AN INNOVATIVE FLOOR HEATING APPLICATION - TRANSFER OF EXCESS HEAT BETWEEN TWO BUILDING ZONES

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ABSTRACT

The performance of an innovative floor heating application is explored. A two zone building is studied; one zone is frequently overheated due to intensive solar gains while the second zone is essentially unaffected from incident solar radiation. The aim is to explore the possibility to simply extract excess heat from the overheated zone. The idea is to transfer extracted heat through the hydronic floor heating pipe to the second zone; hence, the heat demand for the second zone is decreased.

Simulation results yielded a reduced indoor air temperature in the warm zone. The most prominent improvements in thermal comfort were found during night time. Furthermore, the total heat supply was slightly reduced by actively transfer heat between the zones. It can be concluded that the potential to substantially reduce the total heat demand is not found. The duration of heat extraction in the overheated zone is also quite short.

KEYWORDS

Floor Heating, Building Integrated Heating, Passive Solar Heating, Thermal System Analysis, Simulink.

INTRODUCTION

Building integrated heating (BIH) is defined as a heat supply system that maintains the indoor thermal comfort within acceptable limits by means of a controlled heat supply towards the inside of the building envelope. Heat is either supplied or extracted from a hydronic pipe loop embedded within the construction element. Floor heating is a well-known BIH application. Thermally Activated Building Component Systems (TABS) (Koschenz and Lehmann, 2000) is another similar application of BIH. In combination with heat storage in heavy building elements, TABS are used for both cooling and heating of (office) buildings.

A large area of the building structure is utilised in most BIH applications. Thus, a relatively small heat flux density (W/m^2) is sufficient to uphold thermal comfort within the indoor environment. A low temperature design of the hydronic system is hereby possible. However, a correct design of the BIH element is essential, particularly the thermal resistance of the floor covering material is central. Low temperature design has the potential for an increased use of low temperature heat sources such as waste heat, solar heat and energy efficient heat pumps. Utilisation of these heat sources may reduce the environmental impacts from space heating in buildings.

In the present paper, the possibility for further developments of BIH systems is explored. A two zone building is considered where one zone is repeatedly overheated due to intensive solar gains. The aim of the present study is to investigate, through explorative simulations, whether useful excess heat can be extracted within the overheated zone by applying floor heating technology.

Understanding the function of a floor heating application of this kind requires consideration of heat conduction, heat convection and thermal radiation processes which are interrelated; heat conduction within the floor slab is influenced by the supply/extraction of heat from the embedded pipe and by the surface heat flux density through convection, thermal radiation and incident solar radiation. The thermal problem lies in solving the heat transfer from the pipe to the floor construction, and then to the internal surface. In order to attain a realistic assessment of the performance, all these heat transfer processes must be considered on a fundamental and detailed level. To illustrate this position further, models based on steady state heat conduction simplifications are not applicable (Strand and Pedersen, 2002; Laouadi 2004). In order to adequately assess the function of BIH systems, the BIH element must be coupled to a room model taking into account detail surface heat transfer mechanisms. This is a widespread position concluded by several authors (Strand and Pedersen, 2002; Laouadi, 2004; Weitzmann, 2004). Furthermore, Weitzmann (2004) concluded that an electrical implementation of the heat supply is not adequate when hydronic systems are considered. In addition, the function of the control system is essential to understand the overall performance of the BIH system.

In order to assess the performance of various BIH applications, Karlsson (2006) developed a comprehensive numerical simulation tool for BIH systems. This tool is applied to explore the performance of the floor heating system in the present two zone building.

NUMERICAL SIMULATION TOOL

Heat transfer processes that occur within the BIH system during operation of the building are computed by the simulation tool. The BIH model is developed as a subsystem of the building itself and is aimed to work jointly with several other subsystems. Together these subsystems outline a prototype of the whole building as a dynamic thermal system. The dynamical system of various heat transfer processes within the building is illustrated in Figure 14.

Simulink (MathWorks) which is a general-purpose graphical programming language that works on top of Matlab (MathWorks) is used to develop the BIH simulation tool. Interfaces between subsystems follow a list of conventions that are stated by the International Building Physics Toolbox in Simulink (IBPT). Thus, the BIH tool is entirely compatible with IBPT.

The model for the BIH element is of particular interest in this paper. A hybrid three-dimensional model for building elements with embedded hydronic pipe loops was developed by Karlsson (2006). The BIH simulation model is based on transient numerical finite control volume technique. Along with the hydronic pipe loop, the volume of the construction element is modelled as a series of two-dimensional section planes, see Figure 1. All section planes are serially coupled, in the downstream direction, through the convective heat transfer inside the embedded pipe loop. Thus, a heat exchange between the pumping fluid and the embedding material take place along with the pipe loop.

For a BIH system, the requirements for modelling of fundamental surface heat transfer mechanisms are much more precise compared to a traditional hydronic heating system with high temperature radiators. Therefore, Karlsson and Hagentoft (2005) implemented a detailed long wave radiation exchange model for enclosures in the IBPT simulation platform. An empirical model derived by Awbi and Hatton (1999) is applied to estimate the convective surface heat transfer coefficient for the BIH element surface.

The subsequent application is one example of thermal system analysis of BIH systems and buildings were the simulation model is especially suitable.

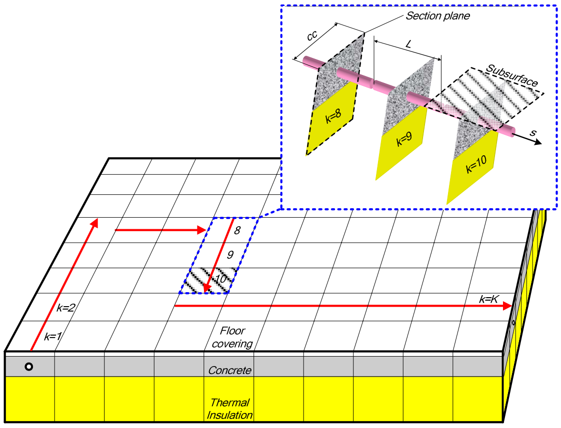

Figure 1 Illustration of space discretisation of a floor heating element with subsurfaces, section planes and pipe segments. The arrows indicate a conceivable pipe loop pattern. (Karlsson, 2006)

APPLICATION

Scope

The intensity of internal heat loads diverge between different areas of a building. If then the building is composed of smaller units (e.g. thermally insulated rooms or apartments) that don’t allow an equalisation of thermal states, the heat demand may also vary significantly among different locations within the building. Some areas would still have a heat demand while others would be uncomfortably warm. To illustrate this experience further: during clear and rather cold autumn and spring days, units that are exposed to solar radiation through windows are commonly overheated, simultaneously units located at the north façade still have a net heat demand. In order to attain a better thermal comfort in this situation, heat gains can be decreased by applying solar shading devices or solar control glass; otherwise heat must be extracted from the overheated unit. Cooling of the unit can for example be done by opening windows and increase the ventilation rate. However, in the former action, useful solar energy is not utilised in the heating of the building as a whole. In the latter action, energy is simply wasted from the building.

The application presented in the subsequent is aimed to explore the possibility to use a conventional hydronic floor heating system in order to transfer heat from areas with intensive internal gains to other locations with a simultaneous heat demand. Hence, the floor heating system will then actually operate as a high temperature cooling system in areas with intensive heat gains.

Building design

Achermann and Zweifel (2003) specifies a test case for comparative evaluation tests for building energy analysis tools including modelling of radiant systems. Based on the building geometry given by Achermann and Zweifel (2003), two identical zones, A and B, are considered in the present application; an internal and thermally insulated wall separates the two zones, see Figure 2. A building envelope constructed in concrete (0.1 m), external foam insulation (0.2 m) and outer wooden panel (0.02 m) is considered. The hydronic floor heating system is embedded within a 0.1 m thick concrete slab. A limestone floor covering (0.012 m thick) is applied all over the concrete surface. Underneath the concrete slab, a 0.25 m thick thermal insulation is situated to prevent heat losses to the ground. All windows are assumed to be positioned in front of an unbroken horizon; window shading is not applied. The air exchange rate is 0.5 1/h and pre-heating of supply air is not provided.

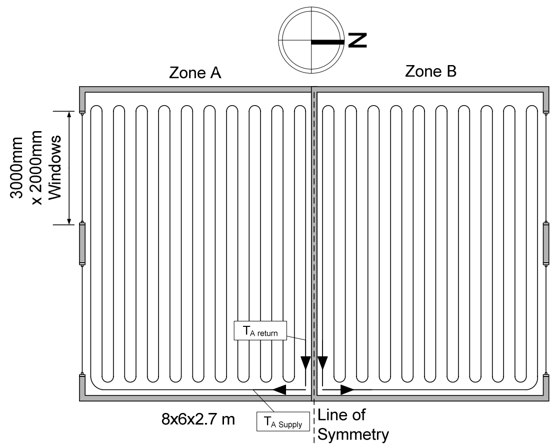

Figure 2 Principal outline of the considered building. Pipe loops are illustrated in each zone

The present simulation case is designed in order to explore the possibility to store and transfer useful solar energy from zone A to B. Altogether, the window orientation, the choice of heavy internal materials are beneficial for a significant heat transfer between A and B. The heat balance at the floor surface is a crucial aspect in the present simulation case. It is assumed that 64.2 % of all incoming solar radiation is absorbed at the floor surface (Achermann and Zweifel, 2003). Moreover, the selection of limestone flooring facilitates the performance of the present application.

Design of floor heating system

A hydronic floor heating system is considered. Pipe loops made of crossed-linked polyethylene pipes that are mounted within the concrete floor slab. A pipe dimension of 25/20 mm (inner/outer diameter) and a centre to centre distance of 0.3 m are used in both zone A and B.

The heat supply to a typical floor heating system is controlled with the supply temperature, which is common for a group of pipe loops which all are connected to a common manifold assembly. Each pipe loop is equipped with a thermostatic valve to prevent overheating due to internal heat gains. However, if heat is to be distributed from zone A to B, as in the present application, the fluid flow can not be stopped when significant heat gains are present. Therefore, the system design has to be adjusted in order to be applicable in the present situation; the heat supply is entirely controlled with the supply temperature as the fluid flow is constant and continuous. These are the prerequisites for the fundamental control of any design of the present system.

Considering the specific application, the relation between fluid temperature level and the indoor temperature is of great importance. The temperature of the fluid that is supplied to zone A must be sufficiently low in order to extract heat from the floor construction. One important issue is how to obtain a ‘cold’ fluid temperature in a system without a cooling device. In the present application, a low fluid temperature is entirely obtained when the fluid exchanges heat as it passes through the floor construction of zone B. Thus, the interaction between these two zones (A and B) is also of great importance.

In the present paper, two alternative systems are explored. Considering the first system design (*Case 1*), the return fluid flow of each pipe loop is mixed to a common return temperature. This design is similar to the typical floor heating system; however, the mixing of the common return flow and heat from the primary heating system can be individually adjusted for each pipe loop in order to prevent overheating in a single zone. In this case, any extracted heat from zone A is transferred to the common supply side of the heating system.

The lowest possible supply temperature to zone A is obtained when the return flow from zone B is connected directly as the supply flow to zone A. In this second system design (*Case 2*), zone A and B outline one single pipe loop (serially coupled). Thus, heat is continuously extracted (zone A) or emitted (zone B) from/to the different floor constructions along this single pipe loop. However, a single pipe loop design is only applicable when the objective is to transfer heat from A to B. When there is no potential to transfer heat from A to B, the heat demand of each zone is supplied in two unique pipe loops. It is much practically to operate the system with a unique pipe loop in each zone without mixing or transferring of return fluids between the two pipe loops, especially when the heat demand of each zone differ significantly.

Therefore, a 4-port valve is applied to interchange between these two operation conditions.

A reference case (*Case 0*) is studied in addition to the two alternative floor heating systems (*Case 1 & 2*). *Case 0* is designed as a typical floor heating system without the function of heat transfer between zone A and B.

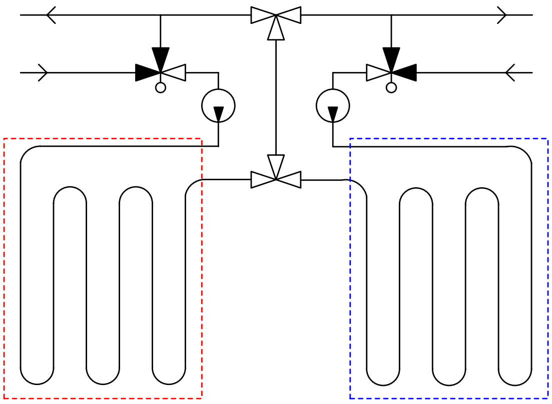

Figure 3 Principal system design for Case 1. Mixed return flows generates the desired heat transfer between A and B.

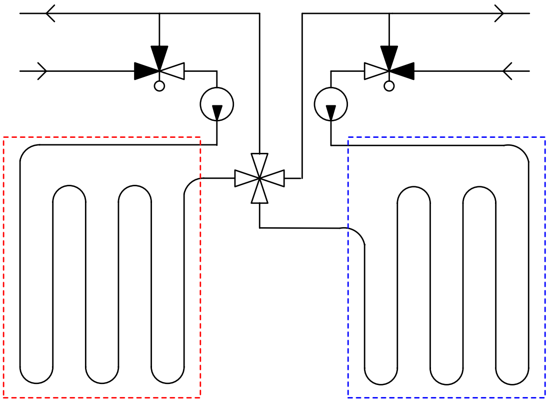

Figure 4 Principal system design for Case 2. The 4-port valve interchange the system operation between two unique pipe loops or one single loop.

Control System

Above all, also absolutely relevant in this application, the function of the floor heating system is to uphold thermal comfort by means of a heat transfer to the floor construction in proportion to the net heat demand in each zone. As internal gains rises within zone A, heat may also be extracted from the floor construction and then be utilised to pre-heat the supply side of the hydronic floor heating system. A control system is essential to ensure the desired function of the system.

A feed forward control strategy is applied for all system designs. The supply temperature is controlled linearly according to the outdoor air temperature. Whenever needed, hot water from the primary system is injected to the supply of each pipe loop according to the linear feed forward control.

A dead band control is applied to trigger the exchange of mass flows between A and B, and hence the heat transfer. The dead band control also prevent overheating of the zones; whenever the indoor air temperature exceeds the upper limit of the dead band (+23°C), the active supply of heat is stopped. In *Case 2*, the dead band controls the 4-port valve; a serially coupled pipe loop able to transfer mass flow directly between A and B is triggered at the upper limit of the control. Every time the indoor air temperature falls underneath the lower limit of the dead band (+22°C), the 4-port valve is adjusted so that two independent pipe loops are formed; at the same time, the ability to inject heat to pipe loop A is enabled.

A purely convective cooling system is applied (cross ventilation strategy) when the indoor air temperature equals +26°C. The system is designed to control the increased ventilation rate in such way that the indoor air temperature always remains less than +26°C (presume an outdoor air temperature less than +26°C).

Climate conditions

Hourly weather data equivalent for a climate typically found at the south-west cost of Sweden is applied. All simulation cases are entirely aimed on the months of March and April since these two months fulfils the climatic conditions needed to explore the maximum performance for the present application. Firstly, the outdoor air temperature is sufficiently low to ensure a heat demand within Zone B throughout the studied period, see Figure 5. Secondly, there are significant solar gains within Zone A during the studied period, see Figure 6.

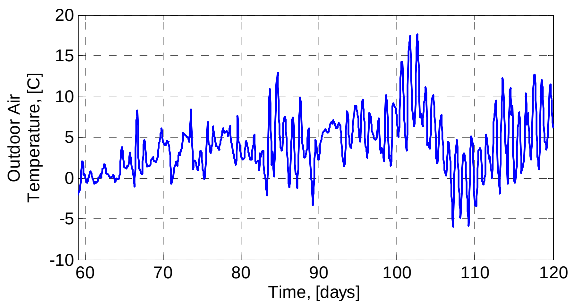

Figure 5 Outdoor air temperature from 1st of March to 30th of April.

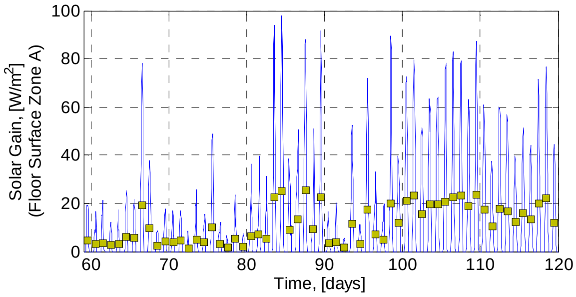

Figure 6 Solar radiation intensity; squares illustrate the diurnal average solar intensity that incident on the floor surface within Zone A.

SIMULATION RESULTS

Reference case

To begin with, the reference case is studied. Simulations yielded, as expected, a noticeable different indoor air temperature between the two zones, see Figure 7. The upper limit of the dead band control is rarely exceeded during March. Consequently, the potential to utilise heat from Zone A is limited with the proposed case. However, during April, the solar gains are much higher, see Figure 6, and hence the indoor air temperature is often above the proposed upper control temperature. During the last 20 days of April, the limit for cross ventilation (+26°C) is frequently reached during daytime within Zone A, sees Figure 7. Simultaneously, the heat supply from the floor heating system is virtually stopped and Zone A is passively heated almost entirely by the solar gain.

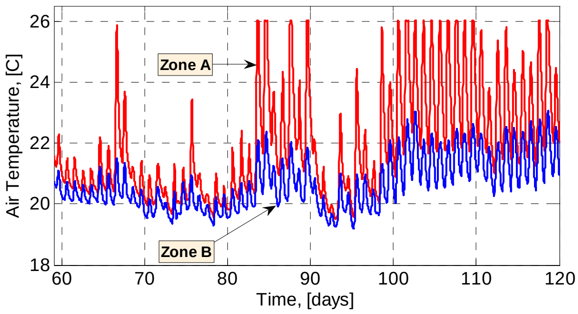

Figure 7 Indoor air temperature for Zone A and B during March and April for Case 0.

Overall system performance

Simulations of both *Case 1* and *2* yielded indoor air temperatures that are appreciable lower than in the reference case for Zone A. The duration of indoor air temperatures are given in Figure 8. As expected, the differences between the reference case and both *Case 1* and *2* is most evident when the indoor air temperature in Zone A rises due to solar gains, see Figure 8. The computations of *Case 1* and *2* yielded an interesting result; the difference in indoor air temperature is very small when comparing *Case 1* and *2*. *Case 2* yielded a slightly lower air temperature in Zone A and a slightly higher air temperature in Zone B compared to *Case 1*. Thus, the system design in *Case 2* is somewhat more efficient than *Case 1*.

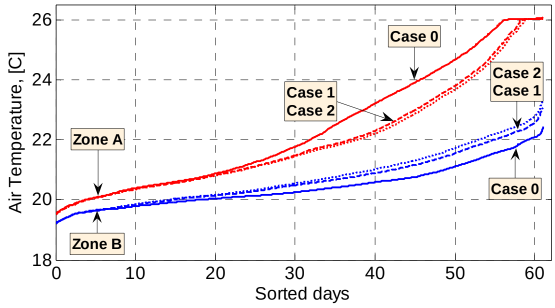

Figure 8 Duration diagram illustrating the indoor air temperatures during the 61 day period. The upper three lines are computed for Zone A, the other lines are for Zone B. Case 0 - solid, Case 1 - dashed and Case 2 – dotted line.

The amount of supplied heat is on the whole lower in both *Case 1* and *2* compared to the reference case, see Figure 9. Again, the differences between Case 1 and 2 are on the whole inappreciable. As heat is extracted from Zone A in *Case 1* and *2*, the heat supply to Zone A actually increases over the two months period. At the same time, the active heat supply to the hydronic pipe loop situated within Zone B decreases compared to the reference case. However, the allocation of supplied heat to Zone A and B differ between *Case 1* and *2*, see inset within Figure 9. Note that Figure 9 illustrates the heat supply from the primary heating system.

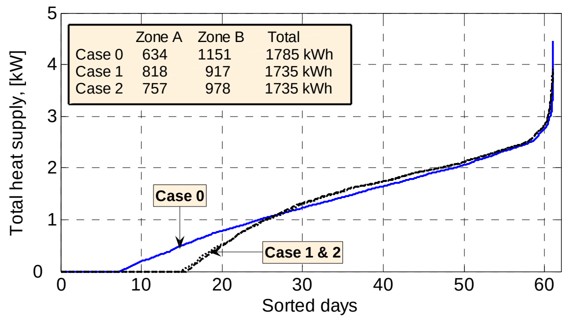

Figure 9 Total heat supply (Zone A and B together) to the floor heating pipe loops illustrated as a duration diagram. The inset illustrates the total amount of heat supplied in the all cases.

The heat flux that is extracted/supplied through the pipe loop within the concrete slab in Zone A is given by Figure 10. A floor heating system that operates according to the present design, cools the overheated concrete slab, from inside, during around 20 days of the studied period. A majority of this duration is allocated to the final 20 days of the studied period. As the slab is repeatedly cooled down, the duration for heating operation in Zone A increases with around 10 days compared to the reference case, see Figure 10.

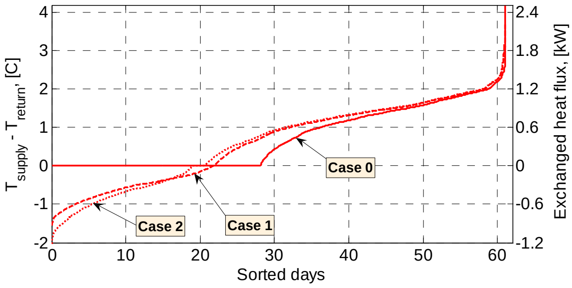

Figure 10 Total fluid temperature decline along the pipe loop within Zone A, illustrated as a duration diagram. The right hand axis represents the corresponding heat flux (fluid to concrete).

Detailed system performance

A three day period in mid April (day 106 to 109) is selected from the two months simulation period to exemplify the performance of the system in more detail. This period is selected since it represents conditions with high intensive solar gains, see Figure 6. When the floor heating system operates according to *Case 1* or *2*, less cross ventilation is applied during influence of high intensive solar gains, see Figure 11. The indoor air temperature in Zone A is, although, noticeably decreased compared to the reference case; this is most evident during night time.

Concerning the reference case, daytime solar gains and heat storage in the heavy concrete floor and walls within Zone A are enough to provide an indoor air temperature above the required indoor temperature during the whole day and night, see Figure 11. Consequently, the amount of supplied heat from the fluid pipe loop towards the surrounding concrete slab is constantly nought for the three day period regarding the reference case, see Figure 12. The operation of the floor heating system in *Case 1* and *2* is completely different compared to the *Case 0*. According to the graphs in Figure 12, heat is extracted and supplied repeatedly during the present period. *Case 1* and *2* are quite similar during daytime as heat is extracted from the slab. In the initial phase for all cooling cycles, see Figure 12; a more intensive heat flux from the surrounding concrete towards the pumping fluid is found in *Case 2* compared to *Case 1*. On the other hand, at the late phase of the cooling cycles, the opposite relationship is evident.

The simulation yielded differences in indoor air temperature within Zone B, see lower group of lines in Figure 11. By means of the applied control system, there is no upper limit for the fluid supply temperature for pipe loop B. Hence, if the heat extraction rate from the floor slab in Zone A is large, the supply temperature in pipe loop B may exceed the supply temperature given by the feed-forward control. This behaviour can be seen from around midday and the following six to eight hours, see Figure 13. If the control of Zone B is regarded as the ideal in the reference case, the heat supply to Zone B is actually oversized in both *Case 1* and *2*. However, the influence of the indoor air temperature is minor. Furthermore, the oversized heat supply during the afternoon results in a warmer slab that stores a part of the extra heat to the night. Therefore, the heat supply is somewhat less than the reference case through the night cycle, see Figure 13.

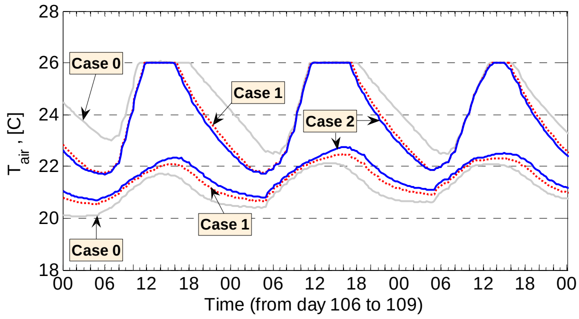

Figure 11 Indoor air temperature variations. Upper lines: Zone A. Lower lines: Zone B.

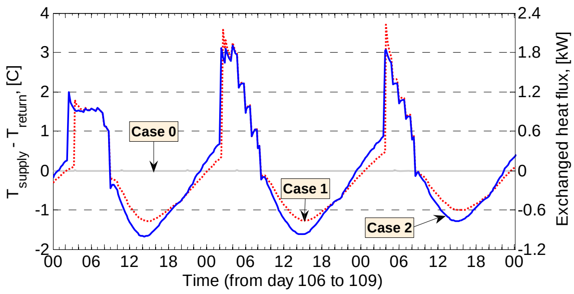

Figure 12 Total fluid temperature decline along the pipe loop within Zone A.

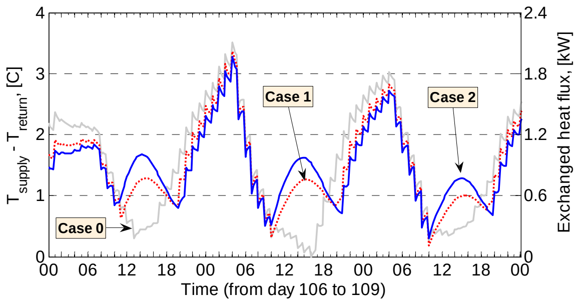

Figure 13 Total fluid temperature decline along the pipe loop within Zone B.

DISCUSSION AND CONCLUSIONS

In the present paper, the performance of a building integrated heating system (floor heating) is explored. A two zone building is studied; the south zone (A) is influenced by intensive solar gains while the north zone (B) is essentially unaffected from solar gains. The aim is to explore the possibility to transfer excess heat from Zone A to B by utilising the hydronic floor heating system. In this manner, the supply side of the floor heating system is pre-heated by extracting heat from Zone

A. As a result, Zone A is actually cooled by the floor heating system which then operates as a high temperature cooling system.

In order to explore the performance, a numerical model of the two zone building, the hydronic floor heating system and the control system was created in Simulink. The structure of the model is achieved by following the conventions given by the International Building Physics Toolbox in Simulink (IBPT).

To begin with, simulations yielded a decreased indoor air temperature within Zone A (compared to a reference case). The decreased air temperature is present under periods while the zone otherwise would be overheated; thus, the thermal comfort is improved. The most relevant improvements in thermal comfort regarding overheating of zone A is actually found during the night period although the extraction of heat takes place during daytime. This can be explained by the fact that the floor slab has a large thermal storage capacity.

The total heat supply to the building is on the whole decreased. However, the potential to substantially reduce the total heat demand is not found. The months of March and April were studied, the highest efficiency was found in April. In fact, the potential to reduce the heat demand in March was marginal. Looking at the entire heating season, it can be concluded that the time period where the accurate conditions emerge truly is short.

The heat extraction rate from the warm zone is another way to quantify the system performance. When the most favourable conditions emerge, simulations yielded a maximum cooling capacity of almost 20 W/m^2. However, the duration of this extraction rate is very short. The figure is comparable with the diurnal average solar intensity that incident on the floor surface during the same period. Thus, it can be concluded that the solar gain is much more intensive than the cooling capacity of the floor heating system.

Two different designs of the hydronic floor heating system were evaluated in the explorative simulation test. The first design is similar to a typical floor heating system where the return flow from each zone is mixed to a common return flow. In the second design, the return from B is directly connected to the supply of A. Thus, the extraction rate would be the greatest in this case since the supply temperature is the lowest possible. When looking at the simulation results, the overall performances of these two cases are almost equal. However, the differences are clearly observable when looking closer at the detailed results provided by simulations. Differences of this small size are difficult, or even impossible, to detect by measuring the performance of the system. A comprehensive simulation model that allows adapting the model to new innovative applications is valuable in these situations.

The applied building and climate data is carefully selected to explore whether the present system design may functioning or not. The internal heat gains applied in the simulations are of course a critical parameter in the explorative simulation study. For instance, other internal gains than solar radiation would most certainly affect the duration of the heat extraction rate and hence the thermal comfort. It is obvious that the applied solar gain is intensive. However, the system would certainly not perform better with a less intensive internal heat load. Thus, if the system would fail to provide a useful function with the present intensive solar gain, then it is not the applied conditions that are the problem; it is more inclined to think that the application itself is a blunder. Furthermore, useful information regarding the maximum performance of the application is provided from an assessment performed under extreme conditions.

ACKNOWLEDGMENT

This paper is a result of the project *Thermal Processes Coupled to Building Integrated Heating Systems with Focus on Floor Heating*. The research project is funded by the Construction Industry Organisation for Research and Development (SBUF) in Sweden and the Swedish Energy Agency (STEM).

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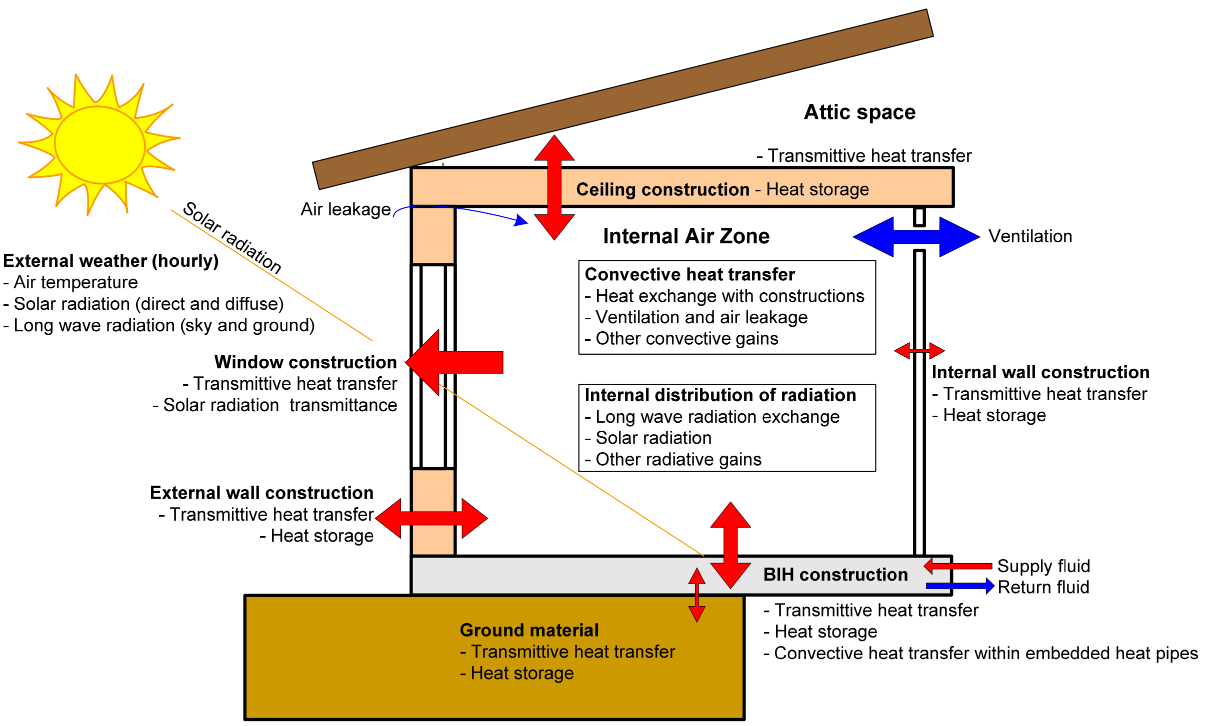

Figure 14 Schematic flow diagram for the general thermal problem with BIH. (Karlsson, 2006)