MODELLING SPACE HEATING SYSTEMS CONNECTED TO DISTRICT HEATING IN CASE OF ELECTRIC POWER FAILURE

Patrick Lauenburg, Per-Olof Johansson, and Janusz Wollerstrand
Lund University, Department of Energy Sciences, Division for Efficient Energy Systems
Patrick. Lauenburg @energy.lth.se

ABSTRACT

Since district heating (DH) is the dominating heating system in Scandinavia, and fairly common in large parts of Europe, it is of vital interest to study the possibility for buildings connected to DH to receive heat during an electric power failure. Our studies have proved it possible to achieve natural circulation in space heating systems indirectly connected to DH if the DH network operation can be maintained.

Natural circulation in modern heating systems has been simulated. The model shows good resemblance with field studies. By using a model the influence of different parameters can be studied, e.g., a changed DH supply temperature and different outdoor conditions.

INTRODUCTION

A large-scale power failure affects many vital functions of society, e.g. space heating. Obviously, heating systems using electricity (either directly or via a heat pump) cannot operate at all, but systems using a boiler (oil, natural gas, pellets, etc.) will generally not work either since electricity is required for the operation of burners and control equipment.

District heating (DH) is common in many countries and it is the dominating heating system in e.g. Denmark, Finland and Sweden. Therefore, it is of vital interest to study what can be expected to happen in buildings connected to DH in case of a power failure, assuming that the production of DH can be maintained.

Hydronic radiator systems in modern buildings are fitted with circulation pumps that will stop when electricity supply fails. Consequently, the heating of buildings connected to a DH network are generally assumed to stop functioning in such an event. Nevertheless, our recent studies have proved that in many cases a substantial natural circulation effect caused by an increased water density differential takes place in many cases.

The major power failures that have occurred in recent years have led to an increased focus on the possibility of local production and distribution of electric power during a breakdown of the national power grid, so-called ‘island operation’. In order for the production of electricity in combined heat and power (CHP) stations to be maintained, it is necessary that excess heat continues to be removed from the power generating plant. If it is possible to use the DH network as a heat sink, i.e., if buildings connected to the DH network carry on consuming heat energy, provisions for additional cooling of the plant may not be necessary. One must keep in mind that, even if an island power grid were established, the access to power would generally be strictly limited and possibly directed to prioritized users (e.g. hospitals, authorities).

For our society, it is essential that building heat supplies be maintained, especially in the event of a power failure of long duration during harsh weather conditions. If evacuations of people from buildings can be avoided, or at least delayed, this will help protect especially elderly people and persons in need of health care from risky exposure to low air temperatures.

Because of the concern for these matters from DH utilities as well as from authorities and owners of property, the present study was carried out, with the aim at finding out what could be expected to happen in buildings connected to the DH network, in the event of a severe power failure.

The objective of the overall study was to investigate what can be expected to happen in space heating systems connected to DH when a power failure occurs. The study is limited to so-called indirect connection, i.e. that primary (DH) and secondary (house-internal) systems are hydraulically separated by heat exchangers (HEX), which in this context must be considered as a worst-case scenario compared to direct connection. We have found that natural circulation can arise in modern space heating systems; most buildings can achieve a space heat supply corresponding to 40-80 per cent of the amount prior to the interruption, at low outdoor temperature [4]. 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 cold water. I.e., hot water from the heat source rises in the vertical supply pipes. In reverse, when the water is cooled off in the radiators, the cold water descends back to the heat source. With natural circulation in a modern system, the flow becomes significantly smaller and, therefore, very hot in the HEX. With a high supply temperature to the radiators and a high temperature drop in the system, the heat supply becomes surprisingly high, despite the low circulation flow rate.

Computer simulations are a useful tool to complement field experiments in the process of estimating the possibilities for natural circulation in different types of heating systems and buildings.

OBJECTIVE

To be able to study the influence of different parameters that might be difficult to capture in reality, e.g. very low outdoor temperatures and the possible gain from an increased DH supply temperature, the field studies have been complemented with computer simulations using models built with the software Matlab and the associated toolbox Simulink.

The objective of the paper is to simulate how natural circulation works in modern space heating systems at differing outer conditions. The simulations should be seen as an isolated project in the sense that the ambition was not to construct a general model, available to anyone, but rather to construct a simple model designed to complement our field studies. Furthermore, because of our limited skills in, and access to, commercial buildings simulation software, previously developed models for DH purposes was used and further developed.

SPACE HEATING SYSTEMS CONNECTED TO DH

Figure 1 below describes a hydronic radiator system with an indirect connection to a DH network. The water from the DH network is led into a HEX where the radiator 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. An electric pump achieves the circulation in the radiator system. 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.

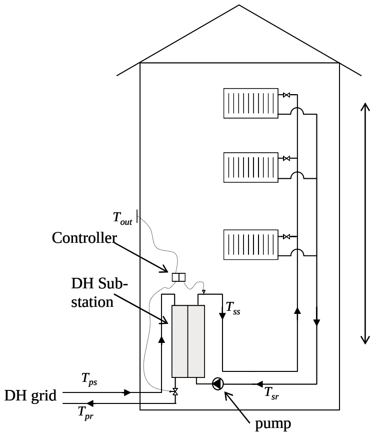

Figure 1 A building with space heating system connected to a DH network.

COMPUTER MODELLING

The building model is based on existing models of HEX, control equipment, actuators, valves, connection pipes, 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 [6].

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 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. With natural circulation, the problem must however be attacked in a slightly different way, which will be described later on.

Some assumptions have to be made in order to limit the complexity of the model and the computational time. One assumption is that there is no heat transfer between the flats. The consequence of the assumption is that if the radiator flow is unbalanced the indoor temperature in the flats will not be accurate because heat conduction through the walls between the flats is neglected. However, the average temperature in the building will still be correct.

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

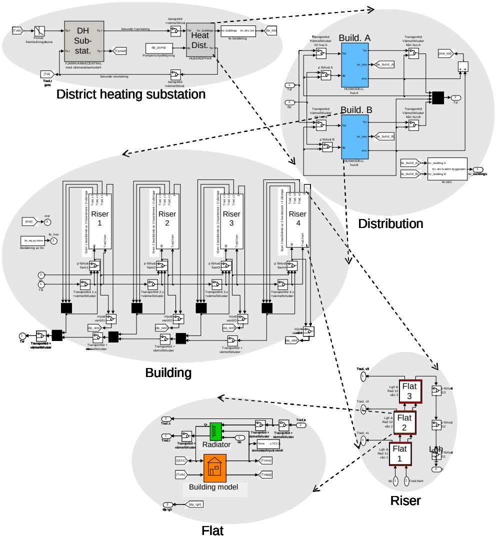

Figure 2 Overview of the computer model of the system including substation, space heating system and building.

NORMAL OPERATION

To begin with, we look at the model when normal (pump) operation is simulated. However, most parts work in the same way in both cases.

Heat exchanger

The first step in the energy transfer from the DH network 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 the 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:

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

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

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

The temperature profile is assumed linear, while the theoretically correct profile is logarithmic. The logarithmic mean temperature difference, *LMTD*, is defined as:

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

The advantage of using an arithmetic mean temperature difference 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 space heating HEX. This means that we must use a sufficient number of sections in the model. On the other hand, more sections will increase the computational time. A suitable choice is to divide the HEX into 3-5 sections, [7].

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], [9].

Piping and heat distribution system

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 heat loss is of minor interest at normal (pump) operation, while the time delay could be of some interest. However, when simulating natural circulation, 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 lower flow velocity. Especially when studying larger buildings, transportation times and heat losses can be considerable and are essential for the operation of the system.

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. We can assume wholly turbulent flows and limited temperature variations, which means that the relation between the volume flow and differential pressure in a component can be approximated as:

$$\dot{V}=k_v\sqrt{\Delta p} \tag{5}$$

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:

$$k_{v,eq,parallel}=\sum_{i=1}^{N}k_{v,i}\ ,\ k_{v,eq,series}=\frac{1}{\sqrt{\sum_{i=1}^{N}\left(\dfrac{1}{k_{v,i}}\right)^2}} \tag{6}$$

The same principles used in electric circuits resistance calculations can be used upon a hydronic heating system, see [6] and [3]. In this way, an equivalent k_v value for the whole circuit can be found, see Figure 3.

Finally, after going through the entire system, we have only one equivalent k_v value for the whole system, and equation (5) can be used to calculate the total circulation flow, $\dot{V}_s$, in the system. Then, the flow in each part of the system can be calculated once again by 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 equation (5) gives us the flow through branch 1. We can then carry on by subtracting the pressure loss caused by branch 1 from the pump pressure and repeat the calculation for branch 2, and so on.

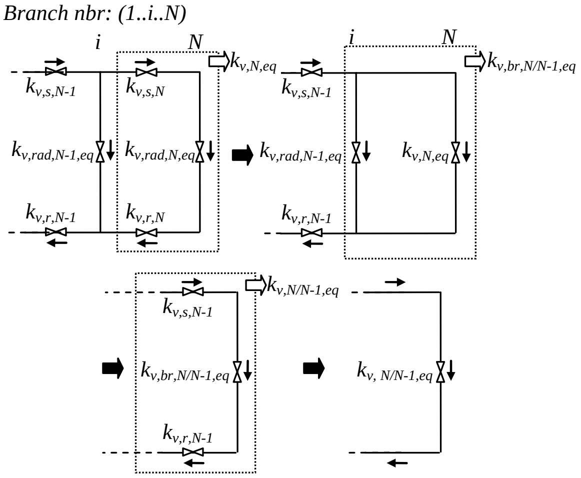

Figure 3 Simplification of the circuit scheme of the space heating system.

Radiators

The next part of the heat transfer in the system takes place in the radiators. The heat transfer in the radiators 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 dominating resistance in the radiator heat transfer. Therefore, the heat transfer resistance on the waterside can be neglected. 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 equation (4)) and do not have to divide the radiator into sections. We then arrive with the following two equations:

$$\frac{\partial}{\partial t}\left(T_{rad,out}\right)=\frac{1}{m_{rad}c_{p,rad}}\Big[\dot{m}_s c_{p,s}\left(T_{in}-T_{out}\right)_{rad} - C_{rad}\cdot A\cdot LMTD^n\Big] \tag{7}$$

$$\dot{Q}_{rad}=\dot{m}_s\cdot c_{p,s}\left(T_{in}-T_{out}\right)_{rad} \tag{8}$$

Note that *LMTD* is raised to the exponent *n*. This is an approximation of 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 equation (7) by introducing the so-called radiator exponent, *n* [8].

Building

A common method to model the dynamics of the building's heat losses is described for example in [1] and [5]. The basic idea is more or less the same as with the HEX and the radiator. A section of the wall is treated as a homogenous material with a homogenous temperature described as:

$$\frac{\partial}{\partial t}\left(T_w\right)=\frac{1}{m_w c_{p,w}}\Big[\alpha_i A\left(T_i-T_w\right)- \alpha_o A\left(T_w-T_o\right)\Big] \tag{9}$$

To use only one section would be sufficient when modelling the operation of a space heating system during "normal" conditions or static calculations, i.e. where the transient course of the indoor air temperature is of minor interest.

However, if the heat supply is cut off (or substantially decreased) the indoor air temperature will drastically move towards the wall temperature. The model must therefore have a realistic approximation of the wall surface temperature (normally just a few degrees cooler than the indoor air).

By using three sections we obtain a good approximation of the wall temperature, see Figure 4. 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.

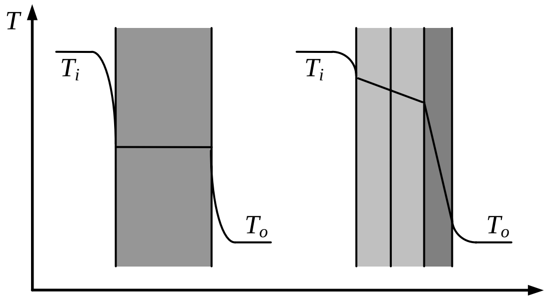

Figure 4 Schematic picture of the one-section (left) and the three-section (right) wall model.

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

$$\dot{Q}_w=\alpha_i A\left(T_i-T_w\right) \tag{10}$$

The indoor air temperature can finally be calculated:

$$\frac{\partial}{\partial t}\left(T_i\right)=\frac{1}{m_i c_{p,i}}\left[Q_{rad}+Q_{int}-Q_w-Q_{vent}\right] \tag{11}$$

$\dot{Q}_{int}$ is internally generated heat from humans and electric equipment. $\dot{Q}_{vent}$ is the heat loss from ventilation of the indoor air.

NATURAL CIRCULATION

Many years ago, before pumps were introduced, heating systems were designed to operate with natural circulation. The differential pressure that drives the circulation can be derived from:

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

The height difference, *h*, of the system is measured between the heat source (HEX) and the heat sink (radiator). The natural circulation force is present also in a pump system, but is negligible compared to the pump's pressure head. When designing a natural circulation system, large pipe diameters must be used in order to minimize pressure drops. The question is how natural circulation works in a system designed for pump operation. Clearly, natural circulation does not work in single-storied buildings, a fact that has also been found during our study.

Dynamic modelling of natural circulation

As a first approach, the differential pressure from the pump can be substituted with a differential pressure calculated from equation (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 place in the system where there is a height and a temperature difference, i.e. risers and substation. When testing natural circulation in large buildings, it turns out that some risers, situated far from the HEX, might not obtain any circulation.

To simulate natural circulation, the model is modified by including these "pumps". Then, an equivalent k_v value for the whole system cannot be calculated. Instead, the flow in each riser is calculated individually. The total flow in the system is equal to the sum of the riser flows.

At first sight, it may seem that natural circulation benefits from high risers (according to equation (12)). However, this need not be the case: the density difference of water means, that one can say that the system has a small virtual circulation pump at all points with a height and a temperature difference. This is illustrated by Figure 5.

Let us consider natural circulation in an extreme system that has a very large height difference at the HEX, situated in a low building with a small bottom area. This is a system with conditions similar to normal pump operation, with the main differential pressure arising from the substation. Conversely, we can imagine a system with a low driving height in the basement circuit while the risers are very high. The heat may then have difficulties to reach the whole system when risers with a large pressure differential tend to "suck" flow from subsequent risers.

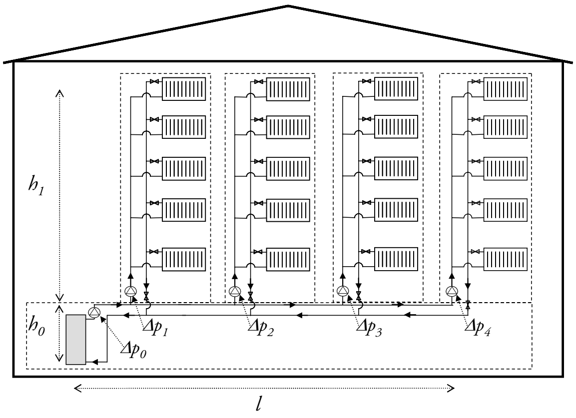

Figure 5 Schematic picture of pressure differentials in the system during natural circulation. The height of the heat exchanger, h_0, the risers, h_1, and the horizontal extension of the system, l, as well as the virtual pumps due to density differentials are indicated.

Static calculation of natural circulation

By a static calculation, using the circuit scheme of the system, negative circulation flows in the risers can be investigated. As mentioned, we now have several pumps and cannot calculate an equivalent k_v value for the whole system. The riser flows are denoted $\dot{V}_1$, $\dot{V}_2$, $\dot{V}_3$ and $\dot{V}_4$. The total flow is denoted $\dot{V}_0$. Figure 6 shows the circuit scheme, described in the previous section, which now has been modified. The valves in the figure correspond to the different pressure losses in the system. Their capacity is denoted with a k_v value. The differential pressures due to density differences are symbolized by pumps.

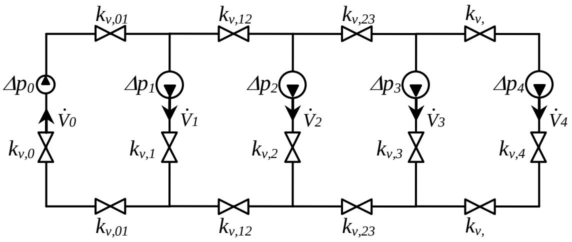

Figure 6 Simplified radiator system with natural circulation, presented as a circuit scheme.

Even though we now deal with natural circulation, the flows are generally still turbulent. Once again, we use equation (5), and it is now possible to set up a system of equations for the whole circuit:

$$\begin{cases} \Delta p_{34} = -\left(\dfrac{1}{k_{v,34}^2}+\dfrac{1}{k_{v,4}^2}\right)^2 \cdot \dot{V}_4^2 + \Delta p_4 = \\ \qquad = \Delta p_3 - \dfrac{1}{k_{v,3}^2}\cdot \dot{V}_3^2 \\ \Delta p_{23} = -\dfrac{1}{k_{v,23}^2}\cdot\left(\dot{V}_3^2+\dot{V}_4^2\right)+\Delta p_{34} = \\ \qquad = \Delta p_2 - \dfrac{1}{k_{v,2}^2}\cdot \dot{V}_2^2 \\ \Delta p_{12} = -\dfrac{1}{k_{v,12}^2}\cdot\left(\dot{V}_2^2+\dot{V}_3^2+\dot{V}_4^2\right)+\Delta p_{23} = \\ \qquad = \Delta p_1 - \dfrac{1}{k_{v,1}^2}\cdot \dot{V}_1^2 \\ \Delta p_{12} = \left(\dfrac{1}{k_{v,0}^2}+\dfrac{1}{k_{v,01}^2}\right)\left(\dot{V}_1^2+\dot{V}_2^2+\dot{V}_3^2+\dot{V}_4^2\right)-\Delta p_0 \\ \qquad = \Delta p_1 - \dfrac{1}{k_{v,1}^2}\cdot \dot{V}_1^2 \end{cases} \tag{13}$$

The equation system can be transferred to the matrix form:

$$\mathbf{A}\cdot\dot{\mathbf{V}}^{\mathbf{2}} = \mathbf{b} \tag{14}$$

where,

$$\mathbf{A} = \begin{pmatrix} 0 & 0 & 1 & a_{14} \\ 0 & 1 & a_{23} & a_{24} \\ 1 & a_{32} & a_{33} & a_{34} \\ a_{41} & 1 & 1 & 1 \end{pmatrix},$$

$$a_{14} = -\left(\frac{1}{k_{v,34}^2}+\frac{1}{k_{v,4}^2}\right)\Big/\frac{1}{k_{v,3}^2},$$

$$a_{23} = -\left(\frac{1}{k_{v,23}^2}+\frac{1}{k_{v,3}^2}\right)\Big/\frac{1}{k_{v,2}^2}, \qquad a_{24} = -\frac{1}{k_{v,23}^2}\Big/\frac{1}{k_{v,2}^2},$$

$$a_{32} = -\left(\frac{1}{k_{v,12}^2}+\frac{1}{k_{v,2}^2}\right)\Big/\frac{1}{k_{v,2}^2}, \qquad a_{33} = -\frac{1}{k_{v,12}^2}\Big/\frac{1}{k_{v,1}^2},$$

$$a_{34} = -\frac{1}{k_{v,12}^2}\Big/\frac{1}{k_{v,2}^2}, \qquad a_{41} = 1+\frac{1}{k_{v,1}^2}\Bigg/\left(\frac{1}{k_{v,0}^2}+\frac{1}{k_{v,01}^2}\right),$$

$$\dot{\mathbf{V}}^{\mathbf{2}} = \begin{pmatrix} \dot{V}_1^2 \\ \dot{V}_2^2 \\ \dot{V}_3^2 \\ \dot{V}_4^2 \end{pmatrix}, \quad \mathbf{b} = \begin{pmatrix} (\Delta p_3-\Delta p_4)\Big/\dfrac{1}{k_{v,3}^2} \\ (\Delta p_2-\Delta p_3)\Big/\dfrac{1}{k_{v,2}^2} \\ (\Delta p_1-\Delta p_2)\Big/\dfrac{1}{k_{v,1}^2} \\ (\Delta p_0-\Delta p_1)\Bigg/\left(\dfrac{1}{k_{v,0}^2}+\dfrac{1}{k_{v,01}^2}\right) \end{pmatrix}$$

Equation (14) gives the different flows ($\dot{V}_0$, $\dot{V}_1$, $\dot{V}_2$, $\dot{V}_3$ and $\dot{V}_4$) for various differential pressures and k_v values. By using typical parameter values, we get the result shown in the first diagram in Figure 7. The gray bars show the relative flow at normal (pump) operation (the total flow, $\dot{V}_0$, is 100 per cent). The black bars correspond to the flows at natural circulation. As indicated in the textbox, the risers are assumed to be five times as high as the HEX and we assume that there is a temperature difference, and consequently also a pressure difference, at all risers. The natural circulation flow is approximately 20 per cent and evenly distributed in the system. In the next diagram (upper right), the height difference is assumed to be the same but now it is assumed that the heat front, typical for natural circulation, has not reached the last riser, which could be the case if the differential pressure in the horizontal distribution is not sufficient. Therefore, the last riser gets a much lower flow. In the last diagram, the pressure conditions are the same as in the previous diagram, but the height relation is changed. The risers are now assumed ten times as high as the HEX. The result is that the flow in the last riser becomes negative.

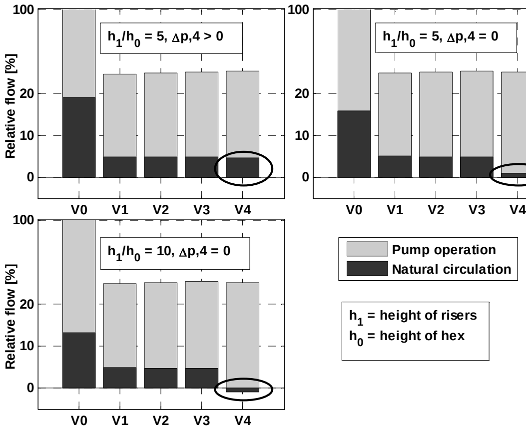

Figure 7 Flow distribution in the radiator system depending on if there is a temperature difference at the last riser (first diagram) and the relation between the height of the risers and the HEX (5 in diagram 1 och 2, 10 in diagram 3).

The fact that the flow might change flow direction in some risers far away from the DH substation was documented in one of the tested objects. The building has 10 storeys and 100 flats and the substation is situated at one end of the building. The heat supply estimated to approximately 85 per cent but did not reach the farthest third of the building. The negative flow is in itself no problem, but it is important to know that in some buildings natural circulation functions perfectly well in some parts of the building while others do not get any heat at all. This should be kept in mind for buildings that are very high and/or horizontally extended. Our studies have shown that this factor is more important than the flow resistance in the system, e.g. if the system is old, or if it is a 1- or 2-pipe system.

SIMULATIONS

The dynamic model of natural circulation is not able to handle negative flows in the system. This would require a more advanced model. For the study below, sufficient precision is achieved with the dynamic model, i.e. that natural circulation is included in the model at every point in the system where there is a height difference. Should such a building be simulated, where negative flows occur, we might get convergence problems. However, this type of buildings represents a minor part of the building stock in Sweden, and in order to study the influence of the outdoor and the DH supply temperatures, it is not useful to extend the model. When estimating the heat supply, it is of less importance if the circulation flow rate in parts of a building is small but positive, or in fact negative.

Assumptions for the simulations

The supply temperature in the DH network is a function of the outdoor temperature. In the study the temperature profile for the network in Malmö is used for the simulations, see Figure 8.

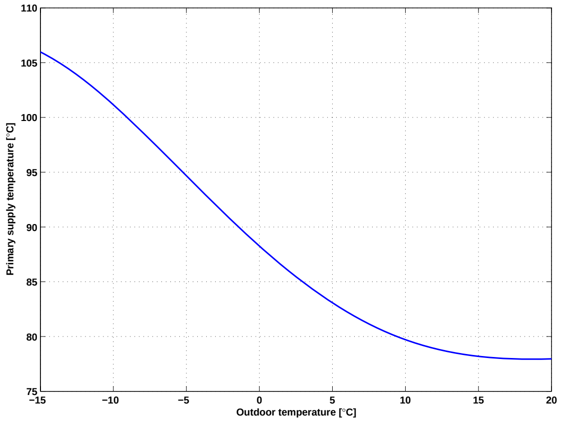

Figure 8 The supply temperature in the DH network in Malmö.

Model evaluation

For evaluation of the model, a comparison between a field study and a simulation are made in Figure 9. The building is built in 1952, with 20 flats distributed on three floors. Before the time zero in the diagram, the operation is normal and circulation flow and heat output is set to 100 per cent. At time zero, power is cut off and the circulation flow decreases drastically. Therefore, 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 though the circulation flow is very small.

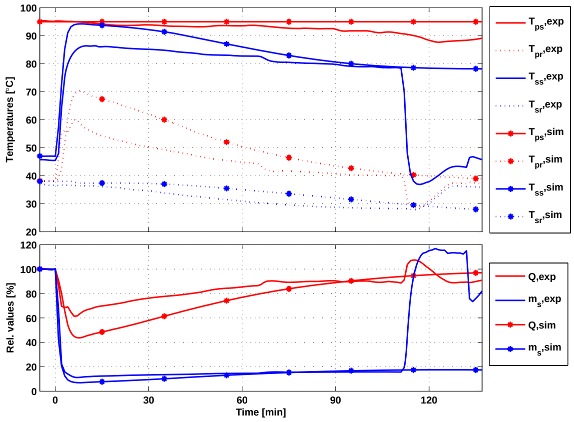

Figure 9 Comparison between field study and simulation.

Even if there is some difference in the transient phase, the simulation shows good resemblance 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.), variation in primary supply temperature and the rather simple building model that has been used. Most important is, however, that the resemblance is reasonably good within the steady state, whereas the transient period hardly affects the indoor temperature.

Parameter variation

In case of a power failure, the DH utility could possibly adjust the primary supply temperature level, which could enhance the natural circulation in the connected systems. In Figure 10, 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 is shown. The lower diagram shows the mean indoor temperature.

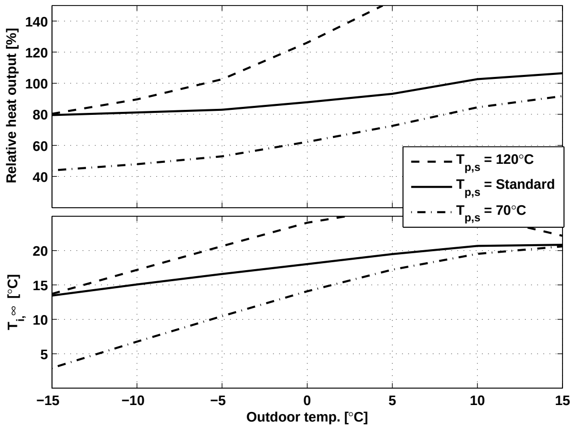

Figure 10 Variation of primary supply temperature at various outdoor temperatures at steady state conditions.

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 11, shows the dynamic indoor temperature at three different outdoor temperatures.

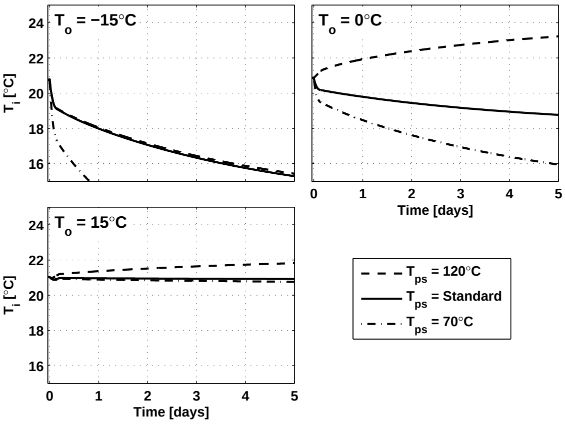

Figure 11 Dynamic indoor temperature at different outdoor temperatures and for various primary supply temperatures.

The figure clearly shows the influence of the building's thermal inertia. A limited heat supply means that an acceptable indoor temperature would be maintained for several days, in this case 16°C after four days with an outdoor temperature of −15°C.

Conclusions

A complete model of a building with a hydronic heating system connected to DH is built up to work properly both with, and without, electric power supply. Results from simulations and field studies have made it possible to assess how buildings connected to DH work during a power failure. The computer model shows good resemblance with field tests and gives possibilities to perform parameter variations, which is difficult to perform in field tests.

Among other things, the height and extension of a building have proven to be important for the distribution of natural circulation within the system. This knowledge has been confirmed by static calculations, but has not been included in the dynamic model.

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NOMENCLATURE

Variables:

A	Area, m^2
c_p	Specific heat capacity, J/kgK
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	Temperature, °C
C	Radiator heat transfer const., W/m^{2}K^n
$\dot{V}$	Volume flow, m^3/s
α	Heat transfer coeff., W/m^{2}K
ρ	Density, kg/m^3

Subscripts:

br	Branch	*p*	Primary
eq	Equivalent	*r*	Return
exp	Experimental	*rad*	Radiator
hor	Horizontal	*s*	Secondary, supply
i	Indoor	*sim*	Simulated
int	Internal	*vent*	Ventilation
N	Nbr of branches	*ver*	Vertical
nat	Natural circulation	*w*	Wall
o, out	Outdoor	∞	Stationary values

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