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Building energy simulation by an in-house full transient model for radiant systems coupled to a modulating heat pump

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Abstract

Radiant heating coupled to a heat pump is a particularly energy-efficient system, recommended in new constructions. However, the potential energy savings associated with this high thermal inertia system can only be achieved with appropriate control laws, to be tested in a full building–plant simulation environment. The developed transient code concurrently solves three tailored dynamic models of each involved sub-system, namely: building envelope (a benchmark room defined by ISO 13791), radiant floor (designed in accordance with EN 1264-2), and heat pump (an air-to-water electrically-driven modulating unit). Different control strategies were implemented, such as variation of internal temperature set-point dead band, supply temperature to radiant panels, and heating modes. Among the examined variables, we found that the higher energy savings (up to 15%) can be obtained by a proper choice of the supply temperature: in particular, fixed supply temperature should be preferred to climate-based control for this case study. The developed model can be used for optimal design of new systems and associated controls and for accurate energy audits of existing buildings employing these technological solutions.

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Keywords: Dynamic models; radiant systems; heat pumps; building–plant simulation; control strategies

1. Introduction

Current European Directives [1] highlight the importance of energy efficiency in buildings, as this sector requires energy for heating, cooling, production of domestic hot water, lighting, and other electrical uses.

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A typical energy-efficient solution for the heating and cooling system is the use of radiant panels together with heat pumps. Radiant panels are employed in more than 50% of newly-constructed residential buildings in Europe [2-4], because they can be used both for heating and cooling, are low-temperature emitters, and are suitable for human comfort. The system is particularly efficient when coupled to heat pumps. Reversible heat pumps provide heating and cooling to buildings and achieve higher performance for low temperature differences between the sources.

In this work, we present a model that simulates, during the heating season, the thermal behavior of a building and of the radiant floor and the performance of an air-to-water electrically-driven modulating heat pump. The full transient model is applied to a test case defined in ISO 13791 [5]: different control strategies are studied, varying internal temperature set-point dead band, control of the water delivery temperature, and heating modes (continuous or intermittent mode).

2. Description of the transient model of the system

The developed in-house model simulates each sub-system involved in the energy flow:

- a routine simulates the temperature evolution of the internal air and of the building structure;
- two sub-routines simulate the evolution of the temperature in the pipework and in the various floor layers;
- a routine simulates the behavior of the heat pump.

The three routines are briefly described in the following sections.

2.1 Routine for the simulation of the building envelope

Transient energy balances of air, opaque walls and windows are solved in the first section of the simulation code. This routine was validated in accordance with EN 15265 [6]: a maximum deviation of 5% with respect to benchmark values was obtained for the available 12 test cases, thus classifying the code in Level A [7].

2.2 Routine for the radiant system simulation

This section of the code divides the floor slab and the pipework in nodes, evaluating the transient 1-D energy balance for each node, considering the heat flow between the water and the adjacent layers, and the capacitive effects of each floor layer. A proper shape factor is used to take into account the 2-D effects due to the distance between two consecutive pipes and their diameter. Further information about this model can be found in [7].

2.3 Routine for the heat pump simulation

We developed a dynamic model that simulates the instantaneous inverse thermodynamic cycle realized by an air-to-water electrically-driven modulating heat pump. The compressor is of rotary type, connected to an inverter. R410A is the working refrigerant. For each time step, the model calculates the refrigerant flow rate and the nodes of the cycle (input and output conditions in correspondence of the main heat pump components: condenser, evaporator, expansive valve, and compressor unit), using a database of thermo-physical properties. The heat exchanges are modeled by the NTU method [8]. Defrost is modeled by means of a COP penalization, depending on the defrost typology (cycle inversion or electrical resistance), external air temperature and humidity [9]: the penalization is applied if the external temperature remains below a minimum value for more than a certain time lapse, as reported in [10]. This model has been validated with manufacturers' data for different sizes (from 6 kW to 100 kW), using both scroll and rotary compressors. Further information on the model can be found in [11].

2.4 Full transient model

The three routines have been coupled to simulate the behavior and the performance of the whole building–plant system, in response to internal usage and external climate. The system response, including electric energy uses, are calculated at a time step of 15 minutes. The water flow rate is fixed, while the target supply temperature can be either fixed for the whole heating season or set by a climate-control law. The heat pump delivers water to the radiant floor at the target temperature, as long as the frequency of the compressor stays within its operative range.

Otherwise, working at the operative boundaries of the device, the supply temperature may be higher than the target in partial-load conditions or lower than the target at too-high thermal demands (no back-up systems are considered).

3. Implemented case study

The full transient model was tested on a case study, in order to check the correct coupling between the sub-system simulation codes and implement different control strategies (heating season only).

The simulated room is defined in ISO 13791: more specifically, geometry and thermal characteristics of test B.3 were used [5]. This benchmark room is characterized by three light adiabatic walls, a west-facing heavy wall with a double-glazed window, and an external roof. It can be considered as a typical new construction, in accordance with legislative limits on thermal transmittance and seasonal energy needs. During the building occupation time (from 8 a.m. to 6 p.m., from Monday to Friday), we applied 6 W/m^2 of internal gains in the room, differently to the value of 20 W/m^2, recommended in [6]. The 6 W/m^2 value is reported in UNI/TS 11300-2 [12] as a typical internal gain in small and private offices and it represents a thermal gain produced by a worker and an electronic device. For the same reason and during the same time we applied 0.8 vol/h as ventilation rate, according to [13], instead of 1 vol/h (again, suggested by [6]). The floor layers were modified to simulate the presence of radiant panels. The flow rate in the pipes and their diameter and spacing were determined by means of the design method reported in EN 1264-2 [14]. Pipes are inside a structure with a screed and a thermal insulation layer, which avoids downward heat losses. We chose typical thicknesses for these layers (see [7] for all the details).

We employed the typical meteorological year of Pisa, Italy, in terms of external temperature and beam and diffuse solar radiation on the horizontal plane. The Italian Thermotechnical Committee (CTI) provides these data in hourly format: a function in the simulation code interpolates them to obtain the evolution on a 15-minute basis.

A heat pump of nominal power 6 kW is used for space heating. We assumed that this heat pump provides heating to five rooms, all identical to the previously-mentioned one given by [5]; they can be thought as a block of adjacent offices. The total heated floor area is 99 m^2 and the total volume of the building is 277 m^3.

A baseline test case was identified, with the following characteristics:

- intermittent heating mode (the heat pump is switched on from 6 a.m. to 6 p.m., from Monday to Friday);
- internal temperature set-point dead band of ±2 K;
- fixed water supply temperature to the radiant floor of 29°C.

We tested different control strategies, varying one variable at once with respect to the baseline case:

- temperature set-point dead bands: ± 1 K, ± 2 K, ± 3 K;
- heating modes: intermittent or continuous heating;
- water delivery temperature to the emitters: fixed supply or weather-based control.

4. Discussion of results

Once the full dynamic simulations of the building system were completed, comparisons and sensitivity analyses can be conducted on energy figures. In particular, having chosen specific climatic conditions and building envelope characteristics (including the radiant floor design), we may consider that the total electric energy utilized by the heat pump during the heating season is an appropriate performance indicator, together with the seasonal coefficient of performance (SCOP) of the system. It is necessary here to stress that all the simulations we are about to discuss were not run at a given set-point room temperature; on the contrary, the set-points were conveniently adjusted, in order to obtain, for every case, a seasonal average internal air temperature of 20°C during the building occupation time. In this way, equivalent thermal comfort conditions are granted and the recorded energy savings can be directly associated to actual increases of system energy efficiency.

A first series of results is summarized in Table 1. The energy performance shows a weak dependence on the dead-band amplitude. With the ±3 K amplitude, the rooms obviously stay for longer periods at temperatures distant from nominal thermal comfort conditions. On the other hand, with the ±1 K amplitude, the dead-band limits are reached more frequently, with corresponding on/off cycles of the heat pump. Hence, the ±2 K amplitude is considered as the most appropriate.

Energy savings are obtained in intermittent heating with respect to continuous operation, not only due to the reduction factor of the thermal energy need, depending on the building time constant, but also to the higher SCOP of the air-water heat pump, avoiding nighttime operation and working at a higher mean temperature of the external air.

At the start of the heat pump following an off period, there is an increased use of electric power by the compressor that can be taken into account by means of a penalization factor, to be applied at the 15-minute time step corresponding to the event. The sensibility analysis conducted on this parameter, with values ranging from 10% to 50% of additional electric energy request, shows a negligible impact on the seasonal energy performance of the system, owing to the limited number of on/off cycles undergone by the heat pump.

Table 1. Comparison of electric energy uses and heat pump SCOP for different control strategies and parameters (heating season).

Simulation case	Electric energy uses during the heating season [kWh]	SCOP
Sensitivity to dead-band amplitude		
±1 K	414	4.57
±2 K*	409	4.69
±3 K	412	4.67
Intermittent versus continuous heating		
Intermittent heating (operational period: 6 am–6 pm, Mon–Fri)*	409	4.69
Continuous operation (24h/7d)	421	4.55
Sensitivity to heat pump on/off penalization factor (additional electric energy request)		
+10%	406	4.74
+30%*	409	4.69
+50%	413	4.66

* Baseline case: dead-band amplitude: ±2 K; intermittent heating; heat pump on/off penalization factor: +30%; fixed supply temperature: 29°C.

In Figure 1, relative to the baseline case, the evolution of a few characteristic temperatures of the system (internal and external air temperatures, mean radiant and operative temperatures, and temperatures of the floor and of the internal surface of the window) is shown for a typical 48-hour period. The occupation and intermittency periods are identified with vertical dashed lines, while the lower and upper limits of the temperature set-point dead band are horizontal dashed lines. The floor temperature is always lower than 25°C, ensuring human comfort and respecting the legislative limits [15]. The temperature of the internal surface of the window is relatively high (it stays in the 15–18°C temperature range), considering that the window is the less efficient component of the building envelope. In Figure 1, the internal air temperature shows a faster response than the mean radiant temperature (which also includes the radiant floor); consequently, their temperature–time curves typically intersect twice a day.

For the next series of simulations, we evaluated the system energy performance as a function of the water supply temperature to the radiant floor, also analyzing the effectiveness of weather-based control. The implemented linear climate-control law was tailored to this specific case study, choosing 35°C as water supply temperature for external air temperatures below or equal to the design temperature of Pisa (0°C) and 25°C as supply temperature for external temperatures equal to or over 17°C (in average steady-state conditions, at 17°C space heating is no longer needed for the building). A maximum water supply temperature of 35°C was meant to avoid uncomfortably-high floor temperatures, while a minimum supply temperature of 25°C ensured the necessary heat exchange from the radiant floor to the other internal walls and to the ambient air.

The two control strategies are compared at the same seasonal average supply temperature (29°C). The total electric energy needs of the heat pump are 6% lower for the fixed supply temperature with respect to the weather-based control. This result can be explained considering that, with the climate-control law, the COP is reduced in cold days, due to both higher supply temperature and lower external temperature; vice versa, the COP is increased in mild days, but the latter ones are also associated to lower thermal loads for the building and, subsequently, have a smaller influence on the seasonal performance of the heat pump.

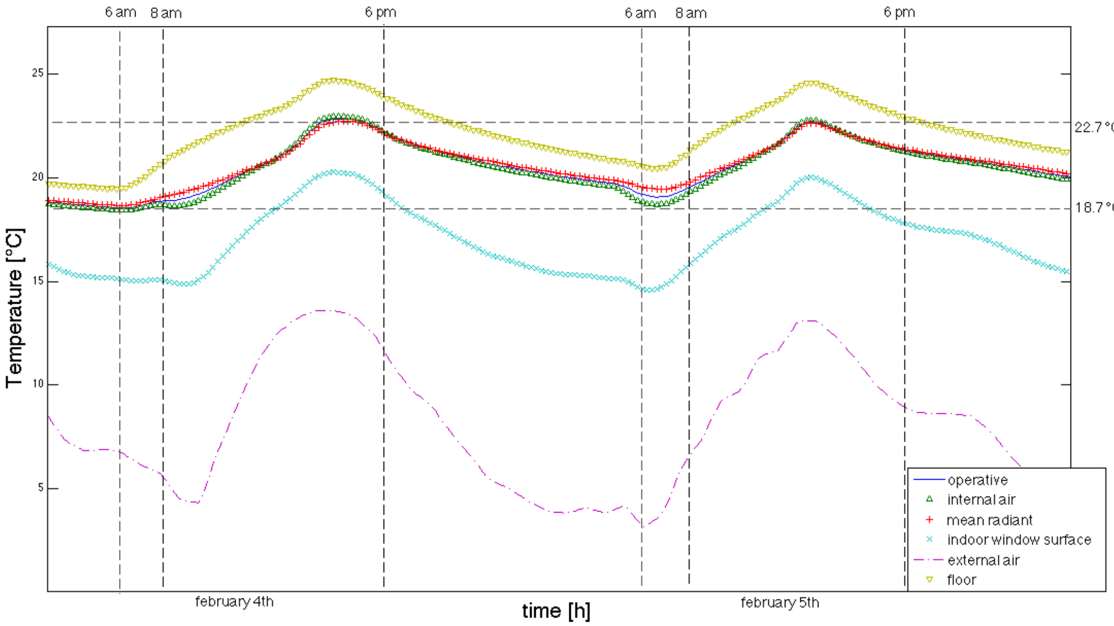

Fig. 1. Evolution of characteristic temperatures of the system during a typical 48-hour period (baseline test case).

As for the simulations with fixed water supply temperature to the radiant floor (tested cases: 25°C, 27°C, 29°C, 31°C, 33°C, and 35°C), we obtain the curves illustrated in Figure 2, relative to the heating season electric energy needs and to the heat pump SCOP. As both curves seem to tend to a saturation of performance at low supply temperatures, a proper trade-off could be to operate in the 27–29°C range, sufficiently far from the operating limits of the heat pump and, at the same time, speeding up the room heating process at each system switch-on (in particular, for the intermittent heating mode, at the morning start-up). Figure 2 also highlights that energy savings as high as 15% can be achieved in this system at no cost, merely reducing the target supply temperature.

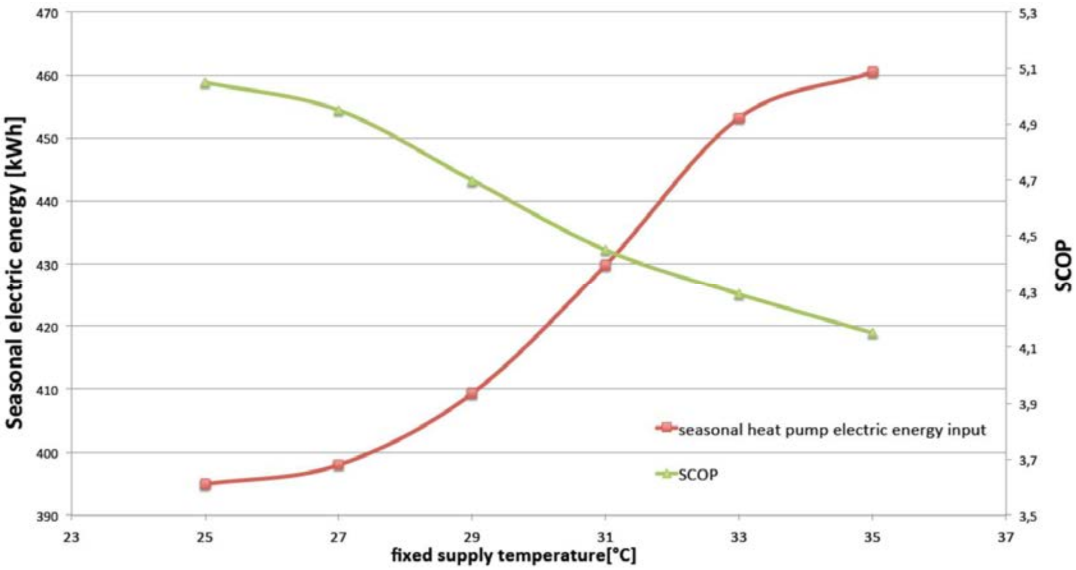

Fig. 2. Heating season electric energy needs and heat pump SCOP at various fixed values of water supply temperature to the radiant floor.

5. Conclusions and future developments

In the present work, an effective integration of three in-house independently-validated dynamic models (i.e. building envelope, radiant system, and vapor compression heat pump) was accomplished, so that the transient thermal response of a building and the instantaneous and seasonal energy performance of a system involving a modulating heat pump coupled to a radiant heating floor could be simulated and predicted in detail.

For a given case study, in which we selected a particular climate, benchmark room, occupation model, radiant floor design, and heat pump type, we analyzed the influence of different control strategies on the heating season energy needs. The results of the simulations showed that the performance of these heating systems is highly sensitive to the water supply temperature control law. Conversely, the temperature set-point dead band amplitude is immaterial in terms of energy needs and the effect of the heating mode (intermittent or continuous) is quite small, also due to the high time constant of the building (77 hours).

The implementation of a typical weather-based control proved to be detrimental with respect to simple delivery at a fixed temperature. On the other hand, energy savings up to 15% could be obtained simply reducing the target supply temperature from 35°C to 25°C and adjusting the internal temperature set-point. These results encourage us to continue the full dynamic simulation of the system and deepen the search for an optimal control, exploring the application of lags to climate-based laws, of controls tailored to comply with scheduled internal activities, and so on.

Apart from the focus on control, the developed simulation code can be used for obtaining detailed and accurate results in activities such as: building energy audits, feasibility studies, cost-benefit analyses, evaluations of thermal comfort conditions, and design for optimal energy efficiency.

Experimental validation of the full dynamic model on a real building with radiant floor and heat pump is in sight.

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