DEPARTEMENT DE GENIE CIVIL
INSTITUT D'HYDRAULIQUE ET D'ENERGIE
L A S E N - LABORATOIRE DE SYSTEMES ENERGETIQUES

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

CH- 1015 LAUSANNE (Suisse)
TÉLÉPHONE: 021 - 693 24 95 TÉLÉFAX: 021 - 693 28 63 TÉLEX: 454 478

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Dynamic Simulation of Heating/Cooling Systems in the Buildings

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Dr. D. Pahud

(e-mail : daniel.pahud@epfl.ch)

Dr. A. Fromentin

(e-mail : antoine.fromentin@epfl.ch)

LASEN, EPFL, Switzerland

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Summary

The problematic of dynamic simulation of heating/cooling in the building is discussed with the two main families of simulation tools: the "special purpose" programmes, which normally use algebraic combinations of analytical formulas, and "general purpose" programmes, which can apply to a large range of systems, but are more difficult to use. Unlike the first category, the second category of programmes provide information on process dynamics. Some examples, which clearly require a dynamic approach, are then presented. Finally, a solar heated building is simulated as well as a heat exchanger pile system as examples.

1. Introduction to System Simulation

1.1 System Simulation

Simulations are numerical experiments. They can give the same kinds of thermal performance information as a physical experiment. They are, however, relatively quick and inexpensive and can produce information on the effect of design variable changes on system performance, by series of adequate experiments. They have the advantage that the weather and loads used to drive them are reproducible, allowing parametric and configuration studies to be made without uncertainties of variable weather and energy use. On the other hands, simulations are only as good as the models that are the basis of the programmes and the skill with which they are used.

Simulation programmes fall into two general categories. The first includes those that are "special purpose" programmes, representing the performances of specific types of systems. In these programmes, the equations for the components are combined algebraically to simplify the computation; they are generally easy to use but are not flexible. They usually produce estimates of annual useful outputs of thermal processes, but do not provide information on process dynamic. Programmes in the second category, the general purpose programmes, are more flexible and can be applied to a wide range of systems, but are more difficult to use. In these programmes, the equations representing system components are kept separate and are solved simultaneously rather than being combined algebraically. The system dynamic can be simulated in details, including the effect of the control strategy used to operate the system. These general purpose programmes are also called "dynamic or transient simulation tools of thermal processes".

1.2 Dynamic Simulation Tools of Thermal Processes

A dynamic simulation tool is required when the system thermal performances can not be obtained with the integrated variables that drive the system. The temporal evolution of these variables is necessary for the reproduction of the system dynamic, which, in this case, is determinant on the system thermal performances.

A simple example is a solar collector. When solar radiation is falling in the collector plane, a fraction of it is absorbed and converted into thermal energy, and results in the warming up of the heat carrier fluid contained in the collector. Heat losses to the environment occur and increase as the fluid temperature rises. Heat can be collected when and only when the fluid temperature becomes larger than the temperature of the incoming fluid in the collector that would result if the collector pump was in operation. Let us assume that the conditions in which the collector operates give a radiation threshold of 500 W/m^2 for solar heat to be collected. During a sunny day, the incident radiation may reach 1'000 W/m^2, whereas it would never be greater than 500 W/m^2 in average during the day. A rough stationary model that would use the mean value of the incident radiation would predict no solar gains, and is clearly inappropriate in this case (cf. fig. 1).

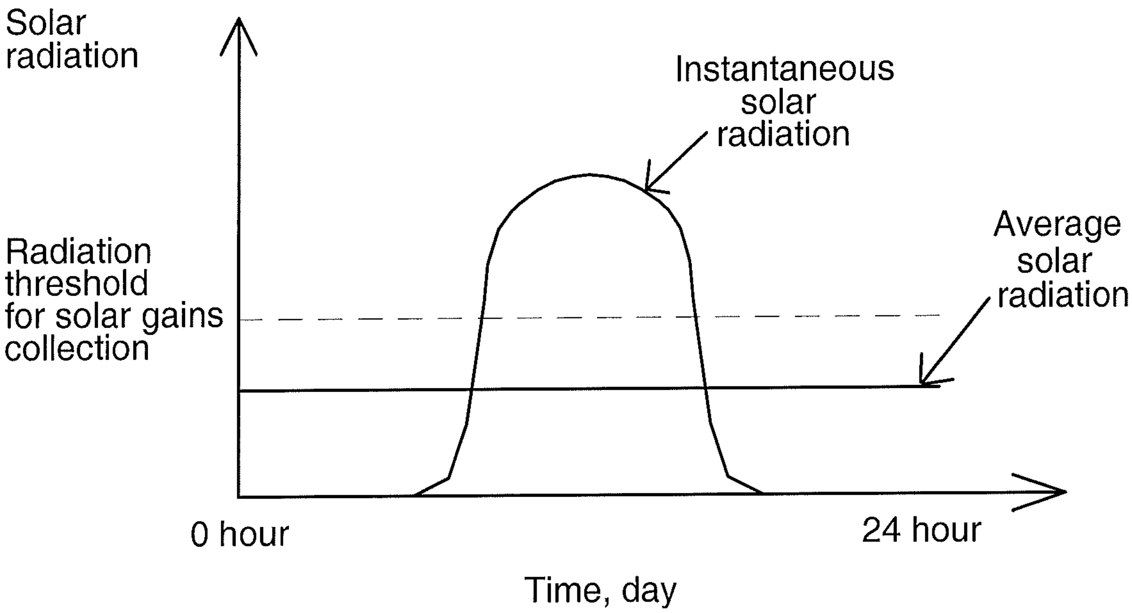


Figure 1: Instantaneous and average solar radiation for a sunny day: the instantaneous radiation exceeds the solar collector threshold value during some time, resulting in the collection of solar gains. This is not the case with the average radiation for the day. A rough stationary model that use this value would not predict any solar gain.

A dynamic simulation tool is not necessary required for any thermal process. The heat balance of a building during the heating period can be done under stationary conditions. For this case, the dynamic effect induced by passive solar gains are normally taken into account with a utilisation factor. Another example is the thermal efficiency of a gas or fuel burner, operating at a fixed temperature, which can be assessed without a dynamic simulation.

A dynamic simulation tool is mostly required for any thermal process whose thermal performances is strongly influenced by the temperature level at which the process occurs, and for driving conditions that may vary with time (weather data, heat and cold energy demand, etc.). Solar processes or processes involving a heat pump usually requires dynamic simulation tools, if a proper prediction of their thermal performances is to be expected.

1.3 Results from Dynamic Simulation Tools

Dynamic simulations provide two kinds of information. The first kind are integrated values of relevant variables (energies for a system heat balance, mean temperatures, etc.) over a representative period, which is typically one month, one year or even the life-time of the system. The second kind of information concerns the process dynamics. The time evolution of intermediate variables is simulated and available to the user. Extreme temperatures of different parts of the system can be known. They also determine the feasibility of the system design if temperature constraints are to be respected (overheating, freezing, etc.).

Dynamic simulations also offer the opportunity to evaluate effects of system configuration, system control and alternative concept on long-term system performances. With cost data and appropriate economic analysis, simulation results can be used to find the system costing the least.

1.4 A Simple Dynamic Simulation Model

A dynamic simulation model is not necessarily complicated. Depending on the desired degree of simplicity, a one node model can already be used for a dynamic simulation. As an example, a "breadbox" solar system is presented and simulated with a simple but dynamic model.

A "breadbox" is a device which collects and stores solar heat in order to provide hot water. A schematic presentation of the device is shown in Fig. 2. The device behaves exactly as the solar collector described above, except that the heat capacity of the collector (or volume of water) is much larger for storage purpose. A question that a dynamic simulation can answer is:

- what will be the evolution of the water temperature Tc in the "breadbox" ? When is it possible to take a shower ?

At a given time, the system behaves according to the following heat balance:

$$Qin = Qout + Qstored \quad (1)$$

Qin: incoming heat rate in the system or absorbed solar radiation (W).

Qout: outgoing heat rate from the system or heat losses plus hot water delivered (W).

Qstored: stored or de-stored heat rate (W).

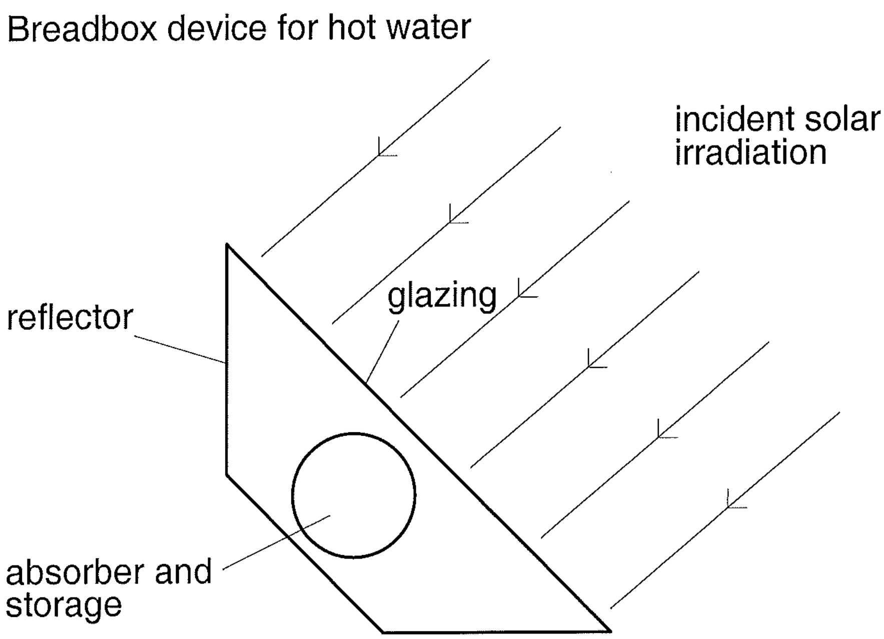


Figure 2: Schematic presentation of a "breadbox" device.

During the time-step Δt_i, the heat balance (1) is written as follow:

$$S\ A\ I_i\ \Delta t_i = S\ k\ (Tc_i - Tai)\ \Delta t_i + Qhot\text{-}water_i\ \Delta t_i + V\ \rho\ cp\ \Delta T_i \quad (2)$$

Relation (2) is re-written to express ΔT_i, the temperature variation of the stored water Tc_i during a time-step, in terms of the weather data (radiation I_i and outdoor air temperature Ta_i), the user (hot water used $Qhot\text{-}water_i$), the thermal characteristics of the system (S, A, k, V, ρ and cp) and the previous value of the stored water temperature (Tc_i).

$$\Delta T_i = (S\ A\ I_i\ \Delta t_i - S\ k\ (Tc_i - Tai)\ \Delta t_i - Qhot\text{-}water_i\ \Delta t_i) / (V\ \rho\ cp) \quad (3)$$

Relation (3) defines the simple model used for the dynamic simulation. The water temperature for the next time-step Tc_{i+1} is calculated with:

$$Tc_{i+1} = Tc_i + \Delta T_i \quad (4)$$

The water temperature evolution can be simulated on the basis of a weather data, a user and the thermal characteristics of the "breadbox". In Fig. 3, a schematic view of the procedure is shown.

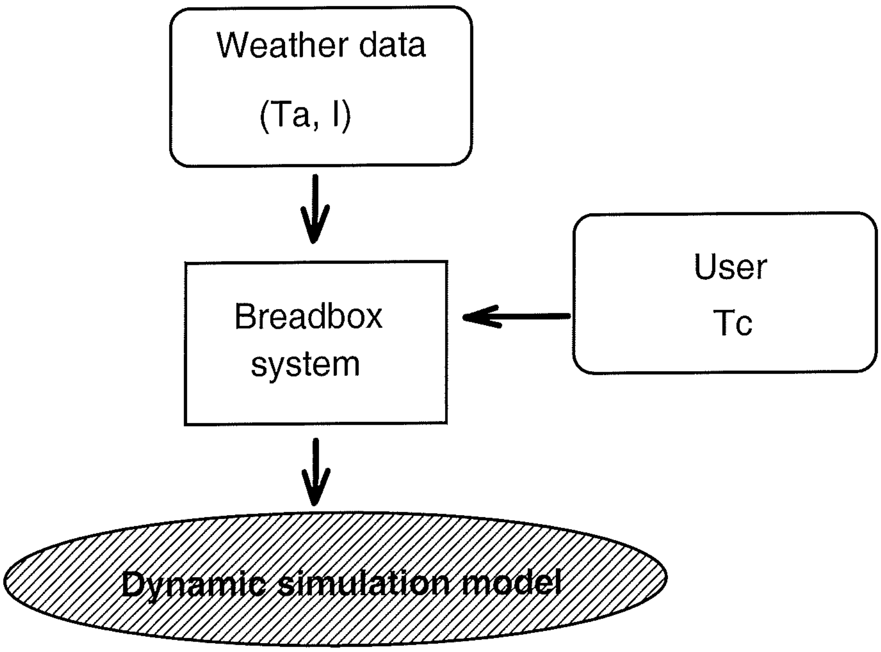


Figure 3: Dynamic simulation of the "breadbox" system.

In Fig. 4, the water temperature is simulated for 4 days without hot water use. This temperature evolution shows that it is possible to take a shower in the afternoon or in the evening, but not in the morning.

Figure 4: Temperature evolution of the water in the "breadbox" device (Tcap). The outdoor air temperature (Text) is also shown. The temperature Tcap is simulated with a simple dynamic model.

1.5 Generalities on Dynamic Simulation Tools

Dynamic simulation tools are often time consuming for the user, which justify their use for large systems only. For small systems, simplified and fast-to-use method are available (for example see the F-chart (DUFIE, 1991) or G3 methods(GUISAN et al., 1990) for residential solar heating systems, etc.).

Dynamic simulation tools are well suited for research studies, due to the high level of details that can be achieved in the simulation of processes. Simulations are complementary to physical experiments. Careful comparisons of experiments and simulations lead to improved understanding of each.

Simulations, like any other calculations, are only as good as the models that are the basis of the programmes and the skill with which they are used. Once simulations have been verified with experiments, new systems can be designed with confidence using simulation methods.

A well-known and widely used dynamic simulation programme is TRNSYS (KLEIN et al., 1996), a transient system simulation programme. A large variety of thermal problems can be addressed, as TRNSYS contains a large library of subroutines that represent, for example, the components of typical solar energy systems (such as solar collectors, water storages, pumps, pipes, valves, controllers, etc.). Users can readily write their own component subroutines if they have a particular need. By a simple language, a TRNSYS deck (input file for TRNSYS) "connects" the components together in a manner analogous to piping, ducting, and wiring in a physical system. The programmer also supplies values for all of the parameters describing the components to be used. The programme does the necessary simultaneous solutions of the algebraic and differential equations which represent the components and organises the inputs and outputs.

2. Examples of Problems Solved with TRNSYS

2.1 Passive Solar House with an Active Solar System

A concept of a prefabricated solar house (150 m^2 of heated floor area) has been proposed by the firm Prefatech SA, Switzerland. This well insulated house (U_{wall}= 0.25 W/m^2K, $U_{windows}$= 1.6 W/m^2K) made of heavy precast concrete parts offers a large window area on its South face (20 m^2) and an important solar collector area on its roof (20 to 30 m^2); it is thus designed to efficiently use both passive and active components of solar energy. Its original feature is to use the massive internal walls as radiative element and heat storage capacity. These features are realised with a heat distribution made of tubes embedded in the core of the walls and an external house insulation. The space heating energy consumption per square meter of floor area should not exceed 60 to 80 MJ/m^2year for the auxiliary heat, which is about 10 times smaller than the average value for Switzerland. A West and South view of the house are shown in Fig. 5.

As the passive and active solar gains share the same storage (the concrete walls), a strong thermal interaction between these two is expected. Only dynamic simulations of the whole house and its solar heating system can answer the following questions:

- what is the optimal wall thickness and embedded tubes position that leads to an efficient use of both passive and active solar gains ?
- how does the annual auxiliary energy decreases with an increase of the collector area ?

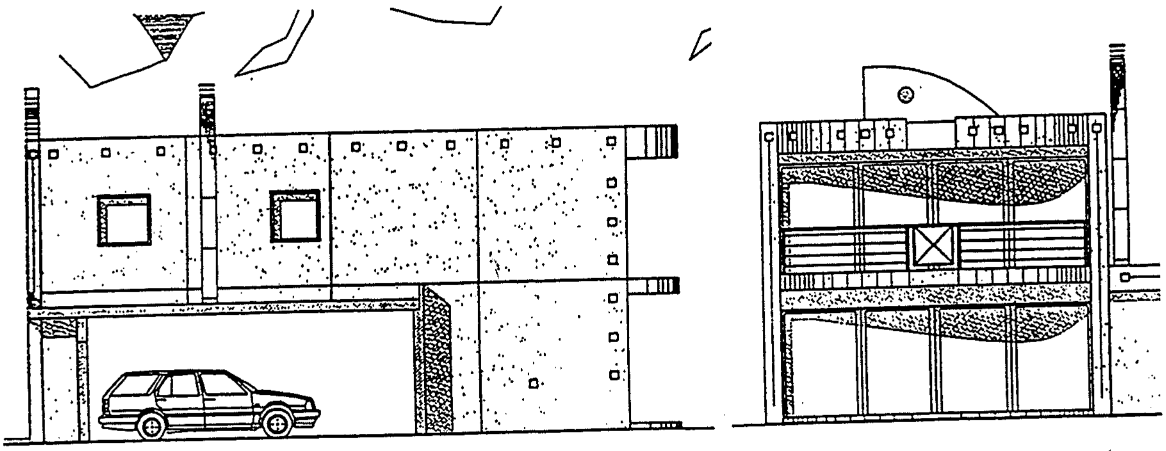
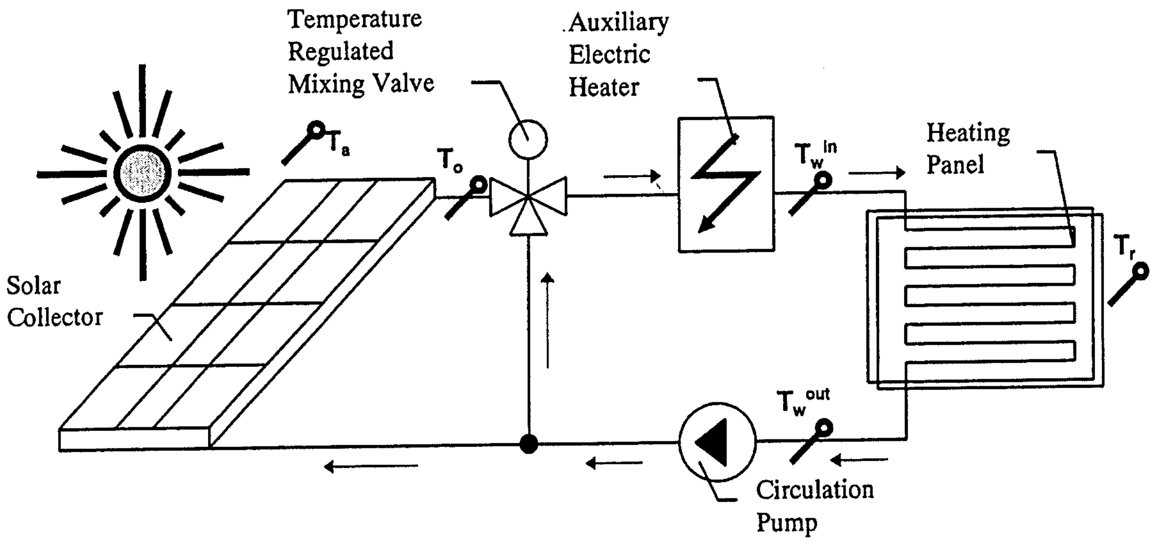


Figure 5: West and South fronts of the Prefatech solar house.

System Layout

The system layout is shown in Fig. 6. The solar collectors are operated as long as solar heat can be collected, but only if the room air temperature T_{int} is below 21 °C. The auxiliary heater, placed in series after the solar collectors, supplies heat if the inlet fluid temperature in the walls is lower than the set point temperature, which varies between 20 and 30 °C in relation to the outdoor air temperature T_a. The auxiliary heater is stopped if the room air temperature exceeds 20 °C, and is not started until this temperature decreases to 18 °C.



T_a - ambient (outside air) temperature
T_o - temperature of heat carrier from collector
T_r - room temperature
T_w^{in} - panel inlet fluid temperature
T_w^{out} - panel outlet fluid temperature

Figure 6: System layout of the active solar heating system of the passive solar house.

Simulation Tool

The version 14.1 of TRNSYS (KLEIN et al., 1996) is used to simulate the whole house together with the active solar heating system. A model for each system component is available in TRNSYS, except for the heating walls. This simulation problem is solved by using the results of KOSCHENZ and DORRER (1996), which replace the two-dimensional temperature field in the plane of the embedded tubes with an effective wall temperature. The problem is reduced to a one-dimensional heat transfer calculation across the walls, simulated with the help of heat transfer functions in the standard multi-zone building model.

Simulation Results

The simulations showed that a wall of 12 to 14 cm thickness is large enough to store both active and passive solar gains. A larger thickness does not further reduce the annual auxiliary energy required for space heating. For a minimal auxiliary energy consumption, the tubes should be embedded between 7 to 11 cm inside the wall (see FROMENTIN et al., 1997a). The annual auxiliary energy versus collector area is shown in Fig. 7 for two types of flat plate collectors (glazed and unglazed collector). For these cases, a wall thickness of 14 cm is fixed and the tubes are imbedded at 7 cm (middle position). As expected, the reduction is greater for glazed than unglazed collector. Together with cost data, this graph provides a basis for a technological choice.

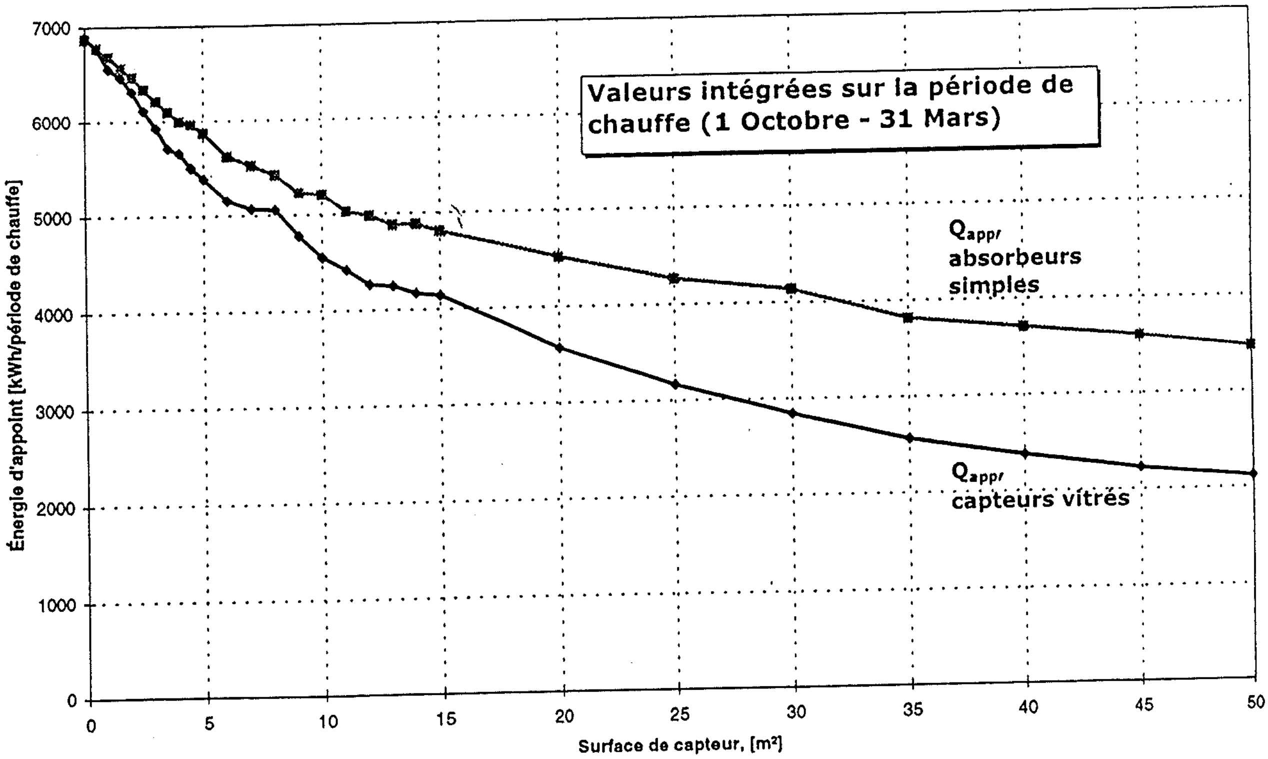


Figure 7: Annual auxiliary energy in relation to the collector area. Glazed and unglazed flat plat collector are simulated. No wind effect was taken into account.

2.2 Heat Exchanger Pile System

A pile foundation is used when the upper layers of soil are too soft and compressible to support the loads of a superstructure, normally a building. A heat exchanger pile is a pile foundation equipped with a channel system, in which a heat carrier fluid can be circulated. Thus, the two main functions of a heat exchanger pile is to transfer the loads of the building in depth and to exchange heat with the surrounding ground. A heat exchanger pile system comprises of a set of heat exchanger piles which are connected together hydraulically, and normally are coupled to a heat pump. Such a system is usually used for heating and/or cooling purposes. A schematic view of a heat exchanger pile system for space heating is shown in Fig. 8.

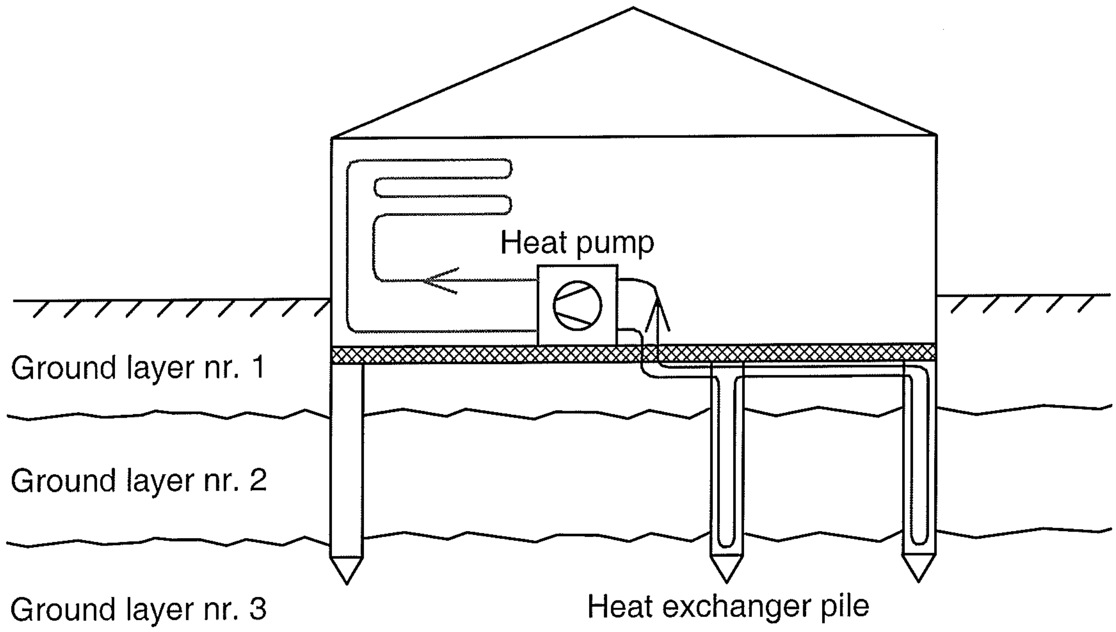


Figure 8: Schematic view of a heat exchanger pile system for space heating.

Temperature Constraint

Freezing of the piles must be avoided, as it may have a negative influence on the static of the building. For safety reason, the heat carrier fluid temperature in the piles should always remain above zero degree.

System Layout

The system layout of a typical heat exchanger pile system is shown in Fig. 8. Three heat pumps are connected in parallel, which may also simulate one heat pump with three speeds. A thermal recharge of the ground is also possible during the Summer, which can be combined with "free cooling" on the piles. During a recharge period, the fluid temperature in the piles is rising, and must not exceed the fluid temperature used for cooling in case of "free cooling". An alternative would use a cooling machine connected on the piles.

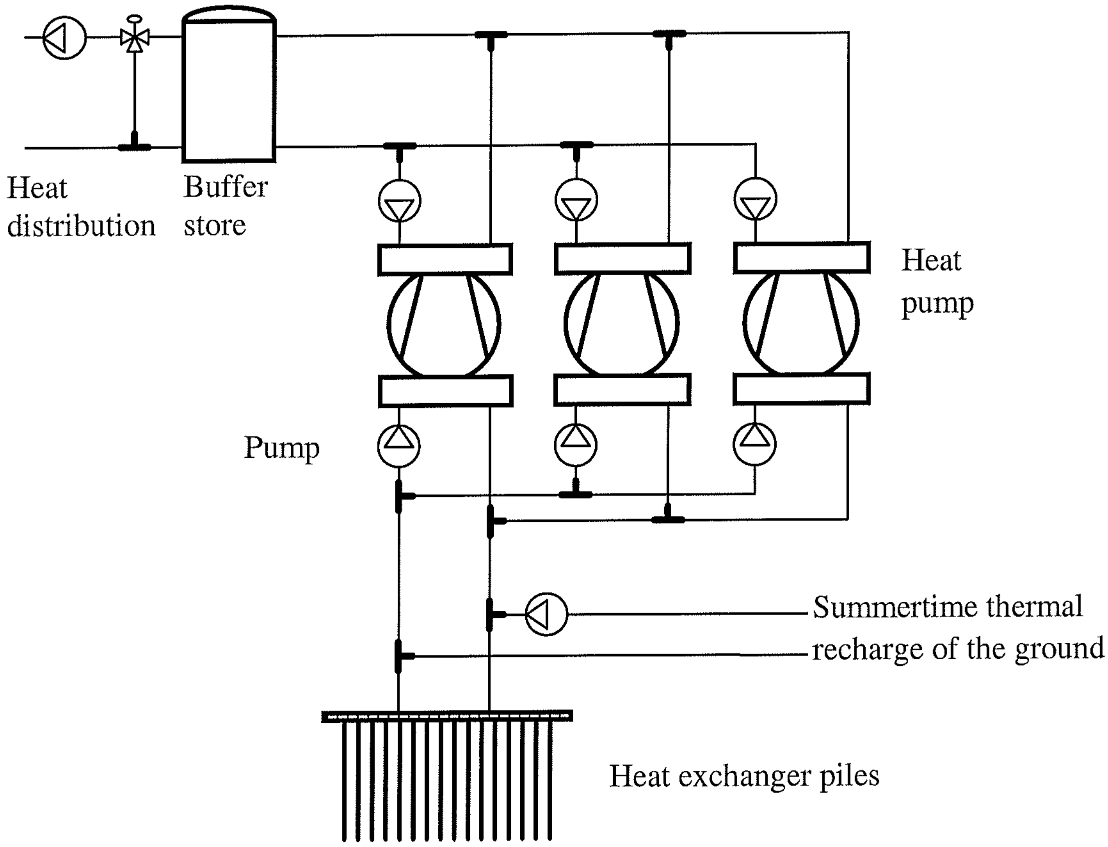


Figure 8: System layout of a typical heat exchanger pile system.

Simulation Tool

It is obvious that a dynamic simulation is required to check the fluid temperature in the piles. This temperature is influenced by short-time effects, due to the loading conditions of the previous days, but also by long-time effects, due to the cooling of the surrounding ground, which may take several years. Only a dynamic simulation of the whole system during several years can give a proper answer on the global thermal heat balance and the viability of the system design, which includes both short-term and long-term effects.

The version 14.2 of the TRNSYS simulation programme (KLEIN et al., 1996) is used to develop simulation tools of such systems, together with non-standard components for the simulation of a set of heat exchanger piles and an electric heat pump.

The model used for the simulation of the piles was devised for the simulation of a duct ground heat storage and has been adapted (PAHUD et al., 1996), so that typical conditions frequently met with heat exchanger piles can be taken into account (for example a ground water flow). The heat pump model (AFJEI et al., 1996) use the steady state thermal performances given by the manufacturer (which depend on condenser and evaporator temperature), and combine them with transient effects due to the on/off setting of the heat pump. Simulations tools were developed by assembling together the corresponding TRNSYS components and were validated with measurements of such installations. A methodology has been established to determine the numerous parameters that are necessary for such a simulation (FROMENTIN et al., 1997b).

Simulation Results

The influence of long term effects is illustrated in this section. The simulation is based on an existing and measured installation, located in Finkernweg, Switzerland. The annual heat demand for space heating and hot water is measured to about 200 MWh, and is entirely covered by three heat pumps of 30 kW each (at the condenser), coupled to a set of 75 heat exchanger piles of 12 m each. The ground volume ascribed to the piles is about 12'000 m^3, which gives an average spacing of 3.8 m. Although the ground water does not appear to move, no thermal recharge of the ground has been performed. The installation started operating in the summer of 1993.

Loading conditions for the piles are extrapolated beyond the period of measurements which stopped at the end of 1996. In Fig. 9, the evolution of the mean fluid temperature in the heat exchanger piles is shown with daily values. The first 6 years of operation are simulated with a three hourly time-step. In a 2.5 m thick ground layer, a Darcy velocity of 0.1 and 1m/day were prescribed. The measured values are closer to the curve obtained with the low Darcy velocity, which confirms the fact that the ground water flow is not important at this location.

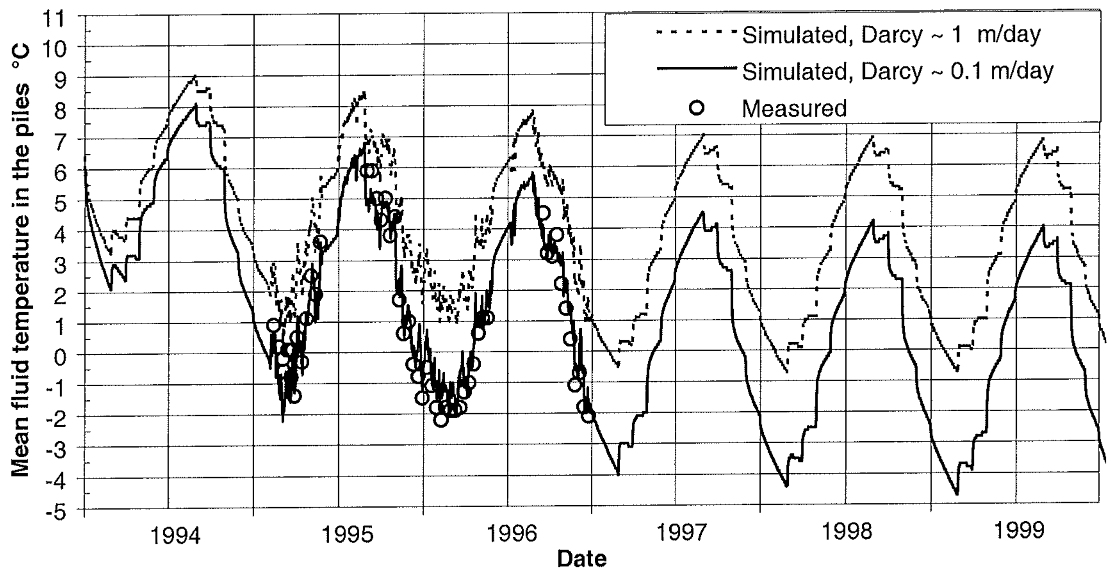


Figure 9: Evolution of the daily mean fluid temperature in the piles of the Finkernweg installation. The simulated curve with the smaller ground water velocity fits better the measured values.

Due to the pile thermal resistance and the heat rate extracted by the heat pumps, a mean fluid temperature below -4°C may lead to the ground freezing in the close vicinity of the piles. This risk is probable after five years of operation, in January or February 1998. Nevertheless, a fluid temperature below 0°C should be avoided. Even with a significant effect of a regional ground water flow (Darcy = 1 m/day), the pipe length is still undersized. A thermal recharge of the ground is necessary in this case. This example clearly shows that with a proper simulation tool, these errors could have been avoided.

Conclusion

Unlike a stationary simulation, a dynamic simulation is required for any thermal process whose thermal performances is strongly influenced by the temperature level at which the process occurs, and for driving conditions that may vary with time. Integrated in a building, solar collectors, heat pumps, heat exchanger piles and so on produce thermal processes that are essentially dynamic.

Dynamic simulations are a powerful complement to physical experiments. Once simulations have been verified with experiments, new systems can be designed with confidence using simulation methods. Dynamic simulation is a useful research tool that help understanding the dynamic of complex thermal processes. The influence of system configuration, system control and alternative concept on long term system performance can be explored with the mean of multiple simulations.

The TRNSYS programme is a transient simulation programme of thermal processes. Its modularity and flexibility makes it possible to simulate a large variety of thermal problems. A passive solar house with an active solar system and a heat exchanger pile system are only two examples which show the great capability of TRNSYS to simulate in details dynamic thermal processes in the building.

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