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MODELLING THE PERFORMANCE OF A DOMESTIC LOW-TEMPERATURE HEATING SYSTEM BASED ON A HEAT PUMP

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ABSTRACT

Low temperature heating systems for single-family houses, based on heat pumps are becoming progressively more preferable in the global market. The possibility of such systems to optimise the energy utilisation and to achieve a high annual energy efficiency make them more promising for future low energy houses. In this study we model and analyse the performance of a low temperature heating system based on a heat pump. A system model is developed in two parallel simulation programs: in EES (Engineering Equation Solver) for simulating the operation of the heat pump and in TRNSYS for studying the performance of the heat distribution system and the building zone. The efficiency factors for the various components in different case studies are calculated. The computation seeks to highlight possibilities for energy savings and for increasing the overall efficiency. The simulation results indicate the need to study the performance of the heat pump and the heat distribution system together.

NOMENCLATURE

A_j: internal overall surface of the J^{th} wall or window
h_j: total heat transfer coefficient of the J^{th} surface
$\dot{Q}_{\mathrm{inf}}$: infiltration energy gains
$\dot{Q}_{lat}$: latent energy requirement
$\dot{Q}_{speop}$: sensible gains from people
$\dot{Q}_{z}$: convection energy gains
T_z : zone temperature
ω_a : humidity ratio of ambient air
ω_z : humidity ratio of zone air
Cap: room air and furniture effective capacitance
$\dot{m}_{\mathrm{inf}}$: mass flow rate of air infiltration
$\dot{Q}_{\mathrm{int}}$: internal energy gains
$\dot{Q}_{sens}$: sensible energy requirement
$\dot{Q}_{v}$: energy gains due to ventilation
$T_{s,j}$: temperature on the J^{th} surface
Δh_{vap}: heat of vaporisation of water
$\dot{\omega}_I$: rate of internal moisture gains to zone

INTRODUCTION

The possibility of optimising the performance of a heating system and minimising the energy requirement for heating a house is of great importance. Especially in a Nordic country like Sweden, where 60% of the annual energy use in the building sector accounts for space heating and domestic hot water production, energy efficient heating systems are concepts with increasing value (Nutek, 1997).

Recently, there has been growing interest in using low-temperature heating systems combined with heat pumps in single-family houses. Considering the heat distribution system, the general trend is to move in the direction of lower inlet temperatures and large heat transfer surfaces. A floor heating system is an interesting solution and has been rather extensively studied in recent years. Furthermore, installers show an increasing preference for it.

Taking the heat-generation side into account, the main technical trend is to choose a system that is environmentally friendly, requires low power input to produce the heat, and eliminates the heat losses. A well-designed and properly dimensioned heat pump fulfils the previously mentioned prerequisites. In Sweden, which is a market leader in manufacturing heat pumps among the European countries, heat pump is a considerable option when selecting a residential heating system (Bouma, 1999). Nevertheless, using a heat pump is more a techno-economic issue than a simple question of performance (Granryd, 1998). System design is probably the most crucial part in the route to successful implementation of heat pumps in dwellings (Traversari et al, 1999). For future low-energy dwellings, there is an urgent requirement for low-cost heat pump heating systems with a high-annual energy-efficiency (Afjei, 1997). Furthermore, when selecting a heating system, great attention should also been devoted to the building construction and its characteristics (Norén et al, 1999). The critical point for every heating system is to achieve the optimum operation after its installation. So the optimisation phase must include the building as well.

The performance of a heating system based on a heat pump has been individually studied at length. However, to achieve the objective of high comfort in a cost efficient and environmentally acceptable manner, the heat pump, the heat distribution system and the building have to be studied as a complete system (Afjei et al, 1999). The aim of the present paper is to study the operation of the heating system and the building as a whole. The results show a comparison of the performance of the heating process based on different cases for the heat generation, the heat distribution system and the building envelope. The significance of the building construction and its behaviour as a dynamic system is extensively highlighted when selecting the appropriate thermal energy system.

CASE STUDY DESCRIPTION

Reference model and system description

The main objective of this paper is to investigate the performance of a low-temperature heating system based on a small-size heat pump for a single-family house. The system analysis focuses particularly on the importance of the building's characteristics when a low-temperature heating system is chosen to serve its thermal requirements. Therefore, a reference system is developed in two parallel simulation programs: one for the building zone and another for the heating system. The simulation tools allow the link between the building zone and the heating system by a method of exchanging information between the programs. Hence, previously set outputs from the heating system can be inputs in the building and vice versa. In this way a unique system is obtained where the simulation can be run in iterative loops between the building zone and the heating system. The system boundary includes everything from the heat source to the evaporator of the heat pump up to the climatic conditions of the geographic location where the building is situated.

Description of the building zone model

The building zone is developed in TRNSYS, a package of stand-alone utility programs that enables a system dependent on time to be built and analysed. The building zone is built by components included in the standard TRNSYS library. The main component in the simulation program describes the building zone. The system includes component routines that handle the input of the weather data and the output of the simulation results.

The zone is specified by separate sets of parameters and inputs describing the internal space, the external weather conditions, the walls, the floor, the ceiling, the windows and doors (ASHRAE, 1993). The ASHRAE transfer function approach is followed for modelling the zone structure. The convection and radiation losses and gains are calculated based on the transfer function coefficients that are determined after selecting the zone construction. The internal energy input is based on the radiant and convective gains due to lights, equipment, presence of people and the level of their activity, as well as any other instantaneous heat gains to space.

The simulation program based on the reference model permits the heating load of the building zone to be estimated. By setting the desired zone temperature and the desired zone humidity ratio, the thermal requirement of the building zone can be calculated. The mathematical description for the sensible and the latent energy requirement of the zone are the two basic equations governing the heat transfer through and between all elements in the zone:

$$\dot{Q}_{sens} = \dot{Q}_z + \dot{Q}_v + \dot{Q}_{\text{int}} + \dot{Q}_{speop} + \dot{Q}_{\text{inf}} + \sum_{j=1}^{N} h_j \cdot A_j \cdot (T_{s,j} - T_z) - f(Cap, T_z)$$

$$\dot{Q}_{lat} = \Delta h_{vap}(\dot{m}_{\text{inf}} \cdot (\omega_a - \omega_z) + \dot{\omega}_I)$$

The sensible energy requirement for maintaining the desired indoor temperature is obtained from an energy balance of the zone air and furnishings considered as a lumped capacitance system. The simulation model takes into account both convection and radiation heat transfer when estimating the sensible load. The latent energy requirement is based on a moisture balance of the room air at any instant. The latent load is the energy required to maintain the zone humidity ratio within the desired humidity comfort zone.

The key inputs to the simulation program are the climatic conditions for a whole year provided on an hour-step basis and the main building characteristics (Table 1). At present, it is worthwhile mentioning that the program allows changes to the window total heat transfer coefficient. Hence, variable window transmittance of solar radiation and thermal energy transfer across the window are achievable.

Table 1. Main input information for the building zone model on the climatic conditions and the building location and construction.

Climatic hourly-provided data	Building location and construction
• Beam radiation on horizontal surface (kJ/m²hr) • Diffuse radiation on horizontal surface (kJ/m²hr) • Dry bulb temperature of ambient air (ºC) • Relative humidity of ambient air (%) • Wind velocity (m/s)	• Malmö, Sweden, 55.8º north latitude • One-storey dwelling, no cellar • Floor area of 120 m² • Window area corresponding to 15% of the total floor area • *Variable gain windows*[1] as an option

[1] *Variable gain window* is a component in the standard TRNSYS library that allows the window total heat transfer coefficient to be changed due to insulating curtains on the window.

Description of the heating system model

The heating system is modelled in the Engineering Equation Solver (EES). EES is an equation-solving program with built-in functions for thermodynamic and transport properties of many substances including refrigerants. Since refrigerant properties can be obtained in EES, it is rather convenient to model the performance of a heating system based on a heat pump. The development of the heating system depends on the building's characteristics and dynamic behaviour. Despite the fact that the simulation programs of the heating system and the building zone are built in two separate environments, the simulation runs simultaneously, connecting the models as if they were one. Therefore, the heating process in the chosen building zone and the interaction between them can be attained.

The heating system model is based on assumptions corresponding to a realistic approach. The model pertains to a ground coupled heat pump unit connected to a low temperature, hydronic distribution system. The heat pump unit is sized so that it covers a certain amount of the maximum energy demand of the chosen building zone. Nevertheless, in Sweden it is common to have an auxiliary heating system supporting the heat pump during the coldest period of the year when the maximum load occurs.

The climatic conditions are the same as the weather input to the building zone. The ground conditions are taken for the location of Malmö in Sweden. For buildings in Malmö the outdoor design temperature (ODT) is set to –17.5ºC.

With respect to the heat source, a single borehole with a U-shape tube is placed in rock. An indirect system is chosen with a brine of ethylene glycol circulating between the heat source and the evaporator. For the sake of simplicity, a constant amount of energy extracted from the ground is assumed equal to 35 W/m. This is typical for a single borehole presupposing sufficient installation in rock with proper backfilling (Granryd, 1998). R410A is chosen as the working fluid. However, performances from using different refrigerants are given later on in this study. The rest of the heat pump components are modelled based on technical details of current components with sufficient performance.

For the heat distribution system, a hydronic floor heating assembly is selected. The floor is directly placed on the ground and the ground is considered in the building zone model as a separate zone attached to the building zone with a constant temperature of 9°C. The total thermal conductivity of the floor depends on its construction and the thickness of the insulation placed on the ground. A major prerequisite is that the ground is properly insulated in order to minimise energy transfer to the ground and the risk for moisture transfer in the construction. A suspended floor heating system is considered in this study with a rather low capacity to absorb large changes of loads in the building. The operation of the heat distribution system is included in the building zone model developed in TRNSYS. However, the flow regulation and control mode are included in the heating system model developed in EES.

With respect to the heat pump, the governing equations in the simulation program enable the calculation of the heating power and the coefficient of performance for the heat pump. The isentropic and volumetric efficiencies are estimated depending on the compressor's pressure ratio and the refrigerant's molar mass (Pierre, 1979). The transmission and electric motor efficiencies are also taken into consideration.

Regarding the floor heating system, its operation is regulated on an ON-Off mode. The design supply-water temperature is 28°C, which gives an overall heat transfer coefficient of 4.8 W/m^{2}°C. Heat transfer due to radiation has a portion of around 65% and the remaining 35% corresponds to convection heat transfer. The main set variables for the heating system are given in table 2.

The heating process is controlled from the temperature of the building zone. A single two-stage thermostat regulates the operation process. When the zone temperature exceeds 20ºC, the brine pump and the compressor are stopped.

Table 2. Main input information for the heating system.

Heat pump unit

- Refrigerant R410A
- Inlet brine temperature –0.5°C
- Capacity of the borehole 35*x W, where x borehole length (m)
- No sub-cooling
- Steady superheating 5°C
- Temperature difference between the condensation and the supply water 5°C
- ON-OFF compressor's function mode

Suspended floor heating system

- Heat flux upwards 40 W/m^{2}

RESULTS AND DISCUSSION

One of the main purposes of this paper is to investigate the energy requirement of different building constructions, taking the building's characteristics into account. For this reason, three building zones with different construction tightness are selected. Table 3 provides information on the chosen building types. As we can see, the variation in the wall and roof heat transfer coefficient is rather small. However, a larger effect factor is taken when the floor heat transfer coefficients are selected. There is also a possibility of varying the window-radiant gains. Three cases are considered. In the first case, it is assumed that there is no internal shading and all the radiation entering the window strikes the floor and is then captured by the internal space of the building zone. In the second case, there is internal shading corresponding to 50% of the total window area and in the third, there is internal shading corresponding to 80%. A time-schedule is used for applying the internal shading only in hours of high solar radiation. The option of a variable gain window affects the transmittance of solar radiation and consequently the thermal energy transfer to the building zone.

At this point, it is worthwhile mentioning that all windows are of the same type with a conduction transfer coefficient of 1.2 W/m²K and an average window transmittance of 0.7.

Table 3. Information on the characteristics of the chosen building zones.

	Super-insulated[3]	Well-insulated[3]	Med-insulated[3]
Wall heat transfer coefficient[1] (W/m²K)	0.213	0.245	0.294
Roof heat transfer coefficient[1] (W/m²K)	0.195	0.226	0.258
Floor heat transfer coefficient[2] (W/m²K)	0.278	0.361	0.417

[1] The wall and roof heat transfer coefficients are increased by a rate of 15% and 30% from super to well-insulated and med-insulated construction respectively.
[2] The floor heat transfer coefficient is increased by a rate of 30% and 50% from super to well-insulated and med-insulated construction respectively.
[3] The fraction of the incoming beam radiation is set to 100%, 50% and 20% respectively, in hours of high solar radiation.

The results, shown in figures 1 and 2, highlight the influence of the chosen building's characteristics on both the heating and cooling requirements of the house. Although the heating requirement is kept low, the cooling requirement might rise considerably in a tight construction especially when big fenestration is applied with the latest types of glazing that allow for high radiation gains but low heat transfer losses. However, the use of the variable gain window mostly influences a very well insulated construction, considerably decreasing the cooling requirement. Nevertheless, due to aspects of aesthetics and thermal comfort, internal shading on windows in building zones is commonly applied, so that using a variable gain window is closer to a more realistic approach.

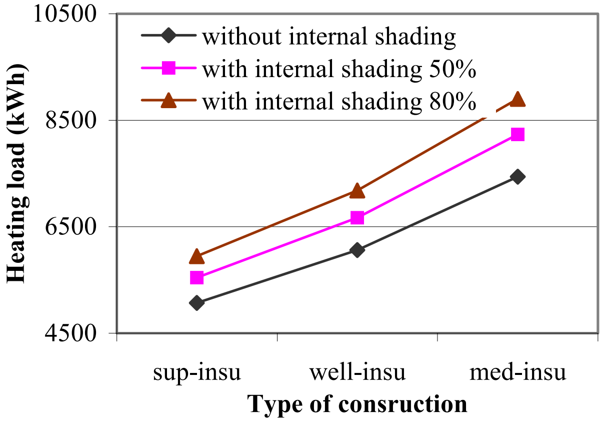

Figure 1. Heating load for different building types and different cases for internal shading.

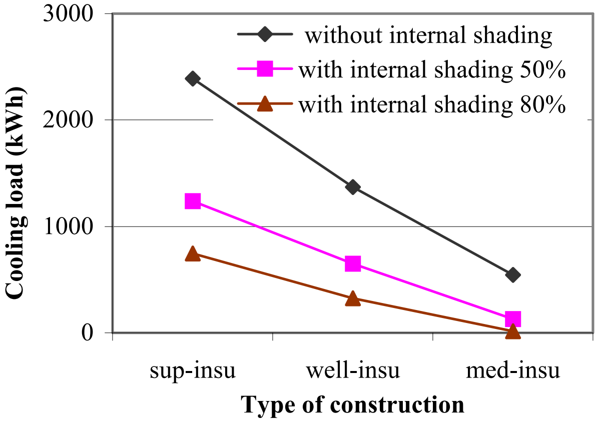

Figure 2. Cooling load for different building types and different cases for internal shading.

Table 4 shows the change in the heating and cooling requirement of the three building types when internal shading is not applied and 80% of internal shading is applied respectively.

Table 4. Change in the thermal energy loads when 0% and 80% of internal shading is applied respectively.

	Super-insulated	Well-insulated	Med-insulated
Increase in the heating requirement (kWh)	870	1120	1400
Decrease in the cooling requirement (kWh)	1640	1050	530

Another important objective of this study is to investigate the interaction between the heating system and the building zone. The following discussion focuses on the influence of the heat pump's chosen characteristics on the heating process and its capability to cover the energy requirement of a specific building construction. Hence, for this part of the discussion the very well insulated building type with internal shading corresponding to 50% of the total window area is taken into account.

The heat pump is sized so that it covers 44% of the capacity. The maximum heating load occurs during the night of the 30th of January and is 13,215 kJ/hr although the maximum heat provided by the heat pump at that time is 5,756 kJ/hr. The heat pump dimensioned in this way covers 87% of the zone's total heating requirement (figure 3). The ambient and zone temperature profiles for a period of a high heating requirement are illustrated in figure 4. The x-axis shows the total hours from the beginning of the year. Thus, the number of 500 hours corresponds to the 21st of January and the number of 740 hours to the 31st of January. As can be seen, the building zone temperature falls under 20°C because at this point there is no supplementary heat provided. The peak for the zone temperature in the time period between 620 hr and 660 hr, despite the decrease in the ambient temperature, occurs because of a high solar radiation rate at that time.

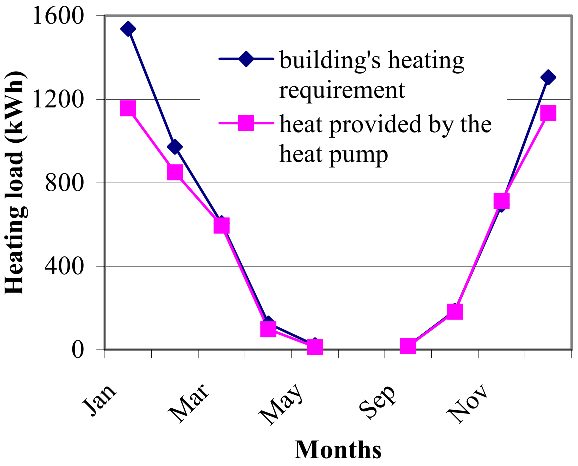

Figure 3. Coverage of the building's heating load by the heat pump.

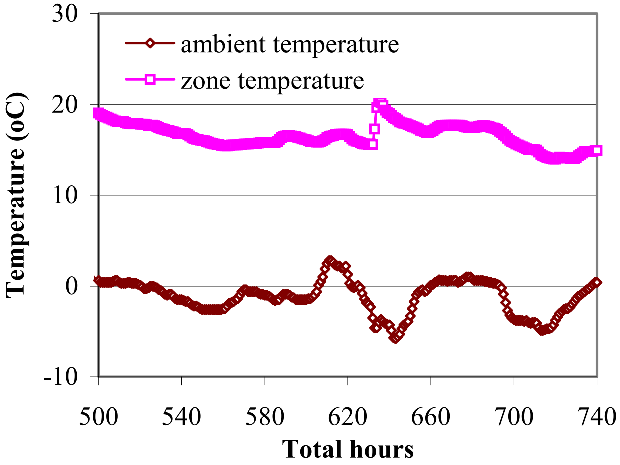

Figure 4. Ambient and zone temperature profiles for a period of a high heating requirement.

The above-stated results refer to a heat pump unit with specific characteristics that are mainly exemplified in table 2. The chosen borehole length is 35 m. The increase of the borehole length by 5 m results in a 3% increase in the coverage ratio of the building's heating requirement by the heat pump. Deciding the preferable borehole length is a pure matter of system economic optimisation. However it is advisable to bear in mind that an oversized heat pump is not desirable from an economic point of view.

With the chosen assumptions for the heat pump, its performance depends merely on the chosen refrigerant. Table 5 below shows a comparison of performances when the heat pump unit described above is used but with different refrigerants. The borehole depth is 35 m and the temperature lift in the vapour compression cycle is 38° C.

Table 5. Comparison in the heat pump's performance when different refrigerants are used.

Refrigerant	R410A	R404A	R407C	R134a
Heat pump's heating power (W)	1626	1658	1703	1639
Coefficient of performance (COP_1)	3.46	3.24	3.05	3.43
Highest temperature in the vapour-compression cycle (°C)	60	48	67	51

A crucial aspect in the selection of the refrigerant is also the possibility to obtain a high temperature at the compressor's outlet while maintaining a low condensation temperature. This is favourable for heating the sanitary water up to a sufficiently high temperature (Sakellari, 2000). Table 5 justifies the choice of R410A as a suitable refrigerant since it allows both high coefficient of performance and high temperature at the compressor's outlet.

Regarding the operation of the floor heating system, its effect on the heating process and the zone is examined. Figures 5 and 6 show the variation of the zone temperature and the operation mode of the floor heating system for four cold days in January and for one day in April respectively.

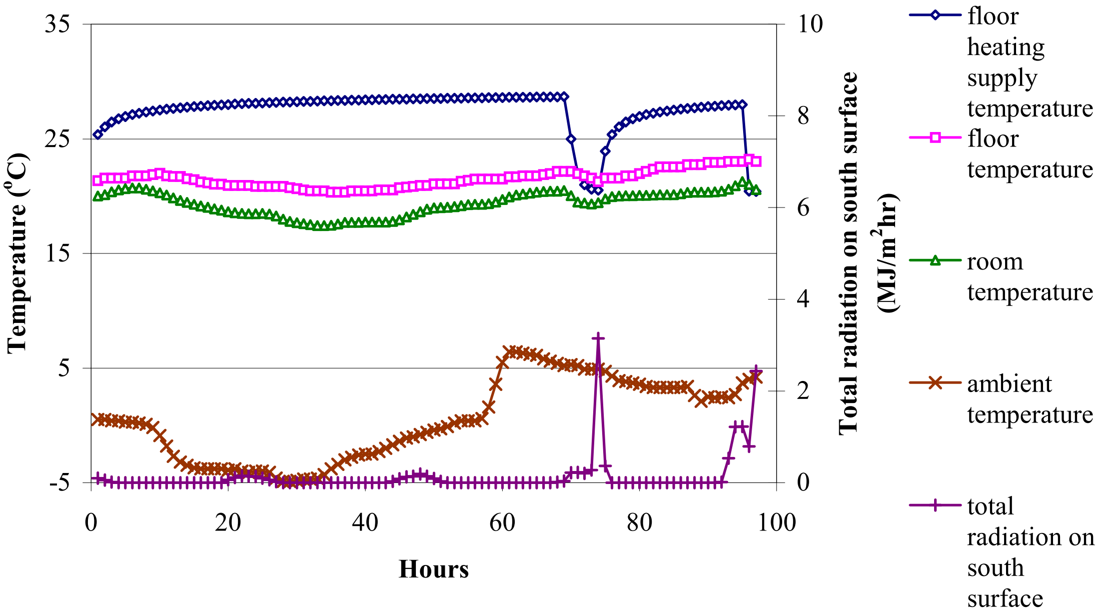

Figure 5. Temperature and total radiation on south surface for four days in January.

Figures 5 and 6 illustrate the operation of the floor heating system in two different periods of the year. The figures show clearly the importance of the system's inertia and its tendency to respond slowly to rapid load changes. By increasing the thermal storage capacity and decreasing the floor heating supply temperature the phenomenon of inertia can be eliminated (Feustel, 1998). Furthermore, modern sophisticated controls might be able to contribute to a better overall performance (Kenneth et al, 2001).

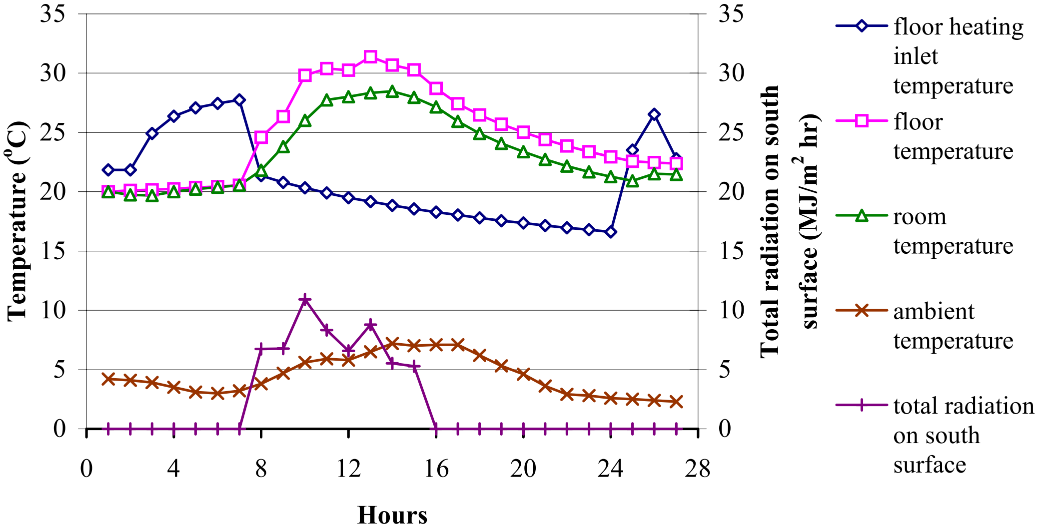

Figure 6. Temperature and total radiation on south surface for the 9th of April.

CONCLUSIONS

This study has attempted to investigate the performance of a low-temperature heating system based on a small-size heat pump. The main objective has been to assess the interaction between the heat generation system, the heat distribution system, and the building zone. The findings provide evidence that the system approach should focus on the energy efficiency of an integrated heating system including the building zone.

The results indicate the significance of the building construction and its dynamic behaviour when selecting the most suitable heating system. Tight building constructions with heavy insulation and low heating requirement allow for low-temperature heat distribution systems and consequently for low condensation temperature on the heat pump side. Hence, the chain of optimisation should be followed for the integrated approach.

However, in tight building zones a critical issue is the increase in the cooling requirement. Important key factors are the solar radiation and the human factor. Rapid load changes might result in a high cooling demand in order to sustain the thermal comfort. This creates the need to decrease the system inertia and increase its capability to show a fast response to unpredicted load changes. Two possible solutions to deal with the above stated problem are to implement latent thermal storage in the building construction and to decrease the supply water temperature in the heat distribution system.

Regarding the heat pump, system design and proper sizing are the most crucial aspects in the route to successful implementation of heat pumps in buildings. Optimising the heat pump is a techno-economic issue depending not only on the operation of the heat pump and the savings but also on its function in the heating process.

At this point, we should state that this study has concentrated on a specific residential building type. It would thus be of interest to investigate other types of residential buildings as well as commercial buildings. Moreover, a simplified building zone model has been developed and used in this study. A more complex model with several zones with different heating requirements and ventilation rates should be developed to provide a more realistic approach.

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