
  The competing direct solar gain overrules other possibilities.
- A minimal system configuration of a passive solar system consists of - a high inertia building with large windows facing south - outside shading device, insulating shutter and a ventilation facility for cooling.
- The optimal control systems designed in a CEC- project meet their requirements. For winter periods they save energy (20% reduction), while for the summer period they can be replaced by a simple and straightforward strategy.
- Only in colder climates temperatures exceeding some comfort threshold can be avoided, provided that the internal load does not exceed 100 W.
  Otherwise, mechanical cooling can not be avoided.
- Natural ventilation with high and low positioned vent windows can compete with mechanical ventilation.

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