



NTNU – Trondheim
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Improved control of the consumer substations by using dynamic simulation tools

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Master's Thesis

Submission date: July 2014

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Norwegian University of Science and Technology
Department of Energy and Process Engineering

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EPT-M-2014- 144

MASTER THESIS

for

Berina Delalic

Spring 2014

Improved control of the consumer substations by using dynamic simulation tools*Forbedret styring av abonnentsentraler ved bruk av dynamisk simuleringsverktøy***Background and objective**

The consumer substations are interface between the district heating system and users. Both increased use of renewable energy sources and decrease of the building heating demand lead to a transition of the district heating system to low temperature district heating system. This change will induce that the supply temperature to the consumer substation should be lower due to low temperature energy sources. Further this change will require that the return temperature should be lower too. To enable this transition to the low temperature district heating system, improvements in the interface between the district heating system and users are necessary. Therefore, it is necessary to study possible improvements in the consumer substation related to changes in components and control. The candidate will use Modelica to develop the consumer substation models. Object oriented symbolic Modelica language for industrial applications will be used within Dymola software environment with extensive utilization of the Buildings library for HVAC components modelling, developed by Simulation and Research group at Lawrence Berkeley National Laboratory (<http://www.lbl.gov/>). Further, the student will validate the models by using measurements from the laboratory at Department of energy and Process Engineering, NTNU on a district heating rig fully equipped for detailed monitoring.

This master thesis has aim to define improvements in the consumer substation so that the transition to the low temperature district heating is enabled. The candidate will use Modelica and laboratory measurements in the study.

This assignment is realised as a part of the collaborative project “Sustainable Energy and Environment in Western Balkans” that aims to develop and establish five new internationally recognized MSc study programs for the field of “Sustainable Energy and Environment”, one at each of the five collaborating universities in three different WB countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2014.

The following tasks are to be considered:

1. Literature review on consumer substations, belonging components, and control. Literature review should include modelling too.
2. Develop dynamic models in Modelica for typical substations. The substation models should be based on the literature review and relevant for the low temperature district heating interface.

3. Perform measurements on the laboratory rig. Organize different scenarios. Test the controllers and the plant operation for different conditions.
4. Validate the dynamic models. Suggest improvements in the substations to enable transition to the low temperature system.
5. Organize and present the results. The results should present improvement and decrease in energy use of the consumer substation.
6. Make a draft proposal (8-10 pages) for a scientific paper based on the performed work in the master thesis.

-- ” --

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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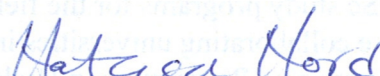
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The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

Department of Energy and Process Engineering, 19. February 2014.



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Acknowledgement

First and foremost I would like to thank my supervisor, prof. Armin Teskeredzic, for help and advice that were indispensable guidance throughout the creation of this work, and for the sincere enthusiasm and support that was never lacking.

Since I was working my master thesis as a guest student at NTNU, I would like to thank prof. Vojislav Novakovic, as a leader of HERD project that provided exchange of master students, and as a wonderful host in Norway.

I would also like to acknowledge the great help and instructions provided by my supervisor at NTNU, prof. Natasa Nord, during my stay and research in Trondheim.

I am particularly grateful to my father who provided professional and emotional support to me, and who always helped me raise above the sea of mediocrity.

This master work could never have been accomplished without my family and friends to whom I express my great gratitude and love.

Berina Delalic

Abstract

Simulation models are becoming important engineering tool that helps in design and adjustment of physical systems. This paper shows application of *Modelica* programming language through *Dymola* simulation environment in analysis and discussion on control system in district heating substation. As a central component of heating substation, the model of plate heat exchanger water-to-water was created and implemented in *Modelica/Dymola*. Verification of that model was done by measurements performed at Laboratory of Department of energy and Process Engineering, Norwegian University of Science and Technology. Beside of the heat exchanger model, the heat substation model was completed using components from *Buildings* library developed at *Lawrence Berkley National Laboratory*. Afterwards, the substation model was integrated in system of four buildings connected to the district heating network in order to show potentials for lowering supply and return water temperature. It has been proven to be very promising, with benefits such as opportunity for low temperature heat sources and reducing the heat losses in district heating network.

This assignment is realised as a part of the collaborative project *Sustainable Energy and Environment in Western Balkans* that aims to develop and establish five new internationally recognized MSc study programs for the field of *Sustainable Energy and Environment*, one at each of the five collaborating universities in three different Western Balkan countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2013.

Key words: model of plate heat exchanger, heating substation, control system, Modelica, Dymola, Buildings library, district heating, low temperature system

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Acronyms

CS – control surface

CV – control volume

DH – district heating

DHW – domestic hot water

EE – energy efficiency

HEX – heat exchanger

HVAC – heating ventilation and air-condition

LMTD – logarithmic mean temperature difference

NTNU – Norwegian University of Science and Technology

OHTC – overall heat transfer coefficient

PHEX – plate heat exchanger

PID – proportional-integrative-derivative control

1 Introduction

Building sector is one of today's most attractive targets for improving energy efficiency and reducing the consumption. It has been established that buildings represents around 40% of total final energy consumption [1] which drew a great deal of attention of agencies dealing with energy field issues. In 2002. the European Parliament and the Council made the document called *Directive on the energy performance of buildings* (EPDB) in order to affect further development and modification of energy systems in buildings. This *Directive* has been revised since the first publishing and today it is setting up high requests, including design of the new buildings as nearly-zero emission.

The most significant part of energy in building sector is consumed for space heating. District heating systems are widely spread solutions in great cities due to the good efficiency of centralized heat generation. Connection between buildings and DH network could be brought out as direct and indirect. This paper will focus on indirect heat substations with plate heat exchangers.

There are various ways of energy efficiency improvements that are being implemented or considered. The heating systems are becoming ever more efficient and production technologies are constantly developing. However, it has become evident that important role is played by interaction and behavior of the energy system components: from production, over distribution, to consumers and vice versa. Focusing on particular measures can often cause neglecting this aspect of system design but the adjustment of heating systems components for proper operation can be crucial. Consumer demand varies depending on season, part of the week and even on daily basis. The production and distribution system is designed in order to satisfy highest possible heat demand and changes in these parts generally occur slowly. Still the final target that needs to be satisfied in any moment is thermal comfort in living areas. Therefore the building's heating system needs to be capable to make quick and efficient respond to building's current need. Most suitable place for the control system can be found in heating substation. For detailed analyses and discussion on this issue, dynamic simulation tools are rapidly gaining in importance and being applied ever more in adjustment of the heating control systems.

Primary aim of this work was to complete simulation model of plate heat exchanger water-to-water that would properly describe its behavior in actual operating conditions of the consumer heat substation. Simulation tool used for that is equation-based object-oriented language *Modelica*, supported by *Dymola* software environment. Additionally, the *Modelica's Buildings* library [2], developed by Simulation and research group at *Lawrence Berkley National Laboratory*, was used in modeling HVAC components and completing heat substation model. Verification of the HEX model was done after the laboratory measurements performed on the plate heat exchanger in the Laboratory at Department of energy and Process Engineering, Norwegian University of Science and Technology.

When completed, model of plate heat exchanger was implemented in simulation model of heat substation and used for discussion on a popular issue – transition to low temperature district heating systems. Conducted research gave an insight in similar problems in European cities and different solution proposal which helped forming idea on how to lower the water

temperatures of DH network in Sarajevo. Guided by these thoughts, the model of four buildings supplied with DH network was designed, using the developed model of a heat substation. This part of the paper showed application of the developed model of plate heat exchanger which also revealed possibilities of *Modelica* for calculations of heat transfer and fluid dynamics.

This master thesis was aiming to produce a dynamic simulation tool that could help discussing the opportunities for improvements of heating systems by DH substation control. Learning the basics of the *Modelica* programming language was essential in order to apply models from basic *Modelica* library and *Buildings* library. The most attention was directed to the plate heat exchanger and operation of heat substation. Mathematical model and description of the components used in simulations needed to be investigated and explained in the theoretical part of the work. Neither production nor consumption side were considered in detail but rather briefly researched in order to find most significant aspects of their mutual influence.

Transition to low temperature district heating is a very complex issue and could not have been taken completely under the scope of this paper. However, lots of interesting questions have been raised and further research became rather appealing.

2 Heat exchanger in district heating system

In order to make more detailed introduction in topics there were involved in this research, a literature review has been made in this chapter. Fundamental idea of district heating systems has been presented, introducing concept of indirect heat substation with plate heat exchanger. Control system of DH substation is described separately since a few matters needed to be mentioned. Benefits of low temperature systems are explained along with barriers in process of transition. Lastly some basic information about development and usage of *Modelica* language with *Dymola* environment is given.

2.1 District heating

District heating is one of today's most preferable solutions for space heating and preparation of domestic hot water in major European cities. There are lots of benefits both for consumers and suppliers and this chapter is giving just a brief overview of fundamental characteristics of DH systems.

Main purpose of DH network is to supply consumers with energy for space heating and preparation of DHW. Sometimes the systems are limited only to space heating, but the trend is to spread DH's range of operation to other services such as cooling and even low temperature industrial heat demand. The basic idea from the very beginning was to produce heat energy in a more efficient way than the consumers could do individually.

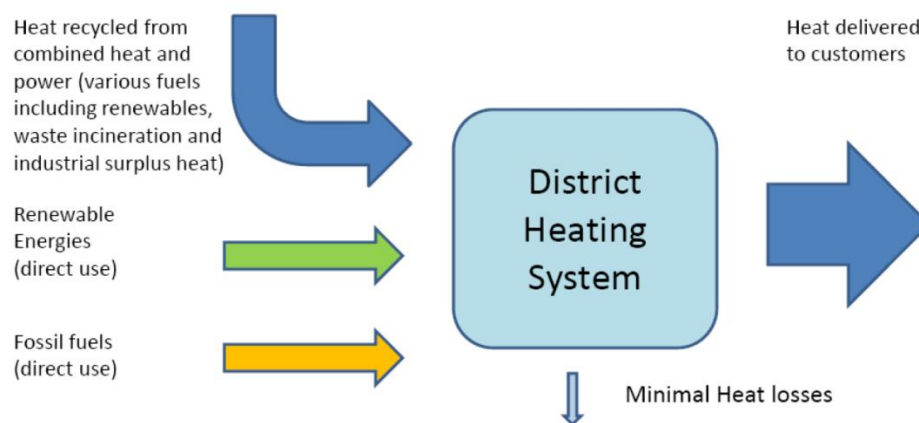


Figure 2.1 Basic concept of district heating system [3]

DH systems have three main sections:

- Production
- Distribution (and transmission)
- Consumption

Production part of DH system today is mostly oriented to alternative heat sources that will provide lower emission of CO₂ than conventional fuels. As shown on Figure 2.1, most attractive idea is combined heat and power production which can achieve high energy efficiency comparing to individual production of required heat and indispensable power. Renewable energy sources are gaining attention especially regarding lower temperature energy systems such as district heating. Although not preferable, fossil fuels are still in use for DH system as a reliable and available source of energy. Often there are few production units with different heat source supplying the DH network. The unit with the lowest operational cost is used for base load and the one with the highest operational cost is used for peak load [4].

Distribution network consists from well insulated pipelines and district heating substations, whose design depends on whether the connection for the building is direct or indirect. Typically, the heat carrier is water, although there are still some systems operating with steam. Temperature regimes differ between countries and even DH networks. Higher supply temperatures are present in Russia (140-170°C) and in Germany (110-160°C). The case is different in Sweden where the supply water temperatures are 100-120°C and even lower in Denmark, around 80-90°C [4].

Consumption side of the DH system can include both residential and commercial buildings. Since the significant part in final energy consumption is related to buildings, this unified heating system made large step in reducing energy consumption of great cities. Common concept of today's district heating is to provide the consumers with space heating and domestic hot water.

All of the system components are connected and depending on each other. Often approach is to consider the consumption demand primary, which defines complete consumer installation and connection to the DH network. Next, the distribution network and the power plant are designed according to predicted heat demand. If the production side is conditioned in a way (e.g. energy source is waste heat from an industrial process), designing can be performed in reverse.

For proper operation of the complete system, it is important to perform correct design, construction and control of the DH system. When these properties are satisfied, DH system is easy to use for consumer and not challenging for maintenance.

2.2 District heating substation

Connection of a building to the DH network is generally made through some kind of substation. Type of substation can be defined regarding the way of connection. In systems with direct connection, water from distribution network is also circulating through buildings' heating system. When indirect connection is applied, there is a heat exchanger integrated in the substation and water from network is separated from the heating system circuit. Both direct and indirect types of connection have advantages and drawbacks. Since this paper is focused on the heat exchanger, only the indirect heating substation will be considered in further text.

Features that make indirect substation attractive connecting solution are low risk of leakages and better possibility for control. Since there is a hydraulic separation between heating system and DH network, it is easier to provide proper pressure arrangement without any large variations. Local damages and leakages can be noticed quickly with no significant

consequences regarding the rest of DH network. Adjustment of temperature and mass flow rate is performed in every substation which enables complete DH system to operate closer to actual buildings' demand.

The leading HVAC component design companies have developed the indirect consumer substation as a final product with all necessary control equipment integrated. There is wide range of substations designed regarding specific performance requirements. This can be conditioned by operating parameters of the DH network, type of heating systems and connected object (single households, residential or commercial buildings, industrial building) or requested services (space heating, DHW, cooling, floor heating). Figure 2.2 illustrates an example of indirect heat substation suitable for domestic hot water, heating, floor heating or air-conditioning system.

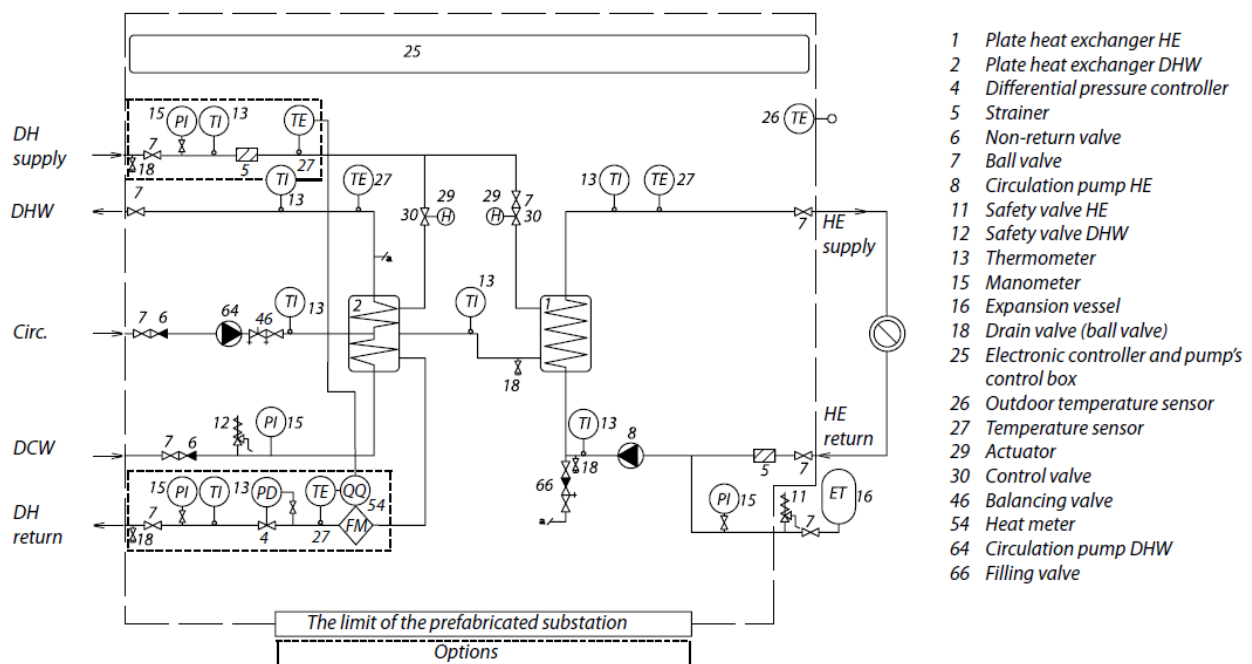


Figure 2.2 Example of circuit diagram for DH substation by Danfoss, type LJ [5]

Basic principle of a modern DH substation operation can be seen on an example of product of Danfoss company (Figure 2.2). When entering the substation, water from DH network divides in two flows: one part of the flow supplies the heating system (HEX1) and another is used for preparation of DHW (HEX2). Beside of heat exchangers, most of the equipment necessary for operating of heating system and for delivering DHW is preferable to be integrated in the substation. Figure 2.2 shows the circulation pumps, temperature sensors, valves, actuators, differential pressure controller and other safety and control equipment, all inside of the limit of prefabricated substation. The substation often contains a power meter. Aspect of control in the DH substation is explained in next subchapter.

Main objection to the indirect substation is the heat loss that occurs due to inevitable temperature difference between primary and secondary flow in heat exchanger. However, the use of modern plate heat exchangers has mitigated this disadvantage. Compact and highly efficient, this type of heat exchanger has become first choice in indirect DH systems today [6].

Figure 2.3 shows assemblage of a typical plate heat exchanger. It consists from a series of plates integrated with gaskets that determine the flow arrangement of the primary and secondary side medium. The plates are pressed together in a frame so the HEX is compact,

light and easy to set apart for cleaning. Hot and cold fluids flow alternately between parallel corrugated plates, exchanging heat with high efficiency.

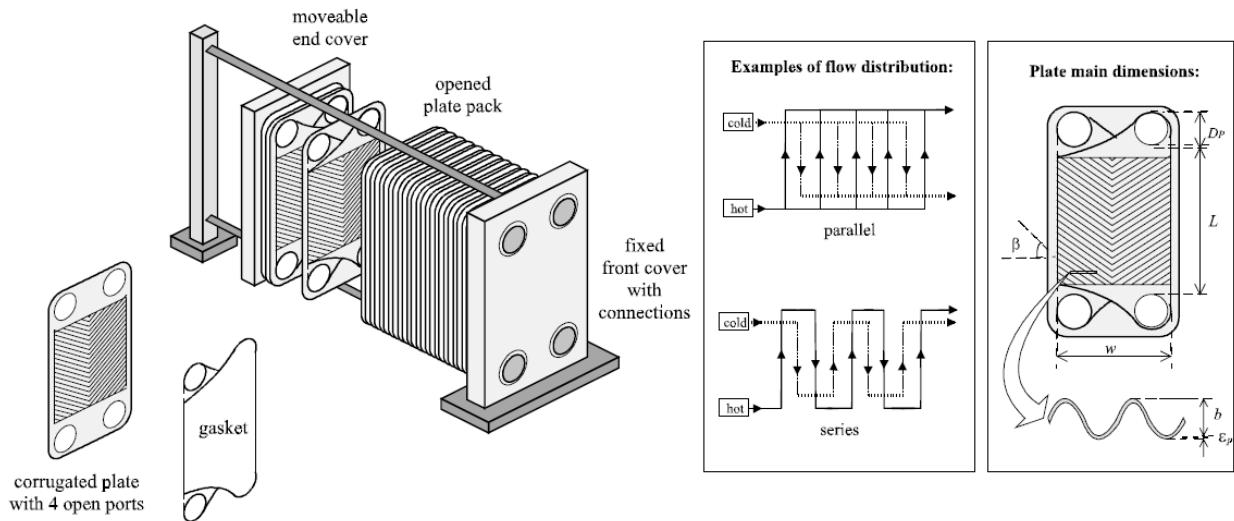


Figure 2.3 Construction of plate heat exchanger with flow distribution examples and plate main dimensions [7]

Performance and load of the plate heat exchanger is defined by number of plates, flow distribution, dimensions of plate, type of gaskets, ports' location and other dimensional data. Low internal water volume could cause temperature problems, but with control system that is fast enough, the plate heat exchanger can easily keep track with varying heat demand.

There are two basic methods for defining thermodynamic behavior of the heat exchanger. Common approach for HEX design is logarithmic mean temperature difference (LMTD) method, where it is assumed that required inlet and outlet water temperatures are known. The heat transfer equation is then defined as:

$$Q = U \cdot A \cdot LMTD \quad 2.1$$

where $Q[W]$ is a heat flow rate, $U[W/m^2K]$ is overall heat transfer coefficient, $A[m^2]$ is heat transfer area and logarithmic mean temperature difference is determined as:

$$LMTD = \frac{\Delta t_1 - \Delta t_2}{\ln \frac{\Delta t_1}{\Delta t_2}} \quad 2.2$$

for Δt_1 being higher temperature difference between hot and cold fluid (for counterflow it is the end with entrance of cold fluid) and Δt_2 is smaller temperature difference between hot and cold fluid (for counterflow it is the end with entrance of hot fluid). This method is used to determine size and type of heat exchanger that would satisfy required heat transfer.

When, on the other hand, the heat exchangers with prescribed mass flow rate and inlet temperature is specified, calculation of heat flow rate and outlet temperatures with LMTD method often becomes a complex iterative procedure. To simplified analysis of HEX performances in this case, another method was conceived. The NTU-effectiveness method takes into account known characteristic of HEX in order to calculate its performances in current operating point. The effectiveness is defined as:

$$\varepsilon = \frac{Q}{Q_{\max}} \quad 2.3$$

where $Q[W]$ is actual heat transfer rate that is still unknown, and $Q_{\max}[W]$ is maximal possible heat transfer rate. On the other hand, effectiveness is related as:

$$\varepsilon = f\left(NTU, \frac{C_{\min}}{C_{\max}}\right) \quad 2.4$$

where $NTU = \frac{UA}{C_{\min}}$ is number of transfer units and it is specified for every HEX; C_{\min} and C_{\max} are minimum and maximum heat capacity determined between heat capacity of hot fluid stream $C_h = \dot{m}_h \cdot c_h$ and heat capacity of cold fluid stream $C_c = \dot{m}_c \cdot c_c$.

Relation between effectiveness and NTU differs for every type of flow configuration [8].

The LMTD method and NTU-effectiveness method are two most present principles when it comes to heat exchanger performances. They are starting point in any further analysis of HEX behavior in different environments and its interaction with other HVAC components.

2.3 Control system of indirect heating substation

In our modern age of technology, the controls make our lives more convenient, comfortable, efficient, and effective. A control enables equipment to operate effectively and gives the ability to change their actions as time goes on. The ultimate aim of every HVAC system and its controls is to provide a comfortable environment suitable for the process that is occurring in the facility. In most cases, the HVAC system's purpose is to provide thermal comfort for a building's occupants to create a more productive atmosphere (such as in an office) or to make a space more inviting to customers (such as in a retail store). Another capability that is expected of modern control systems is energy management. This means that while the control systems are providing the essential HVAC functions, they should do so in the most energy efficient manner possible [9].

The control of heat output in a heating system can be performed in two basic ways: varying mass flow rate and varying water temperature. The first approach is based on a constant supply temperature combined with local flow control, and the other defines constant flow rate in combination with a supply temperature curve [4]. In DH systems today, both methods are combined very often. Another division of the control systems can be made regarding whether there is an open or closed control loop. An open-loop control system, or feedforward, does not have a direct link between the value of the controlled variable and the controller: there is no feedback. An example of an open-loop control would be if the sensor measured the outside air temperature and the controller was designed to actuate the control valve as a function of only the outdoor temperature [9]. The closed loop control is based on feedback principle, e.g. there is a signal from the indoor temperature sensor back to control system.

This paper is dealing with so-called weather compensation control integrated in DH substation. This is an open loop control based on outdoor temperature. The primary circuit – DH network

is at constant supply temperature, but the mass flow rate through HEX is changing in order to provide proper heat flow. Required heat flow is determined by the outdoor temperature. Secondary circuit – consumers heating system has in general constant mass flow rate and the supply water temperature is changing according to heating curve and outdoor temperature.

Usually, the control curve for the radiator supply temperature is such that the temperature varies slightly non-linearly with the outdoor temperature, i.e., the curve is slightly bent due to heat transfer from the radiators increasing at high radiator surface temperatures. The feedforward signal (outdoor temperature) to the controller is nowadays usually dampened to compensate for the buildings thermal inertia: the indoor temperature does not instantly change when the outdoor temperature changes, and can in certain cases be supplemented by, for instance, a correction for the wind speed. The radiators are normally equipped with thermostatic radiator valves, of which the main task is to compensate for free heat (e.g., solar radiation, electrical equipment or body warmth) by reducing the flow through the radiator [4].

Great contribution to the hydronic heating control systems is made by the variable speed pumps. Appearance of this piece of equipment has significantly improved operation of thermostatic radiator valves.

When it comes to control of heat exchanger, there is another matter that needs to be discussed. In all control systems it is desirable for the loop gain to be constant throughout the entire working range. Constant loop gain means that the relationship between a step applied at the control inlet and the resultant step in the controlled variable is constant throughout the entire working range [10]. This provides that the same control adjustments can be optimum across the entire working range.

For the HEX control system the constant loop gain requires linear relationship between the load and controlled variable. When weather compensating control is applied in the HEX, the control variable is the secondary side supply water temperature. Since there is a highly non-linear relationship between variations in heat load and variations in flow temperature (dependent on flow rate on the secondary side) the HEX control circuit can show highly variable loop gain.

In paper by Benonysson and Boysen [10] it has been shown that constant loop gain in a heat exchange circuit with high temperature efficiency is achieved when the flow is altered by the exponent of the valve travel, and thus also by the exponent of the output signal of the control, if the actuator is linear. This can be attained with the aid of an exponential valve characteristic. On Figure 2.4 it is marked as equal percentage. The paper also mentions that the use of an exponential valve is not actually necessary in order to achieve constant loop gain. It can equally well be achieved using a linear valve and then applying the exponential effect somewhere else in the control loop, e.g. in the actuator or the control.

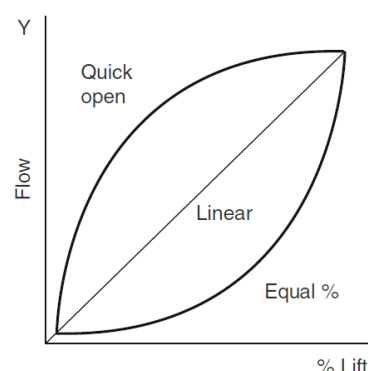


Figure 2.4 Types of control valve characteristics

2.4 Low temperature systems

In order to reduce CO₂ emission, there are few basic ideas that are moving the development of energy management. It has been aiming for better efficiency both for production and consumption side, reduction of heat losses in distribution and replacement the fossil-fuel

combustion with new technologies. DH systems are very comfortable with implementation of different EE measures, especially for improvement of heat generation since it provides possibility for faster and cheaper integration of renewable sources of heat than individual heating sources. However, new production technologies provide heat of lower potential, which for the DH systems mean lower supply and return water temperature, i.e. low temperature system.

Concept of low-temperature DH suggests the supply temperature being reduced to 55-50°C and the return temperature to 30-25°C. The minimum supply temperature of 50°C is defined as the lowest primary temperature needed to supply the required 45°C DHW (domestic hot water) at tapping points [11].

Beside decrease of temperature regime, these systems usually attempt to provide *good cooling of district heating water* [4], i.e. to increase difference between supply and return water temperature. Sometimes a common performance measure for individual substations, or for whole networks, is a low district heating return temperature.

There are numerous advantages for low temperature system in DH network. Most types of heat production benefit from either a reduced supply or return temperature, or both, such as condensing gas boiler, cogeneration production, heat pumps, recovery of waste heat from industries etc. [4] Low-temperature DH is the optimal concept for the integration of 100% renewable sources of heat, with additional benefit of heat losses reduction in distribution. Increase of DH water temperature difference means that the flow rate in the network can be reduced leading to energy saving from pump operation. On the other hand, the higher temperature difference provides more capacity of the network which enables more customers to be connected to the network with the same flow rate.

However, there is still very small share of low-energy building suitable to connect directly to low temperature systems. Moreover, the building blocks have become rather uneven regarding heat demand due to ongoing process of refurbishment of existing buildings. This gradual transition to low temperature system is widely spread issue in European cities since DH networks in general cover large number of object.

Significant role in adjustment of DH network to desirable lower temperature regimes plays DH substation. With proper control, substation can provide heat demand requested by consumers and satisfied conditions of production side. In the *Euroheat & Power* guidelines for substations [6] is stated:

The amount of heat utilized from the circulating district heating system water depends mainly on the design and adjustment of the building's internal heating systems, but also on the performance and the condition of the district heating substation. Good cooling of the district heating water (i.e. more heat subtracted) and good performance of the district heating substation are in the interests of both the customer and the heat supplier.

2.5 Modelica and Buildings library

Simulation tools have already gained great attention in design of HVAC systems and management of energy consumption. The numerical simulations are used worldwide for prediction of different physical processes. However, it is still very challenging to create model that would properly illustrate behavior of real system. Additionally, building the model from a

scratch can certainly be aggravating factor. A flexible environment which allows altering the building system configurations is provided by ever more popular *Modelica* language.

Modelica is a free language and is developed by the non-profit *Modelica Association* since 1996. First applications in industries occurred in year 2000 and ever since *Modelica* is gaining more and more supporters in a field of computer simulation of dynamic systems.

Modelica is primarily a modeling language that provides ground for defining the mathematical models of complex natural or man-made systems. It is also an object-oriented equation-based programming language, oriented toward computational applications [12]. There are several advantaged of *Modelica* that makes it convenient and useful simulation tool. Object-oriented programming allows the user to create systems from standard components, such as pumps or electrical resistance, which are defined as object with stored data and corresponding equations. The basic idea of working in *Modelica* is to decompose the considered system into components that are as simple as possible and then to start from the bottom up, connecting basic components into more complicated classes, until the top-level model is achieved [13]. The mathematical description in *Modelica* is based on differential, algebraic and discrete equations and they are declared inside of fundamental structuring units called classes. It is allowed to create as many models as user desire from the same class and to reuse same base class for different implementation. It is important here to mention another *Modelica* segment that makes this language attractive for modeling. *Modelica*'s software component model includes three items: components, connection mechanism and component framework [12]. Components are connected via connection mechanism and the component framework provides realization of connection. This software component model made it possible for the same components and models to be used over and over in different scenarios and environments, which ended the starting-from-the-scratch era for software developers.

Models developed in the *Modelica* language need to be translated into an executable program by a simulation tool. *Modelica* simulation environments are available commercially or free of charge. One of such simulation environments is *Dymola* used during research for this paper. *Dymola* contains what is believed to be the best symbolic and numerical solver for *Modelica*. The translator of *Dymola* takes the *Modelica* model as an input, generates a differential-algebraic equation system (DAE) and transforms the DAE to state-space form by symbolic manipulation and graph theoretical algorithms. The equations are stored as C-Code which is compiled and linked to the *Dymola* simulator for real-time simulation [13].

Dymola environment provides *Modelica* user with three ways of communication (see figure 2.5). Graphical editor contains two windows: main window is used for composing models and library window allows search and selection of component models from available libraries. At the same time, user can also see and alter the *Modelica* language description of the model, in *Modelica Text window*. Translation to C-code and simulation for set parameters is done in Simulation window, where it is still possible to change parameters between simulations, adjust simulation properties such as time step or integration method etc.

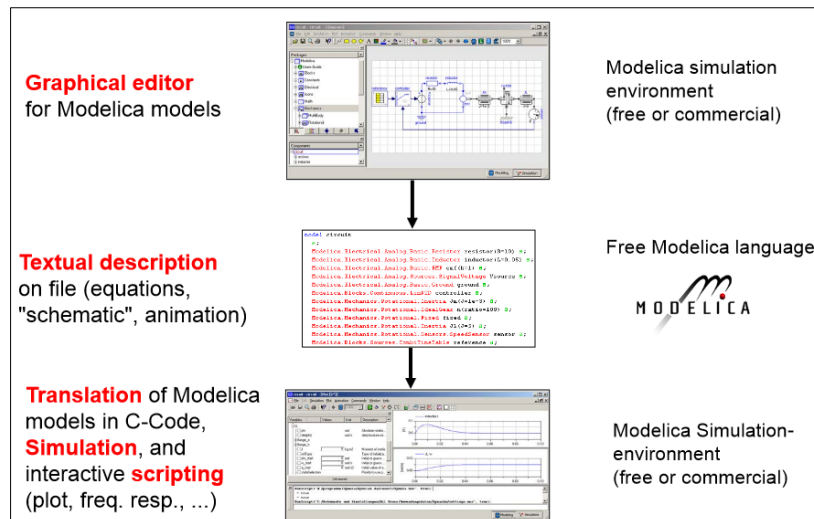


Figure 2.5 Modelica language and simulation environment [14]

As mentioned before, reuse of model has enabled much easier and faster development of complex systems. Large number of developed models is gathered in different *Modelica* libraries, from simple and basic classes to complete models ready to be used. *Modelica Standard* library is a free library developed together with the *Modelica* language by *Modelica* Association. It is an open source library which today contains about 1280 model components and 910 functions from many domains. Beside this, there are about 30 free or commercial *Modelica* libraries developed for different domains and in different parts of the world. One of the free open-source libraries specialized for energy and control systems in buildings is developed by *Simulation and Research group at Lawrence Berkley National Laboratory*. It is called *Buildings* library and was also used extensively for modeling and simulation for this paper. The library contains models for air-based HVAC systems, water-based heating systems, controls, heat transfer among rooms and the outside and multizone airflow, including natural ventilation and contaminant transport. At the web page of the *Simulation and Research group* [2] it is stated:

The primary use of the library is for flexible and fast modeling of building energy and control systems to accelerate innovation leading to cost-effective very low energy systems for new and existing buildings.

3 Laboratory tests and measurements on plate heat exchanger

3.1 Research plan

Process of making the simulation model needs to start from defining all the relevant parameters of the object in focus. Model of plate heat exchanger, which was developed during this research, was oriented towards measurements performed on experimental rig in the Laboratory at Department of energy and Process Engineering, NTNU. This laboratory rig is designed as a district heating substation with three plate heat exchangers. The one that transfers heat from primary circuit to the space hydronic heating system was used for measurements. This HEX was crucial in adjustment of the model in Modelica so it would demonstrate real behavior of HEX in operation.

After analyzing some existing HEX models and getting familiar with Modelica language, a basic draft of the developing model was made. This was initial step that highlighted the most important parameters of HEX behavior. It was determined that the greatest influence on HEX's heat transfer possibility has the value of mass flow rate. The water temperature range also affects HEX performance but in smaller amount than mass flow rate. Therefore, it was crucial to make measurement that would reveal relation between mass flow rate and heat transfer coefficient. However, laboratory equipment made its own restrictions so the plan for measurements needed to be modified regarding the one made in the first place. It was very hard to properly control mass flow rate of the secondary side when there was only radiator in operation. Because of that, only the measurements with varying primary side parameters were taken under consideration. Values were chosen based on the laboratory rig's possibilities, but staying in interval in which PHEX of this kind commonly operates.

3.2 Laboratory equipment and plan for measurement

3.2.1 Description of laboratory rig at NTNU

District heating substation in the Laboratory at Department of energy and Process Engineering, NTNU, is a model of a common indirect substation for heating and preparation of domestic hot water (DHW). This kind of substation can often be found in single-family houses, buildings with a few households or other objects.

In real condition scenario, the substation would be supplied with heat by connecting to the local district heating network. In this laboratory model of the substation, the heat source is an electric boiler which can provide maximum water supply temperature of 90°C. Hot water from the boiler transfers its heat energy in three plate heat exchangers: first for space heating, second for domestic hot water and third for preheating domestic water. In further text they will be denoted as HEX1, HEX2 and HEX3, respectively. Secondary circuit, which gains heat through HEX1, supplies radiator and heating coil. The HEX2 provides desirable temperature of the

domestic hot water. The HEX3 is installed in series with HEX2 so when the fresh water rushes from water city network, it is preheated in HEX3 by the primary circuit fluid in return line. This provides better effects and higher efficiency of the system, since it is easier to hit set point temperature for DHW in HEX2, on the one hand, and on the other the return temperature of primary circuit is decreased.

The substation is fully equipped for detailed monitoring, with possibility of instantaneous manual change of valves position, pump and fan load. Automatic control can be chosen for five valves, as it is described in further text. Data acquisition can be performed for most of the sensors, in desirable period of time and with adjusted time step. Additional description is given for complete primary circuit and part of secondary circuit that supplies space heating system. Preparation of DHW is not explained in next part since it was not in the scope of this work. The measurements were performed on HEX1 so this component is presented in detail.

Primary circuit

Next to the boiler, the primary circuit also connects hot water tank, frequency regulated circulation pump (JP1), expansion tank, eight temperature sensors, three flow meters, two power meters, two three-way valves both with electronic actuators, two two-way valves also with electronic actuators and another circulation pump (JP2). Figure 3.1 shows scheme of primary circuit with all the components. Component marks are made as in existing Lab View program connected to the rig.

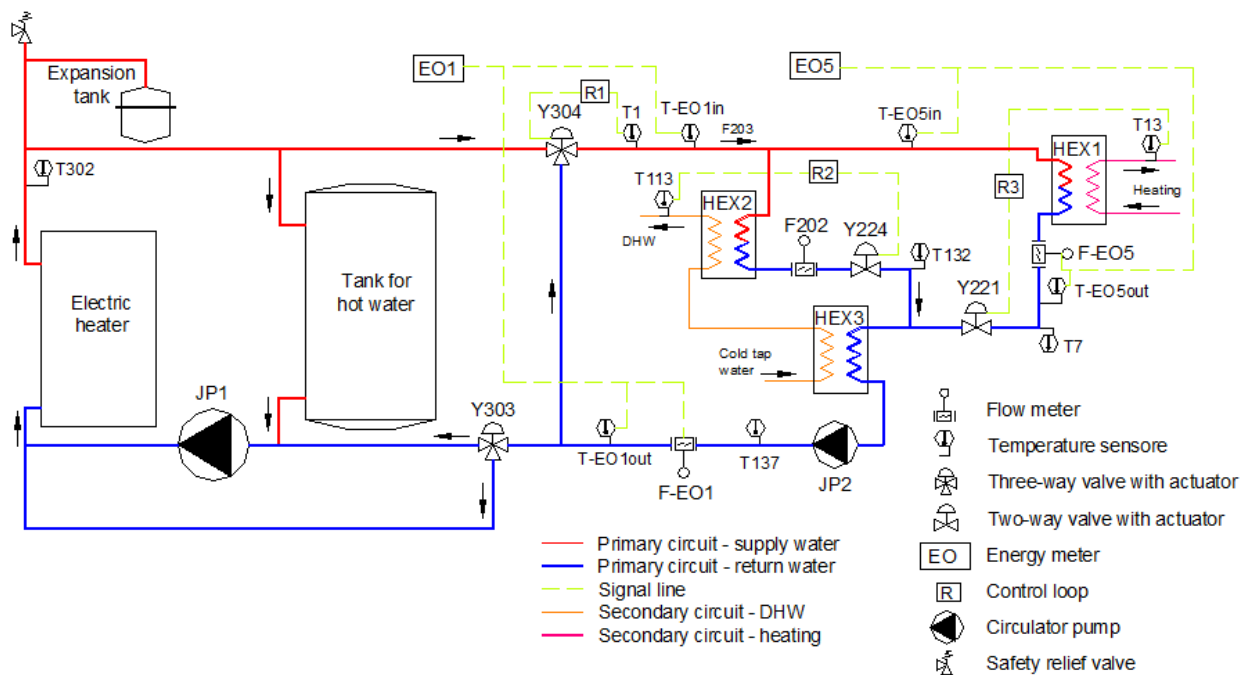


Figure 3.1 Scheme of primary circuit for district heating substation laboratory rig

As shown in Figure 3.1, there are three control loops in primary circuit. Control R1 is set for three-way mixing valve Y304 that adjusts supply water temperature, comparing signal from sensor T1 to the set point temperature. It can also be modulated for manual control, where the position of valve is set by percentage. For the valve Y303 there is only a possibility of manual control.

The heating coil loop includes two-way valve with electronic actuator Y223, circulator pump JP3, a fan with adjustable power load, two air temperature sensors for inlet (T37) and outlet (T80) air, six water temperature sensors, a flow meter (F206) and corresponding power meter (EO8). As can be seen from Figure 3.3, control of heating coil loop (R4) is based on outlet air temperature. After comparing signal from T80 to the set point temperature, valve Y223 adjusts flow rate of supply water that will achieve and hold the desirable outlet air temperature.

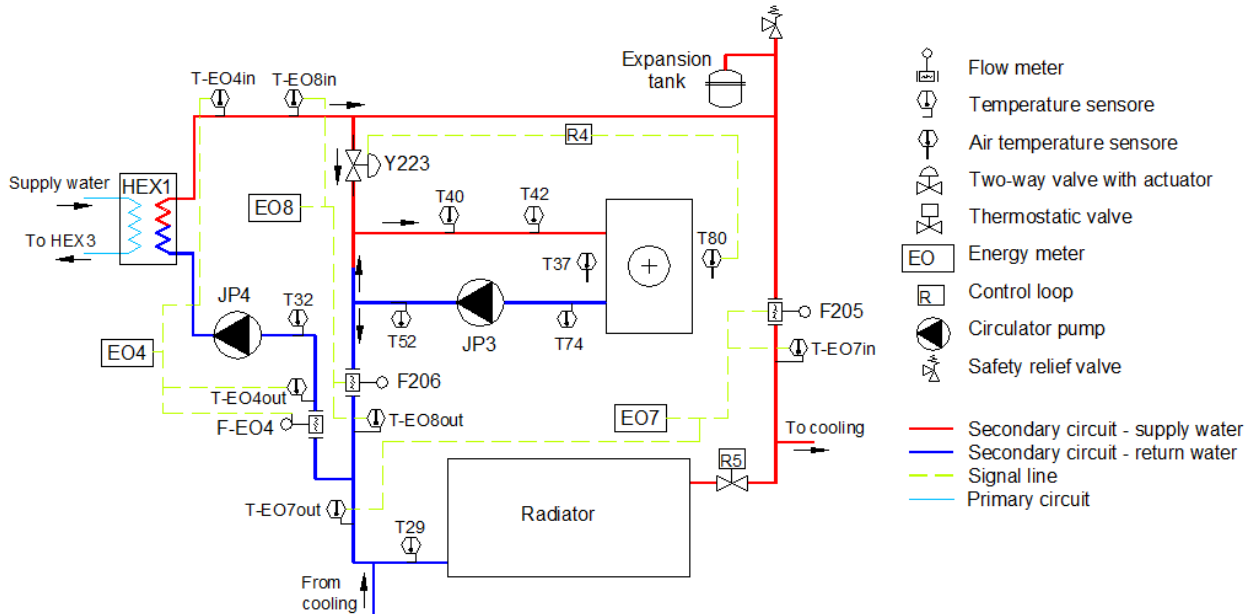


Figure 3.3 Scheme of secondary circuit - heating part of DH substation laboratory rig

Radiator is a part of the heating system which is in direct interaction with the consumer's living or working space. As in most hydronic systems like this, a thermostatic valve has been integrated in the radiator inlet line (control R5, see Fig. 3.3). This self-contained control element plays important role in achieving thermal comfort for every room individually. Unfortunately, the thermostatic valve in the laboratory cannot fulfill its original purpose since the space surrounding radiator is too wide. Accordingly, neither the conditions of thermal comfort can be taken under consideration. Therefore, the heating control system of this substation is based only on heating curve data and outside air temperature, without feedback from the heated room.

Since there is only one radiator unit installed, the need for an additional increase of the heat load has appeared. Therefore the, so called, cooling system has been incorporated in the laboratory setting. This system is a simple way of producing the "artificial load" for radiator. The mass flow from the supply line divides just before entering the radiator, and a part of the flow is taken to the additional HEX4 for cooling (see Figure 3.4). The cold medium in the HEX4 is tap water from the local water network. Cooled water is then returned to the heating system, right after the return line starts from the radiator. The cooling water flow rate is controlled in regards to the secondary circuit return water temperature, after the radiator (R6, see Figure 3.4). This way it is possible to maintain constant water temperature of the return line.

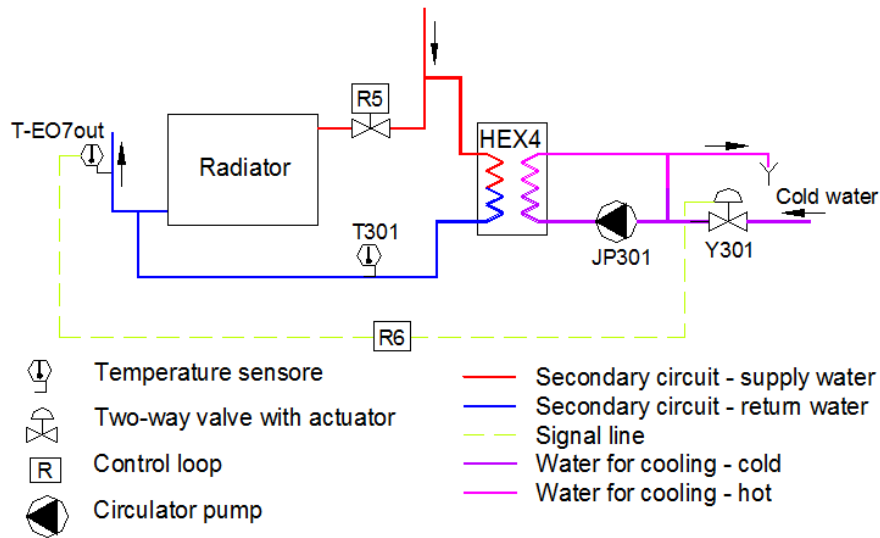


Figure 3.4 Scheme of additional cooling part of laboratory rig, used for increasing heat load of the radiator

3.2.2 Plan for measurements

Measurements were performed in order to get familiar with behavior of plate heat exchanger water-to-water in operating condition. Therefore, the HEX1 was put in focus of measurement since it has proved to have the most possibilities for adjusting desirable input values.

Figure 3.5 shows which parts of DH substation rig were in use. The measurements were performed using complete equipment of primary circuit, except of the pipe segment passing through HEX2, meaning that the valve Y223 was completely closed. This means that the part of rig for preparation of DHW was excluded from measurement. On the secondary side of HEX1, the radiator with additional cooling was in operation. Heating coil was turned off and valve Y223 was completely closed.

Mass flow rate and inlet temperature on both sides were set as the input values. Primary side mass flow was adjusted by the position of valve Y221. Secondary side mass flow rate was held constant. Inlet temperature for primary side was controlled by valve Y304 (control R1), and for secondary side by valve Y301 (control R6). Output values were outlet temperature on both sides. Based on the measured values, heat load and overall heat transfer coefficient were determined.

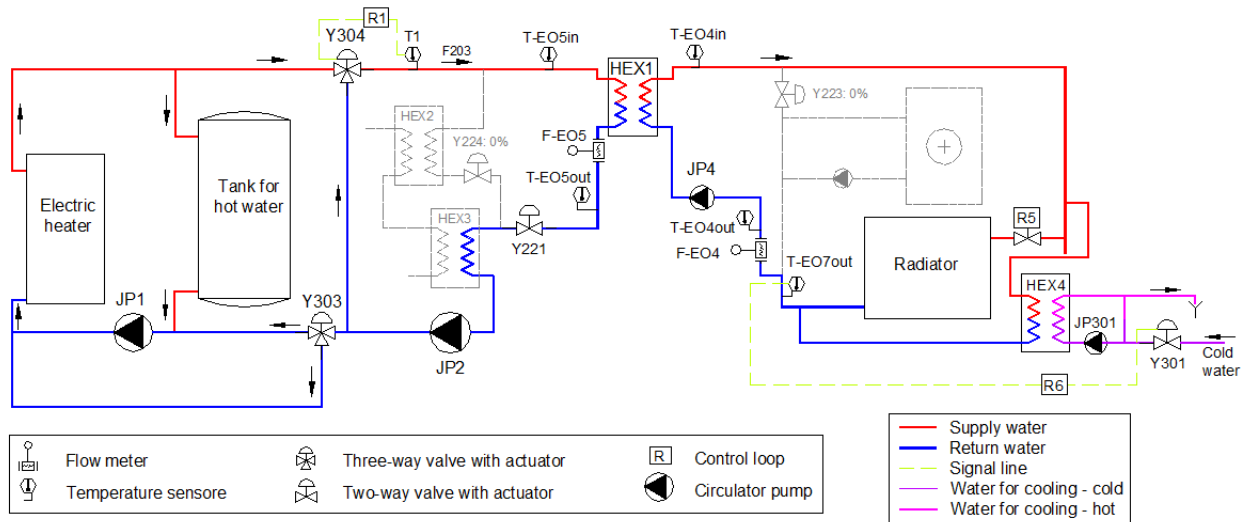


Figure 3.5 Scheme of laboratory rig used for measurements on HEX1

Data acquisition is always done for all sensors connected to the software. This way it was possible to compare values of the same parameter from different sensors and to choose most reliable measurement results. It has been decided that data would be taken from next sensors:

- T-EO5in – inlet temperature of primary side water
- T-EO5out – outlet temperature of primary side water
- F-EO5 – flow meter for primary side
- T-EO4out¹ – inlet temperature of secondary side water
- T-EO4in¹ – outlet temperature of secondary side water
- F-EO4 – flow meter for secondary side

The overview of the laboratory equipment used for the measurement is given in Table 3.1. Plate heat exchanger HEX1 is described in detail afterwards.

Table 3.1 Components of DH substation laboratory rig used for measurement

Component	Manufacturer	Type	Characteristics and notes
Electric heater	ASEA - Per Kure, Norway	ZVK/MB	Volume: 70l; Design pressure: 4bar, Test pressure: 5,2bar; Design temperature: 110°C; Min temperature: 0°C; Heating effect 45 kW; Year of manufacture: 1984.
Tank for hot water	OSO Hotwater, Norway	17 R 600	Volume: 600l; Max operating pressure: 10bar; Test pressure: 20bar; Year of manufacture: 1988

¹ Since these temperature sensors are connected to the power meter and are used to calculate temperature difference, subscript “in” signalize higher temperature value (supply line) and subscript “out” lower temperature value (return line). This is why the subscripts do not match inlet and outlet temperature for HEX1.

3 Laboratory tests and measurements on plate heat exchanger

Circulator pump JP1		Grundfos, Denmark	TPE Series 2000: MGE71A2-14FT85C	Flow Q: max. 370 m ³ /h; Head H: max. 90 m; Liquid temp.: -25°C to +140°C; Operat. pressure: max. 16 bar; Single-stage, centrifugal pump; Differential pressure sensor included		
Three-port seat valve	Y303	Siemens, Germany	VXG44.15-1	DN15; Sv>50; Linear flow characteristic 0...100%; Bronze CC491K (Rg5) valve body; Leakage rate 0...0.02 % of kvs value; Used in combination with actuator SQS...	kvs=1	Diverting valve
	Y304		VVG44.15-0.63		kvs=0.63	Mixing valve
Two-port seat valve Y221			SQS65.2	Operating voltage: AC 24 V; Positioning signal: DC 0/2...10 V or 0...1000 Ω; Positioning time: 35 s; Power consumption: 4.5 VA; can be adjusted both for equal-percentage (factory setting) or linear flow characteristic; The valve can be fully closed (= 0 % stroke) by turning the manual adjuster counterclockwise		
Ultrasonic flow meter Ultraflow	F-EO4	Kamstrup, Denmark	65-5-CDAD-219	Nominal flow qp=1.5 m ³ /h; qi=0.015 m ³ /h; qs=3 m ³ /h; connection G1B (R3/4); Length 130 mm; pulse figure 100 pulses/l; delta p=0.22bar; PN16	Connected to power meter EO4	
	F-EO4				Connected to power meter EO5	
Circulator pump JP2, JP4		Grundfos, Denmark	UPE 25-40, 180	Two control modes are available: proportional pressure (factory setting) and constant pressure		
Temperature sensor: T-EO4in, T-EO4out		Kamstrup, Denmark	66-00-0G0-219	PT-500, PN16, teta: 10°C...150°C; delta teta: 3K...140K	Connected to power meter EO4	
Temperature sensor: T-EO5in, T-EO5out					Connected to power meter EO5	
Plate heat exchanger HEX1		SWEP, Sweden	B8Hx20/1P-SC-S	Max work. temp. (prim and sec): 155°C; Max work. press. (prim and sec): 31 bar; 20 plates, 1 pass of water Volume-prim: 0,378 l; Volume-sec: 0,42 l; replaced in manufacture with model B8T		

Plate heat exchanger HEX1

DH substation in the Laboratory has three plate heat exchangers integrated in its rig. Since the measurements were done on HEX1, this model is in focus. HEX1 is a plate heat exchanger that transfers heat from the district heating network to heating circuit. There was no available documentation in Laboratory regarding this heat exchanger, so its characteristics were determined using SWEP's selection software SSP G7 [15]. This type of heat exchanger is obsolete and no longer in production. It is replaced with model B8T. However, software SSP G7 provides an option for rating all their HEX products, including phase out models of B-type. This way some basic parameters' values for HEX1 were defined. Laboratory measurements helped adjusting these values closer to real respond.

3 Laboratory tests and measurements on plate heat exchanger

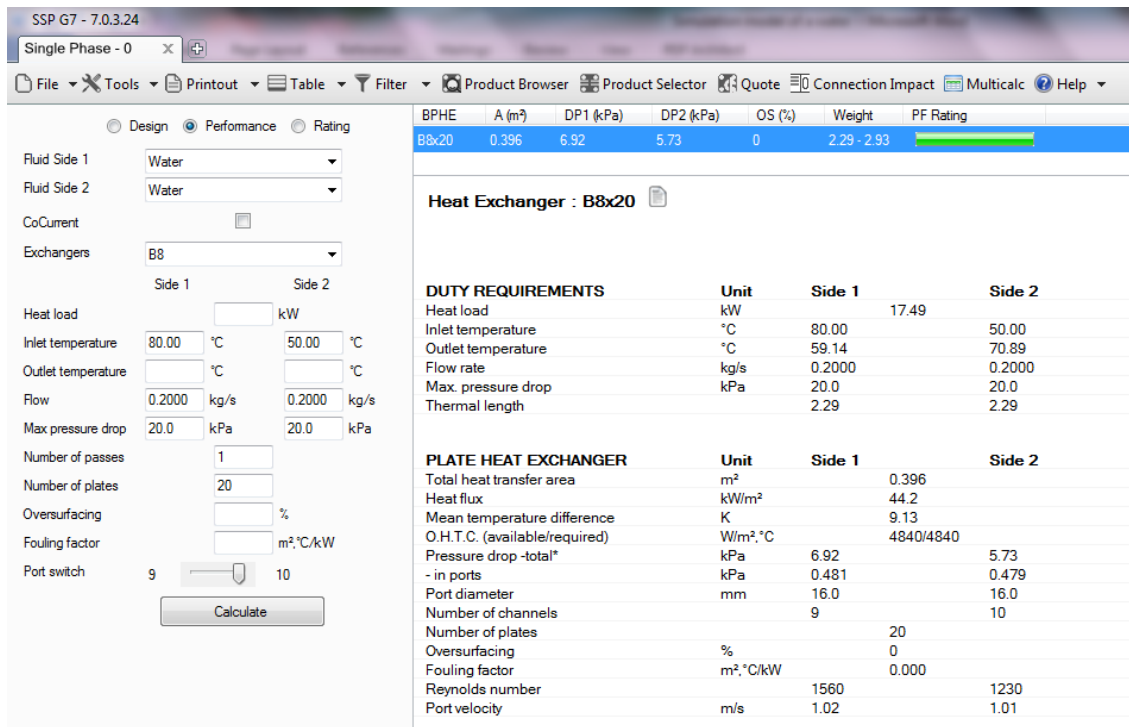


Figure 3.6 Screen shot of SWEP's selection software SSP G7

The HEX1 is manufactured in 2004 by Swedish company SWEP. This model is marked as Type B8Hx20/1P-SC-S, which means it consists from 20 plates with one pass of fluid on both sides. For the performance calculation, the mass flow rate and inlet temperatures on both sides needed to be defined. Figure 3.6 shows a screen shot of program with the results of calculation for one set of parameters.

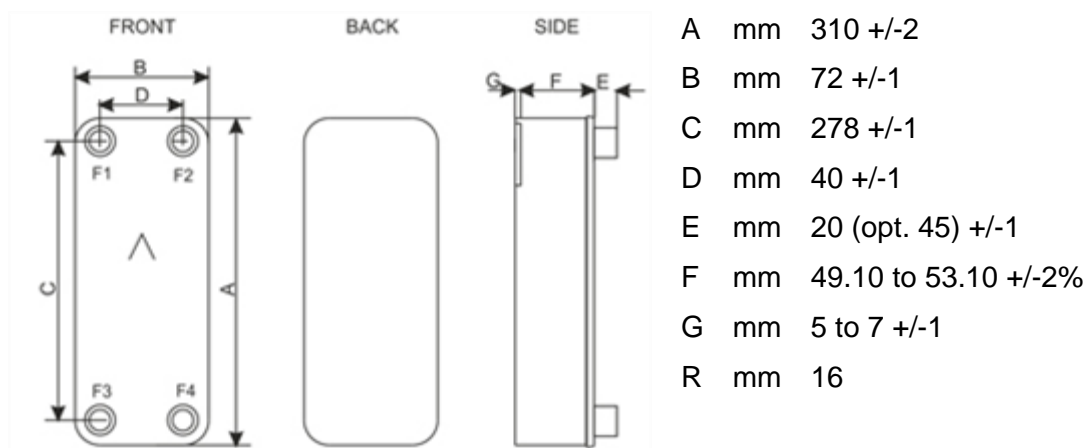


Figure 3.7 Schematic sketch of heat exchanger B8Hx20 with dimensional data

The SSP G7 software for HEX selection also contains data regarding design and dimensions of the model. Figure 3.7 shows basic scheme and dimensions of type B8Hx20, and some relevant data is given in Table 3.2.

Table 3.2 Some dimensional data of HEX B8Hx20 in totals

Totals	Unit	Value
Total weight (no connections)	kg	2,29 – 2,93
Hold-up volume, inner circuit	dm ³	0,378
Hold-up volume, outer circuit	dm ³	0,420
Port Size F1/P1	mm	16,0
Port Size F2/P2	mm	16,0
Port Size F3/P3	mm	16,0
Port Size F4/P4	mm	16,0
Total heat transfer area	m ²	0,396

The fluid distribution for single phase applications is uniform over parallel flow channels. The sketch on Figure 3.8 shows a unit with four plates, where only one is “inner channel” and two of them are “outer channels”. With 20 plates like in the HEX1, there are nine parallel inner channels and 10 parallel outer channels. Flow direction is counter current. Inner channels connect on Ports 1 and 3 and outer channels connect on Ports 2 and 4 (See Figure 3.7). Fluid distribution can also be determined from infrared capture, like in fig. 3.9. The hot fluid enters

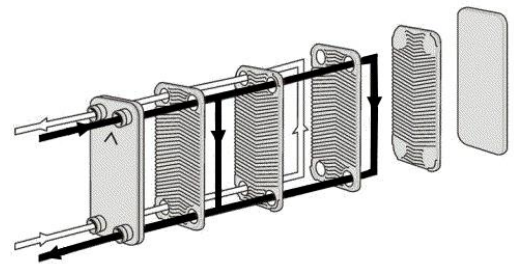


Figure 3.8 Sketch of the HEX unit with four plates showing flow distribution

the HEX1 at the upper port, then the flow divides and as it passes through the parallel channels downwards, it gets colder. Corresponding temperature distribution is visible on the infrared capture of HEX1.



Figure 3.9 Picture and infrared capture of the HEX1 in operation

Since there was no information regarding nominal condition of the DH substation rig, the parameters of the HEX1 nominal operation were defined after the performed measurements. Flow rates with valves fully opened and the possible-to-achieve inlet temperature were chosen as input values for the nominal heat flow rate and all the other relevant parameters (Table 3.3).

Table 3.3 Parameters of HEX1 at nominal operation point obtained from measurements

Parameter	Unit	Value	
		Primary circuit	Secondary circuit
Mass flow rate	kg/s	0.134135	0.134286
Inlet temperature	°C	75	50
Outlet temperature	°C	57.66	67
Heat flux	kW	9.7	9.6

3.3 Results and discussion

Measurement with changing primary side mass flow rate was performed for five operating points. The mass flow rate of primary fluid was adjusted by the valve Y221 integrated on the outlet line of the HEX (see fig. 3.5). Valve position was changed manually from fully opened (100%) to the position of 30% opened when the operation of the rig was becoming slightly unpredictable. Primary side inlet temperature was set at 75°C and maintain by control R1. Secondary side inlet temperature was set at 50°C and maintained by control R6. Mass flow rate on the secondary side was defined by pump JP4 which operating mode was not changed between measurements. Measured parameters of interest were outlet temperatures of water on both sides of HEX. Parameters' values were measured and recorded at the same time. Test data for every operating point was taken for at least 5 minutes (300 seconds), after achieving steady-state conditions [16]. Time step of data acquisition was 0,5 seconds. For every operating point, mean values have been calculated and shown in Table 3.4.

Table 3.4 Results of measurements - mean values

Valve position	m_flow_prim	m_flow_sec	t_prim_in	t_prim_out	t_sec_out	t_sec_in
Y221	F-EO5	F-EO4	T-EO5in	T-EO5out	T-EO4in	T-EO4out
%	l/h	l/h	°C	°C	°C	°C
Y=100	490,56	489,30	74,96	57,65	67,01	49,98
Y=80	443,61	492,90	74,99	56,66	66,25	49,97
Y=60	320,64	492,84	74,54	53,74	63,25	49,97
Y=40	220,51	492,64	74,23	51,56	59,98	50,02
Y=30	134,85	492,03	73,54	50,21	56,29	49,96

Calculated values

Heat load and overall heat transfer coefficient (OHTC) were calculated based on the mean values of mass flow rate and temperatures.

Heat load was calculated both for primary and secondary side of HEX after the equation:

$$Q_i = \dot{m}_i \cdot c_{p,i} \cdot \Delta t_i, \quad i = 1...2 \quad 3.2$$

where i is subscript defining primary ($i = 1$) and secondary ($i = 2$) side parameters, Q_i is heat load, \dot{m}_i is mass flow rate, $c_{p,i}$ is specific heat capacity for water at temperature corresponding to mean value between inlet and outlet water temperature, Δt_i is temperature difference caused by heat transfer.

For every operating point, heat load of tested heat exchanger was determined as the average of the primary and secondary heat load [16].

Overall heat transfer coefficient (O.H.T.C.) was calculated using average heat load, after the equation:

$$U = \frac{Q}{A \cdot LMTD}, \quad 3.3$$

where U is overall heat transfer coefficient, A is heat transfer area (see Table 3.2), and $LMTD = (\Delta t_A - \Delta t_B) / \ln(\Delta t_A / \Delta t_B)$ is logarithmic mean temperature difference.

Calculated values of heat load and O.H.T.C. for every operating point are shown in Table 3.5.

Table 3.5 Results of calculation based on test data

Valve position	Q_primary	Q_secondary	Q_average	LMTD	OHTC
%	W	W	W	°C	W/m ² ,°C
Y=100	9721,93	9570,76	9646,34	7,816	3116,33
Y=80	9317,34	9214,26	9265,80	7,667	3051,74
Y=60	7648,27	7516,85	7582,56	6,858	2791,79
Y=40	5739,29	5634,81	5687,05	5,721	2509,91
Y=30	3613,52	3577,43	3595,47	4,011	2263,08

Data validation

Computerized data validation methods have been applied in order to check reliability of test data [17].

Time-step: The time interval between consecutive time series records corresponded to the programmed interval of 0,5 seconds.

Rational check: Each archived data entry is numerically correct, e.g., does not contain unnecessary characters.

Range gate validation: Each measured value was inside of interval of expected maximum and minimum.

Relational checks: Calculation results, such as heat load and overall heat transfer coefficient using mean values of time series records, were compared with expected values obtained from selection software SSP G7. Small differences were explained by fouling of the heat exchanger's channels.

3 Laboratory tests and measurements on plate heat exchanger

Graphical validation: Selected measured data and calculated results were plotted in order to indicate how they changed with one another. Dependence of all considered parameters on changing primary mass flow rate was as expected.

Statistical check (mean, standard deviation and goodness of fit): The minimum, maximum, mean and standard deviation of measured data was calculated. No large deviation was detected.

Heat balance/conservation of flow or energy methods: Since all the components of the heat process were measured, heat balance needed to be satisfied. For the heat exchanger, energy brought by primary side fluid and energy accepted by secondary side agreed to within 3% which is required by European standard [16].

4 Mathematical model

Making the simulation model of a physical system is a process of a few basic steps. At first it is necessary to become familiar with considered problem as much as it is possible regarding its complexity. After defining physical phenomenon involved in future model, it is required to find proper mathematical relations. The set of equations that describes behavior of the explored system is called mathematical model. Following is discretization of equations in order to form finite number of algebraic equations possible to solve. Lastly the model needs to be translated to computer language so the simulation could be performed.

This chapter will present mathematical models used during this research, including developed model of plate heat exchanger. Well defined mathematical model is crucial for bringing out reliable numerical solution.

4.1 Governing equations

Modeling of physical systems is generally based on well-known conservation principles. The so called governing equations are starting point for every mathematical description of model. This subchapter will introduce basic equations in integral form that are used in later description of considered thermo-fluid systems.

All of fluid dynamics is based on three fundamental physical principles:

- 1 – mass is conserved;
- 2 – Newton's second law ($F = ma$);
- 3 – energy is conserved.

Considering arbitrary control volume V bounded by surface S with unit normal vector \mathbf{n} that is directed outward, mentioned principles for fluid flow can be express in next form:

- **Mass balance (The continuity equation)**

$$\frac{\partial}{\partial t} \int_V \rho dV + \int_S \rho \vec{u} \cdot \vec{n} dS = 0$$

Rate of mass
change in CV

Mass flux
through CS

4.1

- **The momentum equation**

$$\frac{\partial}{\partial t} \int_V \rho \bar{u} dV + \int_S \rho \bar{u} \otimes \bar{u} \cdot \bar{n} dS = \int_S \sigma \cdot \bar{n} dS + \int_V \rho \vec{f}_b dV \quad 4.2$$

Rate of momentum change in CV	Momentum flux through CS	Resulting surface force	Resulting body force
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- **Energy balance (First law of thermodynamics)**

$$\frac{\partial}{\partial t} \int_V \rho c T dV + \int_S \rho c T \bar{u} \cdot \bar{n} dS = \int_S \vec{q} \cdot \bar{n} dS + \int_V (\sigma : \text{grad} \bar{u} + h) dV \quad 4.3$$

Rate of change of internal energy	Energy flux through CS	Surface heat flux	Heat source
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4.2 Modeling of plate heat exchanger

Modelica's standard library and the *Buildings* library contain simulation models for a few types of heat exchangers common in HVAC systems. However, there is no model that would simulate behavior of a plate heat exchanger with water as both heat carrier and heat receiver. Since that kind of HEX is the heart of the heat substation discussed in this paper, appropriate model is designed and verified with measurements.

Main idea of *Modelica* is to provide an open source partial or complete models in order to help further development of more complex models and system. The PHEX model is also completed with the help of the existing partial model for general counter flow type of heat exchangers with dynamics of fluid and solid. It has been establish that, with the appropriate discretization and correct parameters, behavior of a counter flow plate heat exchanger can be described sufficiently precise with the equations of this model.

Figure 4.1 shows *Modelica* diagram of a base class model used in building PHEX model. It is called *PartialHexElement* and can be considered as one element of discretized PHEX model. Every element has the same mathematical model as the final model. The model components shown on Figure 4.1 are *Modelica* classes commonly used in thermo-fluid systems. Every component solves a part of the *PartialHexElement* mathematical model. Interaction between components is defined by the connectors.

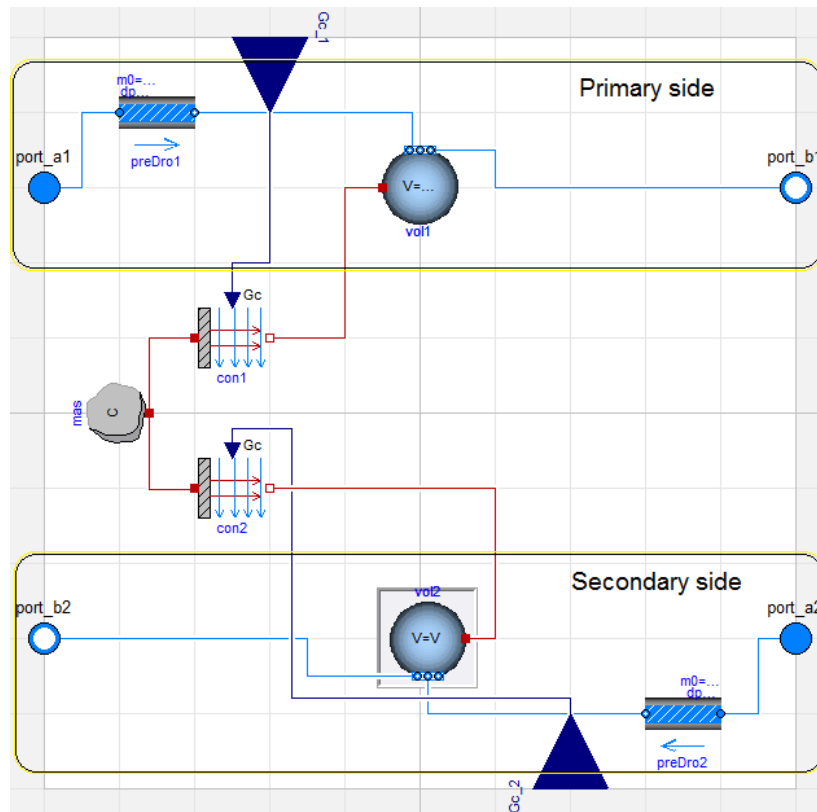


Figure 4.1 Modelica diagram of Partial HEX Element

Yellow line on Figure 4.1 bounds components that build channel for primary and secondary flow. The blue circles marked as `port_a` are the flow inlet and the blue-white circles marked as `port_b` are the flow outlet. The counter flow is evident, since the fluid flow is directed from `port_a` to `port_b`. Two blue spheres marked as `vol1` and `vol2` represent volumes of primary and secondary flow. Components marked as `preDrop` are simulating pressure drop of flow through the channel. The grey object named `mass` represents the metal plate(s) that separates two flows. The blue connecting lines are signaling mass flow and the red ones represents possible heat transfer. As can be seen on Figure 4.1, two fluids are not exchanging any mass (no blue line between `vol1` and `vol2`). The heat flow is certainly allowed for `vol1` and `vol2` but over the metal plate `mass` which is the case in real HEX. Objects marked as `con1` and `con2` simulate heat transfer mechanism of convection between fluid flow and the metal plate. Dark blue arrow marked as `Gc` is providing the `con1` and `con2` with value of convective heat transfer coefficient. Calculation of this coefficient will be explained later in this chapter.

4.2.1 Mathematical description

The component that solves mass and energy balance equations for fluid flow is the blue sphere marked as `vol1` for primary side flow and `vol2` for secondary side flow. This component is called *MixingVolume* and can be found in *Buildings* library. The model represents an instantaneously mixed volume. Potential and kinetic energy at the port are neglected, and there is no pressure drop at the ports. The volume can exchange heat through its `heatPort`. The volume can be parameterized as a steady-state model or as dynamic model.

For steady-state model, the first part of the governing equations 4.1 and 4.3 regarding rate of change is set to zero. The mass balance equation now considers only mass flux through control surface:

$$\int_S \rho \vec{u} \cdot \vec{n} dS = 0 \quad 4.4$$

For the fluid flows in HEX model, this means that the mass flow entering control volume is equal to mass flow leaving same control volume. Both `vol1` for primary side flow and `vol2` for secondary side flow are setting this equation for their parameters:

$$\text{port_a.m_flow} = -\text{port_b.m_flow}$$

In the energy balance equation (Eq.4.3) the last part is also set to zero, since there is no heat source in fluid flows. Now the equation becomes:

$$\int_S \rho c T \vec{u} \cdot \vec{n} dS = \int_S \vec{q} \cdot \vec{n} dS \quad 4.5$$

In HEX model, this equation states that change of enthalpy from one port to another is equal to heat flow occurred through the heat port:

$$\text{port_a.m_flow} * (\text{inStream}(\text{port_a.h_outflow}) - \text{port_b.h_outflow}) = -Q_flow;$$

$$\text{port_a.m_flow} * (\text{inStream}(\text{port_b.h_outflow}) - \text{port_a.h_outflow}) = +Q_flow$$

Explanation on ports in *Modelica*, including `inStream` label, is given in subchapter 4.2.2. The steady-state model is defined only for two-port volume.

As for the dynamic model, first parts of the governing equations 4.1 and 4.3 regarding rate of change cannot be neglected. Example of this model application would be for air flow with moisture condensation. Since in this HEX model the fluid on both sides is water with constant properties, mass balance equation remained as in eq. 4.4. If mass dynamics is set to steady-state model, then the energy dynamics is required to be also as in steady-state model.

4.2.2 Additional equations

The pressure drop of fluid flow through channel is modeled by the component called *FixedResistanceDpM*. On Figure 4.1 it is a blue object in shape of pipe segment, marked as `preDro`. *Modelica* describes it as a model of a resistance with a fixed flow coefficient. The mass flow rate is computed as

$$\dot{m} = k \sqrt{\Delta p} \quad 4.6$$

where k is a constant and Δp is the pressure drop. The constant k is equal to $k = \text{m_flow_nominal} / \text{dp_nominal}$, where `m_flow_nominal` and `dp_nominal` are the input parameters for model [18].

Dynamics of metal plate that separates fluid flows is simulated by component called *HeatCapacitor*, marked by grey object called `mass` (Fig 4.1). *Modelica* info states that this is a generic model for the heat capacity of a material. No specific geometry is assumed beyond a

total volume with uniform temperature for the entire volume. Furthermore, it is assumed that the heat capacity is constant (independent of temperature). For this HEX model, the *Buildings* library contains explanation how the heat capacity C of the metal is assigned. Suppose the metal temperature is governed by

$$C \cdot \frac{dT}{dt} = (hA)_1(T_1 - T) + (hA)_2(T_2 - T) \quad 4.7$$

where hA are the convective heat transfer coefficients times heat transfer area and T_1 and T_2 are the medium temperatures. Assuming $(hA)_1 = (hA)_2$, this equation can be rewritten as

$$C \cdot \frac{dT}{dt} = 2(UA)_0[(T_1 - T) + (T_2 - T)] \quad 4.8$$

where $(UA)_0$ is the overall heat transfer coefficients times heat transfer area at nominal conditions. Hence we set the heat capacity of the metal to

$$C = 2(UA)_0 \tau_m \quad 4.9$$

where τ_m is the time constant that the metal of the heat exchanger has if the metal is approximated by a lumped thermal mass [19].

The convection heat transfer between fluid and surface of metal plate is described by component *Convection* marked as `con1` and `con2` on Figure 4.1. *Modelica Standard* library describes it as a model of linear heat convection. The basic constitutive equation for convection is

$$Q_{flow} = Gc * (solid.T - fluid.T) \quad 4.10$$

Direction of heat flux is determined by its sign: $+Q_{flow}$ means heat transfer from solid (metal plate) to fluid (water) and for $-Q_{flow}$ is vice versa. The Gc is an input signal to the component, since Gc is nearly never constant in practice. For this HEX model, Gc is determined according to $Gc = A * h$ where A is convection area and h is heat transfer coefficient. The calculation of a heat transfer coefficient for current condition is described in further text.

4.2.3 Calculation of the hA value

The convective heat transfer coefficient h is determined by parameters of medium and it always depends on current temperature and velocity of fluid flow. The *Buildings* library contains model for sensible convective heat transfer coefficient for an air-to-water coil which was the starting point for hA model of the PHEX water-to-water.

Basic idea is to calculate hA value for current conditions using nominal condition values. The relation between convective heat transfer coefficient and temperature and mass flow with regards to nominal conditions has been determined [8] as follows:

- Relation between convective heat transfer coefficient and fluid temperature

$$\frac{h(t)}{h(t_o)} = 1 + s(t_o)(t - t_o) \quad 4.11$$

where $h(t)$ is convective heat transfer coefficient for current fluid temperature t ; $h(t_o)$ is convective heat transfer coefficient for nominal fluid temperature t_o ; s is relative sensitivity of convective heat transfer coefficient equations for turbulent flow [8] defined as

$$s = \frac{0,014}{1 + 0,014 \cdot t} \quad 4.12$$

- Relation between convective heat transfer coefficient and fluid temperature

$$\frac{h(\dot{m})}{h(\dot{m}_o)} = \left(\frac{\dot{m}}{\dot{m}_o} \right)^n \quad 4.13$$

where $h(\dot{m})$ is convective heat transfer coefficient for current fluid mass flow rate \dot{m} ; $h(\dot{m}_o)$ is convective heat transfer coefficient for nominal fluid mass flow rate \dot{m}_o ; n is exponent which depends on medium properties and flow arrangement.

The parameters needed for calculation are mostly determined as characteristics of PHEX type:

- Thermal conductance at nominal flow $UA_nominal$
- Nominal water mass flow rate for primary and secondary side $m_flow_nominal_1$ and $m_flow_nominal_2$
- Ratio between primary and secondary side convective heat transfer coefficient $r_nominal$:

$$r = \frac{(hA)_1}{(hA)_2} \approx 1$$
- Nominal water temperatures both for primary and secondary side TO_1 and TO_2
- Exponent for convective heat transfer coefficient both for primary and secondary side n_1 and n_2 (in relation $h \sim m_flow^n$)

Additionally, the model of HEX needs to provide hA model with current values of mass flow rate and temperature for primary and secondary fluid flow. Figure 4.2 shows complete model of PHEX. In the center of diagram there is a partial model described in previous text, which needs the hA value as input signal for the heat transfer calculation. Both primary and secondary flows have temperature and mass flow rate sensors just after the inlet port. These components send information about current fluid parameters to hA model.

The calculation algorithm for hA model has two steps:

- 1 – nominal convective heat transfer coefficient for primary and secondary side $hA_nominal_1$ and $hA_nominal_2$ is calculated based on $UA_nominal$ and $r_nominal$

$$\left. \begin{aligned} r &= \frac{(hA)_1}{(hA)_2} \approx 1 \\ UA &= \frac{1}{\left(\frac{1}{hA}\right)_1 + \left(\frac{1}{hA}\right)_2} \end{aligned} \right\} \Rightarrow (hA)_{1nom} = (hA)_{2nom} = 2UA_{nom} \quad 4.14$$

2 – current convective heat transfer coefficient for primary and secondary side hA_1 and hA_2 is determined after the equations 4.11 and 4.13:

$$\frac{hA}{hA_{nom}} = [1 + s(t_o)(t - t_o)] \cdot \left(\frac{\dot{m}}{\dot{m}_o}\right)^n \quad 4.15$$

There is a possibility to choose to have only mass flow or temperature dependence.

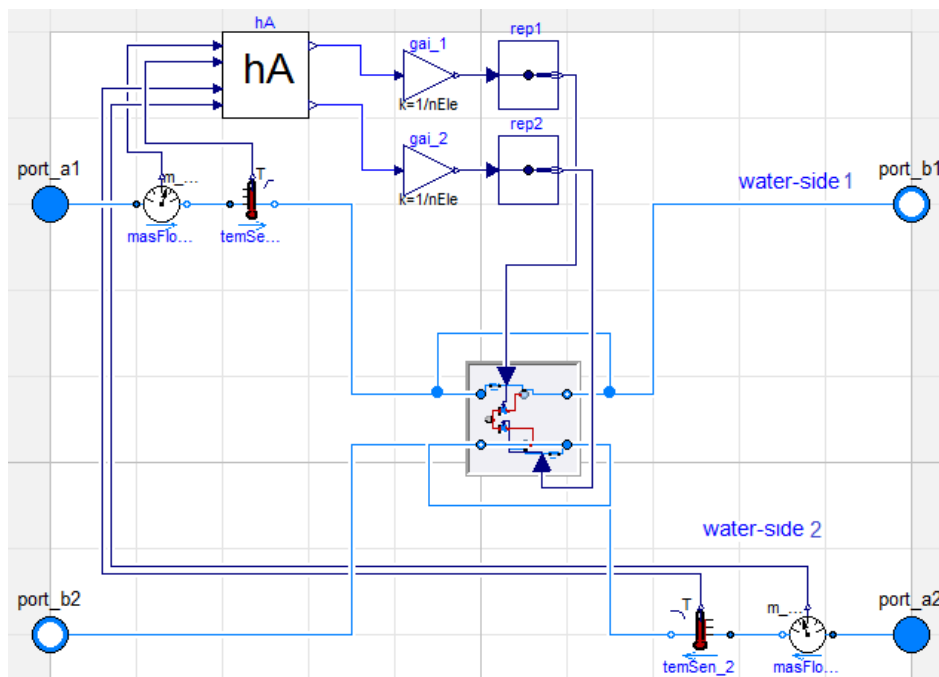





Figure 4.2 Modelica diagram of complete PHEX model

4.2.4 Connecting mechanism

The PHEX model is using three types of connectors presented in Table 4.1 [18]. A connector should contain all quantities needed to describe the interaction. Table 4.1 shows that these quantities can be defined by potential, flow and/or stream variables. The quantity on the connector always corresponds to the value close to the connection point, assuming that the fluid is flowing out of the connector, regardless of the actual direction of the flow. The relation between two or more connectors is determined by two kinds of equations: pair-wise equalities among the potential variables, and a sum-to-zero equation for the flow variables [13].

Table 4.1 Connectors used in *PartialHEXElement*

Domain	Potential variables	Flow variables	Stream variables	Connector definition	Icons
Thermo fluid flow	Pressure	Mass flow rate	Specific enthalpy	FluidPort_a, FluidPort_b	
Heat transfer	Temperature	Heat flow rate	-	HeatPort_a, HeatPort_b	
Block diagram	Real variable	-	-	RealInput	

Fluid ports in *Modelica* are designed as interfaces for quasi one-dimensional fluid flow in a piping network (incompressible or compressible, one or more phases, one or more substances). As a potential variable, pressure values in connected ports need to be equal, and sum of mass flow rates between connected ports is set to zero. Additionally there is a stream variable defined for this type of connector, which helped modeling the flow of matter in more reliable way. Flow and potential variables are both used for conserved quantities, but stream variables (enthalpy h , species concentration X and trace substances C) are used for quantities that are carried by a flow variable (such as mass flow rate) [13].

Heat ports in *Modelica* library are interfaces for one-dimensional heat transfer. They also need to satisfy two described connecting principles. The shell equation defines that all the temperatures in connected ports must be equalized. The balance equation defines that the sum of all heat flows in connected ports need to be equal zero [13].

Regarding the *Modelica* language specification, a connect-equation has the following syntax:

```
connect "(" component_reference "," component_reference ")" ";"
```

In a connect-equation the primitive components of the two connectors must have the same primitive types, and flow-variables may only connect to other flow-variables, causal variables (input/output) only to causal variables (input/output) [20].

In *Modelica* diagram window (see Fig 4.1), the connection between fluid ports is presented as blue line and the red line is connecting heat ports.

4.3 Modeling of other system components

The plate heat exchanger makes the central element of indirect DH substation. However, operation of other components is also important for proper adjustment and desirable response of the system. To complete the model of indirect heat substation, next components were selected from *Modelica* Standard and Buildings library.

Circulator pump was modeled as component from *Buildings* library called *FlowMachine_m_flow*. It is described as pump with ideally controlled mass flow rate as input signal. This means that the model has prescribed mass flow rate which is usually provided by *Modelica*'s block source *Constant*. This mass flow rate will be provided by the pump, i.e., the pump has idealized perfect control and infinite capacity. This model does not have a performance curve for the flow characteristics for two reasons: for given or mass flow rate, the

pressure rise is defined by the flow resistance of the duct or piping network, and at zero pressure difference, solving for the flow rate and the revolution leads to a singularity. The maximum flow rate V_{flow_max} is obtained as

$$V_{flow_max} = m_{flow_nominal}/rho_nominal \quad 4.16$$

where $m_{flow_nominal}$ is the maximum flow rate, which needs to be provided by the user as a parameter for these models, and $rho_nominal$ is the density at the nominal operating point.

Ideal two port **temperature sensor** is another component from Buildings library used for the simulations in this paper. This model outputs the temperature of the medium in the flow between its fluid ports. The sensor does not influence the fluid. The sensor computes a gain that is zero at zero mass flow rate. This avoids fast transients if the flow is close to zero, thereby improving the numerical efficiency.

Two way valve with actuator needed to be integrated in primary side return line. As described in subchapter 2.3, for optimum HEX operation the valve characteristic should be exponential. This kind of valve is simulated by *Buildings* library model of two way valve with an equal percentage valve opening characteristic (*TwoWayEqualPercentage*). This model uses the parameter Kv_SI , which is the flow coefficient in SI units, i.e., it is the ratio between mass flow rate in kg/s and square root of pressure drop in Pa. To prevent the derivative d/dP (m_flow) to be infinite near the origin, this model linearizes the pressure drop versus flow relationship. The region in which it is linearized is parameterized by

$$m_{turbulent_flow} = deltaM * m_{flow_nominal} \quad 4.17$$

where $deltaM$ is fraction of nominal flow rate where linearization starts. Because the parameterization contains Kv_SI , the values for $deltaM$ and $dp_nominal$ need not be changed if the valve size changes. [19]

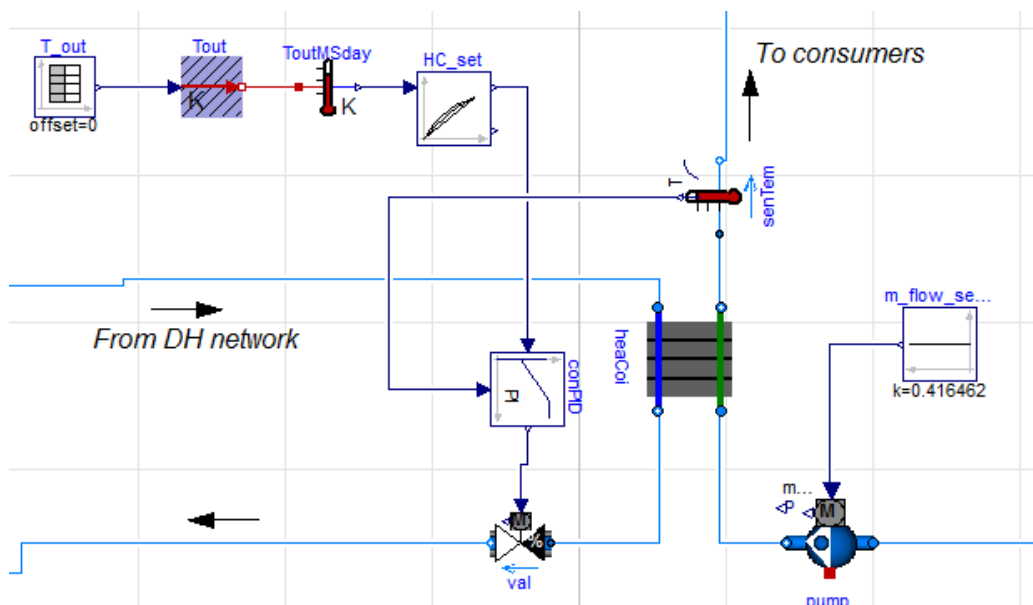


Figure 4.3 Modelica diagram of DH substation model

Control system of DH substation is modeled by a set of *Modelica* components. Figure 4.3 illustrates the model of the substation with heat exchanger labeled as *heaCoi*, circulator pump (*pump*), temperature sensor (*senTem*), two-way equal percentage valve (*val*) and set of

components for control of the valve. As mentioned before, heat load of the HEX is controlled by changing primary side mass flow rate in regards to outdoor temperature and heating curve. The control system in this model is initiated by outdoor temperature simulated by component marked as **T_out** in upper left corner of figure 4.3. This is a block source from *Modelica Standard* library called *TimeTable*. It generates an output signal by linear interpolation in a table. The time points and function values are stored in a matrix table [i,j], where the first column table[:,1] contains the time points and the second column contains the outdoor temperature data to be interpolated [18]. Output signal of block **T_out** defines next connected component labeled as **Tout**. This model is called *PrescribedTemperature* and it represents a variable temperature boundary condition. The temperature in [K] is given as input signal T to the model. The effect is that an instance of this model acts as an infinite reservoir able to absorb or generate as much energy as required to keep the temperature at the specified value. This heat source component is connected by heat port with the ideal absolute temperature sensors **ToutMSday** which returns the temperature of the connected port in Kelvin as an output signal. The sensor itself has no thermal interaction with whatever it is connected to. Furthermore, no thermocouple-like lags are associated with this sensor model [18]. Next control system component in line is a block that computes the supply and return set point of heating systems, i.e. the heating curve. It is marked as **HC_set** in figure 4.3. The parameters that needs to be defined are exponent for heat transfer and nominal temperatures (supply, return, room and outdoor). The set point for the room air temperature can either be specified by a parameter, or it can be an input to the model. The latter allows using this model with systems that have night set back [19]. The **HC_set** component defines set point supply water temperature for secondary circuit. This signal is sent to control components **conPID**, which compares it to the actual water temperature from secondary circuit sensor **senTem**. The component **conPID** is defined as P, PI, PD, and PID controller with limited output, anti-windup compensation and setpoint weighting. The output signal is limited to interval (0-1) which corresponds to valve position from 0% to 100% opened. Via parameter *controllerType* either P, PI, PD, or PID can be selected [19]. According to degree of agreement between set point and actual secondary side supply water temperature, controller **conPID** sends signal to the valve-actuator **val** to adjust proper primary side mass flow rate.

Production side of DH network was out of scope of this paper so it was simplified as heat source and sink (fig. 4.4). Model from *Buildings* library used for this is *Boundary_pT*. It is described as boundary with prescribed pressure, temperature, composition and trace substances [19]. For the heat source (**sou_1**) the prescribed parameter was temperature, since the supply water temperature of primary side was defined to be constant in discussed DH substation. The heat sink (**sou_1**) was defined only by water pressure, since both mass flow rate and temperature are varying during the simulations.

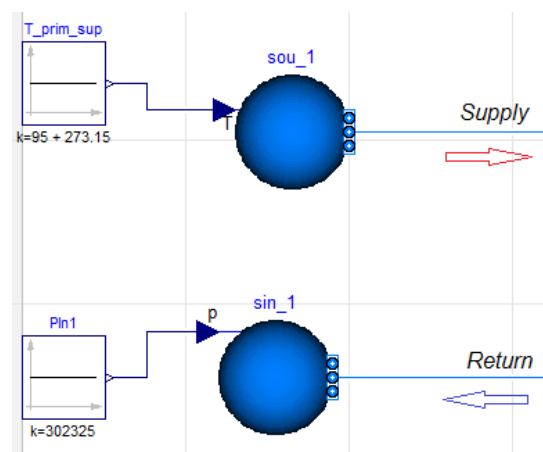


Figure 4.4 Production side of DH substation model in *Modelica* diagram

4.4 Modeling of consumption side

Since the thermal comfort is ultimate aim of every heating system, the consumers can be considered its most important aspect. Although consumption side was not in the scope of this paper, its behavior is still necessary to get familiar with because it defines operation of DH substation more than any other system segment. In fully coupled modeling problem of DH system, presented in chapter 6, the consumption side was based on two components: a room model developed by Teskeredzic [21] and a model of radiator from *Buildings* library [19].

The room model is a simplified version of the existing standard room model from the library. It is designed in order to decrease the number of equations for problems in which part of the building or the whole building with multiple rooms will be simulated. It is important to note that the applied room model does not take into account the heat gains from solar irradiation. It is estimated that the introduction of the radiative heat transfer does not influence the heat balance tremendously. At the other hand, if one excludes the radiative heat gains the number of equations decreases significantly. Figure 4.5 shows *Modelica* diagram of *The room model* connected to the model of radiator.

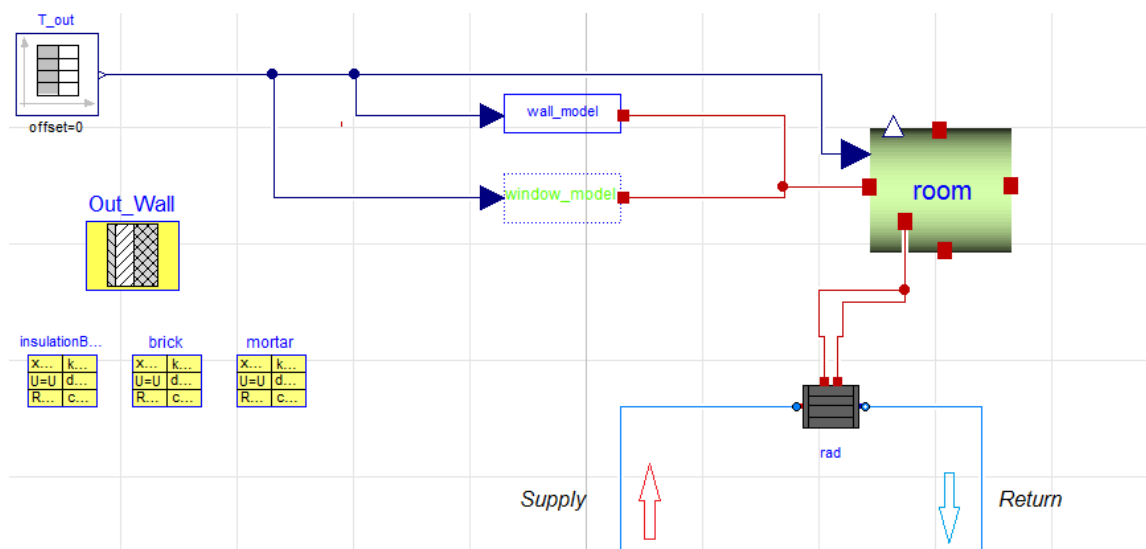


Figure 4.5 Modelica diagram of *The room model* connected with a radiator

The room model takes into account heat losses through walls and windows and infiltration losses. Infiltration losses are prescribed by the number of volume air changes per hour which is modeled within the room model (green rectangle `room`). The heat losses can also occur through walls (blue rectangle `wall_model`) and windows (bright green label `window_model`). The `wall_model` simulates heat transfer as conduction through the wall layers and convection on both sides of wall. The wall structure can consist of arbitrary number of layers with different physical properties which can be defined separately (component `Out_Wall` is composed from insulation, brick and mortar, with defined thickness). The `windows_model` simulates only conduction since it is the dominant heat transfer mechanism for windows. The thermal capacity of windows is neglected.

Radiator is considered as a heat source for consumption side, i.e. for the room model. Used radiator model is named RadiatorEN442_2 since the required parameters are data that are typically available from manufacturers that follow the European Norm EN 442-2. However, to allow for varying mass flow rates, the transferred heat is computed using a discretization along the water flow path, and heat is exchanged between each compartment and a uniform room air and radiation temperature. This discretization is different from the computation in EN 442-2, which may yield water outlet temperatures that are below the room temperature at low mass flow rates. Furthermore, rather than using only one room temperature, this model uses a room air and room radiation temperature. The transferred heat is modeled as follows: Let N denote the number of elements used to discretize the radiator model. For each element $i \in \{1, \dots, N\}$, the convective and radiative heat transfer Q_c^i and Q_r^i from the radiator to the room is

$$Q_c^i = \text{sign}(T^i - T_a) (1 - f_r) UA / N |T^i - T_a|^n \quad 4.18$$

$$Q_r^i = \text{sign}(T^i - T_r) f_r UA / N |T^i - T_r|^n \quad 4.19$$

where T^i is the water temperature of the element, T_a is the temperature of the room air, T_r is the radiative temperature, $0 < f_r < 1$ is the fraction of radiant to total heat transfer, UA is the UA-value of the radiator, and n is an exponent for the heat transfer. The model computes the UA-value by numerically solving the above equations for given nominal heating power, nominal temperatures, fraction radiant to total heat transfer and exponent for heat transfer. This radiator model can be used as a dynamic or steady-state model. For the transient response, heat storage is computed using a finite volume approach for the water and the metal mass, which are both assumed to be at the same temperature.

Figure 4.5 illustrates radiator connected with *The room model* through two heat ports, for convective and radiative heat transfer. The fluid ports connects radiator to secondary circuit of district heating substation.

5 Validation of the model

Simulation software can be very powerful tool for engineers in sense of analysis and discussion on problems without making actual physical system to observe its behavior. However, the laboratory tests and experiments still play major role in research and by no means can be left behind. No matter how precise mathematical model is, it is always necessary to show how close the simulation results and the actual respond of considered system are. Validation of the PHEX model described in subchapter 4.2 is done after measurement results obtained in Laboratory at Department of energy and Process Engineering, NTNU.

5.1 Problem description

Detailed description of modeling the plate heat exchanger is given in subchapter 4.2. Now it will be considered as final model ready to be used in different configurations and for simulation.

Parameters that need to be ascribed to the model in order to define behavior of a certain PHEX type are:

- *Medium* – Type of medium (properties) needs to be defined both for primary and secondary side.
- *hA* – There are four parameters within this parameter/model: exponent for convective heat transfer coefficient and nominal inlet water temperature both for primary and secondary side.

Nominal conditions are also required for calculations on HEX operation (see subchapter 4.2.3):

- nominal mass flow rate for primary and secondary side in [kg/s]
- nominal pressure drop for primary and secondary side in [Pa]
- thermal conductance at nominal flow in [W/K]
- ratio between primary and secondary side convective heat transfer coefficient

It is important to underline one more value that user can inscribe in model. Number of pipe segments used for discretization defines geometric mesh for numerical solver. This can largely affect the results of simulations and in general fine mesh means more reliable results. However, there is a point from where further increase of discretization does not influence the calculation outcome any more. In order to get valid results in shortest time possible, it is necessary to find optimal number of pipe segments used for discretization.

For simulations, the HEX model needs to be provided with the input values of mass flow rate and inlet water temperature for current conditions both for primary and secondary side. The output of the simulation is primary the outlet water temperatures, heat flow rate and convective heat transfer coefficient.

5.2 Model setup and boundary conditions

In order to provide results similar to measurements, the PHEX model was adjusted according to measurement setup (see subchapters 3.2 and 3.3). The first measurement (for fully opened valve on primary side) was adapted as nominal operating point.

- The medium was obviously defined as water. For the PHEX model it was selected as *Buildings* class *ConstantPropertyLiquidWater*.
- The four parameters of the hA -model were defined as follows. Nominal inlet water temperatures match values from first measurement. Exponent for convective heat transfer coefficient n was calculated using Excel tools. The idea was to find the n so that UA value from measurement is as close as possible to UA value calculated the same way it would have been in PHEX model. All five measured operating points were used here since it was important to adjust model calculation according to the actual (measured) UA curve trend. The UA value from measurement was calculated as described in subchapter 3.3. The UA value from *Modelica* algorithm was determined as

$$UA = \frac{1}{\left(\frac{1}{hA}\right)_1 + \left(\frac{1}{hA}\right)_2} \quad 5.1$$

where hA was calculated as

$$\frac{(hA)}{(hA)_{nom}} = \left(\frac{\dot{m}}{\dot{m}_{nom}}\right)^n \quad 5.2$$

Now the solver for n value was set so that the sum of squares of difference between measured and calculated UA value is as small as possible. Since only the primary side mass flow rate was changing, the n value was calculated for primary side. It is assumed that the secondary side has the same conditions since the mass flow rate value is very close to the one in primary side.

- Nominal conditions were defined after first measurement, as mentioned before. The mass flow rates were transformed from [l/h] in [kg/s]. Nominal pressure drop was obtained from selection software SSP G7 for used type of HEX and measured nominal mass flow rates. Thermal conductance at nominal flow is calculated from measurements as

$$(UA)_{nom} = \frac{Q_{nom}}{LMTD_{nom}} \quad 5.3$$

where Q is heat flow rate and $LMTD$ is logarithmic mean temperature difference, both in nominal conditions. Ratio between primary and secondary side convective heat transfer coefficient is already defined in subchapter 4.2.3 as $r = 1$.

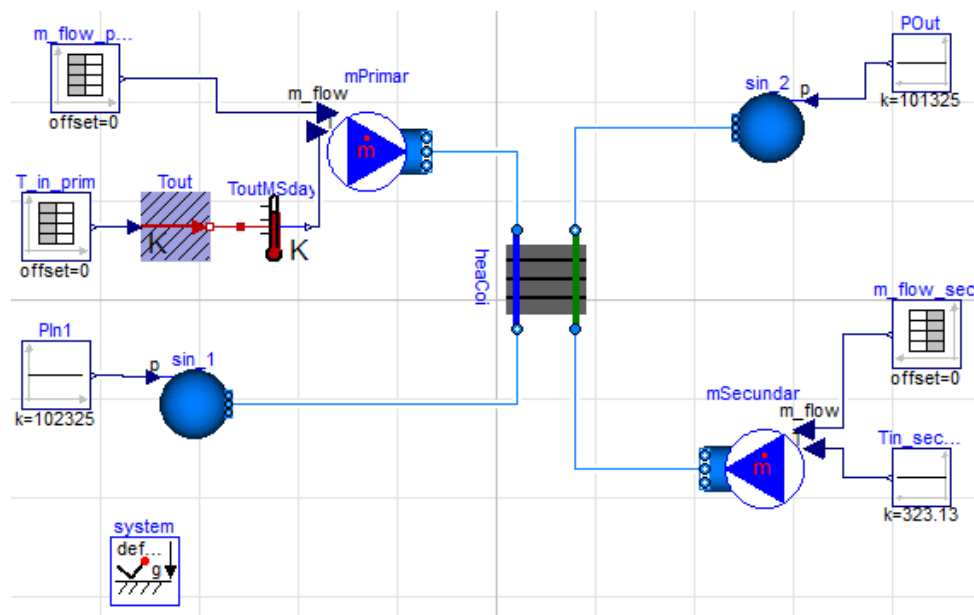
- Number of pipe segments used for discretization was determined by gradually increasing it until there was no more change in simulation results.

Table 5.1 Parameters for defining PHEX model

Parameter		Label	Unit	Value	
				Primary side	Secondary side
hA	Nominal inlet water temperature	T_0	K	348,11	323,13
	Exponent for convective heat transfer coefficient	n	-	0,46	0,46
Nominal conditions	Mass flow rate	m_flow_nom	kg/s	0,134135	0,134286
	Pressure drop	dp_nom	Pa	10000	10000
	Thermal conductance at nominal flow	UA_nom	W/K	1243,736	
	Ratio between primary and secondary side convective heat transfer coefficient	r_nom	-	1	
Number of pipe segments used for discretization		$nEle$	-	160	

Table 5.1 shows the parameters that were inscribed in the model in order to define its behavior. These parameters present performances of specific HEX type – the one that is integrated in the laboratory rig at NTNU (see subchapter 3.2.2), in operation conditions.

When the parameters of the HEX were defined, it was necessary to provide the HEX model with the input values. As mentioned before, input values are mass flow rate and inlet water temperature both for primary and secondary side. These values are defined for every operating point after the measured values of the same parameter (see table 3.4). In *Modelica*, the input values need to be provided with some kind of source components. Figure 5.1 illustrates *Modelica* diagram of PHEX model connected with two mass flow sources (circle with inscribed blue triangle) and two boundary components (solid blue spheres).

**Figure 5.1** Modelica diagram of PHEX model expanded with the boundary components

The mass flow sources, labeled as *mPrimar* and *mSecundar*, are fluid source components from Buildings library. It is defined as ideal flow source that produces a prescribed mass flow with prescribed temperature, mass fraction and trace substances [19]. In our case, only mass flow rate and temperature are of interest so these values were prescribed by the time table components, labeled as *m_flow_p...*, *T_in_prim* and *m_flow_sec*. (See subchapter 4.3 for explanation on modeling the prescribed temperature.) Although only primary side mass flow rate was changed between the measurements, the measurement results showed slight variations also in inlet primary side temperature and secondary side mass flow rate. That is why the time table component was used also for these two parameters. The secondary side inlet temperature was held constant successfully during the measurement, so it was modeled by constant source block (*Tin_sec...*). This was done to eliminate factor of dissimilar input values during the comparison of simulation and measurement results.

Output values were obtained also through *Buildings* component called *Boundary_pT*. Only pressure values were prescribed and the temperatures were required output values of the simulations.

Time step between changes of primary side mass flow rate in *Modelica* was defined as 50.000 seconds, since it has been proven to be more than sufficient period of time for achieving steady-state condition.

5.3 Simulation results vs. measurements

Heat transfer parameters were compared and analyzed for every operating point with purpose of validation of the PHEX model. Main parameters were:

- Outlet temperatures both for primary and secondary side (*t_prim_out* and *t_sec_out*)
- Heat transferred between primary and secondary side medium (*Q_flow*)
- Thermal conductance value (*UA*)

Diagrams on figure 5.2 show agreement between measurement and simulation results regarding the primary side mass flow rate, as the input parameter that was changed between measurements/simulations. Table 5.2 gives the overview of considered values with calculated difference between results of simulation and measurement results.

Table 5.2 Output values and error between measurement and simulation

<i>t_prim_out</i>			<i>t_sec_out</i>			<i>Q_flow</i>			<i>UA</i>		
Meas.	Mod.	Error	Meas.	Mod	Error	Meas.	Mod.	Error	Meas.	Mod.	Error
°C		%	°C		%	W		%	W/K		%
57,66	57,81	0,27	67,01	67,11	0,14	9646,35	9622,52	0,25	1243,74	1243,73	0,00
56,66	56,78	0,21	66,26	66,31	0,09	9265,80	9244,28	0,23	1215,21	1217,22	0,17
53,75	53,86	0,20	63,26	63,41	0,25	7582,57	7601,90	0,25	1115,13	1122,93	0,70
51,57	51,57	0,02	59,98	60,11	0,22	5687,05	5732,47	0,80	1003,06	1016,64	1,35
50,21	50,28	0,14	56,30	56,35	0,10	3595,48	3601,06	0,16	900,68	881,00	2,18

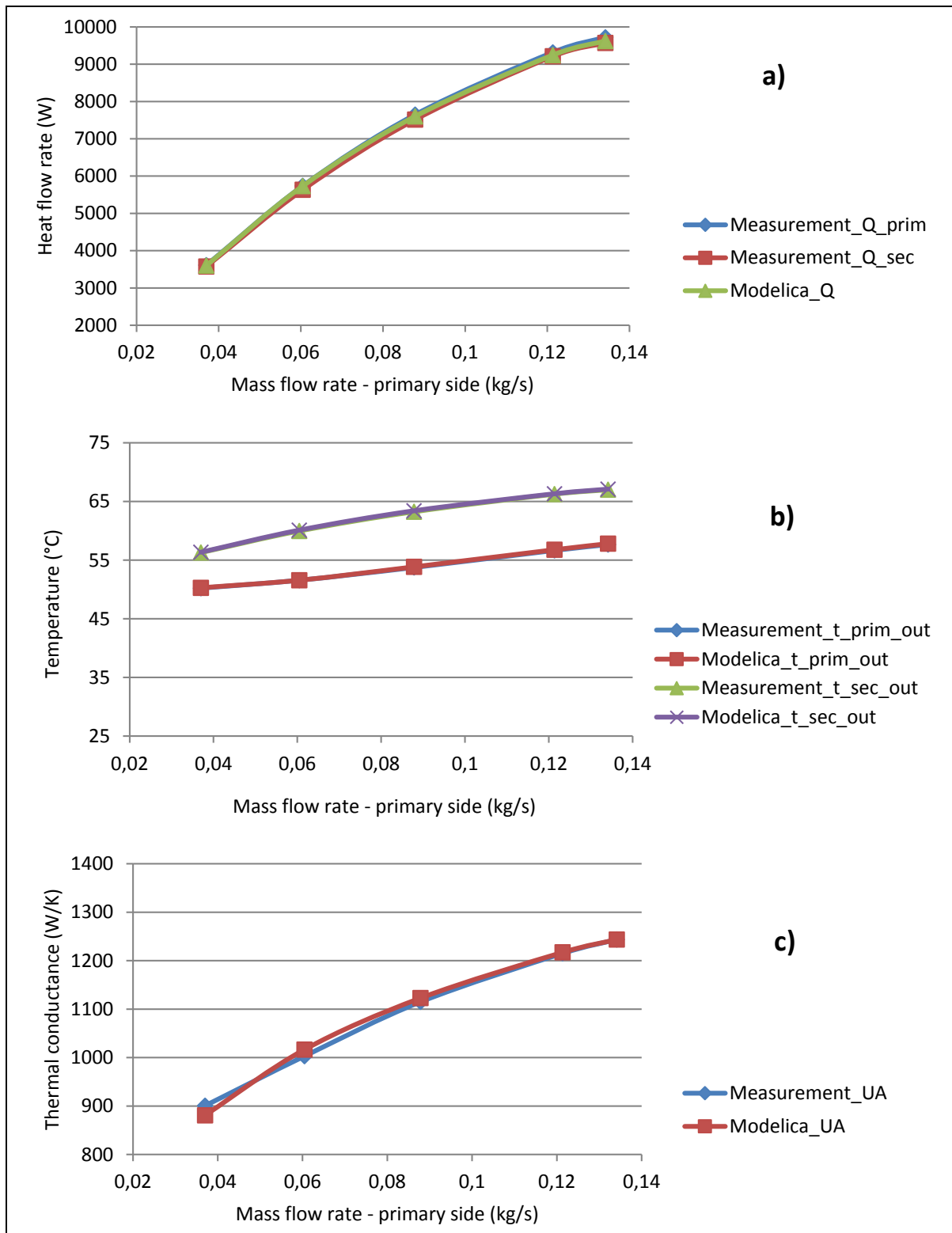


Figure 5.2 Diagrams showing comparison of simulation and measurement values of: a) heat flow rate; b) outlet temperatures; c) thermal conductance

As presented, measurement and simulation results have gotten very close. The average difference is less than 0,5% which means excellent agreement. In diagram, heat flow rate from *Modelica* is compared with two measurement values: the one calculated with primary side

parameters and the one calculated with secondary side parameters. All three curves seem to have almost same trend. The outlet temperatures also showed that *Modelica* PHEX model follows behavior of real heat exchanger to a great extent. The UA-value is also showing good respond of the model. It has been noticed that for lower values of mass flow rate, as in fifth measurement operation point where the valve was only 30% open, the difference between measurement calculation and *Modelica* output was increasing. This might be occurring due to entering the transition flow domain where the used equations for completely turbulent flow could cause slight disagreement between calculation and real behavior. However, for more detailed analysis it is necessary to perform series of measurements for different mass flow rate range and also with different temperature arrangements.

Performed measurement provided significant amount of information that helped analyzing the PHEX behavior, tuning the model and ultimately in validation of developed model. The *Modelica* calculation of plate heat exchanger showed very good respond and it has been proven as a reliable simulation model to be used in other scenarios and modeling problems.

6 Simulation of district heating system: Transition to low temperature

Simulating model of HVAC component is always created in order to analyze problems of a system for energy consumption. This chapter will show an example of application of a DH substation model in a discussion about problem of transition to low temperature systems. This is a very common issue today in cities all around Europe and this work presented an overview of the situation in Sarajevo, the capital of Bosnia and Herzegovina. District heating system in Sarajevo usually meets few obstacles that are crucial for higher efficiency and transition to lower supply temperatures. Primly, there are various types of buildings with different specific heat demand that are often connected to the same DH grid. This puts the limitation in terms of adjustment of supply temperature by heating curve of the “worst” building, i.e. the building with the higher heat demand. Heat demand of the building can also get changed and the cause could be implementation of energy efficiency measures such as better insulation or new windows. Another factor that affects operation of DH system might be the change of weather conditions, which cannot be neglected anymore. This brings into the light widely spread problem – poorly tuned control system, so the heating systems are not reacting properly in accordance with the actual needs of the building. Analyzing some crucial parameters and using the simulation models, but mainly focusing on better control of DH system, it has been shown what improvements can be implemented and how much it will affect operation of the DH network.

6.1 Potential for lowering supply water temperature in district heating network in Sarajevo

In Canton of Sarajevo there are about 141.000 residential units including individual households and buildings. The DH network is supplying about 47.000 apartments in cca. 1.600 buildings that are from 0 to 50 years old. Up to now, major reconstruction and renovation in residential buildings has been done, but this process is still on going. In 2009 a study [22] has been made that covered most of the buildings connected to the local heating network in Sarajevo. According to this data, there are seven types of buildings with different design and construction of walls, roof, windows, façade etc. This means there are seven categories of buildings regarding specific heat demand, but even inside of every category there is an interval of values that are reflecting real situation, as shown in Table 6.1.

Table 6.1 Specific annual heat demand for seven building types defined in Study from 2009 [22]

Type		1	2	3	4	5	6	7
Specific annual heat demand (kWh/m ² ,annu)	Min	136	138	93	131	96	96	104
	Max	219	229	181	203	243	256	193
	Average	171	162	130	167	169	164	134

Most of the DH network in Sarajevo is operated by public company “Toplane-Sarajevo”. Their main activities are production and distribution of heat energy. Natural gas is primary source for all boiler rooms that supply DH network in Sarajevo. Heating period starts when the average daily temperature of two consecutive days gets below 12°C , latest by October 15th. End of the heating period is when the average daily temperature of two consecutive days gets above 12°C , earliest by April 15th. Supplier is obligated to provide inside air temperature of $20\pm 1^{\circ}\text{C}$ to their consumers. Heating systems are in daily operation from 6 to 22 h during heating period. Both direct and indirect schemes are present as parts of Sarajevo DH network. [23]

Major barrier for improvements in operation of network comes from differences in heat demand of neighbor buildings. Figure 6.1 shows distribution of different types of buildings in just one part of Sarajevo, but even the objects that are considered same type can vary in heat demand. In some cases every building is provided by its own substation, so the problem of control stays mostly with the production side. Other scenario is when a few dissimilar buildings are connected to the same circuit that gains heat from one substation. Then the consumption side also needs to be taken into consideration and sometimes great adjustments are required. This current state creates tough conditions for implementing any large-scale measures, even if it involves only one block of connected buildings. Other European cities are also dealing with this transition situation [11]. However, this should not come as a surprise. Energy efficiency is long-term goal that requires a slow process of putting together all the small improvements into a big picture.



Figure 6.1 Segment of a map of Sarajevo showing distribution of different building types [22]

More efficient operation of DH network can be achieved lowering supply and return water temperatures as much as the current system allows. Decrease of temperature in pipeline directly affects heat losses in distribution, since smaller temperature difference between water, heat carrier, and surrounding air or ground causes smaller heat flux from the pipeline to the environment. Reduction of return water temperature has particular benefits. If the water temperature in return line is downsized even more than in supply line, the temperature difference will increase which means more capacity will be in use. Consequently, more heat energy can be provided with the same system and same combustion process, so overall efficiency of the system will be increased.

Climate change

Significant potential for lowering supply water temperature had emerged when the consequences of climate change had become obvious. In the past decade it has been noticed that the climate in Sarajevo has become milder and the number of heating operational hours for design outdoor temperature -16°C has decreased. It is pointed out that the further HVAC design projects could be brought out in relation to higher outdoor temperature (-13°C) and number of degree-days 2381 instead of 3077. Calculations made with these values shows that the real heat demand could be lower up to 22% than the energy requirement value expected with the old design parameters [24].

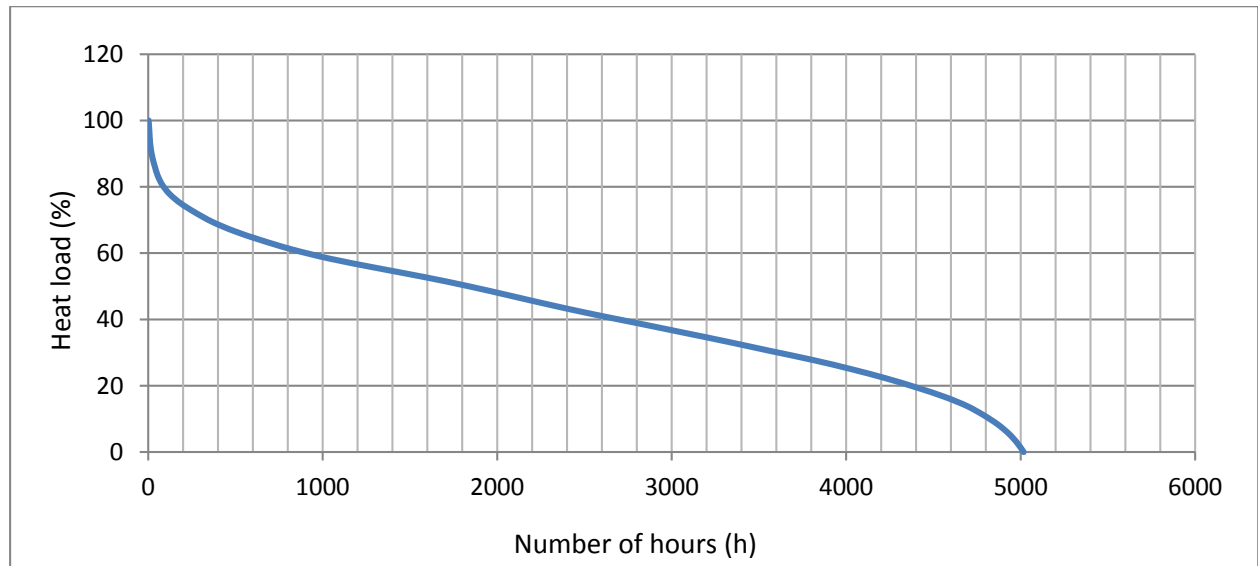


Figure 6.2 Heat load duration curve for Sarajevo, based on period 2001-2010

Based on the temperature measurements from 2001 to 2010 [25] a heat load duration curve has been created (Figure 6.2). This updated graph revealed main possibility for lowering supply water temperature. Outdoor design temperature of -16°C has indeed become even rare for Sarajevo, with average frequency of 2,7 hours in year. Temperature lower than, e.g., -12°C occurs during 33 hours in year. So if DH system would be adjusted by outdoor temperature of -12°C (89 % of system full load), a building with heating curve designed after -16°C could become subcooled around day and a half. Of course, this is not a complete day e.g. in January, but 33 hours spread during the winter season. For residential buildings, few hours now and then with lower heat supply are often overcome due to heat inertia. Application of this idea was shown within simulation model described subchapter 6.2 Model of four buildings.

Implemented EE measures

Large number of residential buildings has had improvements in energy efficiency by renewing its envelope (insulation, new windows). These fundamental measures have significantly decreased heat demand, but the hydronic space heating systems remained the same. Accordingly, installed radiators now have some extra capacity. Replacement of complete heating system would be too expensive and time-consuming at the moment, but this issue could be turned into advantage. Adjustment of the existing heating system to the new operating condition is mostly done in one of the two ways: reducing mass flow rate or reducing temperature difference between supply and return water temperature. This is obvious from the basic energy equation:

$$Q = \dot{m} \cdot c_p \cdot \Delta t$$

6.1

For approximately constant water properties (specific heat capacity c_p), transferred heat Q depends on mass flow rate and/or temperature difference that occurs as consequence of heat flux.

However, new range of possibility appears when both mass flow rate and temperature difference are being altered. The radiators with higher capacity than needed can provide greater temperature drop. This leads to decrease of return water temperature and consequently reduction of heat losses. The simulation model described in subchapter 6.2 performed this idea in even more interesting scenario of few buildings connected to the same DH substation.

6.2 Model of four building

In order to get better insight in behavior of DH substation, a simple simulation model of DH system was made and called the *Four buildings model*. Developed model of PHEX water-to-water (subchapter 4.2) was integrated and it showed great response connected with other *Modelica* components. Production side was set simply as source and sink, with prescribed temperature and pressure. Consumption side was design as four buildings, using *The Room model* (subchapter 4.4).

Basic scenario

The basic model demonstrated scenario of four buildings before any energy efficiency improvements were made. It was important for later comparison and to show what difference has been made. The structure of model remained the same in other scenarios, since the changes were made only in buildings' construction and heating parameters.

Figure 6.3 shows the simple schematic sketch of the *Four buildings model*. The basic model represented four buildings, with absolutely same characteristics (dimensions, wall constructions, windows, radiators and other parts of hydronic heating system, heating curve). All of them are connected parallel in one circuit which gains heat through the HEX – this is the secondary, consumption side. The primary side of the HEX is the hot water coming from DH network. The weather compensation control is adjusting supply water temperature of secondary circuit by changing mass flow rate of primary circuit. This means that the constant parameters are supply water temperature of primary circuit and mass flow rate of secondary circuit.

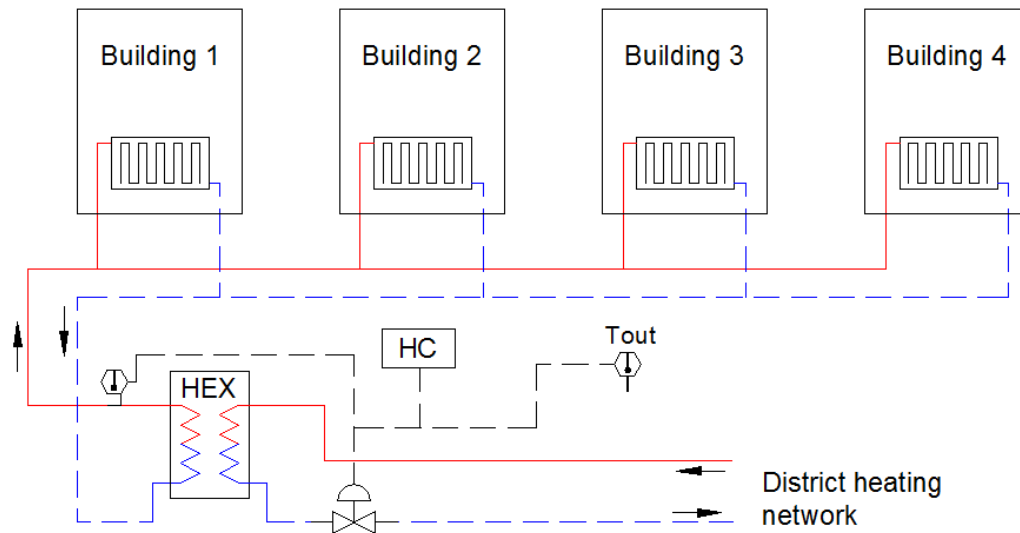


Figure 6.3 Schematic sketch of the Four buildings model

The building model, which was used in basic scenario, was named **Building Type 1**. It is assumed to be “the old building” with high heat demand. Dimensional data has been adopted arbitrarily, but retained for every building and throughout every scenario. For the **Building Type 1** the wall construction is defined as 25 cm of brick with layer of mortar on both sides (in and out). The windows’ U-value is 3 W/(m²K) and the heating system is defined by radiator exponent $n=1.3$. All these assumptions are based on common object design present in Sarajevo [22]. Applying a simple calculation method for heat losses, main parameters of energy consumption are determined and showed in Table 6.2. Obtained value for specific heat demand of **Building Type 1** is 240 kWh/(m²ann), which correspond to real data about heat consumption is Sarajevo for old buildings [22]. Heating curve (Figure 6.4) was constructed based on calculated heat consumption, outdoor design temperature -16°C and temperature regime 90/70/20 (supply/return/indoor), which corresponds to design conditions in Sarajevo’s DH network.

Table 6.2 Main parameters of energy consumption for **Building Type 1**

Annual heat demand	Specific heat demand	Radiator load	Number of operating hours	Temperature drop in nominal operating point ($t_{sup} - t_{ret}$) _{nom}	Mass flow rate	Temperature regime in nominal operating point $t_{sup} / t_{ret} / t_{in-air}$
kWh/a	kWh/m ² a	W	h/a	°C	kg/s	°C
21627	240,3	15974,5	1354	20	0,1903	90/70/20

Since the basic scenario was assumed to represent situation before any EE measures, nominal operating conditions corresponded to full load that would satisfy thermal comfort (inside temperature 20°C) for four buildings of **Type 1**, when the outdoor temperature is -16°C. All the system components were designed regarding these parameters.

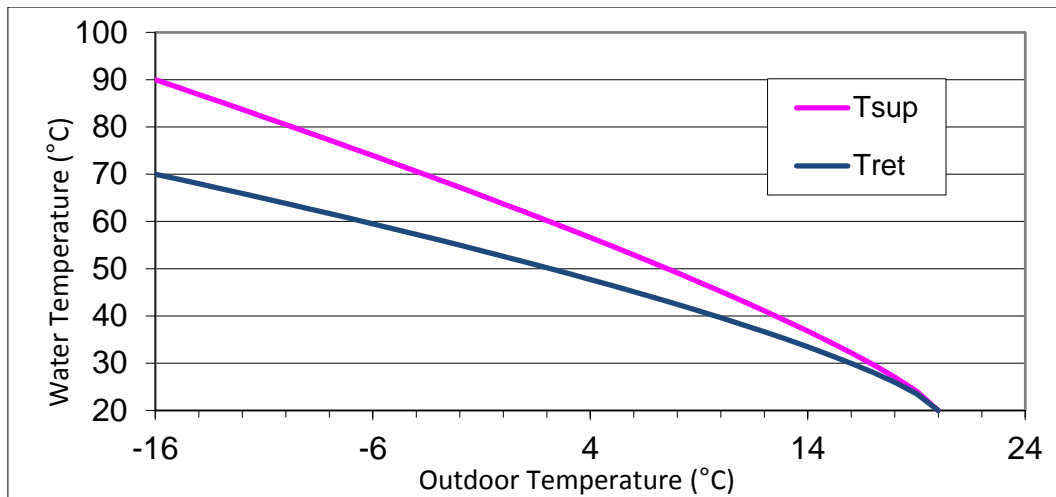


Figure 6.4 Heating curve for *Building Type 1*

The type of a **plate heat exchanger** in the DH substation is chosen by calculation software SSP G7 [15]. The nominal operating conditions were:

- temperature regime for secondary circuit is 90/70 °C (supply/return),
- mass flow rate for secondary circuit is 0,7613 kg/s (sum of mass flow rates for four buildings of *Type 1*),
- supply water temperature of primary circuit was adopted as 100°C.

According to SSP G7 program, the appropriate HEX type is *B8T x 40*. Its characteristics are given in Table 6.3.

Table 6.3 Basic parameters for PHEX type *B8T x 40* in nominal operating point

Parameter		Unit	Primary side	Secondary side
Heat load	Q_{nom}	kW	63,892	
Inlet temperature	t_{11} / t_{21}	°C	100	70
Outlet temperature	t_{12} / t_{22}	°C	79,27	90
Flow rate	\dot{m}_1 / \dot{m}_2	kg/s	0,7329	0,7613
Pressure drop - total	$\Delta p_1 / \Delta p_2$	kPa	19,9	20
Total heat transfer area	A	m ²	0,874	
Overall heat transfer coefficient	U_{nom}	W/ m ² ,°C	7591	
Port diameter	d_1 / d_2	mm	17,5	17,5
Number of channels			19	20
Number of plates			40	

For defining the PHEX model in *Modelica*, it was also necessary to determine the exponent n in the relation between convective heat transfer and mass flow rate regarding current and nominal operating point:

$$\frac{(hA)}{(hA)_{nom}} = \left(\frac{\dot{m}}{\dot{m}_{nom}} \right)^n \quad 6.2$$

This exponent was calculated both for primary and secondary side, using values obtained by SSP G7 software. The calculations of HEX performances were made for 10 operation points. First 5 points were set only by changing mass flow rate on primary side. Constant value was retained for mass flow rate on secondary side and inlet temperature both for primary and secondary side. This way the exponent n for primary side was obtained:

$$\frac{(hA)_1}{(hA)_{1nom}} = \left(\frac{\dot{m}_1}{\dot{m}_{1nom}} \right)^{n_1} \Rightarrow n_1 = 0,6375 \quad 6.3$$

Other 5 operating points were set in the same way, but now by changing secondary mass flow rate, which provided the exponent n for secondary side:

$$\frac{(hA)_2}{(hA)_{2nom}} = \left(\frac{\dot{m}_2}{\dot{m}_{2nom}} \right)^{n_2} \Rightarrow n_2 = 0,5948 \quad 6.4$$

When the nominal operating parameters and exponent were obtained, the PHEX model was adjusted. Unless the brand new HEX type would be integrated in the substation, these parameters would not change.

Production side is out of scope of this paper, so it was not considered in details. Since the control of secondary side was based on varying mass flow rate of primary side, the supply water temperature is constant ($t_{sup_prim} = 100^\circ C$). To eliminate possibility of evaporation, the primary side water pressure was prescribed $p_{prim} = 3bar$.

Scenario with EE measures

To demonstrate slice of real situation in DH system, the basic model was modified regarding few matters. As it has been described in the first part of this chapter, common issue in lot of European cities, as well as in Sarajevo, is variation of heat demand in object connected to the same DH pipeline. This could occur due to locally implemented measures of energy efficiency, such as new windows or building's envelope reconstruction. Along those lines, background story for this scenario was made.

Let us say that there were four building constructed at the same time, perhaps 30 years ago. All of them are designed in the same way, so the wall structure, the windows, roof and floors, everything was the same. The hydronic heating system, including pipelines, radiators and heating substation was also designed at the same time and according to corresponding heat demand of these four buildings. This is previously described *Basic scenario*. In the past 10 years, energy efficiency is gaining great importance so the EE measures are being implemented, but still gradually. In the scenario of four buildings, next improvements have been made:

- Windows on Building 2 were completely replaced. Beside of lower windows' U-value ($U_{new_wind} = 1,4W / m^2 K$), this led to decrease of number of air changes per hour, which also had great influence on heat losses.
- Outside walls of Building 3 were upgraded with 0,5 cm thick layer of insulation. This is one of the ground measures that affected heat losses significantly.
- Analysis of the consumption side revealed that heating system for Building 4 was initially oversized. Being strongly familiar with actual state of consumption side is often overlooked, but very important step in process of EE improvement.

The simple calculations for heat losses were brought out again and new values of energy consumption parameters were obtained. Overview of parameters for all four building in this scenario is given in Table 6.4.

Table 6.4 Building parameters for *Scenario with EE measures*

Building Type		Annual heat demand	Specific heat demand	Radiator load	Nominal radiator load
	Description	kWh/a	kWh/m ² a	W	W
1	Basic construction, no EE measures implemented	21627	240,3	15974	15974
2	Replaced windows	16895	188	12478	15974
3	Installed 0,5 cm insulation	13834	154	10218	15974
4	Basic construction, initially oversized heating system	21627	240,3	15974	19166

All the heating systems components for these four buildings had remained the same. This included radiators, pipelines, the HEX in the substation and main production side parameters of interest. If the operating condition would have stayed the same, Building 2, 3 and 4 would likely become overheated and the secondary side would get more energy than actually needed. Next scenario showed how only by setting appropriate control, the proper operation was adjusted and energy efficiency of the system was improved, at the same time.

Optimized scenario

It has been established that there was fertile ground for achieving two targets:

- lowering supply water temperature due to climate change and
- lowering return water temperature using extra capacity in heating system components.

Heating system for considered four buildings scenario was designed regarding outdoor air temperature $-16^{\circ}C$. This value is still marked as outdoor design temperature for most of the objects in Sarajevo. However, as it has been discussed in subchapter 6.1, the heating systems could work properly regarding $-13^{\circ}C$ as the outdoor design temperature (24). Weather data from period 2001-2010 showed that temperature under $-13^{\circ}C$ had occurred in average 18,5

hours annually. Neglecting this potentially subcooled period of time, the supply water temperature was adjusted as lower value then it was before.

For this scenario, the heating curve for Building Type 1 (Figure 6.4) was referent in determination of new supply water, because others types had more room for coordination between water temperatures and heat demand. Considering this, **maximum supply water temperature for secondary circuit was specified as 85,3 °C**, corresponding to outdoor temperature -13°C in heating curve for *Building Type 1*. According to temperature dependence diagram for the heat exchanger B8T x 40 (Figure 6.5), **the supply water temperature in primary circuit needed to be 94,55°C**.

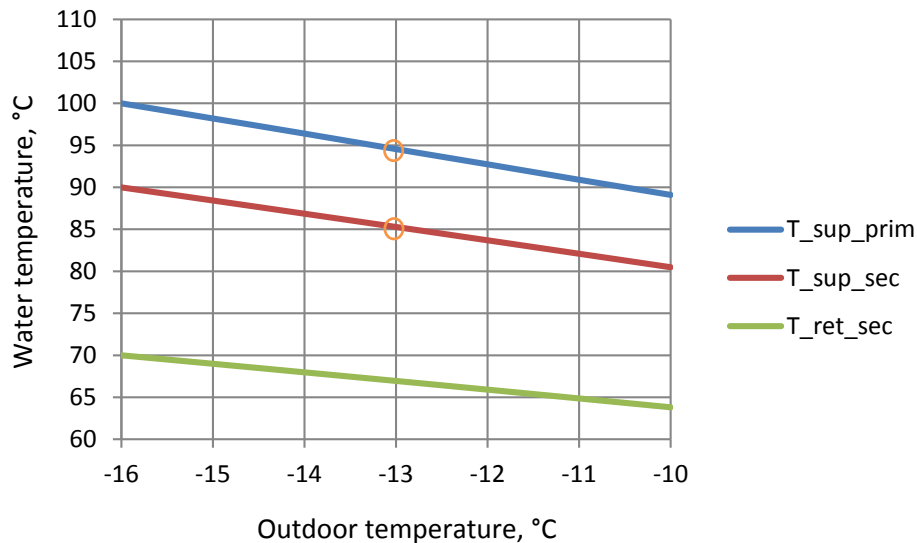


Figure 6.5 Segment of temperature dependence diagram for HEX B8T x 40, regarding the heating curve for *Building Type 1*

Heating curves for other three building types were calculated in the way that the supply water temperature gets closely the same for all four types. But since the Buildings 2, 3 and 4 had gained some extra capacity in their heating systems, there was possibility to achieve **greater temperature drop in radiators**. This was accomplished by **reducing mass flow rate** for these three buildings individually, so the return water temperature was lowered down even more. Constructed heating curves are shown in Figure 6.6.

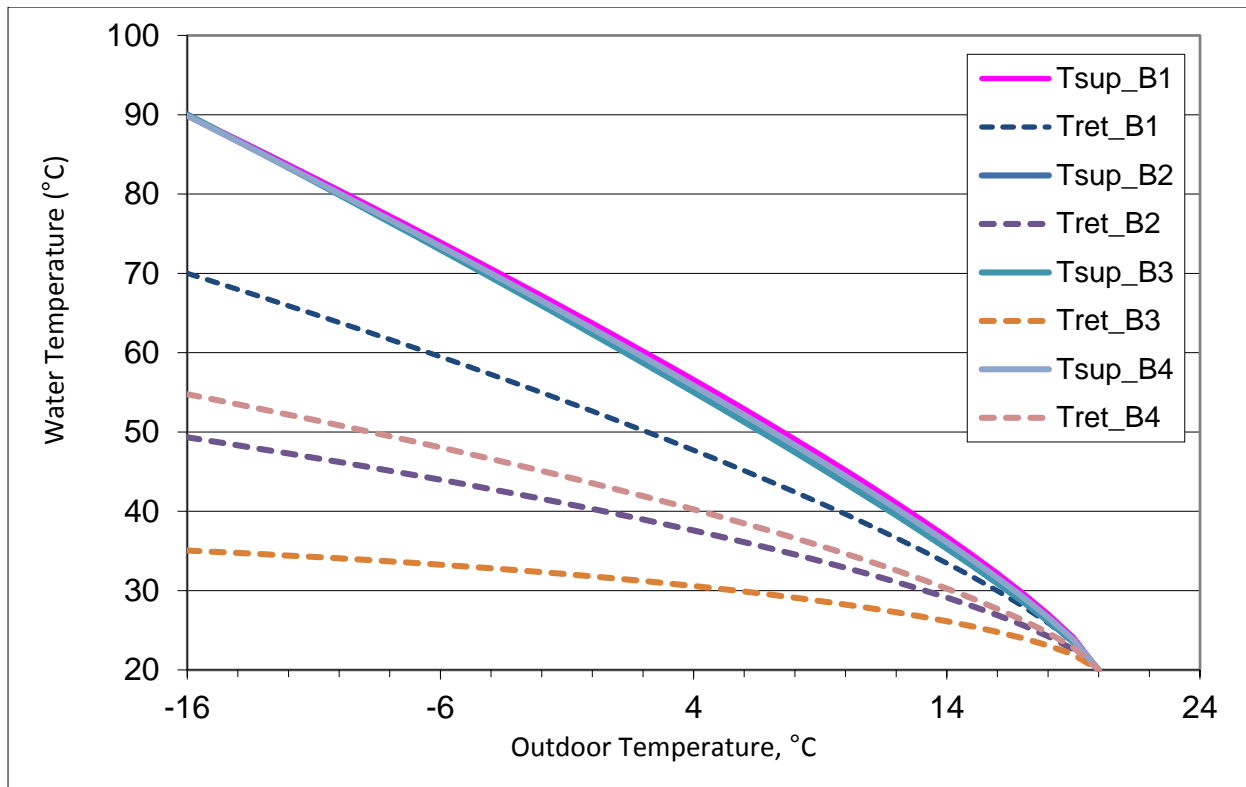


Figure 6.6 Heating curves for all four building types

Four buildings model for this scenario was now modified in two ways:

- primary side supply water temperature was reduced from 100°C to 95°C
- mass flow rate was adjusted for every building individually so the return water temperature would follow the values predicted by heating curves from Figure 6.6

Results of simulation and comparison of different scenarios is presented in further text.

6.3 Results of simulation

The *Four building model* was adjusted by the idea and characteristics described in subchapter 6.2. It was assumed that the heating system operation in *Scenario with EE measures* is the same as in the *Basic scenario* and the adjustment of operating parameters was done in *Optimized scenario*. Therefore, the simulation and analysis were done for *Basic* and *Optimized scenario*. Comparison of the two scenarios' results showed how much did the heat losses of the primary side pipeline decreased. Figure 6.7 illustrates *Modelica's* diagram of *Four buildings model* adjusted after *Optimized scenario*. Simulations were performed for condition of considered minimum outdoor temperature.

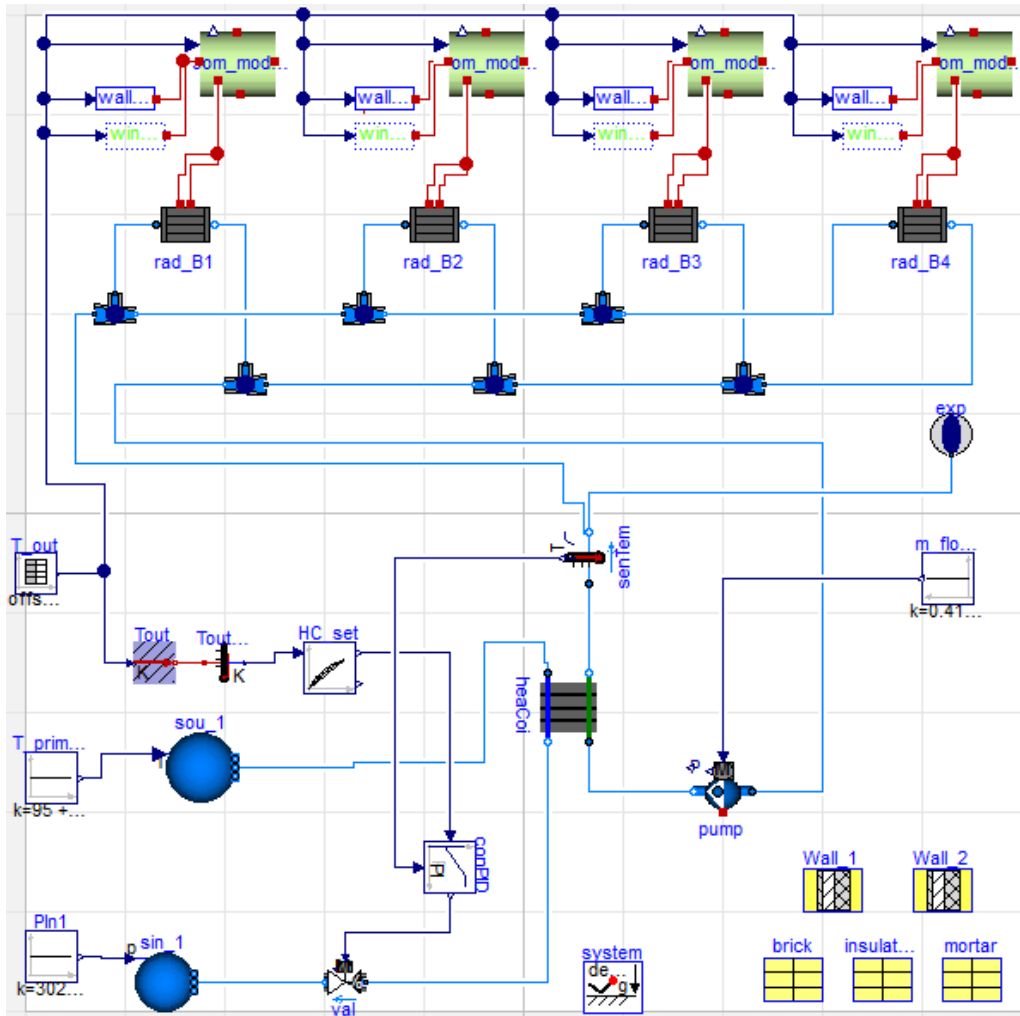


Figure 6.7 Modelica diagram window of the Four buildings model

In order to perform some kind of validation of simulation results, performance of the chosen HEX type B8T x 40 was investigated with the selection software SSP G7. Input values for this software were inlet temperatures and mass flow rate for both primary and secondary side. Calculated values of outlet temperatures, heat flow rate and heat transfer coefficient were compared with *Modelica* results. Considered values showed good agreement (Table 6.5).

Table 6.5 Comparison of the simulation results and values obtained by HEX selection software

Scenario	Calculation method	t _{out}	Primary			Secondary			Q _{flow}	OHTC
			t _{sup}	t _{ret}	m _{flow}	t _{sup}	t _{ret}	m _{flow}		
		°C	°C	°C	kg/s	°C	°C	kg/s	kW	W/m ² K
Basic	Modelica	-16	100	79,38	0,7329	90	70,10	0,7613	63,25	7593,4
	SSP G7			79,26			70,00			
Optimized	Modelica	-13	95	69,05	0,4455	85	57,03	0,4165	48,86	5185,5
	SSP G7			68,60			56,58			

The heat losses reduction is determined for the primary side pipeline. Two methods have been applied: first for individual calculation of supply and return line and other for total heat loss reduction of the production side. Consumption side has not been considered in this part since it was assumed to have relatively insignificant heat losses.

The reduction of heat losses for supply and return line **individually** was determined in percentage, by simplified equation. The heat transfer for one meter of pipeline can be defined by equation:

$$q_{losses} = U \cdot D\pi \cdot (t_{water} - t_{ground}) \quad 6.5$$

where $q_{losses} [W/m]$ is heat loss per unit length of pipeline, $U [W/m^2K]$ is overall heat transfer coefficient for DH pipes, $D\pi [m]$ is circumference of pipes and $(t_{water} - t_{ground})$ is temperature difference between the water from DH network and surrounding ground. Since the DH pipeline remained the same through every scenario, heat losses can be considered directly proportional to temperature difference between water in pipeline and surrounding ground. Therefore the reduction of the heat losses is:

$$\Delta Q_{losses} = \frac{\Delta t_{Basic} - \Delta t_{Optim}}{\Delta t_{Basic}} \quad 6.6$$

where $\Delta Q_{losses} [\%]$ is decrease of heat losses, $\Delta t_{Basic} = (t_{sup/ret} - t_{grou})_{Basic}$ is temperature difference between supply or return water and surrounding ground in *Basic scenario*, $\Delta t_{Optim} = (t_{sup/ret} - t_{grou})_{Optim}$ is temperature difference between supply/return water and surrounding ground in *Optimized scenario*. Temperature of surrounding ground was adapted as 5°C.

Supply water temperature

The highest heat demand for the consumption side was establish to correspond to the outdoor temperature of -13°C. It used to be adjusted by the outdoor design temperature of -16°C. The supply water temperature of the primary circuit was decreased according to this change in maximum heat demand. Lower supply water temperature provided savings in heat losses of the pipeline. Calculation was done according to equation 6.5:

$$\Delta Q_{losses,sup} = \frac{(t_{sup} - t_{grou})_{Basic} - (t_{sup} - t_{grou})_{Optim}}{(t_{sup} - t_{grou})_{Basic}} = 5,26\% \quad 6.7$$

Return water temperature

Decrease of return water temperature made even more significant savings. Temperature drop on primary side had become 25°C instead of 20°C in *Basic scenario*, which reduced heat losses:

$$\Delta Q_{losses,ret} = \frac{(t_{ret} - t_{grou})_{Basic} - (t_{ret} - t_{grou})_{Optim}}{(t_{ret} - t_{grou})_{Basic}} = 13,89\% \quad 6.8$$

Total heat loss reduction of the production side was determined based on recommendation of European standard EN 13941 [26]. This approach takes into consideration heat resistance of

pipe insulation, heat resistance of surrounding ground and interaction between supply and return line. The heat loss per unit length of pipeline is calculated as:

$$q_{losses} = \frac{(t_{sup} - t_o) \cdot R_{sum} + (t_{ret} - t_o) \cdot R_o}{R_{sum}^2 - R_o^2} \quad \mathbf{6.9}$$

where $t_{sup} [^{\circ}C]$ is supply water temperature, $t_{ret} [^{\circ}C]$ is return water temperature, $t_o [^{\circ}C]$ is temperature on ground's surface, $R_{sum} [mK/W]$ is sum of heat resistance of ground and insulation, $R_o [mK/W]$ is heat resistance representing interaction between supply and return line.

Since the influence of supply and return water temperature change on heat losses was in focus here, values for heat resistances were adapted from a design project of similar DH network [26]. The temperature on ground's surface was also defined from this project. Results of calculation are presented in Table 6.6.

Table 6.6 Results of total heat losses calculation

	t_out °C	t_sup_prim °C	t_ret_prim °C	t_o °C	R_sum mK/W	R_o mK/W	q_losses W/m
Basic	-16	100	79.39	5	5.468977	0.148828	17.75404
Optimized	-13	95	69.05	5	5.468977	0.148828	16.78763

Reduction in total heat losses expressed in percentage was:

$$\Delta Q_{loss-tot} = \frac{q_{loss-bas} - q_{loss-opt}}{q_{loss-bas}} = 5,44\% \quad \mathbf{6.10}$$

This method is probably more accurate since it takes into consideration all the parameters influencing the heat losses. However, the individual calculation was interesting to show that reduction of return line temperature in described scenario brought higher reduction of heat losses, although the supply water makes larger temperature difference with the surrounding. This signifies that the return water temperature makes more potential for reduction of heat losses. With other benefits, such as increase of system's heat capacity and improved operation of production technologies (i.e. condensing gas boiler, see subchapter 2.4), decrease of return water temperature is EE measure with significant results and small requirements.

7 Conclusions and recommendations

Simulation software is gaining ever more importance as engineering tool today and there is lot of programs dealing with heat energy generation, transfer, consumption etc. There are also software and/or components specialized for energy in buildings or production technologies or some other segment of the energy system, but there are two features that make *Modelica* language stand out. The *Modelica* language is open-source which provided opportunity to reuse partial and full models from *Modelica* libraries during this research in order to complete desirable system of district heating substation. It was possible to get insight in every component structure, mathematical description and syntax and to alter it in any way needed. After all, this was the main idea of *Modelica* from the beginning and it initiated creating libraries of models, such as *Buildings* library, and it supported faster and easier development of more complex systems. Another *Modelica* advantage has emerge due to implementation of *Modelica* language in an environment with graphical editor. Such can be provided by *Dymola* program. The graphical editor made *Modelica* so user-friendly that the high programing skills are not mandatory to become *Modelica* user. What is necessary is having clear vision of physics of problem.

However, modeling needs to go hand in hand with experimental data. It may seem that the development of computer technology is putting the laboratory in the shadow – simulation programs give so many possibilities, but the computer calculations are driven by laws defined by men and they do not necessarily follow the natural laws. No simulation model today is taken as reliable engineering tool without being proven to create output values that match behavior of a real system. Moreover, experiments can reveal imperfections and possible improvements of considered model. Thus, the plate heat exchanger model, developed during this research, has been upgraded, tuned and validated thanks to measurements performed in Laboratory of Department of energy and Process Engineering, NTNU.

The application of developed heat substation model was performed within the problem of transition to low temperature district heating systems. While investigating this issue, a great deal of ideas and possibilities have been discovered. It was interesting to see how much can be done only by properly managing energy delivered to the consumer. The control system can often be neglected next to various other measures for improvement of energy efficiency, but this is crucial factor in efficient operation of heating systems. Individual steady-state calculations of components are required, but certainly not the last step in design and adjustment of heating systems. It needs to be analyzed and discussed how coupled system works, is the thermal comfort satisfied in every room or every operating hour, what could be obstacles during the operation, will the production and consumption side be in balance and still work in range of highest efficiency – there are so many questions arising from problem of tuning the control system. This paper presented only a slice of possibility to improve operation of district heating system. The milder climate causes decrease of heat demand and consequently supply water temperature can be reduces. Even more benefits are brought by decrease of return water temperature which has been proven to be absolutely feasible. And everything depends only on control system.

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Appendix

I *Modelica* text of plate heat exchanger model with boundary setup

```

model HEX_model_final
  import Buildings;
  extends Modelica.Icons.Example;
  package Medium1 = Buildings.Media.ConstantPropertyLiquidWater;
  package Medium2 = Buildings.Media.ConstantPropertyLiquidWater;
  package MediumA =
    Buildings.Media.GasesPTDecoupled.MoistAirUnsaturated;
  Modelica.Blocks.Sources.Constant POut(k=101325)
    annotation (Placement(transformation(extent={{98,42},{86,54}}, rotation=0)));
  Buildings.Fluid.Sources.Boundary_pT sin_1( redeclare package Medium = Medium1, use_p_in=true, T=273.15 + 25, p=300000,
  nPorts=1) annotation (Placement(transformation(extent={{-68,-28},{-54,-14}}, rotation=0)));
  inner Modelica.Fluid.System system( p_ambient=300000, T_ambient=313.15)
    annotation (Placement(transformation(extent={{-90,-92},{-76,-78}}));
  Modelica.Blocks.Sources.Constant PIn1(k=102325)
    annotation (Placement(transformation(extent={{-96,-22},{-82,-8}}, rotation=0)));
  Modelica.Blocks.Sources.TimeTable T_in_prim(table=[0,348.11; 50000,348.11; 100000,348.14; 100000,347.69;
  150000,347.69; 150000, 347.38; 200000,347.38; 200000,346.69; 250000,346.69])
    annotation (Placement(transformation(extent={{-96,8},{-82,22}}));
  Modelica.Thermal.HeatTransfer.Sources.PrescribedTemperature Tout annotation (Placement(transformation(
  extent={{-7,-7},{7,7}}, rotation=0, origin={-65,15}));
  Modelica.Thermal.HeatTransfer.Sensors.TemperatureSensor ToutMSday
    annotation (Placement(transformation(extent={{-52,8},{-38,22}}));
  Buildings.Fluid.Sources.MassFlowSource_T mPrimar( redeclare package Medium = Medium1 "entrance to HEX primar",
  use_m_flow_in=true, use_T_in=true, nPorts=1) annotation (Placement(transformation( extent={{-10,-10},{10,10}},
  rotation=0, origin={-24,30}));
  Buildings.Fluid.Sources.MassFlowSource_T mSecundar(redeclare package Medium = Medium2 "heat source for infiltration",
  use_m_flow_in=true, use_T_in=true, nPorts=1) annotation (Placement(transformation( extent={{10,-10},{-10,10}},
  rotation=0, origin={52,-34}));
  Buildings.Fluid.Sources.Boundary_pT sin_2( redeclare package Medium = Medium2, use_p_in=true, T=273.15 + 25,
  p=300000, nPorts=1) annotation (Placement(transformation(extent={{62,28},{48,42}}, rotation=0)));
  Modelica.Blocks.Sources.Constant Tin_secundar(k=323.13)
    annotation (Placement(transformation(extent={{88,-58},{76,-46}}, rotation=0)));
  Buildings.Fluid.HeatExchangers.DryCoilCounterFlow heaCoi( redeclare package Medium1 = Medium1,
  redeclare package Medium2 = Medium2, dp1_nominal=10000, dp2_nominal=10000, nEle=160, show_T=true,
  r_nominal=1, waterSideTemperatureDependent=true, airSideTemperatureDependent=true,
  m1_flow_nominal=0.134135, m2_flow_nominal=0.134286, UA_nominal=1243.736,
  hA( n_w=0.46, n_a=0.46, T0_w=348.1137, T0_a=323.1273), tau2=20)
    annotation (Placement(transformation(extent={{10,-10},{-10,10}}, rotation=90, origin={10,4}));
  Modelica.Blocks.Sources.TimeTable m_flow_prim(table=[0,0.1341346; 50000, 0.13413466; 50000,0.1213566;
  100000,0.1213566; 100000,0.0878436; 150000, 0.0878436; 150000,0.0604729; 200000,0.0604729;
  200000,0.0370065; 250000, 0.0370065])
    annotation (Placement(transformation(extent={{-96,32},{-82,46}}));
  Modelica.Blocks.Sources.TimeTable m_flow_sec(table=[0,0.134286; 50000, 0.134286; 50000,0.135274; 100000,0.135274;
  100000,0.135257; 150000, 0.135257; 150000,0.135204; 200000,0.135204; 200000,0.135035; 250000, 0.135035])
    annotation (Placement(transformation(extent={{96,-26},{82,-12}}));
  equation
  connect(PIn1.y, sin_1.p_in) annotation (Line( points={{-81.3,-15},{-75.65,-15},{-75.65,-15.4},{-69.4,-15.4}},
  color={0,0,127}, smooth=Smooth.None));
  connect(T_in_prim.y, Tout.T) annotation (Line( points={{-81.3,15},{-73.4,15}}, color={0,0,127}, smooth=Smooth.None));
  connect(Tout.port, ToutMSday.port) annotation (Line( points={{-58,15},{-56,15},{-56,15},{-52,15}}, color={191,0,0},
  smooth=Smooth.None));
  connect(ToutMSday.T, mPrimar.T_in) annotation (Line( points={{-38,15},{-36,15},{-36,34}},
  color={0,0,127}, smooth=Smooth.None));
  connect(Tin_secundar.y, mSecundar.T_in) annotation (Line( points={{75.4,-52},{70,-52},{70,-30},{64,-30}},
  color={0,0,127}, smooth=Smooth.None));
  connect(POut.y, sin_2.p_in) annotation (Line( points={{85.4,48},{74.4,48},{74.4,40.6},{63.4,40.6}},
  color={0,0,127}, smooth=Smooth.None));
  connect(mPrimar.ports[1], heaCoi.port_a1) annotation (Line( points={{-14,30},{4,30},{4,14}},
  color={0,127,255}, smooth=Smooth.None));
  connect(heaCoi.port_b1, sin_1.ports[1]) annotation (Line( points={{4,-6},{4,-21},{-54,-21}},
  color={0,127,255}, smooth=Smooth.None));
  connect(mSecundar.ports[1], heaCoi.port_a2) annotation (Line( points={{42,-34},{16,-34},{16,-6}},
  color={0,127,255}, smooth=Smooth.None));
  connect(heaCoi.port_b2, sin_2.ports[1]) annotation (Line( points={{16,14},{16,35},{48,35}},
  color={0,127,255}, smooth=Smooth.None));
  connect(m_flow_prim.y, mPrimar.m_flow_in) annotation (Line( points={{-81.3,39},{-56.65,39},{-56.65,38},{-34,38}},

```



```
    color={0,0,127}, smooth=Smooth.None));
connect(m_flow_sec.y, mSecundar.m_flow_in) annotation (Line( points={{81.3,-19},{70,-19},{70,-26},{62,-26}},
    color={0,0,127}, smooth=Smooth.None));
annotation(Diagram(coordinateSystem(preserveAspectRatio=false, extent={{-100, -100},{100,100}}),
    graphics={Line( points={{-42,81},{-42,80}}, color={191,0,0}, smooth=Smooth.None)}),
    __Dymola_Commands(file="modelica://Buildings/Resources/Scripts/Dymola/Fluid/HeatExchangers/Examples/ConstantEffectiveness.mos"
    "Simulate and plot"),
    experiment(StopTime=90000),
    __Dymola_experimentSetupOutput);

end HEX_model_final;
```

II Calculation of heat losses in buildings

Simple methodology was applied in calculation of heat losses for four buildings in chapter 6. Values assumed to be known are:

- dimensions of building:
- floor surface
- outside walls surface
- window surface (15% of floor surface)
- volume of inside air
- U-value of windows
- construction of outside walls

Heat loss per unit of temperature through the outside walls are calculated as:

$$q_{wall} = U_{wall} \cdot A_{wall}$$

where A_{wall} is surface of the outside walls, and U_{wall} is overall heat transfer coefficient for outside walls, determined as:

$$U_{wall} = \frac{1}{\frac{1}{h_{in}} + \sum \frac{\Delta x_i}{\lambda_i} + \frac{1}{h_{out}}}$$

where h_{in} and h_{out} are convective heat transfer coefficients for inside and outside wall surface, Δx_i is thickness of wall layer, λ_i is thermal conductance of material.

Heat loss per unit of temperature through the windows are calculated as:

$$q_{win} = U_{win} \cdot A_{win}$$

where A_{win} is surface of the windows, and U_{win} is overall heat transfer coefficient for windows.

Heat loss from infiltration per unit of temperature is calculated as:

$$q_{inf} = \frac{n_h \cdot \rho_a \cdot c_{p,a} \cdot V}{3600}$$

where n_h is number of air changes per hour, ρ_a is density of air, $c_{p,a}$ is specific heat capacity of air, V is volume of inside air.

Total heat loss is calculated as:

$$Q_{loss} = \frac{(q_{wall} + q_{win} + q_{inf}) \cdot SSD \cdot 24}{1000}$$

where SSD is number of degree-days for particular region.

Annual heat demand of the building is now determined as $Q_{dem} = Q_{loss} / \eta_{sys}$ where η_{sys} is efficiency of the heating system.

Specific annual heat demand is $q_{dem} = Q_{dem} / A_{floor}$ where A_{floor} is floor surface of the building.

Capacity of radiator is $Q_{rad} = (q_{wall} + q_{win} + q_{inf}) \cdot (t_{in} - t_{out})_{des}$, where $(t_{in} - t_{out})_{des}$ is design temperature difference between indoor and outdoor air.

	Building 1			Building 2			
Room							
V_room	m ³	225			225		
n_h	1/h	1.8			0.8		
dens_air	kg/m ³	1.2			1.2		
cp_air	J/kg°C	1006			1006		
q_inf	W/°C	135.81			60.36		
Windows							
A_win	m ²	13.5			13.5		
U_win	W/m ² °C	3			1.4		
q_win	W/°C	40.5			18.9		
Walls							
A_wall	m ²	140			140		
h_out	W/m ² °C	25			25		
h_in	W/m ² °C	7.7			7.7		
Layers		mortar	brick	mortar	mortar	brick	mortar
delta x	m	0.02	0.25	0.02	0.02	0.25	0.02
conduct	W/m°C	0.8	0.81	1	0.8	0.81	1
q_wall	W/°C	267.36			267.36		
eta_sys	-	0.97			0.97		
SSD=	°Cday	1970.02			1970.02		
Q_dem	kWh/a	21625.64			16895.15		
q_dem	kWh/m ² a	240.28			187.72		
Q_rad	W	15972.06			12478.26		

	Building 3				Building 4			
Room								
V_room	m ³	225				225		
n_h	1/h	1.8				1.8		
dens_air	kg/m ³	1.2				1.2		
cp_air	J/kg°C	1006				1006		
q_inf	W/°C	135.81				135.81		
Windows								
A_win	m ²	13.5				13.5		
U_win	W/m ² °C	3				3		
q_win	W/°C	40.5				40.5		
Walls								
A_wall	m ²	140				140		
h_out	W/m ² °C	25				25		
h_in	W/m ² °C	7.7				7.7		
Layers		mortar	brick	EPS	mortar	mortar	brick	mortar
delta x	m	0.02	0.25	0.05	0.02	0.02	0.25	0.02
conduct	W/m°C	0.8	0.81	0.035	0.9	0.8	0.81	1
q_wall	W/°C	72.04				267.36		
eta_sys	-	0.97				0.97		
SSD=	°Cday	1970.02				1970.02		
Q_dem	kWh/a	12105.35				21625.64		
q_dem	kWh/m ² a	134.50				240.28		
Q_rad	W	8940.65				15972.06		

III Calculation of heating curves

Supply and return water temperatures for different outdoor conditions were calculated based on next relations:

$$t_{\text{sup}} = t_m + 0,5 \cdot (t_{\text{sup}} - t_{\text{ret}})_d \cdot \frac{t_{\text{ind}} - t_{\text{out}}}{t_{\text{ind}} - t_{\text{out},d}}$$

where t_{sup} is supply water temperature, t_{ret} is return water temperature, subscript d means design condition, t_{ind} is design indoor temperature, t_{out} is current outdoor temperature, $t_{\text{out},d}$ is design outdoor temperature, and t_m is mean temperature calculated as:

$$t_m = t_{\text{ind}} + \Delta t_d \cdot \left(\frac{t_{\text{ind}} - t_{\text{out}}}{t_{\text{ind}} - t_{\text{out},d}} \right)^{\frac{1}{1+n}}$$

where n is heat transfer exponent for radiator and Δt_d is: $\Delta t_d = \frac{(t_{\text{sup}} + t_{\text{ret}})_d}{2} - t_{\text{ind}}$

Return water temperature is calculated as: $t_{\text{ret}} = t_m - 0,5 \cdot (t_{\text{sup}} - t_{\text{ret}})_d \cdot \frac{t_{\text{ind}} - t_{\text{out}}}{t_{\text{ind}} - t_{\text{out},d}}$

Behavior of radiator in conditions different from design ones is described by relation:

$$\frac{Q_d}{Q} = \left(\frac{\Delta t_d}{\Delta t} \right)^{1+n}$$

This way it is possible to determine Δt for different heat demand.

		Build 1	Build 2	Build 3	Build 4
t_in_design	°C	20	20	20	20
t_out_design	°C	-16	-16	-16	-16
t_sup (tout=-16)	°C	90	89.92	90.05	89.86
t_ret (tout=-16)	°C	70	49.32	35.05	54.76
n	-	0.3	0.3	0.3	0.3
delta t	°C	60	49.62	42.55	52.31
(tsup-tret)_(tout=-16)	°C	20	40.6	55	35.1
m_flow_rad	kg/s	0.190289	0.073349	0.044398	0.108427
Q_rad	W	15972.06	12478.26	10217.67	15972.06

Next table shows results of calculation of heating curves for all four buildings from chapter 6.

Tout °C	Build 1			Build 2			Build 3			Build 4		
	Tm	Tsup	Tret	Tm	Tsup	Tret	Tm	Tsup	Tret	Tm	Tsup	Tret
-16	80	90	70	69.62	89.92	49.32	62.55	90.05	35.05	72.31	89.86	54.76
-15	78.71	88.44	68.99	68.56	88.30	48.82	61.64	88.38	34.90	71.19	88.25	54.13
-14	77.42	86.86	67.97	67.49	86.66	48.32	60.72	86.69	34.75	70.06	86.64	53.49
-13	76.12	85.28	66.95	66.41	85.02	47.80	59.80	85.00	34.59	68.93	85.01	52.84
-12	74.80	83.69	65.91	65.32	83.37	47.28	58.87	83.31	34.42	67.78	83.38	52.18
-11	73.48	82.09	64.87	64.23	81.71	46.75	57.93	81.61	34.25	66.63	81.74	51.52
-10	72.15	80.48	63.82	63.13	80.05	46.21	56.98	79.90	34.07	65.47	80.09	50.84
-9	70.81	78.86	62.75	62.02	78.37	45.67	56.03	78.18	33.88	64.30	78.44	50.16
-8	69.45	77.23	61.68	60.90	76.69	45.11	55.07	76.46	33.68	63.12	76.77	49.47
-7	68.09	75.59	60.59	59.77	75.00	44.55	54.10	74.73	33.48	61.93	75.09	48.77
-6	66.71	73.94	59.49	58.63	73.30	43.97	53.13	72.99	33.27	60.73	73.40	48.05
-5	65.32	72.27	58.38	57.49	71.58	43.39	52.14	71.24	33.05	59.52	71.71	47.33
-4	63.92	70.59	57.26	56.33	69.86	42.79	51.15	69.48	32.82	58.30	70.00	46.60
-3	62.51	68.90	56.12	55.16	68.13	42.19	50.15	67.72	32.58	57.06	68.28	45.85
-2	61.08	67.19	54.97	53.98	66.38	41.57	49.13	65.94	32.33	55.82	66.54	45.09
-1	59.64	65.47	53.80	52.78	64.62	40.94	48.11	64.15	32.07	54.56	64.80	44.32
0	58.18	63.73	52.62	51.57	62.85	40.30	47.07	62.35	31.80	53.29	63.04	43.54
1	56.70	61.98	51.42	50.35	61.07	39.64	46.03	60.54	31.51	52.00	61.26	42.74
2	55.20	60.20	50.20	49.12	59.27	38.97	44.97	58.72	31.22	50.69	59.47	41.92
3	53.69	58.41	48.97	47.86	57.45	38.28	43.89	56.88	30.91	49.37	57.66	41.09
4	52.15	56.60	47.71	46.59	55.62	37.57	42.80	55.03	30.58	48.04	55.84	40.24
5	50.60	54.76	46.43	45.31	53.76	36.85	41.70	53.16	30.24	46.68	53.99	39.37
6	49.02	52.90	45.13	44.00	51.89	36.10	40.58	51.27	29.88	45.30	52.12	38.47
7	47.41	51.02	43.80	42.67	50.00	35.34	39.44	49.37	29.51	43.90	50.23	37.56
8	45.77	49.10	42.44	41.31	48.08	34.55	38.28	47.44	29.11	42.47	48.32	36.62
9	44.10	47.16	41.05	39.93	46.14	33.73	37.09	45.50	28.69	41.02	46.38	35.65
10	42.40	45.18	39.62	38.53	44.16	32.89	35.89	43.52	28.25	39.53	44.40	34.65
11	40.66	43.16	38.16	37.08	42.16	32.01	34.65	41.52	27.77	38.01	42.40	33.62
12	38.87	41.09	36.64	35.60	40.11	31.09	33.38	39.49	27.27	36.45	40.35	32.55
13	37.02	38.97	35.08	34.08	38.03	30.13	32.07	37.42	26.73	34.84	38.26	31.43
14	35.12	36.79	33.45	32.51	35.89	29.12	30.72	35.31	26.14	33.18	36.11	30.26
15	33.14	34.53	31.75	30.87	33.69	28.05	29.32	33.14	25.50	31.46	33.90	29.02
16	31.07	32.18	29.96	29.15	31.41	26.90	27.85	30.91	24.79	29.65	31.60	27.70
17	28.87	29.71	28.04	27.34	29.03	25.65	26.29	28.58	24.00	27.74	29.20	26.27
18	26.49	27.05	25.94	25.37	26.50	24.24	24.61	26.13	23.08	25.66	26.64	24.69
19	23.81	24.09	23.53	23.15	23.72	22.59	22.70	23.47	21.94	23.32	23.81	22.83
20	20	20	20	20	20	20	20	20	20	20	20	20

IV Modelica text of optimized scenario from chapter 6

```

model Model_four_buildings_lowtemp
  "Model of four buildings connected to one DH substation"
  import Buildings;
  extends Modelica.Icons.Example;
  package Medium1 = Buildings.Media.ConstantPropertyLiquidWater;
  package Medium2 = Buildings.Media.ConstantPropertyLiquidWater;
  package MediumA = Buildings.Media.GasesPTDecoupled.MoistAirUnsaturated;
  Buildings.Fluid.Sources.Boundary_pT sin_1( redeclare package Medium = Medium1, use_p_in=true, T=273.15 + 25,
  nPorts=1, p=300000) annotation (Placement(transformation(extent={{-78,-100},{-66,-88}}, rotation=0)));
  inner Modelica.Fluid.System system( p_ambient=300000, T_ambient=313.15)
    annotation (Placement(transformation(extent={{12,-100},{24,-90}})));
    Modelica.Blocks.Sources.Constant PIn1(k=302325)
      annotation (Placement(transformation(extent={{-100,-94},{-90,-84}}, rotation=0)));
  Modelica.Thermal.HeatTransfer.Sources.PrescribedTemperature Tout annotation (
    Placement(transformation( extent={{-4,-4},{4,4}}, rotation=0, origin={-74,-30})));
  Modelica.Thermal.HeatTransfer.Sensors.TemperatureSensor ToutMSday
    annotation (Placement(transformation(extent={{-4,-4},{4,4}}, rotation=0, origin={-60,-30})));
  Buildings.Fluid.HeatExchangers.DryCoilCounterFlow heaCoi( redeclare package Medium1 = Medium1,
  redeclare package Medium2 = Medium2, nEle=160, show_T=true, r_nominal=1, waterSideTemperatureDependent=true,
  airSideTemperatureDependent=true, tau2=20, dp1_nominal=20000, dp2_nominal=20000, hA( n_w=0.6375, n_a=0.5948,
  T0_w=373.15, T0_a=343.15), m2_flow_nominal=0.7613, m1_flow_nominal=0.7329, UA_nominal=6634.42)
    annotation ( Placement(transformation( extent={{7,-7},{-7,7}}, rotation=90, origin={9,-39})));
  Modelica.Blocks.Sources.Constant T_prim_sup(k=95 + 273.15)
    annotation (Placement(transformation(extent={{-100,-58},{-90,-48}}, rotation=0)));
  Buildings.Fluid.Sources.Boundary_pT sou_1( redeclare package Medium = Medium1,
  T=273.15 + 25, use_p_in=false, use_T_in=true, nPorts=1, p(displayUnit="Pa") = 342325)
    annotation (Placement(transformation(extent={{-72,-58}, {-58,-44}}, rotation=0)));
  Buildings.Fluid.Actuators.Valves.TwoWayEqualPercentage val(redeclare package
  Medium = Medium1, dpValve_nominal=20000, m_flow_nominal=0.7329)
    annotation (Placement(transformation(extent={{-32,-98},{-40,-90}})));
  Buildings.Controls.Continuous.LimPID conPID( controllerType=Modelica.Blocks.Types.SimpleController.PI, Td=60, Ti=120,
  k=0.5) annotation (Placement( transformation( extent={{-5,-5},{5,5}}, rotation=-90, origin={-15,-71})));
  Buildings.Fluid.Sensors.TemperatureTwoPort senTem(redeclare package Medium = Medium2, m_flow_nominal=0.7613)
    annotation (transformation(extent={{-5,-5},{5,5}}, rotation=90, origin={13,-9})));
  Buildings.Controls.SetPoints.HotWaterTemperatureReset HC_set( dTOutHeaBal=0, m=1.3, TSup_nominal=358.15,
  TRet_nominal=338.15, TRoo_nominal=293.15, TOut_nominal=260.15, TRoo=293.15)
    annotation ( Placement(transformation( extent={{-5,-5},{5,5}}, rotation=0, origin={-39,-31})));
  Buildings.Fluid.HeatExchangers.Examples.Room_model room_model_B1( V_room=225, dens=1.2, n_h=1.65,
  T_start=293.15) annotation (Placement(transformation(extent={{-68,80},{-48,98}})));
  Buildings.Fluid.HeatExchangers.Examples.Wall_model wall_model_B1( Alfa_out=25, Alfa_in=7.7, AWall=140,
  wallLayers=Wall_1) annotation (Placement(transformation(extent={{-86,76},{-74,90}})));
  Buildings.Fluid.HeatExchangers.Examples.Window_model window_model_B1(Uwindows= 3, Awindows=13.5)
    annotation (Placement(transformation(extent={{-84,70},{-72,82}})));
  Buildings.Fluid.HeatExchangers.Radiators.RadiatorEN442_2 rad_B1( redeclare package Medium = Medium2,
  n=1.3, nEle=80, Q_flow_nominal=15972, T_a_nominal=363.15, T_b_nominal=343.15)
    annotation (Placement(transformation(extent={{-74,52},{-62,64}})));
  Buildings.Fluid.Storage.ExpansionVessel exp(redeclare package Medium = Medium2, VTot=0.08)
    annotation (Placement(transformation(extent={{82,12},{90,20}})));
  Buildings.Fluid.Movers.FlowMachine_m_flow pump(redeclare package Medium = Medium2, m_flow_nominal=0.7613)
    annotation (Placement(transformation( extent={{-6,6},{6,-6}}, rotation=180, origin={40,-56})));
  Modelica.Blocks.Sources.Constant m_flow_sec_nom(k=0.416462)
    annotation (Placement(transformation(extent={{90,-18},{80,-8}}, rotation=0)));
  Modelica.Blocks.Sources.TimeTable T_out(table={0,260.15; 200000,260.15})
    annotation (Placement(transformation(extent={{-102,-16},{-94,-8}})));
  Buildings.HeatTransfer.Data.OpaqueConstructions.Generic Wall_1(nLay=4, material={mortar,brick,brick,mortar})
    annotation (Placement(transformation(extent={{56,-80},{68,-68}})));
  Buildings.HeatTransfer.Data.Solids.Brick brick( k=0.81, c=900, d=1800, x=0.12)
    annotation (Placement(transformation(extent={{48,-98},{60,-86}})));
  Buildings.HeatTransfer.Data.Solids.InsulationBoard insulationBoard( c=1450, d=20, x=0.04, k=0.04)
    annotation (Placement(transformation(extent={{66,-98},{78,-86}})));
  Buildings.HeatTransfer.Data.Solids.Generic mortar( k=0.9, c=1000, d=1700, x=0.02)
  annotation (Placement(transformation(extent={{84,-98},{96,-86}})));
  Buildings.Fluid.HeatExchangers.Radiators.RadiatorEN442_2 rad_B2( redeclare package Medium = Medium2, n=1.3, nEle=80,
  Q_flow_nominal=15972, T_a_nominal=363.15, T_b_nominal=343.15)
    annotation (Placement(transformation(extent={{-24,52},{-12,64}})));

```

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Buildings.Fluid.HeatExchangers.Radiators.RadiatorEN442_2 rad_B3( redeclare package Medium = Medium2, n=1.3, nEle=80,
  Q_flow_nominal=15972, T_a_nominal=363.15, T_b_nominal=343.15)
  annotation (Placement(transformation(extent={{24,52},{36,64}})));
Buildings.Fluid.HeatExchangers.Radiators.RadiatorEN442_2 rad_B4( redeclare package Medium = Medium2, n=1.3,
  nEle=80, Q_flow_nominal=19166.5, T_a_nominal=363.15, T_b_nominal=343.15)
  annotation (Placement(transformation(extent={{74,52},{86,64}})));
Buildings.Fluid.FixedResistances.SplitterFixedResistanceDpM spl_B1( redeclare package Medium = Medium2,
  m_flow_nominal={0.416462,-0.226174,-0.190288}, dp_nominal={29913.2,-4388.6,-17975.6})
  annotation ( Placement(transformation( extent={{4,-4},{-4,4}}, rotation=180, origin={-82,40})));
Buildings.Fluid.HeatExchangers.Examples.Room_model room_model_B2( V_room=225, dens=1.2, n_h=0.6, T_start=293.15)
  annotation (Placement(transformation(extent={{-18,80},{2,98}})));
Buildings.Fluid.HeatExchangers.Examples.Wall_model wall_model_B2( Alfa_out=25, Alfa_in=7.7, AWall=140,
  wallLayers=Wall_1) annotation (Placement(transformation(extent={{-34,76},{-22,90}})));
Buildings.Fluid.HeatExchangers.Examples.Window_model window_model_B2( Awindows=13.5, Uwindows=1.4)
  annotation (Placement(transformation(extent={{-34,70},{-22,82}})));
Buildings.Fluid.HeatExchangers.Examples.Room_model room_model_B3( V_room=225, dens=1.2, n_h=1.65, T_start=293.15)
  annotation (Placement(transformation(extent={{30,80},{50,98}})));
Buildings.Fluid.HeatExchangers.Examples.Wall_model wall_model_B3( Alfa_out=25, Alfa_in=7.7, AWall=140,
  wallLayers=Wall_2) annotation (Placement(transformation(extent={{14,76},{26,90}})));
Buildings.Fluid.HeatExchangers.Examples.Window_model window_model_B3(Uwindows= 3, Awindows=13.5)
  annotation (Placement(transformation(extent={{14,70},{26,82}})));
Buildings.Fluid.HeatExchangers.Examples.Room_model room_model_B4( V_room=225, dens=1.2, n_h=1.6, T_start=293.15)
  annotation (Placement(transformation(extent={{80,80},{100,98}})));
Buildings.Fluid.HeatExchangers.Examples.Wall_model wall_model_B4( Alfa_out=25, Alfa_in=7.7, AWall=140,
  wallLayers=Wall_1)
  annotation (Placement(transformation(extent={{62,76},{74,90}})));
Buildings.Fluid.HeatExchangers.Examples.Window_model window_model_B4(Uwindows= 3, Awindows=13.5)
  annotation (Placement(transformation(extent={{64,70},{76,82}})));
Buildings.Fluid.FixedResistances.SplitterFixedResistanceDpM spl_B2( redeclare package Medium = Medium2,
  m_flow_nominal={0.226174,-0.152825,-0.073349}, dp_nominal={0,-2004.05,-9144.5})
  annotation ( Placement(transformation( extent={{4,-4},{-4,4}}, rotation=180, origin={-32,40})));
Buildings.Fluid.FixedResistances.SplitterFixedResistanceDpM spl_B3( redeclare package Medium = Medium2,
  m_flow_nominal={0.152825,-0.108426,-0.044398}, dp_nominal={0,-2555.9,-5111.7})
  annotation ( Placement(transformation( extent={{4,-4},{-4,4}}, rotation=180, origin={16,40})));
Buildings.Fluid.FixedResistances.SplitterFixedResistanceDpM mix_B1( redeclare package Medium = Medium2,
  m_flow_nominal={0.226174,-0.416462,0.190288}, dp_nominal={0,-30280.7,0})
  annotation ( Placement(transformation( extent={{-4,-4},{4,4}}, rotation=180, origin={-56,26})));
Buildings.Fluid.FixedResistances.SplitterFixedResistanceDpM mix_B2( redeclare package Medium = Medium2,
  m_flow_nominal={0.152825,-0.226174,0.073349}, dp_nominal={0,-4442.5,0})
  annotation (Placement(transformation( extent={{-4,-4},{4,4}}, rotation=180, origin={-6,26})));
Buildings.Fluid.FixedResistances.SplitterFixedResistanceDpM mix_B3( redeclare package Medium = Medium2,
  m_flow_nominal={0.108426,-0.152825,0.044398}, dp_nominal={2555.9,-2028.7,0})
  annotation ( Placement(transformation(extent={{-4,-4},{4,4}}, rotation=180, origin={44,26})));
Buildings.HeatTransfer.Data.OpacityConstructions.Generic Wall_2(nLay=5,
  material={mortar,insulationBoard,brick,brick,mortar}) annotation (Placement(transformation(extent={{78,-80},{90,-68}})));
equation
connect(conPID.y, val.y) annotation (Line(points={{-15,-76.5},{-15,-84},{-36,-84},{-36,-89.2}},
  color={0,0,127}, smooth=Smooth.None));
connect(PIn1.y, sin_1.p_in) annotation (Line( points={{-89.5,-89},{-84.75,-89},{-84.75,-89.2},{-79.2,-89.2}},
  color={0,0,127}, smooth=Smooth.None));
connect(T_prim_sup.y,sou_1.T_in) annotation (Line( points={{-89.5,-53},{-84.75,-53},{-84.75,-48.2},{-73.4,-48.2}},
  color={0,0,127}, smooth=Smooth.None));
connect(sin_1.ports[1], val.port_b) annotation (Line( points={{-66,-94},{-40,-94}},
  color={0,127,255}, smooth=Smooth.None));
connect(spl_B1.port_3, rad_B1.port_a) annotation (Line( points={{-82,44},{-82,58},{-74,58}},
  color={0,127,255}, smooth=Smooth.None));
connect(rad_B1.port_b, mix_B1.port_3) annotation (Line( points={{-62,58},{-56,58},{-56,30}},
  color={0,127,255}, smooth=Smooth.None));
connect(spl_B2.port_3, rad_B2.port_a) annotation (Line( points={{-32,44},{-32,58},{-24,58}},
  color={0,127,255}, smooth=Smooth.None));
connect(rad_B2.port_b, mix_B2.port_3) annotation (Line( points={{-12,58},{-6,58},{-6,30}},
  color={0,127,255}, smooth=Smooth.None));
connect(spl_B3.port_3, rad_B3.port_a) annotation (Line( points={{16,44},{16,58},{24,58}},
  color={0,127,255}, smooth=Smooth.None));
connect(rad_B3.port_b, mix_B3.port_3) annotation (Line( points={{36,58},{44,58},{44,30}},
  color={0,127,255}, smooth=Smooth.None));
connect(rad_B4.port_b, mix_B3.port_1) annotation (Line( points={{86,58},{90,58},{90,26},{48,26}},
  color={0,127,255}, smooth=Smooth.None));
connect(mix_B3.port_2, mix_B2.port_1) annotation (Line( points={{40,26},{-2,26}},
  color={0,127,255}, smooth=Smooth.None));
connect(mix_B2.port_2, mix_B1.port_1) annotation (Line( points={{-10,26},{-52,26}},

```



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    color={0,127,255}, smooth=Smooth.None));
connect(heaCoi.port_b2, senTem.port_a) annotation (Line( points={{13.2,-32},{13,-32},{13,-14}},
    color={0,127,255}, smooth=Smooth.None));
connect(mix_B1.port_2, pump.port_a) annotation (Line( points={{-60,26},{-82,26},{-82,14},{60,14},{60,-56},{46,-56}},
    color={0,127,255}, smooth=Smooth.None));
connect(pump.port_b, heaCoi.port_a2) annotation (Line( points={{34,-56},{13.2,-56},{13.2,-46}},
    color={0,127,255}, smooth=Smooth.None));
connect(exp.port_a, senTem.port_b) annotation (Line( points={{86,12},{86,4},{13,4},{13,-4}},
    color={0,127,255}, smooth=Smooth.None));
connect(val.port_a, heaCoi.port_b1) annotation (Line( points={{-32,-94},{4.8,-94},{4.8,-46}},
    color={0,127,255}, smooth=Smooth.None));
connect(sou_1.ports[1], heaCoi.port_a1) annotation (Line( points={{-58,-51},{-34,-51},{-34,-50},{-8,-50},{-8,-26},{4,-26},{4,-30},{4.8,-30},{4.8,-32}}, color={0,127,255}, smooth=Smooth.None));
connect(HC_set.TSup, conPID.u_s) annotation (Line( points={{-33.5,-28},{-15,-28},{-15,-65}},
    color={0,0,127}, smooth=Smooth.None));
connect(conPID.u_m, senTem.T) annotation (Line( points={{-21,-71},{-26,-71},{-26,-9},{7.5,-9}},
    color={0,0,127}, smooth=Smooth.None));
connect(ToutMSday.T, HC_set.TOut) annotation (Line( points={{-56,-30},{-50,-30},{-50,-28},{-45,-28}},
    color={0,0,127}, smooth=Smooth.None));
connect(Tout.port, ToutMSday.port) annotation (Line( points={{-70,-30},{-64,-30}},
    color={191,0,0}, smooth=Smooth.None));
connect(T_out.y, Tout.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,-30},{-78.8,-30}},
    color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, room_model_B1.Tout) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,94.1},{-66.4615,94.1}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, window_model_B1.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,76},{-85.2,76}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, wall_model_B1.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,83},{-87.2,83}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, room_model_B2.Tout) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{-44,100},{-44,94.1}, {-16.4615,94.1}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, wall_model_B2.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{-44,100},{-44,83}, {-35.2,83}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, window_model_B2.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{-44,100},{-44,76}, {-35.2,76}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, room_model_B3.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{6,100},{6,83},{12.8,83}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, room_model_B3.Tout) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{6,100},{6,94.1},{31.5385,94.1}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, window_model_B3.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{6,100},{6,76},{12.8,76}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, room_model_B4.Tout) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{54,100},{54,94.1}, {81.5385,94.1}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, wall_model_B4.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{54,100},{54,83}, {60.8,83}}, color={0,0,127}, smooth=Smooth.None));
connect(T_out.y, window_model_B4.T) annotation (Line( points={{-93.6,-12},{-84,-12},{-84,6},{-96,6},{-96,100},{54,100},{54,76}, {62.8,76}}, color={0,0,127}, smooth=Smooth.None));
connect(wall_model_B1.port_a, room_model_B1.heatPortW) annotation (Line( points={{-73.76,83},{-68.88,83},{-68.88,90.65},{-65.0769,90.65}}, color={191,0,0}, smooth=Smooth.None));
connect(window_model_B1.heatPort, room_model_B1.heatPortW) annotation (Line( points={{-71.76,76},{-68,76},{-68,90.65},{-65.0769,90.65}}, color={191,0,0}, smooth=Smooth.None));
connect(wall_model_B2.port_a, room_model_B2.heatPortW) annotation (Line( points={{-21.76,83},{-18.88,83},{-18.88,90.65},{-15.0769,90.65}}, color={191,0,0}, smooth=Smooth.None));
connect(window_model_B2.heatPort, room_model_B2.heatPortW) annotation (Line(
    points={{-21.76,76},{-18,76},{-18,90},{-15.0769,90},{-15.0769,90.65}},
    color={191,0,0}, smooth=Smooth.None));
connect(rad_B1.heatPortCon, room_model_B1.heatPortRad) annotation (Line(
    points={{-69.2,62.32},{-69.2,68},{-68,68},{-68,72},{-61.2308,72},{-61.2308,87.05}},
    color={191,0,0},
    smooth=Smooth.None));
connect(rad_B1.heatPortRad, room_model_B1.heatPortRad) annotation (Line(
    points={{-66.8,62.32},{-66.8,70},{-61.2308,70},{-61.2308,87.05}},
    color={191,0,0},
    smooth=Smooth.None));
connect(rad_B2.heatPortCon, room_model_B2.heatPortRad) annotation (Line(
    points={{-19.2,62.32},{-19.2,66},{-18,66},{-18,70},{-11.2308,70},{-11.2308,87.05}},
    color={191,0,0},
    smooth=Smooth.None));
connect(rad_B2.heatPortRad, room_model_B2.heatPortRad) annotation (Line(

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    points={{-16.8,62.32},{-16.8,66},{-16,66},{-16,68},{-11.2308,68},{-11.2308,
      87.05}},
    color={191,0,0},
    smooth=Smooth.None));
connect(rad_B3.heatPortCon, room_model_B3.heatPortRad) annotation (Line(
  points={{28.8,62.32},{28.8,68},{30,68},{30,72},{36.7692,72},{36.7692,87.05}},
  color={191,0,0},
  smooth=Smooth.None));
connect(rad_B3.heatPortRad, room_model_B3.heatPortRad) annotation (Line(
  points={{31.2,62.32},{31.2,66},{32,66},{32,68},{36.7692,68},{36.7692,87.05}},
  color={191,0,0},
  smooth=Smooth.None));
connect(rad_B4.heatPortCon, room_model_B4.heatPortRad) annotation (Line(
  points={{78.8,62.32},{78.8,68},{80,68},{80,72},{86.7692,72},{86.7692,87.05}},
  color={191,0,0},
  smooth=Smooth.None));
connect(rad_B4.heatPortRad, room_model_B4.heatPortRad) annotation (Line(
  points={{81.2,62.32},{81.2,68},{86.7692,68},{86.7692,87.05}},
  color={191,0,0},
  smooth=Smooth.None));
connect(wall_model_B3.port_a, room_model_B3.heatPortW) annotation (Line(
  points={{26.24,83},{29.12,83},{29.12,90.65},{32.9231,90.65}},
  color={191,0,0},
  smooth=Smooth.None));
connect(window_model_B3.heatPort, room_model_B3.heatPortW) annotation (Line(
  points={{26.24,76},{30,76},{30,90},{32.9231,90},{32.9231,90.65}},
  color={191,0,0},
  smooth=Smooth.None));
connect(wall_model_B4.port_a, room_model_B4.heatPortW) annotation (Line(
  points={{74.24,83},{79.12,83},{79.12,90.65},{82.9231,90.65}},
  color={191,0,0},
  smooth=Smooth.None));
connect(window_model_B4.heatPort, room_model_B4.heatPortW) annotation (Line(
  points={{76.24,76},{80,76},{80,90},{82.9231,90},{82.9231,90.65}},
  color={191,0,0},
  smooth=Smooth.None));
connect(pump.m_flow_in, m_flow_sec_nom.y) annotation (Line(
  points={{40.12,-48.8},{40.12,-13},{79.5,-13}},
  color={0,0,127},
  smooth=Smooth.None));
connect(senTem.port_b, spl_B1.port_1) annotation (Line(
  points={{13,-4},{12,-4},{12,2},{8,2},{8,10},{-90,10},{-90,40},{-86,40}},
  color={0,127,255},
  smooth=Smooth.None));
connect(spl_B1.port_2, spl_B2.port_1) annotation (Line(
  points={{-78,40},{-36,40}},
  color={0,127,255},
  smooth=Smooth.None));
connect(spl_B2.port_2, spl_B3.port_1) annotation (Line(
  points={{-28,40},{12,40}},
  color={0,127,255},
  smooth=Smooth.None));
connect(spl_B3.port_2, rad_B4.port_a) annotation (Line(
  points={{20,40},{62,40},{62,58},{74,58}},
  color={0,127,255},
  smooth=Smooth.None));
annotation(Diagram(coordinateSystem(preserveAspectRatio=false, extent={{-100,
  -100},{100,100}}),
  graphics={Line(
    points={{-32,81},{-32,80}},
    color={191,0,0},
    smooth=Smooth.None)}),
  __Dymola_Commands(file="modelica://Buildings/Resources/Scripts/Dymola/Fluid/HeatExchangers/Examples/Const
antEffectiveness.mos"
  "Simulate and plot"),
  experiment(StopTime=604800),
  __Dymola_experimentSetupOutput);
end Model_four_buildings_lowtemp;

```

V Draft proposal for scientific paper: *Model of plate heat exchanger water-to-water in Modelica/Dymola*

Abstract

Simulation models are becoming important engineering tool that helps in design and adjustment of physical systems. This paper shows application of *Modelica* programming language through *Dymola* simulation environment on creating a model of a plate heat exchanger water-to-water. This type of heat transfer equipment is widely spread today especially in heating systems and process industry. Verification of the model was done by measurements performed at Laboratory of Department of energy and Process Engineering, Norwegian University of Science and Technology. Application of HEX model is done by implementing it in a model of heat substation, with extensive use of components from *Buildings* library developed at *Lawrence Berkley National Laboratory*. The heat exchanger model showed very good respond regarding the actual values from laboratory measurement and it can now be used in different simulation models in *Modelica*.

Key words: plate heat exchanger, model, *Modelica*, *Dymola*, *Buildings* library, heating substation, district heating

Introduction

Simulation tools have already gained great attention in design of HVAC systems and management of energy consumption. The numerical simulations are used worldwide for prediction of different physical processes. However, it is still very challenging to create model that would properly illustrate behavior of real system. Additionally, building the model from a scratch can certainly be aggravating factor. A flexible environment which allows altering the building system configurations is provided by *Modelica* language [1].

Modelica's standard library [2] and the *Buildings* library [3] contain simulation models for a few types of heat exchangers common in HVAC systems. However, there is no model that would simulate behavior of a plate heat exchanger with water as both heat carrier and heat receiver. Due to its highly efficient heat transfer and compact design, this kind of HEX has become very common in hydronic heating systems. Preparation of domestic hot water is often performed through the plate heat exchanger since it can provide instantaneous heating. Therefore, modeling of this type of heat exchanger is a milestone for further modeling of HVAC systems such as district heating.

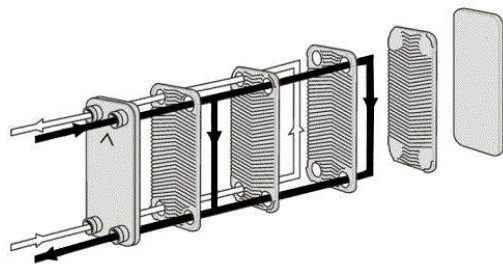


Figure 1 Sketch of the HEX unit with four plates showing flow distribution

Figure 1 shows assemblage of a typical plate heat exchanger. It consists from a series of plates integrated with gaskets that determine the flow arrangement of the primary and secondary side medium. The plates are pressed together in a frame so the HEX is compact, light and easy to set apart for cleaning. Hot and cold fluids flow alternately between parallel corrugated plates, exchanging heat with high efficiency.

Modeling of plate heat exchanger

Explanation on modeling of plate heat exchanger is given in two forms: through illustrations of *Modelica/Dymola* graphical editor and by mathematical equations from *Modelica* text. Figure 2 shows *Modelica* diagram of a base class model used in building PHEX model. It is called *PartialHexElement* and can be considered as one element of discretized PHEX model. Every element has the same mathematical model as the final model. The model components shown on Figure 2 are *Modelica* classes commonly used in thermo-fluid systems. Every component solves a part of the *PartialHexElement* mathematical model. Interaction between components is defined by the connectors.

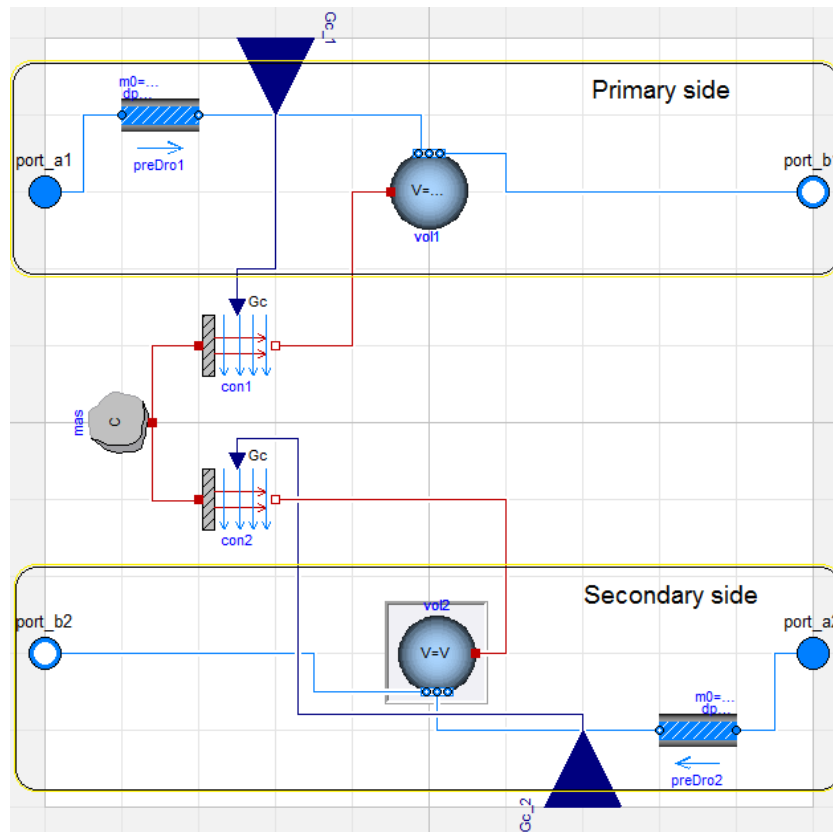


Figure 2 *Modelica* diagram of Partial HEX Element

Yellow line on Figure 2 bounds components that build channel for primary and secondary flow. The blue circles marked as `port_a` are the flow inlet and the blue-white circles marked as `port_b` are the flow outlet. The counter flow is evident, since the fluid flow is directed from `port_a` to `port_b`. Two blue spheres marked as `vol1` and `vol2` represent volumes of primary and secondary flow. Components marked as `preDrop` are simulating pressure drop of flow through the channel. The grey object named `mass` represents the metal plate(s) that separates two flows. The blue connecting lines are signaling mass flow and the red ones represents possible heat transfer. As can be seen on Figure 2, two fluids are not exchanging any mass (no blue line between `vol1` and `vol2`). The heat flow is certainly allowed for `vol1` and `vol2` but over the metal plate `mass` which is the case in real HEX. Objects marked as `con1` and `con2` simulate heat transfer mechanism of convection between fluid flow and the metal plate. Dark blue arrow marked as `Gc` is providing the `con1` and `con2` with value of convective heat transfer coefficient. Calculation of this coefficient will be explained in further text.

Calculation of the hA value

The convective heat transfer coefficient h is determined by parameters of medium and it always depends on current temperature and velocity of fluid flow. The *Buildings* library contains model for sensible convective heat transfer coefficient for an air-to-water coil which was the starting point for hA model of the PHEX water-to-water.

Basic idea is to calculate hA value for current conditions using nominal condition values. The parameters needed for calculation are mostly determined as characteristics of PHEX type:

- Thermal conductance at nominal flow $UA_{nominal}$
- Nominal water mass flow rate for primary and secondary side $m_{flow_nominal_1}$ and $m_{flow_nominal_2}$
- Ratio between primary and secondary side convective heat transfer coefficient $r_{nominal}$:

$$r = (hA)_1 / (hA)_2 \approx 1$$
- Nominal water temperatures both for primary and secondary side $T0_1$ and $T0_2$
- Exponent for convective heat transfer coefficient both for primary and secondary side n_1 and n_2 (in relation $h \sim m_{flow}^n$)

Additionally, the model of HEX needs to provide hA model with current values of mass flow rate and temperature for primary and secondary fluid flow. Figure 3 shows complete model of PHEX. In the center of diagram there is a partial model described in previous text, which needs the hA value as input signal for the heat transfer calculation. Both primary and secondary flows have temperature and mass flow rate sensors just after the inlet port. These components send information about current fluid parameters to hA model.

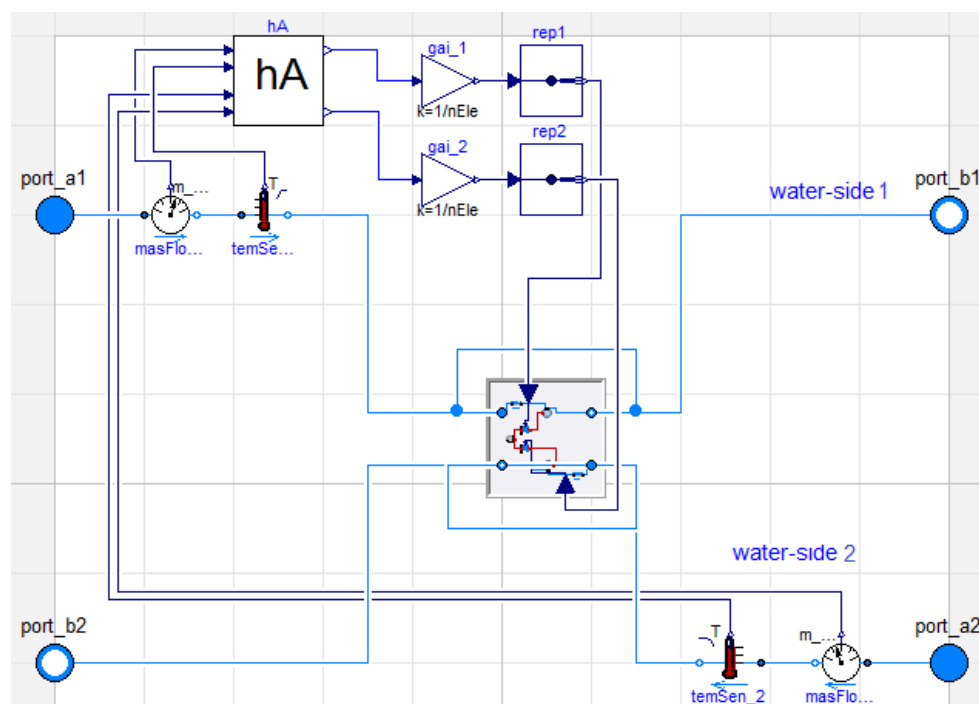


Figure 3 Modelica diagram of complete PHEX model

The calculation algorithm for hA model has two steps [4]:

- 1 – nominal convective heat transfer coefficient for primary and secondary side $hA_{nominal_1}$ and $hA_{nominal_2}$ is calculated based on $UA_{nominal}$ and $r_{nominal}$

$$\left. \begin{aligned} r &= \frac{(hA)_1}{(hA)_2} \approx 1 \\ UA &= \frac{1}{\left(\frac{1}{hA}\right)_1 + \left(\frac{1}{hA}\right)_2} \end{aligned} \right\} \Rightarrow (hA)_{1nom} = (hA)_{2nom} = 2UA_{nom}$$

2 – current convective heat transfer coefficient for primary and secondary side hA_1 and hA_2 is determined as:

$$\frac{hA}{hA_{nom}} = [1 + s(t_o)(t - t_o)] \cdot \left(\frac{\dot{m}}{\dot{m}_o}\right)^n$$

There is a possibility to choose to have only mass flow or temperature dependence.

Validation of the model

Measurement with changing primary side mass flow rate was performed for five operating points. The mass flow rate of primary fluid was adjusted by the valve integrated in the return line. Valve position was changed manually from fully opened (100%) to the position of 30% opened. Primary and secondary side inlet temperature was maintained at 75°C and 50°C respectively. Mass flow rate on the secondary side was defined by pump JP4 which operating mode was not changed between measurements. Measured parameters of interest were outlet temperatures of water on both sides of HEX. Parameters' values were measured and recorded at the same time. Based on the measured values, heat load and overall heat transfer coefficient were determined.

In order to provide results similar to measurements, the PHEX model was adjusted according to measurement setup. The first measurement (for fully opened valve on primary side) was adapted as nominal operating point.

- The medium was defined as water. For the PHEX model it was selected as *Buildings* class *ConstantPropertyLiquidWater*.
- The four parameters of the hA -model were defined as follows. Nominal inlet water temperatures match values from first measurement. Exponent for convective heat transfer coefficient n was calculated using Excel tools. The idea was to find the n so that UA value from measurement is as close as possible to UA value calculated the same way it would have been in PHEX model. All five measured operating points were used here since it was important to adjust model calculation according to the actual (measured) UA curve trend. The UA value from *Modelica* algorithm was determined as

$$UA = \frac{1}{\left(\frac{1}{hA}\right)_1 + \left(\frac{1}{hA}\right)_2}$$

where hA was calculated as

$$\frac{(hA)}{(hA)_{nom}} = \left(\frac{\dot{m}}{\dot{m}_{nom}} \right)^n$$

Now the solver for n value was set so that the sum of squares of difference between measured and calculated UA value is as small as possible. Since only the primary side mass flow rate was changing, the n value was calculated for primary side. It is assumed that the secondary side has the same conditions since the mass flow rate value is very close to the one in primary side.

- Nominal conditions were defined after first measurement, as mentioned before. Thermal conductance at nominal flow is calculated from measurements as

$$(UA)_{nom} = \frac{Q_{nom}}{LMTD_{nom}}$$

where Q is heat flow rate and $LMTD$ is logarithmic mean temperature difference, both in nominal conditions.

- Number of pipe segments used for discretization was determined by gradually increasing it until there was no more change in simulation results.

Table 1 Parameters for defining PHEX model

Parameter		Label	Unit	Value	
				Primary side	Secondary side
hA	Nominal inlet water temperature	T_0	K	348,11	323,13
	Exponent for convective heat transfer coefficient	n	-	0,46	0,46
Nominal conditions	Mass flow rate	m_{flow_nom}	kg/s	0,134135	0,134286
	Pressure drop	dp_{nom}	Pa	10000	10000
	Thermal conductance at nominal flow	UA_{nom}	W/K	1243,736	
	Ratio between primary and secondary side convective heat transfer coefficient	r_{nom}	-	1	
Number of pipe segments used for discretization		$nEle$	-	160	

Table 1 shows the parameters that were inscribed in the model in order to define its behavior. These parameters present performances of specific HEX type – the one that is integrated in the laboratory rig at NTNU in operation conditions.

When the parameters of the HEX were defined, it was necessary to provide the HEX model with the input values. As mentioned before, input values are mass flow rate and inlet water

temperature both for primary and secondary side. These values are defined for every operating point after the measured values of the same parameter.

Heat transfer parameters were compared and analyzed for every operating point with purpose of validation of the PHEX model. Main parameters were:

- Outlet temperatures both for primary and secondary side (t_{prim_out} and t_{sec_out})
- Heat transferred between primary and secondary side medium (Q_{flow})
- Thermal conductance value (UA)

Diagrams on figure 4 show agreement between measurement and simulation results regarding the primary side mass flow rate, as the input parameter that was changed between measurements/simulations. Table 2 gives the overview of considered values with calculated difference between results of simulation and measurement results.

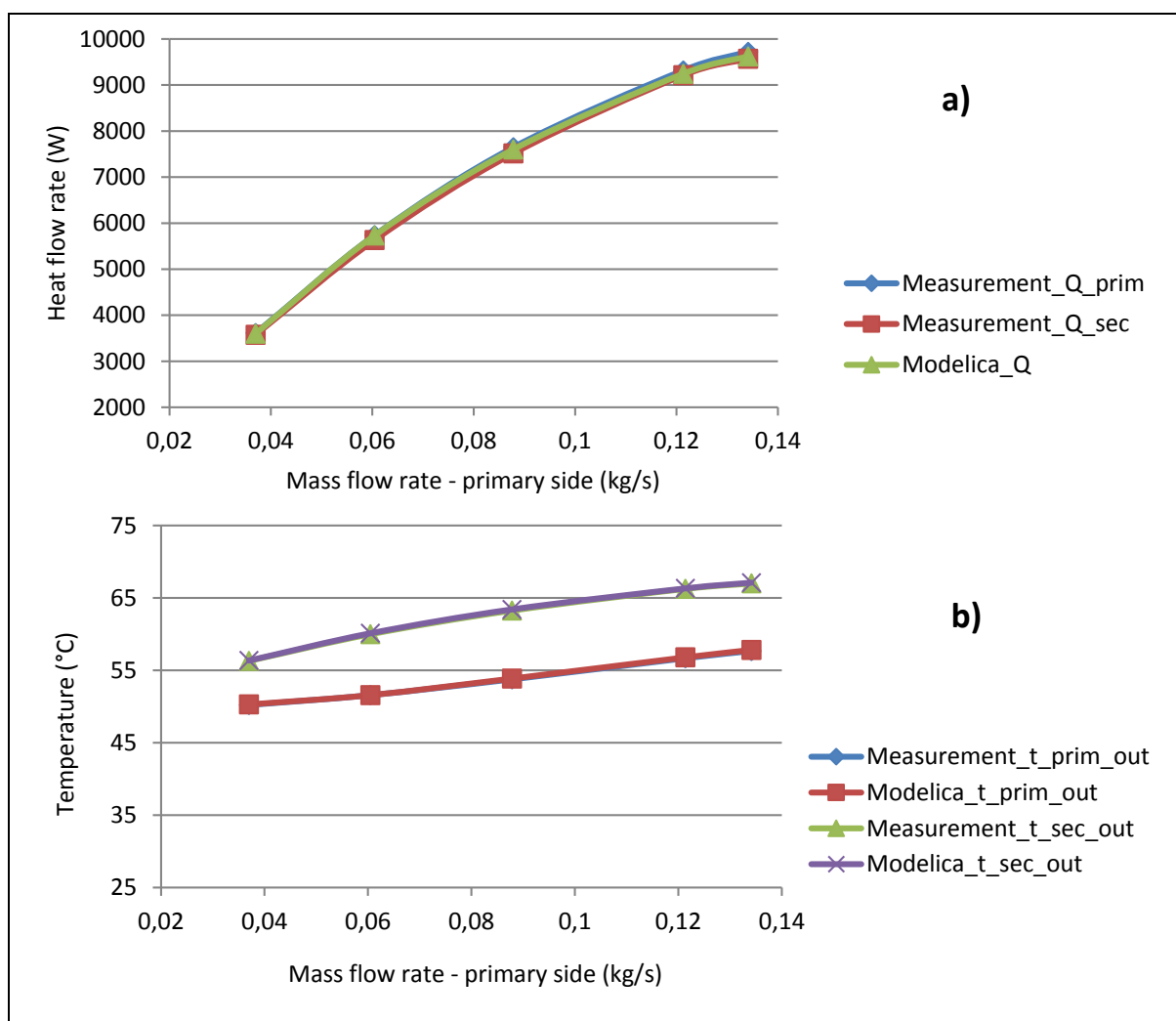


Figure 4 Diagrams showing comparison of simulation and measurement values of: a) heat flow rate; b) outlet temperatures

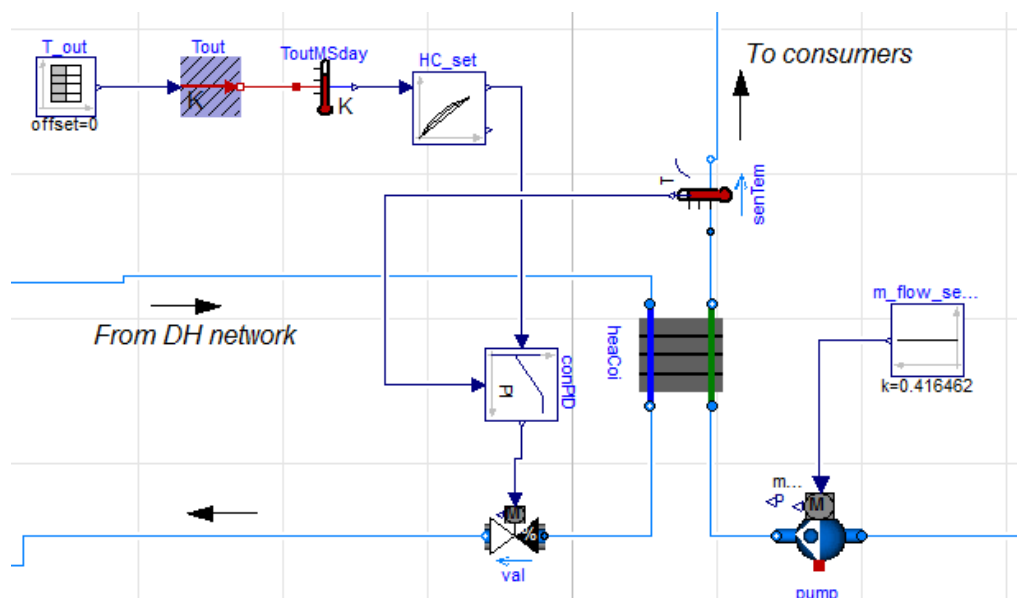
Table 2 Output values and error between measurement and simulation

t_{prim_out}			t_{sec_out}			Q_{flow}			UA		
Meas.	Mod.	Error	Meas.	Mod	Error	Meas.	Mod.	Error	Meas.	Mod.	Error
°C		%	°C		%	W		%	W/K		%
57,66	57,81	0,27	67,01	67,11	0,14	9646,3	9622,5	0,25	1243,7	1243,7	0,00
56,66	56,78	0,21	66,26	66,31	0,09	9265,8	9244,3	0,23	1215,2	1217,2	0,17
53,75	53,86	0,20	63,26	63,41	0,25	7582,5	7601,9	0,25	1115,1	1122,9	0,70
51,57	51,57	0,02	59,98	60,11	0,22	5687,1	5732,4	0,80	1003,1	1016,6	1,35
50,21	50,28	0,14	56,30	56,35	0,10	3595,4	3601,1	0,16	900,7	881,0	2,18

Performed measurement provided significant amount of information that helped analyzing the PHEX behavior, tuning the model and ultimately in validation of developed model. The *Modelica* calculation of plate heat exchanger showed very good respond and it has been proven as s reliable simulation model to be used in other scenarios and modeling problems.

Example of application

Plate heat exchanger is a common component of consumer substation in district heating systems. Main objection to the indirect substation is the heat loss that occurs due to inevitable temperature difference between primary and secondary flow in heat exchanger. However, the use of modern plate heat exchangers has mitigated this disadvantage. Figure 4 illustrates set of *Modelica* components that simulate behavior of an indirect heating substation.

**Figure 5** Modelica diagram of DH substation model

Central component of the substation is heat exchanger labeled as *heaCoi*. Next to the HEX, there is a circulator pump (*pump*), temperature sensor (*senTem*), two-way equal percentage valve (*val*) and set of components for control of the valve. The heat load of the HEX is

controlled by changing primary side mass flow rate in regards to outdoor temperature and heating curve.

The control system in this model is initiated by outdoor temperature simulated by component marked as `T_out`. This is a block source from *Modelica Standard* library called *TimeTable*. It generates an output signal by linear interpolation in a table. Output signal of block `T_out` defines next connected component labeled as `Tout`. This model is called *PrescribedTemperature* and it represents a variable temperature boundary condition. This heat source component is connected by heat port with the ideal absolute temperature sensors `ToutMSday` which returns the temperature of the connected port in Kelvin as an output signal. The sensor itself has no thermal interaction with whatever it is connected to. Next control system component in line is a block that computes the supply and return set point of heating systems, i.e. the heating curve. It is marked as `HC_set` in Figure 5. The parameters that needs to be defined are exponent for heat transfer and nominal temperatures (supply, return, room and outdoor). The set point for the room air temperature can either be specified by a parameter, or it can be an input to the model. The `HC_set` component defines set point supply water temperature for secondary circuit. This signal is sent to control components `conPID`, which compares it to the actual water temperature from secondary circuit sensor `senTem`. The component `conPID` can be defined as P, PI, PD or PID controller with limited output signal (interval 0-1). According to degree of agreement between set point and actual secondary side supply water temperature, controller `conPID` sends signal to the valve-actuator `val` to adjust proper primary side mass flow rate. This type of control is called weather compensation and it can often be found in consumer substations in Europe.

For further discussion, the production and consumption side can be defined. This would complete the system of DH network and provide possibilities to simulate different scenarios of district heating operation [5]. *Modelica* model provides insight into interaction between the segments of DH system which can be significant for efficient operation of the system in total, especially when the conditions are not close to steady state design operation point.

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