REDUCED ORDER BUILDING ENERGY SYSTEM MODELING IN LARGE-SCALE ENERGY SYSTEM SIMULATIONS

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ABSTRACT

The simulation of urban energy systems, e.g. district heating or cooling (DHC) systems often in combination with co- or trigeneration and smart grids has to account for a huge number of different buildings (50 … >500) to be provided with energy, e.g. heat and electricity. In that context is not sufficient to model each building including their dedicated energy system (e.g. hydraulic circuit of a heating or cooling system) in detail. The alternative modelling and simulation approach described in this paper is based on the idea to subsume the building energy system into an equivalent one-node model that accounts for heat exchanger characteristics, domestic hot water generation as well as space heating. Rather than building performance simulation this paper is focusing on the simplified modelling and simulation of the building energy system (i.e. space heating and domestic hot water (DHW) system) itself. Consequently the paper describes a method how to estimate return temperature and flow rate in the pipe connecting the building with a DH system. The underlying models have been validated mainly using empirical data gained at real buildings. Finally results of the co-simulation of large district heating system with simplified building models will be presented and discussed.

INTRODUCTION

Optimization of urban or district energy systems requires appropriate calculation and analysis tools that can be used to simulate their energy performance under either steady state or transient conditions. Simulation results could be used for example to generally decide on investments into the system based on scenario analysis, to design the system, to control and improve the operation of the system or to check for faults. Nowadays district heating (DH) systems are common energy systems in urban areas that are of interest due to the need to either transform existing systems or to built new systems that perfectly match the characteristics of decreasing heat densities in cities as well as low energy demand of high energy performance buildings. So-called 4th generation of DH systems will operate with supply temperatures of 50°C. Using the return mass flow as a heat source for a secondary net increases heat sell of existing systems. Simulation of those DH systems will offer the opportunity to

- deeply analyse the interaction between heat generation and heat consumption in buildings,
- the impact of low temperature on the building energy performance including comfort and DHW issues
- optimizing the operation of the DH system

thus looking for best overall system performance.

Figure 1 shows an example of DH system serving numbers of residential buildings. Those buildings are characterized by their heating demand caused by both space heating as well as domestic hot water generation.

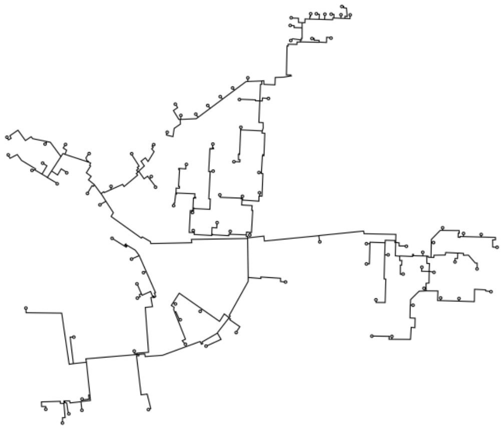

Figure 1 District Heating (DH) system

From the DH system performance point of view the energy demand of each building depending on ambient conditions, schedules and user comfort as well as impact of the buildings on the mass flow rate to be provided as well as return temperature fed back to the DH system is of interest. Normally building simulation programmes are used to calculate both the DH mass flow rate delivered to the building as well as return temperature as a response of the building's energy demand. But including a huge number of buildings (let's assume there are hundreds of them all operated in a slightly different way also differing by size, age and nominal peak load) into one simulation will cause run time problems. On the other hand it is not necessary at all to generate all of the detailed building information in the context of such a large-scale energy simulation. This type of simulation can be satisfied by just a building thermal load profile. It is known that for a given supply water temperature just one specific combination of return temperature and mass flow rate will match the requested heat load in a heating system. Nevertheless it can be observed that simulators are using fixed return temperatures in their simulation runs to simplify simulations. It is then up to the user resp. the modeller to choose the right return temperature matching average operating conditions. It's worth mentioning that normally nominal return temperatures the system is designed for are defined without accounting for any part load deviation from the design status. From that background it is concluded that simplified but reliable building models partially including the building heating system are needed to get a more realistic picture of overall system behaviour. This paper describes a method how to estimate return temperature and flow rate in the pipe connecting the building with a DH system.

Simulation Program

The transient simulation program *TRNSYS-TUD* is used to model DH systems including the simplified building models. It has proved to be the perfect tool to use the long year experiences of the authors and existing models in building simulation for validation of the results at the field of DH. *TRNSYS-TUD* is a special research code derived from the well-known TRNSYS simulation program. The origin of the DH system simulation model is the model of space heating systems in buildings. Few adaptations allow to also calculating large heating systems with different pipe dimensions.

MODELLING APPROACH

Building model

Simplified and reduced order building models are very common to easily calculate energy performance with less effort. Standard ISO 13790 [3] describes a 3R1C network model to be applied as a building model that provides just thermal building load profiles depending on building physics, room temperature set points, internal heat gains as well as ambient conditions (outside air temperature as well solar gains).

$$\dot{Q}_{bldg,SH,dmd} = f(\vartheta_{i,set}, \vartheta_a, \dot{q}_i, \dot{q}_{sol}) \qquad (1)$$

The heating energy that is required to match the demand of the building as calculated by the model has to be provided by the DH system. The space heating system furthermore is modelling the return temperature and mass flow rate taking into account the DH flow temperature and the buildings energy requirements.

Space heating system model

The space heating system consists of the heat emitters (normally radiators or floor heating systems) and the distribution system. Instead of a heat generator (e.g. a boiler or a heat pump) this system is connected to the DH system. Figure 2 shows a space heating system indirectly connected to the DH system using a heat exchanger. Heat to be supplied to the building is known from the simplified building model according to Eq.(1). Heat losses of the space heating distribution system as well as additional heat demand due to imperfect room temperature control inside the building can be taken into account by an expenditure value e_{SH} that typically is in a range of 1.1…1.2. Finally the building energy demand including any additional energy must be equal to the water side energy balance, see Eq. (2).

$$\begin{aligned}\dot{Q}_{bldg,SH} &= \dot{Q}_{bldg,SH,dmd} * e_{SH} \\ &= \dot{m}_{SH} c_p (\vartheta_{s,SH} - \vartheta_{r,SH})\end{aligned} \qquad (2)$$

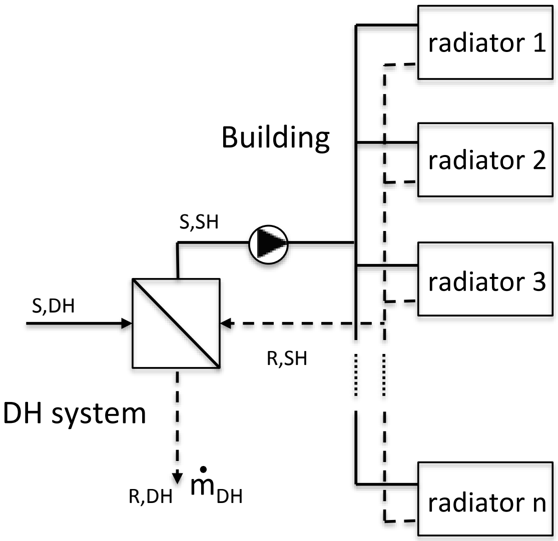

Figure 2 Space heating system with several radiators connected indirectly to a DH system

The basic idea now is to simplify the heating system (Figure 2) to just one – so called equivalent - radiator representing the entire system (Figure 3). This approach does not include domestic hot water generation just space heating. Valdimarsson, 1993, [7] and [2] and others authors [1,4,8,9] have chosen a very similar approach. Johansson's approach [9] and [4] already distinguishes between space heating and DHW heat demand.

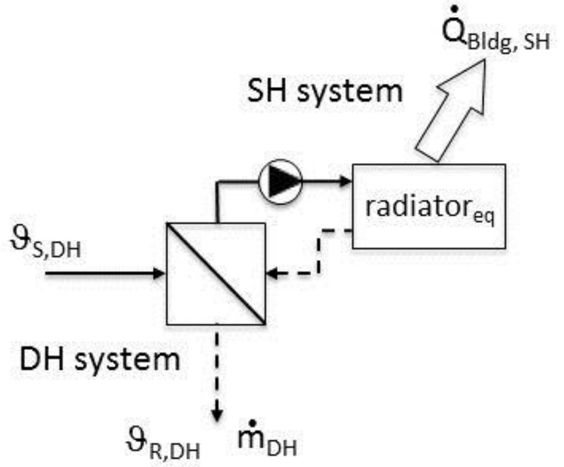

Figure 3 Equivalent heating system connected indirectly to DH

Following the radiator approach the heat emission for a given heat transfer coefficient UA depends on over temperature, Eq. 3

$$\dot{Q}_{bldg,SH,dmd} = UA\Delta\vartheta_{m,SH} \tag{3}$$

With over temperature calculated according to Eq. 4 where internal temperature is equal to the set point used in the building model Eq. 1. This internal temperature is an average value for all zones in building that are heated.

$$\Delta\vartheta_{m,SH} = \frac{\vartheta_{s,SH} - \vartheta_{r,SH}}{\ln\frac{\vartheta_{s,SH} - \vartheta_i}{\vartheta_{r,SH} - \vartheta_i}} \tag{4}$$

As an alternative to the indirect connection between space heating system and district heating system as discussed before a so called direct connection is possible as well. In that case no heat exchanger is used but radiators are charged with the hot water from the DH directly. Such systems are often equipped with an additional bypass (see Figure 4) that allows to control supply water temperature of the space heating system independently from the DH supply water temperature by recirculating return water from the space heating system.

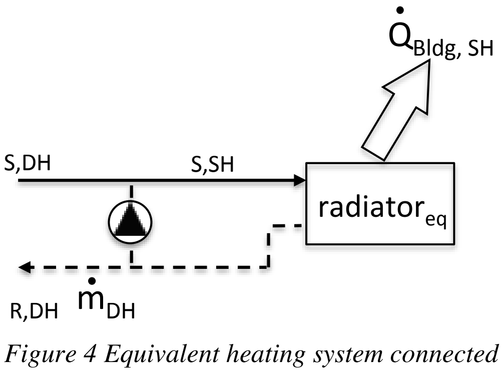

Figure 4 Equivalent heating system connected directly to DH

In both approaches - direct and indirect - the heat transfer coefficient of the analogous radiator model depends on the both radiator over temperature having an impact on the air side convection. The heating water mass flow rate furthermore has an impact on the water side heat transfer, see Eq. 5.

$$\frac{UA}{(UA)_{nom}} = \left(\frac{\Delta\vartheta_{m,DH}}{\Delta\vartheta_{m,DH,nom}}\right)^n \left(\frac{\dot{m}_{DH}}{\dot{m}_{DH,nom}}\right)^m \tag{5}$$

The exponent n depends on the type of heat emitter and is given by Knabe 98 [5] as follows:

- radiators n=0.3
- pipes n=0.25
- coils n=0.25
- flat plate emitters n=0.2-0.3
- convectors n=0.25-0.45
- floor heating systems n=0.1

The higher the radiated part of heat emission the lower n. Contrary to n the impact of mass flow is often neglected for a single radiator. Knabe 98 [5| gives a range of m=0-0.01. If more detailed and specific information is needed values have to be gained from experimental tests.

Nevertheless values are valid for a single radiator only and it has to be checked how the basic approach of Eq. 5 can be used to model the entire space heating systems in a building reduced to a single radiator model. For that reason field test data from real building installations will be used to check the applicability of the analogous radiator model. Field test data have been gained for instance from a DH substation as depicted in Figure 5. This substation connects the building installation to the DH network.

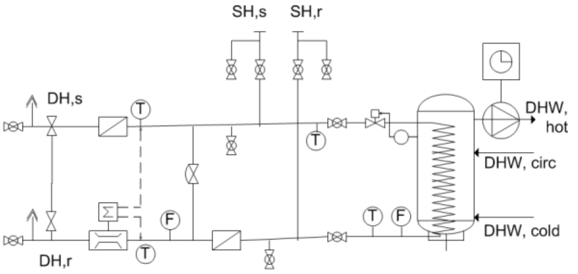

Figure 5 Test building substation configuration: DHW storage at the right hand side; space heating connected at the top; both connected directly to DH to the left

Relevant measurements include:

- temperatures (supply and return) as well as flow rate at the DH site measured in the heat meter to be used to calculate buildings total heat consumption to be provided by the DH system thus called $\dot{Q}_{DH}$

- temperatures (supply and return) as well as flow rate for DHW generation used to calculate DHW heat load $\dot{Q}_{bldg,DHW}$

Space heating load could be easily concluded from the total heat load provided by the DH system and the DHW load following the equation

$$\dot{Q}_{bldg,SH} = \dot{Q}_{DH} - \dot{Q}_{bldg,DHW} \tag{6}$$

Figure 6 shows typical profile of field test data.

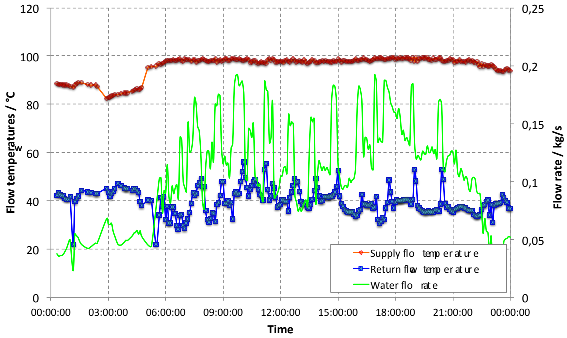

Figure 6 Field test data

Supply water temperature of the space heating system can be (a) in the case of an indirect system calculated by using an heat exchanger model - see Figures 2 and 3 - or (b) in the case of a direct system assumed to be the same as the DH supply temperature neglected minor heat losses of the distribution system - see Figure 4. Return temperature of the space heating system can be calculated from the energy and mass balance at the mixing point where space heating return flow and DHW return flow merge.

In addition to field test data building simulation has been used to generate building performance data. Typical data of a multi-family house gained from those computational simulations are depicted in Figure 7. In that particular case DHW was not taken into account. Flow temperatures are influenced by a nightly setback of supply water temperature set point.

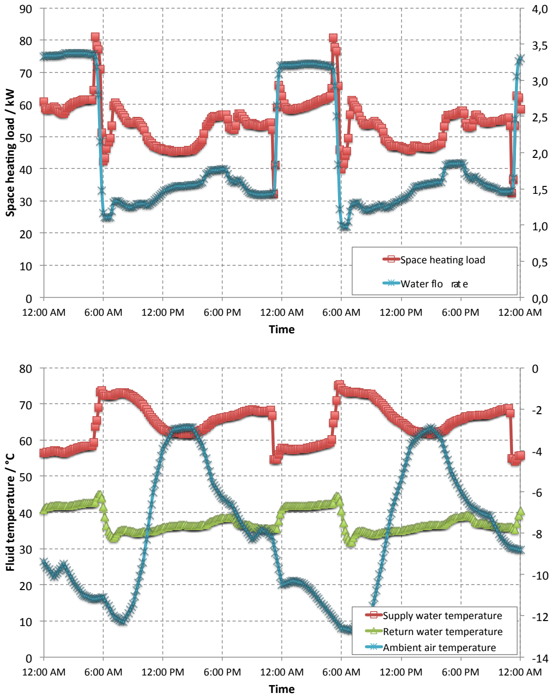

Figure 7 Simulation data (top: heat loads and flow rate: bottom: temperatures)

From space heating load and flow temperatures the resulting UA value of the analogous radiator model can be calculated from Eq.3 leading to the following equation.

$$UA = \frac{\dot{Q}_{bldg,SH}}{\Delta\vartheta_{m,SH}} \tag{7}$$

Eq. 7 is fully based on measurements, i.e. space heating load of the building as well as over temperature have been calculated from the measured data.

Once UA is extracted from the measurement according to Eq. 7. the goal is to find correlations between over temperature and mass flow rates that match Eq. 5. Exemplarily Figure 8 and Figure 9 show correlations based on field test data. It was tried to limit the range of the plot by classifying either mass flow or over temperature. Nevertheless it is to be seen that any correlation to be find will be a compromise simplifying real world behaviour.

Altogether 17 buildings have been analysed and two buildings have been simulated under different conditions. Based on the correlation analysis exponents m and n, respectively have been found in a range of

$$m = 0.2 \ldots 1.2$$

$$n = -1.2 \ldots 0.9$$

They comprise a coefficient significantly different from zero for the mass flow rate dependency and smaller (compared to values given for heating systems by Knabe 98 [8]), often even negative coefficient for the temperature dependency.

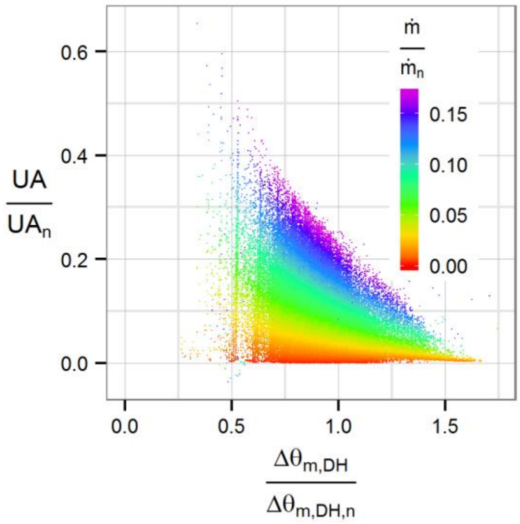

Figure 8 UA correlations depending on temperature conditions derived from field test data

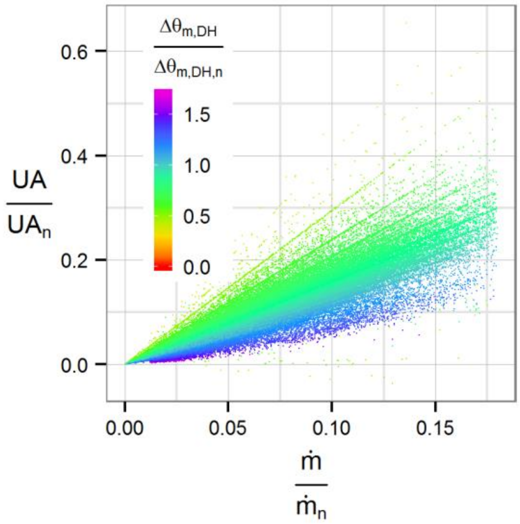

Figure 9 UA correlations depending on mass flow rate derived from field test data (index n refers to nominal values)

A good approximation has always been possible, which proves that the chosen approach (Eq.5) can be used to replace a detailed space heating system model. It was not yet possible to find a general correlation for the coefficients m and n as known for the single radiator. That is why they still have to be determined for each building individually.

A negative exponent for the temperature dependency might seem strange in the first moment, but one has to keep in mind that we are not talking about a radiator anymore but about a building including internal and solar gains and control systems. There might be load reducing solar gains or algorithms coming from the building control system at high excess temperatures. This can cause a negative correlation. Figure 10 shows the correlation between UA and the systems over temperatures as a result of a simulation run, which is a similar behaviour as found from measurements (figure 8).

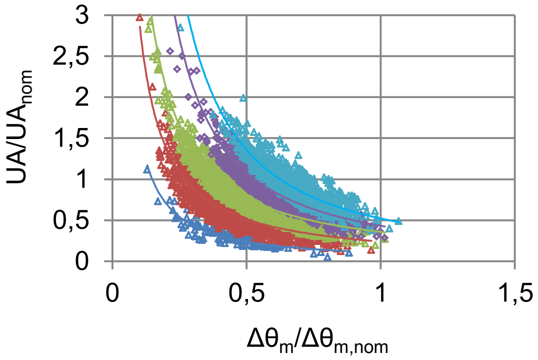

Figure 10 UA correlations depending on temperature conditions derived from simulation data

Finally both return temperature and mass flow rate for space heating can be calculated just knowing building space heating load from the building model, the additional energy to be taken into account to cover space heating system behaviour, and UA correlation of the analogous radiator model. Calculation is based on the setting Eq.2 and 3 into balance. Eq. 8 can be solved iteratively only.

$$\dot m_{SH} c_p(\vartheta_{s,SH} - \vartheta_{r,SH}) = UA\Delta\vartheta_{m,SH} \qquad (8)$$

DHW system model

DHW has been modeled as

- Direct flow system and
- Storage charging system.

For transient simulation of storages the numerical TRNSYS Type 75 can be used. In DH systems with several building units this again leads to running time problems. Hence a simplified one-node storage model considering capacity $C_{DHW,Stg}$ and heat resistance against ambient temperature has been created and validated in comparison to Type 75.

From the energy balance of the DHW storage which accounts for the heat to charge, the heat losses of the storage as well as enthalpy flows on the domestic hot water side including circulation, hot and cold water flow (9) DHW temperature changes per time step can be calculated using Eq.11 just depending on DHW storage heat capacity. Hot water and circulation profiles have to be supplied by the user by means of measuring data or stochastic daily distributions.

$$\dot Q_{Stg} = \dot Q_{ch} - \dot Q_{loss} + \Delta\dot H_{DHW} \qquad (9)$$

$$\Delta\dot H_{DHW} = \dot H_{DHW,cold} + \dot H_{DHW,circ} + \dot H_{DHW,hot} \qquad (10)$$

In case losses are considered to be constant (as usually given by manufacturers) Eq. (11) applies.

$$\frac{d\vartheta_{DHW,Stg}}{dt} = \frac{\dot{Q}_{Stg}}{C_{DHW,Stg}} \quad (11)$$

If losses shall be considered depending on the average storage temperature the correlation changes to Eq. 13.

$$\dot{Q}_{loss} = UA_{Stg}(\vartheta_{Stg,t-\Delta t} - \vartheta_{env}) \quad (12)$$

$$T_{DHW,Stg,t} = \frac{Y}{Z} - \frac{Y - Z * T_{DHW,Stg,t-\Delta t}}{Z * \exp(Z * \Delta t)} \quad (13)$$

with

$$Y = \frac{\dot{Q}_{ch} + UA_{Stg}T_{env} + \Delta\dot{H}_{DHW}}{C_{DHW,Stg}} \quad (14)$$

$$Z = \frac{UA_{Stg}}{C_{DHW,Stg}} \quad (15)$$

The outlet temperature can be found by a correlation to the storage temperature $\vartheta_{DHW,Stg,t}$, which is considered to be constant within the one-node model. Again Type 74 has been used to gain comparative simulation data. For a set of boundary conditions complete charging and discharging cycles have been simulated. Figure 11 shows the colored modulation between 10 °C and 62 °C over time and height of the storage.

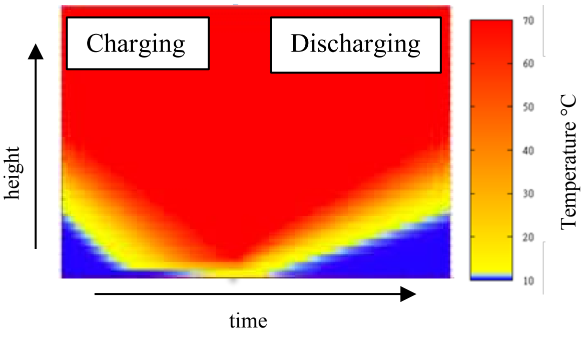

Figure 11 Charging and discharging the DHW storage

From this data the above mentioned correlation to the outlet temperature can be derived, see Figure 12. It can be seen, that the circulation mass flow $\dot{m}_{Zirk}$ has great influence on the outlet temperature, whereas the circulation temperature itself, has less influence.

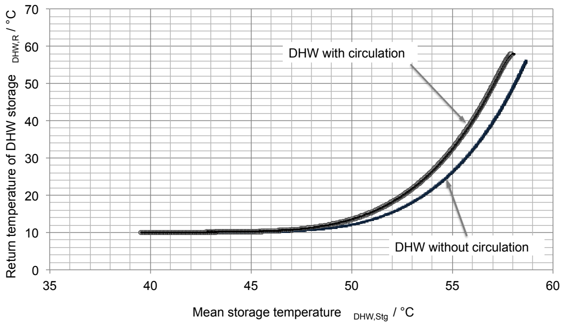

Figure 12 Return temperature of the DHW storage depending on mean storage temperature

A polynomial function of fourth order is employed for the model.

$$\vartheta_{DHW,R} = \sum_{i=0}^{4} k_i * \vartheta_{DHW,Stg}^{i} \quad (16)$$

As it can be seen in Figure 13 approximation given by Eq.16 fits well with the numerical simulation data of Type 74.

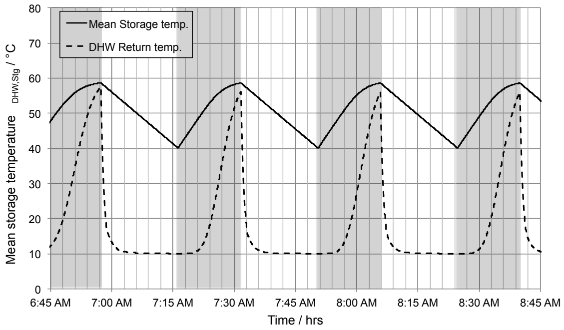

Figure 13 Results of the simplified DHW simulation model

The important part for DH simulation, at which correlations have been adjusted, is marked with blue background.

DH substation model

The DH substation in the building has to balance heat demand for space heating and DHW generation with heat delivered by the DH system. Supply water temperature for the space heating system is set according Seifert 2009 [6] to Eq. (17):

$$\vartheta_{SH,s} = \varphi^{\frac{1}{1+n}} * \Delta\vartheta_{m,SH,nom} + \frac{\varphi}{2} * \Delta\vartheta_{SH,nom} + \vartheta_i \quad (17)$$

With Eq. (4) and

$$\Delta\vartheta_{SH,nom} = \vartheta_{SH,s} - \vartheta_{SH,r} \quad (18)$$

This formula mainly depends on load ratio given by Eq. (19) thus accounting for load dependency on ambient air temperature.

$$\varphi = \frac{\dot{Q}_{bldg,SH}}{\dot{Q}_{bldg,SH,nom}} = \frac{\vartheta_i - \vartheta_a}{(\vartheta_i - \vartheta_a)_{nom}} \qquad (19)$$

Finally the overall return temperature from the building heating system can be calculated by combining return temperature of the space heating system derived from Eq. (8) and return temperature derived from the DHW system derived from Eq. (16) while taking into account also corresponding mass flow rates. This return temperature again is fed back to the DH either directly (Figure 4) or indirectly using an heat exchanger as depicted in Figure 3.

The mass flow rate to be provided by the DH system to meet energy demand for space heating and DHW generation is controlled by a valve. Once that mass flow has been calculated following methodology described before the valve lift in the corresponding DH branch can be adapted to allow the hydraulic system to meet the mass flow rate needed.

RESULTS

The approach described in this paper has been implemented to a building simulation program to be applied in several district heating system simulations. From results shown in Figure 14 it can be concluded that mass flow rate in a substation is easier to predict than the correct return temperature. In that particular case both mass flow rate as well as return temperature predicted are lower than measured data, i.e. lower mass flow but higher temperature difference between supply and return temperature will lead to the same heat provided.

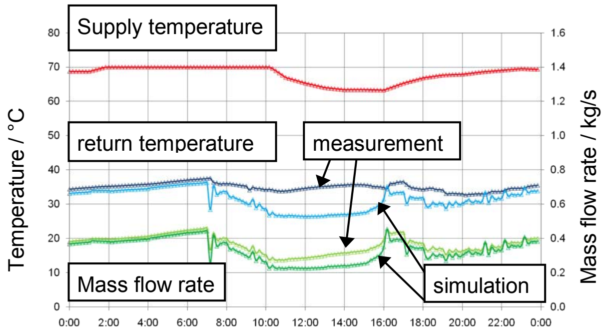

Figure 14 Validation of simulation results with field test data

Figure 15 shows the mass flow rate of the heating system that fits measured data very exactly. As heat load and supply temperature are given, also the return temperature can be predicted in very good manner.

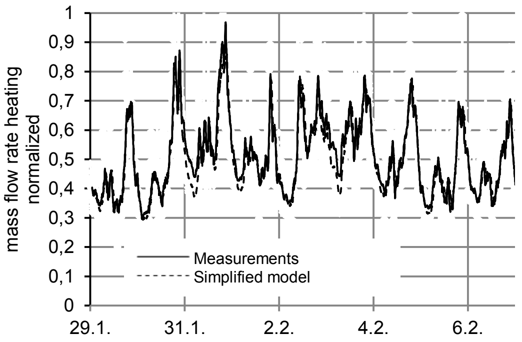

Figure 15 Validation of simulation results with field test data

CONCLUSION

This paper describes an approach how to calculate overall return temperature and mass flow rate of a DH substation providing heat to a building. Heat is needed due to space heating and DHW generation purposes. The substation design (direct or indirect connected) is taken into account. The approach itself bases on the equivalent radiator model. The dependencies of the heat transfer on both temperature and mass flow conditions are derived from a comparison with experimental data. Also detailed simulation runs have been taken into consideration. It was recognised that heat transfer having a big impact on radiator heat balance cannot easily be described as long as impact of mass flow and temperature conditions are in a wide range. Further studies are needed to either narrow the ranges of dependency or to find better correlations probably referencing additional impact factors.

NOMENCLATURE

symbols

$C_{DHW,Stg}$	thermal capacity of DHW storage
c_p	isobaric heat capacity
e_{SH}	energy factor space heating
k	coeffcient
m	coefficient
$\dot{m}$	mass flow rate
n	coefficient
t	time
T	temperature in K
UA	heat transfer coefficient
$\dot{Q}$	heating load
Δt	time step
ϑ	temperature in °C
	load ratio

Indizes, subscripts, Abbreviations

a	ambient
bldg	building
circ	circulation
ch	charge
env	environment

eq	equivalent
DH	District Heating
DHW	domestic hot water
dmd	demand
i	internal
m	mean
nom	nominal
R	return
S	supply
SH	space heating
Sol	solar
Stg	storage

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