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Efficiency of the Hydronic System used for the Space-Heating of Passive Envelopes

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MASTER THESIS

for

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Efficiency of the hydronic system used for the space-heating of passive envelopes

Effektivitet av vannbårne systemer for romoppvarming i passivhus

Background and objective

Building services for heating, cooling, ventilation and lighting are normally required to ensure optimal indoor environment, because the envelope alone is not able to handle the climatic conditions and user demands adequately. New requirements for reduced energy use has led to better insulation and air tightness, and thus greatly reduced need for space heating. For instance, the well-known passive house standard is relying on these super-insulated envelopes.

The space-heating is often based on a hydronic system to perform the distribution and emission of the heat. By drastically reducing the space-heating needs, hydronic system losses may become important. This could decrease the overall heating efficiency and, potentially, also impact the thermal comfort in super-insulated envelopes. Furthermore, the passive house concept offers the opportunity to simplify the space-heating system. It is then important to better understand how this simplification can improve the building performance. Finally, it has been proved that the electricity consumption should be minimised significantly in order to build Zero Emission Buildings (ZEB). In hydronic system, the electric consumption of circulation pumps should also be investigated properly.

This assignment is closely related to The Research Centre on Zero Emission Building at NTNU and SINTEF (FME ZEB) that has the vision to eliminate the greenhouse gas emissions caused by buildings. The main objective of FME ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition.

The following tasks are to be considered:

1. Literature study on the state-of-the-art hydronic systems for space-heating and on the space-heating in passive envelope.
2. Develop a simplified model to estimate the seasonal efficiency of small-scale hydronics systems: including the thermal losses and the electrical consumption of pumps.
3. Apply this model to a typical Norwegian single-familly house using different levels of insulation.
4. Analyse results and discuss them in the context of passive and ZEB buildings.
5. Discuss limitations of the approach and how it should be improved.

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

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

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

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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.

Department of Energy and Process Engineering, 23. January 2012

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Preface

This report was written at the Department of Energy and Process Engineering (EPT) at the Norwegian University of Science and Technology, Trondheim. This master thesis is closely related to The Research Centre on Zero Emission Building at NTNU and SINTEF (FME-ZEB).

I would like to thank my supervisor Vojislav Novakovic, professor at EPT, for coming up with such an interesting topic. I would thank him for interesting discussions through the process and for helping me to find relevant literature.

Also, I would like to thank my co-supervisor, Jens Tønnesen, PhD Candidate at EPT, for giving me constructive feedback and very good advices.

I would like to thank my co-supervisor, Laurent Georges, Postdoctoral Fellow at EPT, for helping me to learn new computer program and for providing me professional support throughout the entire process.

Likewise, I would like to thank Natasa Djuric, Associate Professor at EPT, for helping me to find relevant literature and for good discussions.

August, 2012. Nikola Djordjevic

Abstract

The aim of this thesis is to determine the efficiency of the hydronic heating system implemented in building with passive envelopes. Thermal losses and energy consumption of the pump are relative values for determining the efficiency.

The first step towards this aim is to provide theoretical background for better understanding of the hydronic system. The advantages of this system are also presented.

Good knowledge of hydronic systems, first of all, modes of transport of the work fluid and heat distribution into the space, makes a good basis for the next step- designing the system.

Once the system is designed, it is possible to create mathematical model. This model together with the input values given enables creation and a running of a simulation program.

In the end the results from the simulation are obtained for a typical Norwegian house which satisfies recommendation for the passive house concept.

The analyses of our results shows, in spite of the heat losses from the pipes and pump energy consumption, it is feasible to fulfill the prescribed limitations regarding the Passive house energy consumption. Unfortunately, the heat losses values are not negligible and it will eventually disturb thermal comfort.

The method derived in this report as well as the simulation program presented can serve as a starting point for future investigation of an assortment of hydronic systems variations. One of the logical choices is certainly a system with insulated pipes. Such system could provide the key advantage of hydronic systems compared to other heating systems. In that way they could present themselves as the best heating solution for future buildings with passive envelopes.

Table of contents

1. Introduction

1.1. Background

The threats and consequences of global warming and world's increasing demand for energy are some of the greatest issues today. Based on different scenarios, which cover the period from 2009 to 2035, the world primary energy demand is projected to grow from 0.8% to 1.6% per year, according to [1].

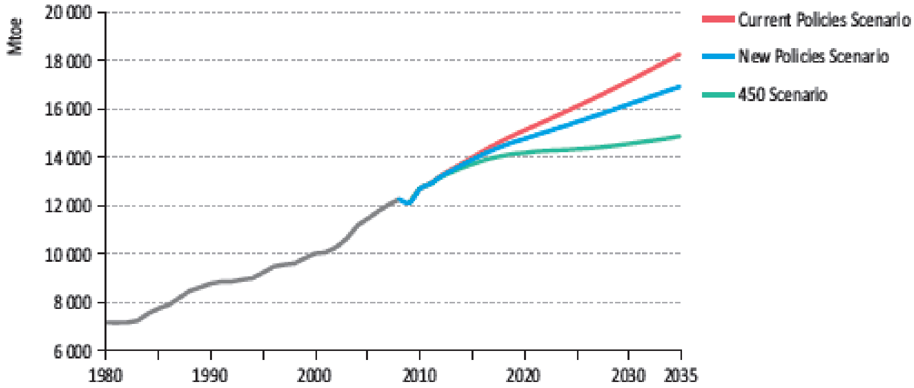


Figure 1- World primary energy demand by scenario [1]

Developed and industrialized countries have the greatest responsibility and they will have to make crucial efforts to use energy more efficiently and to switch to renewable energies [2].

Great potential for energy savings is provided by the residential/commercial sector. Based on [4], by 2040 there will be approximately 2.8 billion households in the world. Consequently, it means that the residential/commercial sector demand for energy, including electricity, is expected to rise by about 25 percent from 2010 to 2040.

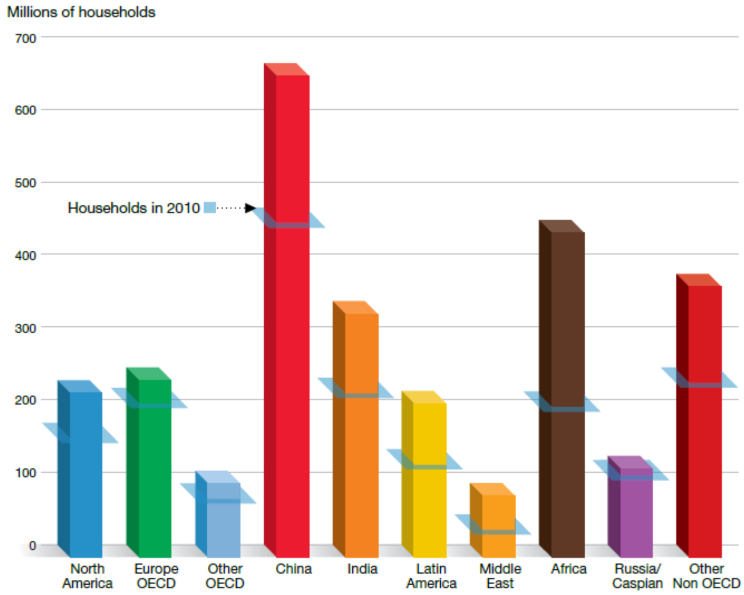


Figure 2- Households by region in 2040 [4]

As it is known, households need energy for lighting, heating, cooking, hot water and refrigeration, as well as electricity to run everything from computers to air conditioners. The way that energy is used in households for each of the mentioned needs can be improved which means it is possible to use less energy and in a more efficient way.

In many countries improvement in energy use is directed by some guidelines. Different concepts collect all guidelines in "one place" and provide aims which designers should seek to achieve.

In Germany the *Passive house concept* was developed. It was the first of this kind and it represents the basis for development of similar concepts. On the one hand, some European countries (for example- Austria and Switzerland) accepted this concept without significant changes. On the other hand, in North America this type of regulations were given through the *Net Zero Energy Buildings* concept.

In Norway, Research Council has established eight national Centres for Environment-friendly Energy Research. Zero Emission Buildings (ZEB), one of those centres, is hosted by Faculty of Architecture and Fine Art at the Norwegian University of Science and Technology in Trondheim. The main goal for the ZEB center is to develop and improve buildings which have zero emissions of greenhouse gases during their lifetime and related to their production, operation and demolition [3].

A common characteristic for all the concepts is that they require super insulated envelopes, the so called *passive envelopes*. Implementing advanced materials, the goal is to build an air tight building, to the maximum possible extent. Buildings designed in that way have very low heating needs which is very important considering that heat load is dominant among other needs for energy. The reduced need for heating influences the heating systems and allows them to be very simplified.

Heating of residential buildings can be provided in several ways and with several kinds of systems. The most common are air-heating systems and hydronic heating systems. A comparison of those two systems shows many advantages of hydronic systems. However, this comparison is based on experiences gained by implementing these systems in buildings with "normal" envelopes. Therefore, the question which should be answered is how hydronic heating systems will behave within buildings with passive envelopes.

Heat losses from pipes and pump consumption of mechanical power have great influence on the answer requested.

In super-insulated buildings any unpredicted heat input can seriously disturb thermal comfort. Because of that, it is important to know which amount of heat is emitted uncontrollably from the pipes of hydronic systems. Determining the mechanical power of the pump could be useful in order to get more information about the behavior of the system. Also, it would provide better insight into the overall system efficiency.

1.2. Objective and content

The main goal of this thesis was to determine efficiency of the hydronic system which is used for the space-heating of a passive house. The initial step in the process of determining should be to design a hydronic heating system that is optimal for a typical Norwegian house. The optimal system is the one which perfectly matches the heating needs of the house. After all the system elemnts are chosen and defined, computation can be done and efficiency obtained. This report is based on the following tasks:

Literature study of the state-of-the-art hydronic heating systems for space-heating and of space-heating in passive envelopes.

In order to achieve the main goal it is necessary to provide a good theoretical background for:

- Basic elements of hydronic systems and principles of their operation
- Passive envelopes within the Concept of passive houses

Knowledge in those fields should make a good basis for further stages of a design process.

Develop a simplified model to estimate the seasonal efficiency of small-scale hydronics systems: including thermal losses and electrical consumption of pumps.

Apply this model to a typical Norwegian single-family house using different levels of insulation.

These two tasks are interconnected. The structure of a typical Norwegian house and heating needs that corresponding to the ZEB concept, influence the design of a hydronic system. The elements such as boiler, pipes, heat emitter and others, have to be chosen. In the selection process attention should be paid to proper sizing. The highest quality components should be taken into consideration. After the design and selection processes, the mathematical model has to be set. Mathematical model should be applicable to show different performances of the hydronic system within the passive envelopes. It should be put together in a simple computer program which will make it possible to do calculations for a set of input parameters automatically.

Analyze results and discuss them in the context of passive and ZEB buildings.

Discuss limitations of the approach and how it should be improved.

The last parts of the report are related to the mathematical model. Dealing with the results obtained should give some preliminary answers about the efficiency of hydronic systems within passive envelopes. Also, it should investigate how it can be improved, as well as the weakness of the mathematical model used.

1.3. Method

Literature was found using the web-based databases *Compendex* and *Scopus* (including *ScienceDirect*). Textbooks which are given by supervisor are also used. Theory for the mathematical model was found both in research articles from databases and in textbooks.

The mathematical method was put together in a program code using functions within MATLAB. Inputs were given through an MATLAB output files and the results were displayed in Microsoft Excel.

Figures were made from the tabulated values with the inbuilt *scatter tool* in Excel. AutoCad is also used for some figures.

2. Literature

2.1 Passive envelopes

One of the most important functions of the building regarding human beings is to provide thermally comfortable spaces for the users. Building envelopes are elements with the largest influence on the quality of indoor climate. Also, they enable control over inner conditions irrespective of changeable outdoor climate. Walls, roof, floor, windows and doors are components of one standard building envelope.

There are two ways to improve building energy efficiency:

1) Active energy efficient strategies
2) Passive energy efficient strategies

All improvements to heating, ventilation and air conditioning (HVAC) systems, electrical lighting, etc. can be considered as active strategies.

Improvements to building envelope elements can be regarded as passive strategies [5].

The term *Passive envelopes,* also referred to as *thermal envelopes*, has been established within a broader concept of *Passive house*.

In the seventies of the last century, new approaches and technologies in the construction industry were developed. The main goal was to reduce the energy demand of buildings. For that purpose, active and passive solar uses, as well as loss reduction, were investigated. During the years, progress was made concerning improvements in quality of individual components and by adding renewable energy sources. But, the sustainable solution was not found because there was no attempt to rethink the concept of a building as a whole. Moreover, some new problems occurred:

1) The savings in fuel consumption could not compensate for the investments made in order to greatly reduce the heat demand.
2) If a ventilation system was not installed, as a result of airtight window and building envelopes, the quality of indoor air was decreased. Also, there was mold growth observed in insufficiently insulated parts of the building (especially on thermal bridges) [2].

The concept of Passive house was developed by Dr. *WolfgangFeist*. He realized that only simplification or excluding of components which are used in conventional buildings can lead to significant cost reductions. Therefore, the basic idea of the Passive House concept is "*to improve the thermal performance of the envelope to a level that* ***the heating system can be kept very simple***" [2]. Thermal comfort requirements regarding radiation asymmetry and space heating load, are the two main criteria that are taken into consideration.

1) Radiation asymmetry – passive envelopes should provide such conditions that surface temperatures of outer walls and windows are close enough to the room air temperature. In that case, without decreasing the thermal comfort, there is no need

to place radiators on outer walls or below the window in order to reimburse radiative asymmetries and cold air downdraught.

2) Space heating power – When the requirements of the Passive House standard are fulfilled, the space heat power is very low and it could be provided by the ventilation system only. With hygienic flow rates, without the need for recirculation or water based heat distribution system in addition, this could be a very simple and cost effective solution. It is not recommended to use an air heating system in the Passive House [2].

2.2 Passive House standard

The passive House is a thickly, correctly insulated and well tight house. The major part (2/3) of heat losses of the building are covered by passive energy inputs:

- Heat from the inhabitants
- Solar energy through the windows and
- The waste heat from the electric devices

A minor part (approximately 1/3) of heat losses has to be provided by heating. Since the demand for energy is greatly reduced, renewable energy sources can be used to cover a significant part of the total energy demand. The thermal comfort increases as well as air quality in the building [6].

If a holistic approach is used to observe the Passive House, then it is possible to discuss global requirements. These requirements for the Passive House standard give a more accurate and closer definition. Instructions inside the concept lead to substantial reduction in terms of space heating power. The maximum load is about $10W/m^2$ net floor area within the thermal envelope. Practice has shown that the yearly space heating power is below ***15 kWh/m²a*** for Central European climates [2].

The criterion which is used to evaluate both heat and electric energy demands for a building is the primary energy demand. The primary energy includes all building related energy uses (space heating, Domestic Hot Water, an auxiliary energy for pumps, control, lighting, electrical devices etc.). This demand is limited to ***120kWh/m²a***, at standardized energy use for electric devices and at standardized energy losses for Domestic Hot Water production and distribution within the thermal envelope. This, so-called side criterion, prevents reduction of space heat demand at the expense of large internal gains from electrical devices, and direct electric heating is discouraged as well [2,6].

	Required	Best practice
Heating energy demand (kWh/(m^2a))	< 15	≤ 10
Primary energy demand (kWh/(m^2a))	< 120	≈ 72/0
Volume related air leakage n_{50} (h^{-1})	< 0.6	≤ 0.2

Table 1- Requirements to comply with the Passive House standard [6]

Besides the mentioned global requirements, recommendations for single components quality as well as planning and construction methods are given.

The Passive House has the same elements as any ordinary house but the differences between those two are better:

1. Insulation
2. Tightness
3. Windows
4. Ventilation

Level of insulation

Choosing an appropriate thickness and type of insulation is crucial in order to reduce heat losses. Overall heat transfer coefficient (U [W/m^2K]) is one of the basic indicators and it provides us with information about insulation quality. A lower value of this coefficient means better insulation. Regarding the passive house standard, this value for all elements of envelope (external walls, roof and floor) should be $U \leq 0.15$ W/m^2K. Climatic conditions, location of the building and heat loads of the house interior are factors that determine optimum insulation thickness. Also, insulation thickness depends upon the material and configuration of the wall. Including all relevant factors, the thickness varies between 25-40 cm [7] (min 30 cm for a new building and min 25 cm for thermo-modernization of the existing building according to [3])

Thermal bridges should be avoided, which means that the thermal bridge coefficient should be $\Psi < 0.01$ W/mK [3].

In the table below, different types of organic or inorganic insulations are reviewed:

Inorganic materials		**Natural and organic materials**	
Mineral fibers	Foam materials	Plants and animal fibers	Foam materials
Slag wool	Expended glass	Coconut fibers	Polyester foam
Glass wool	Vermiculite	Cellulose fibers	Extruded polyester
Rock wool	Perlite	Wood flax	Polystyrene foam
	Expanded clay	Wool	Polyurethane foam
		Straw	Foamy formaldehyde tar
		Cotton	
		Paper	
		Cork	

Table 2- Insulating materials [7]

In practice, glass wool and polystyrene foam are the most popular and widely used insulation materials. *Table 3* shows variations in insulation thickness and U-values. For obtaining results, glass wool, with thermal conductivity lower than λ=0.04 W/mK, was used as thermal insulation in the example studied.

Building element (construction)	**Insulation thickness (cm)**	**Heat transfer coefficient of the building envelope U (W/m^2K)**
External walls	24-30	0.14-0.12
Ceiling below the non-heated attic	30-40	0.11-0.08
Roof above the heated attic	30-40	0.11-0.08
Floor above the ground	15-20	0.16-0.14

Table 3- Overall heat transfer coefficients of the building envelope for recommended thickness of glass wool insulation [7]

Level of tightness

Good tightness of the envelope is necessary in order to prevent uncontrolled infiltration. Diffusion open folios and reinforced cardboard posted together with adhesive tape or special glue are solutions that ensure the envelope which is tight against infiltration but open for humidity diffusion. The air exchange rate has to be lower than 0.6 at a pressure difference of 50 Pascal in both directions (n_{50}< 0.6 h^{-1}). [6]

Windows

Windows are very important parts of building envelopes in terms of energy efficiency and thermal comfort. Three main elements constitute a window: glass, frame and draught excluder. The right sizing and installation on the proper side of the envelope are of significant importance if the passive house standard is to be achieved. Windows should have their exposure from the south to the west or to the east. Their area has to be big enough to ensure satisfying amounts of solar energy for the passive house over the heating period, but again small enough to prevent overheating of the building during the summertime. On the other hand, windows in northern directions should be as small as possible.

Modern windows installed in the Passive House are three-layer insulated windows with U≤0.8W/m^{2}K. This kind of construction leads to decreasing the temperature difference between the room air and window surface which results in higher comfort [6, 7].

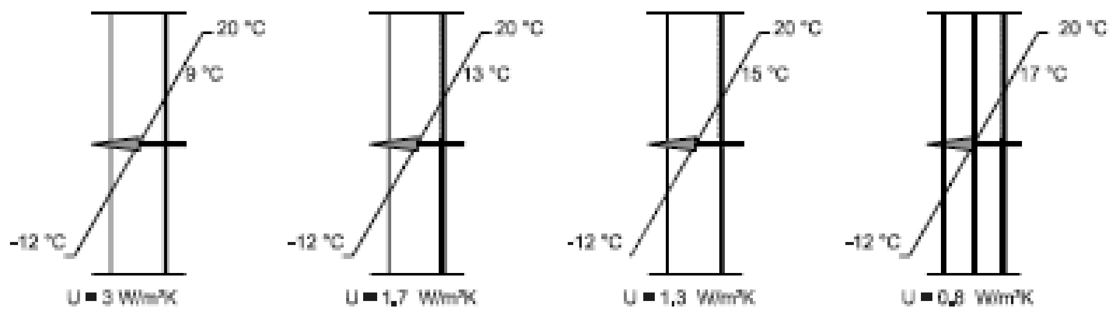


Figure 3- Heat-insulated windows: The temperature of glass surfaces

Ventilations

Because of the very good tightness of the buildings, air leakages through the envelope are negligible and almost the entire air flow goes through the ventilation devices. This device, if an Air Heating System is installed, comprises a heat exchanger with heat exchange rate higher than 85% [7]. Ventilation rates are determined according to the Indoor Air Quality requirements (IAQ). They are established on fresh air flow rates per person, ranging from 5-10 l/s (18-36 m^3/h). In general, with increased flow rates, IAQ also increased [2].

2.3 Space Heating Systems

A heating system is a long term investment from which many years of safe, efficient and trouble-free use should be expected. Installing a heating system is a significant investment. Consideration of available options and the pros and cons, before making a decision, is necessary in order to avoid costly rework or disappointment at a later time. Two popular and time tested systems, the air-heating and hydronic, are briefly compared.

Both systems are representative of the Central Heating Systems. With this kind of heating systems, heat is generated in one (central) place and then from that place distributed via "heat carrier" to elements for heat emission.

The main difference between these two systems is obvious. The air, as a work fluid of Air-heating system and water, as a work fluid of Hydronic heating system, lead to the crucial distinction. Different work fluids mean different physical principles by which they heat space. Heat transfer is classified into three models:

1) Conduction
2) Convection
3) Thermal radiation

Conduction is the type of heat transfer that occurs through solid materials.

Convection heat transfer occurs when a fluid at some temperature moves along a surface at a different temperature.

Thermal radiation is electromagnetic energy. It travels outward from its source in straight lines, at the speed of light. No materials are needed to transfer heat from one location to another.

The air-heating system delivers heat to space by convection while hydronic system provides heating by a combination of convection and radiation. [8]

Choosing one heating system over the other depends upon many other factors:

- Installation costs
- Operating costs
- Flexibility
- Health issue (aspects) and etc.

Taking into account all facts, it is up to the designer to choose the most appropriate solution that will satisfy all relevant requirements. In accordance with the topic of this report, the hydronic heating system will be described in detail further in the text

Advantages of the Hydronic Heating system

There is more than one benefit of using the hydronic heating system. Among many, the most important are:

- Comfort
- Design flexibility
- Quiet operation
- Energy savings
- Clean operation
- Noninvasive installation

Comfort

Comfort is the main criterion which indicates how good a heating system is. Because of that, providing comfort should be the fundamental goal for any heating system designer. Not rarely, this objective is compromised by other factors, and the most common is cost. This happens because people are not aware that even small residential heating systems have great influence on the health, productivity and general well-being of several people for many years.

Supplying heat to the body is not crucial to secure comfort. In order to maintain good thermal environment it is very important to control how the body losses the heat. "*When interior conditions allow heat to leave a person's body at the same rate at which it is generated, that person feels comfortable*" [8]. Otherwise, if heat is released faster or slower than the rate at which is produced, discomfort will be obtained.

In a typical indoor environment there are various processes by which the body of a person at rest releases heat:

- Conduction (approximately 3%)
- Convection (approximately 10%)
- Respiration (approximately 10%)
- Evaporation (approximately 15%)
- Radiation (approximately 62%)

As it can be noticed the majority of body heat losses come from thermal radiation to surrounding surfaces.

Neatly designed hydronic systems are able to maintain optimal comfort by controlling both the air temperature and surfaces temperatures of rooms. Heat emitters which are used within these systems, raise the average surface temperatures. As it is already mentioned, the human body is especially responsive to the radiant heat loss, so this kind of heat emitters significantly enhance comfort. Also, in hydronically heated buildings, comfortable humidity levels are easier to maintain [8].

Energy savings

Experience has shown that installation of different types of heating systems will cause different rates of heat loss in equivalent buildings structures. Buildings with hydronic heating systems have shown lower heating energy consumption than identical buildings with forced-air heating systems.

Among others, there are two reasons that significantly contribute to this finding.

One of them is related to air-pressure in the room. Hydronic systems operate and do not affect the room air-pressure. On the contrary, while a blower of force-air heating system works, small changes in room air pressure are obtained. Under this condition heated air goes out through every small crack, hole or other opening in the exterior surfaces of the room/building. A study which compared several hundred homes, found that air leakage rates averaged 26% higher and eneregy usage averaged 40% greater in homes with forced-air heating.

Air temperature stratification is a tendency of warm air to rise toward the ceiling while cool air falls to the floor. This phenomenon is another factor which has great influence on the building energy use.

High ceilings, poor air circulation and heating systems that supply air into the room at high temperatures, enhance stratification and in that way increase heat loss through the ceiling. In hydronic systems most of the heat transfer is done by thermal radiation which is the reason these systems reduce air temperature stratification, thus reducing heat loss through the ceiling.

The electrical energy consumption of the circulator used in hydronic systems is lower compared to the blower in a forced-air system. The circulator consumes 10% of the electrical energy required by the blower [8].

Design flexibility

With modern hydronic technology there is almost unlimited potential regarding design of heating systems. Space heating, domestic hot water and special loads (such as pool heating and snow melting) can be supplied by a single system. That kind of system leads to the reduction of installation costs because unnecessary components are eliminated (like multipipe heat sources, exhaust systems, electrical hookup, safety devices and fuel supply components).

Nowadays, the modern hydronic market offers a lot of different types of heat emitters. Using them separately (only one type) or combined various heat emitters into the same system, it is possible to satisfy space heating needs in the best possible way. Also, wide varieties of hydronic heat sources are available because that system can easily adapt to special circumstances such as on-site renewable energy generation or waste heat recovery devices [8].

Clean operation

A common complaint about forced-air heating is its tendency to move dust and other airborne particles through a building. Few hydronic systems include forced-air circulation, but even those systems create room air circulation rather than building air circulation. This reduces distribution of airborne particles and microorganisms. It is a major benefit in a situation where air cleanliness is imperative (for example health care facilities) [8].

Quiet operation

A correctly designed and installed hydronic system can work with virtually no detectable sound levels in the occupied areas. Because of that, hydronic heating is ideal for sound sensitive areas (home theaters, reading rooms…) [8].

Noninvasive installation

In a typical forced-air system it is not so easy to conceal ducts from sight within a typical house. This kind of situation often leads to compromises in duct sizing and/or placement. To the contrary, pipes of the hydronic heating system can be easily integrated into the structure of buildings without compromising it or the aesthetic character of the space. The high heat capacity of water is the underlying reason for this characteristic of hydronic systems. A certain volume of water can absorb over 3400 times more heat than the same volume of air for the same temperature change.

Thus, it is obvious that ducts have to have bigger dimensions and as such can potentially destroy structural integrity of walls, floors or ceilings. Also, if the distribution system should be insulated, considerably less material is required to insulate the tubing compared to the ducting. Last, but not least, small flexible tubing of hydronic systems is much easier to retrofit into the existing building than is ducting [8].

2.4 The Hydronic Heating Systems

Within the hydronic heating system, water is used as a carrier of thermal energy from the heat generator (source) to heat emitters. Water, as a work fluid, possesses many characteristics that make it ideal for such an application.

- It has one of highest heat storage abilities of any known material to man.
- It is readily available
- It is non-toxic
- It is non-flammable

Based on different parameters such as: (1) operating temperature, (2) pressurization, (3) flow generation, (4) piping arrangement and (5) pumping arrangement, water systems can be classified.

Different temperatures of water in the system, lead to three possible variants:

- Low-temperature water system (LWS)

The maximum permissible working pressure for a low-temperature boiler is 1100 kPa (gage) with a maximum temperature of 120^0C. These kinds of systems are applied in buildings ranging from small single house dwellings to very large and complex constructions.

- Medium-temperature water systems (MWS)

This system works between 120-175^0C with pressure not exceeding 1100 kPa.

- High-temperature water systems (HWS)

HWS operates at temperatures that exceeds 175^0C (usually 200^0C) and the usual pressure, for boilers and equipment, of about 2 MPa.

Based on different flow generation, hydronic systems are classified as:

- Gravity system- in which, water circulates because of the difference in density between the supply and return water columns of a circuit or system.
- Forced systems- in which, flow is maintained by a pump that is usually driven by an electric motor.

Early hydronic systems were designed as gravity systems and because of the weak buoyancy–driven flows, limitations in design were significant. Today's modern hydronic systems, which contain pumps, allow moving water at higher flow rates through much more complex piping systems.

Beside this classification two subsystems should be distinguished:

- Closed water system
- Open water system

The closed water system is a system with no more than one point of interface with a compressible gas or surface and will not create flow into the system by changes in elevation. On the other hand, an open system has more than one such interface. Hydraulic characteristics of those systems are the main differences between them. Compared to the open system, in a closed system:

1) Flow can not be motivated by static pressure differences
2) Pumps do not provide static lift, and
3) The entire piping system is always filled with water.

Most modern hydronic systems are closed. [9]

Components of Hydronic Systems

Generally, any modern hydronic heating system consists of four interrelated subsystems:
1) Heat Source (Generator)
2) Distribution System
3) Heat Emitters
4) Control Systems

Among these subsystems, pumps are devices the operation of which greatly influences proper work of the entire system. Because of that, they will be described separately.

Heat source

This is a point where heat is added to the system. The heat source is without doubt, a major piece of equipment. Nevertheless, it is still only a part of the system and it is necessary to choose an appropriate generator for each particular installation. Bad performance could be expected even from the best heat generator if it is used incorrectly.

According to [8], hydronic heat sources are classified as follows:

1) Conventional gas- and oil-fired boilers
2) Condensing gas- and oil-fired boilers
3) Electric resistance boilers
4) Heat pumps (vapor compression and absorption driven)
5) Solar thermal heat sources
6) Solid-fuel boilers

Distribution system

The task of the distribution system is to connect all various components of the heating system. In this respect pipes are used as elements that enable transport of working fluid. Hydronic systems are designed with many different configurations of piping circuits. Many factors influence the method of arranging pipe network.

Two main types of distribution system can be distinguished:

1) One-pipe system
2) Two-pipe system

The two-pipe system has a separate pipeline for inlet water, so each load gets water at same temperature. Outlet (return) water is collected by (another), independent pipeline, which leads it back towards the source of heat. This kind of distribution system requires more work during installation and very precise calculation and design of network. It is also needed to put two pipes inside the building, which is particularly difficult when the heating system is installed afterwards. The two-pipe system comprises pipes with different diameters. To the contrary, in a one-pipe system, only one pipe with uniform flow rate and of constant diameter provides heating regardless of the number of loads in the building. It means that function of pipelines for inlet and outlet water is performed by one pipeline. Water passes through one heat emitter to another. After each pass the temperature of water decreases. Finally, from the last emitter in the circuit, water goes out at a temperature, which a represents suitable return temperature of the entire system [8].

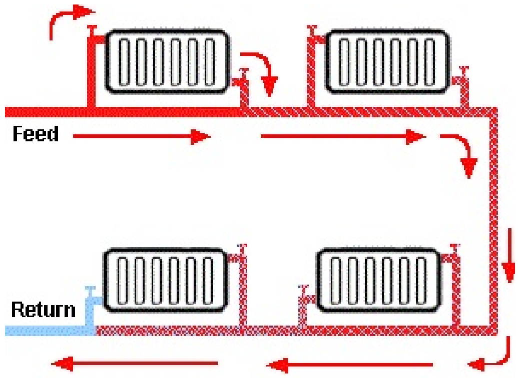


Figure 4- One-pipe system [10]

Because they allow the same water temperature to be available to all loads, two-pipe networks are commonly used in hydronic systems. The two types are:

(1) Direct-return system
(2) Reverse-return system [9]

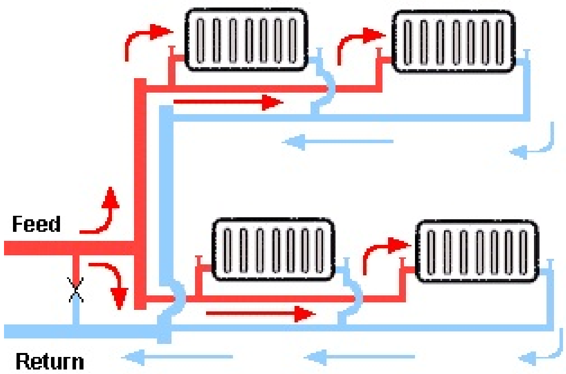


Figure 5- Two-pipes system [11]

Heat Emitters

Hydronic heating emitters are devices that cause heat to flow out of the system's fluid to the space, which should be heated. Wide varieties of heat emitters are available to suit almost any job requirement. On the one hand, this is a distinct advantage of hydronic systems. On the other, the choice is so wide and designers must carefully consider the advantages and disadvantages of the various alternatives in order to gain maximum thermal comfort. The solution selected solution must also satisfy technical, architectural and economic criteria.

Heat emitters can be classified in several ways. Depending on which type of heat transfer is dominant (convection or thermal radiation), heat emitters are properly classified as convectors and radiators. Each type has pros and cons, but often, their combination provides an ideal match for the requirements and comfort.

The classification that follows (based on [9]), encompasses most available types of heat emitters:

- Natural convection units
  Include cabinet convectors, baseboard and finned-tube radiators.
- Forced-convection units
  Include unit heaters, unit ventilators, fan-coil units, air-handling units, heating coils in central station units, and most process heat exchangers.
- Radiation units
  Include panel systems, unit radiant panels, in-floor or wall piping systems and some older style of radiators. These units are generally used in low-temperature water systems, with lower design temperatures.

Control Systems

However designed or installed they are, all hydronic systems try to simultaneously stabilize at two unique operating conditions:

- Thermal equilibrium
- Hydraulic equilibrium

"Thermal equilibrium occurs when the active portion of the distribution system is dissipating heat to the building at exactly the same rate as the heat source is adding heat to the circulating fluid." [8]

"Hydraulic equilibrium occurs when the head energy added to the fluid as it passes through circulator(s) is exactly the same as the head energy dissipated by all the components the fluid is flowing through." [8]

The system only "strives" to achieve these equilibrium conditions without consideration of thermal comfort. It means that even though the system operates under these conditions, there is no guarantee that it will provide proper heating of the building.

A long and reliable life of the system synchronized with thermal comfort for residents of the building, could be achieved and provided by the Control System.

The control system determines precisely when and for how long devices such as pumps, burners and mixing valves will work. Controls, as any other components or subsystem, are responsible for comfort, efficiency and longevity of the whole system. In accordance with that fact it is very important to have a well-designed and properly adjusted control system. Otherwise, even using high-quality heat generators, pumps or other components will never compensate for a non-balanced control system. Each designer should try to get the simplest possible solution, because the more simply control can accomplish a given objective, the better it is.

Many heating control systems based their operation upon the status of various electrical switches at any given time. Some switches are manually set, while others are automatically operated by pressure, temperature or other sensed parameters. Modern hydronic systems, thanks to advanced technology, have a higher level of automation which is reflected by a bigger number of controllers in the system. Controllers provide for many functions that previously required human intervention, to be performed automatically. Among others those functions are:

- Automatic adjustments of the system water temperature based on outdoor temperature
- Automatic shutdown of system pumps during warm weather
- Periodic exercising of components such as mixing valves and pumps to prevent setup during periods when the system doesn't operate.

It should be mentioned that many modern hydronic systems use one or more mixing devices to control temperature of water in various parts of the system [8].

Pumps

Pumps provide the primary force to distribute and recirculate water in a variety of space-conditioning systems. It could be said that the pump represents the heart of the hydronic system. There are different types but most commonly used in hydronic systems are centrifugal pumps.

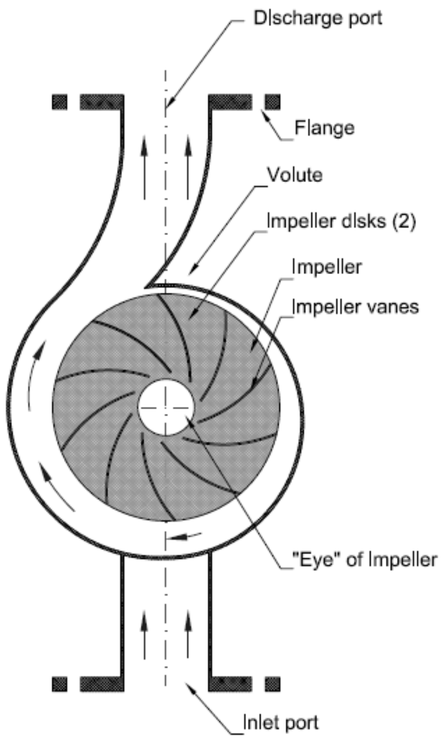


Figure 6- Pump impeller

Centrifugal pumps have a rotating impeller by which they add mechanical energy (head) to the fluid. While the impeller rotates, the fluid within the center opening (or eye) of the impeller rapidly accelerates through the passageways made by the impeller vanes between the two impeller disks. The fluid's mechanical energy is increased as it is accelerated toward the outer edge of the impeller. When it leaves the impeller, the fluid goes to the chamber that surrounds the impeller. This chamber is called volute. At this point of the fluid path through the pump, the fluid's former speed is converted to a pressure increase. Then, it continues to flow around the contoured volute and exits through the discharge port.

For efficient and problem-free operation of the entire system it is very important to install the pump at a proper place relative to other components in the system. "*Always install the pump so that its inlet is close to the connection point of the system's expansion tank.*" [8]

Generally, centrifugal pumps are available in bronze-fitted or iron fitted construction. The choice of material depends on those parts in contact with the fluid being pumped. For example, in bronze-fitted pumps, the impeller is bronze, the shaft sleeve is stainless and the casing is cast iron. Pumps used in residential systems are available with volutes made of cast iron, bronze, brass, polymer or stainless steel.

Manufacturers design special small- and medium-sized pumps for use in hydronic systems. Those pumps, known as wet rotor pumps (glandless), combine the rotor, shaft and impeller into a single assembly. The entire set is put in a chamber filled with system fluid. The motor of wet rotor pumps has not a fan or oiling caps. It is totally cooled and lubricated by the system's fluid [8, 9].

Additional components

Besides components for heat generation, transport, emission and control, one standard installation also contains some additional components, such as valves, regulators, vents, etc. The objective of these components is to provide proper (correct), economical and safe operation of installations. Some of them will be briefly introduced.

Expansion tank

The thermal expansion is inevitable and a very strong force of nature, which appears in hydronic systems also. Upon heating, molecules of work fluid become slightly larger which means that their volume has increased, but the total mass of the system's fluid has not changed. Even though, produced force, that these changes in volume bring, are tremendous and it will not allow compacting a certain volume of liquids into a smaller volume. Because of this phenomenon it could be concluded that liquids are incompressible for all practical purposes.

Water is also incompressible fluid and it expands when it is heated. If there were not be an equipment (within the hydronic system) that will accommodate the increased volume of water after it is heated, devastating damages would occurred and the hydronic heating system would be destroyed. Additional volume is usually provided by a component called Expansion Tank.

The expansion tank in early Hydronic heating systems was simple, open-top drum placed at a high point of the system, usually located in the building's attic.

The next improvement in expansion tank technology brought a closed tank located above the boiler. A certain amount of air was trapped in the tank. As the water expands upon heating, additional fluid volume enters the tank and compresses the air. This, so-called, standard expansion tank, was used in thousands of early hydronic systems.

A new type of expansion tank with an internal flexible diaphragm was available on the market during mid-twentieth century. Expansion tank with diaphragm operates on the same principles as the standard expansion tank. The only purpose of the diaphragm is to separate the fluid from air, but that "small" difference makes this type more favorable and leads to several advantages:

- Air cannot be reabsorbed by the fluid
- Water logging and the possibility of accelerated corrosion are avoided.
- Possibility to adjust air pressure, matching it with the static pressure of the system, results in a significantly smaller and lighter tank.

The expansion tank should always be connected to the system near the inlet port of the pump [8].

Figure 7- Expansion tank with diaphragm [12]

Pressure-relief valve (Safety Relief Valve)

The pressure-relief valve is required equipment for any type of closed-loop hydronic heating system. It is designed to become open just below the pre-set pressure rating. In that way the system fluid can be released from the system before higher pressure develops.

Figure 8- Pressure-relief valve [13]

The pressure-relief valve provides this function very simply - when the force exerted on the internal disc equals or exceeds the force produced by the internal spring, the disc lifts off its seat and allows fluid to pass through the valve.

This valve is the last point of protection, when such circumstances occur that all other controls fail to limit heat production. It should be installed at any point at which pressure can be expected to exceed the safe limits of the system components. A mandatory design requirement is that no valves are installed between the hydronic system piping and pressure-relief valve. In case of systems with a boiler, the pressure-relief valve is almost always attached directly onto the boiler, noting that it should be installed with shaft in a vertical position. In that way the chance of sediment accumulation around the valve's disc is minimized. Also, pressure-relief valves should have waste pipe attached onto their outlet port [8, 9].

Make-up water system

Experience showed that most closed-loop hydronic systems have minor water losses over time due to evaporation from valve encasements, pump seals, air vents and other components. These losses are normal and they have to be made up for, in order to maintain an adequate system pressure. Nevertheless, the quantity of water being compensated has to be monitored to avoid scaling and oxygen corrosion in the system.

The subsystem which is commonly used for replacing the lost water is make-up water system. It consist of a pressure-reducing valve, backflow preventer, pressure gauge and shutoff valves.

Usually, the water pressure in a domestic source is higher than the pressure-relief valve setting in the hydronic system. Because of that, such water source cannot be directly connected to the circuit. A component that is used to reduce and maintain a constant minimum pressure is the *pressure-reducing valve*. This valve enables water to flow into the system whenever the pressure on the outlet side of the valves drops below the valve's pressure settings.

Figure 9- Pressure-reducing valve [14]

Backflow preventer, as its name implies, prevents any water that has entered the system from returning and contaminating the municipal water system.

The shutoff valves are installed in order to provide isolation of the system from its water source due to possible service of the components that are located between the shutoff valves. [8, 9]

Figure 10-Shutoff valves [15]

Flow-check valve

Figure 11- Flow-check valve [16]

Flow check valves are components used commonly in hydronic systems. The flow-check valve can perform one or two functions depending upon the system it is installed in.

In a single-loop system, the flow-check valve prevents hot water in the boiler from slowly circulating through the distribution system when the pump is off [8].

Air separator (eliminator)

Figure 12. Air separator [16]

An air-separator is created to separate air from water and remove it from the system. If air and other gases are not ejected from the flow circuit, they could slow or stop the flow through heat emitters and cause corrosion, noise, loss of hydraulic stability and reducing pumping capacity.

Within a modern hydronic system, the air-separator operates by creating regions of reduced pressure as water passes through. The lowered pressure causes transformation of dissolved gasses in the water, forming bubbles. After the transformation, these bubbles are directed upward into a collection chamber where an automatic air vent expels them from the system. The process of separating air from water is intensified as the water is heated.

The air separator should be installed where fluid temperatures are highest – in the heat generator supply pipe. That position provides the best results [8, 9].

Drain and shutoff

All low points in the system should have drains. Separate shutoff and draining of individual equipment and circuits should be possible so that the entire system does not have to be drained to service a particular component. Whenever a part of equipment or section of the system is isolated and water in that section or device could increase in temperature following isolation, overpressure protection by safety relief must be provided [9].

3. Mathematical model

To predict the performance of the designed Hydronic Heating System within a relevant type of building (with passive envelopes) a mathematical model has to be set. The resulting parameters of greatest interest are the heat (thermal) losses of hydronic heating systems and mechanical power consumption of the pumps.

Results are used as starting point for the present mathematical model:

- Annual weather data for Norway
- Building heating needs for design(nominal) conditions
- Annual heating needs of a real building

3.1 Heat losses from the pipes

Heat losses from pipes can be calculated as [16]

$$Q_{loss} = \psi \cdot l_{pipes} \cdot \left(T_{fluid} - T_{air}\right) \qquad \ldots\ldots (3.1)$$

Where

ψ – The linear thermal transmittance [W/mK]

l_{pipes} – The total length of pipes [m]

$\left(T_{fluid} - T_{air}\right)$ - The temperature difference [K]

The linear thermal transmittance from pipes in air is given by [17]

1) For insulated pipes

$$\psi = \frac{\pi}{\frac{1}{2 \cdot \lambda_D} \cdot ln\frac{d_a}{d_i} + \frac{1}{h_a \cdot d_a}}$$

d_i - inner diameter (without insulation) of the pipe [m]

d_a - outer diameter of the pipe [m]

h_a - The total heat transfer coefficient of the outer transfer (convection and radiation) [W/m^{2}K]

λ_D - thermal conductivity of the insulation [W/mK]

2) For non-insulated pipes

$$\psi_{non} = \frac{\pi}{\frac{1}{2 \cdot \lambda_P} \cdot ln\frac{d_{p,a}}{d_{p,i}} + \frac{1}{h_a \cdot d_{p,a}}} \quad .... (3.2)$$

$d_{p,i}$ - inner diameter of the pipe [m]

$d_{p,a}$ - outer diameter of the pipe [m]

h_a - The total heat transfer coefficient of the outer transfer (convection and radiation) [W/m^{2}K]

λ_P - thermal conductivity of the pipe (material) [W/mK]

As an approximation, the linear thermal transmittance for non-insulated pipes can be calculated by

$$\psi_{non} = h_a \cdot \pi \cdot d_{p,a} \text{ ... (3.3)}$$

h_a has different values for

- Insulated pipes $h_a = 8 \frac{W}{m^2 \cdot K}$
- Non-insulated pipes $h_a = 14 \frac{W}{m^2 \cdot K}$

Six different diameters are changed within the same system:

$$d_{p,a} = [8mm; 10mm; 12mm; 15mm; 18mm; 22mm]$$

l_{pipes} is the total length of pipes. This value can be divided into:

- The length of pipes which transport supply water from boiler to heat emitter
- The length of pipes which transport return water from heat emitter to boiler

This division contributes to more accurate results of simulation because different parts of the distribution system contain fluid at different temperatures.

The difference between T_{fluid} and T_{air} represents the temperature difference between the working fluid in pipes and air which surrounds pipes. In the simplified hydronic system that is used for this simulation, two branches of distribution system can be easily observed:

- The supply branch (boiler – heat emitter)
- The return branch (heat emitter – boiler)

In order to obtain heat losses from the entire distribution system, temperatures of the supply water and return water, have to be determined. With those values, it is possible to calculate heat losses from each branch separately and, in that way, make a more precise calculation.

Based on:

- Annual weather data
- Heating temperature regime for nominal conditions (40/30^{0}C)
- Air temperature for nominal conditions (20^{0}C)
- External temperature for nominal conditions (-20^{0}C)

It could be assumed that temperature of the supply water will be changed by a linear equation. *Figure 13* shows line which presents linear relationship between external and supply temperature.

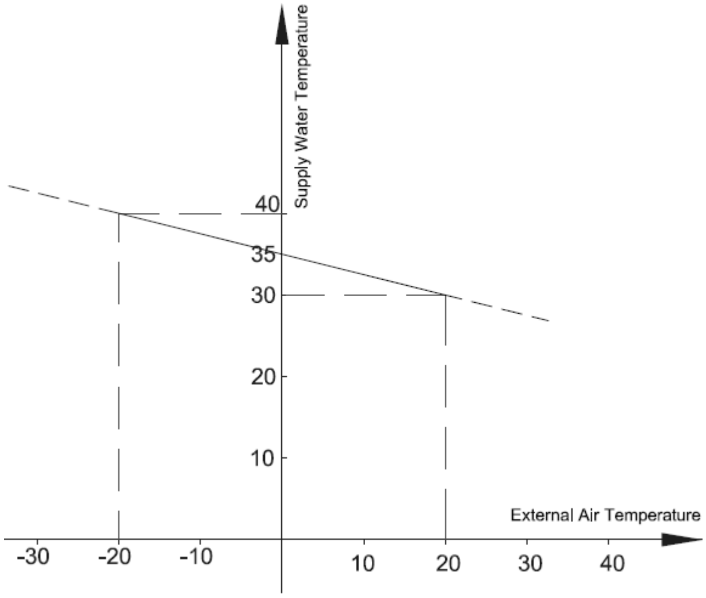


Figure 13- Relation between external air temperature and supply water temperature

General form of the linear equation

$$y - y_A = \frac{y_B - y_A}{x_B - x_A} \cdot (x - x_A) \text{ ... (3.4)}$$

and two known points [A (40, -20) B (30, 20)]

allow to extract the following equation:

$$y = -0.25 \cdot x = 35 \text{ … (3.5)}$$

Using the values of external temperatures from annual weather data and equation (3.5), temperature of the supply water can be calculated.

Before temperatures of the return water can be computed some auxiliary values must be calculated.

Based on an exponential relationship between the heat emission and temperature difference between the radiator and its environment

$$\dot{Q} \sim \Delta t^n \text{ … (3.6)}$$

it is possible to describe the performance of the radiator. The only condition is to know one value of heat emission (i.e. under nominal conditions) and the radiator exponent *n* [18]. The nominal conditions for this simulation are:

- Temperature of supply water $t_{sup}{}^N = 40^0C$
- Temperature of return water $t_{ret}{}^N = 30^0C$
- Indoor temperature $t_{air}{}^N = 20^0C$

- Heat emission of radiator $\dot{Q}^N = 3000\,W$

The nominal performance is used to define the proportional factor in equation (3.6).

$C^* = \frac{\dot{Q}_N}{(\Delta t_N)^n}$ - Proportional factor

$$\dot{Q} = C^* \cdot (\Delta t_N)^n = \dot{Q}_N \cdot \left(\frac{\Delta t}{\Delta t^N}\right)^n \ldots (3.7)$$

where $\dot{Q}$ is the heat emission of the radiator under real conditions.

As the exponent *n* is not given, it is common practice to use 1.3 [18].

There are two possible ways to calculate mean radiator temperature difference:

- Arithmetic mean radiator temperature $\Delta t = \frac{t_{sup} - t_{ret}}{2} - t_{air}$

- Logarithmic mean radiator temperature $\Delta t = \frac{t_{sup} - t_{ret}}{ln\left(\frac{t_{sup} - t_{air}}{t_{ret} - t_{air}}\right)}$

Measurements showed that in equation (3.7) the arithmetic temperature difference gives correct results only if the water mass flow is high. Thus, is necessary to use a logarithmic temperature difference. In equation (3.7), the known values are $\dot{Q},\ \dot{Q}^N, \Delta t^N, n$, so Δt can be computed:

$$\dot{Q} = \dot{Q}_N \cdot \left(\frac{\Delta t}{\Delta t^N}\right)^n \rightarrow \Delta t^N \cdot \left(\frac{\dot{Q}}{\dot{Q}^N}\right)^{\frac{1}{n}} \ldots (4.8)$$

Δt is used to calculate the surface temperature of the radiator by following equation

$$t_s = \Delta t + t_{air}$$

For determining temperatures of the return water, three input values are necessary:

- t_{sup} – temperature of supply water
- t_s – surface temperature of radiator
- t_{air} - indoor temperature

The Matlab routine inverts the non-linear equation of the heat emitter using an iterative Newton-Raphson technique.

As all needed values are already defined it is possible to generate temperatures of the return water.

3.2 Mechanical power of the pump

The first step in determining the mechanical power consumption of the pump is to find the most appropriate pump for the designed system. There are two parameters which define the ideal pump for a particular system:

- Flow rate
- Pressure loss

The flow rate, based on nominal conditions, gives information about the maximal flow rate which should be provided by the pump chosen. The maximum flow rate is relevant for the process of pump selection.

A piece of information that is obtained from building simulation is building heating needs under nominal conditions. Thus, it is quite simple to calculate the nominal flow rate by the equation:

$$\dot{Q}^N = \dot{m} \cdot c_w \cdot \Delta t = \dot{m} \cdot c_w \cdot \left({t_{sup}}^N - {t_{ret}}^N \right)$$

$$\Rightarrow \dot{m} = \frac{\dot{Q}^N}{c_w \cdot \left({t_{sup}}^N - {t_{ret}}^N \right)} \ldots (3.9)$$

where c_w is specific heat capacity of water. The specific heat capacity is the amount of heat required to change a unit mass of a substance by one degree in temperature [18]. For different temperatures it has different values. For water at 40/30^{0}C, c_w is equal to 4174 [J/kgK] [20].

Pressure loss can be divided into:

- Friction losses
- Impact (local) losses

Friction losses

Friction occurs between particles of real fluids and tube's walls. This friction caused pressure loss in the system. The pressure loss calculation is based on the Darcy-Weisbach equation for head loss due to friction in a closed round pipe [20]. This equation is valid for fully developed, steady, incompressible flow [21]

$$\Delta p_{friction} = \lambda \cdot \left(\frac{l}{d_h} \right) \cdot \left(\frac{\rho \cdot w^2}{2} \right) \ldots . (3.10)$$

where

$\Delta p_{friction}$- Pressure loss [Pa]

λ - Friction coefficient

l - Length of pipes [m]

ρ - Density of fluid [kg/m^3]

w - Velocity of fluid [m/s]

d_h - Hydraulic diameter [m]

Hydraulic diameter is not the same as geometrical diameter. It can be calculated by the general equation [20]:

$$d_h = \frac{4A}{P} \ldots (3.11)$$

where

A - area section of duct [m^2]

P - wetted perimeter of duct [m]

Based on equation (3.11) the hydraulic diameter of a pipe can be expressed as [19]:

$$d_h = \frac{4 \cdot \pi \cdot r^2}{2 \cdot \pi \cdot r} = 2 \cdot r \ldots (3.12)$$

where

r - pipe radius [m]

The friction coefficient depends on the flow [21]- if it is

- laminar (Re < 2320)
- transient (2320 < Re < 10000)
- turbulent (Re > 10000)

and the roughness of the tube.

The Reynolds number (Re) gives the relation between inertial and viscous forces of the fluid flow. If the inertial forces are much bigger and the Reynolds number is higher than critical, Re > 2320, turbulent fluid flow will occur. Otherwise, if viscous forces are big enough in comparison to inertial, the Reynolds number is lower than critical, Re < 2320, then the laminar fluid flow will happen [20].

For calculation of the Reynolds number in a closed pipe, the fluid flow mean velocity, fluid viscosity and internal pipe diameter should be known. The Reynolds number is proportional to the fluid flow mean velocity and pipe diameter and inversely proportional to fluid viscosity.

The Reynolds number is calculated using the following equation:

$$R_e = \frac{w \cdot D}{\nu} \ldots (3.13)$$

where

w- velocity [m/s]

D- inner diameter of pipe [m]

ν- kinematic viscosity [m^2/s]

Values of the Reynolds number (Re) that are computed, indicate a turbulent flow in the designed system. For turbulent flow, the friction coefficient depends on the Reynolds Number and the roughness of the pipe wall. In the functional form this can be expressed as:

$$\lambda = f(Re, \frac{k}{d_h})$$

where

k - Absolute roughness of tube wall [mm] (for copper tube k=0.0015mm)

$\frac{k}{d_h}$ - Relative roughness

For determining values of friction coefficients the Moody diagram is used. The Moody diagram is a graphical representation of the Colebrooke equation.

As the Reynolds number and relative roughness are calculated, with the Moody diagram it is possible to determine the friction coefficient. Other elements of the equation (3.10) are known, so the pressure loss due to friction can be calculated.

Impact (local) losses

Impact losses can be caused by contractions, expansion and diffusers, elbows or bands, entrance and valves. The pressure drop due to impact losses can be calculated by [21]:

$$\Delta p_{impact} = \xi \cdot \frac{\rho \cdot w^2}{2} \ldots (3.14)$$

ξ – local impact coefficient [-]

Values of the local impact coefficient are determined experimentally and there are recommendation for different elements of the system, such as boilers, elbows, valves, bents, heat emitter and others. All recommendations are taken from [21].

An exception is made with the electrical boiler VR 3010. The diagram which shows the dependence of pressure drop and flow is given in the catalog and thus it is used to generate more accurate values of the local impact coefficient of the boiler.

Eventually, the total pressure loss occurring in the designed system can be expressed by [20]:

$$\Delta p_{total} = \Delta p_{friction} + \Delta p_{impact} =$$

$$= \lambda \cdot \left(\frac{l}{d_h}\right) \cdot \left(\frac{\rho \cdot w^2}{2}\right) + \Sigma\xi \cdot \left(\frac{\rho \cdot w^2}{2}\right) = \left(\lambda \cdot \frac{l}{d_h} + \Sigma\xi\right) \cdot \frac{\rho \cdot w^2}{2} \quad \text{.... (3.15)}$$

Equations (3.9) and (3.15) define the nominal flow rate and pressure drop of the designed system. Those two pieces of data allow the designer to select the most appropriate pump for his system.

The consumption of the pump chosen will depend on the type of pump control implemented. In figures below, areas of marked rectangles represent the mechanical power consumed ($P_M = \Delta p \cdot \dot{V}$). In *Figure 14* an example diagram consisting of pump curve and system curve is shown. Intersection of these two curves represents operating point.

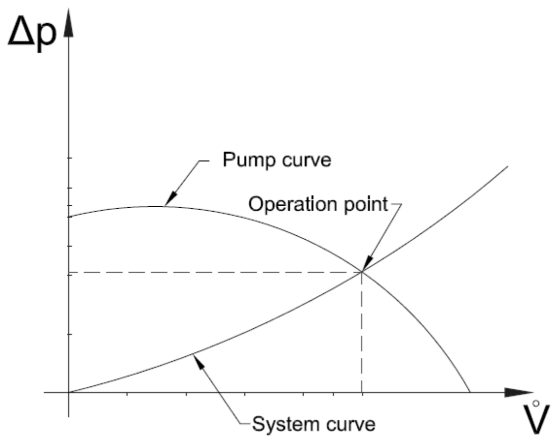


Figure 14

When some changes within the system (for example closing of TRVs) occur, the position of the system curve will be changed and with it, the operating point.

The ideal control of the pump would be if the system could recognize pressure changes and adapt the speed of the pump to new work conditions. In that way the operating point would stay the same, the system curve and consumption of mechanical power would be the lowest possible (*Figure 16*).

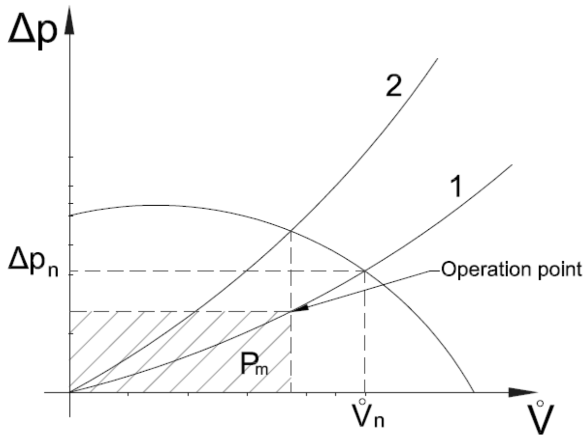


Figure16

Unfortunately, it is not possible to have the ideal control. Today's technology for controlling the pump speed provides:

- Δp-c mode control
- Δp-v mode control

With the Δp-c mode control, the system will adapt the speed of the pump in such a way that the system pressure will be unchanged for any value of the flow rate. *Figure 17* is a graphical representation of Δp-c the mode control. In the same figure could it be seen how this kind of control decreases the mechanical consumption of pump.

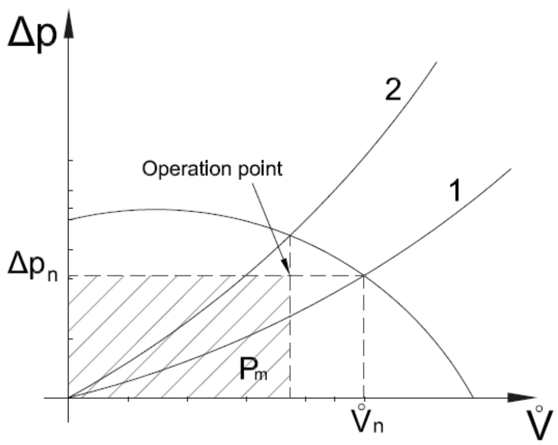


Figure17

The Δp-v mode control is a more advanced type of control. The control system maintains the system pressure in linear fashion between values of the set point and one half of that value. Thereby, the Δp-v mode control achieves a more efficient operation of the pump and the whole system. Graphical confirmation is presented in *Figure 18*.

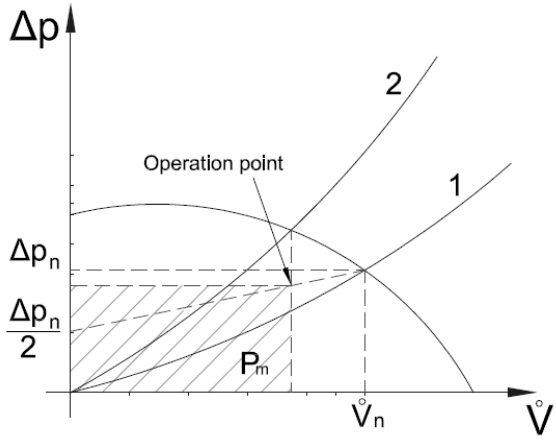


Figure18

3.3 Efficiency of the Hydronic System

After determining the heat losses from pipes (Q_{loss}) and mechanical power of the pump (P_M), it is possible to calculate efficiency of hydronic system. The annual building heating need (Q) is given as input value, thus efficiency can be calculated as:

$$\eta_{hidronic} = \frac{Q}{Q+Q_{loss}+P_M} \dots (4.16)$$

4. Model description

4.1 Model of the building

The building geometry is extracted from a catalogue of a Norwegian house manufacturer. The envelope properties have been established in order to comply with the Norwegian passive house standard for residential buildings (NS 3700: kriterier for passivhus og lavenergihus boligbygninger). The building thermal performance has been evaluated using the SIMIEN software (assuming a single-family house as the building type). The following properties for the envelope have shown to comply with the NS3700:

- U-value: external walls = 0.12 W/m².K; ceiling = 0.11 W/m².K; ground slab = 0.10 W/m².K; overall value for windows and external doors = 0.72 W/m².K
- Cold bridges: 0.03 W/m.K
- Infiltration rate: 0.6/h at 50 Pa
- Efficiency heat exchanger of the ventilation: 85%

Once the building envelope has been established (1), the building properties are introduced in the software TRNSYS 17. This software is more accurate than the SIMIEN. Furthermore, the standard hygienic flow rates are now applied to the building model (i.e. different than in NS3700). TRNSYS then computes, for each time step the exact power that should be emitted by convection in order to have exactly 21°C in each room during daytime. By definition, this is the space-heating needs of the building.

This part of modeling is done by, Laurent Georges, Postdoctoral Fellow at the Department of Energy and Process Engineering.

Drawing of building geometry is presented in Appendix A.

4.2 Model of the Hydronic Heating System

As it is already mentioned, one standard hydronic system consists of a:

1) Heat source (Heat generator)
2) Distribution system
3) Heat emitters
4) Control system

The components selected should provide efficient and quality operation of the system. Also, they have to represent a realistic solution as much as it is possible and thus provide the best possible simulation and results.

the designed system is very simplified. One boiler, one radiator, pipes which connect them, the pump and components of the control system are taken into consideration. Other components (different kind of valves and the expansion tank), which are necessary for safe operation of the installation but not relevant for determining the goal of this thesis, will not be discussed.

Heat source

Because of the very low heating needs (3000W), electrical boilers have been imposed as the most appropriate solution. They usually contain two or more immersion-type resistive elements mounted in a common enclosure through which water flows. Electrical current passes through a resistive heating element and heat is delivered to the water.

Electrical boilers have some advantages compared to the combustion type boilers and some of them are:

- Since combustion is not involved, no air supply is required for combustion or draft, and no exhaust system is necessary.

- Since there are no flue gases, there is no concern about flue gas condensation.
- One-site fuel storage is not required.
- Periodical maintenance is minimal since there is no soot to remove or fuel filters to replace [8].

One of the main questions which determine suitability of the electrical boiler is the ratio between the cost of electricity and competing fuels. Generally, the economics is more favorable in areas where electric utility rates are low. In Norway using electricity for heating is quite common and that fact recommends this kind of boilers as a good solution.

With the effective power of 3000 Watts which is equivalent to the building need at the design condition, the VB3010 boiler represents a matching solution for this system. The manufacturer of this model is NOVEMA *Kuldeas* Company.

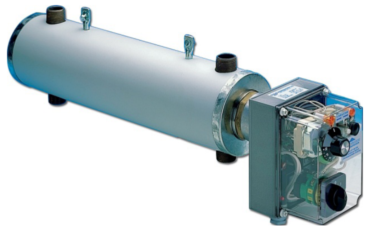


Figure 21 - Boiler VB3010

Distribution system

Pipes which connect the heat generator and heat emitter represent the distribution system. This part of the hydronic system is crucial for the report. Thermal losses and head losses in this subsystem have a decisive impact on the answer to how efficient the system is and which pump should be used. Special attention is given to the system design and selection of material.

It is a two-pipe system with separate pipelines for inlet and outlet water. The position of pipes is shown in Appendix XX.

The total length of pipes is 17.25 m. As the system has only one heat emitter it is possible to use the same pipe size for the whole circuit. There are no changes in the flow rate so there is no need for changes in diameter of the pipes. Six different (external) diameters are tested as a possible solution for this system: 8mm, 10mm, 12mm, 15mm, 18mm and 22mm.

All piping materials have strengths and weaknesses. There is no single material which is ideal for all applications. Among others, copper tube was selected as an optimal solution for this system.

The copper water tube was developed in the 1920s in order to provide an alternative to iron piping. It has advantages where the piping runs are straight, which is the case with this model. Other desirable features include:

- Good pressure and temperature rating for typical residential hydronic applications;
- Good resistance to corrosion of the water-based system;
- Smooth inner walls that offer low flow resistance;
- Lighter than steel or iron piping of equivalent size; [8]

Heat emitter

Among others, radiators are the most widely used heat emitters. The panel radiator is selected as suitable for this system.

Today's market offers panel radiators in hundreds of sizes, shapes, colors, and heating capacities to fit different requirements. Some panel radiators release high percentage of their heat as thermal radiation. To the contrary, other panel radiators are designed to release a significant percentage of their heat output through convection. Which of those two types will be used depends on what kind of heat transfer is desirable for a specific case.

Choosing panel radiators brings several benefits compared to other types of heat emitters:

- They usually require far less wall space than other heat emitters for equivalent operating conditions and heat output. This often improves aesthetics and provides more places for furniture. Also, a wide variety of widths, heights and thicknesses allows panel radiators to be easily integrated into limited wall spaces and still provide the necessary heat output.
- Most panel radiators have low thermal mass because they contain very little water and react very quickly to variations in room air temperature or internal heat gains.
- They are able to work with larger water temperature drops between their inlet and outlet compared to some other heat emitters. It means that flow rates can be lower and lower flow rates allow for smaller tubing and reduced circulator input power.
- Panel radiators have the ability to operate at relatively low water temperatures, which increases the percentage of radiant versus convective heat output from the panel.
- They are relatively durable. Their design and steel construction make them more resistant to physical damage compared to some other heat emitters [8].

The Norwegian company *LYNGSON* is a manufacturer of panel radiators. From their catalog *PRE RADIATORER*, the model PCP40, with the height 400mm and length of 2600mm is an ideal match for this particular system. With the heat output of 3000 W, it will meet expectations for a radiator in a simplified system. Of course, it is possible to combine other types of heat emitters and manufacturers.

Figure 23. *LYNGSON's* panel radiators

Pump

A very low flow rate (0.072 kg/s) and a wide range of pump head (0.12m – 29.57m) for the system studied, make it very hard to find an ideal pump for a particular hydronic system. Because of that, the "smallest" pump from ***Wilo*** catalog was chosen- ***Stratos Pico 15/1-4-130***. Then, with the assumption that ideal pump for the system exists, the pump curve of ***Stratos Pico*** is used as a model for computing the curve for that ideal pump.

Figure 24 - Pump - *Stratos Pico 15/1-4-130*

Wilo-Stratos is the first high-efficiency pump of glandless design with the following advantages:

- Up to 80% electricity savings compared to standard pumps
- For all heating, air-conditioning and cooling systems in the temperature range of -10 °C to +110 °C
- Automatic adjustment of the pump output to continuously varying load conditions of the hydraulic system
- Prevention of flow noise
- Safety and comfort during installation and operation

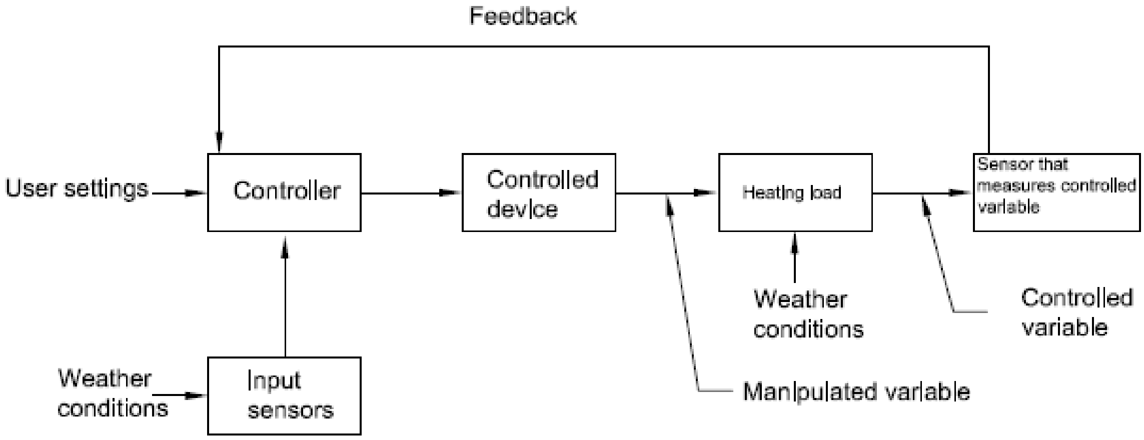
The efficiency of the hydraulics and motor determine the pump's overall efficiency. The Wilo-Stratos series is used as a high-efficiency pump in circulation systems for heating, ventilation and air-conditioning systems in commercially-used residential and functional buildings.

The fluid temperature range of -10 °C to +110 °C without restriction at an ambient temperature of -10 °C to a maximum of +40 °C.

In nearly all circulation systems, correctly sized controlled glandless pumps ensure adequate heat supply at all times at significantly reduced energy costs, while at the same time preventing noise generation.

Control system

In order to better understand how the control system works, some basic concepts will be explained first. Figure 25 shows a simplified block diagram of a feedback control system for space heating applications. Some of the boxes represent information while others represent physical devices.



Figures 25

The block in the lower left represents information which is sent to the control system by one temperature. This information can be more complex and contains data about wind speed, relative humidity and solar radiation intensity. That is the case with a more sophisticated control system. The controller can receive this information as an electrical signal such as variable resistance, voltage or current. Also, it could be sent as a digitally encoded signal.

The controlled process gets user settings as additional information. These additional inputs can be analog (temperatures, pressures, flow rates) or digital (switch status). Analog inputs are physical parameters that can be measured and which vary over continuous range of numerical values. Digital inputs can only have one of two states – open or closed.

The block named controller is a physical device. It receives information from input sensors. Also, it accepts and stores the user settings. Sensor that measures the result of the controlled process sends information to the controller, as well. This information is called feedback and it is represented by controlled variable. In today's hydronic systems, indoor air temperature is usually controlled variable.

The controller uses feedback to compare the measured value of the controlled variable with the target value. The latter is the desired ideal status of the controlled variable. An error will be recognized if there is any deviation between the target value and the measured value. In this context, the word error does not indicate that malfunction has occurred. It only implies on existence of a certain deviation between the target value and measured value of the controlled variable.

In order to generate an output signal based on error, the controller uses a stored set of instructions called a control-processing algorithm. The output signal is passed to controlled devices which respond by changing the manipulated variable. The change in the manipulated variable triggers a change in the process that is controlled. This causes a corresponding change in the controlled variable. The change in the controlled variable is registered by a sensor which provides feedback to the controller. The whole process is continuous as long as the system is working [8].

The closed-loop control systems can be adjusted for very stable operation.

This report is based on a system which can be controlled in two ways:

- By varying the water supply temperature
- By varying the water flow

Additionally, this system has a device with which speed of the pump can be controlled and in that way achieve more efficient operation of the entire system.

The components used to provide control of the system and principles of their operation will be described.

Supply water temperature control

To control temperature of water it is necessary to control the output of the heat source. There are several methods for controlling the heat output and most common are:

- On\Off control of a single-stage heat source
- Multistage heat production
- Modulating heat production

The assumption is that the chosen boiler, VB3010 has electronic equipment which allows the designed system to be controlled with the third method - Modulating heat production.

This method represents ideal control method. With it, heat output from the heat generator will always precisely match the rate of heat loss from the building. Also, heat output could be any value from zero to full design load of the building. When the load changed due to changes in outdoor conditions or internal heat gains, the heat generator would instantly readjust its output to match the load. Figure XX depicts ideal matching between heat production and heat load [8].

This ideal control condition is almost impossible to achieve. Today's technology allows modern boilers to reduce (modulate) their heat output as low as 10% of the full output.

Water flow control

A device for water flow control is implemented to the system in order to get a better and more precise control system. Beside the temperature of supply water, amount of water which goes through the heat emitter also determines rate of the heat output and thus comfort. Thermostatic radiator valves (TRVs) are selected as the most appropriate solution for that purpose.

They are usually installed in the supply pipe of heat emitter. TVRs are composed of two parts – the valve body and the thermostatic operator.

Inside the valve a plug is mounted on a spring-loaded shaft. The plug is held in its fully open position by the force of the spring. The shaft has to be pushed inward against the spring force if the valve should close. Rotation is not necessary. The shaft movement can be achieved:

- Manually - using a knob that threads onto the valve body

- Automatically - through use of a thermostatic operator.

There are several types of thermostatic operators which can be matched to radiator valve bodies. Each of them contains a fluid in a sealed bellow chamber. The fluid expands inside the bellows when the temperature of the air that surrounds the operator increases. That expansion forces the valve shaft inward toward its closed position. This action decreases the water flow and reduces heat output. When the room-air temperature decreases, the process "goes" in opposite direction. The fluid within bellows contracts, allowing the spring force to slowly reopen the valve plug and increase the heat output.

With TRVs, the heat output of each heat emitter can be individually controlled. The combination of the valve and thermostatic operator represents control subsystem which continually adjusts flow through the heat emitter to maintain a constant room temperature. Their proper installation must provide faultless operation. The valve stem should be in a horizontal position with thermostatic operator facing away from the heat emitter.

Pump speed control

The *Wilo Stratos Pico 15/1-4-130* model can be controlled by a frequency converter.

The frequency converter is a control device which is used for controlling and regulating circulation pumps with electronic control or integrated pump output electronics. The differential pressure of the system is controlled according to the load with appropriate signal transmitters. The controller affects the frequency converter which has an effect on the pump speed. The speed modification changes the delivery head and thus the power output of the single pumps. According to load requirements, the pumps are either activated or deactivated. The control device can control up to 4 pumps [22].

For this specific series of pump, there are two possible control modes:

- Δp-c (differential pressure constant)
- Δp-v (differential pressure variable)

Control mode Δp-c

In the Δp-c control mode, the electronic module keeps the differential pressure generated by the pump constant at the set differential pressure set point HS over the permissible volume flow range.

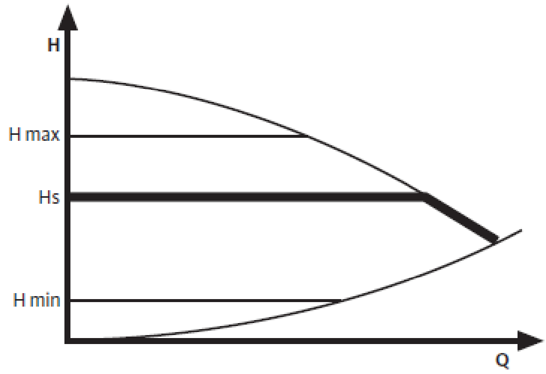


Figure 26- Control mode Δp-c [22]

The differential pressure set point to be adjusted at the control devices is kept constant across the entire volume flow range. That means that any reduction of the volume flow (Q) caused by the throttling of the hydraulic control units will in turn adjust the pump output to actual system requirements by reducing the speed of the pump. Along with the change in speed, the power consumption is reduced to below 50% of the nominal power. The application of the differential pressure control requires a variable volume flow in the system. [22]

Control mode Δp-v

In the Δp-v control mode, the electronic module changes the differential pressure set point to be maintained by the pump in linear fashion between Hs and 1/2 Hs. The differential pressure set point value H varies with the volume flow Q.

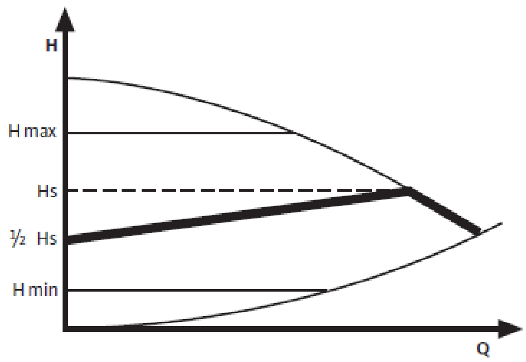


Figure 27- Control mode Δp-v [22]

An extension of the control range is nevertheless possible using the Δp-v control mode (recommended for single- pump systems). A processor unit of the control system adapts the differential pressure set point value to a preset variable differential pressure curve by means of a comparison of the set point / actual value. In parallel operation, the differential pressure is kept constant at the design level after the first peak-load pump has been cut in. [22]

5. Simulation program

The thought behind the program was to calculate the heat losses from pipes for a given geometry of the building and consumption of the pump which operates under the designed hydronic system.

The program developed, based on the mathematical model presented in Chapter 3, was run for a specific set of input values. These values are listed in the table below.

Nominal conditions		
Temperature of indoor air	${t_{in-air}}^N = 20$	${}^oC$
Temperature of outdoor air	${t_{out-air}}^N = -20$	${}^oC$
Temperature of supply water	${t_{sup}}^N = 40$	${}^oC$
Temperature of return water	${t_{ret}}^N = 30$	${}^oC$
Building heating needs	$\dot{Q}^N = 3000$	W
Physical properties of water		
Specific heat capacity	$c_w = 4174$	$J/kg\,K$
Density (at 40°C)	$\rho_{40} = 992.2$	kg/m^3
Density (at 30°C)	$\rho_{30} = 995.7$	kg/m^3
Kinematic viscosity (at 40°C)	$\nu_{40} = 0.659 \cdot 10^{-6}$	m^2/s
Kinematic viscosity (at 30°C)	$\nu_{30} = 0.805 \cdot 10^{-6}$	m^2/s
Physical properties of pipe material (copper)		
Absolute roughness	$\varepsilon = 0.0015$	mm
Total surface coefficient of heat transfer	$h_a = 14$	W/m^2K
Range of pipe diameters		
$d = 8$		mm
$d = 10$		mm
$d = 12$		mm
$d = 15$		mm
$d = 18$		mm
$d = 22$		mm

Table 4- Input values

The hour based outside air temperature and building heating needs are given as input parameters. Five types of building constructions are investigated. They influence to have five different values of building heating needs.

Modeling of buildings is done by Laurent Georges, Postdoctoral Fellow at EPT, as a part of his own research. The building is constructed in 5 different ways in order to get 5 different levels of internal thermal masses: "very-heavy", "heavy", "medium", "light" and "very-light". The heavy structures are made using concrete blocks and external insulation while the light structures are built using wooden structures. In order to have more variations in thermal mass, the position of the insulation in the ground slab is also changed between the 5 cases. The insulation is indeed above or under the slab to change the accessible thermal mass.

The program also includes a variable which allows simulation of the hydronic system operation with six different pipe diameters.

Two types of control system are compared within the simulation. The first of them uses external temperature as a signal relevant for the input sensor. This means that each time the value of external temperature goes below the value of nominal indoor temperature the control system will activate the heating system.

In *Figure 28*, the red line corresponds to the nominal indoor temperature (20^{o}C) and the blue one represents fluctuations of external temperature during the year (based on weather data for Oslo, Norway).

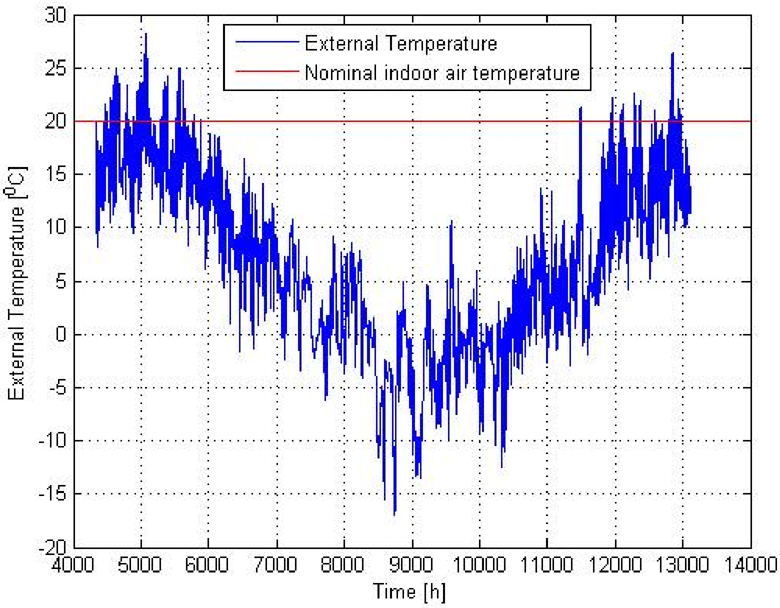


Figure 28- External Temperature Diagram

From the figure above it is quite obvious that the heating system will operate almost the entire year. This kind of control has great influence on heat losses from pipes which will be proved by the results of simulation.

The second control system tested represents a more advanced type of control. It based its operation on values of the indoor temperature as a relevant signal for the input sensor. Maintaining the indoor temperature on the desired value means that at any point of time the condition of thermal equilibrium is satisfied. In other words, all heat inputs (heat from sun, electrical devices, inhabitants etc.) are equal to heat losses of the building. *Figure 29* presents annual building heating needs. The control system will start up heating each time when the heating needs are not equal to zero. From figures two clearly separated periods are visible:

- When the building heating needs exist (*7123 h - 10871 h*)
- When there is no need for heating (*4344 h - 7122 h* and *10872 h – 13104 h*)

Heating period in this case is much shorter than with the first type of control system.

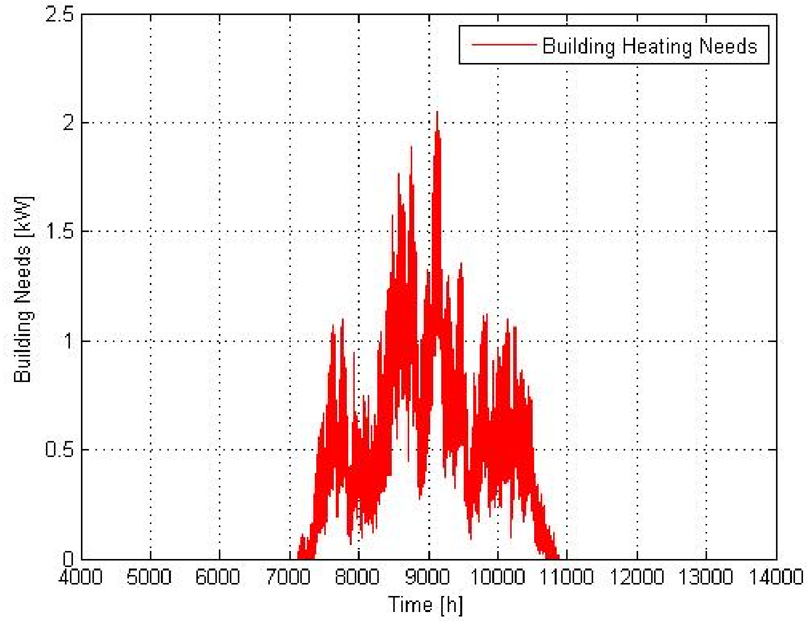


Figure 29- Building Heating Needs Diagram

Figure 30 gives a visual confirmation of that conclusion. A more precise control system provides more efficient operation of the heating system and ensures preservation of the thermal equilibrium thereby maintaining thermal comfort.

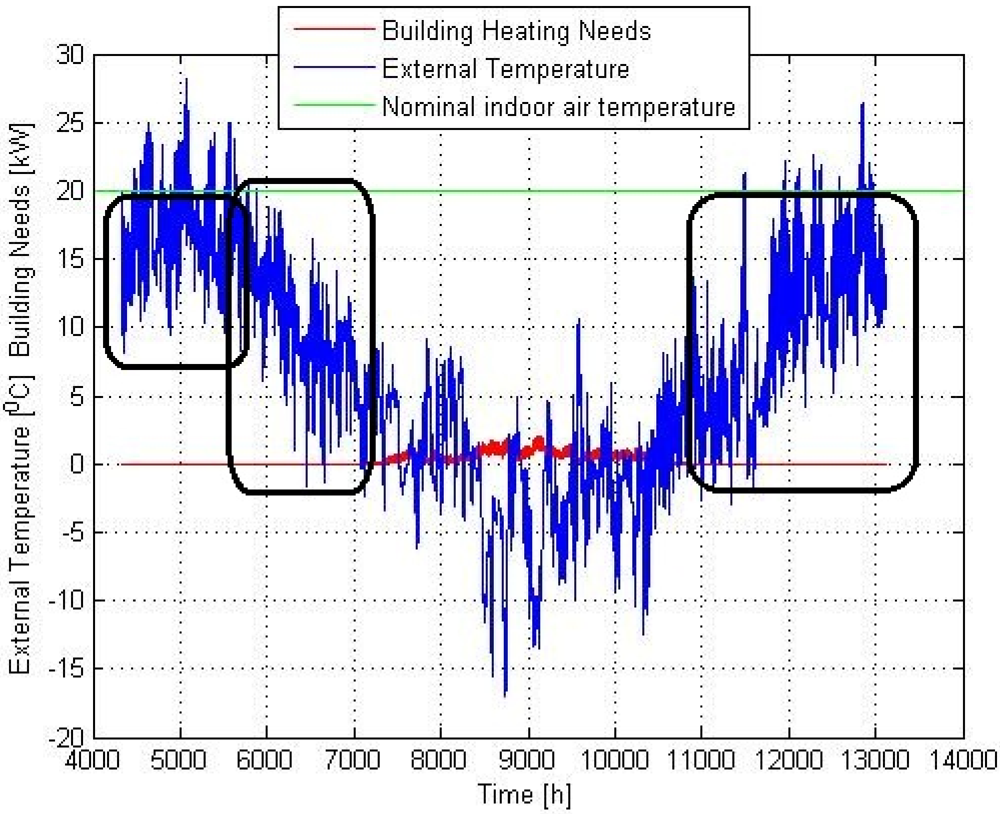


Figure 30

Controlling the pump speed is of great interest for this report. The frequency convertor (see chapter XX), changes the speed of the pump thus allowing the system to use less energy.

As it is already mentioned that there are two ways to control the speed of the pump : the $\Delta p - c$ control mode and $\Delta p - v$ control mode. Within the simulation program, beside these modes, a system without any control is also investigated. The program code is based on the mathematical program described in Chapter 3.

Figure 30 shows the pump consumption of mechanical power for each of these modes. Observing the figure below, it is obvious that the smallest area (green) is for the $\Delta p - v$ control and, the biggest is for the pump without any speed control (blue). It could be concluded that the pump will use least energy with the $\Delta p - v$ control, then little more with the $\Delta p - c$ control and of course the most without any device for controlling. The results presented in Chapter 6 will confirm this visually based conclusion.

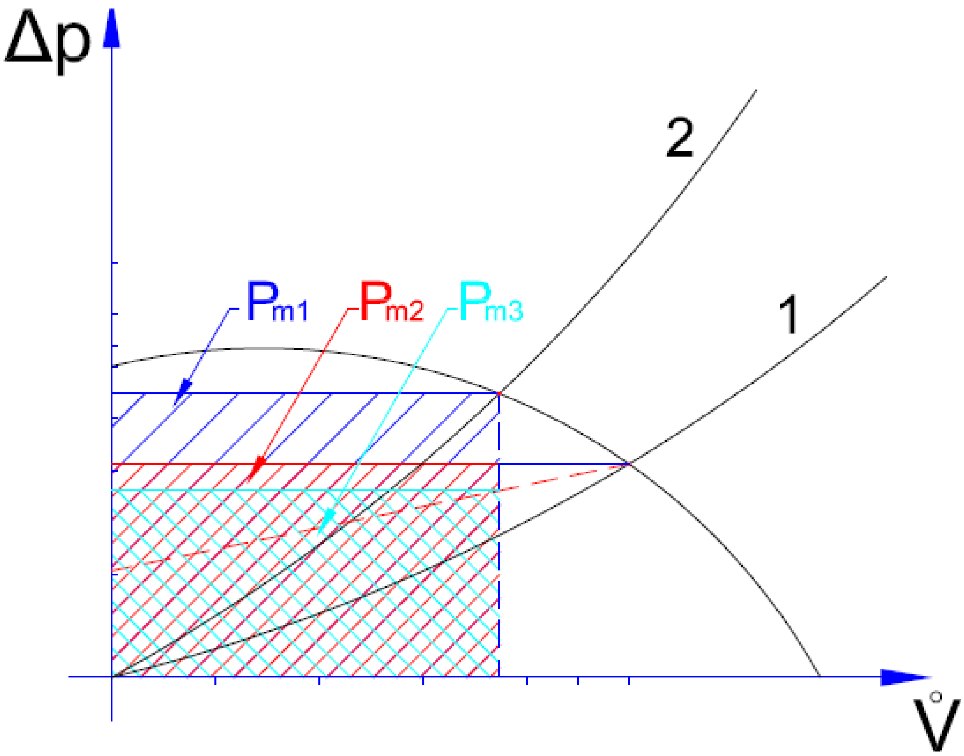


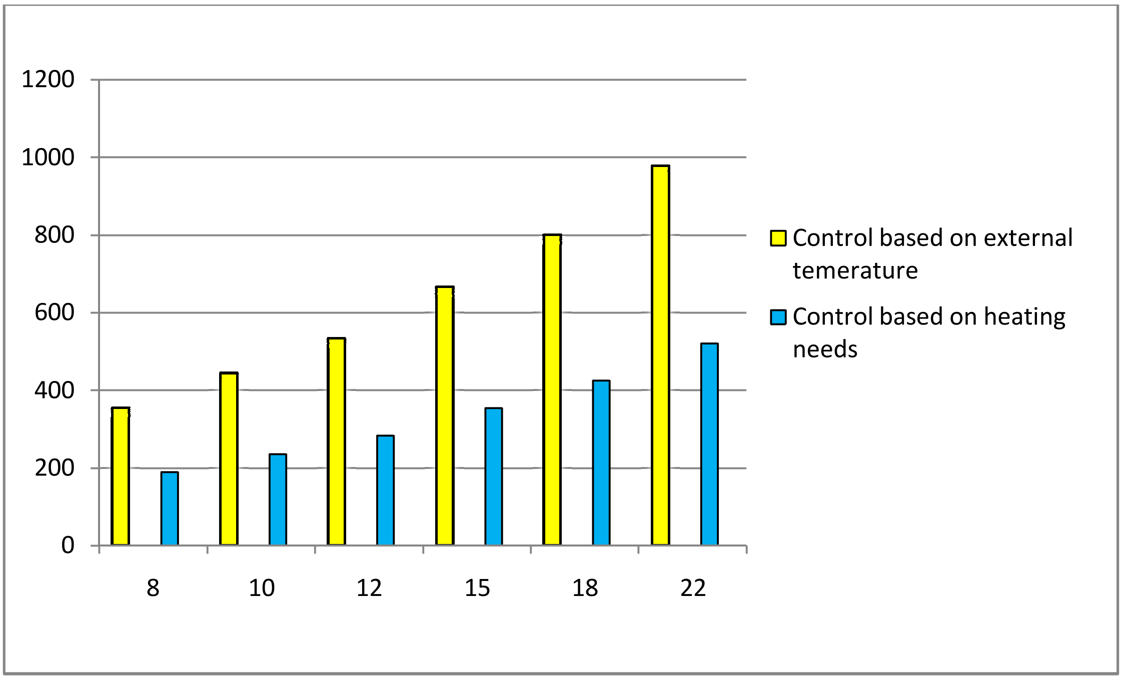
Figure 30- Review of all possible types of control and comparison of power consumption for each of them

6. Results

First part of this chapter is devoted to review of results which are obtained from simulation. For each type of building they are showed separately. Afterwards, results are analyzed and discussed. Comparison of results for different building types and determining efficiency of hydronic system are topics of interest for discussion.

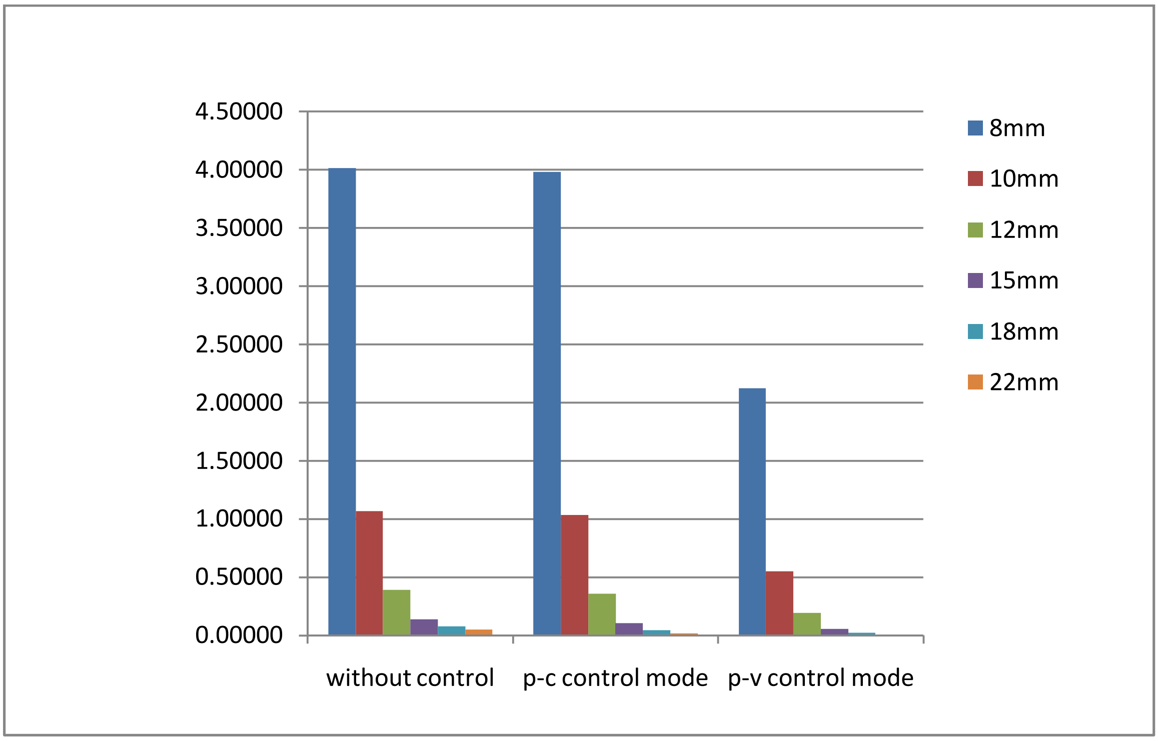
Building 1

	Heat Losses	
Diameter	With control based on external temperature	With control based on building heating needs
[mm]	[kWh/year]	
8	354.98381	176.64075
10	443.72977	220.80094
12	532.47572	264.96113
15	665.59465	331.20141
18	798.71358	397.44169
22	976.20549	485.76206



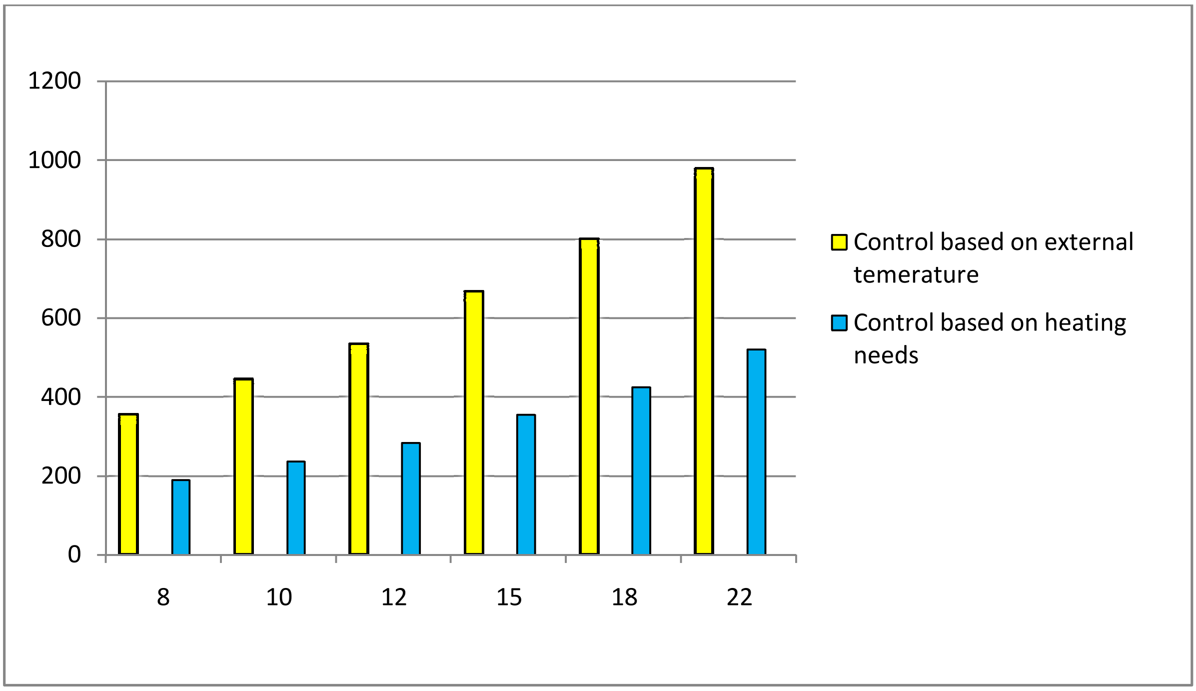
Building 1

	Pump consumption		
Diameter	Without control	$\Delta p - c$ control mode	$\Delta p - v$ control mode
[mm]	[kWh/year]		
8	3.90850	3.87539	2.05540
10	1.03876	1.00565	0.53337
12	0.38204	0.34892	0.18506
15	0.13400	0.10089	0.05351
18	0.07343	0.04032	0.02138
22	0.04803	0.01491	0.00791



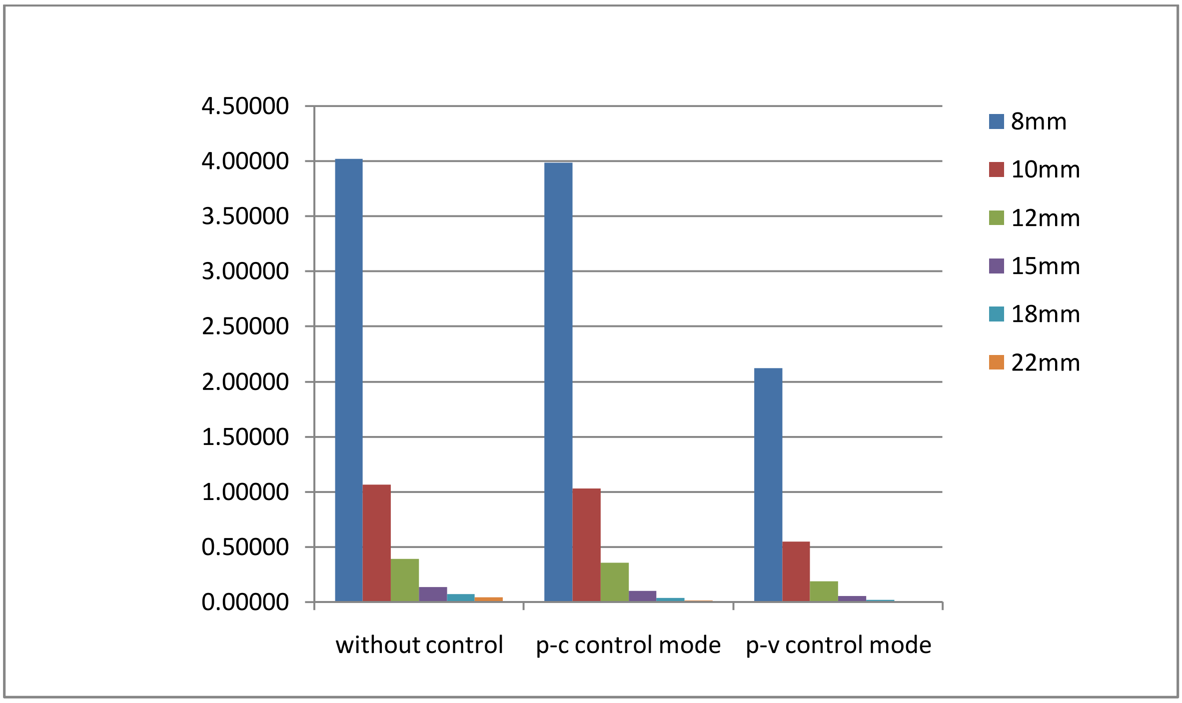
Building 2

	Heat Losses	
Diameter	With control based on external temperature	With control based on building heating needs
[mm]	[kWh/year]	
8	355.33474	193.63256
10	444.80559	242.0407
12	533.76671	290.44884
15	667.20838	363.06105
18	800.65006	435.67326
22	978.5723	532.48954



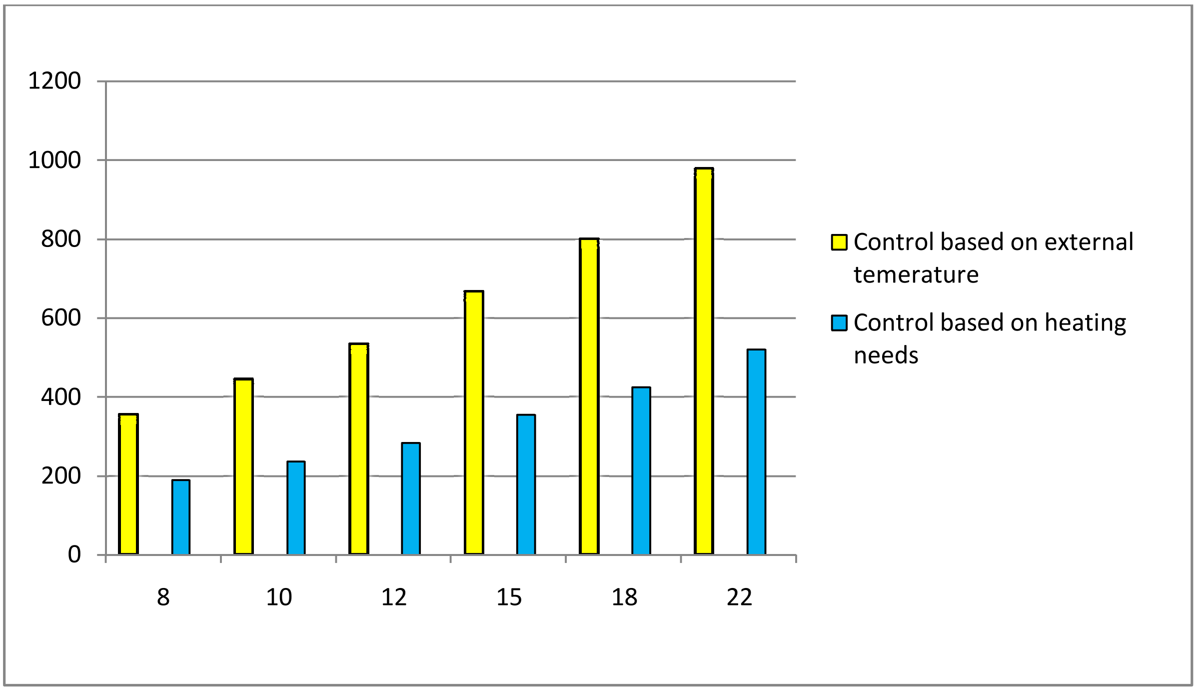
Building 2

	Pump consumption		
Diameter	Without control	$\Delta p - c$ control mode	$\Delta p - v$ control mode
[mm]	[kWh/year]		
8	4.090544	4.05609	2.16223
10	1.08700	1.05254	0.56109
12	0.39965	0.36519	0.19468
15	0.14005	0.10559	0.05629
18	0.07665	0.04220	0.02249
22	0.05006	0.01561	0.00832



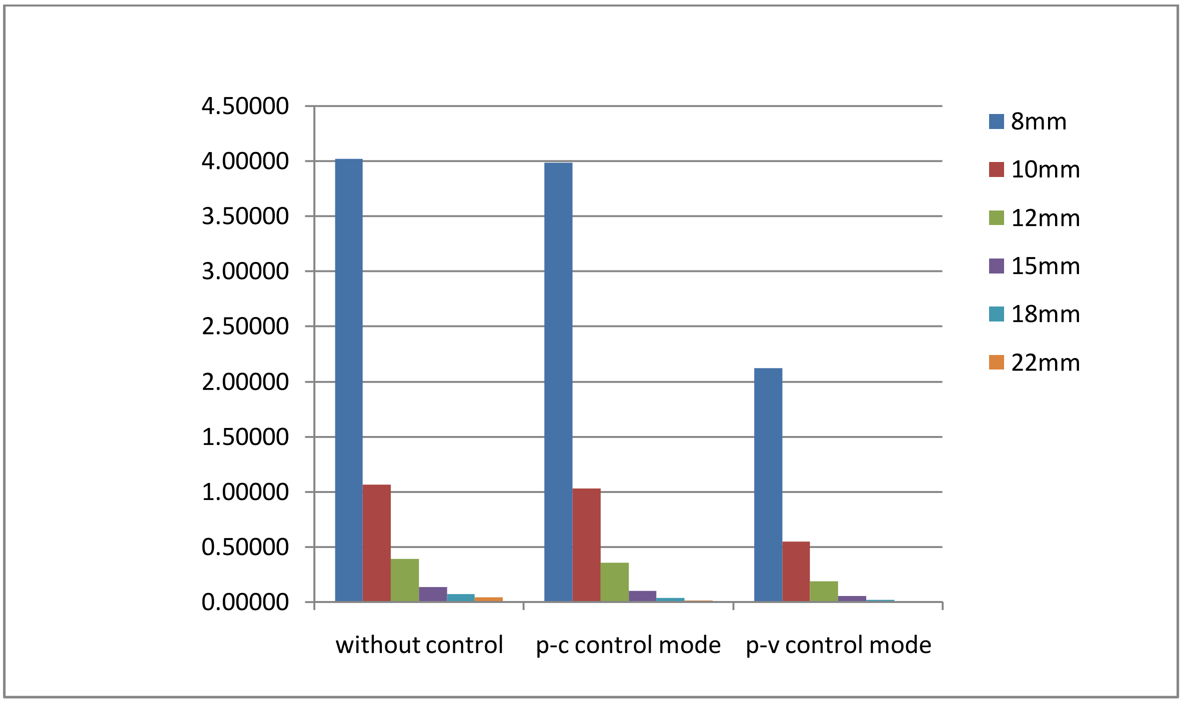
Building 3

	Heat Losses	
Diameter	With control based on external temperature	With control based on building heating needs
[mm]	[kWh/year]	
8	355.33474	190.73026
10	444.16842	238.41282
12	533.0021	286.09538
15	666.25263	357.61923
18	799.50316	429.14308
22	977.17053	524.5082



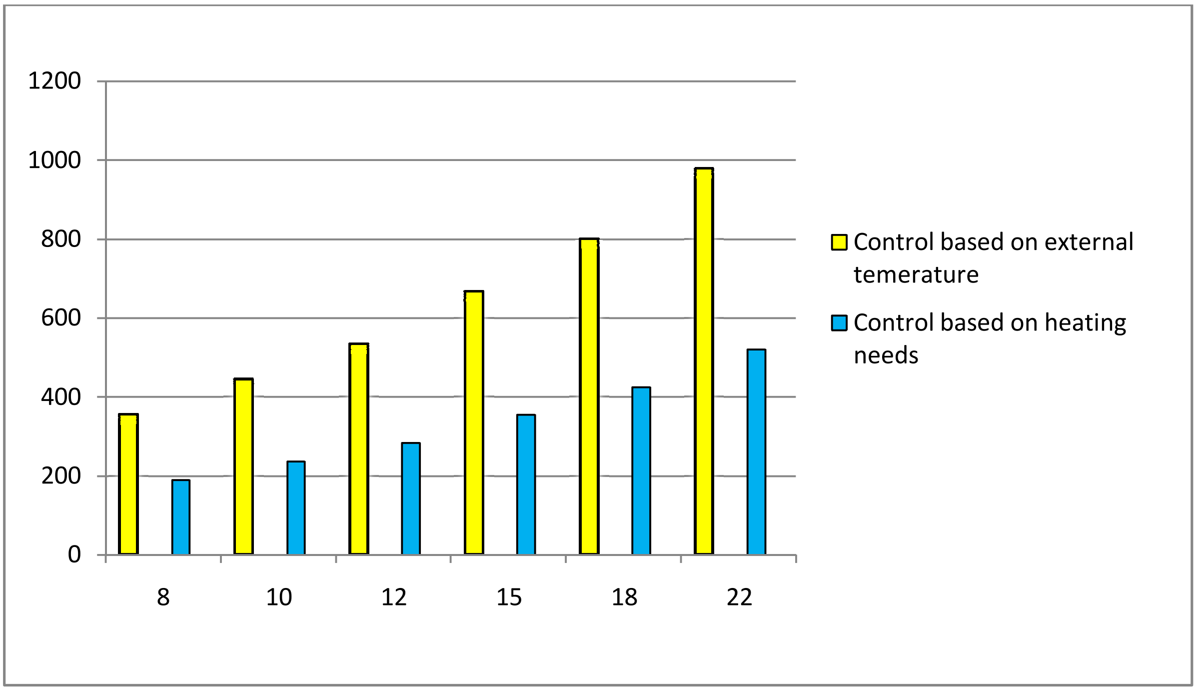
Building 3

	Pump consumption		
Diameter	Without control	$\Delta p - c$ control mode	$\Delta p - v$ control mode
[mm]	[kWh/year]		
8	4.00981	3.97591	2.11236
10	1.06564	1.03173	0.54815
12	0.39188	0.35797	0.19019
15	0.13741	0.10351	0.05499
18	0.07527	0.04136	0.02197
22	0.04920	0.01530	0.00813



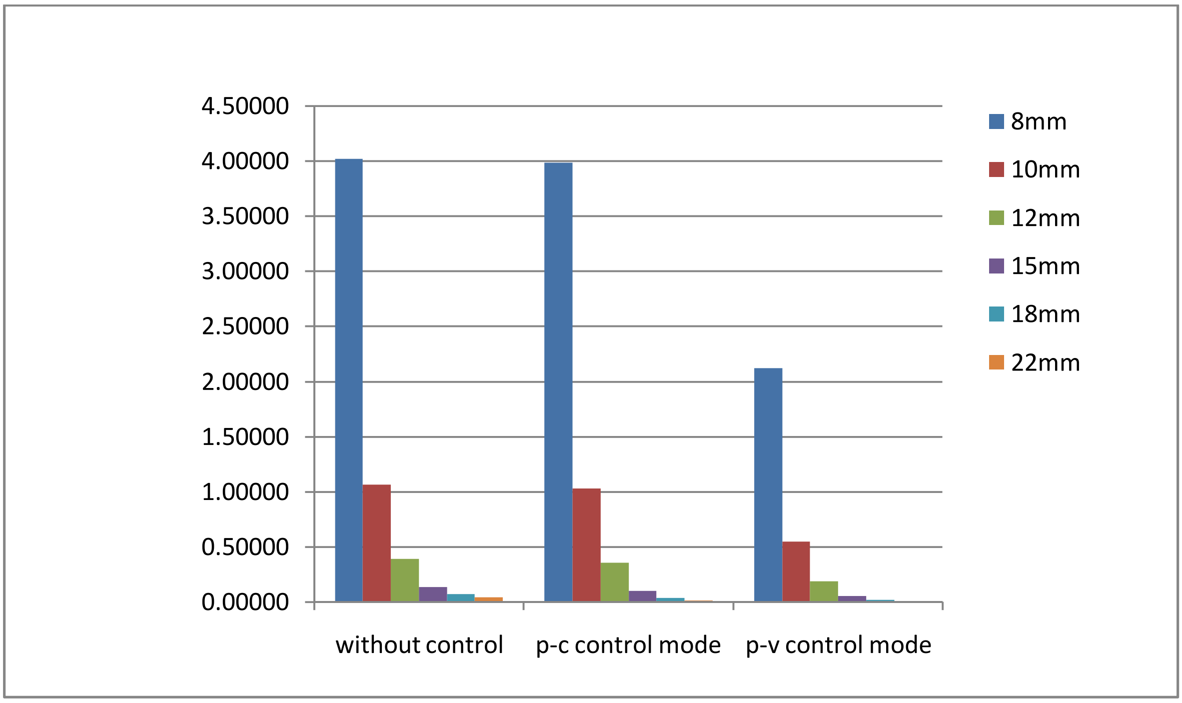
Building 4

	Heat Losses	
Diameter	With control based on external temperature	With control based on building heating needs
[mm]	[kWh/year]	
8	356.35436	177.43538
10	445.44295	221.79423
12	534.53155	266.15308
15	668.16443	332.69135
18	801.79732	399.22961
22	979.9745	487.94731



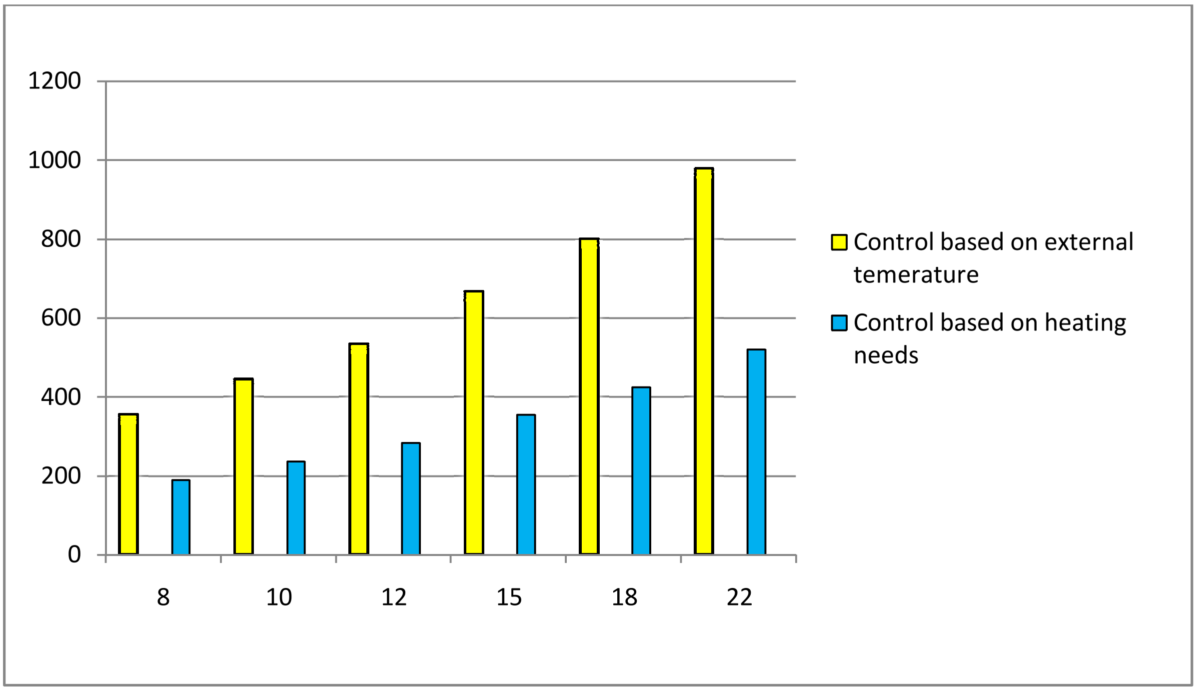
Building 4

	Pump consumption		
Diameter	Without control	$\Delta p - c$ control mode	$\Delta p - v$ control mode
[mm]	[kWh/year]		
8	4.18636	4.15120	2.21862
10	1.11238	1.07722	0.57573
12	0.40892	0.37376	0.19976
15	0.14323	0.10807	0.05776
18	0.07835	0.04319	0.02308
22	0.05113	0.01597	0.00854



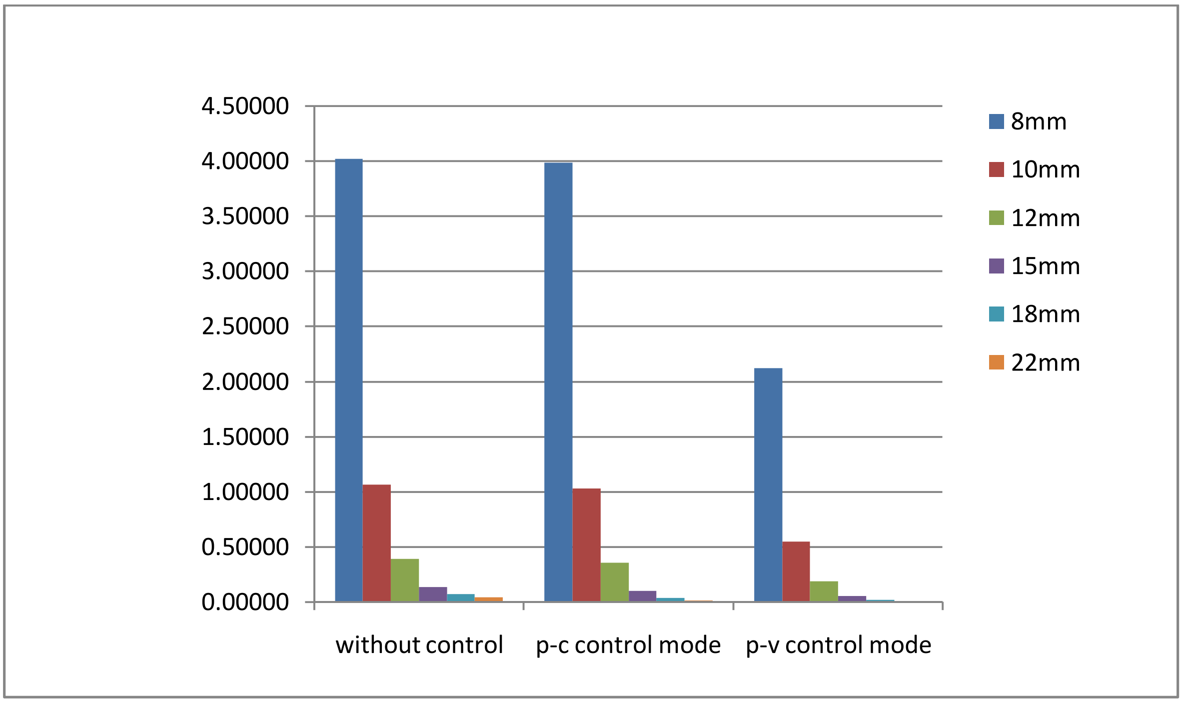
Building 5

	Heat Losses	
Diameter	With control based on external temperature	With control based on building heating needs
[mm]	[kWh/year]	
8	355.67627	189.14072
10	444.59534	236.4259
12	533.51441	283.71109
15	666.89301	354.63886
18	800.27161	425.56663
22	978.10975	520.13699



Building 5

	Pump consumption		
Diameter	Without control	$\Delta p - c$ control mode	$\Delta p - v$ control mode
[mm]	[kWh/year]		
8	4.01622	3.98237	2.12198
10	1.06726	1.03341	0.55065
12	0.39240	0.35856	0.19105
15	0.13752	0.10368	0.05524
18	0.07528	0.04143	0.02207
22	0.04917	0.01532	0.00817



7. Discussion

The best solution of the hydronic heating system for each type of building is under consideration. The best solution means that the sum of heat losses from pipes and consumption of the pump is the smallest among all the combinations of diameters and pump control modes. From the previous chapter it could be seen that for all types of buildings the best solution is with the diameter $d = 8mm$ and $\Delta p - v$ control mode.

7.1 Conclusion

Since the pipe surface is directly determined by its diameter and, that it in turn affects the losses directly, it is clear why the system with the smallest diameter is the most favorable solution.

Even though the pump consumption is negligibly small compared to heat losses, they are taken into consideration.

Building type	Building needs	Heat losses + pump consumption	Ratio
	kWh	kWh	%
Building 1	2282.061	178.696	7.83
Building 2	2282.061	195.795	8.58
Building 3	2324.119	192.843	8.30
Building 4	2393.144	179.654	7.51
Building 5	2318.723	191.263	8.25

Table 5

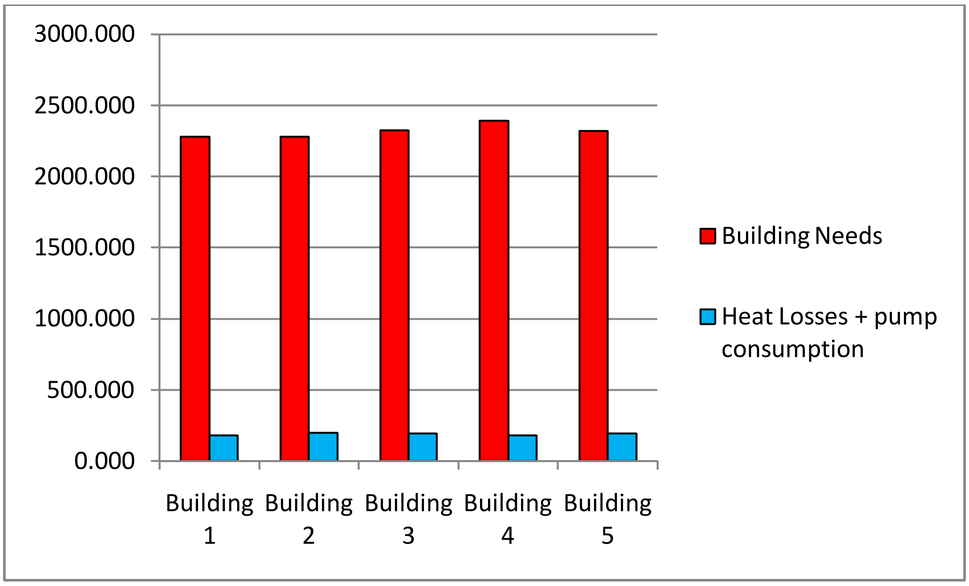


Figure 31- Comparison of Building heating needs and losses

Heating needs and losses of each building type are presented in Table 5 and on Figure 31. In table can also be seen how big losses are compared to the building needs for heating. These values are given in percentages, in last column.

According to *table 1*, (page XX), the energy for heating within the passive house concept is between $10\frac{kWh}{m^2}$ (for best practice) and $15\frac{kWh}{m^2}$ (recommendation is below this value). Taking house area of model used ($190.046\ m^2$) recommended range of values for energy for heating can be determined as:

$$1900\ kWh\ \leq Desired\ value\ < 2850\ kWh$$

As it can be noticed, all investigated building types satisfy the mentioned recommendation. A more important observation is that even if losses were added to basic heating needs, their sum would still be within the recommended range of values for energy for heating.

Building type	Sum of the building needs and losses
	kWh
Building 1	2460.757
Building 2	2477.856
Building 3	2516.961
Building 4	2572.798
Building 5	2509.986

Table 6

Using the this sum (*from Table 6*) and building heating needs (*from Table 5*) it is possible to determine efficiency of hydronic heating system within each type of building according to equation (4.16).

Building type	Efficiency of Hydronic Heating System
	%
Building 1	92.74
Building 2	92.10
Building 3	92.34
Building 4	93.02
Building 5	92.38

Table 7

Based on above results it could be concluded that hydronic heating systems are very efficient (mean efficiency 92.54 %) and can be successfully implement in buildings with passive envelopes, which means the ZEB buildings also (From energy use for heating point of view). On the contrary, (from thermal comfort point of view) it is known that every heat input in a building with passive envelopes, even very small, can disturb thermal comfort. *Having* in mind that heat losses in the pipes are not in the least negligibly small, it is obvious that installation of the hydronic heating system will be seriously detrimental to thermal comfort.

7.2 Limitations

There are a few limitations which have to be taken into consideration. Among other, the most important are:

- *In the program the indoor air temperature is to be given as a constant value.*
  This would have a surplus energy use for heating (which normally has night set-back of temperature).

- *The program is made for a very simplified hydronic system.*
  Simplification leads to the smaller total length of pipes which make the distribution system. As it could be seen from chapter 3 (equation 3.1), the total pipe length has a great impact on thermal losses from pipes. In the same chapter, equation *3.10* shows how this value influences the process of pump selection. In both cases, the total length of pipes is an important factor. A more complex distribution system also means more heat emitters, valves, elbows and bents and they are primary elements in the calculation of impact losses.

- *Pump, the characteristics of which are taken for simulation, does not exist.*
  On the one hand, a very low flow rate directs to the smallest pump from the catalog. On the other hand, high values of pressure loss in the system make that solution inappropriate. As a solution for that situation the smallest pump was taken as a model which will be adapted for higher pressure losses. As the real pump is not adapted to designed system, it would operate with very bad efficiency. Therefore, it makes no sense to estimate electrical consumption of such low pump efficiency. Because of that, mechanical power of the pump was chosen as relevant value to determine energy pump consumption.

7.3 Further work improvements

In order to obtain more accurate results, some improvements should be introduced in further work. With them the simulation program would be better and results which are generated would be more relevant.

Today's commercial market does not offer a pump which satisfies parameters of the designed hydronic system. As it is already mentioned, that is the reason why electrical consumption of pump can not be determined. In order to improve this part of approach, real pump should be implemented. In that way, it would be possible to determine pump electrical consumption and generates better results.

Also, the more complex hydronic heatinng system should be implemented in order to understand better behavior of hydronic systems within buildings with passive envelopes. Results could provide better insight in relation between heat losses from pipes and total efficiency of hydronic heating system.

Having a variable value of indoor air temperature could also contribute to generate more precise results.

It is mentioned a problem with disturbing thermal losses in previous chapter. A possible solution for this problem is a certain level of insulation. This solution should be investigated in some further work with special reference to cost analyses and, of course, values of heat losses.

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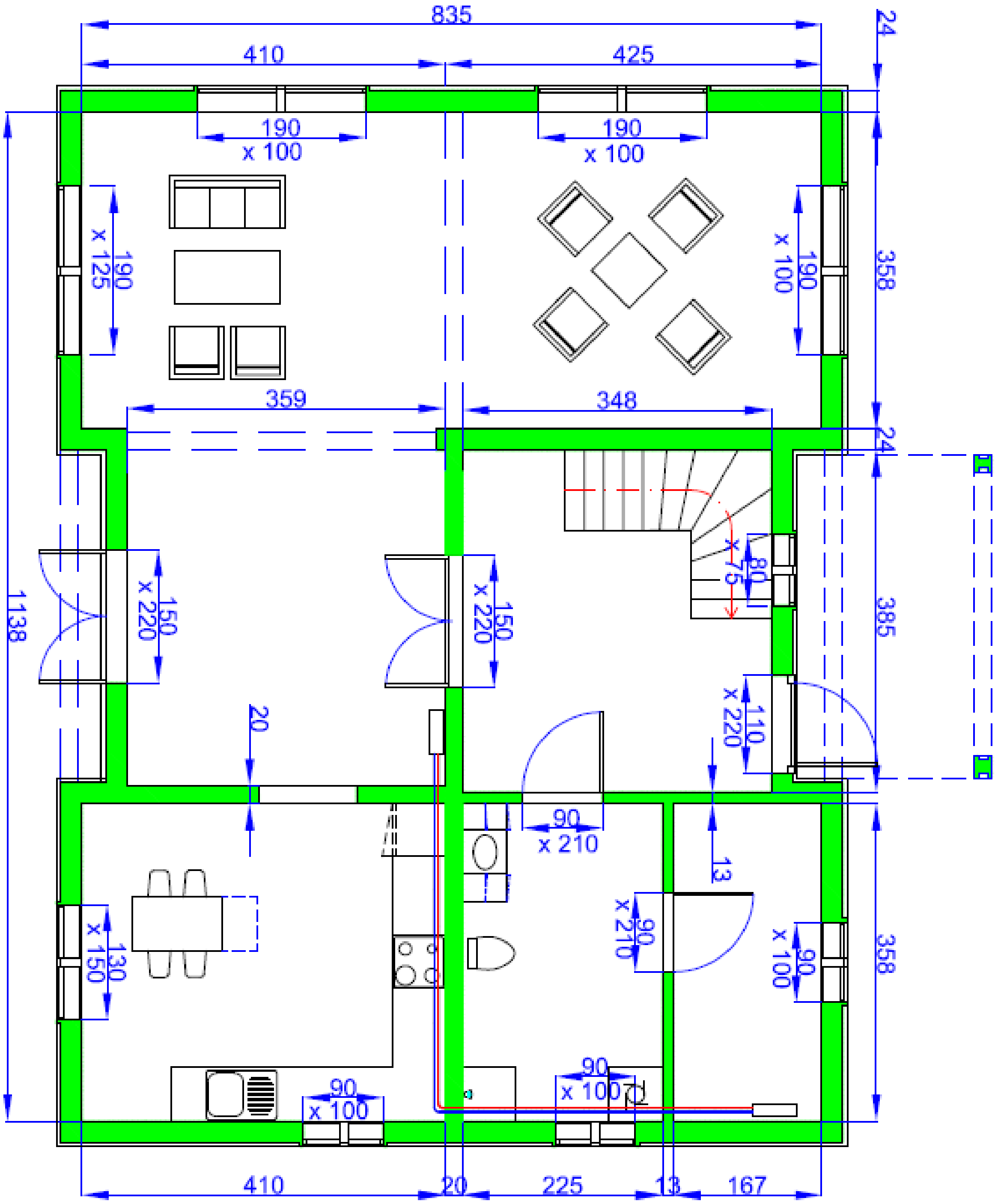
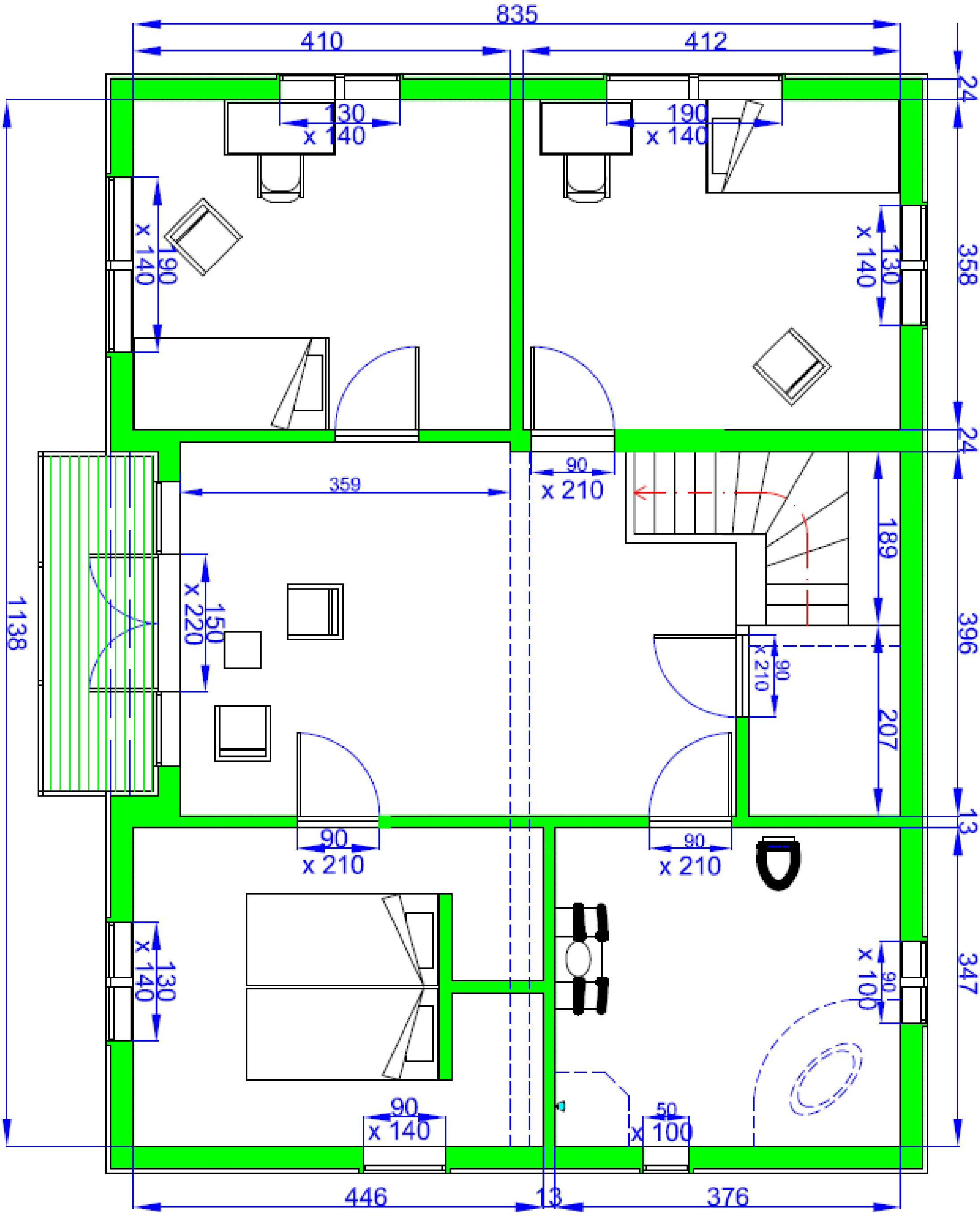
Appendix A

The Building geometry - First floor



The Building geometry - Second floor



Appendix B

Simulating program code in MATLAB (example for one building type)

Supply water temperature

```
function A_Inlet_temperature_Heating_1
%============================
BuildingNeeds = load('buildingneeds_1.out');
sizedata = size (BuildingNeeds);
%==============================================
Text = BuildingNeeds(2779:6527,2);
var = size(Text,1);
for i =(1:var);
if (Text(i)>20)
Tin(i) = 30;
else
Thelp(i)= Text(i);
Tin(i) = (-0.25)*Thelp(i)+35;
end
end
%==============================================
Tinlet =  Tin';
%==============================================
savename = ['A_InletTemperature_Heating_1.out'];
save(savename,'Tinlet','-ascii','-tabs');
end
```

Temperature difference

```
function A_deltaT_Heating_1
%============================================
BuildingNeeds = load('buildingneeds_1.out');
sizedata = size(BuildingNeeds);
%==============================================
Qreal = BuildingNeeds(2779:6527,13);
n = 1.3;
TinN = 40;
ToutN = 30;
Ta = 20;
Qn = 3000;
dTn = (TinN-ToutN)/(log((TinN-Ta)/(ToutN-Ta)));
%===============================================
var = size(Qreal,1);
for i = 1:var
    if (Qreal(i)==0);
        Qhelp(i) = 0.0;
    else
        Qhelp(i)= Qreal(i);
     end
end
 dT = dTn*(((Qhelp*1000)/Qn).^(1/n));
%==================================
deltaT =  dT';
%=================================
savename = ['A_deltaT_Heating_1.out'];
save(savename,'deltaT','-ascii','-tabs');
end
```

Radiator Surface Temperature

```
function A_SurfaceTemperature_Heating_1
%==========================
deltaTtemperature = load('A_deltaT_Heating_1.out');
Ta = 20;
%=======================
dT = deltaTtemperature(:,1);
var = size(dT,1);
for i = 1:var
    if (dT(i)==0);
        dThelp(i) = 0.0;
    else
        dThelp(i)= dT(i);
     end
    Ts = dThelp+Ta;
end
%==============
Tsurface = Ts' ;
%================
savename = ['A_SurfaceTemperature_Heating_1.out'];
save(savename,'Tsurface','-ascii','-tabs');
end
```

Return water temperature

```
%##################################################################
function [To,niter,finded] = get_outlettemp_radiator(Ti,Ts,Ta)
%##################################################################
T= min(Ts,Ti);
dTs = Ts - Ta;
Res0 = ((Ti-T)/log((Ti-Ta)/(T-Ta))) - dTs;
%========================
N = 100;
tolconv = 1e-6;
epsconv = 1e-9;
%========================
finded = 0;
if (Ts == Ti)
    To = Ti;
    niter = 0;
    finded = 1.0;
    return
end
if ((Ts > Ti)|(Ts < Ta))
    To = -10;
    niter = -1;
    disp(['ERROR : unphysical surface temperature => ' num2str(Ts)]);
    finded = 0.0;
    return;
end
%========================
if (finded == 0)
%========================
    for i = 1 : N
        Resn = ((Ti-T)/log((Ti-Ta)/(T-Ta))) - dTs;
        Relres = abs(Resn/Res0);
        if (Relres < tolconv)
```

```
        To = T;
        niter = i;
        finded = 1;
        return;
      end
      Jacnpart1 = - log((Ti-Ta)/(T-Ta)) + ((Ti-T)/(T-Ta));
      Jacnpart2 = log((Ti-Ta)/(T-Ta))^2.0;
      Jacn = Jacnpart1/Jacnpart2;
      dT   = -Resn/Jacn;
      T    = max(T+dT,Ta+epsconv);
      T    = min(T,Ti);
      Thist(i) = T;
    end
end
%=======================
% Thist'
To = T;
niter = i;
finded = 0;
% disp(['not converget outlet temperature']);
% disp(['Relative residual : ' num2str(Relres)]);
% disp(['Residual value    : ' num2str(Resn)]);
% disp(['Jacobian value    : ' num2str(Jacn)]);
% disp(['Unconverged temp  : ' num2str(T)]);
%=======================
```

Heat losses

```
function A_Heat_Losses_Heating_1_improved
%===================
InletTemperature = load('A_InletTemperature_Heating_1.out');
OutletTemperature = load('A_OutletTemperature_Heating_1.out');
%=========================================
Tin=InletTemperature;
Tout=OutletTemperature;
Tair=20;
Pi= pi;
ht= 14;
dout=[0.008 0.01 0.012 0.015 0.018 0.022];
lin=8.4;
lout=8.85;
%==============================
for i=(1:6)
Psi(i)=Pi*dout(i)*ht;
end
savename = ['A_Psi_Heating_1_improved.out'];
save(savename,'Psi','-ascii','-tabs');
%==============================
for i=(1:6)
   for j=(1:3748);
Qloss_in(j)=Psi(i)*lin*(Tin(j)-Tair);
Qloss_out(j)=Psi(i)*lout*(Tout(j)-Tair);
   end;
Qinl(i)=sum(Qloss_in);
Qoutl(i)=sum(Qloss_out);
end
%========================
 for k=(1:6)
Qtota(k)=Qinl(k)+Qoutl(k);
```

```
 end
%========================
 Qin=(Qinl/1000)';
 Qout=(Qoutl/1000)';
 Qtot=(Qtota/1000)';
%=====================
savename = ['A_Heat_loss_inlet_Heating_1_improved.out'];
save(savename,'Qin','-ascii','-tabs');
%===========================
savename = ['A_Heat_loss_outlet_Heating_1_improved.out'];
save(savename,'Qout','-ascii','-tabs');
%=================================
savename = ['A_Heat_losses_Heating_1_improved.out'];
save(savename,'Qtot','-ascii','-tabs');
end
```

Flow rate

```
function Flow_rate_1
%=========================
BuildingNeeds = load('buildingneeds_1.out');
sizedata = size(BuildingNeeds);
InletTemperature = load('InletTemperature_1.out');
OutletTemperature = load('OutletTemperature_1.out');
%==========================================
Qreal = BuildingNeeds(:,13);
Tin = InletTemperature(:,1);
Tout = OutletTemperature(:,1);
Cw=4174;
var1=size(Qreal,1);
%===========================
for i=(1:var1);
   if (Qreal(i)>0)
      Mw(i)=(Qreal(i)*1000/((Tin(i)-Tout(i))*Cw));
   else
      Mw(i)=0;
   end
end
%====================================
figure(1)
hold off;
plot ( BuildingNeeds(:,1), Mw,'r');
grid on;
hold on;
xlabel ('Time [h]'),
ylabel ('Flow rate[kg/s]');
legend ('Flow rate'),
title ('Test1')
%==========================
MW = Mw';
savename = ['Flow_rate_1.out'];
save(savename,'MW','-ascii','-tabs');
```

Pressure loss

```
function PressureLoss_improved
%======================
Q=3000;
Cp=4174;
Ti=40;
To=30;
Ro1=992.2;
Ro2=995.7;
Dex=[8 10 12 15 18 22];
s=1;
Lambda = [0.027 0.0286 0.0293 0.03 0.033 0.036];
Linlet=8.4;
Loutlet=8.85;
Einlet=[8.800043 8.80014 8.80033 8.80095 8.8022 8.8053];
Eoutlet=2.3;
%========================
Ro=(Ro1+Ro2)/2;
m=Q/(Cp*(Ti-To));
V=m/Ro;
for i=(1:6);
    dh(i)=Dex(i)-2*s;
    w(i)=V/(((dh(i)/1000)^2)*pi/4);
    deltaPin(i)=(Lambda(i)*Linlet/(dh(i)/1000)+Einlet(i))*(Ro1*w(i)^2)/2;
    deltaPout(i)=(Lambda(i)*Loutlet/(dh(i)/1000)+Eoutlet)*(Ro2*w(i)^2)/2;
    deltaPtot(i)=deltaPin(i)+deltaPout(i);
end
D=(deltaPtot/1000)';
W=w';
%==================================
figure(1)
hold off;
plot ( dh, D,'r');
grid on;
hold on;
xlabel ('Pipe diameter [mm]'),
ylabel ('Pressure Loss [kPa]');
legend ('Pressure Loss'),
title ('Test1')
%=================================
savename = ['PressureLoss_improved[kPa].out'];
save(savename,'D','-ascii','-tabs');
%====
Dm=deltaPtot/(993.95*9.81);
DM=Dm';
%========
savename = ['PressureLoss_improved[m].out'];
save(savename,'DM','-ascii','-tabs');
end
```

Ideal pump model

```
function IDEAL_PUMP
%=========================
Pressure_loss=load('PressureLoss_improved[m].out');
x=[0 0.23 2.5];
y=[4 3.5 0.67];
Vn=0.2592;
Pn=Pressure_loss(1,1)/0.8;
%==============================
% pn=-1975*Vn+3.9041 (y=alfa*x+beta)
% pn=0.1375 (approximately)
beta = Pn+1.2975*0.2592;
ceta = beta/1.2975;
x1=[0 ceta];
y1=beta-1.2975*x1;
%===============================
pn=interp1(x,y,Vn);
%============================
plot (x,y);
hold on
plot(Vn,Pn,'m*','markersize',8);
hold on
plot (x1,y1);
hold on
plot(Vn,pn,'m*','markersize',8);
axis ([0 30 0 50]);
%===============================
savename = ['ceta.out'];
save(savename,'ceta','-ascii','-tabs')
%=================================
savename = ['beta.out'];
save(savename,'beta','-ascii','-tabs')
end
```

Pump mechanical power

```
function IDEAL_Pump_Control
%=========================
FlowRate=load('Flow_rate_1.out');
ceta=load('ceta.out');
beta=load('beta.out');
%==============================
x=[0 ceta];
y=[beta 0];
Vn=0.2592;
RO=993.95;
g=9.81;
%========================
pn=interp1(x,y,Vn);
%=====================
plot(Vn,pn,'m*','markersize',8);
hold on
plot (x,y);
axis ([0 30 0 40]);
%=========================
V=FlowRate(:,1);
```

```
var = size(V,1);

%========_CASE_1_============
for i =(1:var);
   P_CASE1(i)=interp1(x,y,V(i));
   Wm_CASE1(i)=(V(i)*P_CASE1(i)*RO*g)/3600;
end
Mechanical_power_CASE_1=sum(Wm_CASE1)/1000;

%========_CASE_2_============
for i=(1:var);
   Wm_CASE2(i)=(V(i)*pn*RO*g)/3600;
end
Mechanical_power_CASE_2=sum(Wm_CASE2)/1000;

%========_CASE_3_==============
for i =(1:var);
   P_CASE3(i)=pn/2 + (pn/2)*(V(i)/Vn);
   Wm_CASE3(i)=(V(i)*P_CASE3(i)*RO*g)/3600;
end
Mechanical_power_CASE_3=sum(Wm_CASE3)/1000;

%================================
Wm1=Wm_CASE1';
Wm2=Wm_CASE2';
Wm3=Wm_CASE3';
%===============================

%=========================
savename = ['IDEAL-Total_Mechanical_power_CASE_1.out'];
save(savename,'Mechanical_power_CASE_1','-ascii','-tabs')
savename = ['IDEAL-Mechanical_power_CASE_1.out'];
save(savename,'Wm1','-ascii','-tabs')

savename = ['IDEAL-Total_Mechanical_power_CASE_2.out'];
save(savename,'Mechanical_power_CASE_2','-ascii','-tabs')
savename = ['IDEAL-Mechanical_power_CASE_2.out'];
save(savename,'Wm2','-ascii','-tabs')

savename = ['IDEAL-Total_Mechanical_power_CASE_3.out'];
save(savename,'Mechanical_power_CASE_3','-ascii','-tabs')
savename = ['IDEAL-Mechanical_power_CASE_3.out'];
save(savename,'Wm3','-ascii','-tabs')

savename = ['IDEAL-pn_1.out'];
save(savename,'pn','-ascii','-tabs');
```