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# Thermal losses from hydronic heating systems in highly-insulated residential buildings

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Innovative Sustainable Energy Engineering
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# MASTER THESIS

for

Tomasz Iwanek

Spring 2016

Thermal losses from hydronic heating systems in highly-insulated residential buildings:

*Varmtapper fra vannbaserte oppvarmingssystemer i super-insolerte byggninger:*

## Background and objective

Many of the building concepts for current and future energy-efficient buildings are based on highly-insulated building envelopes, such passive houses, zero emission buildings or nearly-zero energy buildings (nZEB). As the building is highly-insulated, it is possible to simplify the space-heating distribution subsystem and reduce the number of heat emitters to a few elements. One solution is to use a hydronic distribution equipped with few low-temperature radiators, for instance, one in each floor as well as one in the bathroom. This solution reduces thermal losses from the pipes and the investment, but theoretically provides for less thermal comfort than a complete/standard loop. This Master thesis investigates the thermal efficiency of the space-heating distribution, essentially as regards thermal losses from pipes, and also of the heat storage tanks. This work is performed within the framework of a competence project supported by Husbanken and in collaboration with the ZEB centre and the EBLE project.

This Master thesis is the follow-up of two specialization projects where two similar passive row houses and two similar passive apartments of the MiljøGrånåsen project developed by Heimdal Bolig were investigated. Based on these building geometries, two different heat distribution systems will be designed (one simplified and one standard). These systems will be implemented in existing IDA-ICE model(s) and their respective energy efficiency investigated.

**The following tasks are to be considered:**

1. Critical analysis of results from the first measurement and interview campaign.
2. Literature review about thermal losses from hydronic systems (e.g. EN 15316).
3. Design of the two distribution systems (simplified and standard approaches) with a detailed description of the design rules that have been used. Ideally, Norwegian design rules should be applied.
4. Implementation of these systems and their thermal losses into the existing IDA-ICE models (with support of the supervisor).
5. Discuss the performance of both distribution systems in terms of energy efficiency.

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

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

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

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

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

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering
☐ Field work

Department of Energy and Process Engineering, 13. January 2016

Olav Bolland

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# ABSTRACT

Many of the building concepts for current and future-efficient buildings are based on highly-insulated envelopes, such passive houses, zero emission buildings or nearly-zero energy buildings (nZEB). As the building is highly-insulated, it is possible to simplify the space-heating distribution system and reduce the number of heat emitters to a few elements. One solution is to use a hydronic distribution equipped with few low-temperature radiators, for instance, one in each floor as well as one in the bathroom. This solution reduces thermal losses from the pipes and the investment, but theoretically provides for less thermal comfort than complete loop. This Thesis investigates thermal conditions in the building with both systems. Studied cases contribute to the worst conditions, which may happen in the winter and also more probable situations in order to be as close to reality as possible. Two systems are investigated also in terms of efficiency. Losses from pipes are considered as recoverable internal gains, and two variables of distribution coefficient are counted.

# NOMENCLATURE

## Latin symbols:

| | |
|---|---|
| $c_p$ | specific water heat, J/kgK |
| d | diameter, m |
| f | friction factor, - |
| g | standard gravity, $m/s^2$ |
| $h_{in}$ | heat transfer coefficient in the pipe, $W/m^2K$ |
| $h_{out}$ | heat transfer coefficient at the outside insulation surface, $W/m^2K$ |
| H | pressure drop, m |
| $k_{insulation}$ | thermal conductivity of insulation material, W/mK |
| $k_{pipe}$ | thermal conductivity of pipe material, W/mK |
| K | loss coefficient, - |
| $\dot{m}$ | mass flow, kg/s |
| $\Delta p$ | pressure drop, Pa |
| Q | heat flow rate, W |
| r | bend's radius, m |
| $t_r$ | temperature of return water, K |
| $t_s$ | temperature of supply water, K |

## Greek symbols:

| | |
|---|---|
| $\alpha$ | bend's angle, rad |
| $\eta$ | distribution's coefficient, - |

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# 1. Introduction

Over the last few decades, due to high energy consumption and climate change, the need to prevent this phenomenon was being considered more and more. Because of general development, energy demand is rising significantly and also natural resources being depleted with every day, should be respected by humankind. When we wonder where the energy is consumed, we can see that residential sector takes big part. Some developed nations started to think what can be done in this area. If couple of rules are followed, reductions in energy demand can be achieved both for dwellings and industrial buildings. It was called Passive house concept and means low energy building. There are more and more houses being built with this standard in Germany, Austria, Switzerland and United States. Other countries are also interested in this idea. Experience shows that passive house concept can be adjusted to any climate in the world and works equally as well both in warm and cold climates. It was also tested, that different materials can be used for passive house: masonry, insulated concrete, steel, timber and prefabricated elements. Passive house can be designed in traditional way or in modern and contemporary style. Very important issue is reduction of energy demand, whilst creating acceptable thermal comfort level. This is first considered topic in Thesis. The second one is heating system in passive house. There are two ways to design heating system, which can be strongly simplified thanks to very well insulated envelope. When the house is built strictly according to concept rules, traditional heating system is no longer considered as irreplaceable. The third question raised in this paper is heat loss from pipes in heating system, what is poorly described in literature and should be investigated to define distribution efficiency.

## 1.1. Passive house concept

### Orientation

Good planning of building orientation can decrease heating demand by 30% compared to the same building, but with not considered orientation [2]. Passive house should be oriented along east/west axis, so it gets as much solar gains as possible. Sometimes designers recommend cutting trees in front of the house, to prevent blocking sunbeams. Such an orientation requires good shading because there is a risk of overheating during summer. Orientation of building determines also setting of rooms and topology in order to get more gains to habitable rooms, such as living room and dining room.

### Building form

Next to the orientation, shape of building is also extremely important factor from heating demand point of view. It’s described by A/V ratio. In other words, relation between external surface area and internal volume of building. The same buildings have significantly different heating demand because of different A/V ratio. It affects especially small one-family houses which should be designed as close to rectangular shape as possible. In case of bigger buildings designers can afford more complex geometries. The figures below show how change of building shape affects thickness of insulation needed to achieve the same heating demand [2]. Besides higher proportion of thermal bridges, buildings with complicated forms have also increased shading factors that have impact on energy balance.

**Figure 1: Connection between surface area and thickness of insulation (description in text)**

## Insulation and thermal bridging

In passive house insulation of whole building envelope is the most important thing. All parts of construction should have U-value ≤0,15 W/m$^2$K. Insulation should be led continuously around building envelope without any gaps. This approach reduces heat loss so much, that even during winter they can be negligible. When it's designed and done properly the temperature of internal surface will be the same in whole house. Indoor climate in such a house is comfortable and risk of appearing moisture is decreased to very low level. It has to be noticed, that thick insulation is also barrier for heat during summer. House has to be protected from overheating by shading and ventilation. Special attention must be devoted to thermal bridges. It's obvious that every connection between construction elements is easy way for heat to escape from the building. Junctions should be designed with structure in mind, but also with thermal conditions.

## Windows and doors

In last years, due to great heat restrictions, companies producing windows developed very good standard of triple glazed windows. Each pane of glass is separated by a space bar, which creates air gap or cavity. The cavities provide insulation and reduce condensation. Sometimes argon is used between the panes instead of air, because it insulates better. It's possible to achieve U-value of 0,8 W/m$^2$K. These types of windows should be used for passive house. The important issue is window's installation, when it's done properly, U-value can be less than 0,85 W/m$^2$K [3]. Triple glazed windows are necessary also because of temperature of internal surface, which should be similar to walls, then the occupants will not feel thermal discomfort from large temperature difference.

## Airtightness

Lack of any leakage is essential in passive house because of three reasons. Firstly, every leakage causes raise of heat demand. Secondly, it causes local discomfort due to draughts. Moreover, it can cause a moisture, which is dangerous for both occupants and construction. Air leakage can be result of two phenomena: buoyancy and wind. Buoyancy takes place when warm air goes up because of less density and escapes through gaps in envelope at a higher level. Then this air is replaced by colder air coming through gaps in lower level. If it's uncontrolled, residents can feel draught. Second phenomenon is the wind, which burst into building because of the pressure. On the leeward side pressure outside is lower than inside the building, so warm air leaks out from the house. There is a pressure test which should be done in every passive building. It's called n50 because of the difference – 50 Pa between interior and exterior. Result in this test is the volume of air changed in one hour. In passive house the result should be of ≤0.6 ACH/hr [4]. The test has to be done with pressurisation and depressurisation. Achieving this level of airtightness is not easy and has to be considered during designing and also made properly on worksite. It’s necessary to use some materials and things which are not being used in normal building, for example: membranes, tapes and wet plastering. In each place, where the continuity of barrier for air is interrupted, suitable tape should be put to prevent airflow. This requires designer’s attention, because every detail should be specified in project and in production drawings. Also workmanship has huge impact on airtightness of building. Every building worker should be aware of importance this part in building process. Any oversight may jeopardise final airtightness and increase heating demand in consequence.

## Mechanical ventilation

Mechanical ventilation is completely necessary in passive house. It’s needed to maintain a quality of indoor air by replacing carbon dioxide, moisture and unwanted odours with fresh, external air. Here, natural ventilation is not even taken into account. In such an airtight building occupants would have to open windows very often to let some fresh air in. This may be acceptable during summer time, but it’s not acceptable during cold winter, because of heat loss. Ventilation is one of the most energy consuming system in whole building, so it’s crucial to design it properly. Heat recovery unit should have efficiency greater than 75% and also have a low specific fan power (SFP). Ventilation should be designed together with whole building to shorten length of ducts and apply the best, possible system. One of the many solutions is cascade ventilation which saves a lot of space for ducts in a building and also much heat for warm up the air. This was very well described in [10]. However this system requires well designed building’s topology to ensure that air flows through every room. The best way to design this type of ventilation is using numerical analysis and algorithms called computational fluid dynamics (CFD).

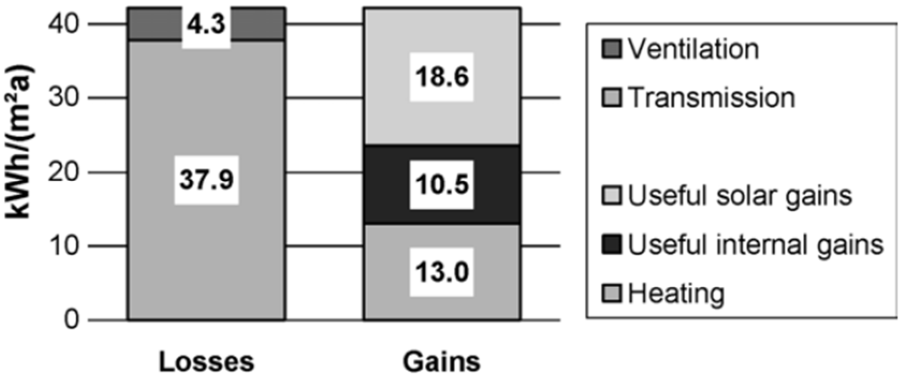
## Principles

When foregoing requirements are fulfilled, building should have very good heat indicators and promising energy balance. There are some values which have to be achieved in order to call the building ‘Passive house’ [1]:

- Specific heating demand ≤15 $kWh/m^2 \cdot yr$
- Specific cooling demand ≤15 $kWh/m^2 \cdot yr$
- Specific primary energy demand ≤120 $kWh/m^2 \cdot yr$
- Airtightness ≤0,6 ach (n50)

The figure for specific primary energy demand includes domestic hot water, lighting, pumps, fans and all the others appliances which can be predicted in project. It’s worth to notice that value 15 $kWh/m^2 \cdot yr$ is similar to solar and internal gains. It’s visible in Fig. 2 [6], that overall losses can be covered almost by these gains, if only a set of above-mentioned conditions are fulfilled.

Figure 2: Heat losses and gains in typical Passive House [6]



Since The Passive House concept is being developed, a lot of building components got better properties. U-values of insulation materials, windows and doors decreased so much, that now it's totally manageable to face rough restrictions given to them. The lowest available on market values of components are even better than necessary. For example U-value of glazing can be of 0,51 W/m$^2$K (0,75 W/m$^2$K installed) and U-value of insulation of opaque envelope 0,06 W/m$^2$K [6].

### CEPHEUS

Concept of Passive House was deeply investigated also in practice. Cooperation of couple of European countries and European Commission led to very robust project called 'Cost Efficient Passive Houses as European Standards' (CEPHEUS). Over 200 houses took participate in this operation in order to check, whether it was worth to bear extra investment costs for further savings. These savings were achieved thanks to decreasing heating demand by sticking to Passive House principles. Investigated buildings had different constructions. All of them were equipped with a mechanical ventilation with heat recovery. The results of project were impressive. Investigation proved that it was possible to reduce space heat consumption by 80%. In the best cases, it was reduced even by more than 80% [6].

### Thermal comfort in Passive House

It's not difficult to notice that thermal comfort is arguable issue in case of Passive House. General question is: Is it possible to maintain acceptable temperature in building without any traditional radiator or with simplified heating system? One of the assumptions for Passive Houses is that temperature can't decrease below 16$^o$C in any room even during coldest winter. This issue was also checked in CEPHEUS project and results were very positive. Occupants answered in surveys that thermal conditions were satisfying both in the winter and in the summer. Average, general votes were between 'good' and 'very good' [6].

## 1.2. Simplified heating systems

When the building is very well insulated, it's possible to simplify heating system. Such a simplification means that number of heat emitters is reduced and thanks to this, distribution system is not that complicated. Investment costs decrease in case of simplified heating system because an owner have to pay only for one radiator instead of couple of them. Overall length of pipes is lower and this also translates into economic benefits. Operational costs are also decreased because both pressure drop and heat losses from pipes are lower. The only question is how one heat source is able to cover heating demand for whole building and if it's able to maintain acceptable thermal comfort level in every zones. The room which is the furthest from heat source is obviously in the worst location. It may be found, that maintaining acceptable temperature in this room, depends on periodic raising temperature in living room, where radiator is placed. The issue is not easy because everything depends on other factors as well. Properties of building influence temperature in rooms very much. This is result of different thermal mass for different materials. Higher thermal mass means that the wall warms up longer. This will have significant impact on thermal comfort in Passive House. Nevertheless, the easiest way for heat transfer are holes in walls. Opening internal doors has the biggest impact on temperatures in whole building. Obviously, the best and desirable situation takes place with every doors open. This situation generates natural convection between rooms and it's prevailing heat diffusion in the building. However, in practice, internal doors can't be open all the time. Obvious reason for it is intimacy and simulation should correspond to reality as close as possible. On the other hand, it's very difficult to define how long internal doors can be open during the day. For accurate and satisfying results, real measurement should be provided.

Simplified heating system doesn't mean that it can contain only traditional water based units. There are ideas about changing traditional heating system to one wood stove in the living room, which makes cosy atmosphere and also takes care of covering heating demand in whole house. Problems with maintaining thermal comfort in every zone are the same like for one water radiator. However, provided investigations proved that wood stove with solar gains are able to provide thermal comfort, when internal doors are open [7]. Designer should also consider material of construction, taking into account thermal conditions.

## 1.3. Distribution system

Heating system with water radiators or floor heating are the most popular to cover heating demand of the residential building. Properties of water fit very well to transfer the heat from source to the room fast and effectively. However every system has certain efficiency which may decide about success. Due to general movement towards low-energy buildings, engineers try to find a way to improve every installation, that they design. Heating systems have to be controlled to prevent releasing the heat to spaces, where it's not necessary. The amount of created energy should be used as efficiently as possible. Heat losses in heating systems have been divided on four parts: generation, storage, distribution and emission. The formula to calculate total efficiency of heating system is:

$$\eta_{tot} = \eta_{generation} \times \eta_{storage} \times \eta_{distribution} \times \eta_{emission}$$

This paper is focused on losses from pipes, so only distribution efficiency is investigated and the others are not studied. So far, this problem has not been described strictly and probably, more suitable efficiency value could be define. Efficiency factor, which is currently being used was calculated long time ago and it doesn't correspond to reality. This value can't be defined with hand calculation because flow through pipes is dynamic process. It's changing all the time and depends on amount of water flowing through pipes and the temperature of water. Furthermore, losses from pipes are not actually losses, at least in case, when pipe is running through heated room. Then such a loss is treated as gain. In this way, losses can be divided on two parts: recoverable and non-recoverable. Loss is recoverable, when it causes increase of temperature below set-point, e.g. 21$^{o}$C. In this case, effect is beneficial. When the heat is released during exceeding the set-point, it will be called non-recoverable. It can be understood that the heat is needless. This problem was also not widely studied because of lack of software to create a model of heating system. Since the need to make accurate calculations has appeared, some companies has created suitable modes to their programs. Now, they are offering very precise software and engineers are able to design efficient installations in the proper way.

Next chapter describes, what heating systems were designed and how the model in programme IDA-ICE was built.

## 2. Methods

The most important objectives in this paper are description of thermal comfort in Passive House and definition of distribution efficiency in heating system with water radiators. In order to describe them, two heating systems have been designed for house with very well insulated envelope. First heating system is traditional and contains one radiator in every room. The second one is simplified and contains only two radiators, one on each floor. Radiators were chosen with software IDA-ICE 4.6.2. Next, these systems, including pipes, were introduced to IDA-ICE and results have been studied.

### 2.1. Building

Investigated building is one-family, two-storey house, located in Trondheim. On the first floor, there is a large living room with kitchen part. On the second floor, there are three bedrooms and one bathroom. The house has also a basement, where technical room is placed. The building is oriented to get as much solar gains as possible to the living room through huge window and doors to terrace. The following construction of building's parts were defined:

**External wall**

| | |
|---|---|
| · Gypsum | 0,013 m |
| · Glass wool | 0,300 m |
| · Wood | 0,025 m |

**Internal wall**

| | |
|---|---|
| · Gypsum | 0,013 m |
| · Glass wool | 0,072 m |
| · Gypsum | 0,013 m |

**The roof**

| | |
|---|---|
| · Roofing paper | 0,003 m |
| · Sheet membrane | 0,002 m |
| · Polietylen | 0,005 m |
| · EPS insulation | 0,550 m |
| · Chip board | 0,050 m |
| · Aluminium | 0,015 m |

**Floor on the ground**

| | |
|---|---|
| · Gypsum | 0,013 m |
| · Polietylen | 0,005 m |
| · Concrete | 0,300 m |
| · Heavy insulation | 0,150 m |
| · Soil | 0,300 m |

**Internal floor**

| | |
|---|---|
| · Floor coating | 0,015 m |
| · Chip board | 0,022 m |
| · Air gap | 0,150 m |
| · Glass wool | 0,200 m |
| · Gypsum | 0,013 m |

## 2.2. Heating system

Radiators in both heating systems have been chosen based on power of ideal heater for each room defined in IDA-ICE. Following tables shows selection of radiators in standard heating system and simplified one. In first and second case, radiators with two and three panels were chosen, respectively. The last column shows power of chosen radiator. Temperature of supply water is 55°C, and return 45°C. There is a underfloor heating in technical room and bathroom, belonging to another system which is not the topic of this paper. In whole project, only materials available in Norway have been taken into account.

Table 1: Selection of radiators for standard heating system

| Selection of radiators, standard heating system | | | | | | | |
|---|---|---|---|---|---|---|---|
| **No.** | **Name** | **$t_i$, °C** | **Q, W** | **correction factor** | **$\varphi_u$, W** | **type of radiator** | **$\varphi_r$, W** |
| **001** | Technical room | 16 | 343 | Underfloor heating | | | |
| **101** | Hall | 20 | 0 | no radiator | | | |
| **102** | Stairs 1 | 20 | 0 | no radiator | | | |
| **103** | Living room | 20 | 693 | 1,96 | 1359 | C 22 600 x 1100 | 943 |
| | | | | | | C 22 600 x 500 | 428 |
| **201** | Bedroom 1 | 20 | 132 | 1,96 | 258 | C 22 450 x 400 | 272 |
| **202** | Bedroom 2 | 20 | 224 | 1,96 | 440 | C 22 600 x 500 | 444 |
| **203** | Bedroom 3 | 20 | 183 | 1,96 | 359 | C 22 500 x 500 | 370 |
| **204** | Bathroom | 24 | 22 | Underfloor heating | | | |
| **205** | Hall 2 | 20 | 151 | 1,96 | 295 | C 22 300 x 600 | 293 |
| **206** | Stairs 2 | 20 | 0 | no radiator | | | |

Table 2: Selection of radiators for simplified heating system

| Selection of radiators, simplified heating system | | | | | | | |
|---|---|---|---|---|---|---|---|
| **No.** | **Name** | **$t_i$, °C** | **Q, W** | **correction factor** | **$\varphi_u$, W** | **type of radiator** | **$\varphi_r$, W** |
| **001** | Technical room | 16 | 343 | Underfloor heating | | | |
| **101** | Hall | 20 | 0 | no radiator | | | |
| **102** | Stairs 1 | 20 | 0 | no radiator | | | |
| **103** | Living room | 20 | 696 | 1,96 | 1364 | C 33 600 x 1200 | 1408 |
| **201** | Bedroom 1 | 20 | 0 | no radiator | | | |
| **202** | Bedroom 2 | 20 | 0 | no radiator | | | |
| **203** | Bedroom 3 | 20 | 0 | no radiator | | | |
| **204** | Bathroom | 24 | 30 | Underfloor heating | | | |
| **205** | Hall 2 | 20 | 669 | 1,96 | 1311 | C 33 550 x 1200 | 1317 |
| **206** | Stairs 2 | 20 | 0 | no radiator | | | |

Heating systems have been designed according to obligatory standards in Norway. Technical drawings of both systems are attached to the paper. Pipes are running under the floor or 10 cm over the floor. Mass flow in every pipe was calculated with formula:

$$\dot{m} = \frac{Q}{c_p \cdot (t_s - t_r)}$$

Where:
Q – Heat flow rate, W
$c_p$ – Specific water heat, J/kgK
$t_s$ – temperature of supply water, K
$t_r$ – temperature of return water, K

Diameters of pipes have been selected with a rule of maximum velocity 0,5 m/s, because of the noise and pressure loss. Pressure drops for local losses have been calculated with formula [11]:

$$H = K \cdot \frac{V^2}{2 \cdot g}$$

where:
H – pressure drop, m
g – standard gravity, $m/s^2$
K – loss coefficient, dimensionless value calculated individually for bends, tees etc.

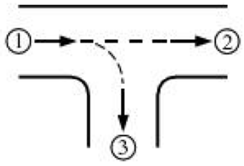
Loss coefficient for bends [11]:

$$K = f \cdot \alpha \cdot \frac{r}{d} + (0{,}1 + 2{,}4 \cdot f) \cdot \sin(\alpha/2) + \frac{6{,}6 \cdot f \cdot \left(\sqrt{\sin(\alpha/2)} + \sin(\alpha/2)\right)}{(r/d)^{\frac{4 \cdot \alpha}{\pi}}}$$

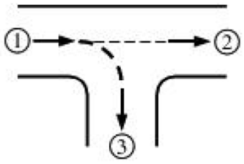
where:
f – friction factor, -
α – bend’s angle, rad
r – bend’s radius, m
d – diameter, m

Loss coefficient for tees [11]:
In this case, loss coefficient value depends on the main flow path:

Flow through run:



Flow through branch:



Flow through run:

$$K = 0{,}62 - 0{,}98 \cdot \frac{\dot{w}_1}{\dot{w}_2} + 0{,}36 \cdot \frac{\dot{w}_1^{\,2}}{\dot{w}_2^{\,2}} + 0{,}03 \cdot \frac{\dot{w}_2^{\,6}}{\dot{w}_1^{\,6}}$$

Flow through branch:

$$K = 1{,}0 - 1{,}13 \cdot \frac{\dot{w}_3}{\dot{w}_1} + \left[ 0{,}81 + \left( 1{,}12 \cdot \frac{d_3}{d_1} - 1{,}08 \cdot \frac{d_3^{\,3}}{d_1^{\,3}} + K_{9.3} \right) \cdot \frac{d_1^{\,4}}{d_3^{\,4}} \right] \cdot \frac{\dot{w}_3^{\,2}}{\dot{w}_1^{\,2}}$$

$$K_{9.3} = 0{,}57 - 1{,}07 \cdot \left( \frac{r}{d_3} \right)^{1/2} - 2{,}13 \cdot \left( \frac{r}{d_3} \right) + 8{,}24 \cdot \left( \frac{r}{d_3} \right)^{3/2} - 8{,}48 \cdot \left( \frac{r}{d_3} \right)^{2} + 2{,}90 \cdot \left( \frac{r}{d_3} \right)^{5/2}$$

Pressure loss for radiators was calculated according to formula recommended by producer [13]:

$$\Delta p = 0{,}0105 \cdot q^2$$

where:
Δp – the drop of water flowing through the radiator, Pa
q – the mass flow of water flowing through the radiator, kg/h

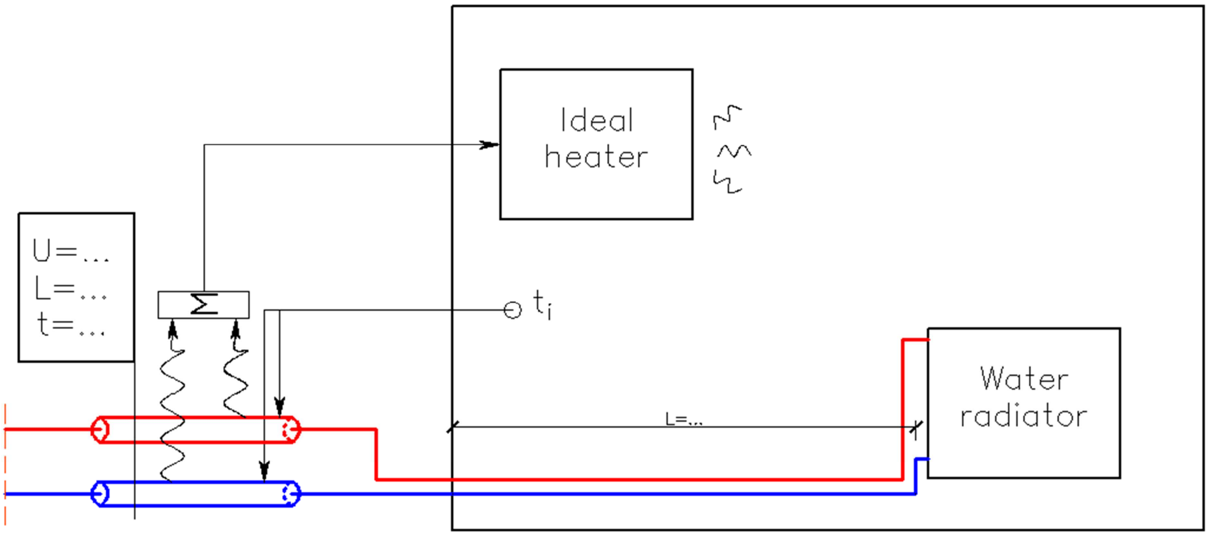
After hydraulic calculations, thermostatic valves were chosen. Every detailed tables with results are attached to the paper. Next, heating systems have been implemented to IDA-ICE.

## 2.3. Simulation model

All simulations have been done in software IDA-ICE 4.6.2. This programme offers advanced mode to design heating system and has plenty of irreplaceable options. Software has been validated, so results are fully reliable. Simulations were run with weather data, provided by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). Set-point temperature 21$^{o}$C has been used in every room. Building is equipped with Air Handling Unit and the system is CAV. As internal gains, light, equipment and occupants have been predicted. Occupants are always present, and equipment is being used from 7am to 11pm every day. Activity of occupants is 1,0 MET.

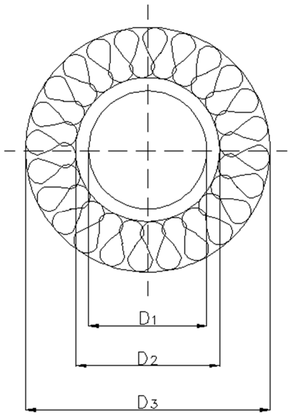
Water radiators have been introduced to rooms according to project. They are controlled by PI-controllers. Every room, which has gains from pipes has been additionally equipped with ideal heater. This is the unit without defined location and dimensions, but with convection and radiation factor. **The main task was using losses from pipes, as a gains to adequate room.** In order to count it properly, the pipe needs a signal about temperature in the room, because it influences the loss. Then the signal with the amount of heat is sent to ideal heater. The idea is presented on the next page:

Figure 3: Scheme of using losses from pipes as internal gains



Length of every pipe has been taken from the project. U-value depends on diameter of pipe, insulation and thermal conductivity of these materials. It has been calculated for all pipes according to formula:

$$U = \frac{1}{\frac{D_3}{D_1 \cdot h_{in}} + \frac{D_3 \cdot \ln\left(\frac{D_2}{D_1}\right)}{2 \cdot k_{pipe}} + \frac{D_3 \cdot \ln\left(\frac{D_3}{D_2}\right)}{2 \cdot k_{insulation}} + \frac{1}{h_{out}}}$$



where:

$h_{in}$ - heat transfer coefficient in the pipe
$h_{out}$ - heat transfer coefficient at the outside insulation surface
$k_{pipe}$ - thermal conductivity of pipe material
$k_{insulation}$ - thermal conductivity of insulation material

Heat transfer coefficients depend on Reynolds number, Nusselt number and properties of water. It has been calculated according to scheme from [12].

The model presented on next page is quite complicated, so it was redrawn in graphical programme for better understanding. First loop is going into bedroom 3 through two other rooms: technical room and hall. Second loop is going to ‘Hall 2’ through ‘Stairs 2’. Other branches (bedroom 1, bedroom 2, living room) have been modelled separately. There are four pipes going to living room, because there are two radiators. The unit ‘ICE-MACRO’ has been built for every room and all information about pipes (U-value, diameter, etc.) are included inside. Construction of this unit is also presented below. Both standard and simplified heating system were designed in this way. Total length of pipe network is 29,3 m and 18,6 m for standard and simplified heating system, respectively. In the second one, there are only two radiators, but pipes are running through five rooms, what is visible in the model. After model had been built, a dozen or so dynamic simulations were run. Couple of cases have been investigated. In order to check whether thermal comfort is maintained in the building simulations were run both with internal doors open and closed. In the next step, insulation has been added to pipes. Thickness of insulation was chosen according to producer's recommendations. All results are described in the next chapter.

**Figure 4: Construction of 'ICE-MACRO'**

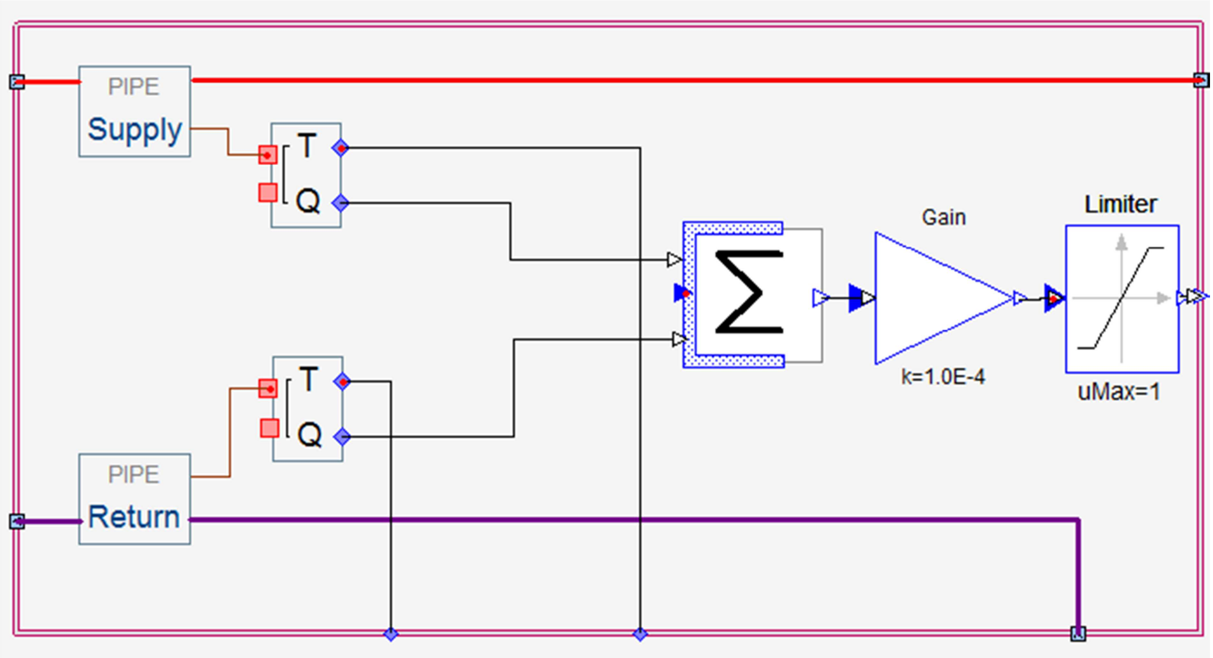
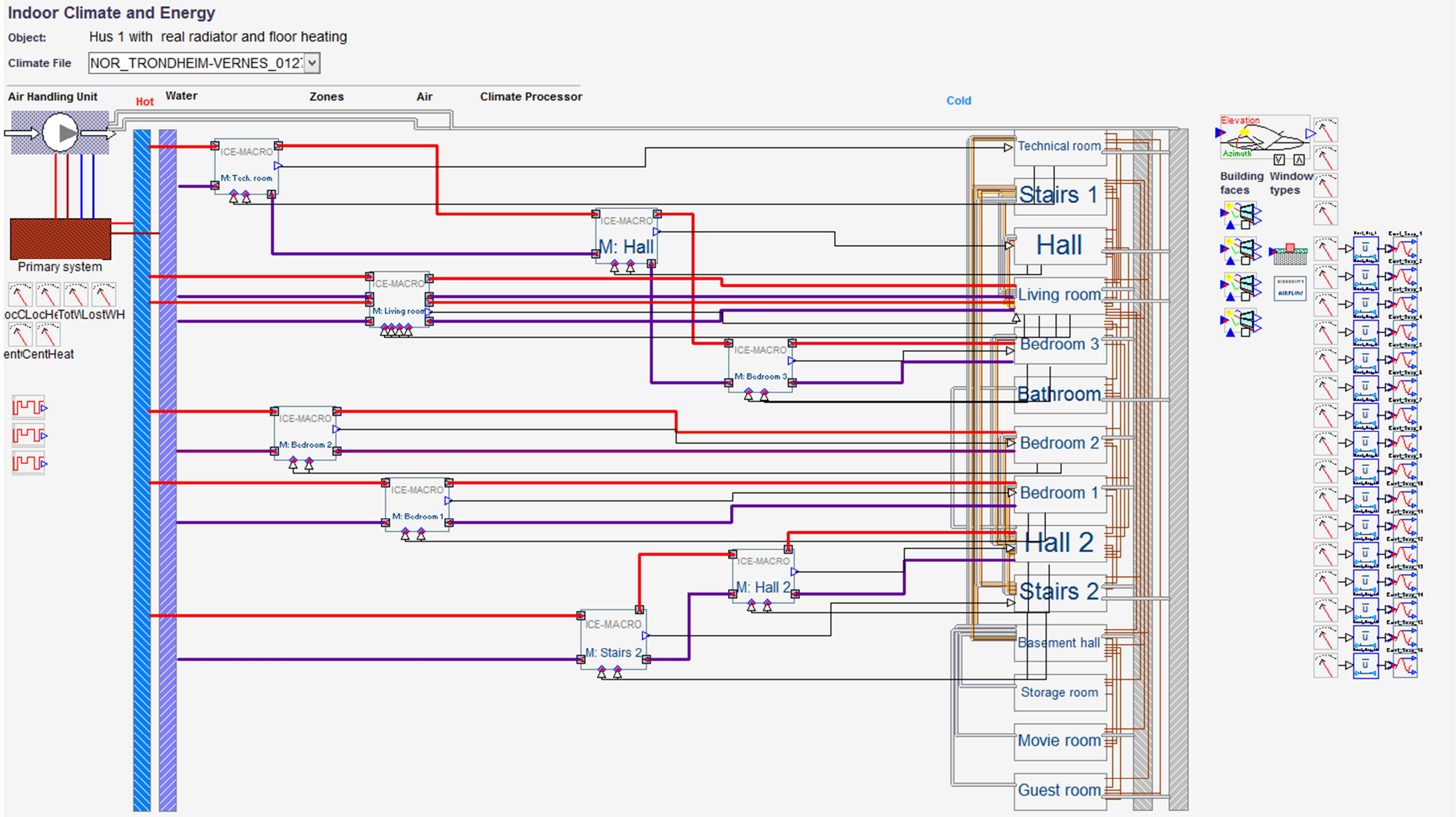


Figure 5: IDA model for standard heating system



Indoor Climate and Energy

Object: Hus 1 with real radiator and floor heating

Climate File NOR_TRONDHEIM-VERNES_012

Figure 6: Scheme of IDA model for standard heating system

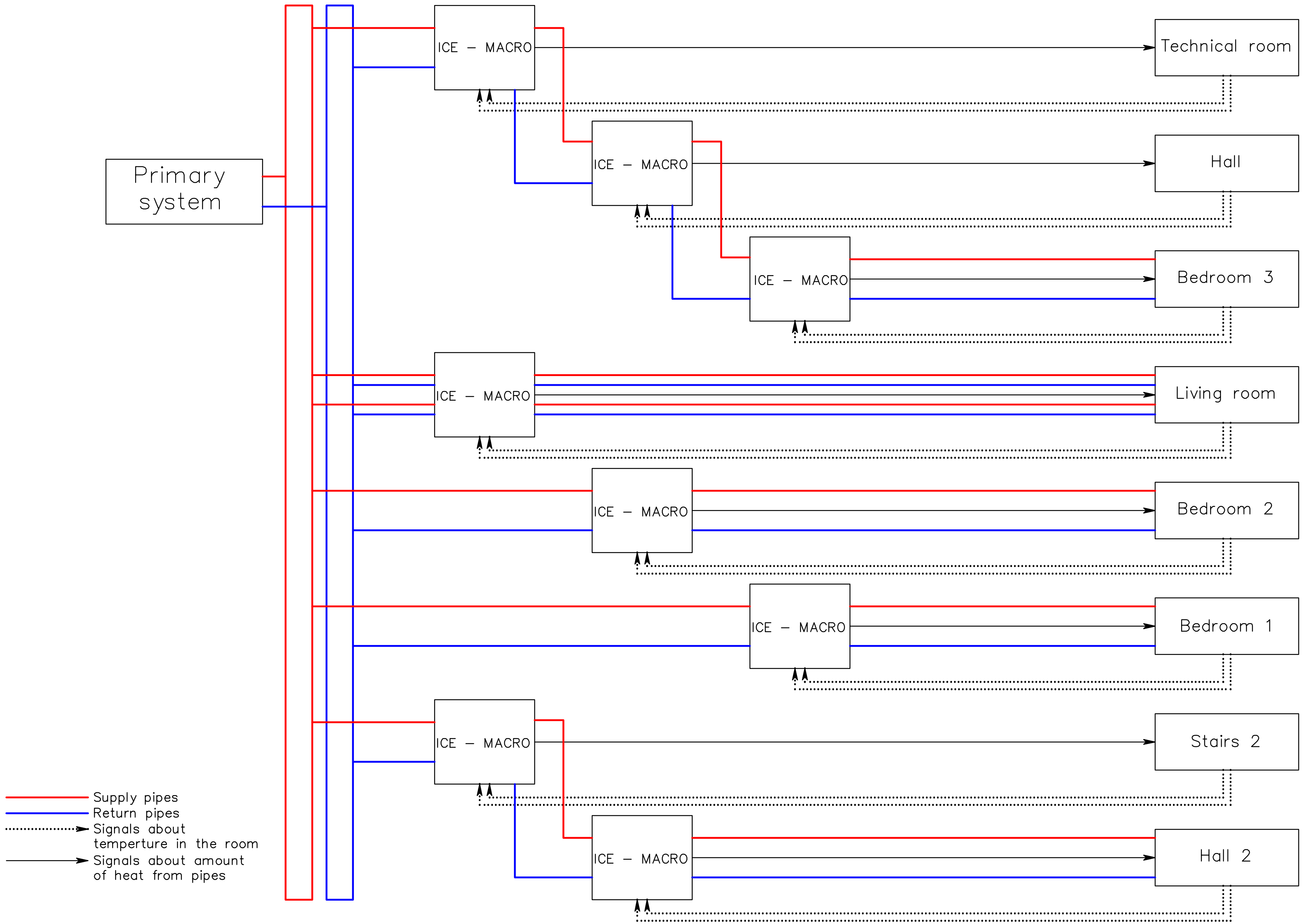
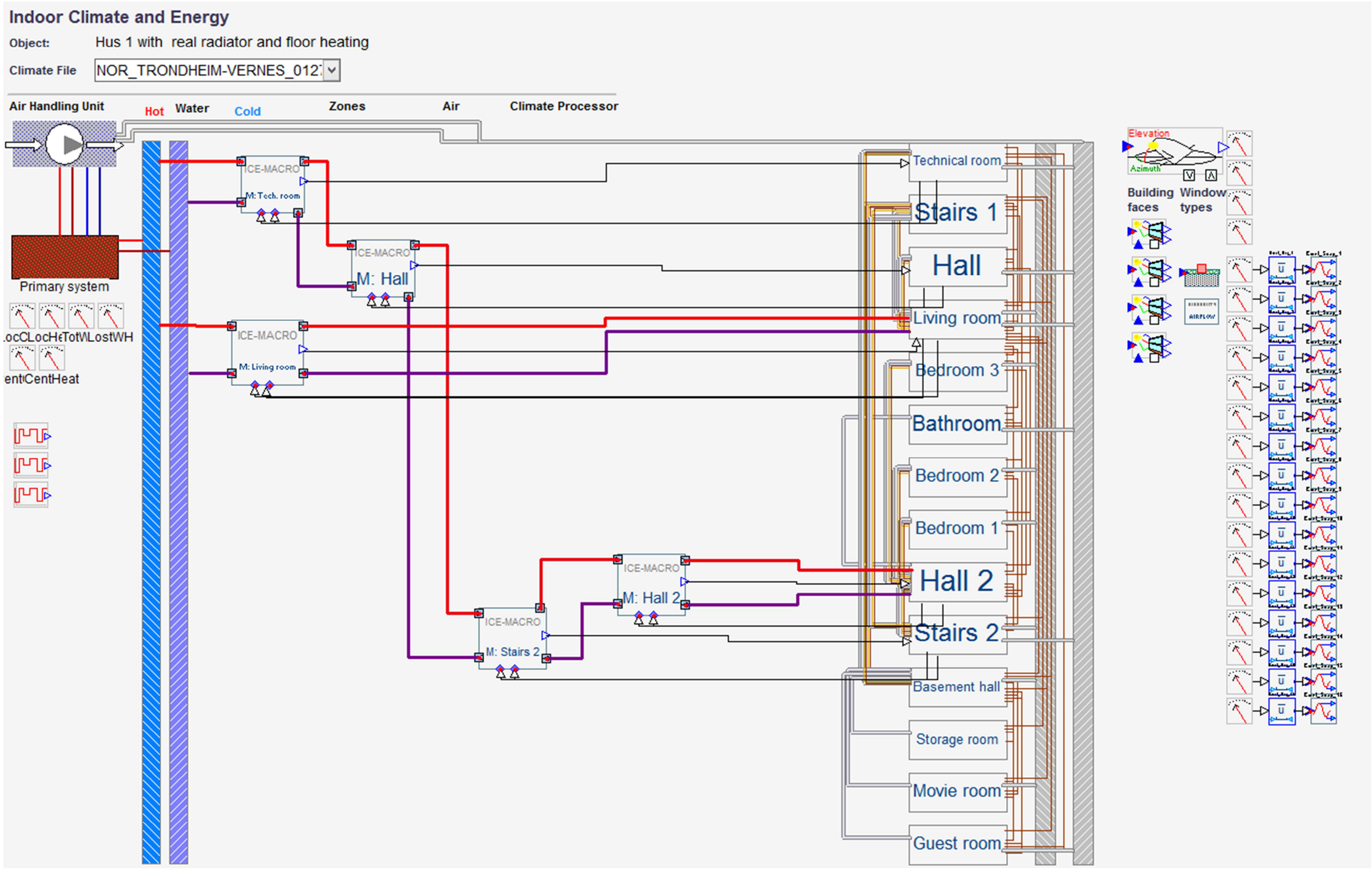


Figure 7: IDA model for simplified heating system

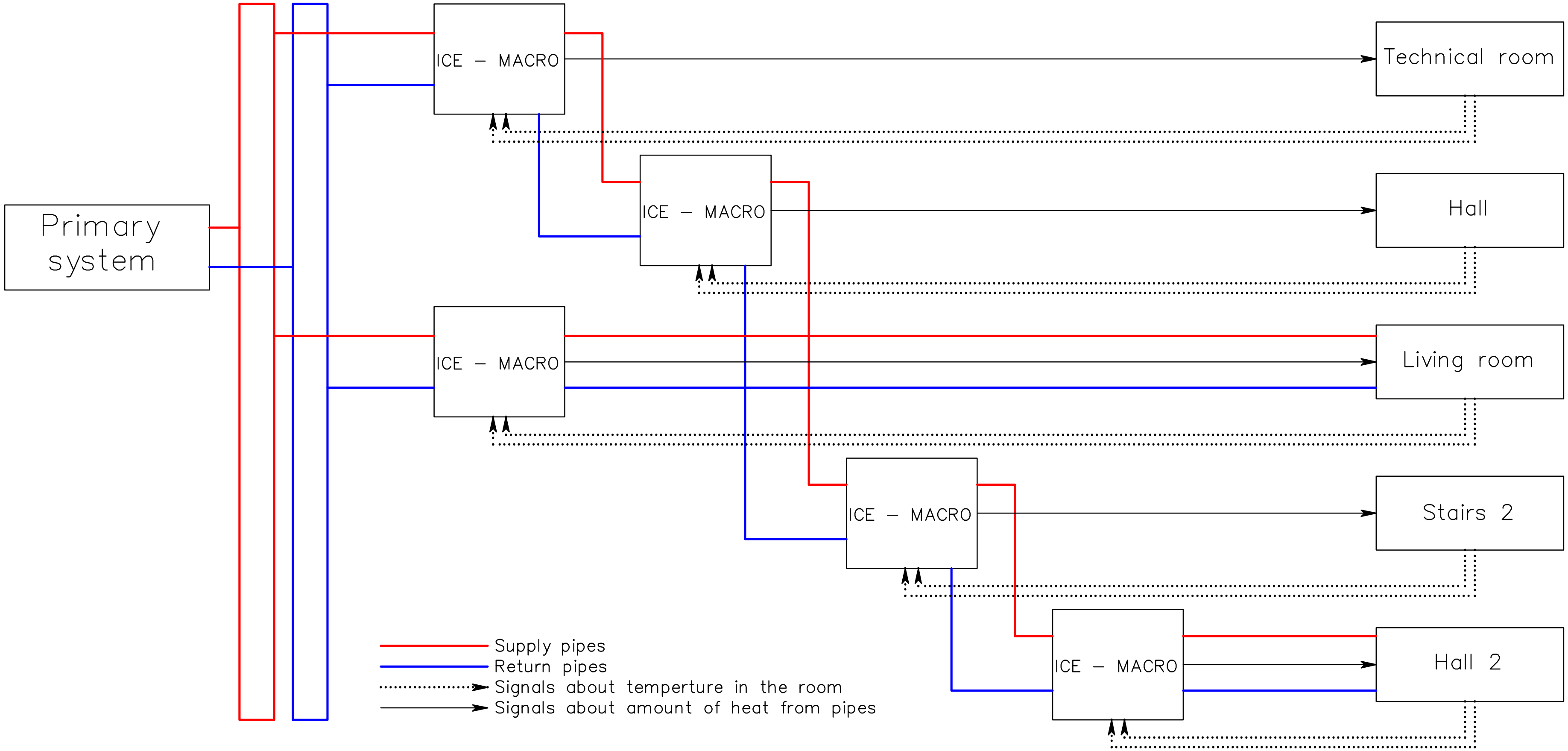


Indoor Climate and Energy

Object: Hus 1 with real radiator and floor heating

Climate File: NOR_TRONDHEIM-VERNES_012

Figure 8: Scheme of IDA model for simplified heating system



# 3. Results

Simulations have been performed for whole year, but software gives an opportunity to check results also from shorter periods. Detailed results can be studied for whole building and for every room separately. Both temperatures and power from units have been checked in different cases.

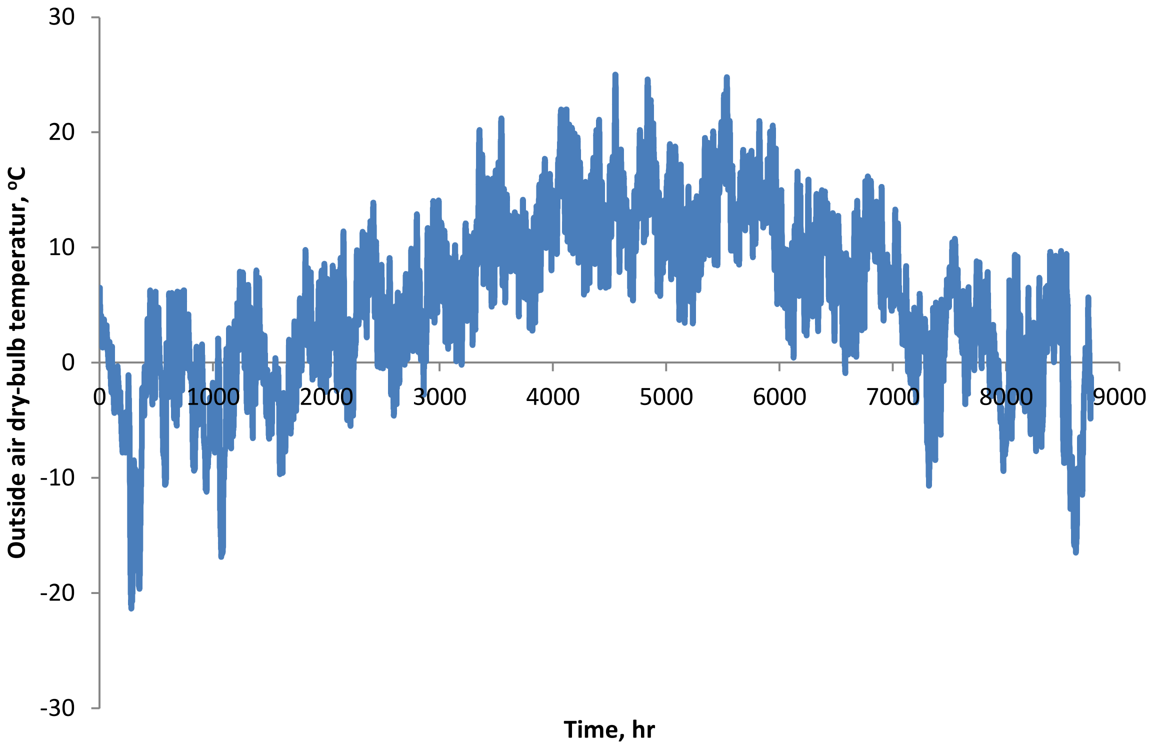
## 3.1. Thermal comfort

Firstly, the main purpose was comparison between standard and simplified heating system. Investigation has to check, if it's possible to maintain acceptable thermal conditions in second case. Simulations have been run with internal open and closed, because they have extremely important influence on thermal conditions. Three rooms have been chosen, as a representative in whole house to check temperatures. These are:

- Living room, because it's the only zone on the first floor
- Hall 2, as the only zone with radiator on the second floor in simplified heating system
- Bedroom 2, the furthest zone from radiator on the second floor in simplified heating system

Indicators PMV (Predicted Mean Vote) and PPD (Predicted percentage Dissatisfied) have been also studied for these zones and results are presented. One representative week (12-18 January) was chosen to study thermal comfort, because, as it's visible on the diagram below, it's the coldest week in the whole year.

**Figure 9: Outside dry-bulb temperature**



## Internal doors open

Analysis with internal doors open shows that it's possible to maintain desirable thermal conditions in whole house during whole year. Temperature in living room and 'hall 2' is practically the same for standard and simplified heating system (figures 10, 11). These are rooms with radiators in both cases. For simplified heating system very important issue is that it's not necessary to overheat these rooms in order to maintain temperature in next zones. Sometimes, sudden gains cause jumps of temperature on these two graphs, but it's controlled by PI-controller and temperature is decreasing afterwards. On the figure 12, temperature in 'bedroom 2' is presented and there is difference between standard and simplified heating system, but this is still acceptable. Temperature does not go down below 19,5°C, even during the coldest day in whole year and it's very promising for simplified heating systems in general. In order to check what would be people's reaction on these conditions, figures 13 and 14 have been generated. They show variables of PMV and PPD in 'bedroom 2'. The difference between standard and simplified heating system is visible, but still in range of acceptance. It should be noted, that this is the coldest week during whole year. Simplified heating system really can manage with maintaining acceptable thermal conditions, if only internal doors are open. Nevertheless, it's hard to say how often during the day, they can be open. Intimacy is the most important factor here, but it also depends on individual preferences. Hence the worst case with internal doors always closed is investigated afterwards.

Figure 10: Temperature in living room for two systems - internal doors open

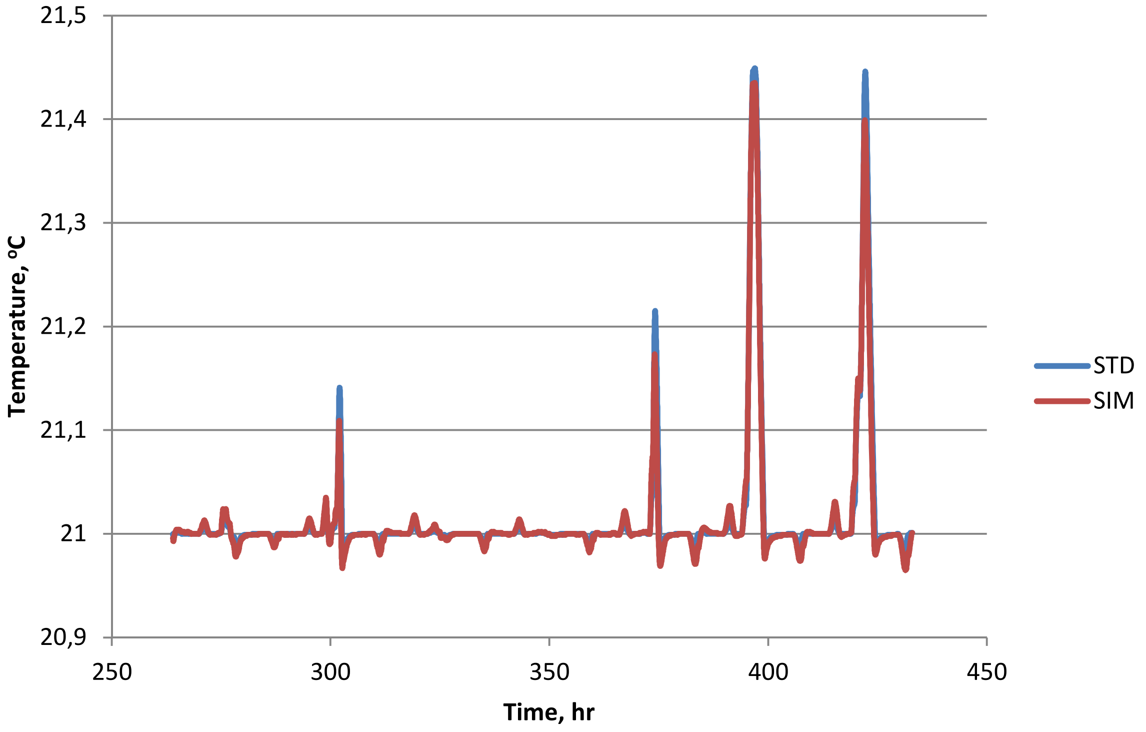


Figure 11: Temperature in hall 2 for two systems - internal doors open

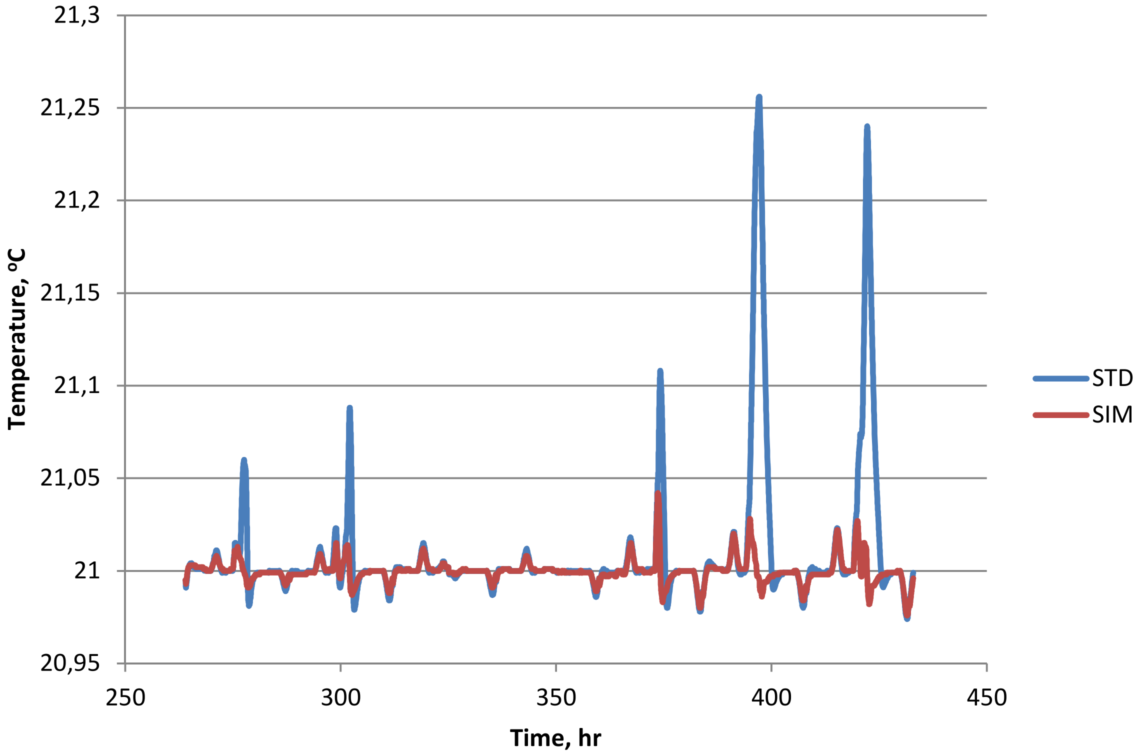


Figure 12: Temperature in bedroom 2 for two systems - internal doors open

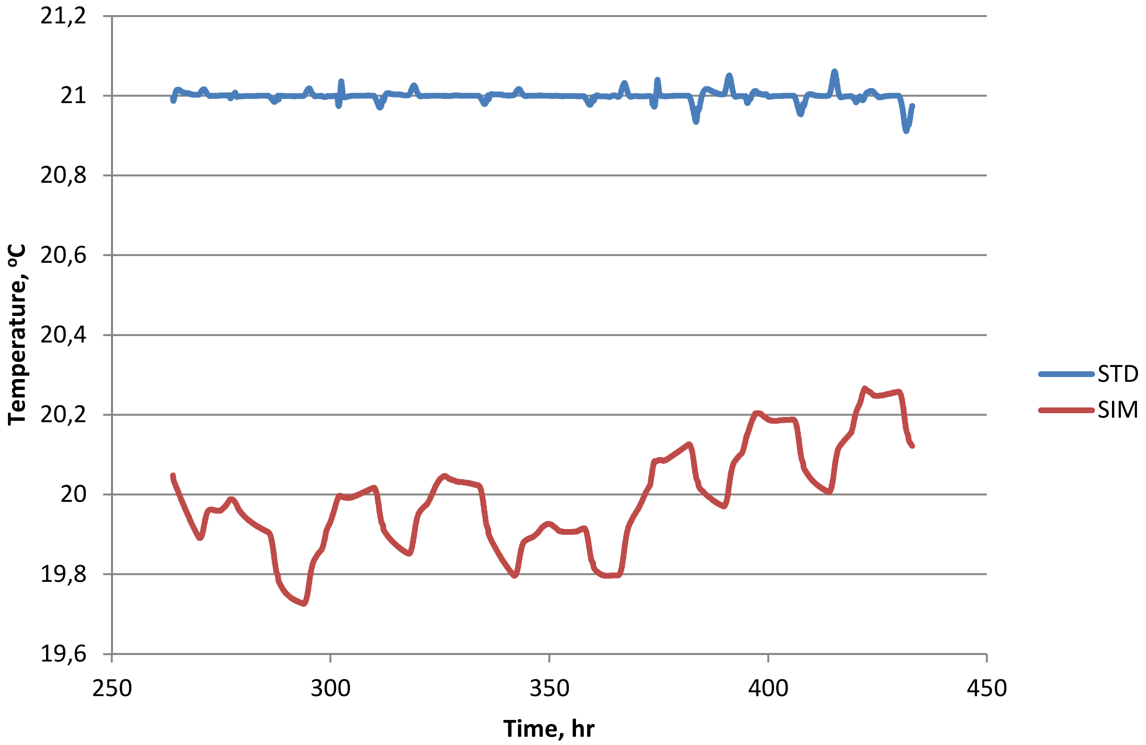


Figure 13: PMV in bedroom 2 for two systems - internal doors open

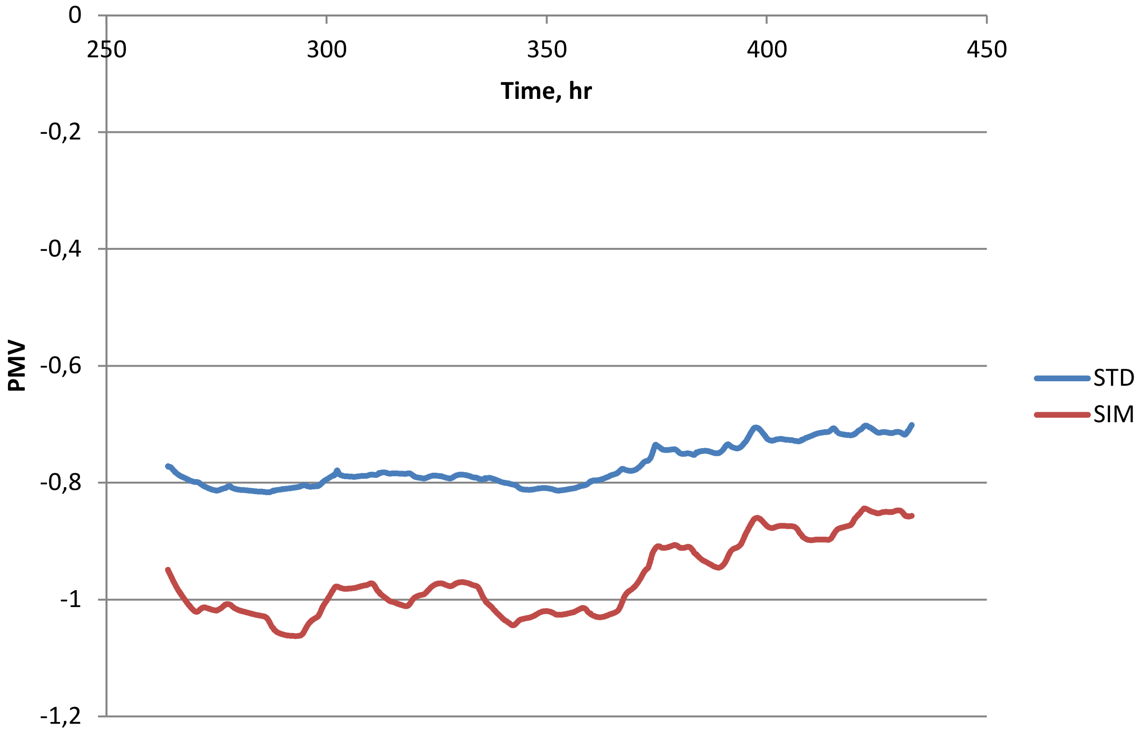
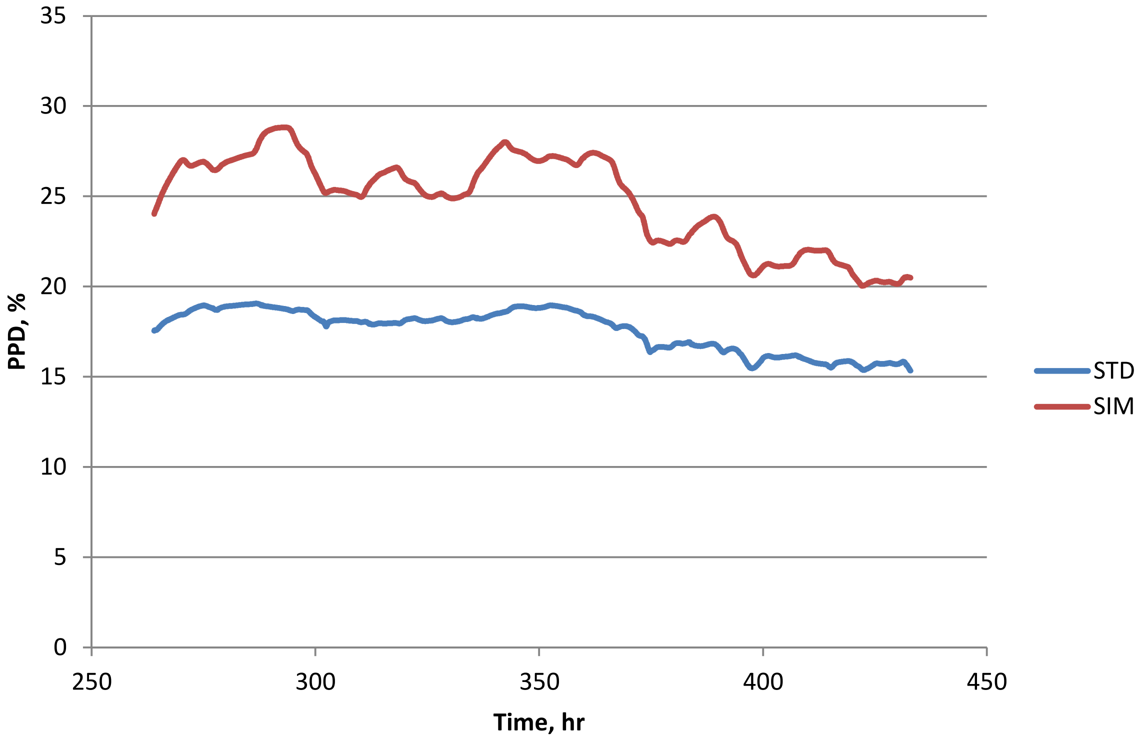


Figure 14: PPD in bedroom 2 for two systems - internal doors open



## Internal doors closed

When internal doors are closed, the situation is much different. In simplified heating system thermal comfort can be maintained in living room and 'hall 2', but it's difficult in bedrooms, where radiators are not designed. Figures 15 and 16 show temperatures in rooms where radiators are designed in both systems and the difference is imperceptible. These graphs are very similar to situation with internal doors open and simplified heating system gets positive mark again. Figure 17 shows temperature in 'bedroom 2' and this is not satisfying. Temperature goes below 16$^{o}$C, what means that basic assumption for Passive House is not fulfilled. Once again, people's reaction is being studied on the next figures (18 and 19). Here, the difference between two systems is evident. Inhabitants in such a house would be clearly dissatisfied from thermal conditions and the designer can't let it happen. In the worst moment Predicted Mean Vote goes below -2 and Predicted Percentage of Dissatisfied is greater than 80%. However these graphs present situation only in one week. In the next step, graphs with PMV, PPD and temperature have been generated for whole year.

Figure 15: Temperature in living room for two systems - internal doors closed

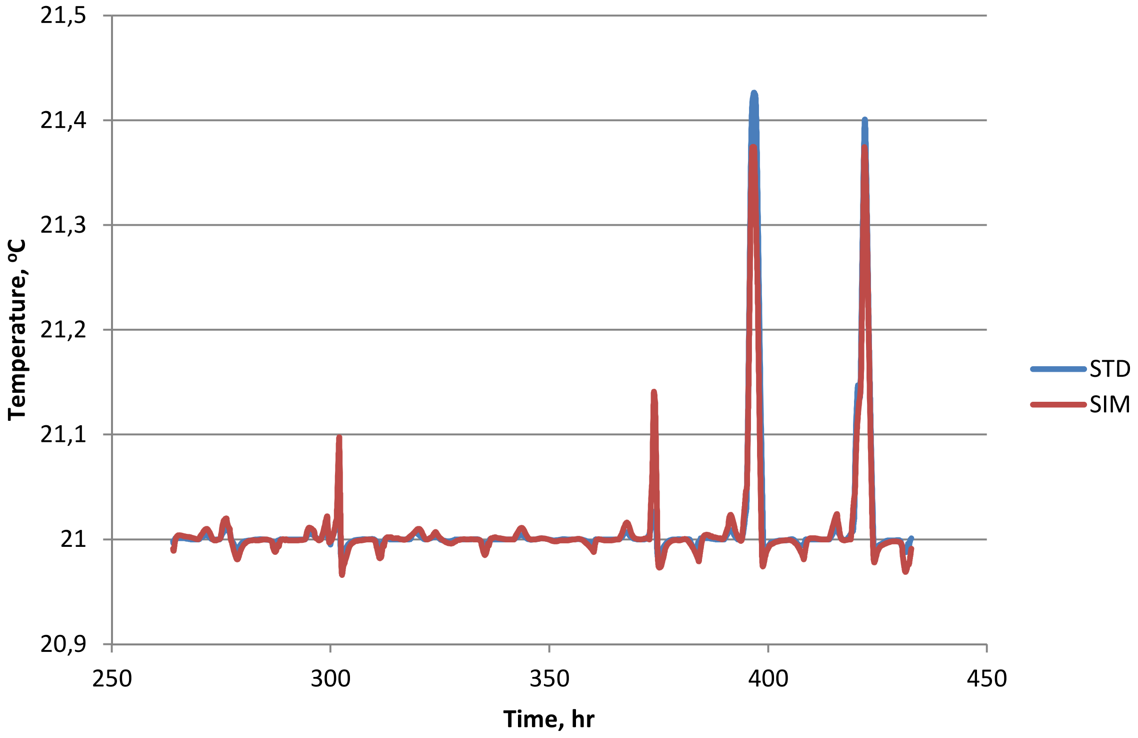


Figure 16: Temperature in Hall 2 for two systems - internal doors closed

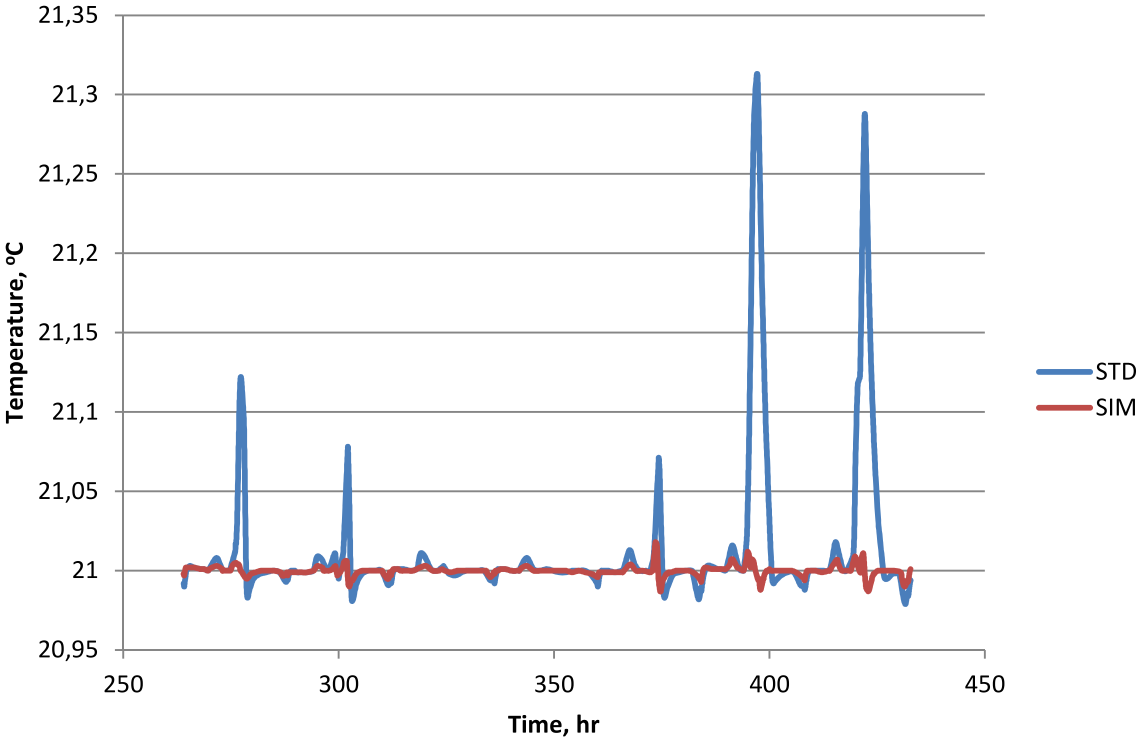


Figure 17: Temperature in bedroom 2 for two systems - internal doors closed

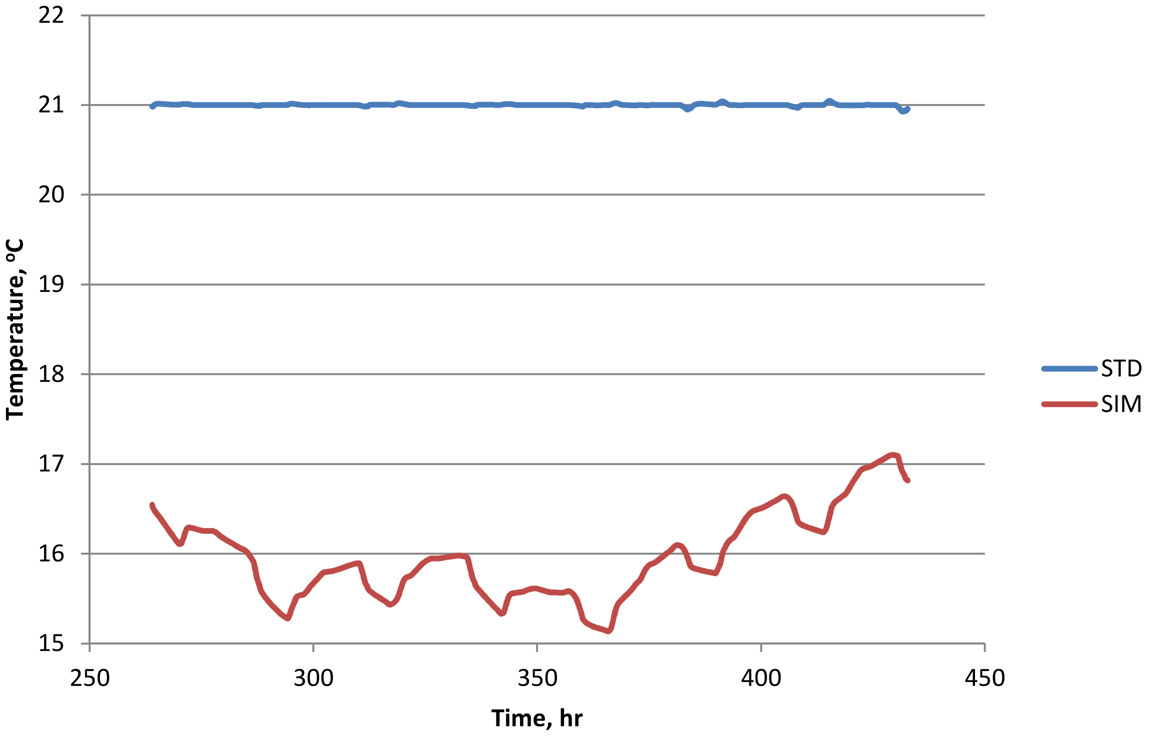


Figure 18: PMV in bedroom 2 for two systems - internal doors closed

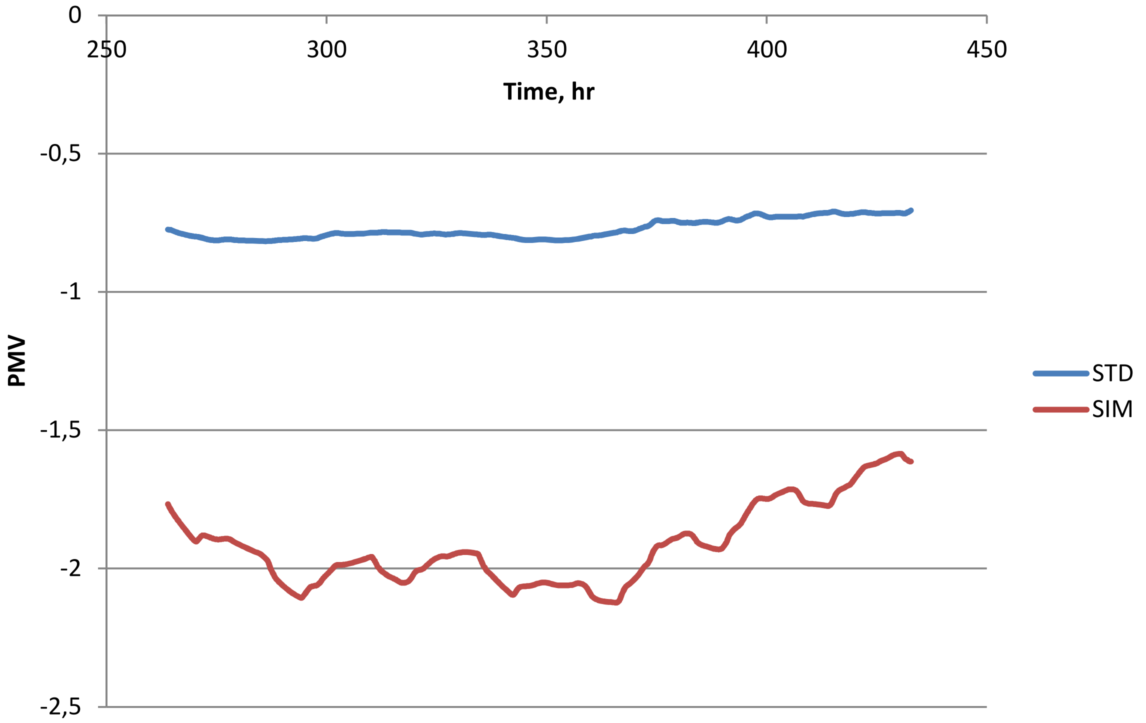


Figure 19: PPD in bedroom 2 for two systems - internal doors closed

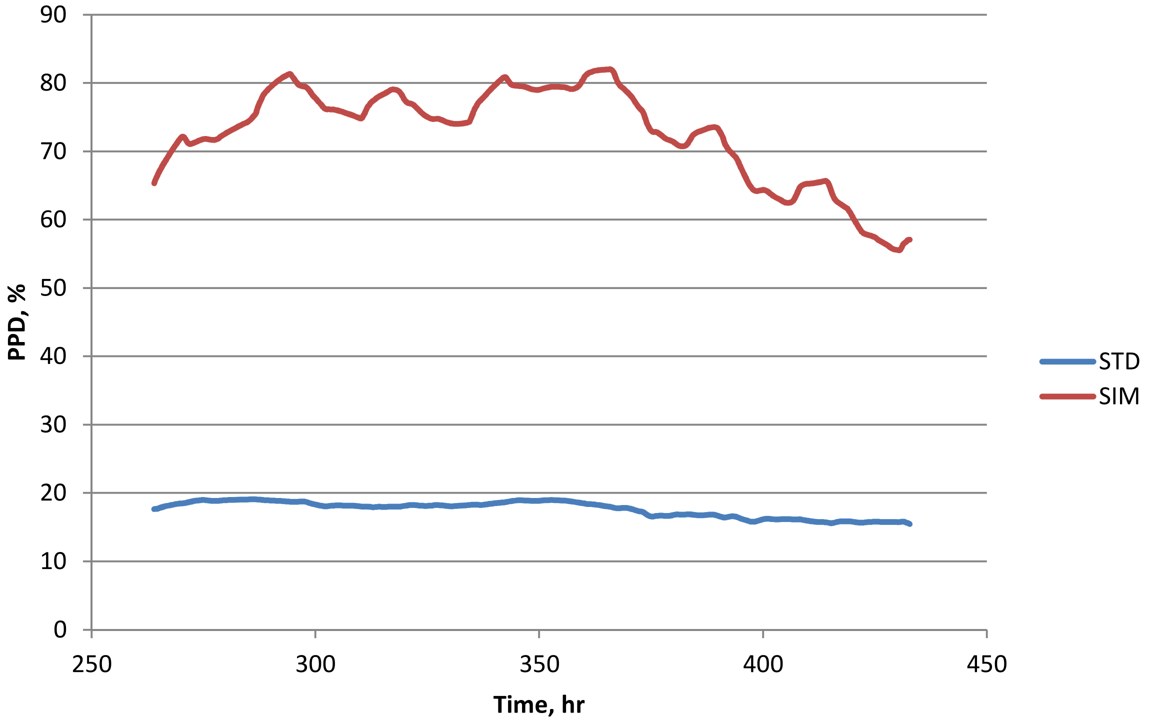


Figure 20 on the next page shows temperature in ‘bedroom 2’ for both systems during whole year. Results can be rated in two ways. On the one hand temperature goes below 16$^{o}$C only in eight days during whole year. This is not long time considering that inhabitants only have to open a door to cause natural airflow and rebalance the temperature. From the other side keeping the temperature above 16°C is only one purpose for passive building, but the main gall is to deliver thermal comfort for residents every time they are inside. Looking at the graph again, we can see that temperature is lower than 20°C practically during whole winter time and this fact is alarming. Figures 21 and 22 show people's reaction on thermal conditions during whole year and calculations say that over 50% of residents are dissatisfied in 109 days. However, it has to be said again, that presented case is the worst because the room is the furthest from radiator and doors are closed all the time. Such a case practically doesn't occur in reality. Normally doors to bedrooms are closed mainly in the night and lower temperature is even desirable. During the day people can keep the doors open and temperature is satisfying. In order to give final opinion about simplified heating system, schedule for doors has been predicted. In this case doors to bedrooms are open during the day (7-23). This is the closest situation to reality. Moments with internal doors closed for example for one hour are negligible because the building has ability to keep warmth inside.

**Figure 20: Temperature in bedroom 2 for two systems - internal doors closed**

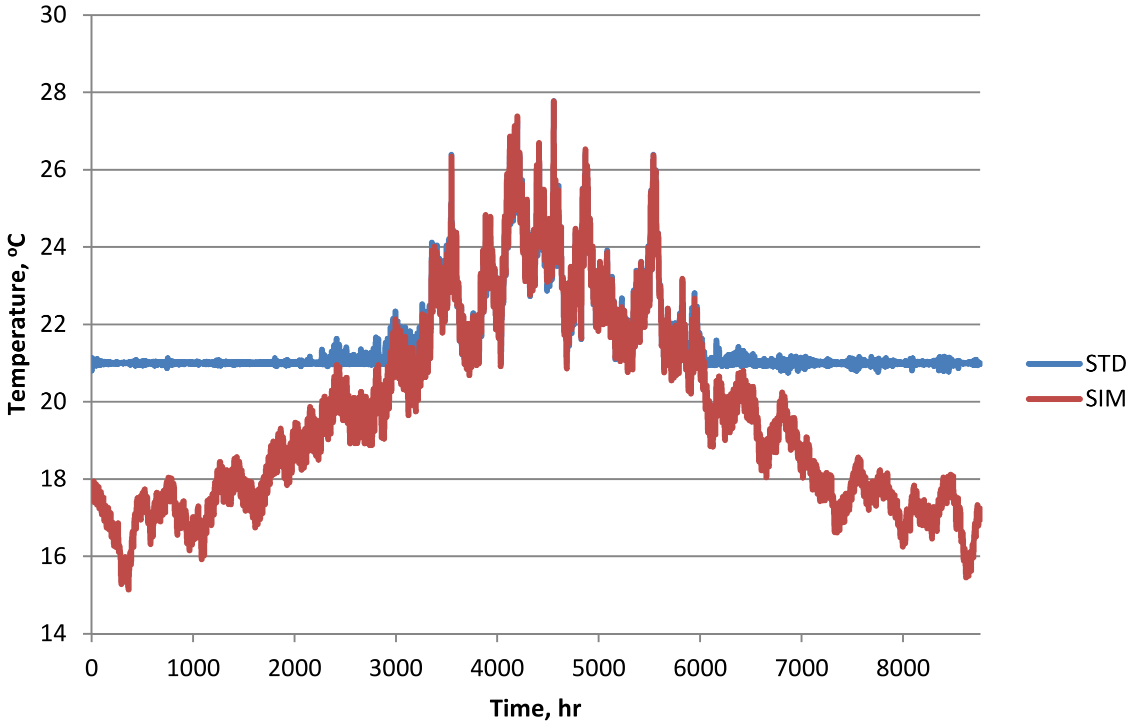


Figure 21: PMV in bedroom 2 for two systems - internal doors closed

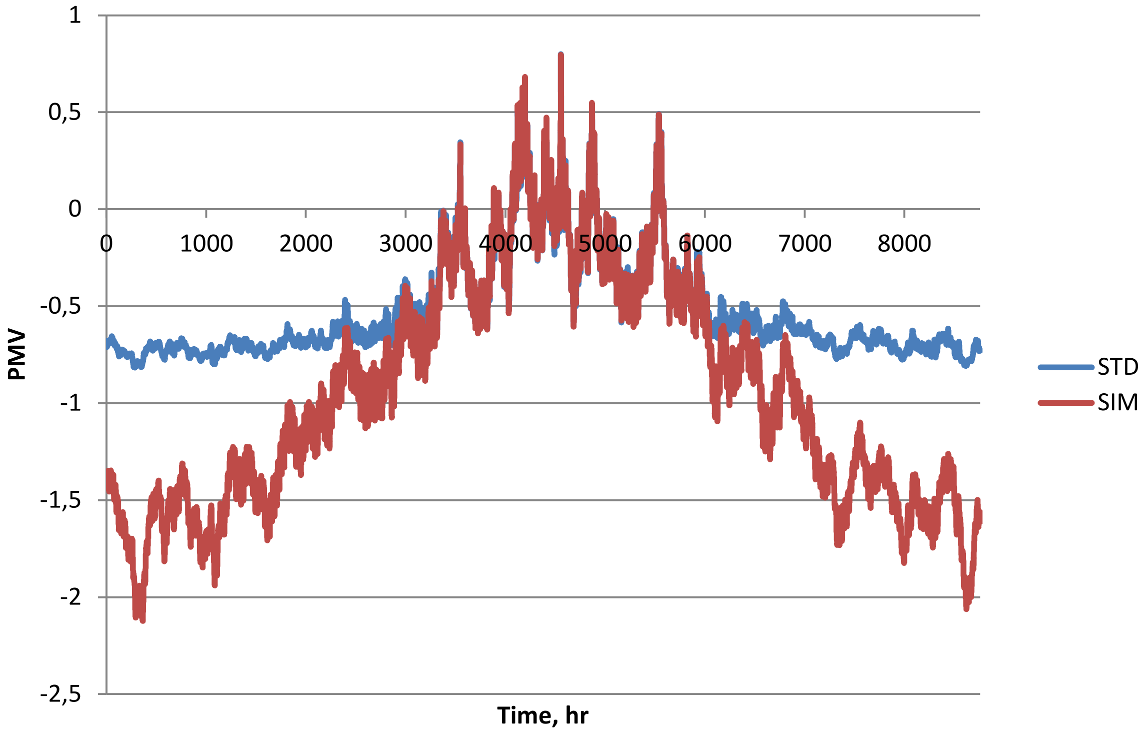
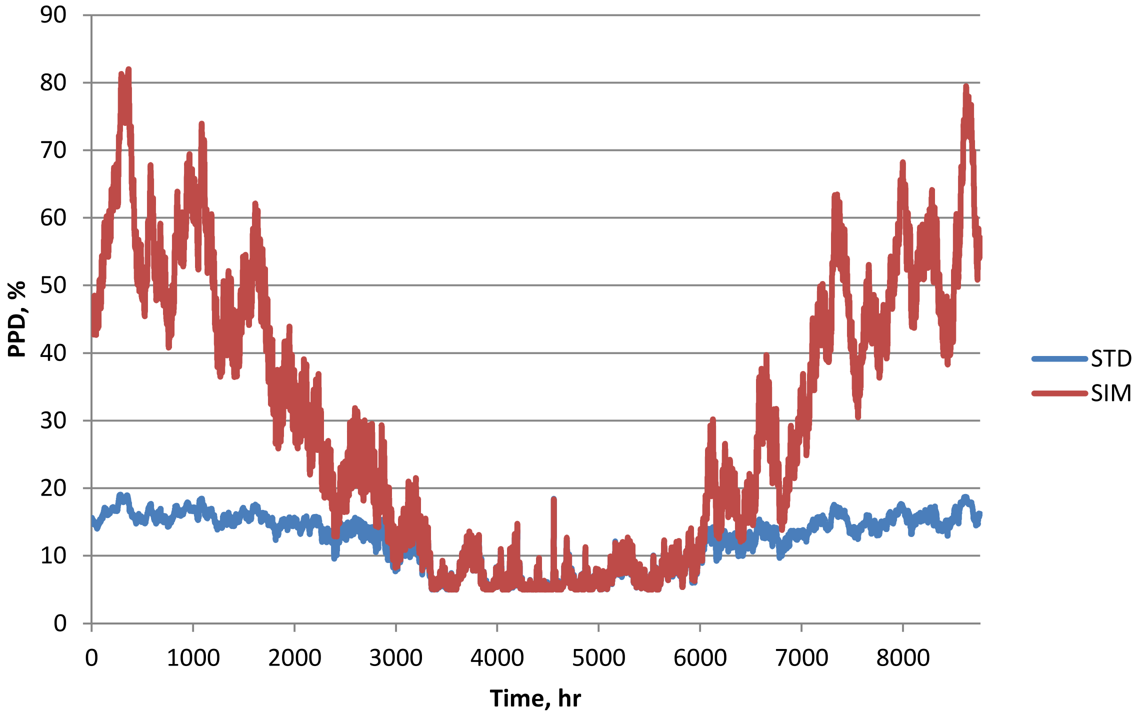


Figure 22: PPD in bedroom 2 for two systems - internal doors closed



### Schedule for doors

Using a schedule gives interesting results. During the day, when doors are open temperature can be kept on the required level. After closing the doors temperature in bedrooms start to fall and reach the lowest point just before opening doors in the morning. Then, some time is needed to rebalance previous conditions. Temperature rises again and required level is achieved. Two variables are incredibly important here: the lowest temperature before opening the doors and time needed to reinstate earlier situation. It can be seen on the figure 23 that temperature in the worst moment doesn’t decrease below 18$^{o}$C and the number of dissatisfied people is about 45% (figure 24). These values are acceptable considering that a bit lower temperature is even desirable during sleeping. It should be also noted that temperature is not constant – in the moment of falling asleep conditions are the same, as with internal doors open all the time. Furthermore, considered day is the coldest and such a low temperature is very rare in the whole year. Figure 23 shows also that room needs only 3-4 hours to rebalance the temperature and this is a time when people are active because of preparing to go out. Analysis with schedule for doors is the closest to reality and it shows that simplified heating system is able to deliver desirable conditions. Thermal comfort is of course little lower than in case of standard heating system, but savings coming from less number of radiators and shorter pipes are definitely worth it.

**Figure 23: Temperature in bedroom 2 for two systems - schedule for internal doors (7-23)**

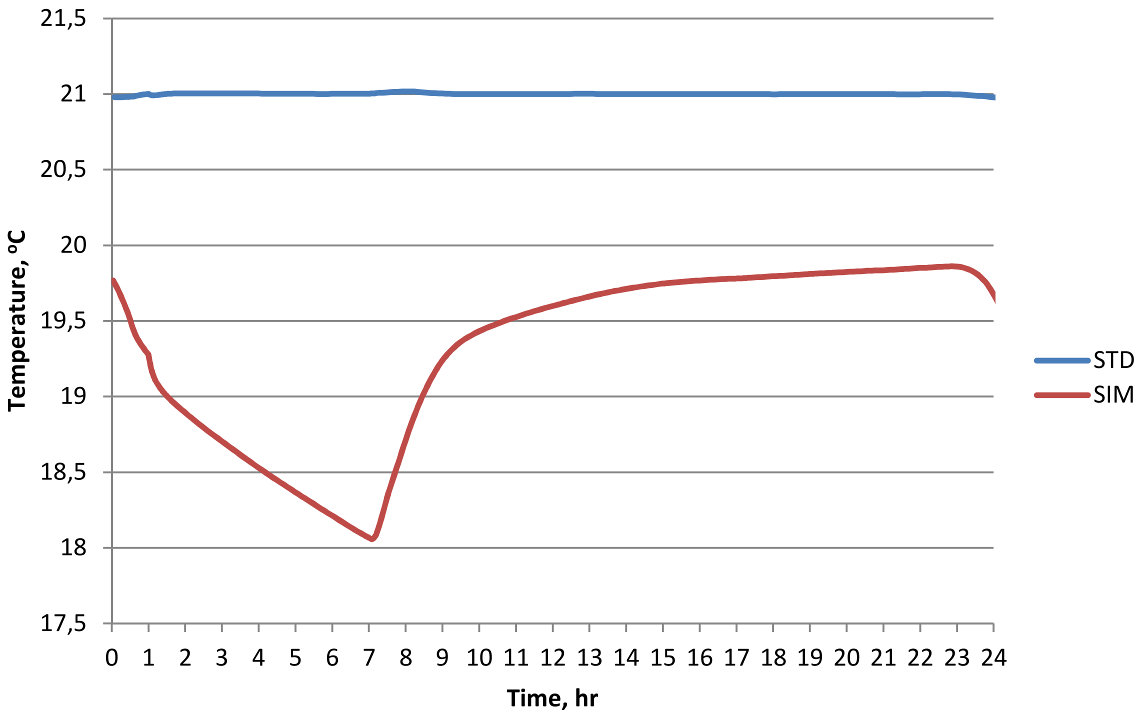


Figure 24: PMV in bedroom 2 for two systems – schedule for internal doors (7-23)

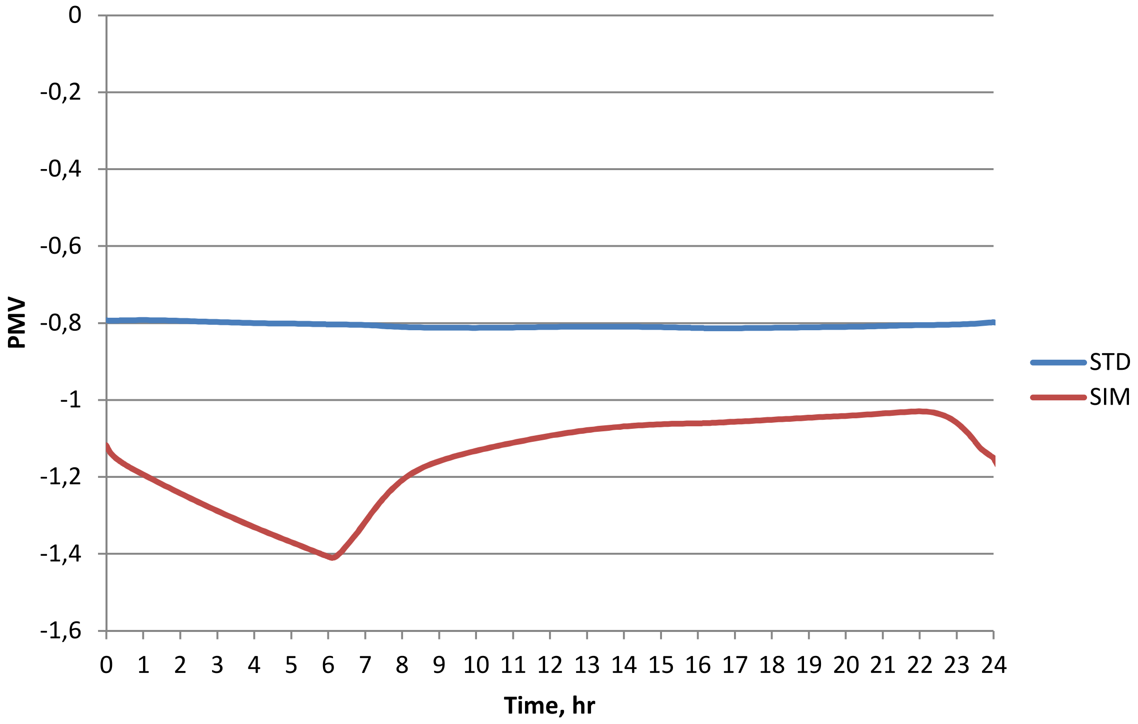
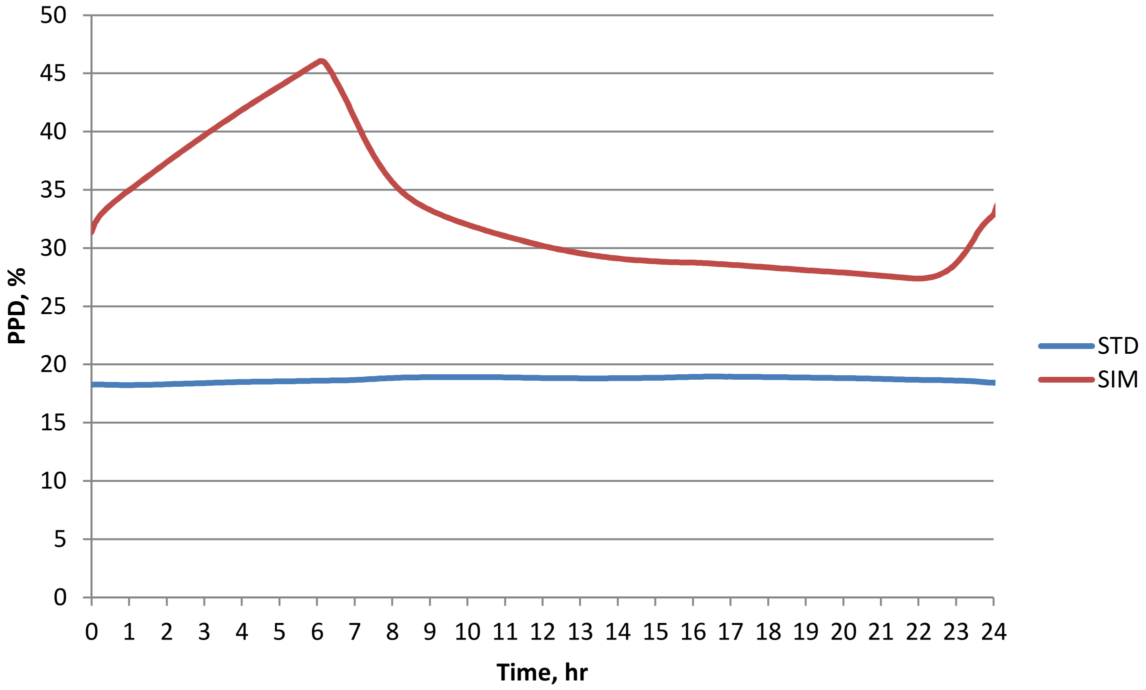


Figure 25: PPD in bedroom 2 for two systems – schedule for internal doors (7-23)



## 3.2 Distribution's efficiency

Investigation of distribution problem shows that losses from pipes are extremely relevant and cannot be ignored in designing. Figure 26 shows power of all radiators and losses from non-insulated pipes in January. Maximum power needed to maintain required temperature in the building is 1282 W and heat released from pipes in this moment is nearly 20% - 236 W. Situation is way better when insulation is added to distribution system. In this case losses from pipes pose about 5% of the water based power (figure 27). It can be seen that required power is changing all the time. Losses from pipes contribute to power of radiators, but fluctuations are not that deep. Because of this, losses from pipes can pose even 35% and 15% in case without and with insulation, respectively. Analysis shows how important is this problem and how essential is using dynamic simulations. Next two graphs compare losses from insulated and non-insulated pipes in standard (figure 28) and simplified heating system (figure 29). These diagrams are very similar to each other because the difference is between length of pipes, so power is almost the same and released energy will be different. However, it has to be noted that both systems deliver different thermal conditions, so they cannot be compared in terms of efficiency. Definitely, using insulation is essential in order to prevent unneeded losses, especially in the basement, technical rooms etc. In warmed rooms losses from pipes are partly recoverable and this has been also deeply investigated in Thesis.

**Figure 26: Heat balance, pipes without insulation - January**

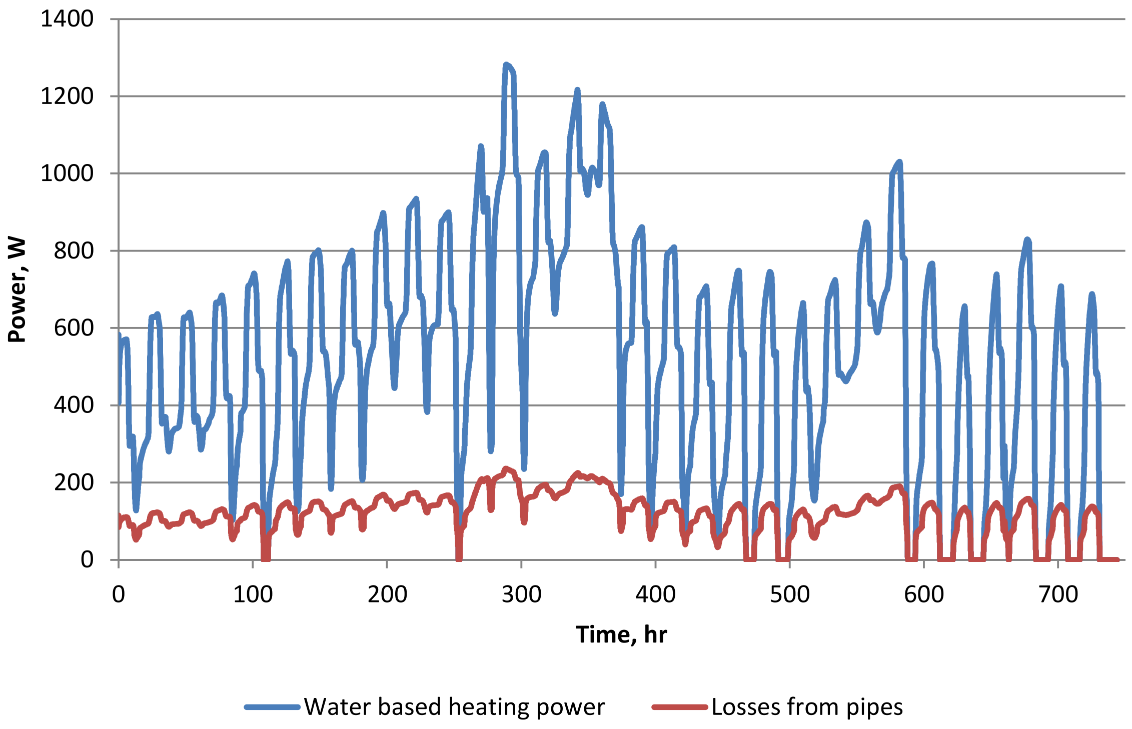


Figure 27: Heat balance, pipes with insulation - January

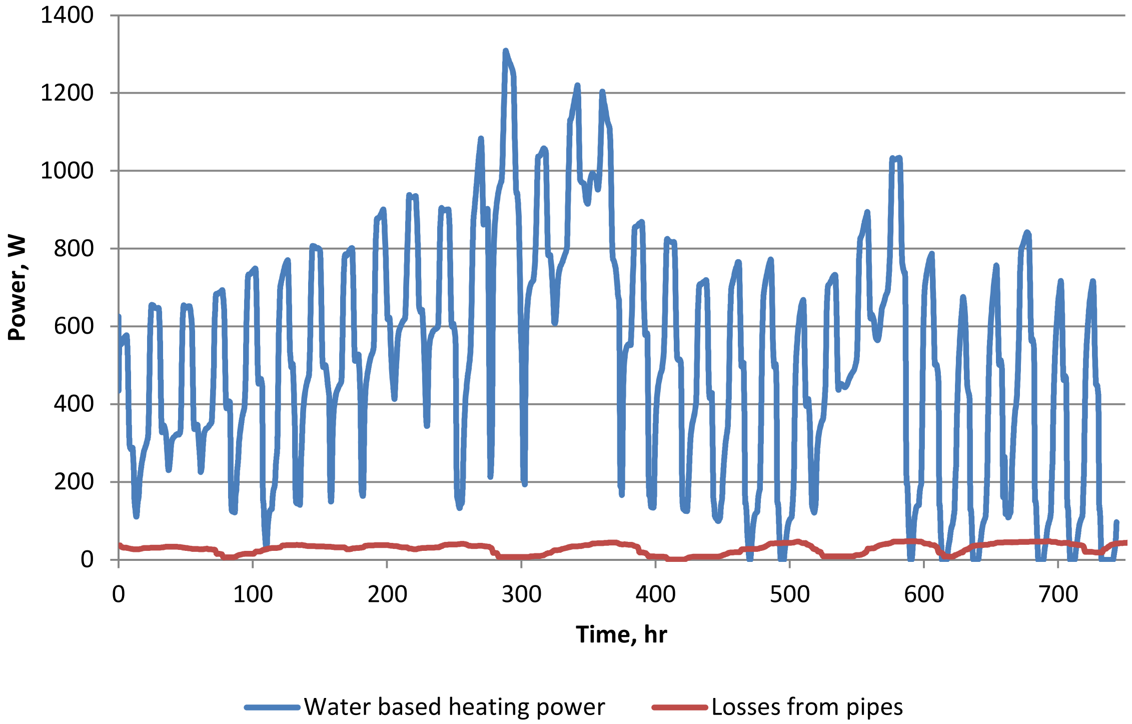


Figure 28: Losses from pipes in standard heating system - January

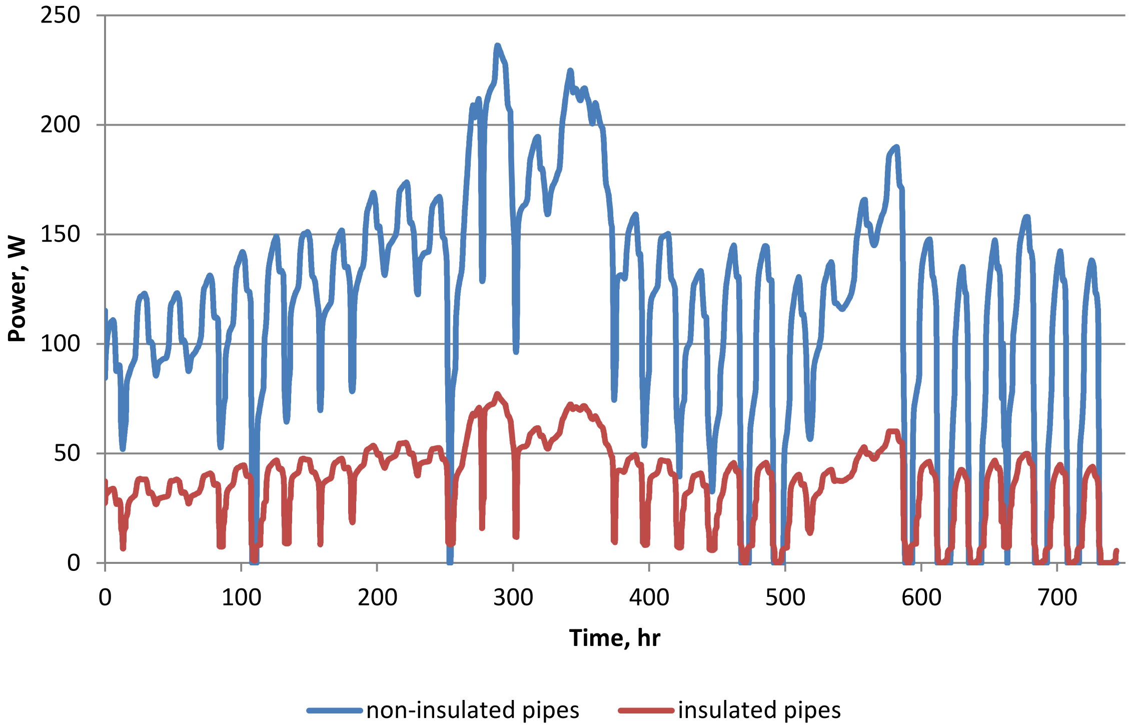
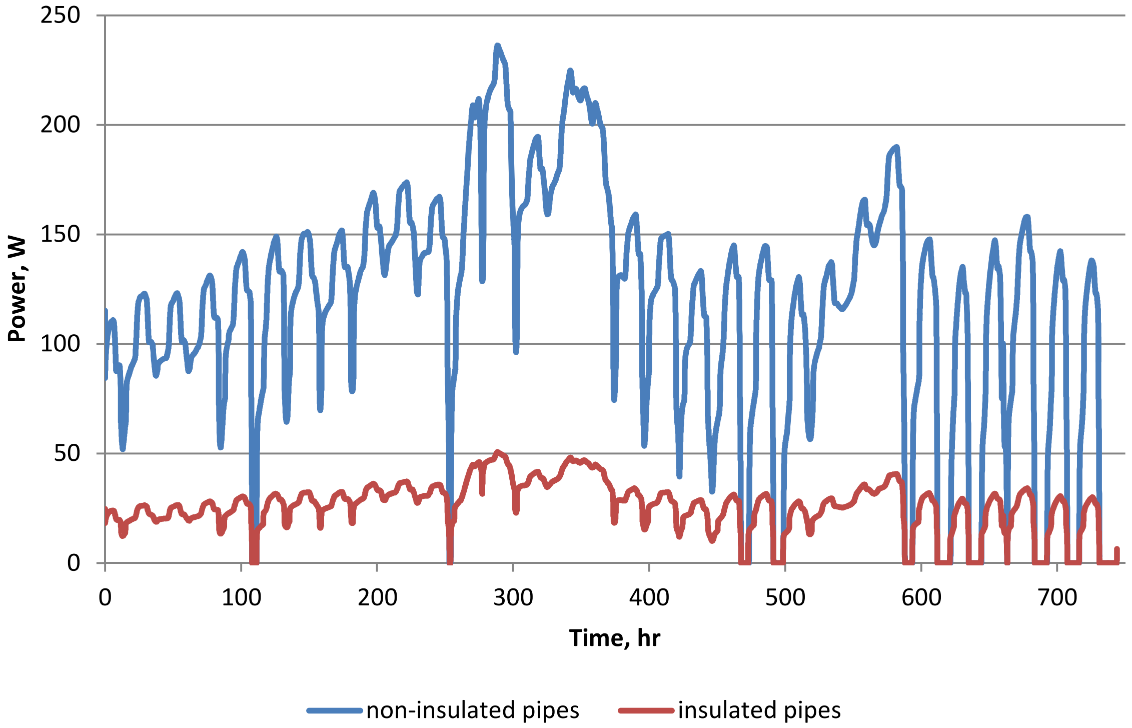


Figure 29: Losses from pipes in simplified heating system - January



## Gains from pipes

Losses from pipes are now considered as a recoverable heat released to rooms. Model with pipes described in previous chapter is compared with basic file where losses from pipes are not being counted. It gives opportunity to quantify how much heat can be recovered from distribution system. Two variables of efficiency factor are counted:

$\eta_1$ – distribution's coefficient without losses from pipes taken into account

$\eta_2$ – distribution's coefficient with losses from pipes used as internal gains.

Variables of power have been averaged for every month and also counted for whole year. Such a procedure has been done for standard heating system and simplified one, both with and without insulation. Simulations have been run with internal doors open and closed. Results are presented in the tables and on the graphs. In the tables, there are some variables in April, Mai and September, but they are too low to be the base to define coefficient. It has been counted only in six months during the year. In highly insulated building, only these months are relevant for heating system.

## Internal doors open

Table 3: Power and energy in standard heating system with non-insulated pipes – internal doors open

| STANDARD HEATING SYSTEM WITHOUT INSULATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Without pipes | | With pipes | | | | $\eta_1$ | $\eta_2$ |
| | Averaged heating power/energy to zones | | Averaged heating power/energy to zones | | Thermal losses | | | |
| | W | kWh | W | kWh | W | kWh | | |
| January | 519,3 | 386,4 | 531,2 | 395,2 | 113,4 | 84,4 | 0,79 | 0,98 |
| February | 328,3 | 244,3 | 368 | 273,8 | 79,4 | 59,1 | 0,78 | 0,89 |
| March | 134,4 | 100,0 | 193,1 | 143,7 | 43,8 | 32,6 | 0,77 | 0,70 |
| April | 8,9 | 6,6 | 30,6 | 22,8 | 8,1 | 6,0 | | |
| May | 0,6 | 0,4 | 3,5 | 2,6 | 0,9 | 0,7 | | |
| June | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| July | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| August | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| September | 4,9 | 3,6 | 10 | 7,4 | 2,7 | 2,0 | | |
| October | 107,8 | 80,2 | 145,5 | 108,3 | 35,8 | 26,6 | 0,75 | 0,74 |
| November | 374,2 | 278,4 | 391,8 | 291,5 | 88,3 | 65,7 | 0,77 | 0,96 |
| December | 520,5 | 387,3 | 531,6 | 395,5 | 114,5 | 85,2 | 0,78 | 0,98 |
| | | **1487,2** | | **1640,7** | | **362,3** | **0,78** | **0,91** |

Table 4: Power and energy in standard heating system with insulated pipes - internal doors open

| **STANDARD HEATING SYSTEM WITH INSULATION** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Without pipes** | | **With pipes** | | | | $\eta_1$ | $\eta_2$ |
| | **Averaged heating power/energy to zones** | | **Averaged heating power/energy to zones** | | **Thermal losses** | | | |
| | W | kWh | W | kWh | W | kWh | | |
| January | 519,3 | 386,4 | 522,2 | 388,5 | 31,6 | 23,5 | 0,94 | 0,99 |
| February | 328,3 | 244,3 | 360 | 267,8 | 22,3 | 16,6 | 0,94 | 0,91 |
| March | 134,4 | 100,0 | 188,4 | 140,2 | 12,5 | 9,3 | 0,93 | 0,71 |
| April | 8,9 | 6,6 | 28,6 | 21,3 | 2,4 | 1,8 | | |
| May | 0,6 | 0,4 | 3,2 | 2,4 | 0,3 | 0,2 | | |
| June | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| July | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| August | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| September | 4,9 | 3,6 | 8,9 | 6,6 | 0,8 | 0,6 | | |
| October | 107,8 | 80,2 | 138,3 | 102,9 | 10,1 | 7,5 | 0,93 | 0,78 |
| November | 374,2 | 278,4 | 380,1 | 282,8 | 24,7 | 18,4 | 0,94 | 0,98 |
| December | 520,5 | 387,3 | 523,5 | 389,5 | 32,1 | 23,9 | 0,94 | 0,99 |
| | | **1487,2** | | **1602,0** | | **101,8** | **0,94** | **0,93** |

**Table 5: Power and energy in simplified heating system with non-insulated pipes - internal doors open**

| SIMPLIFIED HEATING SYSTEM WITHOUT INSULATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Without pipes** | | **With pipes** | | | | $\eta_1$ | $\eta_2$ |
| | **Averaged heating power/energy to zones** | | **Averaged heating power/energy to zones** | | **Thermal losses** | | | |
| | W | kWh | W | kWh | W | kWh | | |
| January | 513,2 | 381,8 | 521 | 387,6 | 101,3 | 75,4 | 0,81 | 0,99 |
| February | 320,2 | 238,2 | 319,6 | 237,8 | 66,2 | 49,3 | 0,79 | 1,00 |
| March | 123,1 | 91,6 | 130,8 | 97,3 | 29,2 | 21,7 | 0,78 | 0,94 |
| April | 4,6 | 3,4 | 5,8 | 4,3 | 2 | 1,5 | | |
| May | 0,1 | 0,1 | 0,2 | 0,1 | 0,1 | 0,1 | | |
| June | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| July | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| August | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| September | 1,5 | 1,1 | 2 | 1,5 | 0,7 | 0,5 | | |
| October | 94,6 | 70,4 | 98,5 | 73,3 | 23,4 | 17,4 | 0,76 | 0,96 |
| November | 368,1 | 273,9 | 371,5 | 276,4 | 76,6 | 57,0 | 0,79 | 0,99 |
| December | 513,2 | 381,8 | 523,7 | 389,6 | 102,3 | 76,1 | 0,80 | 0,98 |
| | | **1442,3** | | **1468,0** | | **298,9** | **0,80** | **0,98** |

Table 6: Power and energy in simplified heating system with insulated pipes - internal doors open

| SIMPLIFIED HEATING SYSTEM WITH INSULATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Without pipes** | | **With pipes** | | | | $\eta_1$ | $\eta_2$ |
| | **Averaged heating power/energy to zones** | | **Averaged heating power/energy to zones** | | **Thermal losses** | | | |
| | W | kWh | W | kWh | W | kWh | | |
| January | 513,2 | 381,8 | 509,5 | 379,1 | 26,8 | 19,9 | 0,95 | 1,00 |
| February | 320,2 | 238,2 | 311,7 | 231,9 | 17,7 | 13,2 | 0,94 | 1,00 |
| March | 123,1 | 91,6 | 126,9 | 94,4 | 7,9 | 5,9 | 0,94 | 0,97 |
| April | 4,6 | 3,4 | 5,2 | 3,9 | 0,6 | 0,4 | | |
| May | 0,1 | 0,1 | 0,2 | 0,1 | 0 | 0,0 | | |
| June | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| July | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| August | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| September | 1,5 | 1,1 | 1,6 | 1,2 | 0,2 | 0,1 | | |
| October | 94,6 | 70,4 | 93,7 | 69,7 | 6,3 | 4,7 | 0,93 | 1,00 |
| November | 368,1 | 273,9 | 359,8 | 267,7 | 20,3 | 15,1 | 0,94 | 1,00 |
| December | 513,2 | 381,8 | 512 | 380,9 | 27,1 | 20,2 | 0,95 | 1,00 |
| | | **1442,3** | | **1428,9** | | **79,5** | **0,94** | **0,99** |

Figure 30: Distribution coefficient for standard heating system with non-insulated pipes - internal doors open

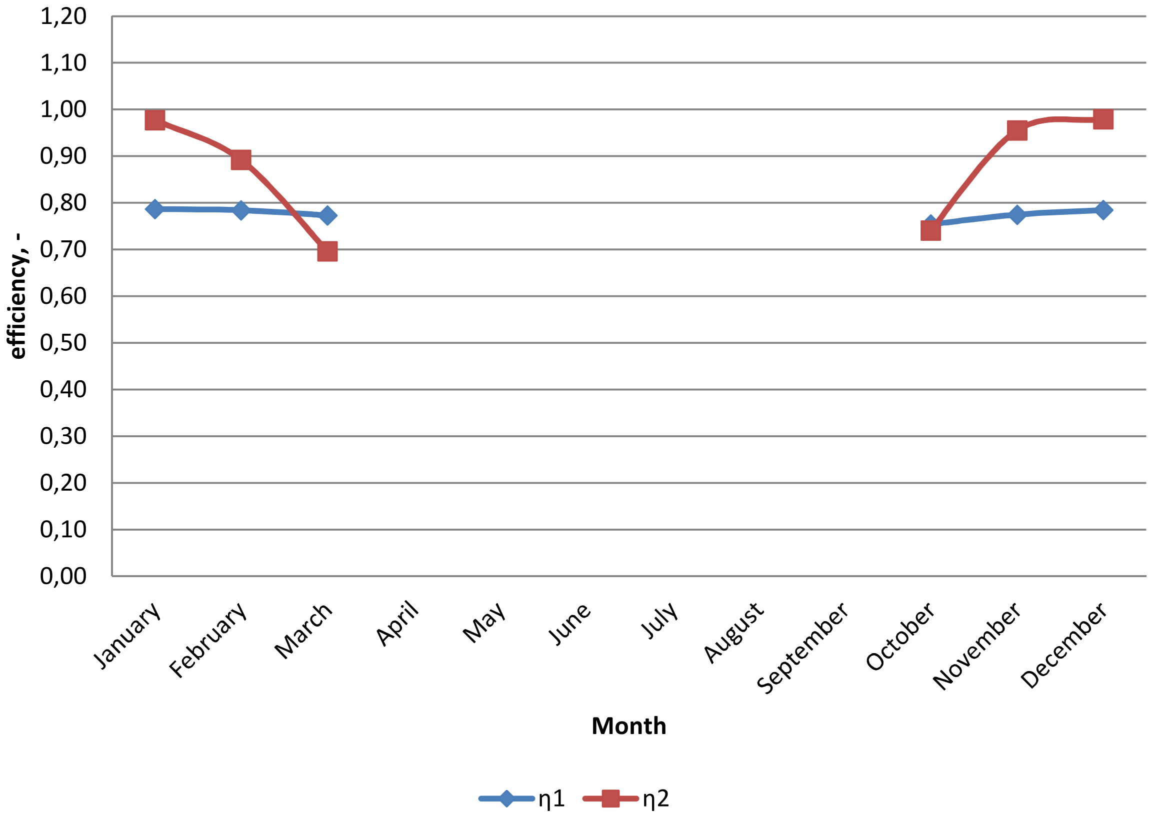


Figure 31: Distribution coefficient for standard heating system with insulated pipes - internal doors open

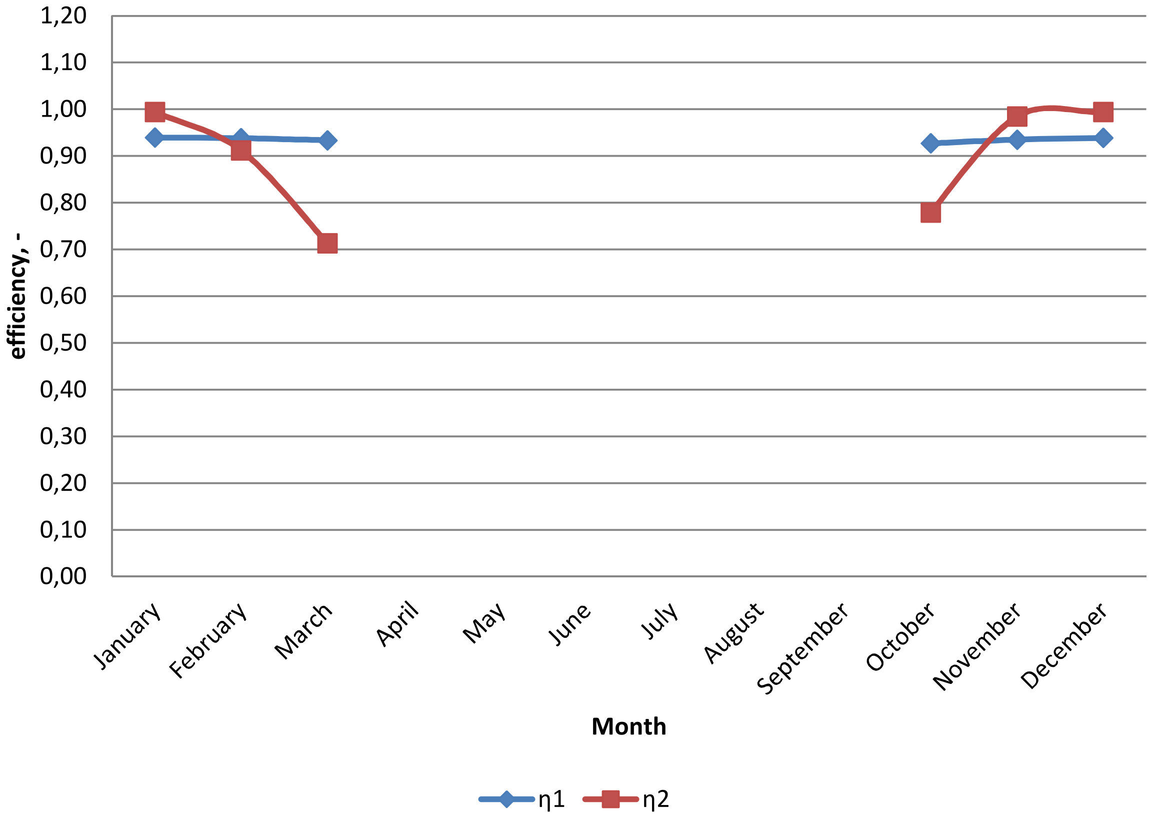


Figure 32: Distribution coefficient for simplified heating system with non-insulated pipes - internal doors open

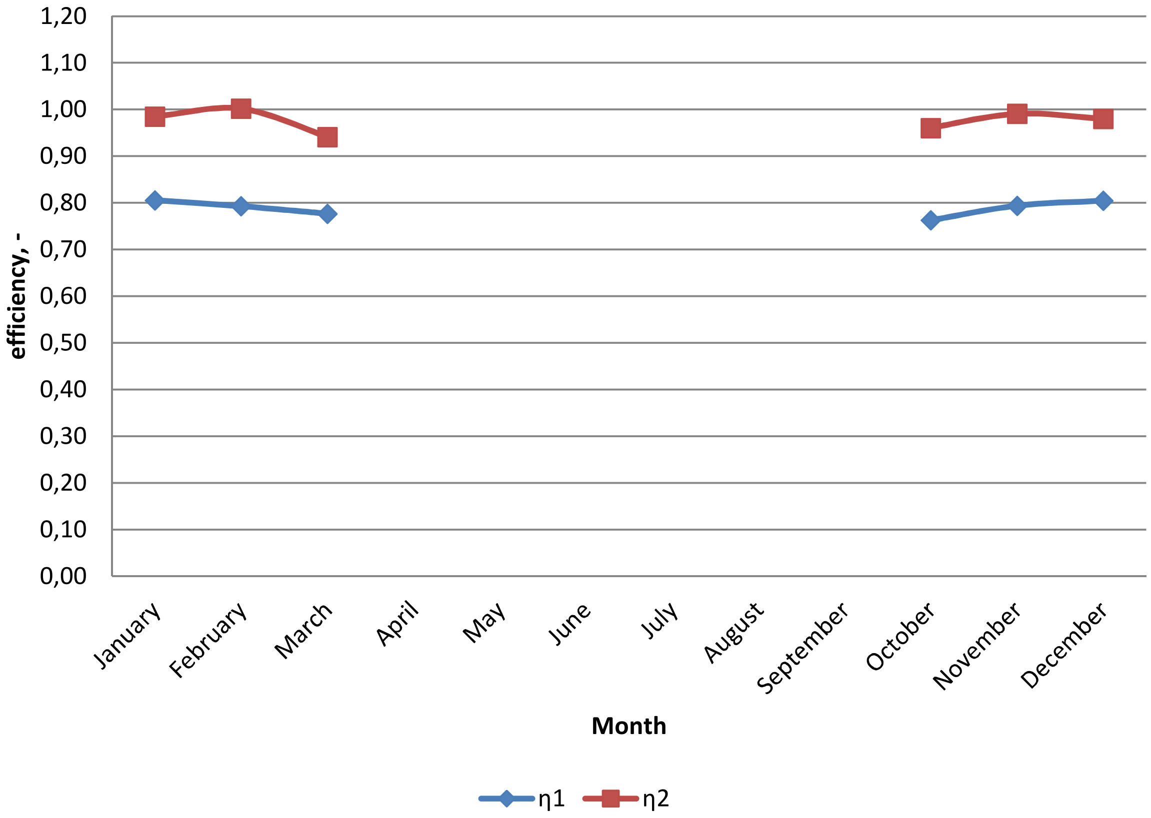
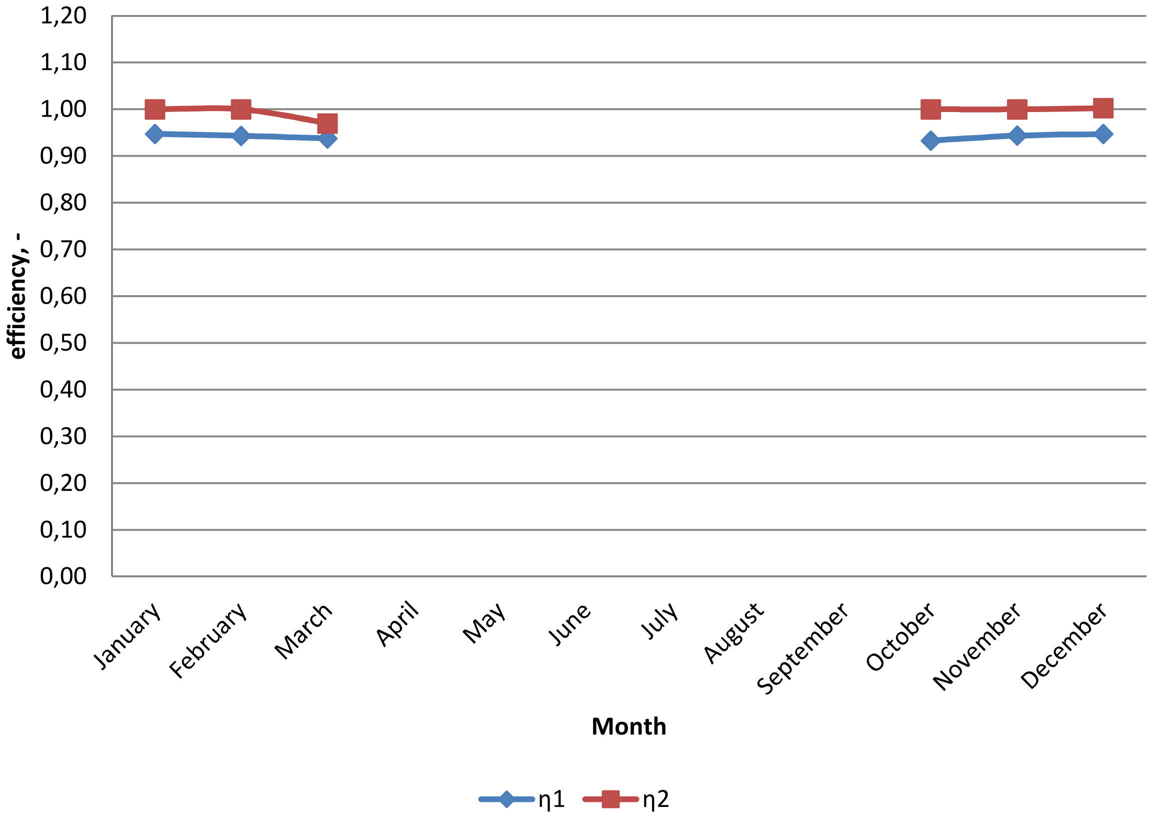


Figure 33: Distribution coefficient for simplified heating system with insulated pipes - internal doors open



On the figures 30 and 31 distribution's coefficient starts at the high point in January, then goes down to the lowest point in March. It has to be noticed, that during winter $\eta_2$ is very close to 100%. It means that almost all losses from pipes are recoverable. Efficiency goes down because of rising outside temperature and increasing solar gains. Losses from pipes, even if taken into account, are less and less useful. They are not recoverable when setpoint $21^oC$ is exceeded. In the summer heating system is not being used, so efficiency is not calculated. The previous tendency is visible from October to December. Efficiency is rising because it gets colder outside and solar gains decline. Diagrams show that real efficiency of water based systems are greater when losses from pipes are not ignored. In standard heating system with non-insulated pipes losses from distribution system pose 22% of whole energy, but only 9% is completely lost because the rest is recoverable (table 3).

Results are slightly different for simplified heating system (fig. 32, 33) The line showing variable $\eta_2$ is not going down like in standard heating system. Looking for explanation of this change we can see that losses from pipes, from every room have been taken into account. It means that losses from basement are treated as recoverable. In simplified heating system main part of pipe network runs through zones without solar gains on the contrary to standard heating system. There is no factor, which caused decline of variable $\eta_2$ in standard loop. This is the reason of difference between standard and simplified heating system. When losses to unheated zones are treated as recoverable, efficiency of simplified distribution system is very high. When pipes are not insulated, losses pose 24%, but 21% is recoverable. Real efficiency is 97% (table 5). When insulation is added to pipes this value is rising to 99% (table 6). Another investigation could take into account only gains from pipes to heated rooms, but in this case everything depends on system topology and size of the house.

Provided by many standards old approach to quantify distribution's efficiency in water based systems didn't take losses from pipes into account. As a result, so far designed systems may be slightly oversized and some savings are achievable from economic point of view. Another investigation could study more cases with different topology of the system. Bigger installations could be taken into account. Water based systems are widely used in multi-storey buildings and losses from pipes are there even more meaningful. Distribution's coefficient would change also because of bigger diameters of pipes. When such an investigation is performed, it would be possible to define new distribution's coefficient for better standards and designing guidelines.

In the next step, doors to bedrooms have been closed. This operation caused increase of delivered energy because every zone has to be heated individually. However in terms of efficiency, the difference is negligible. Variables $\eta_1$ and $\eta_2$ are nearly the same to the case with internal doors open. All the results are presented below.

# Internal doors closed

Table 7: Power and energy in standard heating system with non-insulated pipes - internal doors closed

| STANDARD HEATING SYSTEM WITHOUT INSULATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Without pipes** | | **With pipes** | | | | $\eta_1$ | $\eta_2$ |
| | **Averaged heating power/energy to zones** | | **Averaged heating power/energy to zones** | | **Thermal losses** | | | |
| | W | kWh | W | kWh | W | kWh | | |
| January | 526,8 | 391,9 | 538,5 | 400,6 | 113,6 | 84,5 | 0,79 | 0,98 |
| February | 336,8 | 250,6 | 374,8 | 278,9 | 77 | 57,3 | 0,79 | 0,90 |
| March | 155,2 | 115,5 | 206,9 | 153,9 | 43,2 | 32,1 | 0,79 | 0,75 |
| April | 32,5 | 24,2 | 56,3 | 41,9 | 11,6 | 8,6 | | |
| May | 5,5 | 4,1 | 11,8 | 8,8 | 2,3 | 1,7 | | |
| June | 0 | 0,0 | 0,2 | 0,1 | 0 | 0,0 | | |
| July | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| August | 0 | 0,0 | 0,2 | 0,1 | 0 | 0,0 | | |
| September | 16,8 | 12,5 | 27,3 | 20,3 | 5,1 | 3,8 | | |
| October | 125 | 93,0 | 156,2 | 116,2 | 35,7 | 26,6 | 0,77 | 0,80 |
| November | 377,9 | 281,2 | 395,2 | 294,0 | 87,3 | 65,0 | 0,78 | 0,96 |
| December | 525,6 | 391,0 | 535,7 | 398,6 | 114,4 | 85,1 | 0,79 | 0,98 |
| | | **1564,0** | | **1713,5** | | **364,7** | **0,79** | **0,91** |

Table 8: Power and energy in standard heating system with insulated pipes - internal doors closed

| STANDARD HEATING SYSTEM WITH INSULATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Without pipes** | | **With pipes** | | | | $\eta_1$ | $\eta_2$ |
| | **Averaged heating power/energy to zones** | | **Averaged heating power/energy to zones** | | **Thermal losses** | | | |
| | W | kWh | W | kWh | W | kWh | | |
| January | 526,8 | 391,9 | 529,3 | 393,8 | 31,7 | 23,6 | 0,94 | 1,00 |
| February | 336,8 | 250,6 | 368,8 | 274,4 | 21,9 | 16,3 | 0,94 | 0,91 |
| March | 155,2 | 115,5 | 203,1 | 151,1 | 12,5 | 9,3 | 0,94 | 0,76 |
| April | 32,5 | 24,2 | 54,6 | 40,6 | 3,5 | 2,6 | | |
| May | 5,5 | 4,1 | 11,4 | 8,5 | 0,7 | 0,5 | | |
| June | 0 | 0,0 | 0,2 | 0,1 | 0 | 0,0 | | |
| July | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| August | 0 | 0,0 | 0,2 | 0,1 | 0 | 0,0 | | |
| September | 16,8 | 12,5 | 26,1 | 19,4 | 1,5 | 1,1 | | |
| October | 125 | 93,0 | 150,4 | 111,9 | 10,2 | 7,6 | 0,93 | 0,83 |
| November | 377,9 | 281,2 | 384,4 | 286,0 | 24,5 | 18,2 | 0,94 | 0,98 |
| December | 525,6 | 391,0 | 527,3 | 392,3 | 32 | 23,8 | 0,94 | 1,00 |
| | | **1564,0** | | **1678,3** | | **103,0** | **0,94** | **0,93** |

**Table 9: Power and energy in simplified heating system with non-insulated pipes - internal doors closed**

| SIMPLIFIED HEATING SYSTEM WITHOUT INSULATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Without pipes** | | **With pipes** | | | | $\eta_1$ | $\eta_2$ |
| | **Averaged heating power/energy to zones** | | **Averaged heating power/energy to zones** | | **Thermal losses** | | | |
| | W | kWh | W | kWh | W | kWh | | |
| January | 468,1 | 348,3 | 474,1 | 352,7 | 94,4 | 70,2 | 0,80 | 0,99 |
| February | 287,2 | 213,7 | 287,2 | 213,7 | 62,1 | 46,2 | 0,78 | 1,00 |
| March | 106,3 | 79,1 | 113,9 | 84,7 | 27,1 | 20,2 | 0,76 | 0,93 |
| April | 4,1 | 3,1 | 4,7 | 3,5 | 1,8 | 1,3 | | |
| May | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | | |
| June | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| July | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| August | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| September | 0,8 | 0,6 | 1,1 | 0,8 | 0,5 | 0,4 | | |
| October | 77,8 | 57,9 | 80,7 | 60,0 | 20,7 | 15,4 | 0,74 | 0,96 |
| November | 328,5 | 244,4 | 331,6 | 246,7 | 70,6 | 52,5 | 0,79 | 0,99 |
| December | 469 | 348,9 | 478,5 | 356,0 | 95,2 | 70,8 | 0,80 | 0,98 |
| | | **1296,0** | | **1318,3** | | **277,1** | **0,79** | **0,98** |

Table 10: Power and energy in simplified heating system with insulated pipes - internal doors closed

| SIMPLIFIED HEATING SYSTEM WITH INSULATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Without pipes | | With pipes | | | | $\eta_1$ | $\eta_2$ |
| | Averaged heating power/energy to zones | | Averaged heating power/energy to zones | | Thermal losses | | | |
| | W | kWh | W | kWh | W | kWh | | |
| January | 468,1 | 348,3 | 464,4 | 345,5 | 25 | 18,6 | 0,95 | 1,00 |
| February | 287,2 | 213,7 | 278,9 | 207,5 | 16,6 | 12,4 | 0,94 | 1,00 |
| March | 106,3 | 79,1 | 108,2 | 80,5 | 7,3 | 5,4 | 0,93 | 0,98 |
| April | 4,1 | 3,1 | 3,8 | 2,8 | 0,5 | 0,4 | | |
| May | 0,1 | 0,1 | 0,1 | 0,1 | 0 | 0,0 | | |
| June | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| July | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| August | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 | | |
| September | 0,8 | 0,6 | 0,8 | 0,6 | 0,1 | 0,1 | | |
| October | 77,8 | 57,9 | 76,3 | 56,8 | 5,6 | 4,2 | 0,93 | 1,00 |
| November | 328,5 | 244,4 | 320,2 | 238,2 | 18,8 | 14,0 | 0,94 | 1,00 |
| December | 469 | 348,9 | 467,8 | 348,0 | 25,3 | 18,8 | 0,95 | 1,00 |
| | | **1296,0** | | **1280,1** | | **73,8** | **0,94** | **1,01** |

Figure 34: Distribution coefficient for standard heating system with non-insulated pipes - internal doors closed

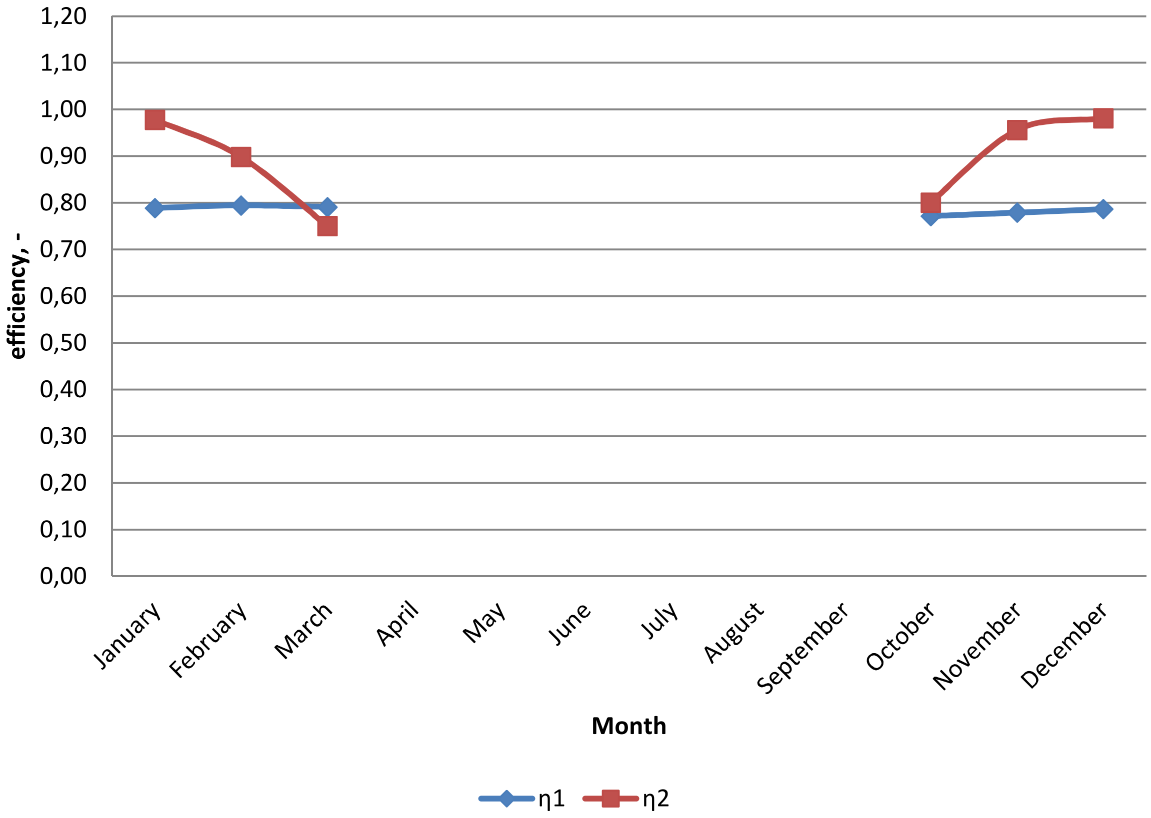


Figure 35: Distribution coefficient for standard heating system with insulated pipes - internal doors closed

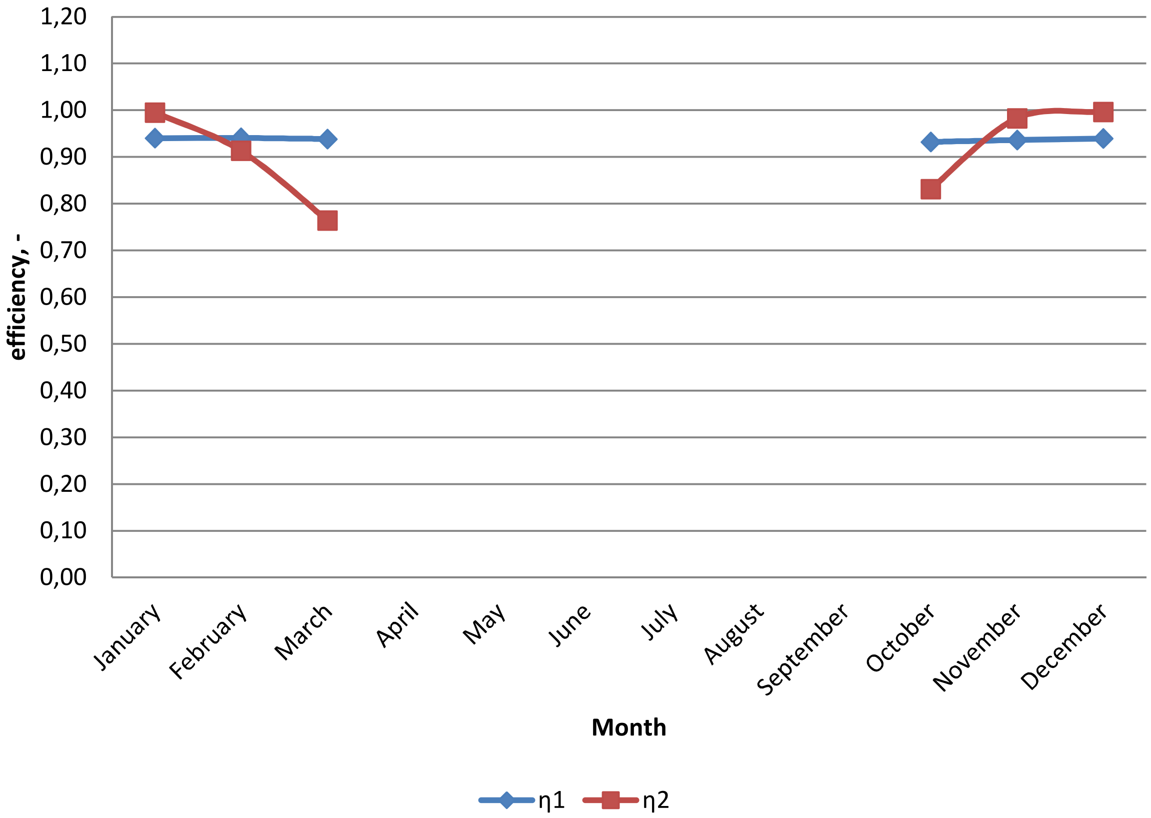


Figure 36: Distribution coefficient for simplified heating system with non-insulated pipes – internal doors closed

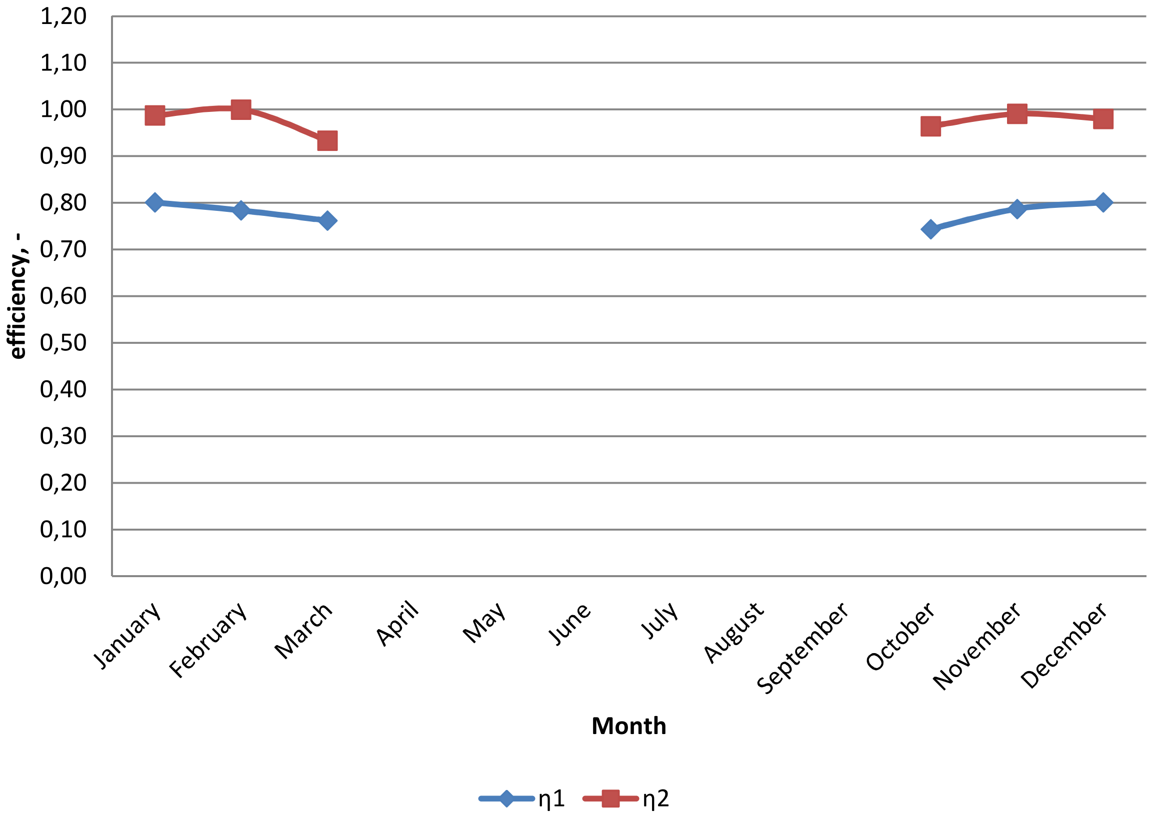
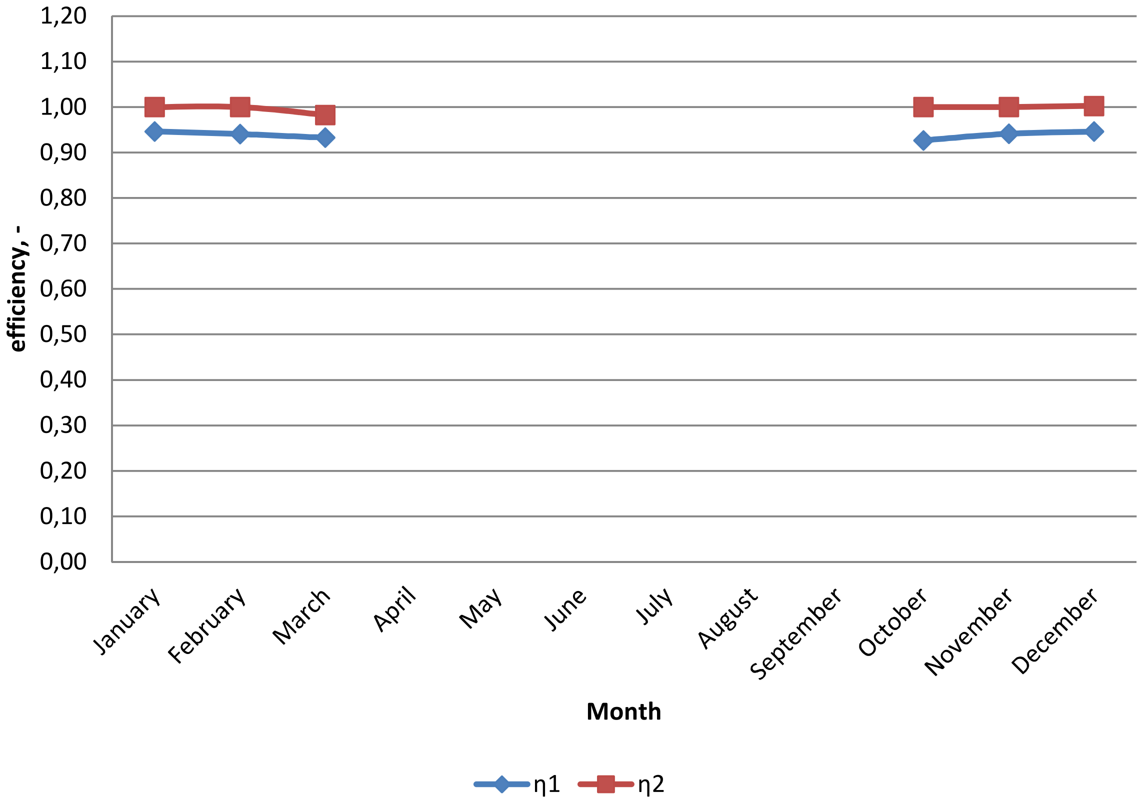


Figure 37: Distribution coefficient for simplified heating system with insulated pipes - internal doors closed



## Standard and simplified heating system

On the beginning, it has to be said that both systems deliver different thermal conditions, so comparison between them is not totally clear. Nevertheless, an attempt may be done with awareness of this fact. Averaged delivered energy in every month has been categorized in four cases in the same way like before.

**Table 11: Heating energy in standard and simplified heating system – internal doors open**

| | Heating energy to zones, kWh | | | |
|---|---|---|---|---|
| | STD | STD INS | SIM | SIM INS |
| January | 395,2 | 388,5 | 387,6 | 379,1 |
| February | 273,8 | 267,8 | 237,8 | 231,9 |
| March | 143,7 | 140,2 | 97,3 | 94,4 |
| April | 22,8 | 21,3 | 4,3 | 3,9 |
| May | 2,6 | 2,4 | 0,1 | 0,1 |
| June | 0,0 | 0,0 | 0,0 | 0,0 |
| July | 0,0 | 0,0 | 0,0 | 0,0 |
| August | 0,0 | 0,0 | 0,0 | 0,0 |
| September | 7,4 | 6,6 | 1,5 | 1,2 |
| October | 108,3 | 102,9 | 73,3 | 69,7 |
| November | 291,5 | 282,8 | 276,4 | 267,7 |
| December | 395,5 | 389,5 | 389,6 | 380,9 |
| | 1640,7 | 1602,0 | 1468,0 | 1428,9 |

**Table 12: Heating energy for standard and simplified heating system - internal doors closed**

| | Heating energy to zones, kWh | | | |
|---|---|---|---|---|
| | STD | STD INS | SIM | SIM INS |
| January | 400,6 | 393,8 | 352,7 | 345,5 |
| February | 278,9 | 274,4 | 213,7 | 207,5 |
| March | 153,9 | 151,1 | 84,7 | 80,5 |
| April | 41,9 | 40,6 | 3,5 | 2,8 |
| May | 8,8 | 8,5 | 0,1 | 0,1 |
| June | 0,1 | 0,1 | 0,0 | 0,0 |
| July | 0,0 | 0,0 | 0,0 | 0,0 |
| August | 0,1 | 0,1 | 0,0 | 0,0 |
| September | 20,3 | 19,4 | 0,8 | 0,6 |
| October | 116,2 | 111,9 | 60,0 | 56,8 |
| November | 294,0 | 286,0 | 246,7 | 238,2 |
| December | 398,6 | 392,3 | 356,0 | 348,0 |
| | 1713,5 | 1678,3 | 1318,3 | 1280,1 |

Following graphs show that simplified heating system let save some energy. When internal doors are open the greatest difference is visible in February, March and October. In these months savings about 50 kWh have been noted. In the whole year simplified loop is able to save ~170 kWh (table 11). It should be mentioned, that previous analysis proved acceptable thermal comfort for simplified loop when doors are open. When some savings are achievable without significant change of thermal comfort, this type of system should be used. When internal doors are closed savings are even greater (~400 kWh in the whole year, table 12). These additional savings are achieved at the expense of less thermal comfort. In reality doors are closed mainly in the night and previous analysis proved acceptable thermal comfort. The amount of savings in this case will be between 170 and 400 kWh. It has to be mentioned, that these savings are not the only one. Simplified loop means less number of heat emitters and less investment costs. This installation needs also less electricity for pump because pressure drop is lower. Doubtlessly, simplified heating system can be designed in highly insulated buildings.

Figure 38: Heating energy in different systems - internal doors open

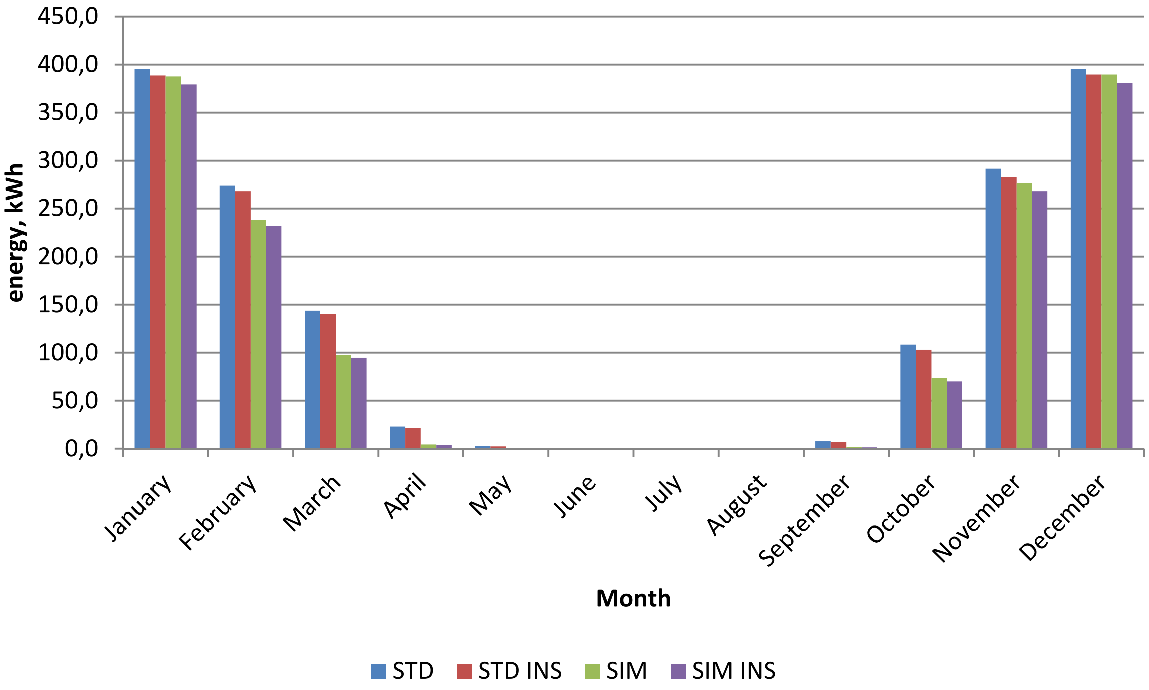
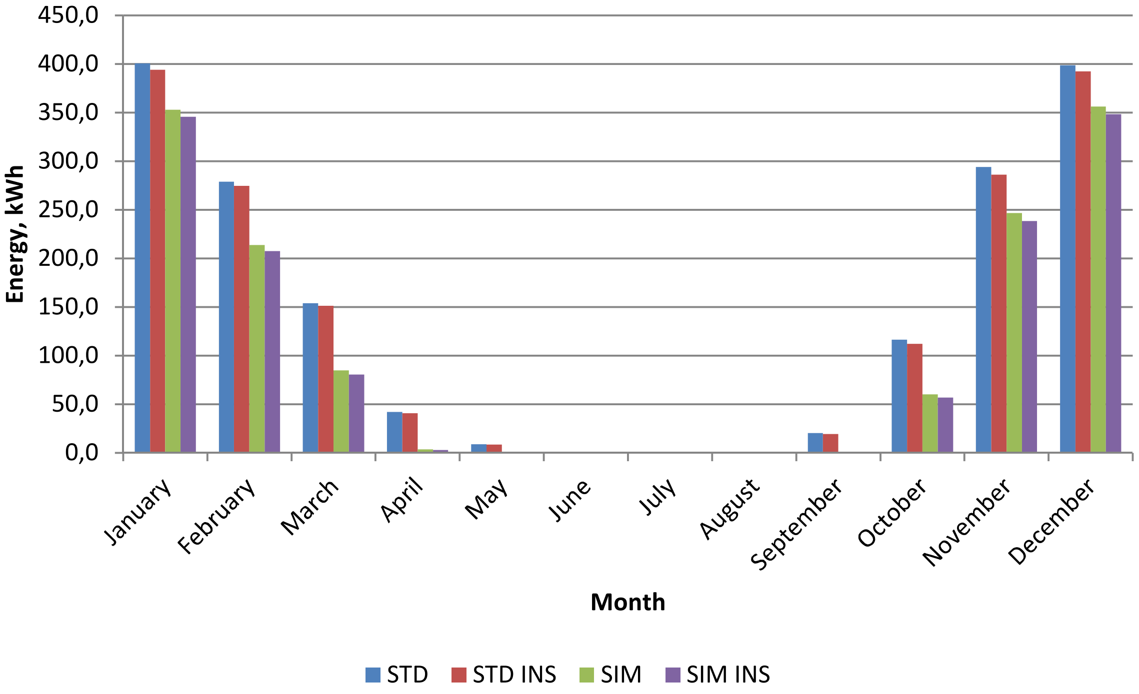


Figure 39: Heating energy in different systems - internal doors closed



# 4. Conclusions

Two heating systems in very well insulated building have been investigated in Thesis. The point was to check how these systems work when envelope of the building has very good thermal properties. Firstly, thermal comfort has been studied and people's reaction on conditions in the building. The question was, if it was achievable to maintain thermal comfort on satisfying level, when water loop in heating system is simplified and there are only two radiators in whole house. It was stated, that internal doors influence thermal conditions in the house. When they are closed, temperature in bedrooms is too low and unacceptable. However, such a case doesn't occur in reality. Doors to bedrooms are mainly open and people close them in the night for about eight hours. Simulations for this situation have been run and results were positive. There was no big difference between standard and simplified heating system and it can be clearly said,  that with high-standard envelope, full number of radiators is no needed anymore. This lead to wide savings because number of units is lower and total length of pipe network is shorter. Furthermore the pressure needed to provide is lower in simplified loop. The future of simplified heating systems in energy-efficient buildings is very promising.

These systems have been also investigated in terms of efficiency. Old approach to define distribution's efficiency assumes that losses from pipes are not recoverable, despite pipes run through zones, which are needed to be warmed. When recoverable losses have been taken into account, systems turned out to be more efficient. The difference depends on topology of the system, its size and thickness of insulation, but the fact is unbeatable: losses from pipes are extremely important and cannot be ignored in dimensioning of heating systems. When they are taken into account, real variable of distribution coefficient can be quantified and whole installation will not be oversized. This will lead to savings in energy and in costs.

In order to define universal distribution coefficient for standards and designing guidelines next investigations should be done. Other houses with different size and topology of heating system could be analysed. Other diameters should be taken into account. Parameters of supply and return water also influence losses from pipes. This problem is complex, but possible to solve with suitable amount of research.

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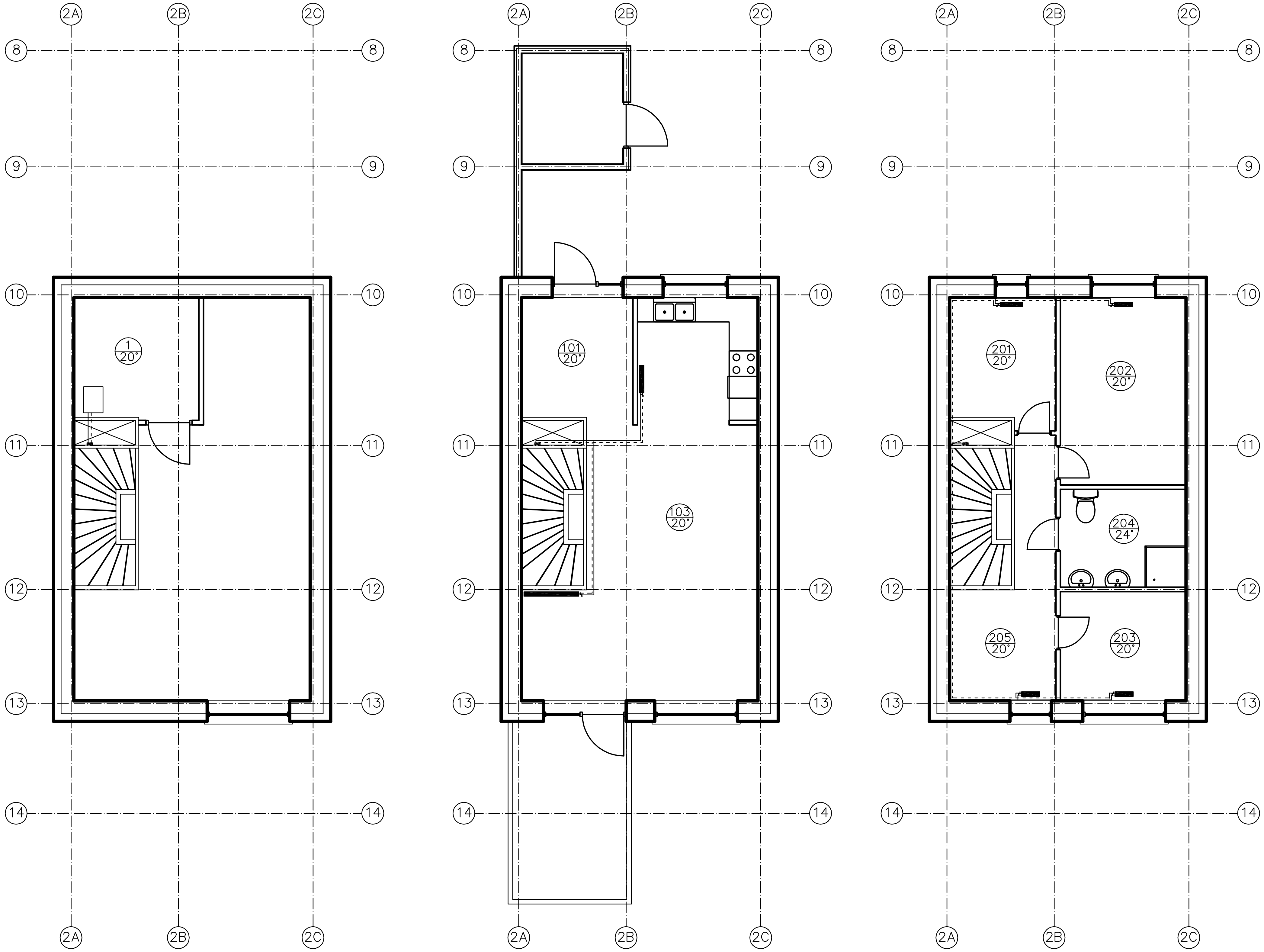
# Appendix 1: Standard heating system (scale 1:100)

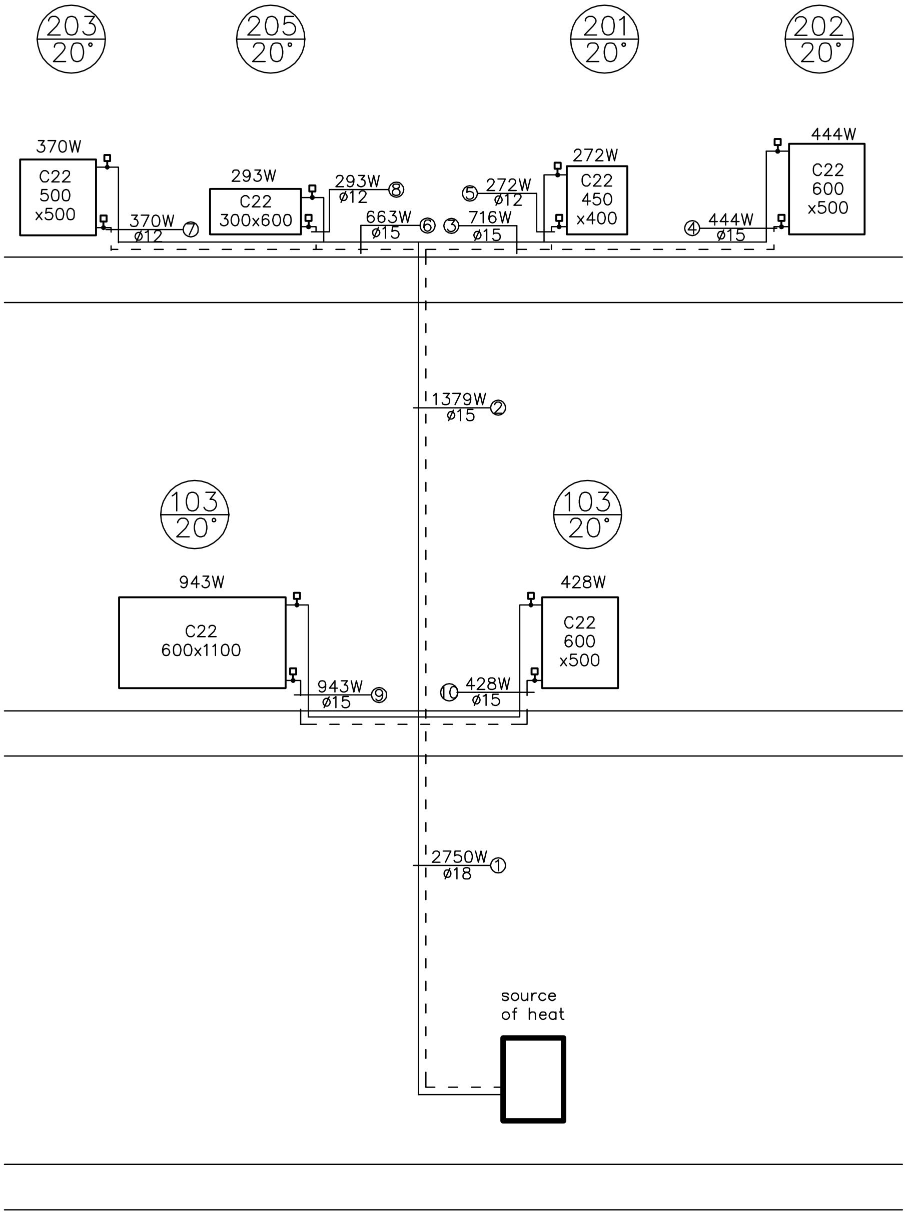


Basement

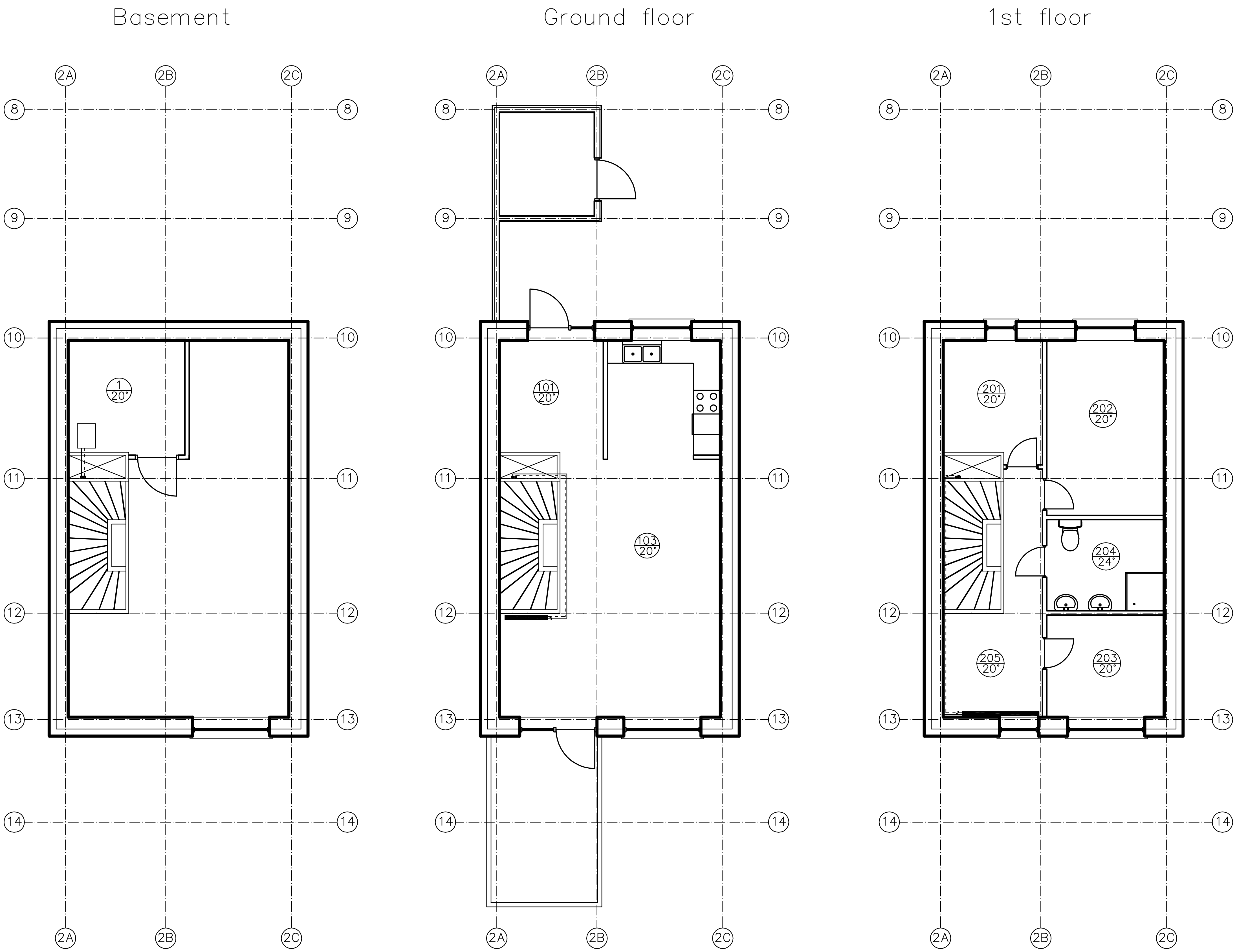
Ground floor

1st floor

# Appendix 2: Scheme of standard heating system



# Appendix 3: Simplified heating system (scale 1:100)

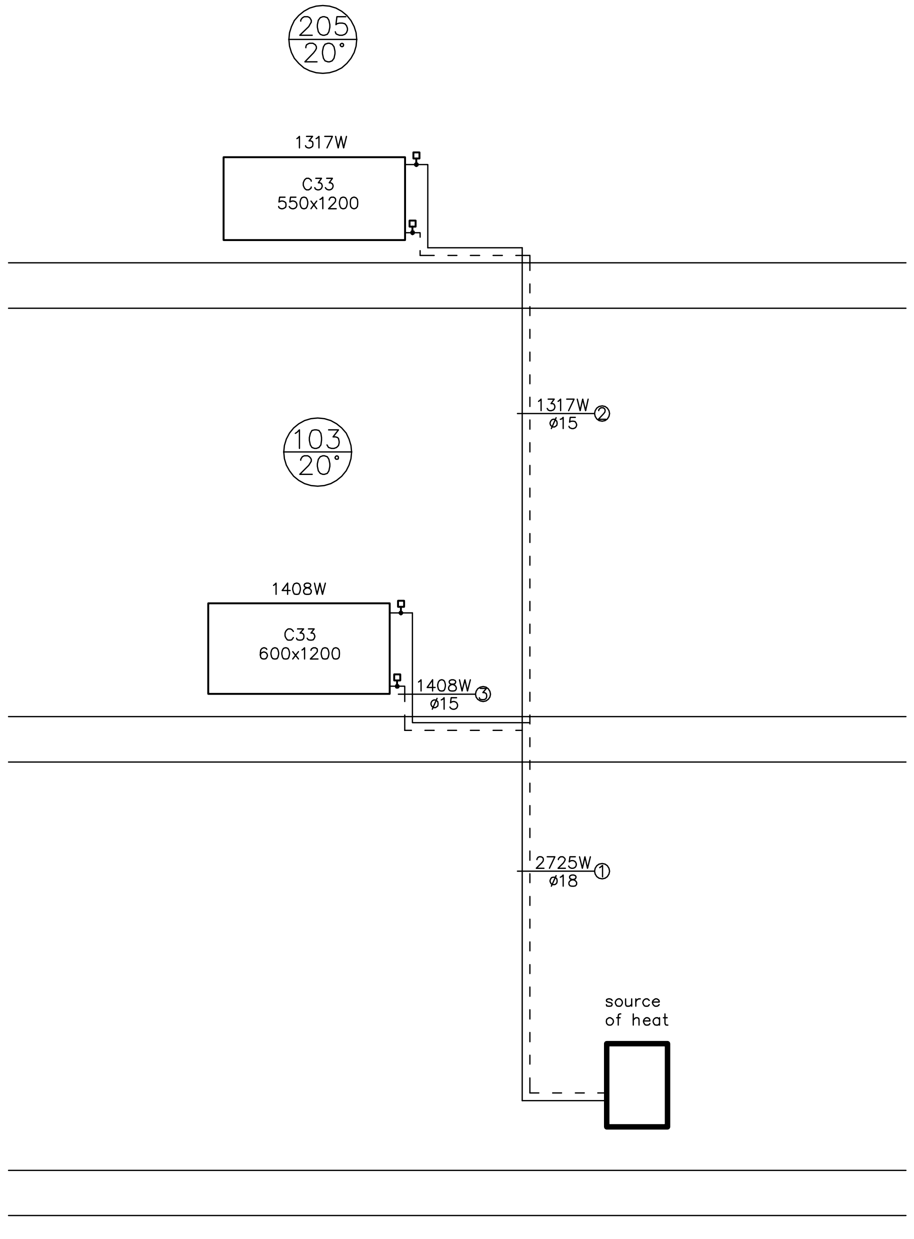


Basement

Ground floor

1st floor

# Appendix 4: Scheme of simplified heating system



# Appendix 5: Standard heating system - hydraulic calculations

| Standard heating system - hydraulic calculations | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Part number | Q, W | m, kg/s | V, l/s | l, m | d, mm | R, Pa/m | v, m/s | K, - | $\Delta p_l$, Pa | $\Delta p_p$, Pa | $\Delta p$, Pa | | description, loss coeficients |
| Loop with radiator in room 202 | | | | | | | | | | | | | |
| 1 | 2673 | 0,064 | 0,065 | 3,13 | 18 | 250 | 0,50 | 4,09 | 783 | 504 | 1287 | | 2 bends K=0,475, 2 tees K=0,848, swing check valve K=1,5, filter K=4,7 |
| 2 | 1302 | 0,031 | 0,032 | 3,48 | 15 | 240 | 0,40 | 5,80 | 835 | 458 | 1293 | | 2 bends K=0,475, 2 tees K=2,426 |
| 3 | 716 | 0,017 | 0,017 | 4,36 | 15 | 170 | 0,24 | 2,59 | 741 | 74 | 815 | | 2 bends K=0,475, 2 tees K=0,794 |
| 4 | 444 | 0,011 | 0,011 | 2,63 | 15 | 110 | 0,20 | 1,90 | 289 | 53 | 342 | | 4 bends K=0,475, radiator Δp=15 Pa |
| | | | | | | | | | | Σ | 3736 | | |
| | | | | | | | | h, m | 5,64 | $\Delta p_{gr}$, Pa | 187 | | |
| | | | | | | | | | | | 3549 | | |
| Loop with radiator in room 201 | | | | | | | | | | | | | |
| 1,2,3 | counted in previous loop | | | | | | | | | | | | |
| 5 | 272 | 0,006 | 0,007 | 0,40 | 12 | 190 | 0,32 | 0,95 | 76 | 54 | 130 | | 2 bends K=0,475, radiator Δp=6 Pa |
| | | | | | | | | | | Σ | 3524 | | |
| | | | | | | | | h, m | 5,64 | $\Delta p_{gr}$, Pa | 187 | | |
| | | | | | | | | | | | 3336 | | |
| Loop with radiator in room 203 | | | | | | | | | | | | | |
| 1,2 | counted in previous loop | | | | | | | | | | | | |
| 6 | 586 | 0,014 | 0,014 | 7,07 | 15 | 150 | 0,31 | 2,69 | 1061 | 127 | 1188 | | 2 bends K=0,475, 2 tees K=0,813 |
| 7 | 293 | 0,007 | 0,007 | 2,13 | 12 | 190 | 0,32 | 1,90 | 405 | 103 | 507 | | 4 bends K=0,475, radiator Δp=7 Pa |
| | | | | | | | | | | Σ | 4275 | | |
| | | | | | | | | h, m | 5,64 | $\Delta p_{gr}$, Pa | 187 | | |
| | | | | | | | | | | | 4088 | | |
| Loop with radiator in room 205 | | | | | | | | | | | | | |
| 1,2,6 | counted in previous loop | | | | | | | | | | | | |
| 8 | 293 | 0,007 | 0,007 | 0,40 | 12 | 190 | 0,32 | 0,95 | 76 | 55 | 131 | | 2 bends K=0,475, radiator Δp=7 Pa |
| | | | | | | | | | | Σ | 3898 | | |
| | | | | | | | | h, m | 5,64 | $\Delta p_{gr}$, Pa | 187 | | |
| | | | | | | | | | | | 3711 | | |
| Loop with radiator in room 103 (kitchen) | | | | | | | | | | | | | |
| 1 | counted in previous loop | | | | | | | | | | | | |
| 9.10 | 1371 | 0,033 | 0,033 | 1,27 | 15 | 250 | 0,42 | 1,29 | 318 | 112 | 430 | | 2 tees K=0,664 |
| 10 | 428 | 0,010 | 0,010 | 2,15 | 15 | 105 | 0,2 | 2,85 | 226 | 70 | 296 | | 6 bends K=0,475, radiator Δp=14 Pa |
| | | | | | | | | | | Σ | 2013 | | |
| | | | | | | | | h, m | 2,45 | $\Delta p_{gr}$, Pa | 81 | | |
| | | | | | | | | | | | 1931 | | |
| Loop with radiator in room 103 (living room) | | | | | | | | | | | | | |
| 1, 9.10 | counted in previous loop | | | | | | | | | | | | |
| 9 | 943 | 0,023 | 0,023 | 3,71 | 15 | 150 | 0,3 | 2,85 | 557 | 195 | 752 | | 6 bends K=0,475, radiator Δp=82 Pa |
| | | | | | | | | | | Σ | 2469 | | |
| | | | | | | | | h, m | 2,45 | $\Delta p_{gr}$, Pa | 81 | | |
| | | | | | | | | | | | 2388 | | |

# Appendix 6: Simplified heating system - hydraulic calculations

| Symplified heating system - hydraulic calculations | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Part number | Q, W | m, kg/s | V, l/s | l, m | d, mm | R, Pa/m | v, m/s | K, - | $\Delta p_l$, Pa | $\Delta p_p$, Pa | $\Delta p$, Pa | | description, loss coeficients |
| Loop with radiator in room 205 | | | | | | | | | | | | | |
| 1 | 2725 | 0,065 | 0,066 | 3,13 | 18 | 250 | 0,51 | 8,80 | 783 | 1128 | 1911 | | 2 bends K=0,475, 2 tees K=0,916, swing check valve K=1,5, filter K=4,7 |
| 2 | 1317 | 0,031 | 0,032 | 9,36 | 15 | 240 | 0,4 | 4,75 | 2246 | 509 | 2755 | | 10 bends K=0,475, radiator Δp=198 Pa |
| | | | | | | | | | | Σ | 4666 | | |
| | | | | | | | | h, m | 5,64 | $\Delta p_{gr}$, Pa | 187 | | |
| | | | | | | | | | | | 4478 | | |
| Loop with radiator in room 103 | | | | | | | | | | | | | |
| 1 | counted in previous loop | | | | | | | | | | | | |
| 3 | 1408 | 0,034 | 0,034 | 4,983 | 15 | 250 | 0,42 | 3,80 | 1246 | 484 | 1730 | | 8 bends K=0,475, radiator Δp=396 Pa |
| | | | | | | | | | | Σ | 3641 | | |
| | | | | | | | | h, m | 2,45 | $\Delta p_{gr}$, Pa | 81 | | |
| | | | | | | | | | | | 3559 | | |

# Appendix 7: Selection of Thermostatic valves

Standard heating system

Thermostatic valve in room 203

| Q, W | V,l/h | valve parameters | $\Delta p_{valve}$, Pa, counted | $\Delta p_{valve}$, Pa, chosen | $\Delta p_{loop}$ | valve authority |
|---|---|---|---|---|---|---|
| 293 | 25,5 | RA-N 15 preset: 3.5 | - | 2600 | 6688 | 0,39 |

Thermostatic valve in room 205

| Q, W | V,l/h | valve parameters | $\Delta p_{valve}$, Pa, counted | $\Delta p_{valve}$, Pa, chosen | $\Delta p_{loop}$ | valve authority |
|---|---|---|---|---|---|---|
| 293 | 25,5 | RA-N 15 preset: 3.5 | 2977 | 2600 | 6688 | 0,39 |

Thermostatic valve in room 202

| Q, W | V,l/h | valve parameters | $\Delta p_{valve}$, Pa, counted | $\Delta p_{valve}$, Pa, chosen | $\Delta p_{loop}$ | valve authority |
|---|---|---|---|---|---|---|
| 444 | 38,7 | RA-N 15 preset: 4.5 | 3139 | 2500 | 6688 | 0,37 |

Thermostatic valve in room 201

| Q, W | V,l/h | valve parameters | $\Delta p_{valve}$, Pa, counted | $\Delta p_{valve}$, Pa, chosen | $\Delta p_{loop}$ | valve authority |
|---|---|---|---|---|---|---|
| 272 | 23,7 | RA-N 15 preset: 3 | 3351 | 3200 | 6688 | 0,48 |

Thermostatic valve in room 103 (kitchen)

| Q, W | V,l/h | valve parameters | $\Delta p_{valve}$, Pa, counted | $\Delta p_{valve}$, Pa, chosen | $\Delta p_{loop}$ | valve authority |
|---|---|---|---|---|---|---|
| 428 | 37,3 | RA-N 15 preset: 4 | 4756 | 3780 | 6688 | 0,57 |

Thermostatic valve in room 103 (living room)

| Q, W | V,l/h | valve parameters | $\Delta p_{valve}$, Pa, counted | $\Delta p_{valve}$, Pa, chosen | $\Delta p_{loop}$ | valve authority |
|---|---|---|---|---|---|---|
| 943 | 82,2 | RA-N 15 preset: 6 | 4300 | 4100 | 6688 | 0,61 |

Symplified heating system

Thermostatic valve in room 103

| Q, W | V,l/h | valve parameters | $\Delta p_{valve}$, Pa, counted | $\Delta p_{valve}$, Pa, chosen | $\Delta p_{loop}$ | valve authority |
|---|---|---|---|---|---|---|
| 1317 | 122,7 | RA-N 15 preset: 7 | - | 5000 | 8228 | 0,61 |

Thermostatic valve in room 205

| Q, W | V,l/h | valve parameters | $\Delta p_{valve}$, Pa, counted | $\Delta p_{valve}$, Pa, chosen | $\Delta p_{loop}$ | valve authority |
|---|---|---|---|---|---|---|
| 1317 | 114,8 | RA-N 15 preset: 7 | 4669 | 4250 | 8228 | 0,52 |