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Analysis of the Dynamical Behavior of a Condensing Gas Boiler using the Modelica/Dymola Simulation Environment

Amar Aganovic

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

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ABSTRACT:

The thermal dynamics of condensing gas boiler will be investigated using a state-of-art software package and some available libraires for modeling and simulation of the HVAC systems. A special atetion will be given to modeling of heating equipment such as: boiler, pumps, flows in pipes, valves and fittings as weel as standard control elements of the heating system. The object-oriented symbolic Modelica language for industrial applications will be used within Dymola software environment with extensive use of the Buildings library for HVAC components modeling, developed by Simulation and Research Group at Lawrence Berkley National Laboratory. This work mainly focuses on the heat generation so that the consumption side is not the primary subject of the current work. The buildings will be modeled as a simplified object/volume which is heated uniformly. Available data will be based on readings from hourly meaurements of supply and return temperatures of the boiler room, outside temperatures, boiler gas consumption and representative room temperature readings.

This assignment is realized 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 2011-2013.

Key words: Condensing gas boiler, Control system, Efficiency, Return water temperature, Modelica, Buildings Library Dymola

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Acronyms

HVAC	*Heating, Ventilation and Air Conditioning*
USAID	*United States Agency for International Development*
UNDP	*United Nations Development Programme*
LBNL	*Lawrence Berkley National Laboratory*
EEI	*Energy Efficiency Improvements*
MEF	*Mechanical Engineering Faculty Sarajevo*
CH_4	*Methane*
O_2	*Oxygen*
CO_2	*Carbon Dioxide*
H_2O	*Water*
PID	*Proportional-Integrative-Derivative Controller*
LHV	*Lower Heating Value*
HHV	*Higher Heating Value*
R	*Regulating Thermostat*
S	*Safety Thermostat*
Q	*Burner Output*
L	*Limit Output*
RM	*Regulating Module*

1. Project background

The UNDP BiH, USAID Enterprise Energy Efficiency (3E) Project, and Mechanical Engineering Faculty in Sarajevo (MEF) have implemented energy efficency measuers in the faculty building including installation of new building insulation, window replacement and installation of the new boiler. The new condensation gas boiler with a modern automatic heating control system has been installed, with much better energy efficiency characteristics and more efficient energy use than the old conventional gas boiler. The aim of this master thesis is to analyse the thermal dynamics of the condensing gas boiler in and its automatic control installed in MEF using model components developed from the so-called „Buildings" library in the Modelica / Dymola simulation environment. The „Buildings" library contains the model of a boiler whose efficiency can be described by a polynomial expressed in terms of the return water temperature and part load. Constituting the essential part of the boiler room, the condensing boiler model represents the starting point for the implementation of a multi-physical boiler room model. Before the implementation is done, a thorough research into the characteristics of the gas condensing boiler is done together with an analysis of the applied control system. This will provide the necessary background to compare the simulated boiler room model in the Modelica/Dymola environment with the boiler technology used in the Sarajevo University. Even though simulation is the aim of this study, it is only the final task to carry out. The next phase of the thesis is relied on an extensive literature review of the environment Modelica/Dymola in order to learn the basics of the programming language. Furthermore, the work will give special attentions to coupling thermo-fluid systems in Modelica language in order to apply models from the so-called "building library" developed by the Lawrence Berkley National Laboratory. This library should allow researchers and engineers to develop accurate and dynamical thermal simulations of 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. The Buildings library is based on Modelica, an equation-based object-oriented language that is well positioned to become the standard for modeling of dynamic systems in various industrial sectors. Modelica-based tools, such as Dymola, allow the generation of accurate models of complex systems in an efficient way.The purpose is to get a comprehensive and efficient use of the language, in order to take advantage of its qualities and to be aware of all its constraints.

The next step will be to to apply and connect the boiler model with the control system based on the Modelica coupling rules and adapt it for simulation, and then perform the simulation using real data from a condensing gas boiler at the Mechanical Engineering Faculty in Sarajevo. Available data is based on readings from hourly measurements of supply and return water temperature from the boiler room, outside temperatures, boiler gas consumption and representative room temperature readings. Special attention is given to highly transient situations , like after weekend days. The boiler room model should not be too complex, as it should be possible to use it for real time simulations, but still accurate enough to capture the dynamics and behavior of the boiler at different operating conditions

In addition the boiler model and its control system will be applied to an existing heating system model consisting of the following components from the buildings library: circulation pump, supply, return pipeline and a radiator as the heat source at the consumption side and the model of room with the multilayer construction of walls and windows. Although the consumption side in not the primary subject of the current work, yet it is considered in order to fully justify the application of a gas – condensing boiler in well insulated spaces.

Thus, the main objective is to conduct comparative analysis of the boiler model with real exprimental data in order to validate the model and reveal the needs for improvement. The scope and the limits of the model will be discussed and compared to the condensing gas boiler technology used in Sarajevo. The current work focuses also on simulation and validation of HVAC components simulation models form the Buildings library and demonstrates capabilities of equation based modeling environment for the recently installed boiler room. By using simulation models of the boiler and control componetns the operator can test different operating conditions and gain a deeper understanding of the boiler and find some criteria to evaluate the boiler model dynamic behaviour. As well this represents an important task to estimate the potential of Modelica simulation approach

2. Boiler room

The subject of this thesis, the condensing gas boiler is located in the boiler room of the Mechanical Engineering Faculty Sarajevo as an integral part of the Faculty'***s*** heating system. The main components of the boiler room at MEF Sarajevo such as: boiler, burner, expansion vessel, system for chemical treatment of boiler-feed water, pumps, valves and other heating equipment are shown in the technological scheme in Figure 2.1.

In boiler room, three gas-fired boilers are placed and supplied with natural gas from municipal gas distribution network. This is shown in the Technological Scheme of the Boiler room in Figure 1. Two classic conventional gas-fired water boilers (Q_{H1}= Q_{H2} =1510 kW) together with a new condensing gas boiler (Q_{H2} =404 kW) supply heat for the load of hot water heating system. The old conventional boilers operate at nominal temperature regime 90/70 ^{o}C for external design conditions, while the condensing boiler operates at 60/45^{o}C regime.

The following factors are considered when selecting condensing boiler in the design of the overall heating system:

1**.** Condensing boilers require a low return water temperature to operate at their highest efficiency.

2**.** Systems should be designed with lower flow rates. This means that piping, pumps and valves should be smaller than those used in mid-efficiency boilers.

3. Heating coils and radiators should be sized for a higher rate of heat transfer at lower supply water temperatures

The new condensing boiler is equipped with a forced-draught natural gas burner. Basically, all of the mentioned heating equipement is installed to provide a functional, safe and economical operation of the boiler room. The expansion vessel and the system for chemical treatment of boiler-feed water ensure functional and safe operation, but they are not important for the scope of this worn the present work special attention will be given to heating equipment that ensures , not only a functional and safe operation of the boiler room, but also an overall economical feasible operation of the MEF heating system. The boiler, burner and the boiler system control have important impact on boiler performance, and can affect long-term boiler operating costs. The proper selection of the boiler and burner with the applied system of modulated regulation - PI control, is the starting point for further analysis which will be carried out in this paper, in accordance with the requirements of the the master's thesis objectives. It should noted that the burner and boiler are installed in accordance with aligned European standards (EN 483, EN 677), which is a starting point for their mutually balanced and compatible operation, primarily in order to achieve the expected efficiency of the selected condensing boiler.

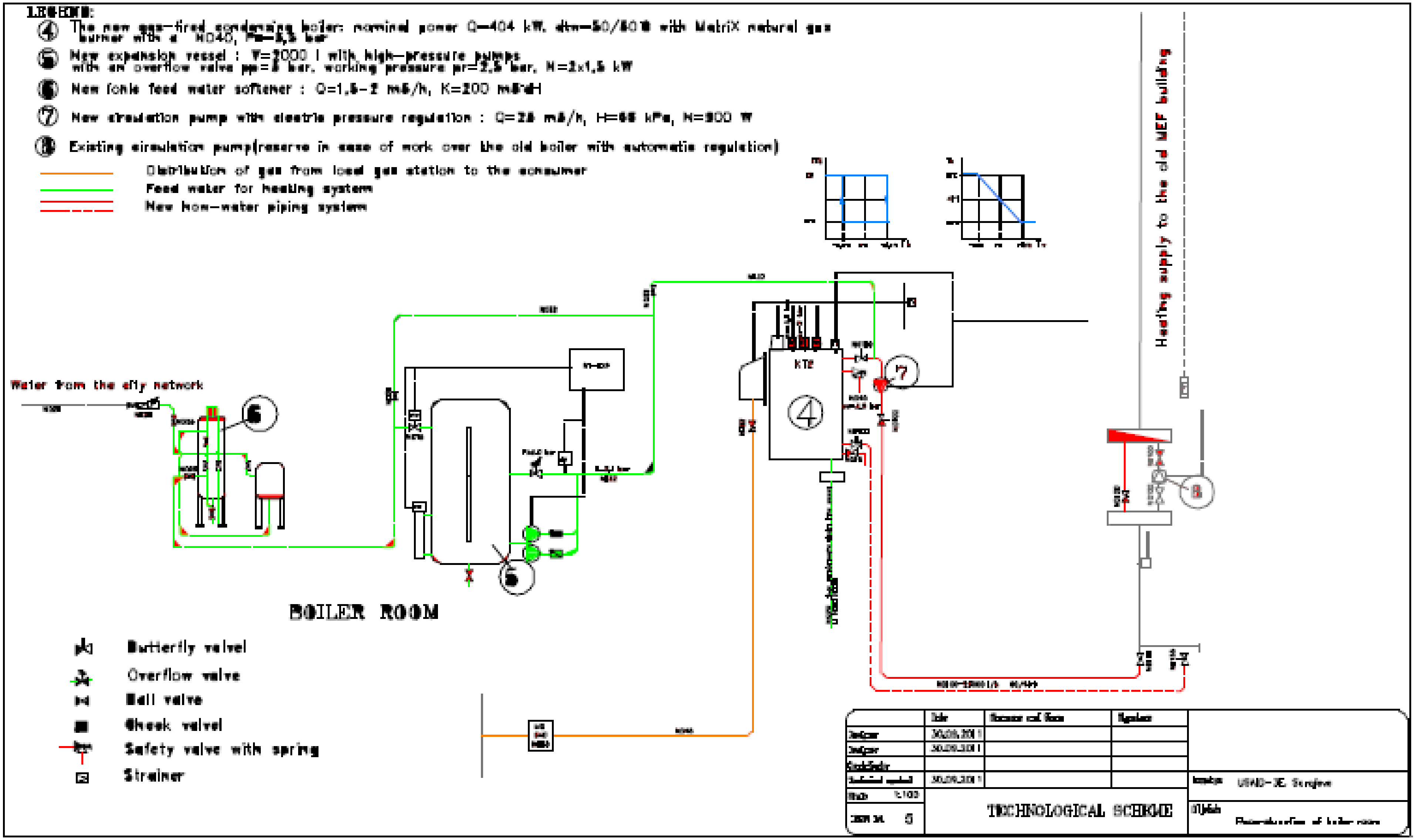
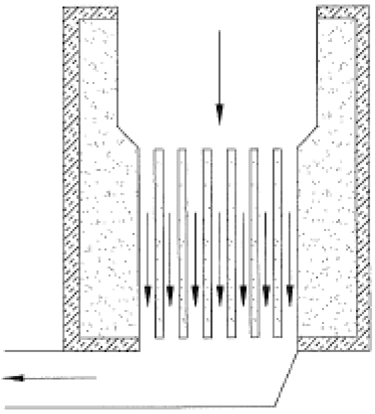


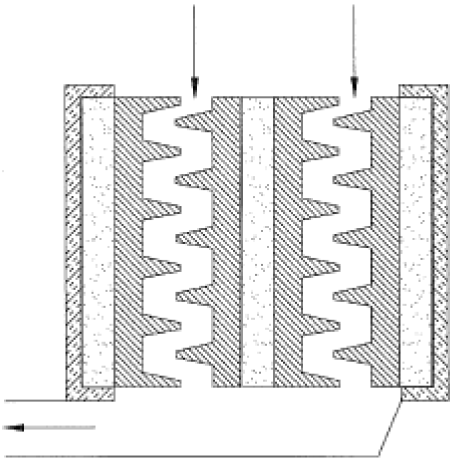
Figure 2.1: Technological scheme of boiler room at MEF Sarajevo

3. General description of boilers

Boilers are classified into different types based on their capacity, fuel type, materials, working pressure and temperature and whether they are condensing or non-condensing [1]. Hot Water boilers**-** are generally available in standard sizes from 10 kW to over 30 MW. In commercial buildings, natural gas is the most common boiler fuel, because it is usually readily available, burns cleanly, and is typically less expensive than oil or electricity.

There are three major types of boilers used for natural gas combustion for space heating applications in commercial buildings: water tube, fire tube, and cast iron-sectional. Residential boilers generally resemble fire tube boilers with flue gas (hot combustion gases) traveling through several channels or tubes which heat the water circulating outside the tubes. Alternatively, in a water tube boiler, water flows in the inside of the tubes and the hot gases from combustion flow around the outside of the tubes. Cast iron-sectional boilers don't use tubes, instead they have sections that have water and combustion gas passages. Boilers are classified as either low pressure or high pressure when considering conditions for safety operation. Most boilers used in HVAC applications are low-pressure boilers. Low-pressure boilers are constructed for maximum working pressures up to 1100 kPa and are limited up to 95°C maximum building supply water temperature. Operating and safety controls and relief valves, which limit temperature and pressure, are devices required to protect the boiler and prevent operation beyond design limits. Most non-condensing boilers are made with cast iron sections or steel. Some small boilers are made of copper or copper-clad steel. Condensing boilers are typically made of stainless steel or aluminum because copper, cast iron, and carbon steel will corrode because of acidic condensate .The two types of commercial condensing boilers are shown in Figure 3.1.





(a) Single-pass fire tube (b) Cast-aluminum modular

Figure 3.1: Residential Boilers [1]

Based on the previous general observation of boilers, the boiler type in the MEF room Sarajevo is a single-pass fire-tube steel gas-condensing boiler.

3.1. Condensing vs. non-condensing mode

In a conventional gas-fired boiler, natural gas is burned and the hot gases produced are passed through a heat exchanger where the heat is transferred to water, thus raising the water's temperature.When natural gas is burned , which is a hydrocarbon mixture comprised primarly of methane (CH4), water is formed as one of the by-products . Because of the high temperature inside combustion chamber (the flame temperature of complete combustion of methane is 1960 ℃[2]), the water forms as superheated vapor. The complete combustion of methane is as follows:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g) + \text{energy}$$

(Applying Avogadros law[1]: 1 mole of methane, consisting of one carbon atom and four hydrogen atoms, combines with 2 moles of oxygen, consisting of two oxygen atoms, to produce one mole of carbondioxide plus 2 moles of water vapor). The masses of the compounds involved in the combustion can be obtained from the relative masses of the atoms of the elements:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g) + \text{energy}$$

$$16 + 64 \rightarrow 44 + 36 + \text{energy}$$

When all of the products of a complete combustion of fuel remain in gaseous state the energy released is called the lower heating value of a specified amount of fuel as opposed to the higher heating value that accounts for the energy released when all the products of combustion are brought back to the original pre-combustion temperature, and in particular condensing any vapor produced.

The lower heating value of 1 mole of methane is 802 kJ/mol [3]. By condensing all of the water vapor formed in the combustion process a relevant amount of energy is released in the form of latent heat of vaporization. For water this value is 2260 kJ/kg [4]. So, complete

[1]Avogadro's law states that under the same condition of temperature and pressure equal volumes of all gases contain the same number of molecules.

combustion of 1 mole of methane releases and additional 81.36kJ of energy ; thus if every molecule of water vapour is condensed in the complete combustion process of a specified amount of methane , an additional 9.5% of the lower heating value would be recovered.

The lower and higher heating value differ by a factor of 1.11, or 11%[5]. This is greater than the 9.5% figure obtained above because additional heat could be extracted by cooling all flue gases to the original starting temperature, usually taken as 25 ℃, and this is how the higher heating value is worked out.

3.2. Materials

In conventional cast-iron and steel boilers the flue gases are maintained at high temperatures in gaseous state to avoid condensation inside the boiler (around 140℃) [6]. As the exhaust gases contain carbon dioxide and water vapor, when condensation forms in a conventional boiler, these two elements combine to form carbonic acid. Dissolved carbon dioxide and some sulfur-oxides in the condensed water make it mildly acidic with a pH value between 3 and 4 [7]. The result is corrosion of the final tubes and flue collectors, which are made of cast-iron and not designed for it.

In contrast to conventional cast-iron and steel boilers, condensing boilers are designed to avoid corrosion of the wet heat transfer surfaces by use of suitable materials such as high-grade stainless steel, aluminum or other special alloy that bear carbonic acid corrosion. The discharge piping in condensing boiler is usually made of plastic material to resist potential corrosion (acid attack).

The condensing boiler used at MEF boiler room in Sarajevo contains a stainless steel heating surface for utilizing condensing technology. The smooth surface allows condensate created by this process to simply run off, resulting in a longer service life whilst reducing maintenance costs.

3.3. The effect of return water temperature on efficiency of condensing boiler

In order to utilize the latent heat of vaporization of the flue gases through the heat exchanger of a condensing boiler, the temperature gases must be cooled to a certain temperature at which condensation occurs. Condensation starts to separate from the smoke at a temperature called smoke dew temperature, which has the highest value for complete combustion and is slightly below 60 ◦C for methane(around 57°C for CH4 and for an overall air excess of 10% [8].). The actual water dew-point depends on many factors, including the amount of excess combustion air and the amount of moisture in the combustion air. Actually, the exact return temperature causing condensing varies with the design of the boiler itself.

To obtain high efficiency, water vapor in the exhaust gas must be condensed and the latent heat that is released must be used as the first step in reheating the return water. The colder the return water temperature, the greater the amount of water vapor that can be condensed and the higher the boiler efficiency. Cooling the flue gasses to this extent requires that the system provides return water to the boiler at a temperature somewhat below the dew temperature.

However, in most cases as the flue gas approaches 60 ◦C degrees or so condensing starts to occur. Above this temperature, the moisture entrained in flue products as water vapor will remain vaporized. Below this temperature, the water vapor will change phase and condense out of the flue products as liquid Condensing boilers will operate at high temperatures but with reduced recovery of heat from the exhaust gas water vapor. When this happens they are said to be operating in non-condensing mode and efficiency suffers though remain higher than for conventional boiler. Figure 3.2 shows the efficiency curve (HHV) against the return temperature of a typical condensing boiler:

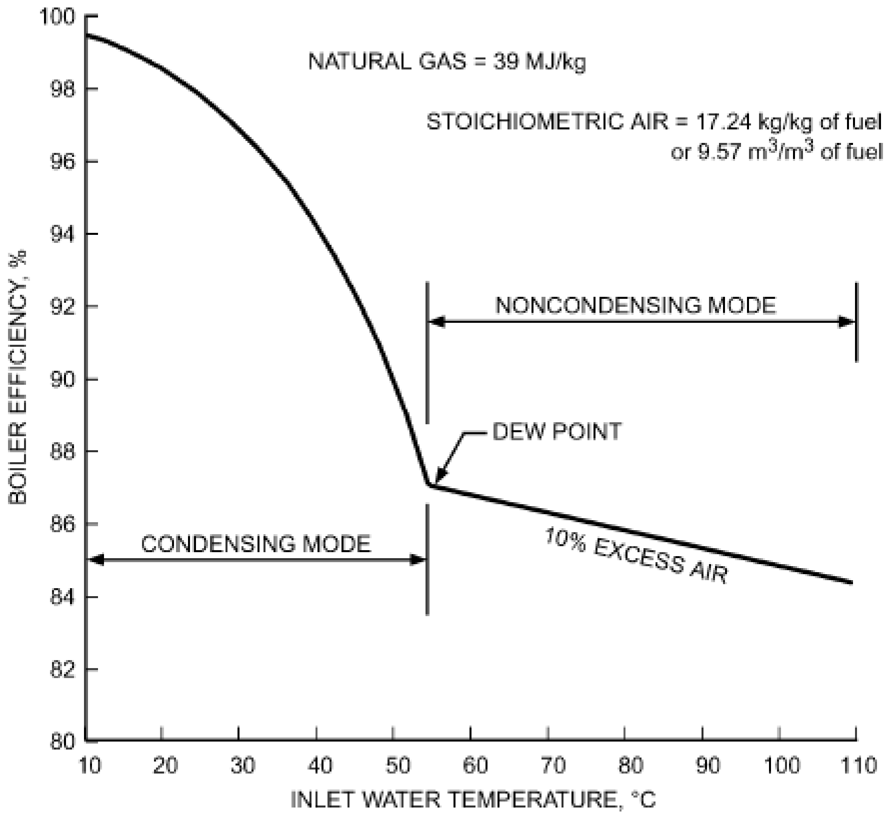


Figure 3.2: Effect of return (inlet) temperature on efficiency of condensing boilers [8]

When an inflexion point is met in the curve, the dew point temperature is reached and from there the efficiency improvement is very rapid. The inflexion point is met at a temperature lower than 55 °C (the dew temperature for complete combustion of methane). Efficiency declines dramatically as return water temperatures rise beyond 54°C because little condensation is possible at such high temperature.

3.4. Efficiency curve under different part load conditions

Another point regarding efficiency of condensing boiler relates to the fact that the efficiency increases as load decreases. A boiler receiving 32°C return water and operating at 100-percent load has a efficiency of about 94 percent (LHV), as shown in Figure 3.3. For the same boiler operating at 30-percent load, efficiency increases to nearly 97 percent.

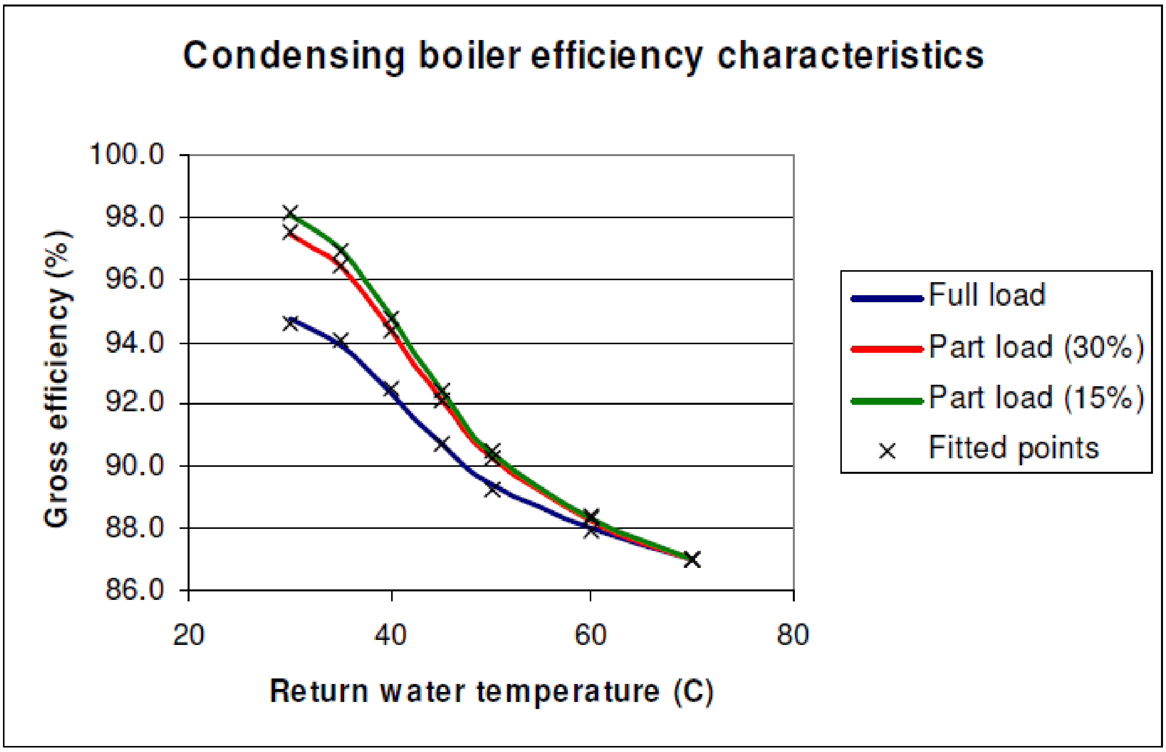


Figure 3.3: Condensing boiler efficiency characteristics for different part load conditions [9]

A study report from 2007[9] contains a complex polynomial describing the efficiency curve of a condensing boiler under different load conditions and return temperatures:

$$\eta = a_1T + a_2T^2 + a_3T^3 + a_4T^3 + a_5y + a_6yT + a_7yT^2 + a_8$$

This is the only relevant published efficiency curve in this area taking into account not only the effect of the return water temperature but also the part load conditions.

The coefficients, derived from supplied data for the condensing boiler in the study, are illustrated in Table 1.for three different part load conditions (15%, 30% and 100%):

a_1	0.124
a_2	-0.0408
a_3	0.00054
a_4	-0.000000271
a_5	-0.104
a_6	0.00256
a_7	-0.0000153
a_8	-0.349

Table 3.1: Coefficients for efficiency curve described by a complex polynomial

In order to derive the coefficients $a_1 - a_8$ from the efficiency curve polynomial for the condensing boiler in Sarajevo, the Excel tool Solver was used. Based on experimental data of the condensing boiler efficiency for given return water temperatures(the points shown in Figure 3.5), and part load conditions, the Excel based tool Solver will find the equation of the nonlinear efficiency curve which most closely fits the set of data points. However, as the part load conditions were not available from the measurements data in Sarajevo, the same were used from the mentioned study (15%, 30% and 100%). Fig.5 shows the screenshot of the Excel Solver used for obtaining the coefficients for the efficiency curve for the condensing-gas boiler in Sarajevo:

$$\eta_i = A_1\, T_i + A_2\, T_i^2 + A_3\, T_i^3 + A_4\, T_i^4 + A_5\, y + A_6\, T_i\, y + A_7\, T_i^2\, y + A_8 + d_i^- - d_i^+$$

A1	A2	A3	A4	A5	A6	A7	A8
1.24E-01	-4.08E-03	5.54E-05	-2.71E-07	-1.04E-01	2.56E-03	-1.53E-05	-3.49E-01

	T	T^2	T^3	T^4	y	T*y	T^2*y	1	d-	d+	Efficiency	Measuerd	Calculated	Error
1	30	900	27000	810000	0.15	4.5	135	1	0.0E+00	0.0E+00	0.980	0.980	0.980	0.0%
2	35	1225	42875	1500625	0.15	5.25	183.75	1	0.0E+00	0.0E+00	0.970	0.970	0.970	0.0%
3	40	1600	64000	2560000	0.15	6	240	1	3.0E-03	0.0E+00	0.950	0.950	0.947	0.3%
4	45	2025	91125	4100625	0.15	6.75	303.75	1	0.0E+00	0.0E+00	0.922	0.922	0.922	0.0%
5	50	2500	125000	6250000	0.15	7.5	375	1	0.0E+00	4.6E-05	0.902	0.902	0.902	0.0%
6	60	3600	216000	12960000	0.15	9	540	1	0.0E+00	2.8E-03	0.882	0.882	0.885	0.3%
7	70	4900	343000	24010000	0.15	10.5	735	1	0.0E+00	0.0E+00	0.870	0.870	0.870	0.0%
8	30	900	27000	810000	0.30	9	270	1	1.2E-03	0.0E+00	0.975	0.975	0.974	0.1%
9	35	1225	42875	1500625	0.30	10.5	367.5	1	0.0E+00	2.0E-03	0.963	0.963	0.965	0.2%
10	40	1600	64000	2560000	0.30	12	480	1	0.0E+00	1.0E-03	0.942	0.942	0.943	0.1%
11	45	2025	91125	4100625	0.30	13.5	607.5	1	1.0E-03	0.0E+00	0.920	0.920	0.919	0.1%
12	50	2500	125000	6250000	0.30	15	750	1	2.1E-03	0.0E+00	0.902	0.902	0.900	0.2%
13	60	3600	216000	12960000	0.30	18	1080	1	0.0E+00	3.0E-03	0.881	0.881	0.884	0.3%
14	70	4900	343000	24010000	0.30	21	1470	1	2.1E-10	0.0E+00	0.870	0.870	0.870	0.0%
15	30	900	27000	810000	1.00	30	900	1	0.0E+00	0.0E+00	0.945	0.945	0.945	0.0%
16	35	1225	42875	1500625	1.00	35	1225	1	0.0E+00	1.6E-03	0.940	0.940	0.942	0.2%
17	40	1600	64000	2560000	1.00	40	1600	1	3.7E-04	0.0E+00	0.925	0.925	0.925	0.0%
18	45	2025	91125	4100625	1.00	45	2025	1	0.0E+00	0.0E+00	0.905	0.905	0.905	0.0%
19	50	2500	125000	6250000	1.00	50	2500	1	3.3E-03	0.0E+00	0.893	0.893	0.890	0.4%
20	60	3600	216000	12960000	1.00	60	3600	1	0.0E+00	0.0E+00	0.880	0.880	0.880	0.0%
21	70	4900	343000	24010000	1.00	70	4900	1	0.0E+00	0.0E+00	0.870	0.870	0.870	0.0%

Fig 3.4: Excel solver for condensing boiler efficiency curve coefficients

Figure 5: The efficiency of the condensing boiler at different part load conditions and return water temperatures are shown in the Efficiency cell. The range 30 - 70 °C is the usual temperature range of boiler return water in exploitation conditions. The calculations were based on measurements for seven different temperatures at three different load conditions for the rated heat capacity of the boiler (15%, 30% and 100%). The idea was to obtain the relationship that describes the efficiency of the boiler under all possible operating conditions. Efficiency contents are expressed here as Lower Heating Value**.**

The graph in Figure 3.5 shows how the boiler efficiency based on the Excel Solver is fitted for seven data points of the return water temperature and part load capacity of 15 %:

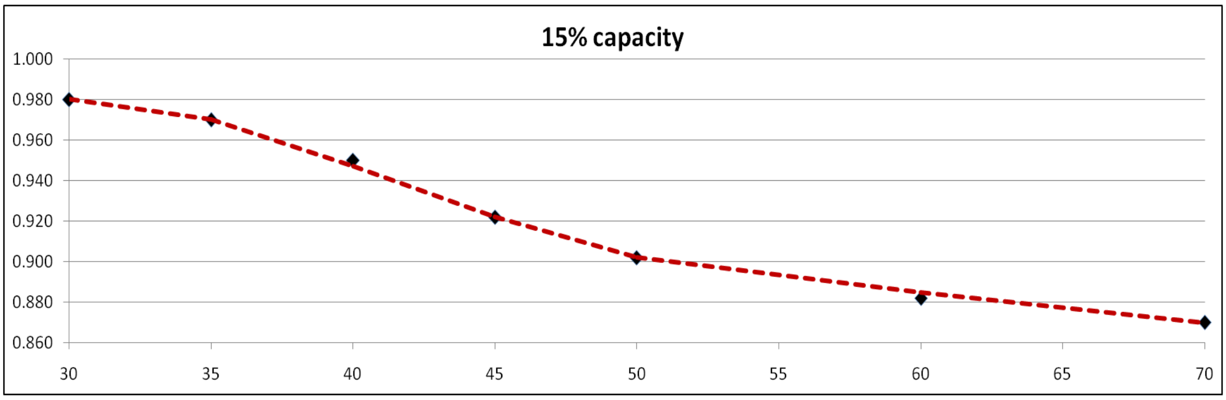


Figure 3.5: Efficiency of condensing boiler under part load condition 15% capacity (HHV)

3.5. Thermal mass

An important general characteristic when considering boilers is the thermal mass.

The combination of metal and water weight gives cast-iron boilers the ability to absorb a significant amount of heat. Such boilers are said to have a high thermal mass [10]. The energy stored in the thermal mass helps prevent short cycling of the boilers burner during part load conditions. This reduces wear on the burner and improves efficiency. Although steel-fire boilers generally have less metal weight than cast-iron boilers of similar capacity they often hold more water. Thermal mass of various materials is rated by their heat capacities and since water has a relatively high heat capacity, it results in a boiler with a relatively high thermal mass.

Based on my calculations, a typical cast-iron boiler rated at 22 kW.-output has about 12.5 times more thermal mass due to its metal and water content, compared to a condensing boiler made steel and of the same maximum capacity.

The heat up and cool down rate of a boiler depends on how much thermal mass the boiler contains. By knowing how fast the boiler heats up and cools down, the control can more accurately determine the required number of stages to turn on.

3.6. Burners

A primary function of a gas burner is mixing fuel gas and combustion air in the proper ratio before their arrival at the flame.

Burners can be classified based on the fuel type and by air supply to the combustion chamber [11]. The burner may alternatively fire on gas, oil or gas-oil combination. Based on the air supply to the combustion chamber burners are classified as either natural draft or forced draft burners**.** In a natural draft burner, the combustion air is drawn in by natural convection and there is no control of the air/fuel ratio (no use of fans or blowers). For forced draft burners, a fan controls the quantities of combustion air and the air/fuel mixture.

4. Boiler burner control system:

Boiler controls provide automatic regulation of burner and boiler performance to ensure safe and efficient operation. Three main modes are typically available for the control of burner heat output in forced draft natural gas burners [12]. These are:

- On/off
- High/low/off (two-stage control)
- Modulating

The on/off mode of control is the simplest form of the burner control. The burner is either firing at its maximum heat output or it is not firing at all.

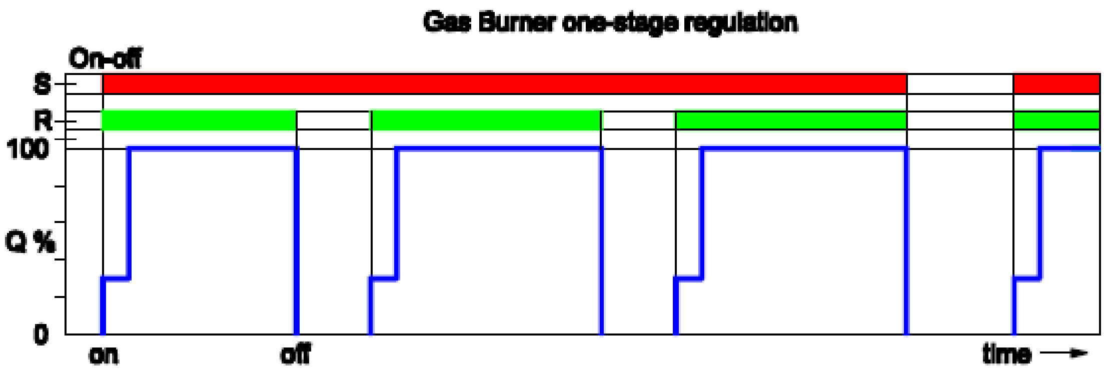


Figure 4.1 : Gas burner one-stage regulation [13]

R - Regulating Thermostat

S - Safety Thermostat

Q - Burner Output (%)

In the high/low/off mode of control the burner has two firing rates, “high” and “low”. The high firing rate naturally provides the maximum heat output from the burner, while the low firing rate provides a heat output that is intermediate between the burner maximum and zero. The high/low/off mode of control is also termed two-stage control.

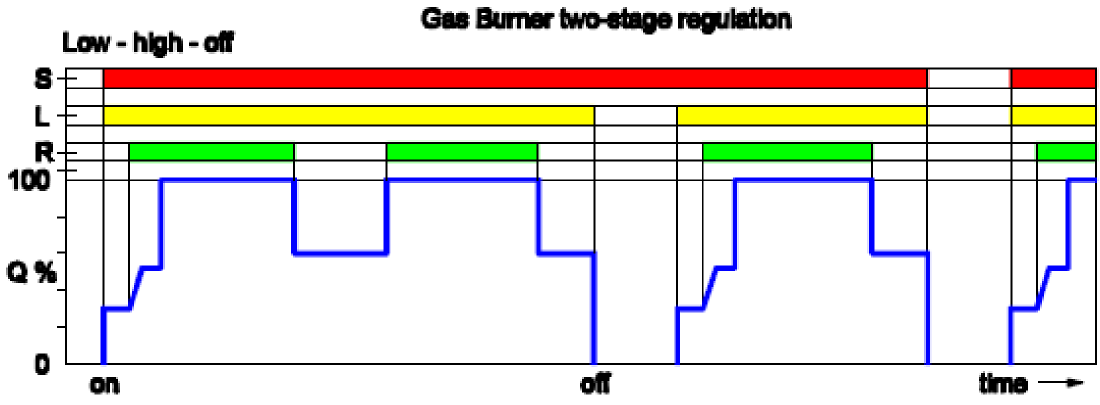


Figure 4.2: Gas burner two-stage regulation

L - Limit Thermsostat

Non-condensing boilers generally use on/off cycling, because reduction in fuel flow can cause condensation, something they are not designed for as described in ch.3. On/off cycling is inefficient, as heat is lost during the off-cycle and the boiler has to be reheated to some extent at the start of each on-cycle [14]. Overall efficiency therefore falls with decreasing load in non-condensing boilers at least below about 80% of full load (where peak efficiency occur in some cases).

Modulating control provides a burner heat output that is continuously adjustable between its maximum (design) rating and some lower value. The latter represents the minimum limit of burner modulation, and the minimum firing rate of the burner. Any further reduction in boiler heat output to water can only lead to cycling the burner off/on.

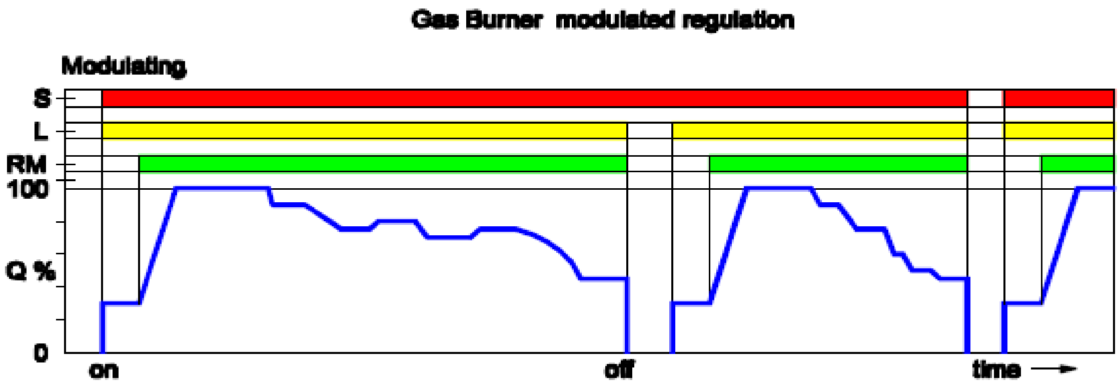


Figure 4.3: Gas burner modulated regulation

RM - Regulating Module

The boiler incorporates a proportional controller that compares the temperature sensed by boiler flow temperature sensor with the desired set-point value and provides an output signal that continuously modulates the burner firing rate between its minimum level of modulation (maximum turndown) and full output. Below the maximum turndown in burner firing rate, the burner cycles on and off. In modern boilers the controller will typically offer proportional-plus-integral (PI) or proportional- plus-integral-plus derivative (PID) control. The ability of a boiler to modulate its heat output rate is sometimes expressed as a turndown ratio [15]. The turn down ratio is the reciprocal of the lowest possible decimal percentage of full-heat output rate the boiler can maintain. For example, if a boiler can maintain stable operation down to 20% of its maximum heat output rate, it would have a turndown ratio of 5:1. The boiler MEF boiler room in Sarajevo is fired by forced-draft modulating burner with range from 33% to 100%.

4.1. Control of the heating circuit during boiler start-up operation

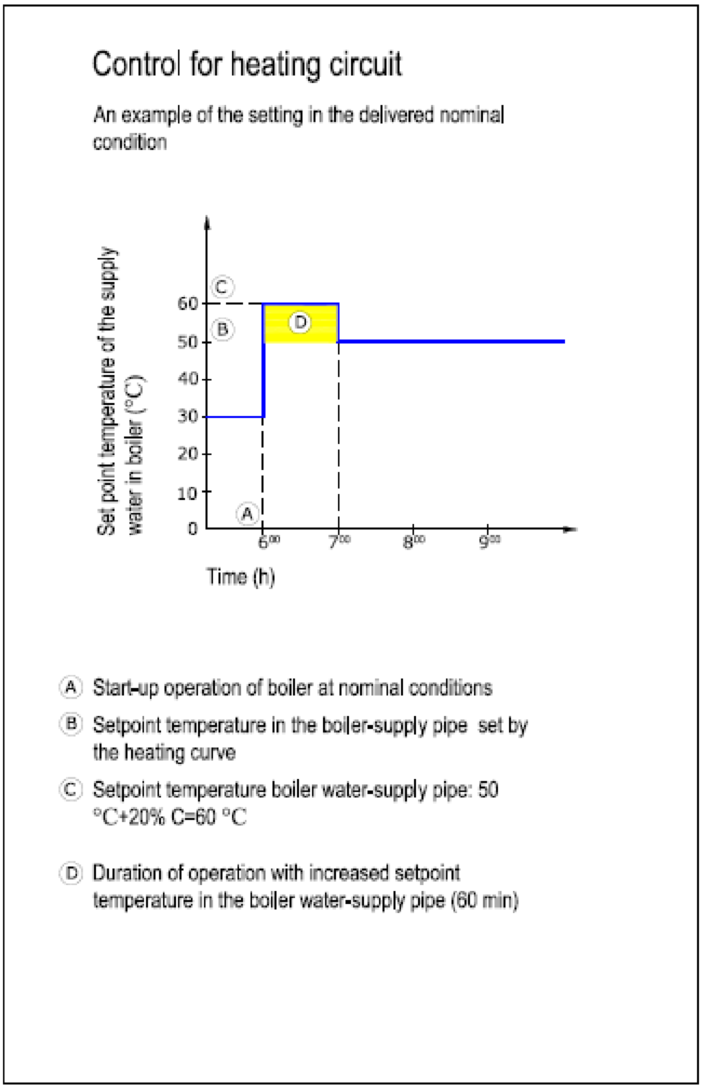


Figure 4.4: Control of heating circuit during the start-up of the boiler operation in control unit at MEF Sarajevo [9]

Figure 4.4 shows the control of the heating circuit in the control unit of MEF boiler room. During the first 60 minutes of the boiler start up the control dictates the supply temperature to have 20% additional value compared to the set point temperature in the boiler supply pipe set by the heating curve.

4.2. Outdoor reset control

In Germany, the country of manufacturer of the condensing boiler and its control system, the set supply temperature of the heating system is normally controlled according to the ambient air temperature [16]. All outdoor reset controls use outside air temperature to determine the ideal “target” water temperature to be supplied to the system’s heat emitters. An outdoor reset control varies the supply temperature of the water in boiler system in response to outdoor temperature. As the load increases, so does the water temperature supplied by the boiler. Outdoor reset controls regulates the amount of heating entering the building based on a heating curve. The so called heating curve copes with the fact that the building’s heat load depends on the outside temperature: As the load increases, so does the water temperature supplied by the boiler and vice versa.

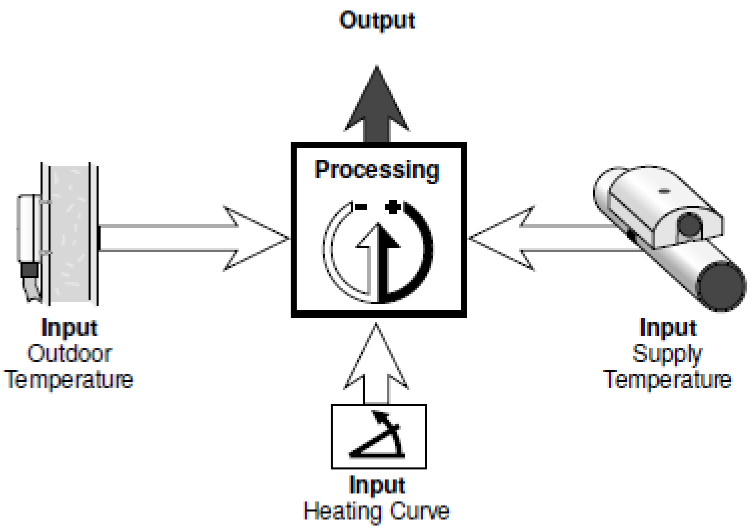


Figure 4.5: Outdoor reset control. [17]

An electronic control calculates the supply set temperature based on a heating curve. Referring to figure 4.5, we see that as the outdoor sensor measures a colder temperature, the control device compares that reading with both the heating curve and the reading from the supply water temperature sensor.

4.3. Heating Curve in the boiler control unit at MEF

The heating curve scenario is handled differently by different designs of controls/systems. The correct heating curve is selected for each building by considering those factors that affect rates of heat gain vs. heat loss. The most important are the construction type, location and insulation levels of the building, along with the heating system design. The illustration of the heating curve in Figure 4 shows how the supply water temperatures relate to the outdoor temperatures in the heating curve provided by the boilers manufacturer at MEF.

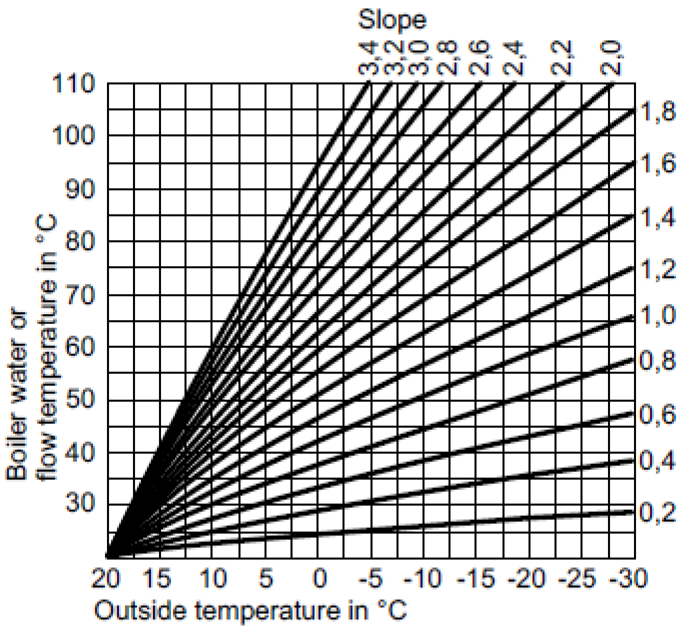


Figure 4.6: Heating curve of the boiler control unit at MEF [18]

The illustration of the heating curve in Figure 4.6 shows how the supply water temperatures relate to the outdoor temperatures in the control of the condensing boiler in MEF boiler room. The number shown on each curve indicates the ratio of supply water temperature increase to outdoor air temperature decrease. If a heating curve of 1.4 is selected, the control will increase the supply water temperature by 1.4°C for every 1°C drop in outdoor temperature. In the heating curve in Figure 4, the heating curve selected is 1.0. When the outdoor temperature is -10°C, the control will increase the supply water temperature to 56°C. Using the same heating curve, one can see that if the outdoor temperature 10°C, the supply water will be 33°C.The reset control measures two temperatures: the outside air temperature and the water supplied by the boiler. At the time of installation, the control must be set manually. Once set, the water temperature will change in response to the outside temperature, depending on the selected heating curve.

4.4. Control action

In its simplest form, a control system consists of three basic elements: a sensor, a controller and a controlled device [19]. The sensor measures a variable, such as temperature, and transmits its value to the controller. The controller uses this value to compute an output signal, which is transmitted to the controlled device. When the signal is transmitted, the controlled device changes the output of the load. The simplest method of water temperature control is called “set-point control.” As its name implies, a single (set) water temperature is supplied to the distribution system regardless of which loads are active, or how great the demand for heat is (as long as there is a demand).The ideal control should regulate a heating system to allow it to provide the exact amount of heat required to replace the heat lost from a building. When this is accomplished, the result is a steady and comfortable room temperature combined with efficient operation of the system.

With the correct heating curve selected, the condensing boiler is controlled to maintain the supply water at the lowest practical temperature required to supply sufficient heat to the building. The temperature controller uses the sensor signal to control work load temperature. The input is the part of the temperature controller which receives and interprets the sensor information (Figure 4.7). Input information is typically supplied by a temperature sensor (such as a thermocouple).

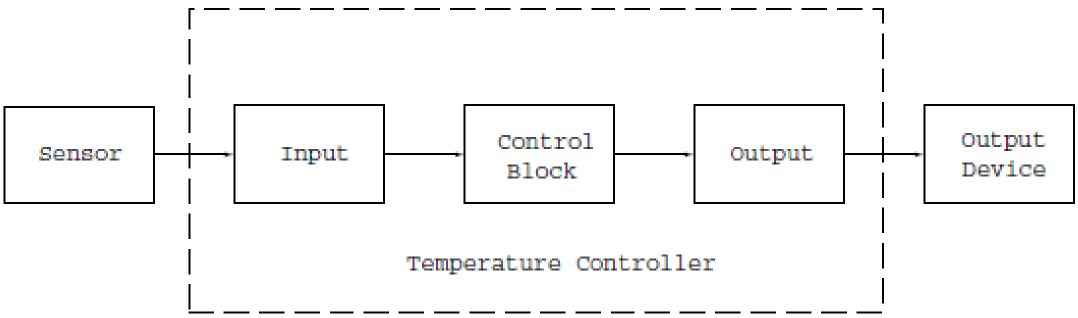


Figure 4.7: Basic configuration of a temperature controller [19]

When the control block receives the input information, it compares the actual process temperature to the set point temperature. It then uses a set control algorithm to tell the output what to do. In an ON/OFF control the control block may tell the output to turn the heater either full ON or full OFF.

The control output implements the action commanded by the control block. The control block provides control action on the input signal to reach the set-point (temperature).

However, many applications require a more precise form of control called PID control. Complex control strategies will usually have a control algorithm that dictates how and in what circumstances the controls will operate. The boiler supply temperature in the control unit of the condensing boiler at MEF is maintained using a PI control algorithm.

4.5. PI control

The PI controller compares the measured boiler supply water temperature from the previous step with the set-point value, obtained from the heating curve. The difference or error is then processed to calculate a new process input. This input will try to adjust the measured value back to the desired temperature set-point. The control then generates an output signal to the modulating burner, which increases its modulation range (turndown ratio), thus increasing the supply temperature to the desired value.

The error will be managed in two ways: the proportional element P and the integral element I.

4.5.1. Proportional control:

The proportional term (P) gives a system control input proportional with the error. A constant gain K_p is acting on the error signal e:

$$controller\ output = K_p e$$

A proportional control sets up a “proportional band” below the set point temperature. This “band” is measured in degrees C, units, or is measured as a percent of temperature range. The proportional band is normally adjustable in width. For example, a proportional band might be set at 11˚C. Or on a control with a 100˚C temperature range, a proportional band of 5% means a proportional band of (100˚C x 0.05) or 20˚C.

When the process temperature is inside the proportional band, the control block commands the control output to vary the amount of heat flow to the heat exchanger inside the boiler. The output varies the heat flow by switching the burner ON and OFF within a set period of time. The longer the burner is ON, the greater the percentage of heat is delivered to the water inside the boiler.

A matching programming unit is part of the standard delivery of condensing boiler at MEF : The programming unit contains a digital time switch with allow for the on/off function to be programmed to cover each day of the week. Switching times are individually programmable, i.e. up to four switching periods per day. The shortest switching interval is 10 minutes, thus preventing short-cycling in small time intervals. The actual boiler simulated has two switching periods during the day, one for on period, and another for the off period:

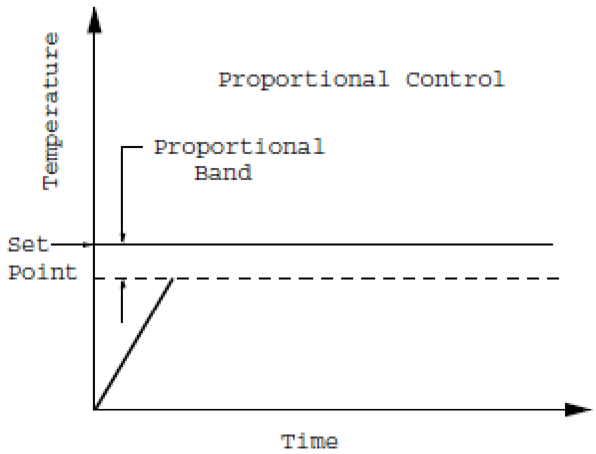


Figure 4.8: Proportional Band

On start up, the heater is ON 100% of the time. Once the process temperature crosses into the proportional band the burner is periodically switched ON and OFF. By intermittently switching the burner ON and OFF, the burners power output is reduced and there is a slowdown in temperature rise.

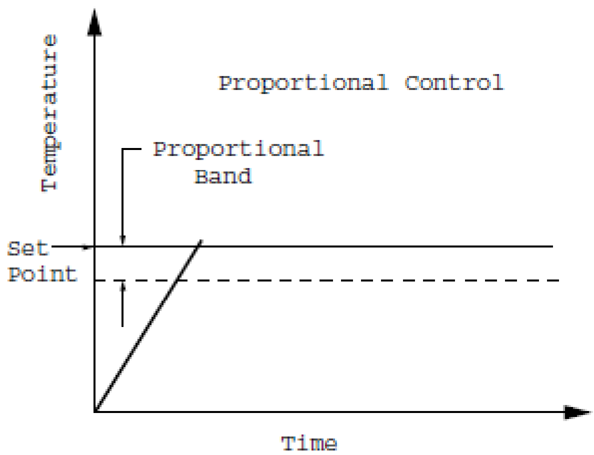


Figure 4.9: Proportional Control

At the lower portion of the band, the heater is ON most of the time. As process temperature gets closer to set point, the burner is switched ON for a shorter time and OFF for a longer time. Half way into the proportional band, for example, the burner is ON half the time and OFF half of the time.

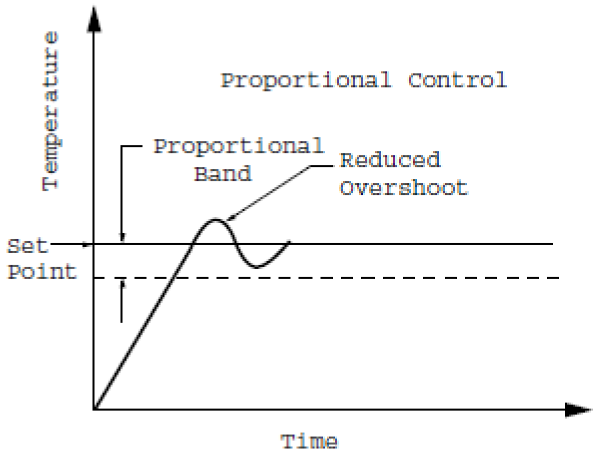


Figure 4.10: Proportional Control

The proportional ON and OFF switching of the burner reduces temperature overshoot. At some point the temperature peaks, drops below set point and re-enters the proportional band. Again the burner is switched ON and OFF in an effort to push the temperature back up to set point.

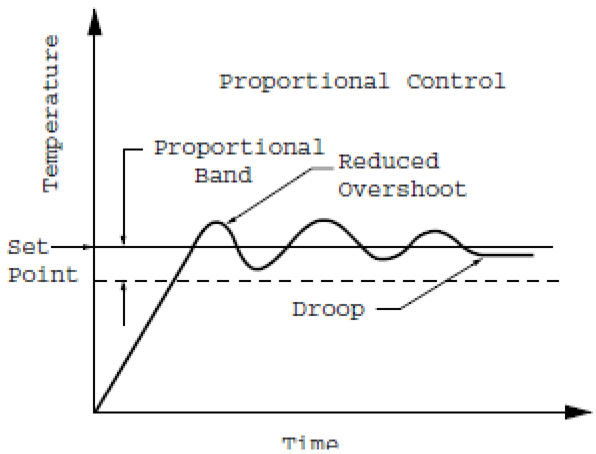


Figure 4.11: Proportional Control

This ON and OFF proportioning action continues until a stable process temperature is reached. Because there is a 0% power level at set point, the temperature usually stabilizes at a temperature somewhere below set point. This is called droop. The amount of droop increases with larger proportional bands and vice versa.

4.5.2. Integrative control:

Integral is also called "reset." Integral or reset has one main task- to eliminate droop. Reset "pushes" the actual temperature toward the set point temperature until it is reached. This eliminates the droop condition due to proportional control. The integral term (I) gives an addition from the sum of the previous errors to the system control input. With PI control, the proportional element is augmented with an additional element:

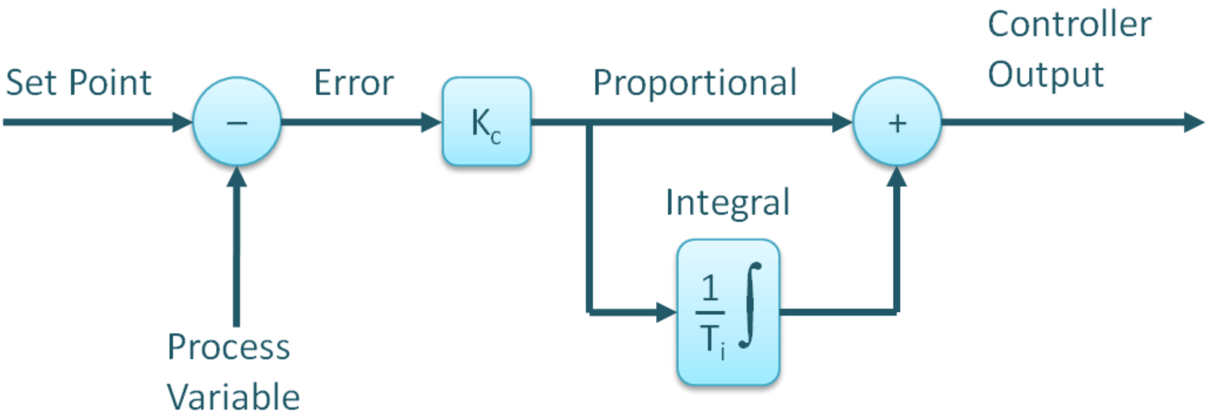


Figure 4.12: PI controller [20].

The PI controller gives an output proportional to the integral of the error with time. The proportional element has an input of the error e and an output of $K_p e$.The integral element has an input of e and an output which is proportional to the integral of the error with time:

$$K_i \int e\,dt$$

where K_i is the integrating gain. Thus the controller output is :

$$controller\ output = K_p e + K_i \int e\,dt$$

The second term in Equation (2) implies that the longer the period during which the error e exists, the more the controller output will change in attempting to eliminate the error.

In terms of the Laplace transform:

$$controller\ output(s) = \frac{K_p}{s}\left(s + \frac{1}{T_i}\right)E(s)$$

Where $T_i = \frac{K_p}{K_i}$ and is called the integral time constant.

Selecting proportional and integral gain constants is critical to stability. Proper selection eliminates offset, obtaining greater control accuracy and is generally important feature required in a control system [21].

The summing of the error will continue until the system process value equals the desired value. As can be seen the control system does not monitor the room temperature, instead it controls the boiler water temperature to reach the supply temperature adjusted by the heating curve. This is called an open loop system since the controller does not receive any feedback (room temperature) to determine if its output (supply temperature) has achieved the desired goal of the input.

5. Modelica

In spite of the large number of available building energy software tools a real building system performance usually differs from the operation predicted by simulations. In addition to achieving the closer match between simulations and real building operation, the researchers point out an overall need for the building simulation tools to support flexible modeling environments which allow simulations of alternative building system configurations [22]. One of such flexible modeling environments is provided through usage of Modelica, a programming language to model complex physical systems. The Modelica language has been developed since 1996 by the Modelica Association, a non-profit organization based in Linköping, Sweden, which gathers members from Europe and the US. Modelica language specification (Modelica Association, 2010) states this [23]:

“Modelica is an object-oriented, declarative, multi-domain modeling language for component-oriented modeling of complex systems, e.g., systems containing mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented subcomponents. The free Modelica language is developed by the non-profit Modelica Association”

Compared to most widespread simulation languages available today this language offers several important advantages

5.1. Object-oriented modeling:

Object-oriented programming is a type of programming that that represents concepts as objects that have stored data and associated processing routines. In Modelica objects correspond to model components from several different domains such as e.g. electrical, mechanical, thermodynamic, hydraulic and control applications. Object-oriented modeling means that one can build a model similar to a real system by trying to find standard components like compressor and heat exchanger from manufacturers’ catalogues with appropriate specifications and interface, and then connecting them into a model.

5.2. Structured mathematical modeling

Unlike traditional object-oriented programming languages like C++ and Java, the objected-oriented approach in Modelica is based on structured mathematical modeling. Models in Modelica are mathematically described by differential, algebraic and discrete equations. The equations are declared in the fundamental structuring unit of modeling in Modelica, the class. Modelica allows creating any number of models from the same class, also known as instances of that class, and then reusing the same base classes for various model implementations. The Modelica language defines all parts of a model and structures model components in libraries, called packages.The basic idea of implementation in Modelica is to decompose the described system into components that are as simple as possible and then to start from the bottom up, connecting basic components (classes) into more complicated classes, until the top-level model is achieved. In the context of Modelica class libarires software components are Modelica classes. However, when building particular models components are instances of those Modelica classes.

5.3. Software Component Model

Modelica offers a powerful software component model with constructs for creating and connecting model components. The software component includes the following three items :

- components
- a connection mechanism
- a connection diagram

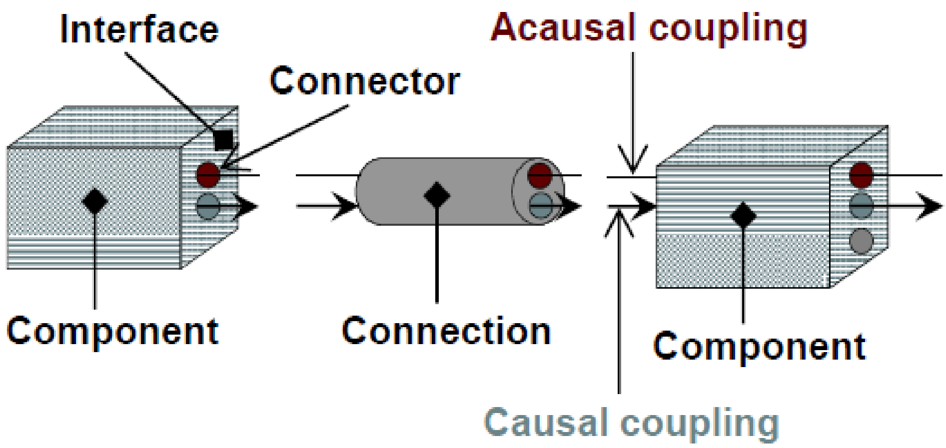


Figure 5.1: Software component model [18]

Components are connected via the connection mechanism realized by the Modelica system, which can be visualized in connection diagrams. The connection diagram consists of components and connections, and ensures that communication works over the connections as shown in Figure 5.1 [24]. The connection (interaction) of a model component to other components is defined by physical ports, called connectors. A connector is a special class that defines how models can interact (connect) with other models. The connector or port defines the variables of the model shared with other models, without prejudicing any kind of computational order. The interaction of thermo-fluid systems in Modelica is described by two kinds of connector interfaces: heat ports and fluid ports.

5.3.1. Heat ports

Fig. 5.2 illustrates the concept connection of three thermal state states in Modelica coupled by their in their heat interfaces, connectors:

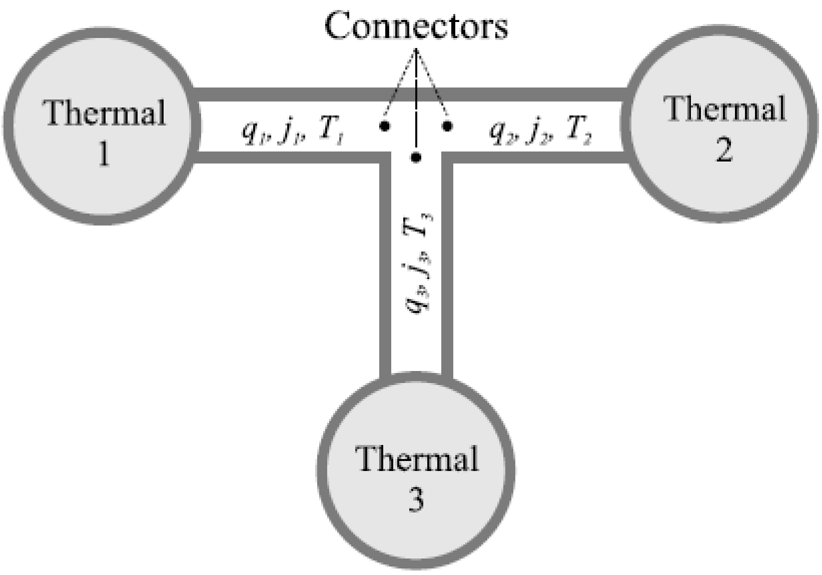


Figure 5.2: Connectors of thermal classes

The classes are interacted with two relevant types of variables: temperatures and heat flows. All the temperatures in each connector must be equalized (shell equation)

$$T_1 = T_2 = T_3 \quad 5.1$$

While the sum of all the heat flows should be zero (balance equation)

$$q_1 + q_2 + q_3 = 0 \quad 5.2$$

The Modelica classes for heat transfer are based on these connection rules. The variables from Eq. 5.1 are often referred to as potential variable in Modelica nomenclature while the variables from Eq. 5.2 are flow variables. Two kinds of equations are generated: pair-wise equalities among the potential variables, and a sum-to-zero equation for the flow variables.

Figure 5.3. illustrates the components for 1-dimensional heat transfer modeling with lumped parameter (Thermal Conductor from Modelica Standard Library).

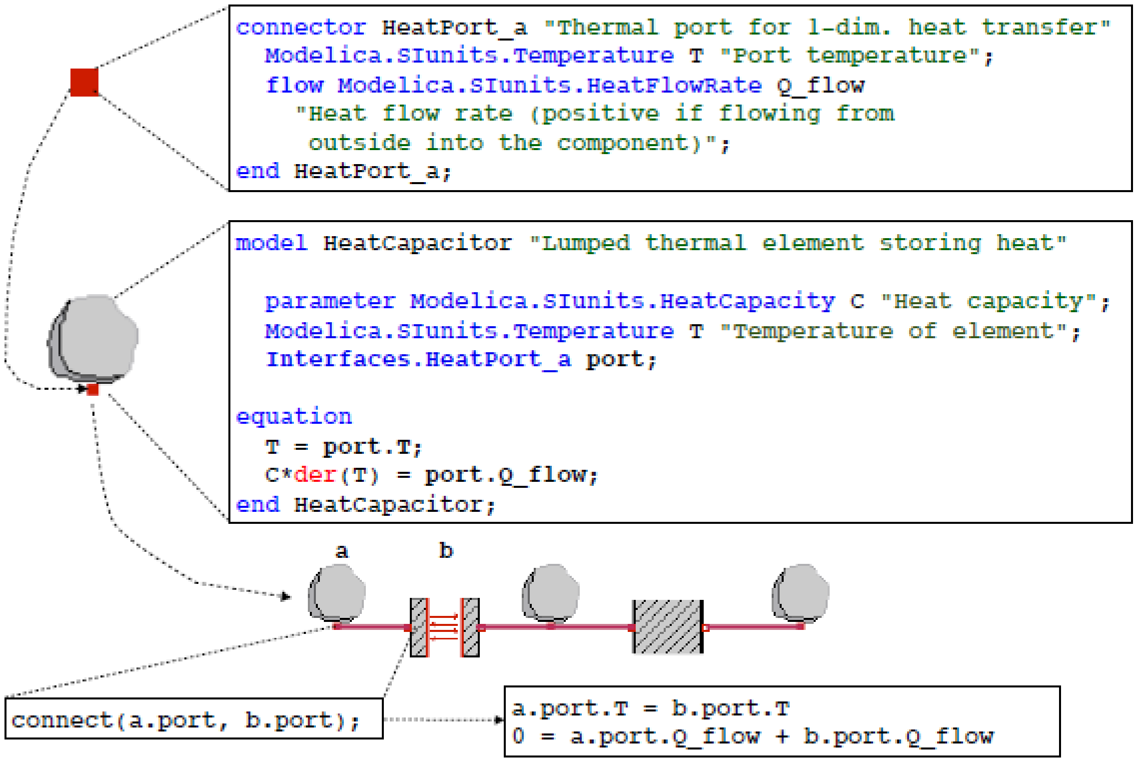


Figure 5.3: Basic principles of 1-dimensional heat transfer modeling in Modelica

Modelica Standard Library contains a HeatTransfer library with components for 1-dimensional heat transfer models with lumped parameters, e.g., ‘‘ThermalConductor”, ‘‘BodyRadiation”, ‘‘Convection”, etc. All these components contain a single connector, the HeatPort. The connector HeatPort contains two variable declarations: the temperature T and the heat flow rate Q_flow. The former is without any qualifier, making it the potential variable, and it is connected according to the pair-wise equalities. The latter has an additional qualifier flow and is connected according to sum-to zero equation.

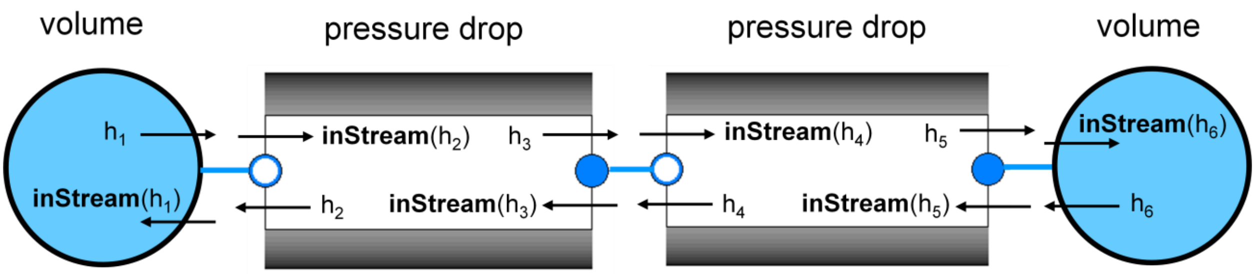
During the model translation the originating from the connector definitions, are automatically generated and added to the other equations of the model.

5.3.2. Fluid ports

The “Fluid” library provides the generic fluid connectors and the most important basic devices, such as sources, sensors, and pipes for quasi 1-dimensional flow of media with single or multiple phases and single or multiple substances. For the Modelica_Fluid library the fluid port is defined for quasi-1 dimensional fluid flow in a piping network, with incompressible or compressible media models, one or more phases, and one or more substances.

In addition, ports for fluid flow also have a stream variable. A new fundamental type of connector variables "stream" was introduced for the next Modelica Language Specification Version 3.1[25]:, because the two standard types of port variables used in all component oriented modeling systems were not sufficient to model flow of matter in a reliable way. Modelica_Fluid library1.0 is based on this new concept.

Flow and stream 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). The good insight to the stream variable concept can be given from the following example of volume-pressure drop network:



inStream(h1) = h2 = **inStream**(h3) = h4 = **inStream**(h5) = h6
inStream(h6) = h5 = **inStream**(h4) = h3 = **inStream**(h2) = h1

Figure 5.4: Stream variables in Modelica [25]

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. A model using a stream connector must expose the outflow value, which is known from internal storage or from inflow values of other connectors, independently of the flow direction. The inflow value can be obtained by a model on demand by using the new operator:

inStream(h_outflow)

while the value of the stream variable corresponding to the actual flow direction can be inquired through the built-in operator actualStream(h_outflow) :

```
actualStream (port.h_outflow)=if port.m_flow >0

then inStream(port.h_outflow)

elseport.h_outflow
```

The stream variables are selected such that the equations of the connect(...) statements of connected components fulfill the following balance equations (sum-to-zero equation described for heat ports).

5.4. Modeling fluid flow in Modelica using the Finite Volume Method

The Modelica.Fluid.Pipes sub-package provides a rigorous implementation for such as in a quasi-one-dimensional flow in a device with flow ports (such as a pipe), [25]:

5.4.1. Mass and momentum Balance

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho A v)}{\partial x} = 0$$

$$\frac{\partial(\rho v A)}{\partial t} + \frac{\partial(\rho v^2 A)}{\partial x} = -A\frac{\partial p}{\partial x} - F_F - A\rho g\frac{\partial z}{\partial x}$$

$$\frac{\partial(\rho(u + \frac{v^2}{2})A)}{\partial t} + \frac{\partial(\rho v(u + \frac{p}{\rho} + \frac{v^2}{2})A)}{\partial x} = -A\rho v g\frac{\partial z}{\partial x} + \frac{\partial}{\partial x}(kA\frac{\partial T}{\partial x}) + \dot{Q}_e$$

$$F_F = \frac{1}{2}\rho v|v|\, fS$$

The energy equation can be considerably simplified by subtracting the momentum balance multiplied by v. Simplifications that are shown in the appendix, give the result.

$$\frac{\partial(\rho u A)}{\partial t} + \frac{\partial(\rho v(u + \frac{p}{\rho})A)}{\partial x} = vA\frac{\partial p}{\partial x} + vF_F + \frac{\partial}{\partial x}(kA\frac{\partial T}{\partial x}) + \dot{Q}_e$$

If x=a and x=b be the coordinates for the ends of any such segment, x=r represent the midpoint of such segment

Integrating the mass balance equation over the spatial coordinate, x, between a and b, gives

$$\int_a^b \frac{\partial(\rho A)}{\partial t} dx + \rho A v\Big|_{x=b} - \rho A v\Big|_{x=a} = 0$$

Assuming the segment boundaries (a,b) to be constant, we can interchange the integral and derivative:

$$\frac{d(\int_a^b \rho A dx)}{dt} + (\rho A v)\Big|_{x=b} - (\rho A v)\Big|_{x=a} = 0$$

In order to handle the general case of changing volumes for, e.g., displacement pumps, tanks, or moving boundary models of two phase flows, this formula needs to be extended by use of the Leibnitz formula.

Introducing appropriate mean values for density and area, associated with the midpoint r, and introducing incoming mass flow rates $\dot{m} = \rho A v$, $\Delta x = b - a$, we can rewrite the mass balance as:

$$\frac{d(\rho_r A_r \Delta x)}{dt} = \dot{m}_a - \dot{m}_b$$

5.4.2. Energy balance

Integrating the energy balance for internal energy over the interval a to b gives:

$$\int_a^b \frac{\partial(\rho u A)}{\partial t}dx + (\rho v h A)\big|_{x=b} - (\rho v h A)\big|_{x=a} = \int_a^b vA\frac{\partial p}{\partial x}dx + (kA\frac{\partial T}{\partial x})\bigg|_{x=b} - (kA\frac{\partial T}{\partial x})\bigg|_{x=a} + \int_a^b \dot{Q}dx$$

Interchange of integral and derivative, introduction of $\dot{H} = \rho v h A$, substitution and approximation gives

$$\frac{d(\rho_r u_r A_r \Delta x)}{dt} + \dot{H}_b - \dot{H}_a = v_r A_r (p_b - p_a) + k_b A_b \frac{\partial T}{\partial x}\bigg|_{x=b} - k_a A_a \frac{\partial T}{\partial x}\bigg|_{x=a} + \dot{Q}_r \Delta x$$

The term $v_r A_r$ is written as $\dot{m}_r / \rho_r$.

The diffusion term contains the temperature gradients at the segment boundaries. A first order approximation of the gradient is

$$\frac{\partial T}{\partial x}\bigg|_{x=a} = \frac{T(a+\frac{\Delta x}{2}) - T(a-\frac{\Delta x}{2})}{\Delta x}$$

5.5. Implementation of thermo-fluid systems in Modelica

There are no language elements to describe directly partial differential equations, although some types of discretized partial differential equations can be reasonably defined, e.g., based on the finite volume method and there are Modelica base classes to import results of finite-element programs. Pipes.BaseClasses.PartialTwoPortFlow implements the balances. It extends from Modelica.Standard.Library.Interfaces. PartialDistributedVolume that defines the mass and the energy balance for one-dimensional distributed flow models by applying the finite volume approach to the discretization along the spatial coordinate *x* with n flow.

The model equations are formulated for n flow segments, which are characterized with the variable vectors:

```
SI.Volume[n] fluidVolumes;

SI.Mass[n] ms;
```

```
SI.Energy[n] Us;
```

for the volume, the mass and the internal energy ofthe fluid per segment. Moreover:

```
SI.Mass[n,Medium.nXi] mXis;

SI.Mass[n,Medium.nC] mCs;
```

model the substance masses and the trace substancemasses if a multi component medium is used.

The mass balance is defined as

```
der(ms) = mb_flows;
```

With mb_flows[n] a vector of n boundary and source terms.

The energy balance is defined as

```
der(Us) = Hb_flows + Wb_flows + Qb_flows;
```

distinguishing enthalpy flow rates Hb_flows[n], mechanical power Wb_flows[n] and heat flow rates Qb_flows[n] for boundary and source terms.

5.6. Buildings Library:

The Modelica language is a textual description that defines all parts of a model and structures model components in libraries, called packages.

The Modelica Standard Library is a free library that is developed together with the Modelica language by the Modelica Association. It consists of sublibraries that provide model components and standard component interfaces in many engineering domains including mechanics, fluids, thermal, and control. The Modelica.Fluid sub library provides a set of component models for one-dimensional thermo-fluid flow in networks of vessels, pipes, fluid machines, valves and fittings. It demonstrates how to implement fluid flow component models that may have flow friction, heat and mass transfer.

While many classes of Modelica Standard Fluid can be used for the thermodynamic and control application domain, the Buildings library, a freely available Modelica library provide classes that extend models from Modelica.Fluid where applicable, using the same modeling approach as Modelica.Fluid.library. It has been developed to support research and development of integrated building energy and controls systems. The primary applications are controls design, energy analysis and model-based operation

The Modelica Buildings library is a free open-source library with dynamic simulation models for building energy and control systems developed by Simulation and Research group at Lawrence Berkley National Laboratory. 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.

The library contains dynamic and steady-state component models that are applicable for analyzing fast transients when designing control algorithms and for conducting time-dependent simulations when assessing building system performance.

For the modeling applications, the main interest of the Buildings library is in enabling [26]:

1. Prototyping of new building components and systems.

2. Development of advanced control systems.

3. Reuse of models during operation for controls, minimizing fault detection and diagnostics.

The Builings library is organized into the packages as shown in Fig.5.5 the Modelica Fluid library. As mentioned, components in these packages extend components from the Modelica Standard Library and from the Modelica.Fluid library.

```
Buildings.Controls.Continuous
                  .Discrete
                  .SetPoints
Buildings.Fluid.Actuators.Dampers
                         .Motors
                         .Valves
               .Boilers
               .Chillers
               .Delays
               .FixedResistances
               .HeatExchangers
               .HeatExchangers.CoolingTowers
                              .Radiators
               .Interfaces
               .MassExchangers
               .MixingVolumes
               .Movers
               .Sensors
               .Sources
               .Storage
               .Utilities
        .HeatTransfer
        .Media
        .Utilities.Diagnostics
                  .IO
                  .Math
                  .Psychrometrics
                  .Reports
```

Figure 5.5: Buildings library [26]

The package Controls contains models of controllers that are typically needed to implement controllers of building energy systems.

The Fluid package contains component models for thermo-fluid flow systems. Most models in Buildings.Fluid extends models from Modelica.Fluid to form components that are usually needed when modeling building energy.

The model for components that exchange heat or mass with one or two fluid streams are defined in Buildings.Fluid.Interfaces package. The package Fluid.Actuators contains models of valves and air dampers, and motors that can be conjucted with the actuators.

In Fluid.delays, there are model components for transport delays in fluid flow systems.

The dynamic boiler, which is the main interest of this study and will be specified later, is found in the Fluid.Boilers and several different models of heat and mass- exchangers can be found in Fluid.HeatExchangers and Fluid.MassExchangers.

The medium models, such as for dry air, moist air and water are stored in Fluid.Media , while the models for completely mixed volumes of medium are stored in Fluid.MixingVolumes. The package FixedResistances contains models for flow resistances that do not change the flow coefficient. Fan and pump models are implemented in Fluids.Movers.

Sensors components that can be connected to a fluid stream are stored in Fluids.Sensors. Sources for fluid connectors with predefined ambient conditions, such as mass, pressure, temperature, specific enthalpy and trace substances can be found in Fluid.Sources. The package Fluids.Storage contains thermal energy storage models .

The package Utilities contains psychrometric models and blocks for input and output. Fluid.HeatTransfer is a package with model components for various heat transfer modes, such as heat conduction, convective heat transfer and radiation.

Most packages contain a package called Examples, which contains example applications that illustrate the typical use of model components in the parent directories and that are used to conduct unit tests.

5.6.1. The control volume of the boiler model in the Buildings Library

The concept of control volume when modeling the heat exchanger in Buildings library is usually the adiabatic volume mixing two flows. The model contain where the kinetic and gravitational terms in the energy balance are neglected for simplicity.

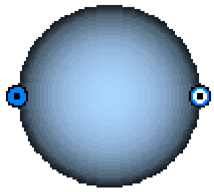


Figure 5.6: Control volume of boiler model in Buildings Library

The concept of control volume 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.

If the model is operated in steady-state and has two fluid ports connected, then the same energy and mass balance implementation is used as in steady-state component models, i.e., the use of actualStream are not used for the properties at the port.

The dynamics energy and mass balances of the volume for the are defined for steady-state and transient response by the following declaration in Mixing volume:

```
der(U)  = Hb_flow + Q_flow;
```

The Q_flow is a flow variable that represents the heat exchanged with an outside heat source or or sink through the mixings volume heatPort, and Hb_flow is a stream variable representing the sum of the enthalpy flows across volume fluid ports :

```
Hb_flow=sum(ports_H_flow);
```

where

```
ports_H_flow[i]= ports[i].m_flow*actualStream(ports[i].h_outflow);
```

is the enthalpy flow through one port .

5.6.2. The Boiler model Buildings Library

Constituting the essential part of boiler room system the boiler model from the LBNL building library was starting point for the implementation of a multi-physical boiler room model:

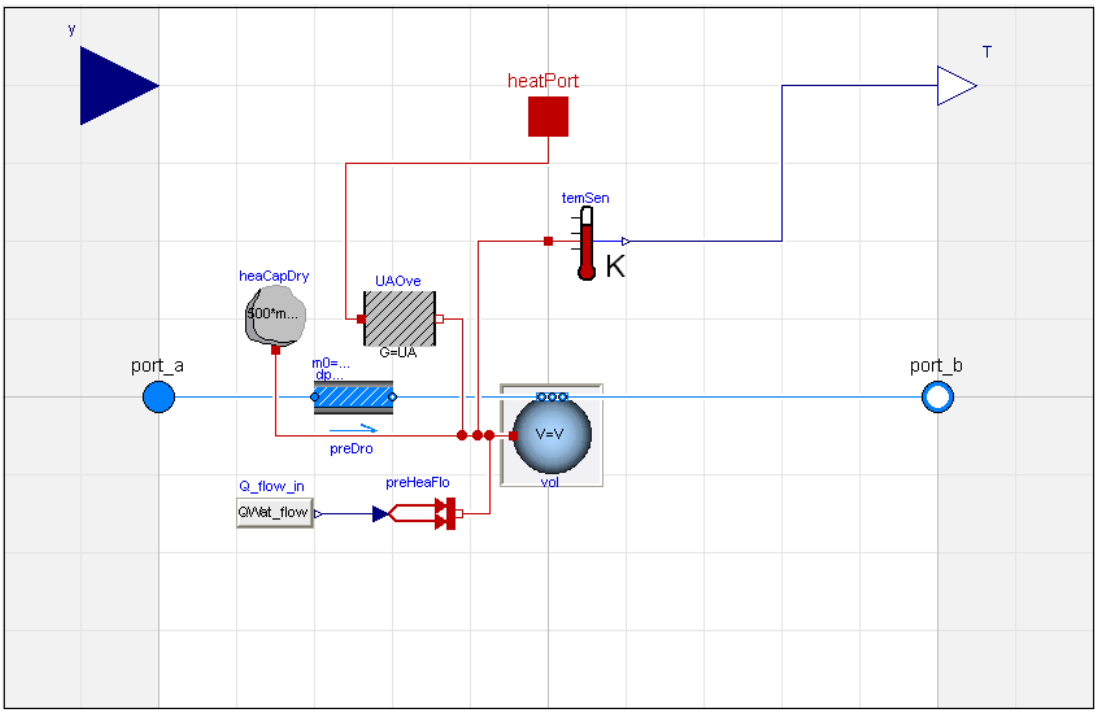


Figure 5.7: Boiler model in Buildings Library

The boiler extends from a heat exchanger interface consisting of the previously described mixing volume *vol* representing the water content of the boiler with a pressure drop resistance model *preDro* between the fluid ports. The fluid ports labeled *port_a* and *port_b* represent the boilers water flow inlet and outlets that can be connected to pipeline models using components from the package Buildings.Fluid. The ports connect directly to the energy balance of the mixing water volume *vol*. The bright blue line is a fluid connector that equates pressure P, conserves mass flow rate $\dot{m}$, and transports enthalpy h, species concentrations X(such as water vapor) and trace substances C (such as CO2).The red lines are connectors for heat ports that equate temperature T and conserve heat flow rates $\dot{Q}$ among the connected ports. The water volume heat port is also connected to a solid heat storage component *heatCapDry* to model the heat stored in the metal and water content of boiler. The model can be parameterized to compute a transient or steady-state response. The transient response of the boiler is computed using a first order differential equation to compute the boiler's water and metal temperature, which are lumped into one state. The boiler outlet temperature is equal to this water temperature. The model also exposes a heat port of a heat conductor *UAOve* to allow modeling heat losses to the ambient environment. The conduction heat losses are computed as UA* (T-heatPort.T), for the boiler water T and conductance UA.

The Volume heat port is connected to a prescribed heat source that computes transferred from the combustion process to the boiler water, thus raising the water temperature in the volume which is sensed by the temperature sensor. The heat input to the water is computed as :

$\dot{Q} = \dot{Q}_0 \frac{\eta(y,T)}{\eta(1,T_0)} y$

Where $\dot{Q}_0$ is the nominal power and $y \in [0,1]$is the control signal the model receives as an input. The control signal input is represented by a blue arrow in the upper left corner of the picture.

The nominal efficiency$\eta(1,T)$:$[0,1] \times \Re \rightarrow \Re$ is the boiler efficiency at full load operation y=1 and nominal return temperature by the parameter T_nominal.

The boiler efficiency$\eta(y,T)$:$[0,1] \times \Re \rightarrow \Re$ at a current operating point is based on the load fraction y and the boiler return temperature$T$ at that point.

The combustion process is not of direct consideration by the model, rather it is computed explicitly:

$\dot{Q}_{fuel} = y \frac{\dot{Q}_0}{\eta(1,T_0)}$

The parameter effCur determines what polynomial is used to compute the efficiency, which is defined as:

$$\eta = \frac{\dot{Q}}{\dot{Q}_f}$$

where $\dot{Q}_f$ is the heat of combustion released by the fuel.

The model allows users to select different functional forms of :

ParametereffCur	**Efficiency curve**
Building.Fluid.Types.EfficiencyCurves.Constant	$\eta = a_1$
Building.Fluid.Types.EfficiencyCurves.Polynomal	$\eta = a_1 + a_2 y + a_3 y^2$
Building.Fluid.Types.EfficiencyCurves.QuadraticLinear	$\eta = a_1 + a_2 y + a_3 y^2 + (a_1 + a_2 y + a_3 y^2)T$
Building.Fluid.Types.EfficiencyCurves.CondensingBoiler	$\eta = a_1 T + a_2 T^2 + a_3 T^3$ $+a_4 T^3 + a_5 y + a_6 yT + a_6 yT^2 + a_8$

Table 5.1: Efficiency Curves in the Buildings Library Boiler model

Where T_nominal=T is the nominal temperature of the supply water, while in the case of the condensing efficiency curve the T is equal to the return water temperature. The efficiency curve from chapter 2. Is implemented in the function ParamatereffCur.

5.6.3. Dymola

Models developed in the Modelica language cannot be executed directly. Rather, a simulation tool translates a Modelica model into an executable program. The current study uses Dymola . Dymola contains what is believed to be the best symbolic and numerical solver for Modelica [27]. The Modelica translator of the Dymola modeling and simulation environment takes the described Modelica model of the boiler room 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 original sorted equations contain a linear system of large number equations. The model is solved by standard numerical procedures. The equations are stored as C-Code which is compiled and linked to the Dymola simulator for real-time simulation [28].

Dymola has a graphic editor for composing models. Dymola has two kinds of windows: Main window and Library window as shown in Figure 5.8. The modeling mode of Main Window is used to compose models and model components. The simulation mode is used to make experiment on the model, plot results and animate the behavior when it changes as a function of time. The package browser in the Library window of Dymola allows viewing and selecting component models from a list of models. To implement new models the model components are dragged from the package browser and dropped to the diagram layer in Main window, and then connected.

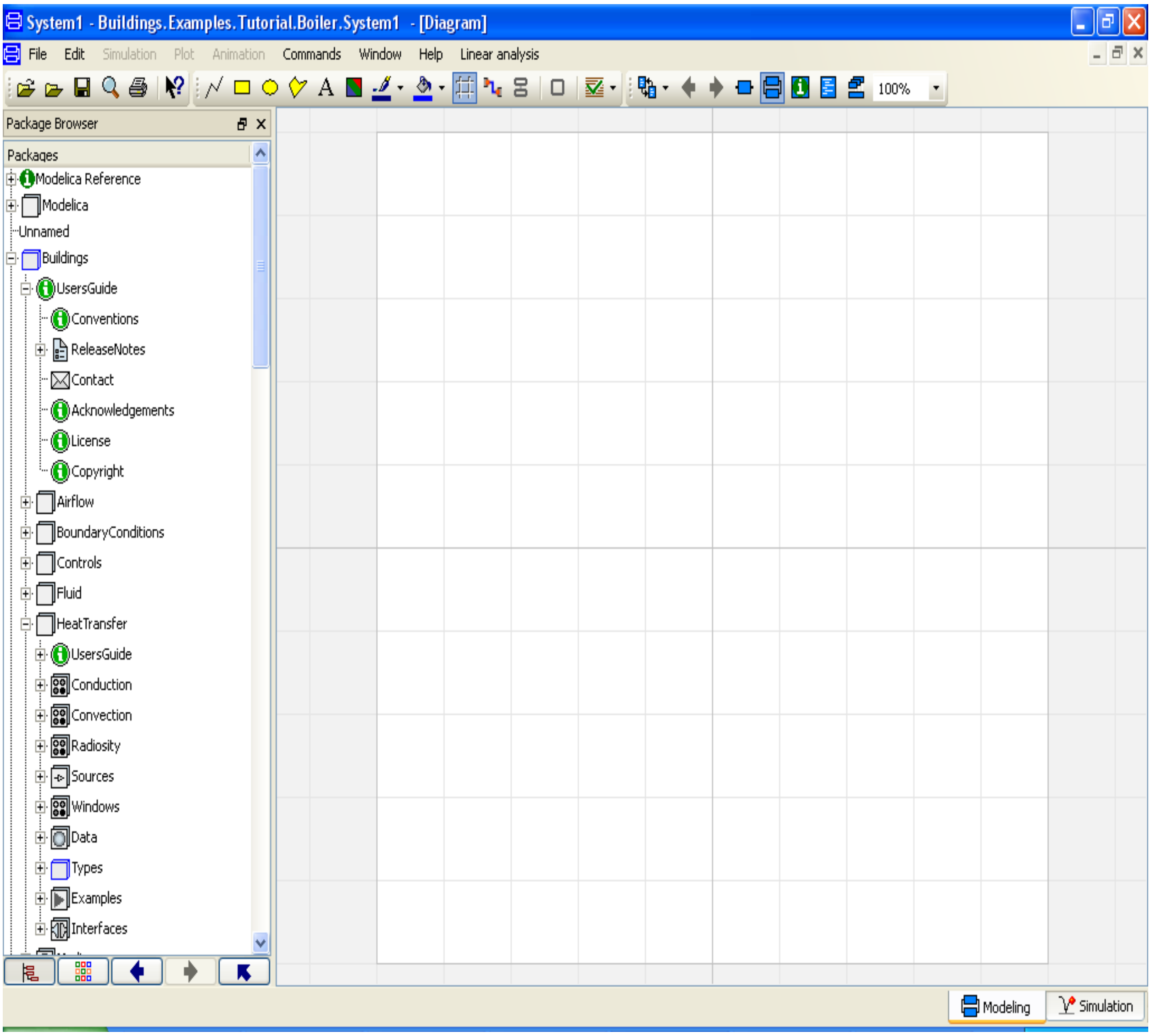


Figure 5.8: Main and Library Window Dymola

Using this editor, a model can be defined by drawing a composition diagram (also called schematics) by positioning icons that represent the models of the components, drawing connections and giving parameter values in dialog boxes:

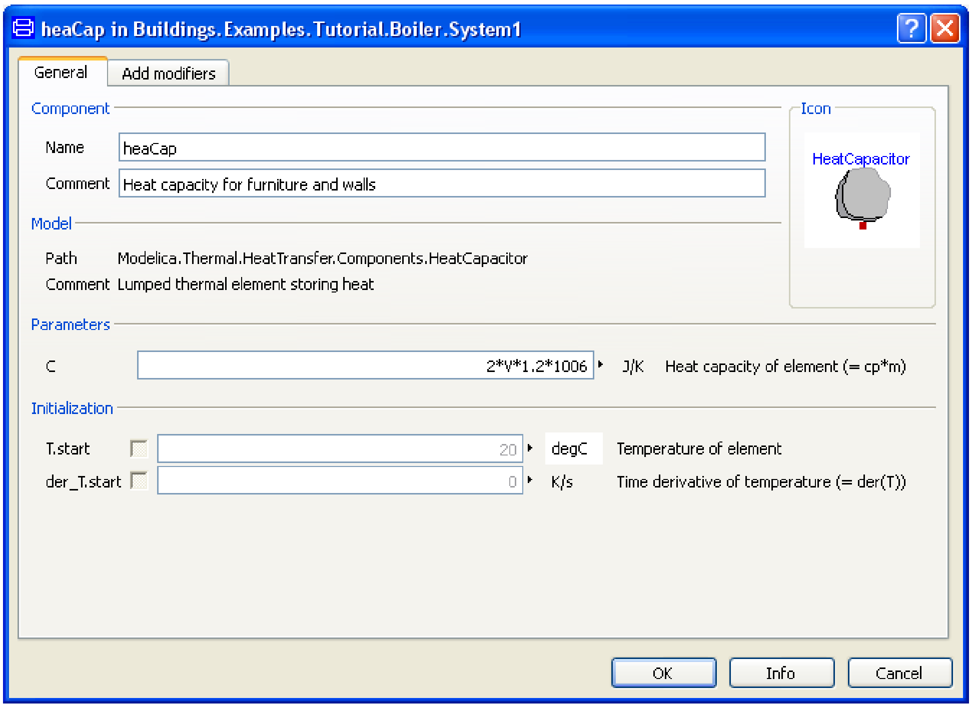


Figure 5.9: Dialog box of the HeatCapacitor model from Buildings Library

When double clicking on a component, a parameter menu opens and displays the parameter data that can be modified for this component. For example, in Figure 5.9 b the parameter menu of the HeatCapacitor is shown. The left column contains the names of the parameters, the middle column the actual values and the right columns the units and description texts.

6. Implementation of the boiler room model in Modelica/Dymola environment

The boiler room model consists of:

- the boiler model
- prescribed mass flow (including prescribed return water temperature conditions) simulating the pump behavior in the boiler room (red rectangle)
- the open loop control block modulating the boiler control signal based on outside air temperature (blue rectangle)
- simplified volume object/volume which is heated uniformly by the boiler heat output (brown rectangle)
- the ambient conditions (air temperature) inside the boiler room (green rectangle)

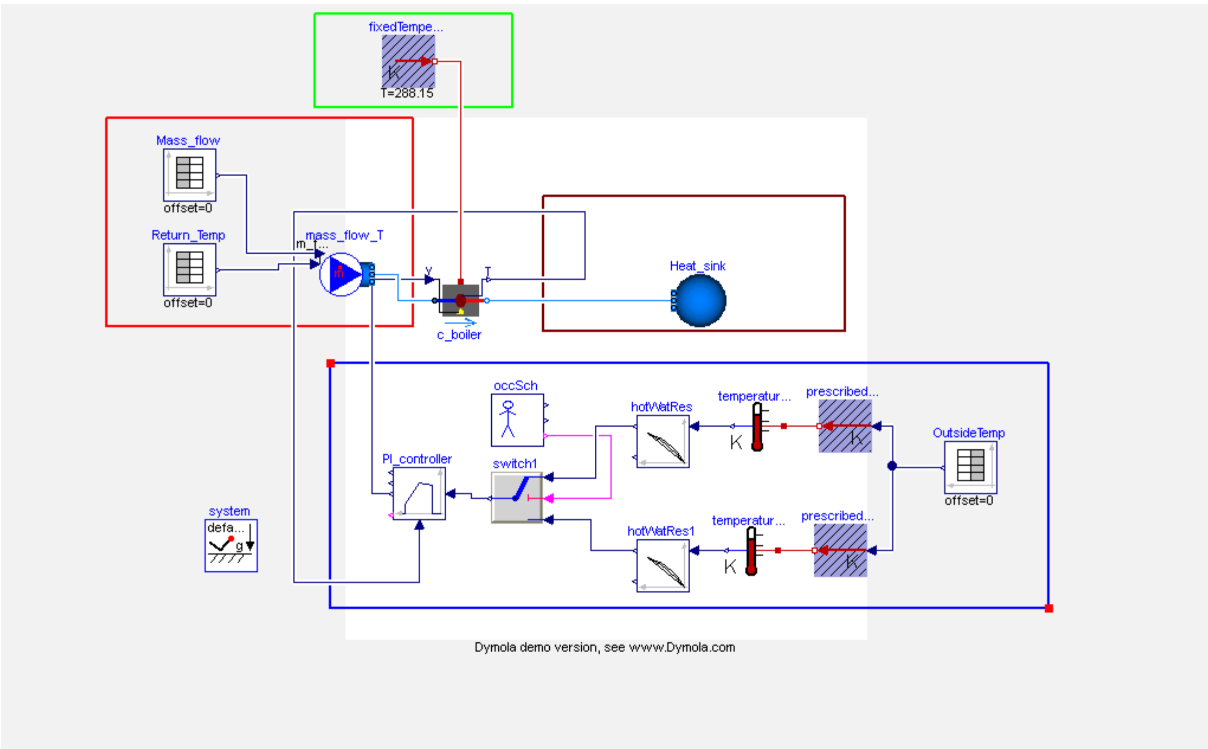


Figure 6.1: Boiler room model

The boiler room model was modeled in Dymola using the existing component models from the available Modelica libraries. The boiler, mass flow source, heat sink and the control loop elements models were used from the LBNL building library.

The Boiler room model, which is capable of simulating boilers thermal performance contains a control system for simulating boiler controls and a boiler model with routines for simulation of heat input to water from combustion, boilers heat capacity (water and metal mass lumped under one state) and boilers heat losses to the ambient. Although the boiler model from the Buildings library can either be used for conventional boilers or condensing boilers, only the results from condensing boiler simulation will be used in this work. Figure 6.1 is a schematic view of the boiler room model:

The part load input y to the boiler model component is controlled by a control-loop consisting of hot water reset controls for day and night set back, occupancy schedule control, a logical switch and a PI-controller. The outdoor air temperature measurements, previously interpolated using time-table model component labeled *OutsideTemp*, are sensed by an absolute temperature sensor model component *temperatureSensor* which outputs the temperature values in Kelvin to the hot water reset controls. The hot water reset models components for day and night set back *hotWatRes* and *hotWatRes1* compute the supply and return set temperatures based on nominal conditions for the supply, return, outside and room temperature. The supply and return temperature are derived from the energy balance by which the heat transfer from hot boiler water to radiators, heat transfer from radiators to room and heat transfer to environment should be equal:

$$\frac{Q_{bhw-rad}}{Q_{bhw-rad}^{n}} = \frac{Q_{rad-room}}{Q_{rad-room}^{n}} = \frac{Q_{env}}{Q_{env}^{n}}; (1)$$

n-as superscript denotes nominal conditions

m - heating body exponent

$$\frac{t_S - t_R}{t_S^N - t_R^N} = \left(\frac{\Delta t_n}{\Delta t_n^N}\right)^n = \frac{t_{room}^{set} - t_{out}}{t_{room}^N - t_{out}^N}; (2) \rightarrow \Delta t_n \Rightarrow \Delta t_n^n \left(\frac{t_{room}^{set} - t_{out}}{t_{room}^N - t_{out}^n}\right)^{\frac{1}{n}} \; ; (3)$$

From (2):

$$t_S - t_R = (t_S^n - t_R^n)\left(\frac{t_{room}^{set} - t_{out}}{t_{room}^N - t_{out}^n}\right); (4)$$

Additional condition:

$$\Delta t_m = \frac{t_S + t_R}{2}; (5) \Rightarrow t_S + t_R; (6)$$

Adding (4) and (6) gives

$$t_S = \Delta t_m + \frac{(t_S^n - t_R^n)}{2}\left(\frac{t_{room}^{set} - t_{out}}{t_{room}^n - t_{out}^n}\right); (7)$$

And from (6) and (7):

$$t_R = \Delta t_m - \frac{(t_S^n - t_R^n)}{2}\left(\frac{t_{room}^{set} - t_{out}}{t_{room}^N - t_{out}^n}\right); (8)$$

$$\Delta t_n^N = \frac{(t_S^n + t_R^n)}{2} - t_{room}^n; (9)$$

And from (7) and (9) and (3):

$$t_S = (\frac{(t_S^n + t_R^n)}{2} - t_{room}^n)\left(\frac{t_{room}^{set} - t_{out}}{t_{room}^N - t_{out}^n}\right)^{\frac{1}{n}} + \frac{(t_S^n - t_R^n)}{2}\left(\frac{t_{room}^{set} - t_{out}}{t_{room}^N - t_{out}^n}\right);$$

$$t_R = (\frac{(t_S^n + t_R^n)}{2} - t_{room}^n)\left(\frac{t_{room}^{set} - t_{out}}{t_{room}^N - t_{out}^N}\right)^{\frac{1}{n}} - \frac{(t_S^n - t_R^n)}{2}\left(\frac{t_{room}^{set} - t_{out}}{t_{room}^n - t_{out}^n}\right);$$

The set supply temperature output of both reset models is then connected to a logical element *switch1* that based on an occupancy schedule model defines when the system comes out of setback or goes into setback. The logical element switches between two possible input signals: the upper and lower connector based on the logic of the middle connector that is connected to the occupancy schedule model *occSch*. The upper connector is connected to the reset model *hotWatRes* for day-set back while the lower connector is connected to the reset model for night set-back *hotWatRes1* as shown in Figure 6.1.

The occupancy schedule model is defined by a schedule of the form:

Occupancy =3600 *(7, 15)

This indicates that during the occupancy from 7 AM to 3 PM, the logical element outputs the set supply temperature from the upper connector with nominal conditions for day set back:, while during non-occupied hours it is switched to the set-supply temperature from the lower connector that is connected to the hot water reset model for night set back. The PI controller model component *PI_controller* receives the set supply temperature from the logical *switch1* and compares the set value to the actual supply temperature from the boiler model component. The model component manages the error using a hysteresis element. Instead of controlling the process precisely to the set-point (e.g. 59) the controller will respond when the present value of the supply temperature is +/- 2.5 within the range of the set-supply temperature. This gives 5 degree band for hysteresis response. If the control error becomes larger than 2.5, then the controller switches to on and remains on until the control error is smaller than 2.5. When the controller is on, the set point tracking is done using a PI-controller. In its off-mode, the control output is zero. The controller has a timer that prevents the burner switching on too fast. When the controller switches off, the timer starts and avoids the controller from switching on until a minimum time interval has elapsed. This property prevents short cycling explained in Ch.2. if the load is small and the system has little heat capacity.

The model *mass_flow_T* is an ideal flow source that produces a prescribed mass flow rate with prescribed temperature, mass fraction and trace substances. It simulates the mass flow rate through the circulation pump of the boiler room. The flow component is connected to the inlet fluid port of the boiler model, thus generating the mass flow input with prescribed return temperature conditions. The time-table components *mass_flow* and *Return_temp* generate mass flow and return temperatures measurements from Sarajevo as input to the mass flow source, respectively.

The boiler models heat port is connected to prescribed temperature component with boundary conditions to model heat losses to the ambient environment.

The consumption side (heat output of the boiler) is note the primary subject of the current part of the work and is modeled as a simplified object/volume which is heated uniformly. The consumption side will be discussed in detail in the Example of Application in ch.7.

6.1. Mathematical interpretation of the model

The mathematical interpretation of the boiler model will be given as a result of analyzing the energy balance f the mixing volume explained in ch.3 and the characteristics of stream connectors in Modelica explained in ch. 5.:

Since we have a one-directional fluid flow between two fluid port_a and port_b for the boiler model in the boiler room we can rewrite the enthalpy flow rates across the fluid ports:

```
ports_H_flow[a]     = ports[a].m_flow * actualStream(ports[a].h_outflow)

ports_H_flow[b]     = ports[b].m_flow * actualStream(ports[b].h_outflow)
```

The sum of the enthalpy flow across the volume boundaries can now be written as:

```
Hb_flow = ports[a].m_flow * actualStream(ports[a].h_outflow)+
ports[b].m_flow * actualStream(ports[b].h_outflow)
```

and the Energy balance as follows:

```
der(U) = ports[a].m_flow * actualStream(ports[a].h_outflow)+
ports[b].m_flow * actualStream(ports[b].h_outflow)+Q_flow
```

Using the properties of the actualStream operator when connecting fluid ports with stream variables (enthalpy flows):

```
der(U)= - ports[a].m_flow * ports[a].h_outflow + ports[b].m_flow * inStream
(ports[b].h_outflow)+Q_flow
```

The heat input to the boiler model is described by the equation Q_flow $= \dot{Q}_0 \frac{\eta(y,T)}{\eta(1,T_0)} y$. The boiler model also exposes a heat port of a heat conductor to allow modeling heat losses to the ambient environment the total energy balance can be finally written as (following the balance equation at heat ports (3) :

$$\frac{dU}{dt} = \dot{m}(h_b - h_a) + \dot{Q}_0 \frac{\eta(y,T)}{\eta(1,T_0)} y - UA \cdot \left(T_{supply} - T_{outside}\right)$$

The UA value can be tuned in the boiler model parameterization. Since the design flow direction is given, can be solved for the outlet temperature, since T=T_{supply} and the specific enthalpy h_b=$c_p \cdot T_{supply}$. The density ρ and the specific heat capacity $c_p$can be calculated as functions of temperature. As the specific heat capacity of the metal content of boiler is lumped to the water volume heat capacity, the change in the internal energy (the heat capacity of the lumped element) of the boiler assuming ideal mixing can be written as:

$$\frac{(\rho c_p V_{water} + c_p m_{metal}) dT}{dt} = \dot{m} c_p (T_{supply} - T_{return}) + \dot{Q}_0 \frac{\eta(y,T)}{\eta(1,T_0)} y - UA \cdot (T_{supply} - T_{outside})$$

The boiler model generates the supply temperature in accordance to the mathematical model. Since the mass flow rate input is equal to the mass flow rate output under steady state conditions, the UA value can be selected so the supply temperature can be optimized with known inputs of return mass flow rate and temperature, as modeled in the boiler room and assuming the control signal is correctly manipulated by the heating curve. The metal mass, water volume and the UA conductance parameter data can be modified in the existing boiler model from the Buildings Library.

6.2. Physical properties

The physical properties of boiler at nominal load are taken from the manufacturer submittal are provided with the description below.

Physical Property	[unit]	Value
Nominal thermal load	[kW]	404
Weight – Boiler Body	[kg]	596
Total Weight –Boiler with burner, thermal insulation and boiler control unit	[kg]	736
Content -Boiler water	[litres]	260
Thermal Conductivity UA –Stainless steel	$\left[\frac{W}{mK}\right]$	15

Table 6.1: Physical properties of boiler

The control data, including the nominal set return, supply and outside air temperature for the heating curve were set in accordance to the current operating conditions set at the boiler control in the MEF boiler room. The parameters for the heating curve with day set-back are *60*°C for supply water temperature and *45*°C for return water temperature at an outside temperature of *-16*°C and a room temperature of *21* °C, while the parameters for night set-back are *60/45/-16/17* respectively. The temperature of the ambient conditions in the boiler room is set to 15°C.

In the current model the boiler is set to have 20% additional capacity compared with the heating needs at the designed conditions. The modulating boiler with outside compensation (open loop) PI control is used, with hysteresis ±2.5^{o}C and minimum cutoff time of 600 s and minimum operational capacity of 30%. It is supposed that the current outside temperature determines the supply water temperature instantly according to the heating curve (no inertial constant in outside temperature averaging).

6.3. Validation of the model

The aim of the boiler room model is to predict the thermal behavior during different time intervals and load conditions in the boiler room in accordance to measurement data. To validate the Modelica boiler model a comparison was made between the supply water temperature measured during the field trials and the supply water temperature calculated by the boiler model. The data recorded the boiler room in Sarajevo included:

- Supply water temperature
- Return water temperature
- Outside air temperature
- Mass flow
- Temperature inside the boiler room

As input for the Dymola simulation, the return temperature, outside air temperature and the mass flow rate were used for various time intervals in the month of July 2013, based on hourly measurements and data collected in 5-minute intervals from the MEF boiler room in Sarajevo. The measuring data process was 9 days long (starting at 15.03.2013 00:00:00 and ending at 23.03.2013 23:55:00), with measurements taken at a frequency of 5 minutes for the first iteration. The second iteration was 6 days long (starting at 08.02.2013 00:00:00 and ending at 13.02.2013 23:55:00), with measurements taken at a frequency of 5 minutes as for the first iteration. The third iteration included separate simulation runs for four different days based on 5- minute measurements to outline the importance of the return temperature on the boiler efficiency.

All simulations have been done using the Dymola 7.4 FD01 simulation program for Modelica on Windows 7 using one 2.67 GHz Intel Xeon processor. The total system model contained 62 components that led to a differential algebraic equation system with 241 scalar equations. The translated model had 2 continuous time states and 7 nonlinear systems of equations with no numerical Jacobians. The simulation of the boilers model thermal behavior in terms of the output supply temperature for the first iteration is shown below:

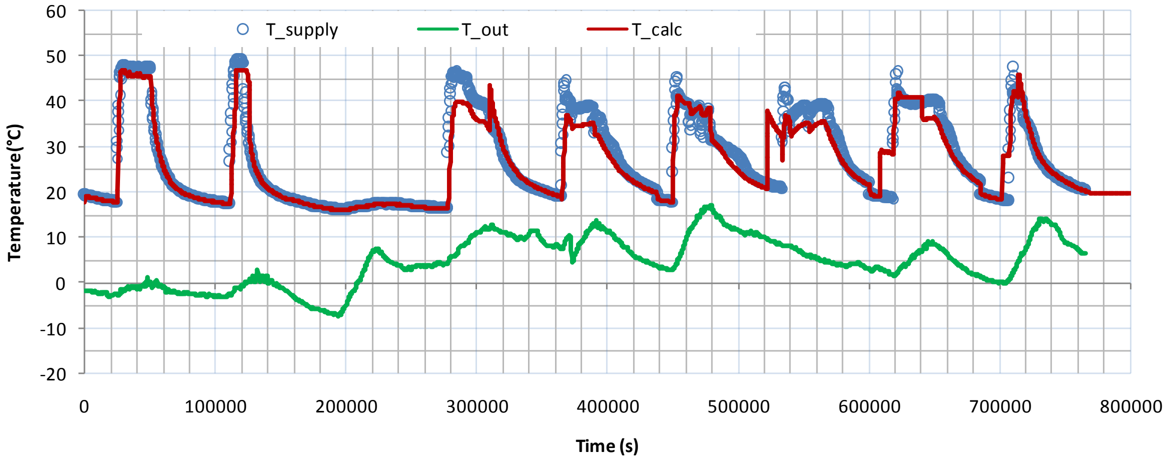


Figure 6.2: Simulation results vs. Measurements 15.03. - 23.03.2013

The boiler model generates the supply temperature in accordance to the mathematical model described in the validation section. The model captures the temperature variations, particularly the swell and shrink capture of the meausurments supply temperature very well.

Te differences between the model predictions and the experimental measurements occur when the outside temperature of the boiler is relatively high and the boiler is cycling in ON/OFF mode, as shown in Fig 1. This can possibly be attributed to factors of the complex assemblies of mechanical, electrical and electronic components of the control technology in the boiler room in Sarajevo that are no taken into consideration by the Modelica model control components for same heating regimes. In the first setback the night temperature setback ends at 6.AM and begins at 15 PM. The sudden rise and drop in the temperatures occur as the system comes out of setback or goes into setback.

From figure 6.2. and the first day it is clear that the boiler water temperature is kept close to the average set point value 45°C for 7 hours and the supply set-point water temperature is varying along with the outdoor temperature as the control modulate the heat ouput in response to changes in outdoor air temperature. The supply temperature is relatively low when the boiler is for (around 41°C), higher outside tempertures as the temperature rises during the occupancy scheudele up to 5°C. The Modelica supply temperature captures the data during on-mode (7 AM-3 PM), but that cannot be said for the period when the boiler is cooling down: the passage from one temperature level to another is quicker in the model than in the real data: this can be related to the reduced building thermal inertia considered in the simulation.

From figure 6.3. it can be seen that the boiler supply water temperature response is very good when considering that the system does not receive any feedbackfrom the room temperature. This is outlines importance of the PI controller that commands the supply temperature to “catch” the set-point value accurately, even though no feedback is present from the building.

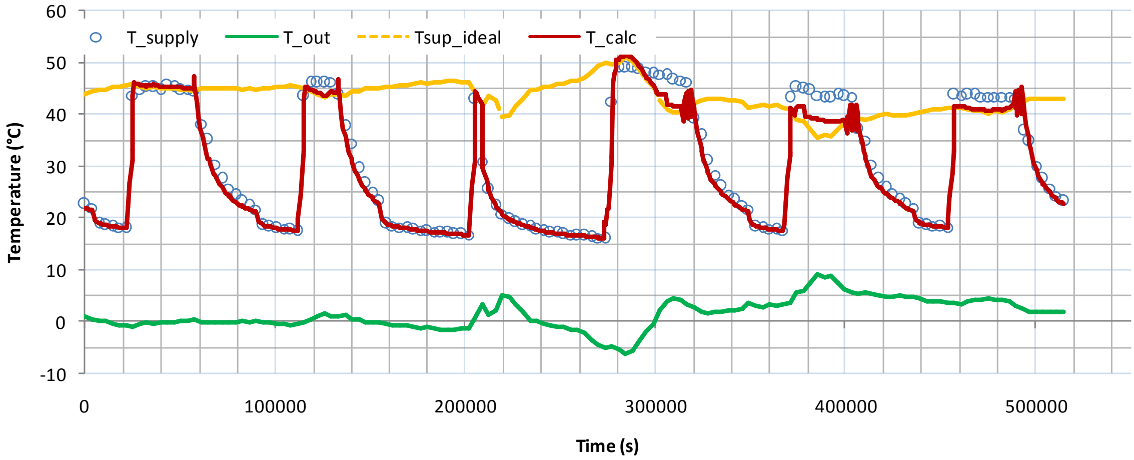


Figure 6.3 : Simulation results vs. Measurements 08.02-13.02.2013(1)

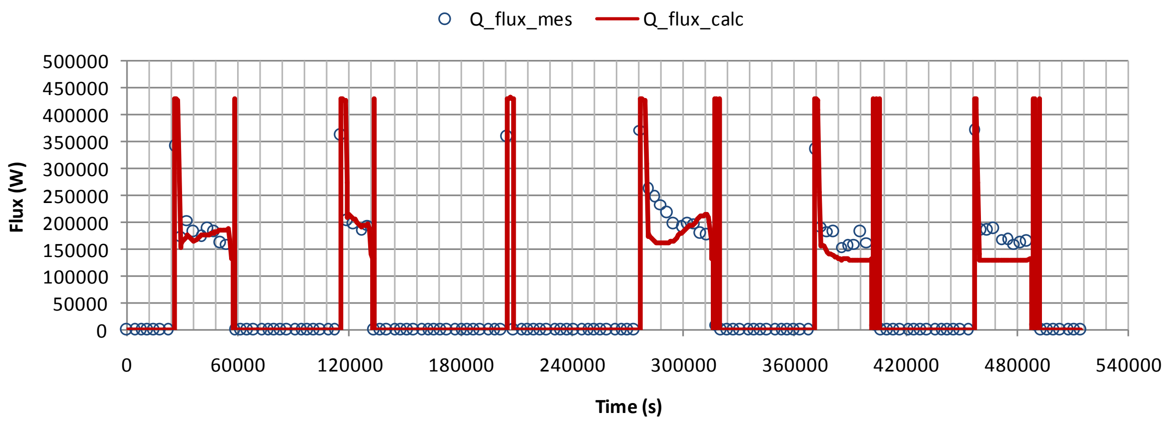


Figure 6.4 : Simulation results vs. Measurements 08.02-13.02.2013(2)

The model open loop-control, including the outdoor reset control with a heating curve captures the supply temperature very well. It is important to notice that the simulations run were based on relatively mild outdoor temperature, and lower return water temperature, and so allowing condensing mode of the boiler.For the third day one have to take into account that it is a Sunday and the on-mode is shorter than usual (8.AM-14 PM, instead of 7 AM -16 PM), thus less heat is stored and the cooling is faster. The last day has the coldest outside temperatures slightly below (0°C). As the temperatures are colder, the outdoor reset control calls for higher supply temperatures. Again there is a gap between the model and measuerement data during the cooling down phase but this due the same reason explained for the day 06.02. Figure 6.4. Compares the heat transffered heat flux to the boiler water as calculated by the Dymola solver and the measured heat flux. The calculated data shows good agreement with results.

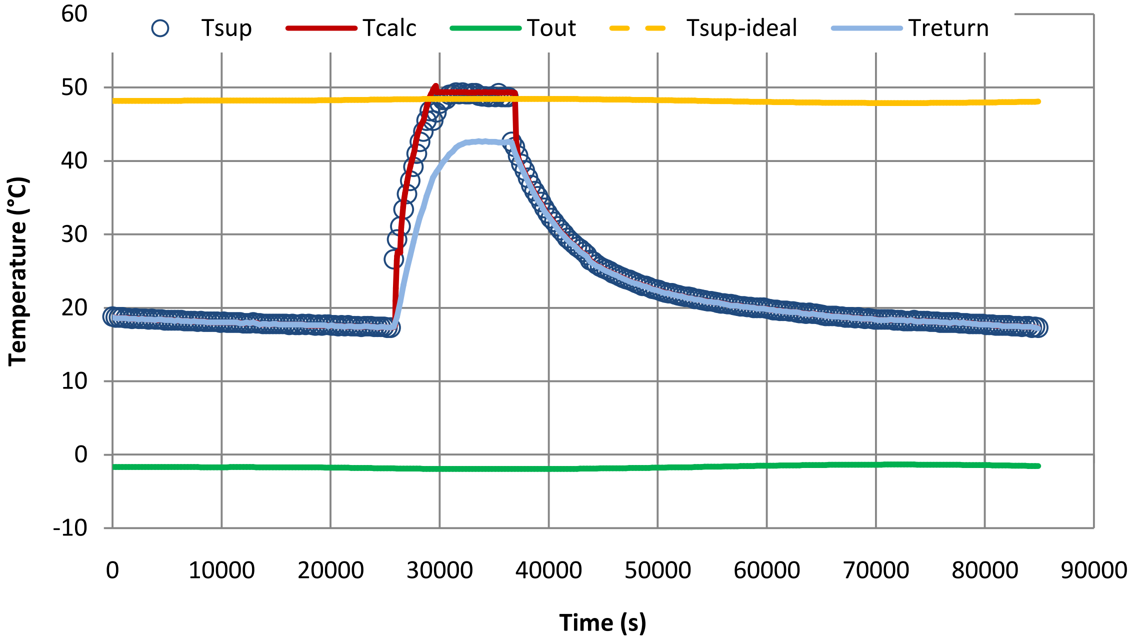


Figure 6.5: Simulation vs. measurement results for 16.03.2013

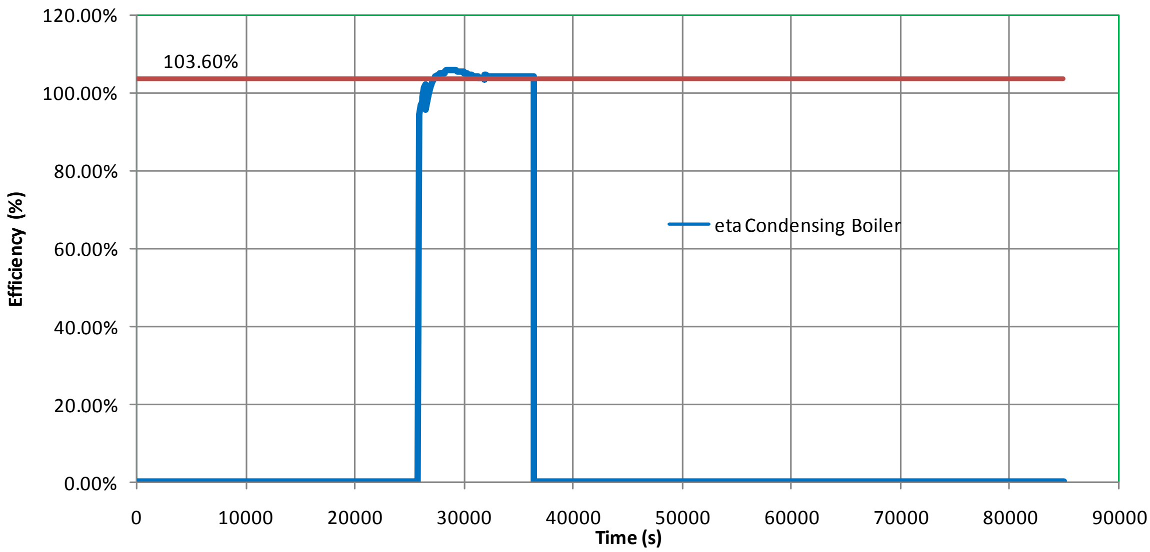


Figure 6.6.: Simulation results for 16.03.2013.

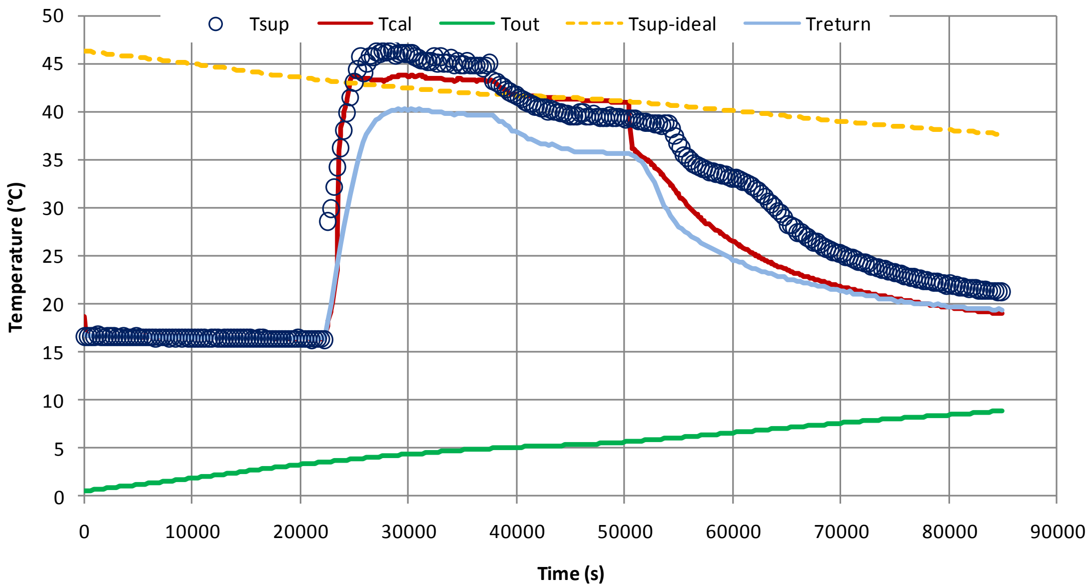


Figure 6.7: Simulation vs. measurement results for 18.03.2013.

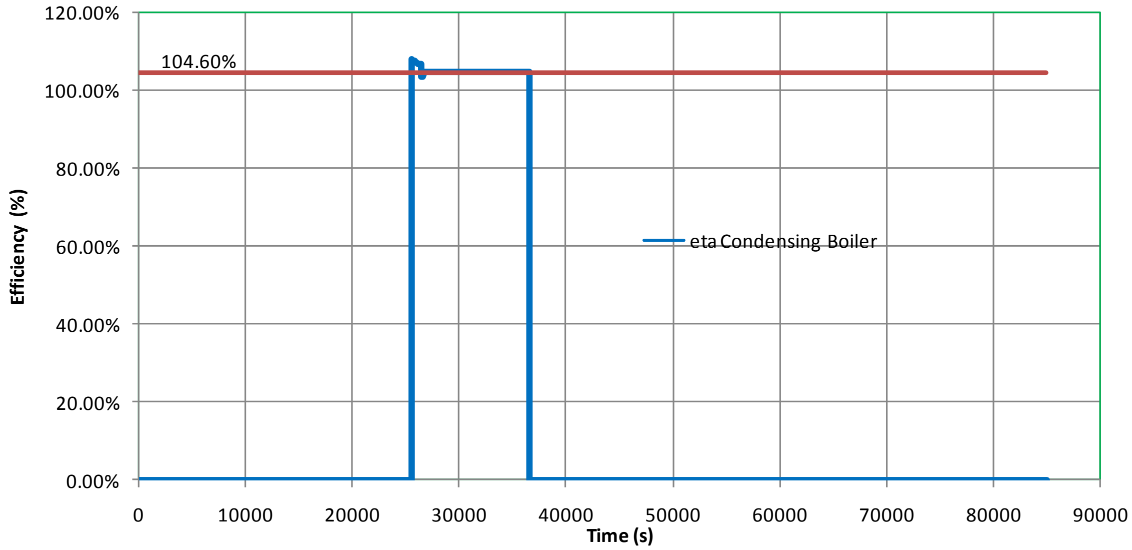


Figure 6.8: Simulation results for 18.03.2013.

Figures 6.5. and 6.7. show the supply, return and outside temperature profiles for two different days 16.03. and 18.03 based on 5-minutes measurements. The heating curve set-supply temperature is also shown to depict correct performance of the boiler control unit. The outside temperature for 16.03 varies between 5.8°C at and 8.5°C during the occupancy period with an average outside temperature value of 7.51°C. Using the same weather data for 16.03. the outside temperature varies between -2.65°C and –0.35°C, while the average temperature for the ON period is -1.47. The average return water temperature for 16.03. is 42°C, while the average return temperature for 18.03 is slightly below 40°C. The efficiency values of the condensing boiler for the same days are shown in Figures 6.8 and 6.10. For 16.03 the average efficiency is 103.6% (LHV) as shown in 6.8. The corresponding efficiency value for 18.03 is slightly higher, 104.6 % as shown in Figure 6.10. This due to the fact that condensing boiler achieves higher efficiency for lower return water temperatures as shown in Figures 6.8 and 6.10.

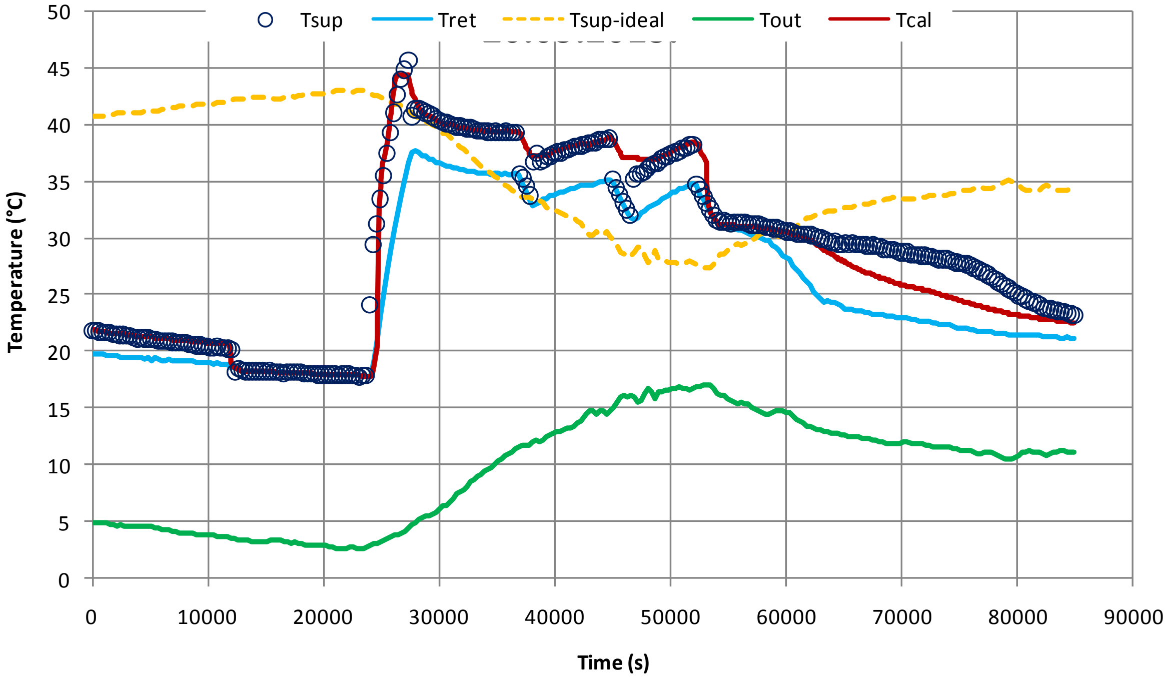


Figure 6.9: Simulation vs. measurement results for 20.03.2013.

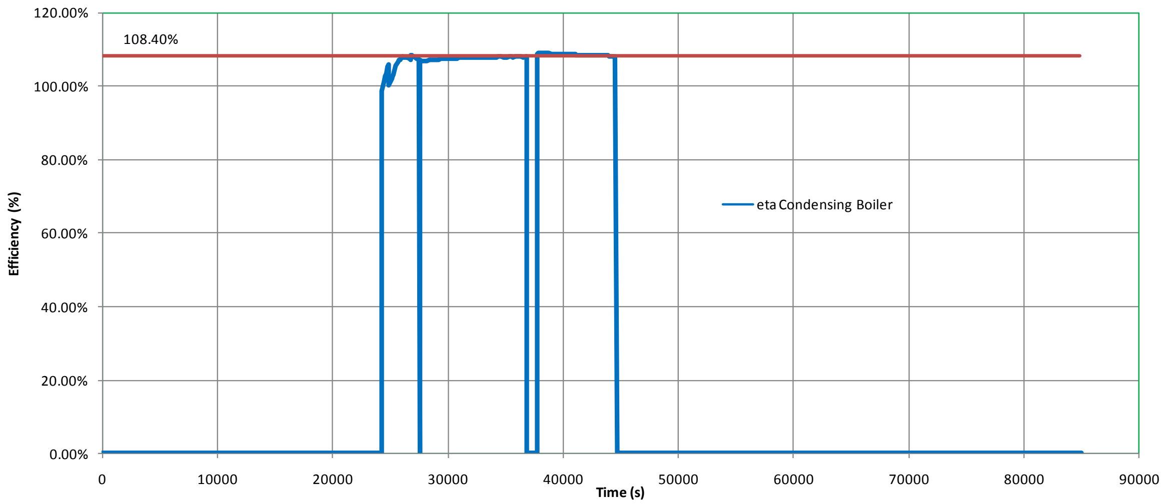


Figure 6.10: Simulation results for 20.03.2013.

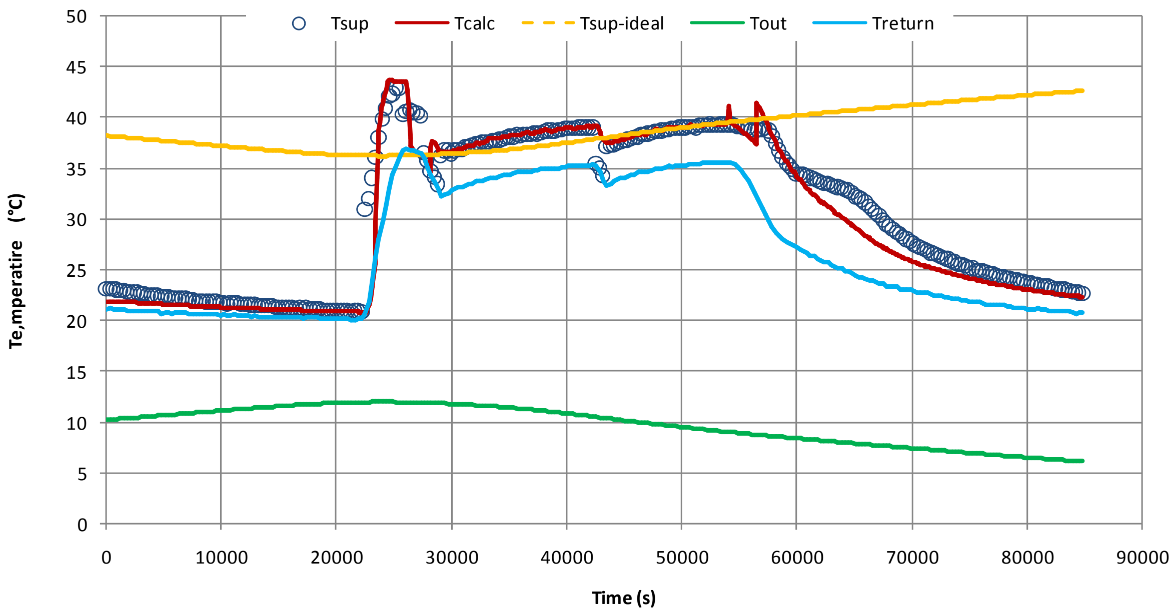


Figure 6.11: Simulation vs. measurement results for 21.03.2013.

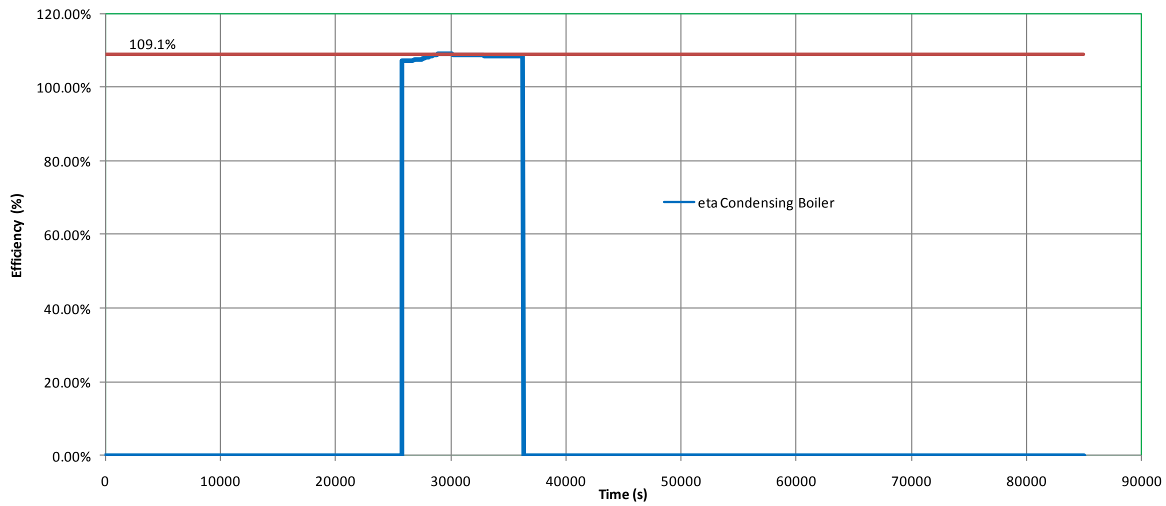


Figure 6.12: Simulation results for 21.03.2013.

The effect of the return water temperature on the boiler efficiency is illustrated again for the next two days simulated: 20.03. and 21.03. 2013. as shown in figures 6.9-6.12. From the results of simulation exercises Figure 6.9 for 20.03. it can be seen that the average outside temperature under boiler operation is 8.4°C, while simulation results in Figure 6.11 for 21.03. shows the average outisde temperature of 11.7°C. The average return water temperature for 20.03. is 34.8°C, while the average return temperature for 21.03 is slightly below 33.2°C.The same pattern for higher efficiences at lower return temperatures is demonstrated for the two days in Figures 6.10 and 6.12, respectively. For 20.03 the average efficiency is 108.4% (LHV).The efficiency of the condensing boiler for 21.03 is slightly higher, 109.1 % as shown in Figure 6.12. All of the 4 days simulated show the same pattern for condensing boiler as described in the theory part : The lower the return water temperature, the more condensate forms, thus increasing the utilization of latent heat of vaporization in the boiler that resulting in higher overall efficiencies.

7. Example of Application

In the previous Chapters in theoretical and part with examples the major focus was put on the boiler and the boiler room. In the real life situations the boiler is always one component in the heating system. In what follows the results of the simulations will be presented for the models of the whole heating system. Boiler will be a part of the energy generation side, distribution side will be covered with circulation pump(s) and the pipelines and at the end the consumption side will be modeled. The following examples demonstrate fully coupled modeling problem of the heating system. All models consist of the following components:

- Boiler with its automatic control,
- circulation pump with its control,
- supply and return pipeline with calculation of the heat loses in the pipeline,
- radiator as the heat source at the consumption side,
- room with the multilayer construction of walls, with attached windows, with modeled influence of the infiltration of the outside air, with inner walls surrounding the room and the additional lumped heat capacity (furniture, books, etc).

Most of the used components are taken from the standard Buildings library except the room model. The room model is a simplified version of the existing standard room model from the library. It was 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 solar heat gains. It is estimated that the introduction of the radiative heat transfer does not influence the heat balance tremendously especially during the peak consumption months in the heating season. At the other hand, if one excludes the radiative heat gains the number of equations decreases significantly and it is possible to make calculation with multiple rooms [29]).

The room model, developed by Teskeredzic [30] takes into account: infiltration losses prescribed by the number of volume air changes per hour, wall structure can consist of arbitrary number of layers with different physical properties and the influence of windows on the heat transfer is taken into account as a transmission heat portions room envelope (thermal capacity of windows in neglected). In all calculations which will be demonstrated the solar gains as well as the internal gains were not taken into account.

7.1. Objective of simulations

As a result of the Energy Efficiency Improvement (EEI) project at the Mechanical Engineering Faculty in Sarajevo the following measures were applied: replacement of old windows with new more efficient ones, existing walls are insulated with 10 cm thick PVC insulation and the new condensing boiler is installed. The main objective of the following examples is to demonstrate the applicability of the Buildings library on a real-life problem simulation in which transient effects are important to capture. In that sense, the energy savings as a result of the EEI measures can be estimated with higher degree of accuracy than in the case that the standard engineering approach is used. Standard approach is mostly used to evaluate ex-ante savings from EEI projects assuming the quasi steady state and the energy savings are calculated according to the temperature differences between the prescribed set room (space) temperature and the average temperature during the calculation period (or the whole heating season). Modeling and simulation tools, at the other side, use transient solver and some effects not recognized by the standard approach can be captured. In the Discussion of results subsection some important differences between standard and detailed approach will be outlined. At the end, for the period of nine days for which the measurements of the outside temperature exists, the energy consumption will be estimated for baseline (before EEI measures) and after the EEI measures. Additionally, in order to demonstrate the applicability of the simulation tool different energy efficient measures and their influence on the energy savings are analyzed as presented in the Table below.

Energy Efficiency Improvement measures	Consumption side		Generation side
	Insulation	Windows	Bolier
Baseline (before EEI)			
Option 1	+		
Option 2		+	
Option 3	+	+	
Option 4			+
Option 5	+		+
Option 6		+	+
New (after EEI)	+	+	+

Table 7.1: Simulated energy efficiency improvement measures.

Note that Table 7.1 shows the different options of EEI measures, the first row represents the baseline condition before any EEI measures and the last row represents the actual status after the EEI measures.

7.2. Problem description

Heating system model in Modelica is given in Figure 7.1 and consists of the following components: boiler with its automatic control, expansion vessel, circulation pump with its control, supply and return pipeline, radiator and the already mentioned room model. For the following calculation a single room model is made, based on the dimensions of the existing room at the fourth floor of the Mechanical Engineering Faculty building. Physical properties of the multi-layer construction are taken from the existing wall and the U values for windows is used based on the manufacturer data.

Material	Conductivity [W/mK]	Specific heat [J/kgK]	Density [kg/m^3]	δ [mm]
Plaster	1.40	1,050.00	2,100.00	20.00
PVC Insulation	0.04	1,260.00	20.00	100.00
Brick	0.64	920.00	1,600.00	250.00
Plaster	0.81	1,050.00	1,600.00	20.00

Table 7.2: Physical properties and thicknesses of the wall layers.

Multi-layer construction (see part of Figure 7.2 in green rectangle) consists of the three layers for the baseline building and four layers for the wall after the additional layer of insulation is installed (PVC Insulation layer in Table 7.2). Physical properties of the wall are given in Table 7.2. Note that Figure 7.1 represents the case of the already refurbished building with four layers in the wall construction.

Circulation pump is set up as the pump with fixed flow rate. Although, the real pump installed at the facility is frequently controlled pump (note that model of this pump also exists in the Buildings library) due to non-existing thermostatic valves at the radiators the real pump practically operates as the fixed flow rate pump. Taken into consideration the available measurements and as a result of the fact that the heating system is not perfectly hydraulically balanced, a 20% more mass flow rate is prescribed in the existing model, than the flow rate which corresponds to the design conditions.

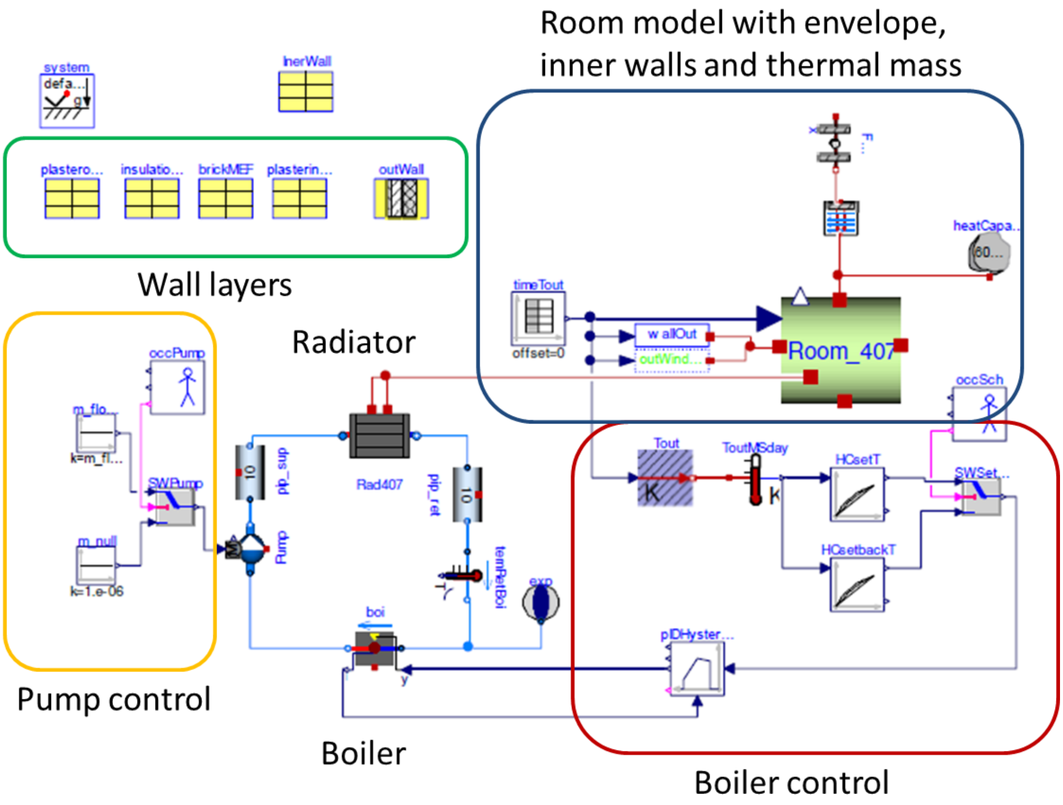


Figure 7.1**:** Component and model description of the simulated problem.

Supply and return pipes are 12 mm in diameter and 20 m long each. Expansion vessel which controls the increase of the pressure in the system is set with max allowable pressure of 5 b with 2 m^3 volume. The occupancy schedule for boiler and pump are identical and are set having in mind the assumption that system works for 9 hours per day, starting from 6 AM until 3 PM. It is supposed that the initial moment when the calculation starts is the time at which heating system switches from ON to OFF (3 PM). The influence of the non-working days and operating conditions during the weekends are not taken into account.

In the current models the boiler in both cases is set to have 20% additional capacity compared with the heating needs at the designed conditions. In both cases the same modulating boiler with outside compensation (open loop) PI control is used, with hysteresis ±2.5°C and minimum cutoff time of 600 s and minimum operational capacity of 30%. It is supposed that the current outside temperature determines the supply water temperature instantly according to the heating curve (no inertial constant in outside temperature averaging).

Simulations which are conducted as part of the application example are:

- Validation of the model on steady-state heating system for designed conditions
- Comparison of energy consumption before and after EEI measures
- Analysis of energy savings for different EEI scenarios

7.2.1. Validation of the model on steady-state heating system for design conditions

Before the comparison of the cases before and after the EEI measures is made, the coupled model is validated on a simple case for which an analytical solution exists. The case is set up with fixed outside temperature which corresponds to the design temperature during the heating season (T_{out} = -16^{o}C). For this test case, boiler and radiator are dimensioned to cover the steady heat losses coming from the transmission through walls and windows and infiltration of the outside cold air into the room. As a result, the heat flux provided by radiators and supplied by the boiler should balance the heat losses from the room when the steady-state is reached. In this case the mass flux rate is set to the design value such that the boiler (and radiator) supply and return temperature value should be equal to the temperatures in the designed conditions or in this case T_{sup} = 90^{o}C and T_{ret} = 70^{o}C (see Figure 9.2).

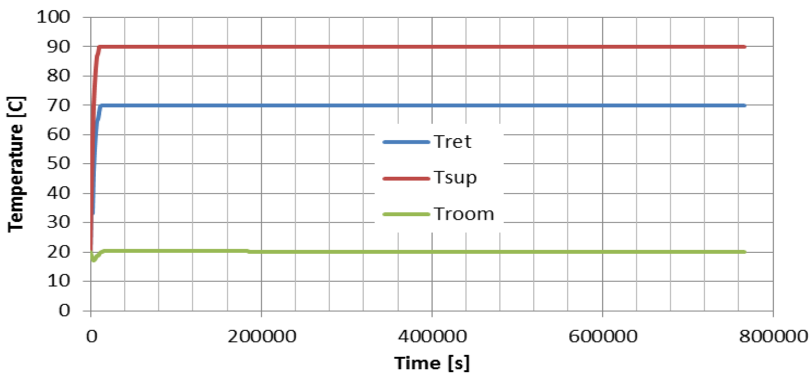


Figure 7.2**:** Boiler supply and return temperatures in steady (design) conditions.

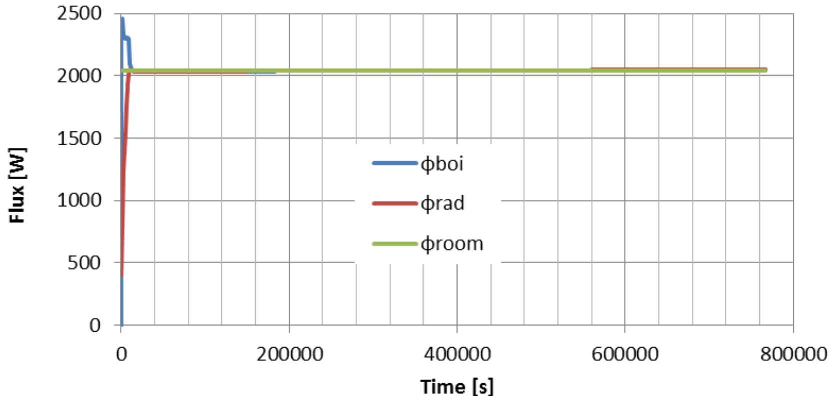


Figure 7.3: Heat fluxes from boiler, radiator and room, balanced in steady state (design) condition.

Results of the simulation are presented in Figure 7.2and it can be seen that the test procedure was successfully conducted. Supply boiler temperature, return boiler temperature and the room temperature are equal to analytical solution values. In Figure 7.3 heat fluxes from boiler, radiator and room are in balance (are equal).

This means that the heat transferred to the hot water in the boiler is equal to the heat released from the radiator to the room which is at the end equal to the heat transferred from the room to the environment. Above mentioned tests clearly show that the model produces correct and expected results. Note that for validation case the heat losses in pipeline and in the boiler room are neglected.

7.2.2. Comparison of energy consumption before and after EEI measures

After the testing procedure is conducted, the results from the cases before and after the EEI measures will be discussed. The test simulations are run for 9 days of heating with variable outside temperature (see Figure 7.4), based on the measurements in 5 minutes interval. It is important to note that in the baseline case,fixed efficiency of the old boiler is assumed (η=84%) which corresponds to the seasonal efficiency of the old boiler. This estimation was done during the preparation of the EEI project at Mechanical Engineering Faculty as part of the prefeasibility study.

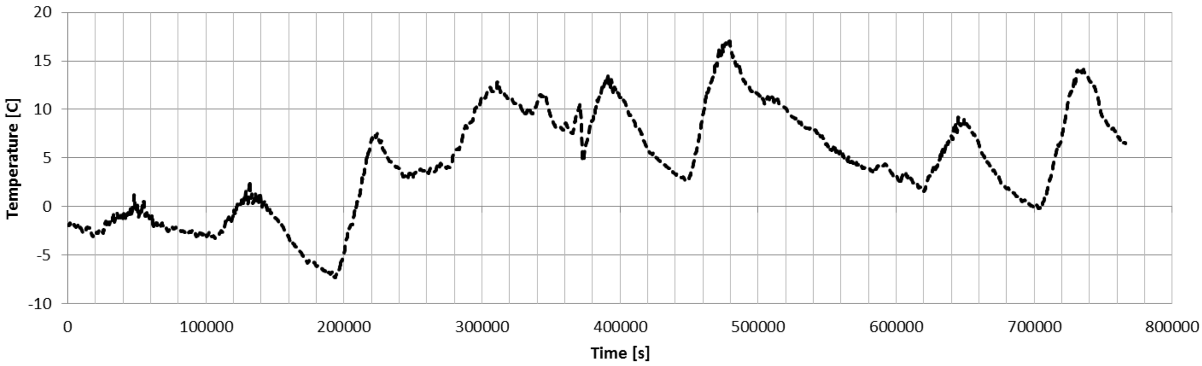


Figure 7.4**:** Outside temperature measured in 5 minutes interval.

In Figure 7.5 room temperatures for both calculated cases are given.It can be seen that the temperatures in the room for both cases in the period of occupancy are almost identical for both calculated cases, which is ideal for comparison of the energy consumption before and after the EEI measures.

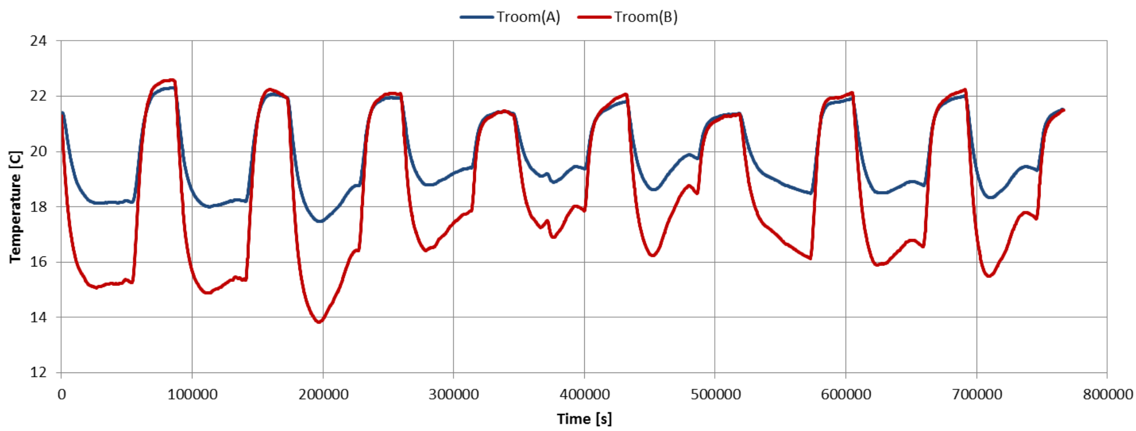


Figure 7.5: Room temperatures before and after EEI measures

It can be noted that the space is overheated in the observed period, which can at the end influence the calculated energy savings. Analyzing the temperature profiles in the room it is visible that for the baseline building temperature drops significantly during the night periods when the heating system is OFF, which can be easily explained by the higher heat losses from the baseline building.

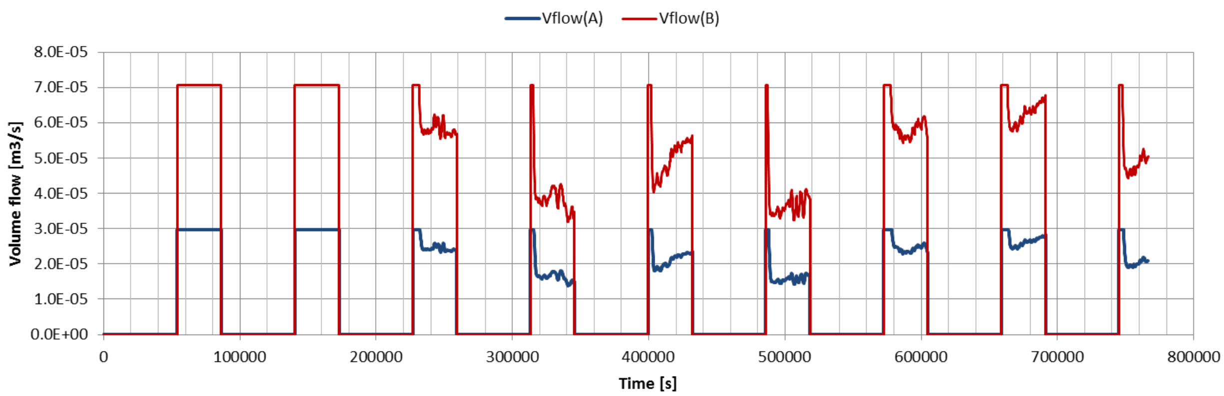


Figure 7.6: Volume flow of natural gas before (B) and after (A) EEI measures.

In Figure 7.6 the volume flow of natural gas is shown for both cases in which is clearly visible that the natural gas volume flow (and energy consumption as well) is significantly higher for baseline conditions (before EEI measures). For the observed period of nine days and based on the values of the volume flows, the total consumption of natural gas was calculated. High differences between natural gas consumption for the observed cases come from the fact that the heat need at the consumption side decreased as a result of new insulation layer in the wall construction and installation of new windows, which affected not only the transmission heat transfer than also influenced the infiltration losses. Additionally, a new boiler with significantly higher efficiency is installed and also influenced the gas consumption. At the end it should be said that the seasonal efficiency of the old boiler was rather low compared with the efficiency of the new condensing boiler.

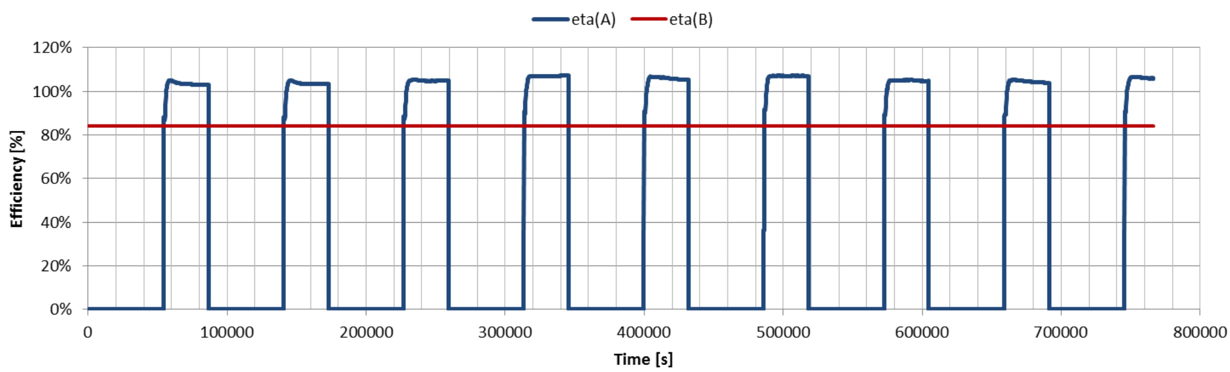


Figure 7.7**:** Efficiencies of boiler before (B) and after (A) EEI measures.

Figure 7.7 shows the differences in efficiencies of the new installed condensing boiler and the old one for which a constant value of 84% was prescribed in the calculations. Period efficiency of the condensing boiler is calculated as:

$$\eta_{period} = \frac{\sum_{i=1}^{NP} \eta_i \delta_i}{\tau_{ON}} \quad 7.1$$

Where η_{period} is the efficiency of the condensing boiler in the observed period, η_i is the efficiency during the time step δ_i, NP is the number of time steps when the heating is ON and τ_{ON} is the total time in which the heating is ON.

By using eq. 7.1 the efficiency of the new boiler is $\eta_{period} = 104\%$. This is high efficiency which can be explained by the fact that the return water temeprature in most of the time of calculation was bellow due point for flue gasses (see Figure 7.8).

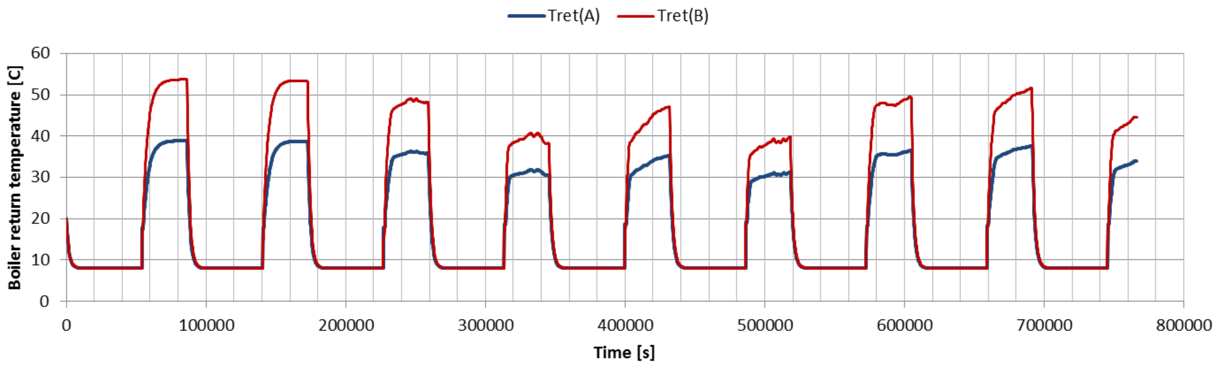


Figure 7.8: Boiler return temperature before (B) and after (A) EEI measures.

Finally, after integrating the volume flow of natural gas in the whole heating period the total consumption of the gas for both cases is obtained. Energy savings for the case after EEI measures is 57,5% based on the baseline consumption. If one takes into account the fact that the average outside temperature in the observed period was 4.6°C which is close to the average temperature in Sarajevo during the heating season (4.4°C), it means that these relative savings can be extrapolated for the whole season.

At the end it should be noted that for the building without thermal insulation (baseline building) temeprature in the observed room drops to 14°C, which is too low. In that case, it is expected that the heating system should also work for some period when the space is not occupied (during the night) which will lead to the additional energy consumption. In the refurbished building, due to the high thermal mass of the building and decreased heat losses because of the insulation and new windows the cooling over night is not so drastic. Namely, the temprature drops approximately to 18°C and no additional heating during the night is necessary.

7.2.3. Analysis of energy savings for different EEI scenarios

Applicability of the simulation tool on the analysis of the different EEI measure options are given in the text which follows. Also, the combinations of the EEI measure options are simulated and the energy consumption is evaluated, according to the different options given in Table 7.1. For all these options the same boundary conditions are prescribed according to the temeprature profile given in Figure 7.4. In all cases, the target room temperature profile was supposed to be similar if not identical as the profiles given in Figure 7.5. This was done by changing the supply and return temepratures as well as the set temeprature in the space (part of boiler control). After the temeprature profile within the room was satisfactory close to the temeprature profile from the baseline condition, the energy savings are estimated by comparison in the natural gas consumption in the calculation period.

For cases (Options 1 – 3) at which only EEI measures at the consumption side are analyzed, the boiler capacity was kept at the same value as the boiler in the baseline case (no replacement of the boiler is envisaged). In cases (Options 4 – 6) at which new boiler is envisaged, the boiler capacity was chosen to be 20% higher than the heat need at the design conditions, based on the steady-state heat losses of the room.

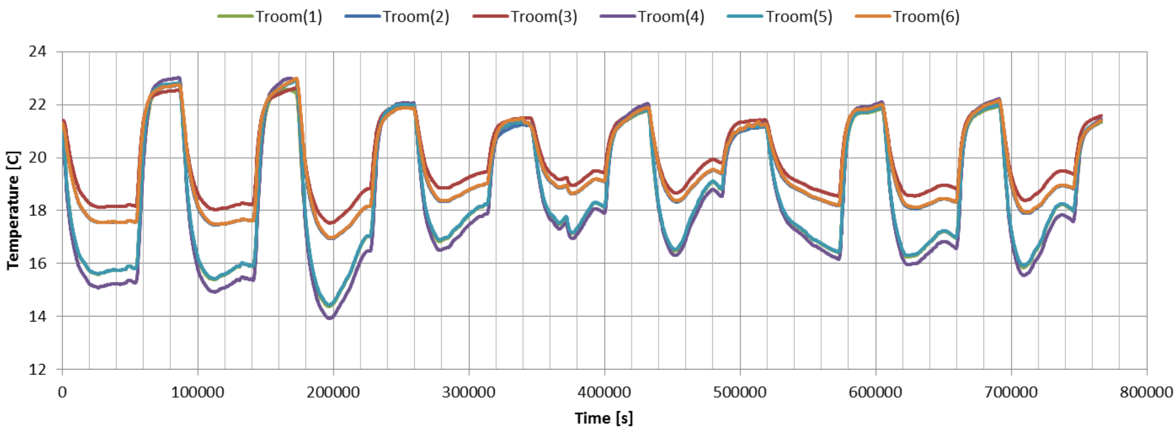


Figure 7.9**:** Room temeprature profiles for all analyzed and calculated cases.

All simulations were conducted by taking into account that the average room temeprature and the temperature profile during the heating period should be as close as possible to the room temperatures in cases before and after EEI measures. As close as these temepratures for different options are the more accurate analysis of energy savings can be obtained. For Options 1 – 6 the set temeprature for room, the supply and return temepratures of the boiler control heat curve and mass flows in the system were varied until the reasonable agreement in room profile temepratures was reached. Temeprature profiles in the room for all analyzed options are given in Figure 7.9. Note that Troom(1) means room temeprature for Option 1 from the Table 7.1.

Energy Efficiency Improvement measures	U_{wall} [W/m^{2}K]	$U_{windows}$ [W/m^{2}K]	n_H [1/h]	η_{boi} [%]	Energy savings %
Baseline (before EEI)	1.44	3.30	1.0	84.0%	0.0%
Option 1	0.31	3.30	1.0	84.0%	6.8%
Option 2	1.44	1.40	0.5	84.0%	35.8%
Option 3	0.31	1.40	0.5	84.0%	41.2%
Option 4	1.44	3.30	1.0	100.0%	13.0%
Option 5	0.31	3.30	1.0	100.6%	19.0%
Option 6	1.44	1.40	0.5	103.7%	45.7%
New (after EEI)	0.31	1.40	0.5	104.0%	57.5%

Table 7.3: Parameter values for different EEI measures and resultining efficiencies and energy savings for all analyzed options.

Table 7.3 shows U_{wall} values for multilayer walls with and without insulation layer, $U_{windows}$ before and after the replacement of windows and their corresponding number of air-changes for different EEI measures according to Options 1 – 6. As a result of calculations the period efficiency of the boiler and the energy savings are presented.

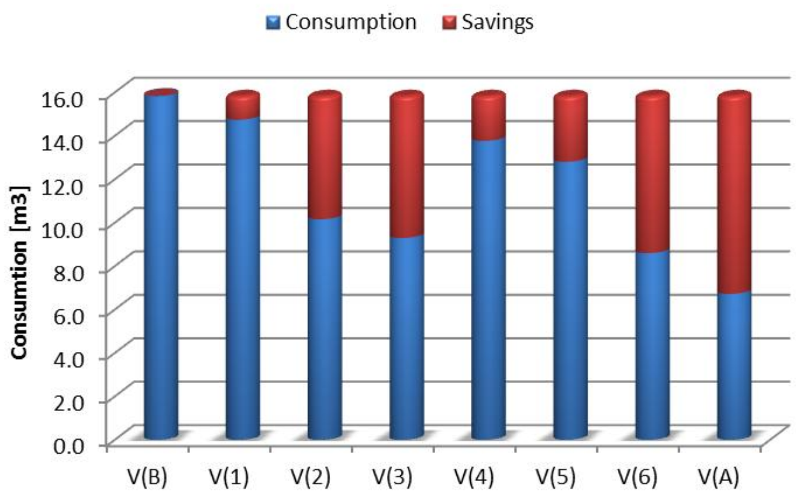


Figure 7.10: Consumtion and savings in terms of natural gas for observed room.

Note that the energy savings shown in the Table 7.3 represent the savings in fuel, which take into account the system efficiency (boiler with its automatic control and the efficiency of the distribution network).

In order to demonstrate the different levels of analysis applicable in the simulation tool, the Option 6 was elaborated in more details. Option 6 assumes replacement of windows and new boiler room, while the wall construction remained the same as in the baseline case.

In Figure 7.10 three diagrams from the Modelica results are plotted. At the top in red color, the supply temeprature in the heating system is given, while the black line represents the set supply temeprature which comes from the boiler control. At the diagram in the middle, current boiler signal which defines the current boiler capacity is presented and the room temperature for Option 6 is given at the bottom.

It can be seen than during the day 6 in the calculation period boiler is cycling. This is because the outside temeprature is high, the set supply temeprature which comes from the control system is low and the supply temeprature is hunting the set supply temeprature in ON/OFF mode. Boiler modulation range works in 30-100% capacity and the heat necessary to provide the required supply temperature would be lower than the 30% nominal capacity of the boiler. Therefore when supply temeprature in the boiler is higher than 2.5 degrees than the set boiler temeprature, the boiler switches to OFF. At the other hand, when the supply temeprature drops 2.5 degrees bellow the set boiler temperature and if the minimum OFF time is larger than 10 minutes (prescribed in the calculation), the boiler switches to ON and is again working with PI regulation to match the required set temeprature.

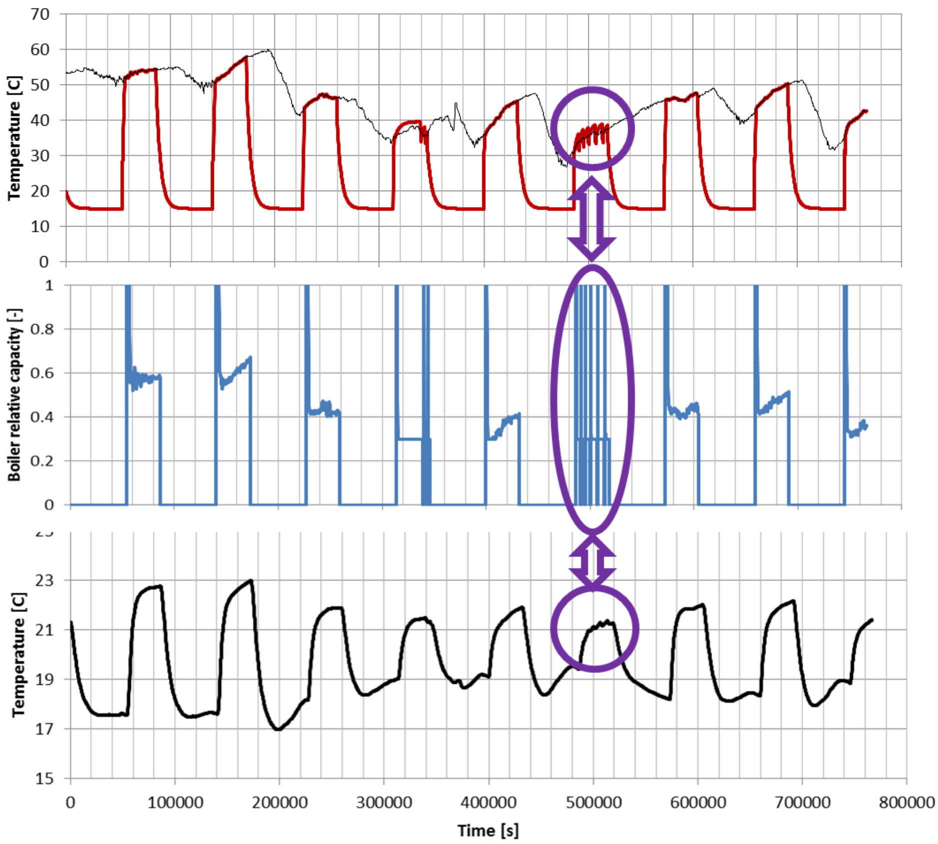


Figure 7.11: Analysis of the boiler cycling in the sixth day for Option 6.

The ON/OFF work of the boiler is reflected by the boiler supply temperature as well as the room temperature at the end (see the purple circles and arrows in Figure 7.11).

8. Conclusion

The need to design energy efficient buildings, improve the thermal performance of existing heating components such as boilers and the availability of powerful digital computers have led to the development of building energy analysis computer programs. Modelica, as an equation based object-oriented modeling language, provides the opportunity to utilize flexible modeling and simulation techniques for building energy and control systems. Modelica is designed to support reuse of model knowledge. Modelica allows users to solve a real problem by a ready-made model from open-source model libraries.

Another advantage is that it is possible to develop the desired model by just putting together components from the model library by using a graphical editor as Dymola. Use of the new general object-oriented modeling language Modelica has been illustrated, and discussed in detail for coupling thermo-fluid systems.

The model libraries components of the Buildings library have been presented and successfully used for the purpose of analyzing the thermal behavior of the condensing boiler and its automatic control system in the MEF boiler room. The LBLN boiler model has been illustrated and discussed in detail.

The boiler room model consisting of a heat source, condensing boiler, control system and heat sink has been connected in the Modelica/Dymola environment based on previously presented principles and rules of coupling thermo-fluid systems in Modelica. The control strategy model components have been presented that adapts the supply set temperature according to the actual load. The model control components from the Buildings library were able to reproduce behavior of the existing control system in the MEF boiler room relatively good. The restrictions of the model components were also outlined.

The boiler room model has been validated using measurement data based both on 5-minute and hourly measurements and the agreement between measured and simulated behavior is very good. The simulation results indicate that the boiler efficiency during load operation is mainly affected by the return water temperature. It can be concluded that lower outside temperatures and lower return temperatures enhances the formation of condensate in the boiler, thus resulting in higher efficiencies. So, in principle the lower the temperature at which water is returned to the boiler, the better.

In the example of application the applicability of the Buildings library was demonstrated on the model of the real life heating system with its all components. The simplification was introduced in the sense that only one room was representing the consumption side. The boiler, circulation pump and the pipeline are scaled to represent the closed system. Geometry of the room and actual wall layers, windows and other parameters are taken from the existing characteristic room at the Mechanical Engineering Faculty in Sarajevo. Comparison of the energy consumption before and after EEI measures was done. Moreover, the different options of the energy efficiency measures were analyzed and for every option the characteristic energy savings are evaluated. The full applicability of the object oriented simulation tool for rapid prototyping was utilized, i.e. different options were tested by changing parameters in the records or simply by choosing different parameters from calculation. All these changes were performed fast and different tests were set up in minutes.

The aim of this simulation task to capture the thermal dynamics of the gas-condensing boiler using the Modelica/Dymola environment has shown to be successful.

The previous analysis opens up the possibility to prepare the financial calculations of the different EEI measures and their feasibility. In that sense it is possible to find the most feasible combination of the EEI measures for analyzed buildings.

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