Modelling Space Heating Systems Connected to District Heating in Case of Electric Power Failure

Per-Olof Johansson, M Sc, Patrick Ljunggren, M Sc, Janusz Wollerstrand, Ass. professor
Lund University, Department of Energy Sciences, Division for Efficient Energy Systems
Per-Olof.Johansson@vok.lth.se

Abstract

Recent year's extensive power failures have put focus on the importance of secure local production and distribution of energy. Since district heating (DH) is the dominating heating system in Scandinavia it is of great importance to investigate the possibility for buildings connected to DH to receive heat during an electric power failure.

By using computer models, buildings' heating systems can be simulated, and by comparing the results with field studies the model can be evaluated. The model shows good resemblance with the field study.

By using a model the influence of different parameters can be studied. The influence of, e.g., changed primary supply temperature and outdoor temperature can be studied.

Keywords: Power failure, District heating, Computer modelling, Space heating system

Nomenclature

Variables

A	Area, m^2
c_p	Specific heat capacity, J/kgK
g	Gravity force, m/s^2
h	Height, m
k_v	Flow capacity, kg/(s·Pa$^{1/2}$)
LMTD	Logarithmic mean temp. diff., °C
m	Mass, kg
$\dot{m}$	Mass flow, kg/s
n	Radiator exponent
p	Pressure, Pa
$\dot{Q}$	Heat flow, W
t	Time, s
T	Temperature, °C
U	Overall heat transfer coeff., W/m^{2}K
α	Heat transfer coeff., W/m^{2}K
ρ	Density, kg/m^3

Subscripts

br	Branch
eq	Equivalent
exp	Experimental
hor	Horizontal
i	Indoor
int	Internal
N	Number of branches
nat	Natural circulation
o	Outdoor
p	Primary
r	Return
rad	Radiator
s	Secondary
s	Supply
sim	Simulated
vent	Ventilation
ver	Vertical
w	Wall
∞	Stationary values (after long time)

1. Introduction

In case of a large-scale power failure many important functions in the society are interrupted. Space heating is such an important and critical function. Obviously, heating systems using electricity (either directly or indirectly via e.g. a heat pump) cannot operate. Systems using oil, natural gas or pellets will not work either since electric power is demanded for the operation of burners.

District heating (DH) is the dominating heating system in Scandinavia. It comprises central heat production and distribution by hot water circulated in a grid constituted of buried pipes. The concept allows for making use of waste heat, e.g. from industries or thermal power stations.

Buildings connected to DH are also assumed not to be functioning in case of a power failure. Even if the DH supplier has back-up power in order to maintain production and distribution of heat, the buildings are generally assumed not to be able to receive any heat when the house-internal heating system is dependent on electric power to pump and control equipment. Recent studies have, however, proved that this does not have to be the case.

Extensive power failures in recent years have produced large efforts on the possibility to produce and distribute electric power locally during a breakdown on the national power grid, so-called island operation. Many power stations can produce both heat and electric power, so-called cogeneration or CHP (combined heat and power). In this case, the DH grid functions as cooler to the power generating process. To be able to produce electricity during island operation, CHP stations still need cooling. If it is still possible to use the DH grid as a cooler, the power station could still operate. However, then the end users must be able to receive district heat during a power failure.

The society can also benefit if heat supplies is functioning to an extent as large as possible. If, e.g., evacuation of citizens could be avoided or at least delayed, this could benefit not at least elderly people and persons receiving health care.

The objective of our study is to investigate what will happen in buildings connected to DH in case of a power failure. Is it possible, if the DH network still is functioning, that natural circulation will arise in modern space heating systems, and to what extent? Natural circulation was used many years ago, before pumps were introduced in space heating systems, and is based on the difference in density between hot and cool water. I.e., hot water from the heat source will rise in the vertical supply pipes and then, when heat is emitted in the radiators, the cold water will descend back to the heat source.

Computer simulations are a useful and necessary tool and good complement to field experiments in the process to establish how different heating systems and buildings are able to receive heat.

2. Objective of the study

In the study, a number of buildings of various sizes, age and type have been examined through practical field studies. To be able to study different outer circumstances and the influence of different parameters, e.g. the outdoor temperature, the field studies have been complemented with computer simulations using MATLAB's toolbox Simulink. The simulations are a useful instrument when estimating how much district heat that could be distributed during a power failure. It is also possible to study the influence from various parameters that might be difficult to capture in reality, e.g. the possible gain from an increased DH supply temperature.

The objective of the paper is to show possibilities to simulate natural circulation in space heating systems and the dynamic influence on the indoor air temperature. The agreement between results from simulations and field experiments will be discussed.

3. Space heating systems connected to DH

Figure 1 below describes a waterborne radiator space heating system connected to a DH grid. The water from the DH grid (primary water) is led into a heat exchanger (HEX) where the radiator water (secondary water) is heated. The secondary supply temperature, T_{ss}, is regulated by a controller which in turn regulates the DH flow passing through the HEX. The set point for T_{ss} is based on the current outdoor temperature and the building's time constant (a sudden change in outdoor temperature should not momentarily be compensated for due to the thermal inertia of the building shell). The circulation in the radiator system is achieved by an electric pump. In order to receive proper indoor temperature in the whole building, valves are used to balance the flow between risers and radiators in different parts of the system.

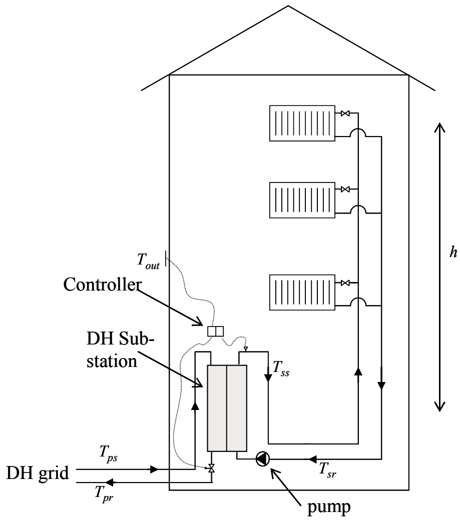

Figure 1 A building with space heating system connected to a DH grid

4. Computer modelling

The building model is based on existing models of HEX, control equipment, actuators, valves, connection pipes (taking into account pressure drop, heat loss and time delay), radiators and building. The theory and function of these components have been described in detail by a number of authors, for example [1], [2] and [4].

In this work, these components have been put together in order to constitute a complete building model with DH substation, space heating system and building shell. To be able to meet the objective of this work, the model has also been modified and improved on several points. The space heating system has been extended to comprise four risers and three storeys, making it possible to study the heat distribution in the building during natural circulation. The flow distribution with pump operation is built on a method based on an analogy to Kirchoff's circuit laws. In case of natural circulation the problem must however be attacked in a different way, which will be described in section 4.1. In order to study the dynamics of the indoor air temperature, in case of a complete or partial break in heat supply, the modelling of the building shell has been modified, which will be described in section 4.2.

The overall structure of the complete model is shown in Figure 2 below.

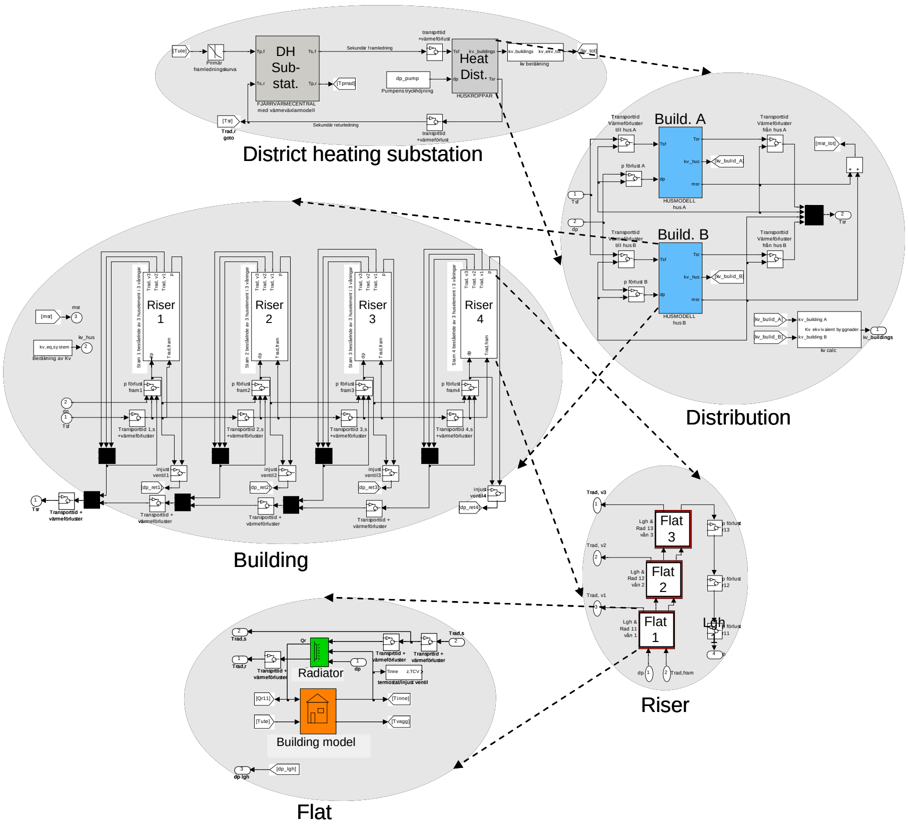

Figure 2 Overview of the computer model of the system including substation, space heating system and building

4.1 Basic parts of the model

The first step in the energy transfer from the DH grid to the building takes place in the DH substation where heat is transferred via a HEX. A control valve adjusts the DH flow in order to achieve a correct outgoing temperature on the secondary side of the HEX, i.e. the radiator supply temperature. A traditional way to handle the dynamic thermal behaviour of the HEX is to divide it into a number of sections. For each section energy balances can be stated for both primary and secondary side flows, and for the wall separating them. After differentiating the following equations are obtained:

$$\frac{\partial}{\partial t}\left(T_{s,out}\right)=\frac{1}{m_s \cdot c_{p,s}}\left[\dot{m}_s \cdot c_{p,s}\left(T_{s,in}-T_{s,out}\right)-\alpha_s \cdot A\left(\frac{T_{s,in}+T_{s,out}}{2}-T_{wall}\right)\right] \quad (1)$$

$$\frac{\partial}{\partial t}\left(T_{p,out}\right)=\frac{1}{m_p \cdot c_{p,p}}\left[\dot{m}_p \cdot c_{p,p}\left(T_{p,in}-T_{p,out}\right)-\alpha_p \cdot A\left(\frac{T_{p,in}+T_{p,out}}{2}-T_{wall}\right)\right] \quad (2)$$

$$\frac{\partial}{\partial t}\left(T_{wall}\right)=\frac{A}{m_{wall}\cdot c_{p,wall}}\left[\alpha_p\left(\frac{T_{p,in}+T_{p,out}}{2}-T_{wall}\right)\right.$$
$$\left.-\alpha_s\left(\frac{T_{s,in}+T_{s,out}}{2}-T_{wall}\right)\right] \tag{3}$$

The equations are easily implemented in Simulink. The temperature profile is assumed to be linear, while the theoretically correct profile is logarithmic .The logarithmic mean temperature difference, *LMTD* is defined as:

$$LMTD=\frac{\left(T_{p,s}-T_{s,s}\right)-\left(T_{p,r}-T_{s,r}\right)}{\ln\left(\dfrac{T_{p,s}-T_{s,s}}{T_{p,r}-T_{s,r}}\right)} \tag{4}$$

As mentioned, an arithmetic mean temperature difference has been used. The advantage with the later is that the heat transfer can be directed in both ways, i.e. from primary to secondary side and vice versa. Such situations can occur for short periods in the radiator HEX. This means that we must use a sufficient number of sections in the model. On the other hand, an increasing number of sections will increase the computational time. A suitable choice is to divide the HEX into 3-5 sections, [5]. The method involves a number of assumptions such as uniform temperature in each section, no conduction in the water flow direction or in the length direction of the HEX wall. The heat transfer coefficient, α, is approximated to be a function of the flow only, ignoring minor influence from temperature dependant quantities. The thermal resistance in the wall material can be ignored due to the thinness of the plate. All these assumptions ease the mathematical description, but investigations still have proved a good resemblance to real data. [1], [7].

The piping system model includes three features, pressure drop, heat loss and time delay. The pressure drop due to friction in pipes, valves, radiators and HEX is essential when calculating the flows in the system. The time delay could be of some interest at normal (pump) operation, while the heat loss is of minor interest. While simulating natural circulation, however, all of these features become essential. The driving force from natural circulation is rather small, leading to a substantially smaller circulation flow and, consequently, a low flow velocity. Especially when studying larger buildings, transportation times and heat losses can be considerable and essential for the operation of the system.

The pressure loss calculations will be discussed later on in connection to flow calculations.

The next level of heat transfer in the system takes place in the radiators. Basically, the heat transfer here works in the same way as in the HEX. The model can, however, be simplified on some points. On both sides of the HEX the medium is water, while in the radiator we have water on one side and air on the other. The air has a substantially lower heat transfer coefficient than water and is the absolutely dominating resistance in the radiator heat transfer. The overall heat transfer number, *U*, can therefore be assumed to be constant. We are interested in calculating the return temperature and the emitted heat from the radiator. The air temperature can be regarded as constant in the calculations. In the radiator, we can expect that the heat transfer always will be directed from the radiator water to the air. Therefore, we now can use the *LMTD* calculation (as shown in (4)) and do not have to divide the radiator into sections. We then arrive with the following two equations:

$$\frac{\partial}{\partial t}\left(T_{rad,out}\right)=\frac{1}{m_{rad}\cdot c_{p,rad}}\Big[\dot{m}_s\cdot c_{p,s}\left(T_{rad,in}-T_{rad,out}\right)$$
$$-U_{rad}\cdot A\cdot LMTD^n\Big] \tag{5}$$

$$\dot{Q}_{rad}=\dot{m}_s\cdot c_{p,s}\left(T_{rad,in}-T_{rad,out}\right) \tag{6}$$

Note that the *LMTD* is raised to the exponent *n*. This is an approximation to the fact that only part of the heat transfer from the radiator is due to convection, the rest is due to radiation. The contribution from radiation (which normally amounts to 30-50 per cent of the heat transfer) is also a function of the temperature difference between the radiator's surface and the surrounding walls. The complex relation, which also includes physical quantities, can be simplified by including the radiation in (5) by introducing the so-called radiator exponent, *n* [6].

A common method to model the dynamics of the building's heat losses is described for example in [1] and [3]. The basic idea is more or less the same as with the HEX and the radiator. The wall is treated as a homogenous material with a homogenous temperature described as:

$$\frac{\partial}{\partial t}\left(T_w\right)=\frac{1}{m_w\cdot c_{p,w}}\Big[\alpha_i\cdot A\left(T_i-T_w\right)-$$
$$\alpha_o\cdot A\left(T_w-T_o\right)\Big] \tag{7}$$

With the wall temperature known the heat flow from the indoor air to the wall can be calculated from:

$$\dot{Q}_w=\alpha_i\cdot A\left(T_i-T_w\right) \tag{8}$$

The indoor air temperature can finally be calculated from:

$$\frac{\partial}{\partial t}\left(T_i\right)=\frac{1}{m_i\cdot c_{p,i}}\left[Q_{rad}+Q_{int}-Q_w-Q_{vent}\right] \tag{9}$$

Q_{int} is internally generated heat from humans and electric equipment like TV's, refrigerators etc. Q_{vent} is the unavoidable heat loss from ventilation of the indoor air.

The heat carrier from the HEX to the radiator is the circulating water in the system. The flow depends on the available pump head and the flow resistance in the system. For fully turbulent flows and limited temperature variations, the relation between flow and differential pressure in a component can be approximated as:

$$\dot{m} = k_v \sqrt{\Delta p} \tag{10}$$

It is reasonable to assume that the flow is turbulent, even when dealing with natural circulation. If a laminar flow should occur, the pressure drop will be so small, in absolute numbers, that the influence will be negligible. The factor k_v describes the flow capacity of a component (to be precise, the flow capacity at 1 bar differential pressure). A k_v value can be calculated for all components, a pipe section, valve (which has a variable k_v value depending on the opening degree), HEX or radiator, as long as the pressure loss for a specific flow is known. For a system with many components (connected in parallel or series), equivalent k_v values can be calculated from:

$$k_{v,eq,parallel} = \sum_{i=1}^{N} k_{v,i} \ , \quad k_{v,eq,series} = \frac{1}{\sqrt{\sum_{i=1}^{N} \left(\frac{1}{k_{v,i}} \right)^2}} \tag{11}$$

Let us now consider the hydronic radiator system as a circuit diagram, see Figure 3. This analogy to electric circuit laws is described in [4] for a domestic hot water system. For branch i, k_v values are indicated for supply and return pipes to the branch and to the radiator, respectively, and for the radiator itself, including its control valve which can be controlled manually or by a thermostatic head. In fact, every branch in the model consists of three storeys, although only one is indicated in the figure. However, each branch in turn comprises a system just like the one shown in the figure.

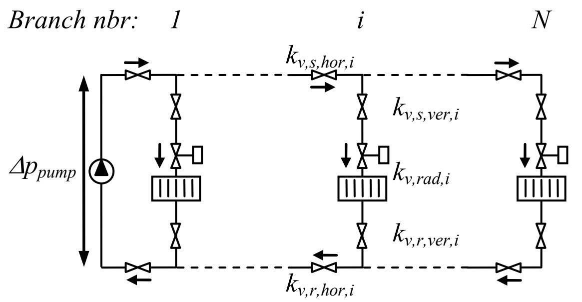

Figure 3 Schematic picture of a space heating system

Equation (11) can now be used to simplify the system by replacing flow capacities, in series or in parallel, by equivalent capacities which in turn can be simplified. The procedure is shown in Figure 4 below.

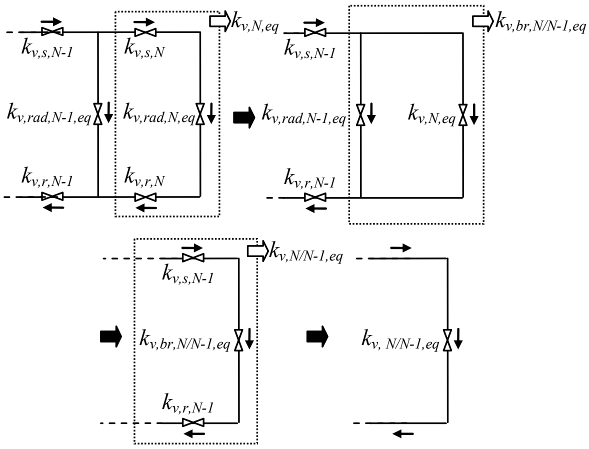

Figure 4 Simplification of the circuit scheme of the space heating system

Finally, we arrive with just one equivalent k_v value for the whole system, and (10) can be used to calculate the total circulation flow, $\dot{m}_s$, in the system. Then, the flow in each part of the system can be calculated by once again going through the system, but now in the opposite direction. We know the available differential pressure for the first branch (after the pump) and the equivalent k_v value and (10) gives us the flow through branch 1. We can then carry on by subtracting the pressure loss from branch 1 and repeat the calculation for branch 2, and so on.

Nowadays, the use of speed controlled pumps is a rule rather than an exception. In the model the pump pressure head is therefore assumed to be constant.

4.2 Improvements and expansion of the model

In this work, the model is used to facilitate the studies on how space heating systems connected to DH will behave without electric power. In order to do that the model needs to be modified. The first step is to introduce the driving force from natural circulation.

4.2.1 Natural circulation

This mechanism is based on the difference in density between hot and cold water. Many years ago, before pumps were introduced, heating systems were designed to operate with natural circulation. The differential pressure originating from natural circulation can be derived from:

$$\Delta p_{nat} = g \cdot h \left(\rho_r - \rho_s \right) \tag{12}$$

The height, h, in the system is measured between the heat source (HEX) and the heat sink (radiator). This force is of course present also in a pump operated system, but is negligible compared to the pump's pressure head, and can be neglected. When designing a natural circulation system, large pipe diameters must be used in order to minimize pressure drops. As seen in (12) a high building and a high supply temperature support natural circulation. The question is how this works in a system designed for pump operation.

The problem is that the Kirchoff method will have limitations when the pump head is lost. As a first approach, the differential pressure from the pump can be substituted with a calculated differential pressure from (12), based on supply and return temperatures at the HEX and the system's height. This is, however, a simplified model, since the differential pressure actually arises at every riser in the system, i.e., where the height actually is situated. When testing natural circulation in large buildings, it turns out that some risers, situated far from the HEX, might not obtain any circulation, or it might take a long time until circulation arises. Also, the magnitude of the circulation tends to be exaggerated when the temperature difference at the HEX is used for calculations in all risers. During natural circulation, the flow velocity is drastically reduced which means that heat losses will be significant and the supply temperature at the risers will be more or less reduced, a fact that gives a reduced driving force from natural circulation.

The mechanism for natural circulation could be compared to having a small "pump" at every riser. In our case, the model has four risers which mean that we have four such "pumps" or sources for differential pressure. With four sources instead of one, we must consider four circuits when calculating the flow distribution. The flow in each circuit is calculated individually and the total radiator flow corresponds to the sum of the four circuit flows. The difference between calculating flows in the system driven by pump or by natural circulation, respectively, is shown in Figure 5.

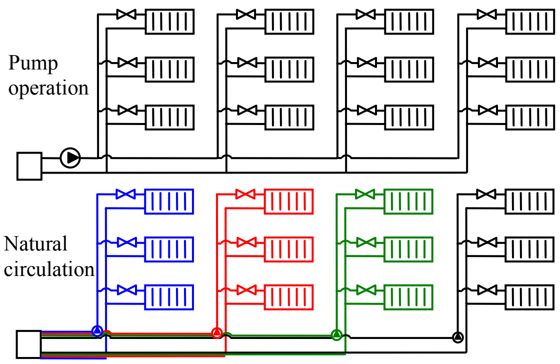

Figure 5 Difference between pump and natural circulation regarding flow calculations

Regarding the implementation of natural circulation in Simulink, a smooth way to handle the to operational modes, pump or natural circulation, is to introduce a control variable which has the value 1 as long as the power supply is OK (pump operation) and 0 when the power fails (natural circulation). The control variable will then govern the switching between the operational modes and, consequently, flow calculations. The control equipment is also affected by a power failure, and this is easily taken care of using the control variable to freeze the position of the DH valve in its current position.

4.2.2 Building shell model

The model of the building shell showed in section 4.1 has proved to be sufficient when modelling the operation of space heating systems during "normal" conditions or static calculations, i.e. where the transient course of the indoor air temperature is of minor interest. However, dealing with power failures must be considered as rather extreme conditions. The existing model showed problems using the conventional building model where the wall is modelled as one section with a homogeneous temperature. Let us consider an example: The outdoor temperature is -10°C and the indoor temperature is 20°C. The temperature throughout the wall will then be (20 – (-10)) / 2 = 5°C. If the heat supply is cut off (or substantially decreased) the indoor air temperature will drastically approach the wall temperature, 5°C. This is not realistic since the wall will have a temperature gradient where the inside surface is just a few degrees cooler than the indoor air temperature.

Figure 6 below shows data from an experiment carried out in a small office at our department. The radiator and ventilation in the room was shut of and an electric radiator, equipped with a timer function, was installed. Several temperatures were measured in the room, among them indoor and outdoor air, the temperature on the inside wall and on the inner surface of the outer wall. The figure shows what happens when the heat supply is cut of. During the test the outdoor temperature was about 5°C.

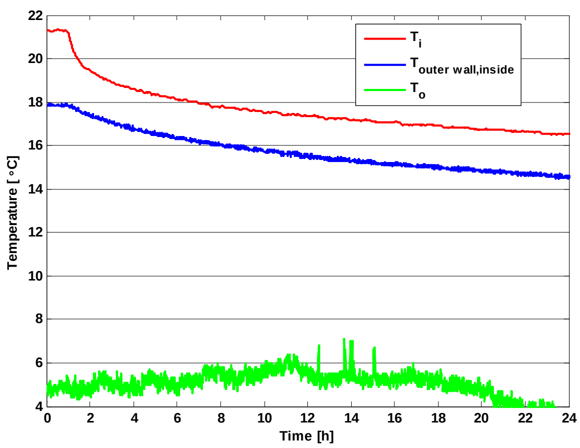

Figure 6 Results from an experiment where the heat supply to a room is cut off

As can be seen, the indoor temperature initially approaches the inside surface temperature of the outer wall. Figure 7 below shows a simulation corresponding to the experiment above. The figure comprises results from, on one hand, the existing model (the curve indicated with "◊") and, on the other, the modified model (the curve indicated with "o"). With the one-section model the wall temperature lies exactly between the indoor and the outdoor temperature. As already mentioned, the indoor temperature drastically approaches the wall temperature and estimates to 7°C already after 24 hours.

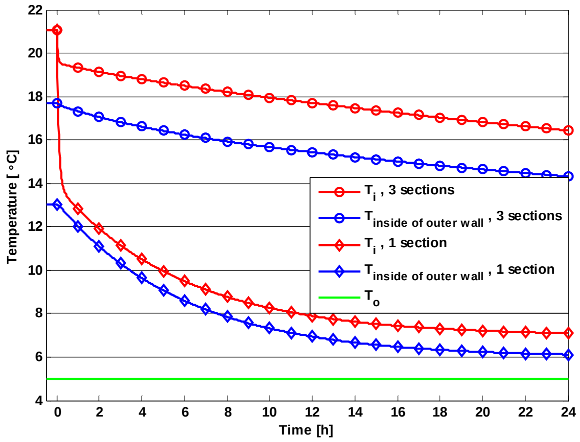

Figure 7 Simulation using the one-section and the three-section building wall model, respectively, where the heat supply to a room is cut off

To improve the modelling of the indoor temperature the building model has been modified according to Figure 8. To the left is the simple, one-section, model and to the right is the new, three-section, model. By using more sections, different wall materials can be used. Here, the two innermost sections are assumed to be made of concrete, which has a high conductivity but a large mass, and the outermost section is the insulation, which has a low conductivity but a small mass. Both materials are essential. The concrete will assure that we have an inside wall temperature relatively close to the indoor temperature and make sure that the building has a realistic thermal inertia. The insulation will assure that we get the correct heat loss and temperature drop through the wall. The choice to use three sections is a compromise; more sections give higher accuracy but longer computational times.

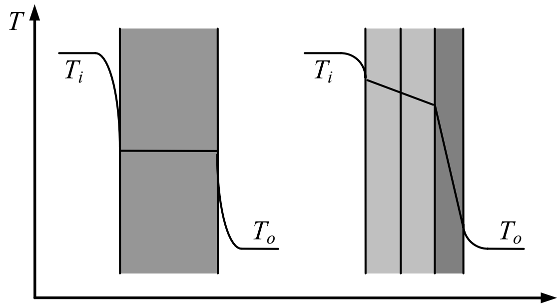

Figure 8 Schematic picture of the one-section (left) and the three section (right) wall model

Now, using the new three-section model, the simulation was run once again. The simulation result, already shown in Figure 7, is now much more in accordance with the results of the real experiment (Figure 6).

4.3 Assumptions for the model

Regarding the model, a number of assumptions have to be made in order to limit the complexity of the model and the computational time.

Most of the assumptions are already discussed, such as *LMTD* versus arithmetic mean value calculation in the HEX model and number of sections in the wall model. Another essential assumption is that there is no heat transfer between the flats. Without this assumption the model would be extremely complex and demand large computational power. The consequence of the assumption is that if the radiator flow is unbalanced the indoor temperature in the flats will not be accurate due to the fact that heat conduction through the walls between the flats is neglected. However, the average temperature in the building would still be correct. This is only relevant if the flow is unbalanced for a long time since heat transfer between the flats is very slow.

The supply temperature in the DH grid is a function of the outdoor temperature. In this study the temperature profile for Malmö is used for the simulations, see Figure 9.

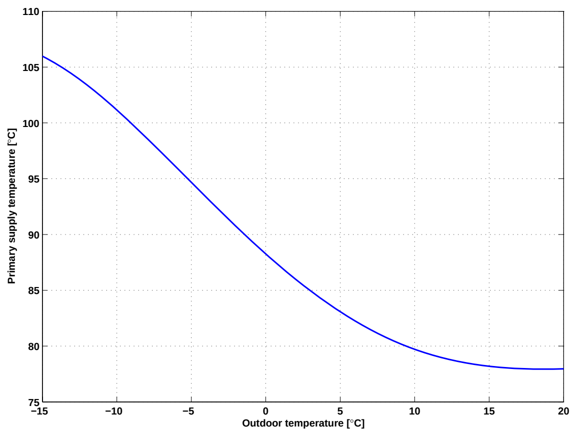

Figure 9 The supply temperature in the DH grid

5. Results

In order to evaluate the accuracy of the model, field studies and simulations with similar outer conditions have been compared. The model has thereafter been used for parameter studies.

5.1 Model evaluation

For evaluation of the model a comparison between a real field study and simulations are made in Figure 10. The studied object is a building located in Malmö. The building was built in 1952 and consists of 20 residential flats distributed on three floors. Before the time 0 in the diagram, the operation is normal and we have 100 per cent circulation flow and heat output. At the time 0, a power failure occurs and the circulation flow decreases drastically. As a consequence, the radiator supply temperature increases substantially. Finally, we end up with a substantially higher temperature drop in the space heating system, which leads to a rather high heat load even with natural circulation.

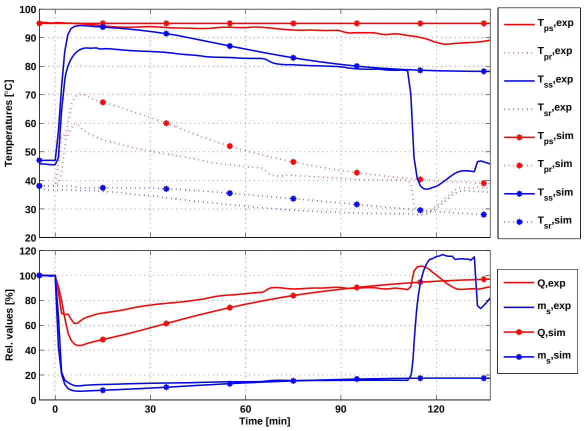

Figure 10 Comparison between field study and simulation

As seen, the simulation shows good resemblance with the field experiment. Even if there is some difference in the transient phase good resemblance is shown both initially (before the power failure) and when the natural circulation has come to a steady state.

Possible explanations to the deviation are the estimated time constant for the building and the space heating system (water volume, pipe lengths etc.) and variation in primary supply temperature.

The model now makes it possible for example to investigate long time effects of a power failure for the building. In Figure 11 a power failure lasting for three days is simulated for the same building.

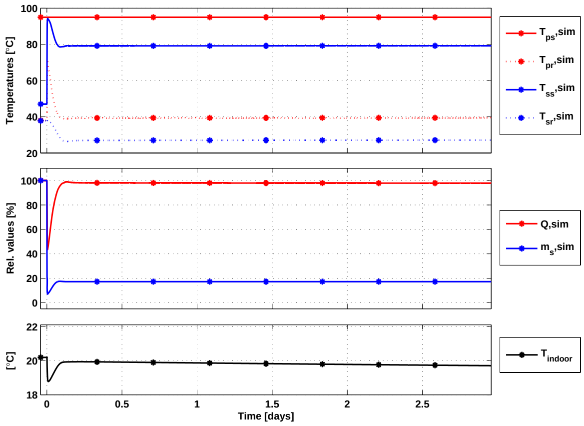

Figure 11 Simulation of a power failure lasting for three days

The figure shows the obvious fact that the natural circulation, once started, will go on at the same level after reaching a steady state. The mean indoor temperature is also represented in the figure.

5.2 Parameter variation

In the modelling world it is possible to investigate the influence of different parameters and outer conditions.

In case of a power failure the DH company can adjust the primary supply temperature level. As described in section 4.2.1 the magnitude of the natural circulation flow is dependent on the temperature drop in the radiator system. In Figure 12 steady state results (the state after infinite time) from simulations with different primary supply temperatures are shown at different outdoor temperatures. In the upper diagram the relative heat load (natural circulation compared with normal operation) is shown. The lower diagram shows the mean indoor temperature.

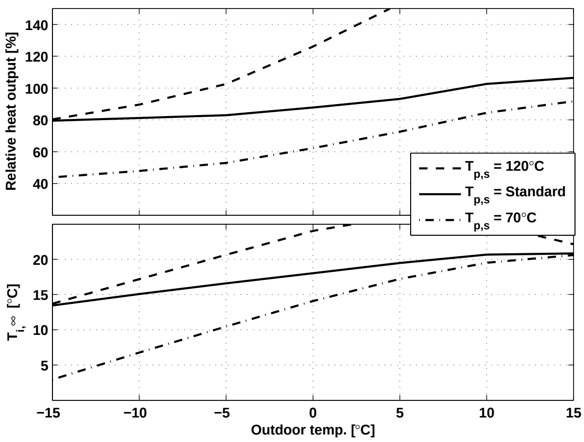

Figure 12 Variation of primary supply temperature at various outdoor temperatures at steady state conditions

The figure shows that by increasing the primary supply temperature the relative heat load increases, especially for outdoor temperatures above -10°C. At low outdoor temperatures the effects of increasing the primary supply temperature to 120°C is small due to the already high supply temperature.

The next diagram, Figure 13, shows the dynamic indoor temperature at three different outdoor conditions. Also in this figure the influence of changed primary supply temperature is shown.

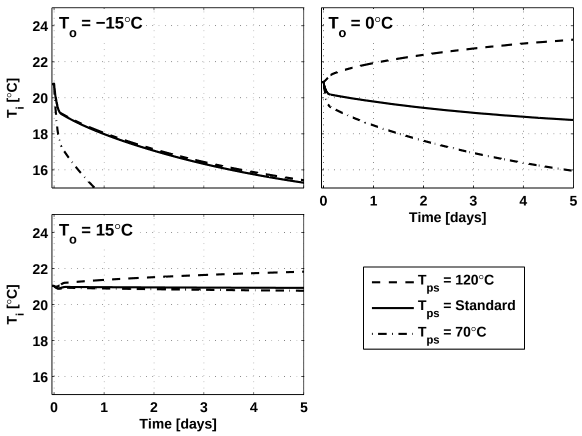

Figure 13 Dynamic indoor temperature at different outdoor temperatures and variation of primary supply temperature

5.3 Conclusions

A complete model of a building with a hydronic space heating system connected to DH has been built up. Parts of the model have been improved and developed to make it possible to simulate not only normal operation using a pump but also natural circulation during a power failure. By comparing the results from simulations with field studies good resemblance can be shown. A model makes it possible to study a building when changing input parameters, e.g. outdoor temperature. It is also possible to simulate the expected indoor temperature dynamic as well as at steady state in case of a power failure.

The model will constitute an important tool in our further studies regarding secure heat distribution during power failure.

6. Acknowledgements

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