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ANALYSING BOREHOLE ENERGY SYSTEM INFLUENCE ON A HEAT RECOVERY UNIT IN WINTER TIME

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Abstract

This investigation studies how AHU system is influenced by the heat gained from the vertical boreholes besides the certain H-building. Chosen H-building is a part of XAMK campus and located in Mikkeli, Finland. The idea of this thesis is to understand how big impact the direct energy (no heat pump) from the ground has to the liquid coupled heat recovery unit at cold season.

One of the main concern is to evaluate the influence of the energy the boreholes via needle heat exchanger give to the supply air and to compare result when the outdoor air is not preheated (when there is no needle heat exchanger). At this point, having boreholes system as a preheater, the temperature ratio of the HRU might get reduced. However, as the supply air entering the HRU is warmer, it is believed the limitation of the exhaust air should last shorter when compared to the system without any preheater.

Structure of the investigation consist of both theoretical and practical parts. In the first part, the reader is familiarized with the main information the research is related to – about ground source energy, needle heat exchanger, liquid coupled heat recovery unit and brief review about control systems installed in the investigated air handling unit system.

Results were gained after estimations based on the collected data. In order to avoid getting inaccurate results some parameters were accepted as constant values. Results were presented in tables and graphic forms. In the end, it was concluded that having borehole energy system as a preheater for the outdoor air, can lead to some savings as this type of energy gives free preheating and the need for using district heating is reduced.

Keywords

Energy, AHU, borehole, needle heat exchanger, liquid-coupled heat recovery unit

CONTENTS

1 INTRODUCTION 1

2 AIMS AND METHODS 2

3 THEORY PART 2

3.1 Ground source energy and ways for utilisation in the HVAC 3

3.2 Needle heat exchanger unit 8

3.3 Liquid-coupled heat recovery unit 10

3.4 Limiting the exhaust air 13

3.5 Control systems in HVAC 16

4 PRACTICAL PART 24

4.1 Air handling unit system in H-building 24

4.2 Calculations 30

4.3 Results 38

4.3.1 Analyze of the fluid inside the HRU 42

4.3.2 Determining the COP for the needle HE 44

4.3.3 Sensibility test for the HRU 47

4.3.4 Estimated savings 48

4.3.5 Annual efficiency of the AHU system 49

5 DISCUSSION 54

REFERENCES 56

1 INTRODUCTION

Today, energy is one of the main targets to use in an effective way. As it is known, companies are funding and engineers are intensely working in the research and development fields to make progress in energy saving as much as possible. Simultaneously, scientists are looking for new ways to adopt free, renewable energy. Between the main green energy sources such as solar, hydro, wind and geo, the latter will be discussed in this research as a part of the energy efficiency of the AHU work.

Ground source energy is favourable by its present being in everywhere as it is obtained from the surface of the earth. In addition, just a few meters below surface line there is constant positive temperature what leads into profitable usage of free energy during whole year. It means, for both cold and warm seasons ground source energy can serve respectively for heating or cooling demand of the building.

During this thesis research, there will be examined an air handling unit with supplemented geo-exchange system. This investigation studies how AHU system is influenced by the heat gained from the vertical boreholes besides the certain H-building. In other words, what kind of the impact it is possible to get for the HRU operation, when instead of directly coming cold outside weather to the AHU system, the one is preheated before by using the heat from the ground via boreholes system.

Thesis is based on both theoretical and practical parts. The first part focuses on the systems that were used in the investigation – on the ground source energy, on the needle heat exchanger, on the liquid-coupled heat recovery unit and on the control systems in HVAC, mostly. The second part tells about the investigation itself carried on during the research, concerning the analysing object, collected data and gained results.

2 AIMS AND METHODS

The aim of this thesis is to estimate how energy efficient air handling unit with supplemented system of three boreholes can be during the cold season. Indeed, how borehole energy affect the operation of the heat recovery unit and the heating coil at extremely cold (up to -29 ˚C) outdoor temperature. Following this aim it can be calculated how much energy can be saved in the heating coil as borehole system is based on free ground source energy.

In order to achieve given aims there must be involved adequate methods. The chosen object - the AHU system of the H-building in XAMK, Mikkeli, Finland – will be investigated by using three methods. To begin with, measurements, such as collected temperatures in the different places of the air handling unit, air flows, relative humidity and ect. plays an important role in determining how energy efficient the AHU system is.

Secondly, calculations of the heating power in a needle heat exchanger, heat recovery unit and heating coil of the AHU system in the H-building must be taken into account, also. By following mentioned calculations, it is possible to get practical and precise numbers of the air handling unit work for the heating purpose for supply air.

Lastly, comparison of the results. The effectiveness of the system can be assessed by comparing the research information of the borehole energy system with other type of energy source (electricity for instance) which could stand as a replacement for the one.

3 THEORY PART

This chapter covers the main theoretical information related to the topic of the thesis - Analysing Borehole Energy System Influence on A Heat Recovery Unit in Winter Time.

3.1 Ground source energy and ways for utilisation in the HVAC

Energy, probably, is one of the most powerful things that lets civilization live and thrive on this planet. This is why it is very important to use energy sources in a smart, eco-friendly way. This idea is a key for using renewable energy instead of the fossil fuels more and more often, nowadays. According to the Annual national accounts of Finland /1/, space heating is one of the sectors where energy is being used the most. It is not important what kind of building it is – a residential one family house, a hotel, a hospital, a museum or a police department – usually, all of them are equipped with building services networks, which require a huge amount of energy to ensure the comfort conditions for a human inside. This chapter provides an overview presented in the literature on how ground source energy could be used for HVAC purposes of the building.

To begin with, there are lots of articles and other kind of materials about ground source energy. The ground heat will be considered here not only as geothermal energy, but as a combination of deep geothermal energy and solar energy stored in the near-surface layers of the earth, altogether. The idea of this literature review is to focus on the heat transferred directly from the ground soil or ground water to a particular medium. It is important to emphasize that all following cases explains about the heat transfer between mediums and not about the heat extracted from the ground by using a heat pump.

The “Geothermal Energy In Finland” by Ilmo T. Kukkonen /2/ says: “Temperatures in the soil at 1 m depth vary annually between +2 ºC to +12 ºC in southern Finland, and -2 to +12 ºC in northern Finland. Temperature in the uppermost (< 200 m) bedrock below the penetration depth of annual variations is +2 to +8 ºC.” According to the quote above, ground ability to remain positive temperature during whole calendar year is the main reason why it can be utilized in HVAC systems either in the winter or in the summer time.

Following examples give some overviews about the cases of the HVAC systems in Germany, Denmark, Portugal, Malaysia, Switzerland, Sweden and the same

H-building of the XAMK campus in Mikkeli, Finland. Usually, geothermal cooling or heating system consist of deep boreholes or horizontal pipelines, which give us the heat transfer between the media inside the pipe and soil/ground water, a pump/fan for circulation of the media and a heat exchange unit (not necessarily) as Figure 1 shows.

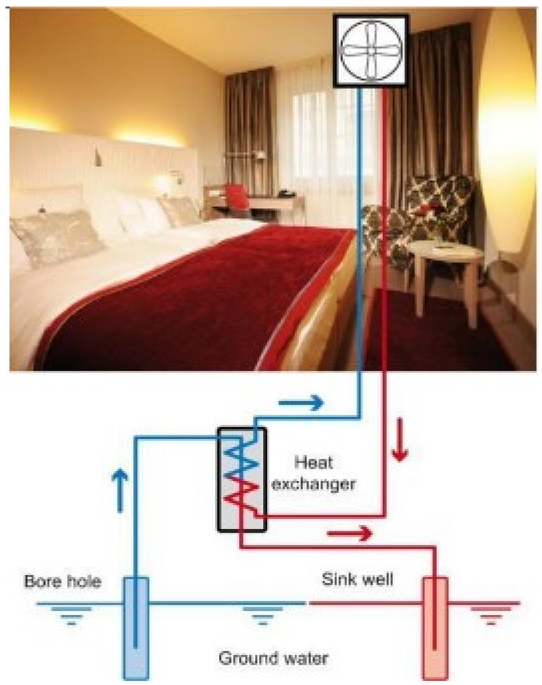

Figure 1 Schematic presentation of a groundwater cooling system in Hotel Victoria /3/

There are several means of how ground source heat can be applied to the HVAC system. For instance, extracting the cool groundwater during summer is sufficient to provide even 100 % of cooling demand in Hotel Victoria in Freiburg, Germany, and in the Crowne Plaza Copenhagen Towers hotel in Denmark. In the end of the loop, warmed water is being returned through a sink well what results in warming the groundwater during the summer. In time of the cold period, this slightly warmer water may then be pumped up to provide heat to the HVAC system via a heat pump. According to this, only for cooling purposes the direct coolness of the ground source is used in this case. To be more precise, according to the “Efficient Applications of Heat Pumps and Geothermal Heating/Cooling”, released by European Commission, the system installed in the Crowne Plaza Copenhagen

Towers hotel is able to return 8 kWh of cooling per 1 kWh of electricity used to run the system in cooling mode. /4/

The same source states that using outdoor or recirculated indoor air as the media, 95 % savings on the energy for cooling can be achieved. This number is based on the example in the Alma Verde holiday villas located in Portugal. Cooling technology inside this building works as 15 - 50 cm diameter and about 10 meters length tubes are installed in the depth of 2 meters below the ground level. Tubes are used for air to discharge the heat to the shallow, which is surrounding the tubes. At this point condensation might appear on the internal walls of the tubes. Unfortunately, there is no information provided about the way how the condensation is treated. Ground cooling tubes are an alternative technique for summer cooling that may be suitable under the circumstances as sufficient outdoor space and the excavable earth. /4/

Furthermore, about the ground soil serving as a heat sink tells a case held in Malaysia, as well /5/. During research it was investigated what depth (1, 2, 3, 4 or 5 meters) is the most efficient way to install pipes for getting the best results in heat transfer between the circulated outdoor air inside the tubes, which later would be distributed to the ventilation system of the building, and the soil. As Malaysia is a country of tropical area, the experimental in finding the most reasonable depth was held twice – in the period of the August-December of the 2008, which represents wet and cooler climate, and in the May of 2009, when weather is hot and dry. It was measured, that the best depth for free cooling in horizontal way installed 30 meters long pipes, is 1 meter. As a result, outdoor air temperature was reduced by 6,4 ˚C in wet season and by 6,9 ˚C during dry season. /5/

Equally important is the example of the HVAC operating system in the Schwerzenbacherhof Office and Industrial Building in Schwerzenbach, Switzerland /4/. With the similar advantages - same system for cooling and heating, simple integration in ventilation system, high peak-load performance, low operating and maintenance costs - to the systems discussed above, this one is called ground coupled system. Pipes of the 23 meter length and 23 cm diameter are buried under the foundation of the building in, approximately, 6 meters below the groundwater line, and serve as a passive cooling or heating. “After passing through the piping system, the air is collected in a further large plenum duct. From there it is supplied to the ventilation plant.”, explains an author. This system is most efficient in terms when air temperature exceeds 22 ˚C during the summer and drops lower 7 ˚C in winter. When looking to the numbers, 23 MJ per square meter was measured for consumption of the electricity for ventilation of this building while 90 MJ per square meter is needed for the comparable in size and type building with a usual ventilation system. In addition, the performance of the system gives 62 kW in heating as the outlet temperature of the pipes system occurs in 6 ˚C at the outside temperature of -11 ˚C. It is a useful way for applying the ground heat (coolness), especially, when such system is claimed to serve as long as the building itself. /4/

One more on the economical and ecological perspective successful example includes The SAS Frösundavik Office Building which is situated in Stockholm, Sweden. /4/. The ground source heat for the HVAC system of this building is obtained from the aquifer, in an almost uniform way as it is given in the example of Germany and Denmark. In this free cooling or free (pre)heating type, the most significant role is played by the idea of an energy storage. In detail, in the area of 100 – 200 meters width between the ridges of the aquifer and around 15 -30 meters depth, there are five drilled wells installed. Two wells are used for warm water and the rest for cold water with a prerequisite of having a distance to each other from 150 to 300 meters. This condition is required in order to keep system in most efficient way while avoiding slightly warmer and slightly cooler water to mix. The working principle of this ground water based HVAC system is that during the summer, the cold well water is pumped up to the heat exchanger filled up with the glycol, and using this substance as a medium, the coolness is transferred to the air cooling system. In return, the heat from the offices rooms is conveyed back to the heat exchanger and ends up in discharging in the warm well. Respectively to this, the system in winter is working similar as all heat transfer occurs in vise versa. It must be mentioned, that during winter, the heat pump is used to ensure the building with comfort air temperature inside and hot domestic water at 55 ˚C. Having such system equipped to heating/cooling plant of the building, the energy is saved by 65 % in comparison to conventional, electricity power driven HVAC system. According to the source, “Based on measurements the annual system efficiency value should be between 4,5 and 5,0 for a normal year.” In other words, when taking into account a sum of the heating and cooling demand, and the consumption of the electricity, the Seasonal Energy Efficiency Ratio (SEER) is equal to 4,5 or even 5. /4/

Last but not least includes the investigation held on the summer time for the AHU of the H-building in Mikkeli, Finland /6/. The report by Anastasiia Bykova /4/ gives an understanding about the boreholes energy influence on the supply air at hot days. In the research it is given that cooliness from the ground is taken by the mean of needle heat exchanger. According to the numbers, when outdoor air temperature extremely exceeds the supply air temperature, the needle heat exchanger provides the AHU system with up to 80 % of all required coolness. As it is presented in the source, the average COP for July reaches 22 and for the hottest days in the summer – 30. A. Bykova‘s example proves the great success of such installed system for the summer time. This thesis will give the analyze for this borehole energy system adaptation to work during the cold period. Now needle heat exchanger would serve not as a precooler/cooler but as a preheater for incoming supply air. /6/

On the whole, while utilizing geothermal (a combination of deep geothermal energy and solar energy stored in the near-surface layers of the earth) heat for HVAC systems, the benefit on financial and nature-friendly side is obvious as the objects in the Germany, Denmark, Malaysia, Switzerland and Sweden show. In regards with cases investigated above, is it possible to save up to eight times more finance and to reduce the general pollution as ground source energy is free with acidifying gases, greenhouse CO_2 gases, waste from the coal burning and many more. Those technologies are already in successful use in several commercial, school and residential buildings. The potential for widespread of the technologies is greatest for them being ‘green’, for saving money and for being long lasting. In addition, while minimizing the needs of energy, it is possible to maximize the duration of the planet with no climate changes.

3.2 Needle heat exchanger unit

Needle heat exchanger unit is distinguished by its flexibility which leads to a wide range of applications in already existing or new buildings, equally. Such heat exchangers give a solution in air conditioning systems from hospitals and schools to industrial plants and office buildings. According to the manufacturer Retermia Oy /7/, these needle heat exchanger units are able to recover about 50-70 % of the annual heating energy demand for supply air. The payback time is calculated according to the local energy prices, operation time, type of the system and the geographical location on the building. When taking all these aspects into account, the payback period of this investment varies from 2 to 6 years.

Needle heat exchanger has a number of advantages when compared to the conventional heat exchangers. Because of the unique design of this unit, it serves not only as preheater but as pre-filter, also. During the heavy snowfall in the winter time, usually snow enters the intake air side damper and melts on the surface of the filters. At this time, all the sediments on the filter get wet which leads to a favourable medium for microbes and mould to thrive. Many a time, this problem is the main cause for sick building syndrome to occur.

Furthermore, melted snow sometimes freezes again on the filter (Figure 2) and causes restrictions of the supply air flow. As the air passage becomes narrower, the pressure drop in the filter increases. Because of this reason not only pressure inside the building is being unbalanced but the energy consumption for fan operation increases, also. This means that filters must be replaced at frequent intervals, which causes a significant increase in maintenance cost.

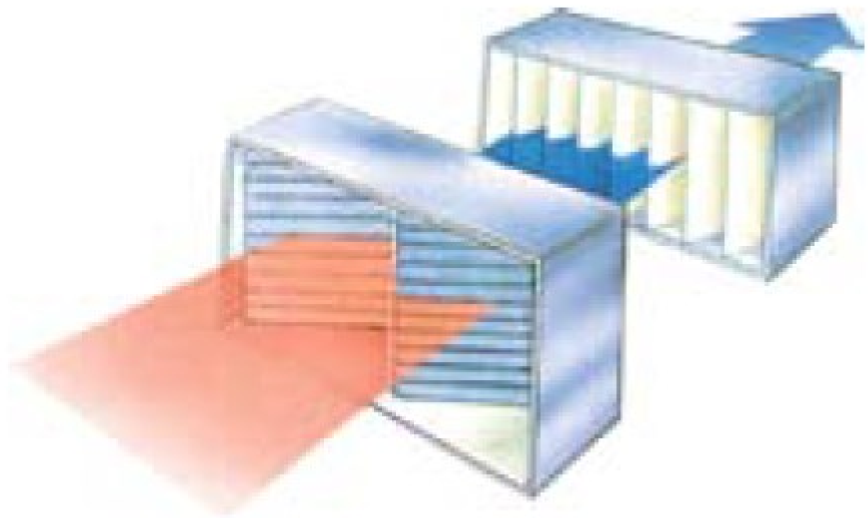

Figure 2 Supply air filtration through the needle heat exchanger and a filter /7/

Idea is, that the needle heat exchanger serves as an air intake louvre. While outdoor air is being sucked in to the supply air side, the majority of all impurities are filtered and set aside on the needle surfaces. In following, the main filters installed inside the AHU remain clean and dry what helps to keep their lifetime longer and supply air at high quality as long as possible.

In addition to keeping operating cost down and supply air quality improved, this unit is helpful in space saving, as well. One of the benefits needle heat exchangers characterizes in, is that they can be installed in already existing buildings. As the available space in machinery room is usually limited, installing the conventional heat exchangers is impossible while this unit can be placed straight on the roof. As energy transfer proceeds between the liquid, running inside the pipes, and the air, the distance of heating and cooling coils might be adjustable. Similarly to the liquid-coupled heat exchangers.

Because of its unusual design, this unit can be installed in various conditions the building operates. In hospitals, where AHU is usually setted up to work all the time, this unit will give a considerable cost savings. Apart the preheating and prefiltering functions, it also does not let the supply and extract air to mix, which is one of the main restrictions for AHU in hospitals. Another type of utilization includes efficient operating with exhaust air from the kitchen /8/. Even though extract air from such places is greasy and odoured, the high level of humidity and particularly high temperature gives a valuable heat capacity which might be utilized in the mean of heat transfer (Figure 3). Conventional units are not able to obtain the potential heat from the extract air of the kitchen but needle heat exchanger is. There is only one potential drawback at this point – such units require to be washed from the grease and other impurities a few times per year.

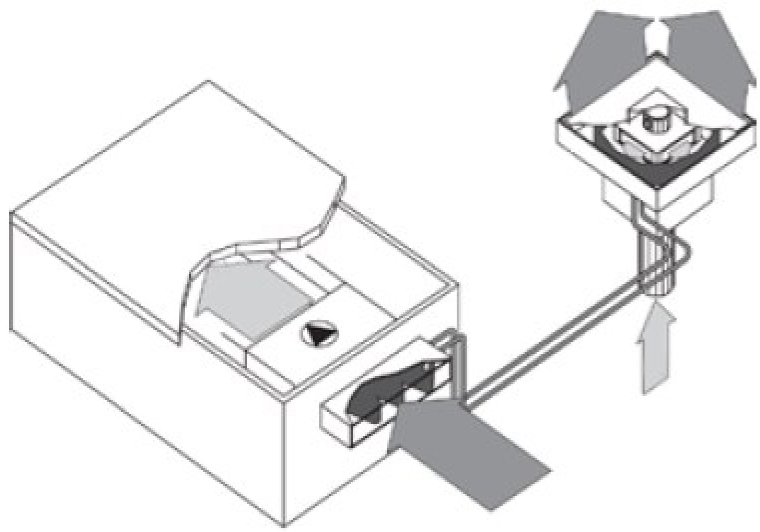

Figure 3 Schematic principle of the needle heat exchanger utilization /8/

3.3 Liquid-coupled heat recovery unit

A liquid-coupled heat recovery unit, illustrated in Figure 4, contains three main components – two heat exchangers and a pipeline system. The idea is, that the solution of water and nonfreezing substance is being pumped through heating (supply air side) and cooling (exhaust air side) coils. This medium takes heat from the extract air and transfers it to the supply air. In some cases, in order to prevent the filter, which is installed after HRU, in the extract air side from getting wet, the heat exchanger might be installed with droplet separator. It collects condensate, which may happen when indoor air is at high relative humidity and high temperature level. In addition to droplet separator, the stainless steel drip tray must be installed without any exceptions. Usually, coils are made of copper pipes and fins which are, normally, 2 mm long. /10/

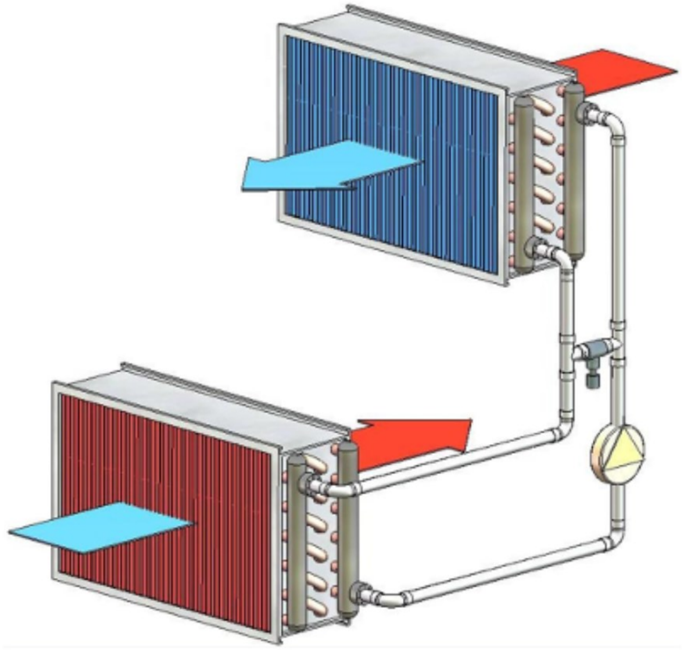

Figure 4 Liquid coupled heat recovery unit /9/

Such heat recovery units are suitable for a huge range of air flow. The capacity HRU can provide, depends on the size of the coils. In other words, when increasing the number of tube rows in the coil, the capacity increases, also (as the heat transfer surface increases). As a consequence, the temperature efficiency has a linear relation to the number of tube rows. The higher number of tube rows means a higher pressure losses in the heat exchanger coil. In general, it is possible to expect "50 % with 6 tube rows, 55 % with 8 and 60 % with 10 tube rows" /10./ Coils shall be connected so that flow in the pipes, which shall be insulated, would be in the counter-flow arrangement.

This type HRU differs from others (rotary, plate heat recovery units) in a number of valuable advantages. Not only do the supply and extract air not give any leakage to each other (which is especially suitable for hospitals) but there is no need for having supply and extract air duct in the same location, too. Moreover, such units can be installed in existing AHU as the installing is widely flexible.

The heat capacity that fluid is conveying might be controlled in two ways - by-pass shunt pipe and flow regulation. The by-pass option means that a part of the liquid enters the return side flow without reaching the heating coil (supply air side). The control of by-pass is based on the three-way valve position, which is adjustable in accordance with the amount of the required capacity. The circulation pump, located on the supply liquid stream, gives a constant flow of solution through the exhaust air coil as the three-way valve mixes a portion of the supply side fluid with a portion of the colder return side liquid, in order to achieve a correct heating output capacity, as a Figure 5 represents. Flow regulation principle is based on combining both by-pass option and by controlling the pump speed with frequency inverter. In all these cases, the actuators should be connected to the AHU controller in order to provide the proper amount of heat capacity and prevent the frost buildup on the cooling coil side of the HRU. /10/

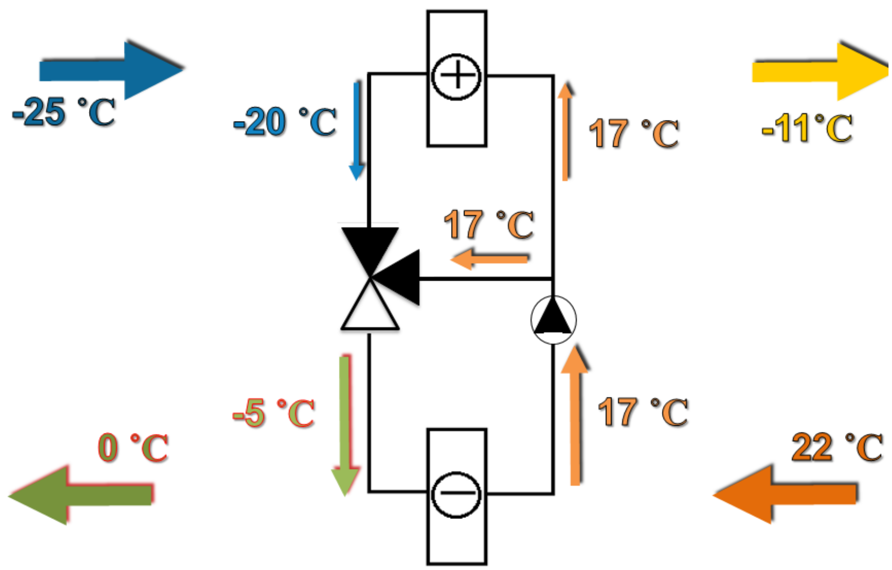

Figure 5 A scheme representing the meaning
of the mixing valve in the HRU /11/

The heat conveying fluid in the pipes must have good properties in below zero conditions. It implies that the liquid must be a solution of water and one more component that would conclude in no freezing at negative temperature. Unfortunately, because of this supplementary substance, the efficiency of heat transfer decreases. Mostly, as for an anti-freeze additive in liquid-coupled heat recovery units the ethylene glycol is used. Table 1 shows the specific heat capacity of some of the substances.

Table 1 Representative Specific Heat Capacities /12/

Substance	Specific Heat Capacity ($J\ g^{-1}\ °C^{-1}$)	Substance	Specific Heat Capacity ($J\ g^{-1}\ °C^{-1}$)
Elements		***Compounds***	
Aluminum, Al	0.902	Ammonia, $NH_3(\ell)$	4.70
Carbon (graphite), C	0.720	Water, liquid, $H_2O(\ell)$	4.184
Iron, Fe	0.451	Water, solid, $H_2O(s)$	2.06
Copper, Cu	0.385	Ethanol, $C_2H_5OH(\ell)$	2.46
Gold, Au	0.128	Ethylene glycol (antifreeze) $HOCH_2CH_2OH(\ell)$	2.42
Common solids		Propylene glycol (antifreeze) $HOCH_2CHOHCH_3(\ell)$	2.5
Wood	1.76		
Concrete	0.88	Carbon tetrachloride, $CCl_4(\ell)$	0.861
Glass	0.84	A chlorofluorocarbon, $CCl_2F_2(\ell)$	0.598
Granite	0.79		

According to table above, the specific heat capacity of a pure ethylene glycol is equal to 2,42 kJ/kg·K. As specific heat capacity of the pure ethylene glycol is more that 1,7 times lower than the water is, correspondingly 2,42 kJ/kg·K < 4,184 kJ/kg·K, the idea of having stronger solutions means that the properties of heat transfer decrease. It is measured that every 10 % of ethylene glycol mixed into the water, reduces the efficiency by approximately 1 %. The same source says that a glycol concentration of 15 % (freezing point is at -5,5 ˚C /7/) is theoretically enough, but in order to have a certain margin, a 30 % (freezing point is at -15,6 ˚C /7/) mixture of glycol is recommended. As these values serves for the guideline purpose only, the actual required concentration shall be determined according to the weather temperature the unit is going to operate in. /10/

3.4 Limiting the exhaust air

Usually, when air handling units are equipped with the heat recovery unit the problem of frostiness in the heat exchanger of the exhaust air side may occur. Having the ambient temperature below 0 ˚C can cause the ineffective working of HRU as the frost and ice layer covers the surfaces of the coils and plates. This phenomenon leads to blocking the access in the heat exchanger for the air flow and causes the pressure drop increased as the frost makes the passage in the coil more narrower. The reason for this to happen is because the extract air has a certain amount of water vapour that condensates and freezes.

Habitants of the building emit water vapour while breathing (it was estimated about 60 g per hour on average), cooking, taking shower and etc. Thus, extract air becomes more *“wet”* and during the process in the heat recovery unit, both sensible and latent heat play role in heat transfer. The heat amount which was gained from the cooling in HRU later on is used for heating. When the extract air enters the heat exchanger of the HRU, the heat is being taken from both air and water vapour. If during this process the temperature of the dew point of water vapour is reached, water vapour condensate and water is being taken by the drainage pipes. The problem which is going to be discussed in this research is at how low ambient temperature that condensate appears in the state of frost.

The same authors also investigated spatial and temporal variations in heat flux, frost surface temperature, and stressed that the heat transfer coefficient is strongly dependent on the roughness of the frost surface (Figure 6) and the flow conditions. According to this material, heat transfer increases when the pitch of the fins are decreased but the row number of tube increased.

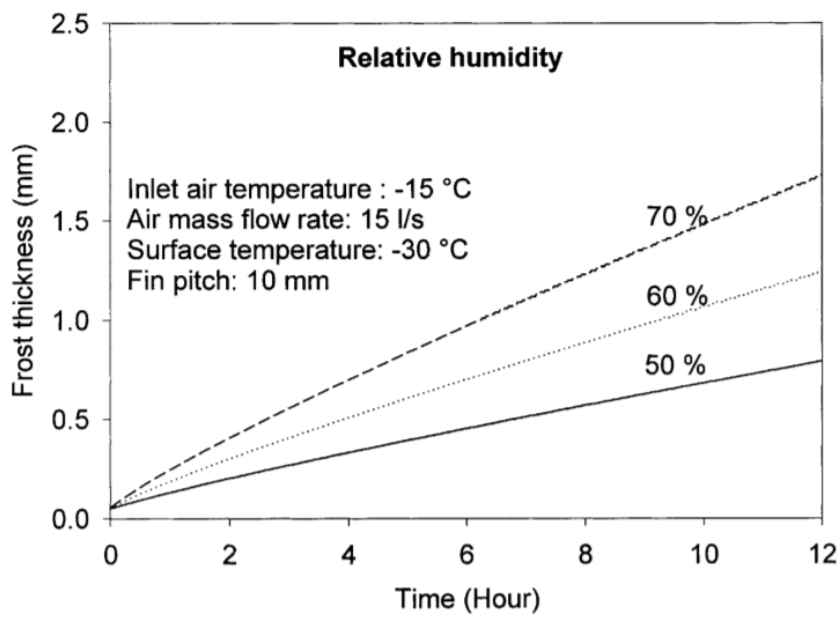

Figure 6 Graph showing relation between frost thickness and relative humidity /13/

Frost formation on the heat exchangers (visible in Figure 7) and its effects on thermal performance is a major issue for thermal equipment operating at low ambient temperatures and has been investigated extensively. It was concluded that at a constant air temperature, the probability of frost formation increased with increasing humidity ratio, and at constant air humidity, frost formation was greater at high temperature /13/. In addition, with the increase in frost accumulation, the total airside heat transfer and air flow rate decreased with increased airflow resistance.

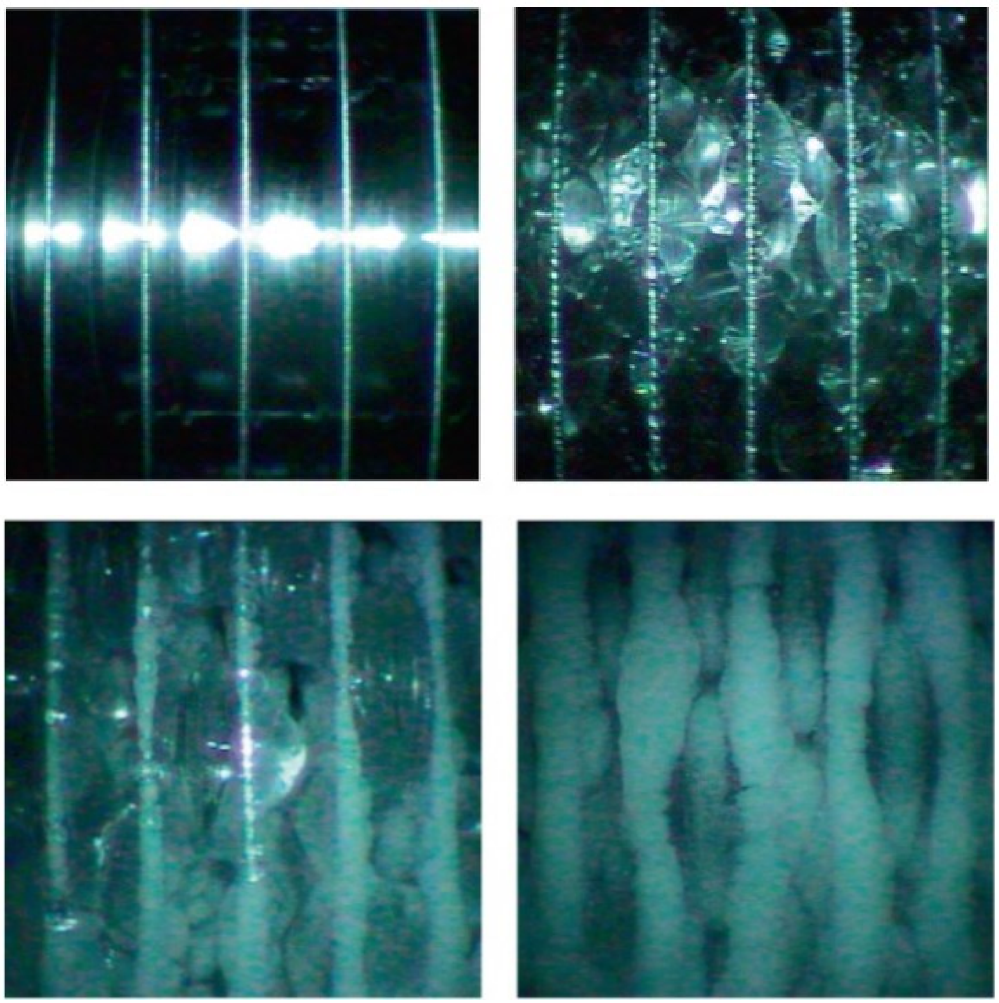

Figure 7 Stages of frostiness inside the heat exchanger /13/

The manufactures of HRU take the risk of the frost in their considerations when designing their products and present the limit values for exhaust air in specifications sheet in order to avoid frost formation. The limitation of the exhaust air temperature depends on moisture content of exhaust air, on the type of heat recovery unit and the type of the building and are provided by the Finland National Building Code D5 regulations /14/:

- Plate heat exchangers in residential buildings +5 ˚C
- Thermal wheel in residential buildings 0 ˚C
- Plate heat exchanger in other buildings 0 ˚C
- Thermal wheel exchanger in other buildings -5 ˚C
- Liquid coupled heat recovery unit 0 ˚C

According to the values above it is easy to notice that in those building where tenants activities are taken into account, the exhaust air minimum values are higher as a prevention of the frost. The reason why plate heat exchangers and thermal wheels have different temperature limitation is the different operating principle of each. In brief, thermal wheel exchanger characterizes in mixing the supply and extract air flows. Even though it happens at a very low percentage it is enough to dilute the exhaust air with supply air which leads to it becoming warmer. In a liquid coupled heat recovery unit exhaust air temperature is limited to zero, mostly. In addition, there must be limited not only exhaust air but the refrigerant temperature, also. When heat exchangers are longer in length, the limited regriferent temperature can be reduced to as low as possible, leaving only 1 ˚C as a delta t ˚C between two mediums (air and refrigerant). Unfortunately, it is not convenient in practice to have large units as they take some useful space. In that case mostly smaller heat exchangers are installed in the liquid coupled heat recovery unit but at with higher delta t between air and refrigerant what leads in reduced effectiveness of HRU.

3.5 Control systems in HVAC

All topics discussed above are summarised here as it shows how all parameters are related. The automatic control system in AHU helps to ensure all parameters meet the required values for system to operate most effectively. By adjusting the set points for temperature, pressure, humidity, contaminants level and etc., it is possible to ensure the required indoor climate with the parameter fluctuation as slight as possible.

Usually, there are two types of control systems – open and closed loops. The later one is designed in the air conditioning system of H-building. Closed loop consist of a sensor, a controller, controlled variable and controlled device. /15/

The controlled variable is measured by the sensor (Figure 8), which later transmit a signal, proportional to the measured value in pressure, voltage or current value mean. The purpose of the controller is to compare the measured value with the given set point and give the signal to the controlled device for re-adjusting action. Such devices as a valve, a damper, a heating element or a variable-speed drive are referred as controlled devices. /15/

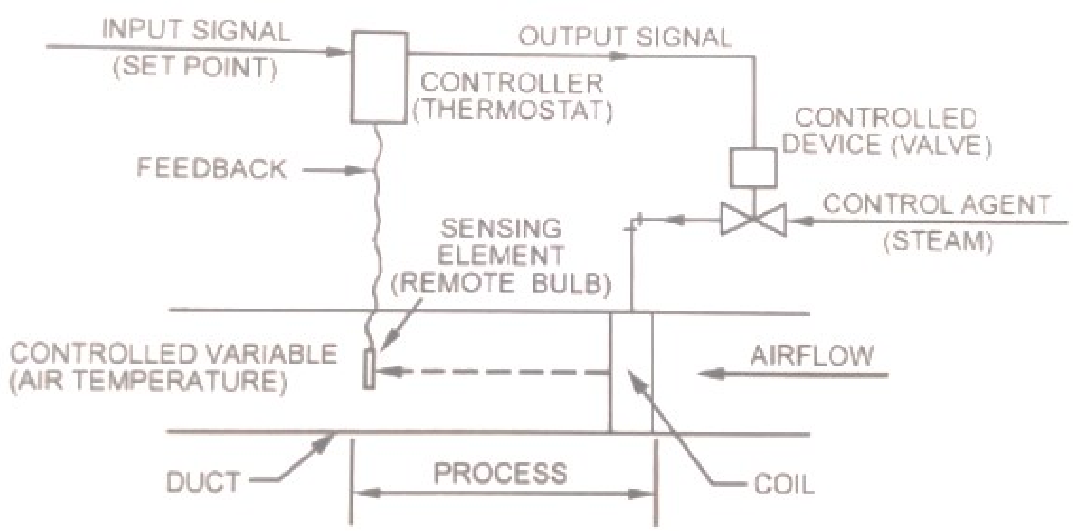

Figure 8 The example of the control system /15/

The setpoint is a preferable value for the controlled variable – temperature, humidity, pressure or other dimension – to be at. This value is achieved when control agent is being regulated by the controlled device. For instance, the air flow is controlled by the damper, or the liquid, by the valve. A fan, coil and etc. are placed, where the measured output of the control agent give a signal to have changes in the controlled variable. For example, the flow after the valve, depends on the measured temperature before the valve. /15/

The main idea of control system is to ensure the controlled devices adjust the target flow for certain conditions. In other words, control device is one of the control loop components to alter the controlled variable properly. The most commonly used controlled devices, include the valves (for liquid based media) and dampers (for gas based media). The position of the stem of these components is regulated by one more component - an actuator. The actuator, as a response to the received signal from the controller, uses the electricity, compressed air, hydraulic fluid or other type of the mean of power and make the changes in the position of how open/closed damper or valve is. /15/

Different types of valves are designed for particular use. In range of single-seated valve, double-seated valve, butterfly valve, three-way diverting valve and three-way mixing valve (Figure 9), the last one is used in this investigated air handling unit system. A three-way mixing valve is not only uniq by its two inlet connections and one outlet connection but a double-faced disk operating between two seats, also.

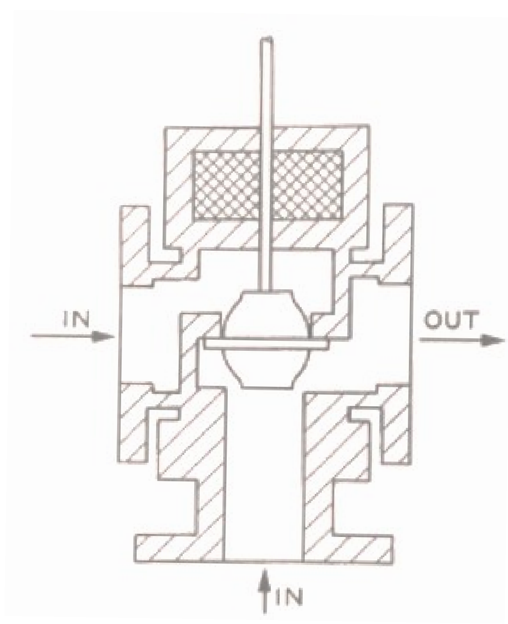

Figure 9 3-way mixing valve /15/

Figure 10 illustrates dampers. It is a component, which is used in air conditioning and ventilation systems for controlling the air flow.

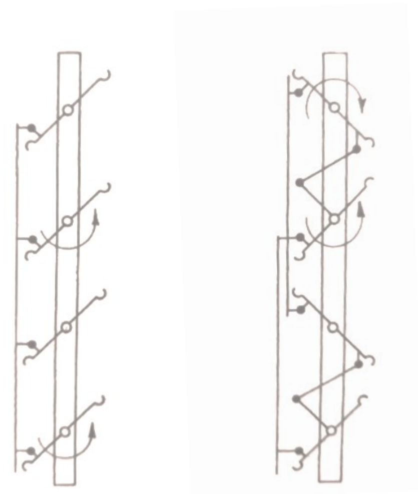

Figure 10 Typical multi-blade dampers. On the left side parallel arrangement and on the right side opposed arrangement /15/

The main purpose for the control unit in air handling unit is to control the properties of the air flow. The main functions include:

- Temperature control
- Air flow/pressure control

Besides the functions listed above, control system has some extra functions, too:

- Anti-frosting protections
- Outdoor compensation
- Night-time heating
- Night-time cooling
- CO_2 compensation

The most relevant, temperature control, function might be carried out in three ways: supply air control, extract air control and room control. Supply air method is used in the H-building supply air temperature controlling. Temperature sensor and the heating coil are wired to the controller. The controller, after receiving the reading for the supply air temperature, sends the instruction to the heating coil to increase or decrease the heating capacity for supply air. Next, the extract air control system is more flexible than the supply air as the controller is also connected to the extract air side temperature. In other words, the supply air temperature is now regulated in accordance with the extract air temperature, which maintains the inside air at desired more precise temperature. Unfortunately, this method gives quite an equal temperature condition for all rooms being maintained. Lastly, room control is the most accurate way as the room temperature here is directly connected to the controller. Therefore this option is mainly applied to maintain the conditions of a single space, only. /15/

Overall, there are two types of air flow treatment on the supply air side – constant air flow (CAV) and variable air flow (VAV). The idea is, the constant air flow is obtained by regulating the fan to provide a uniform air flow, while in variable air flow system, the fan aim is to operate to provide a particular pressure in the duct. /15/

As a rule, the intersection point of the fan and system curve~~s~~ (shown in Figure 11) defines the values of the air flow and the pressure drop in the fan. In the need of flow (pressure) changes, either fan or system curve must be adapted. Hence the system curve depends on the pressure drop in the system and the fan curve shows relation of the design of the impellers and the speed a fan is operating, only three variables might be changed – pressure drop in the system, the speed of the impeller or the design of the impeller.

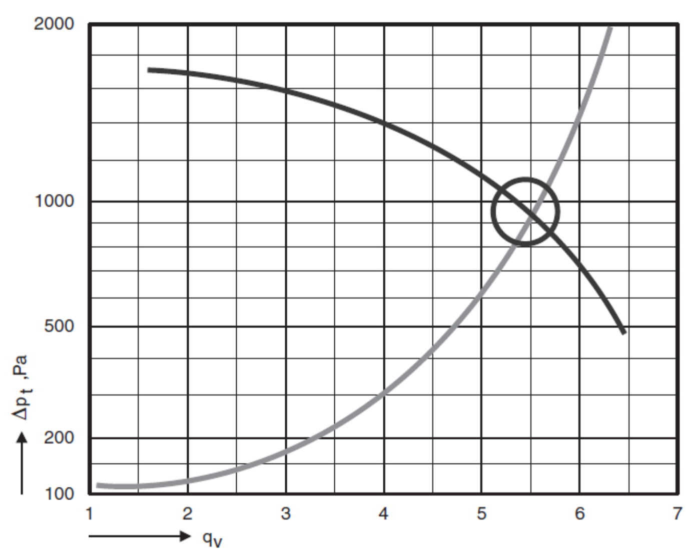

Figure 11 Intersection between fan and system curve /10/

Most conventional means include:

- Adjusting the air flow by utilizing an air damper (the changes in system curve)
- Inlet guide vanes that changes the fan characteristic (the changes in fan curve)
- Controlling the impeller blade angle (the changes in fan curve)
- Frequency inverter (changes in fan curve)

The latter one is used in the H-building AHU system (Figure 12). The flow or the pressure is controlled according to the fan speed which is proportional to the electrical frequency. Frequency inverter increases or decreases the frequency of the voltage before supplied to the fan motor, which, respectively, makes the fan speed higher or lower.

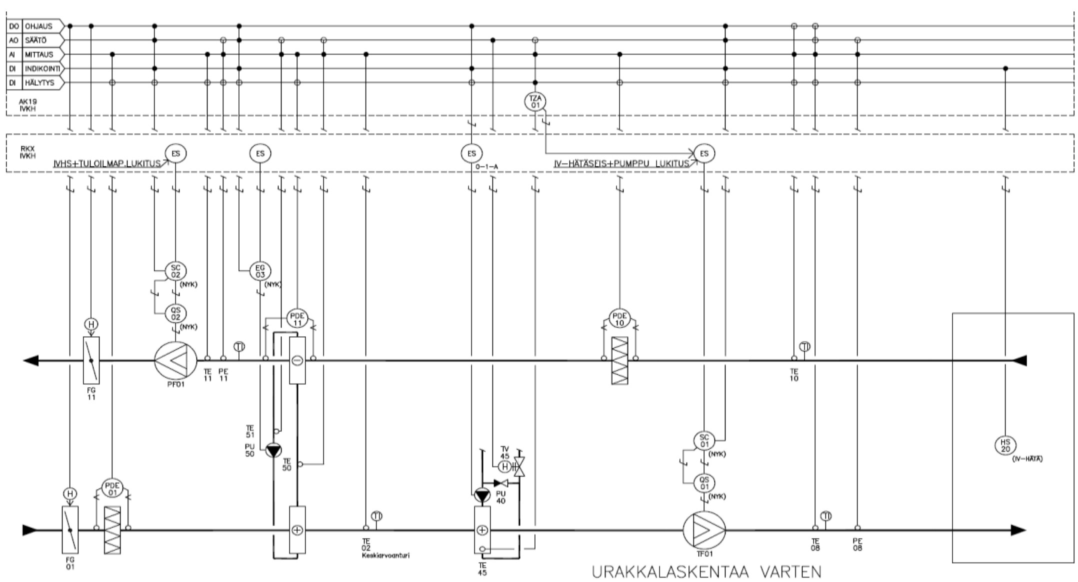

Figure 12 The scheme of the control system of the AHU system in the H-building /16/

TF01 fan air flow is proportional to its fan speed. The relation is gained using two days example of the H-building AHU system. The real case comparison might be seen from the Figure 13 below:

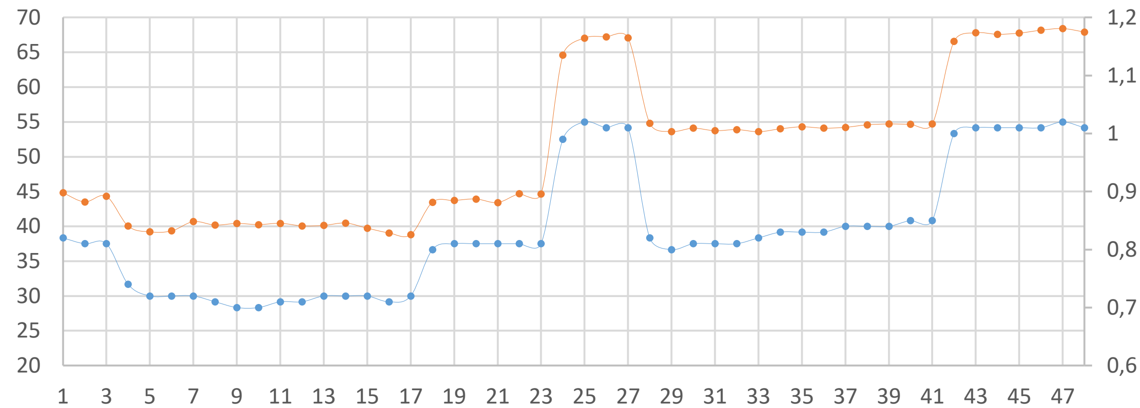

Figure 13 Relation of fan speed and
the time on the day /11/

In VAV air flow system, the sensors of the pressure control is installed downstream of the fan in the duct, while sensors of the CAV for the flow control are located just after the fan nozzle. Both cases are shown in the illustration (Figure 14) below:

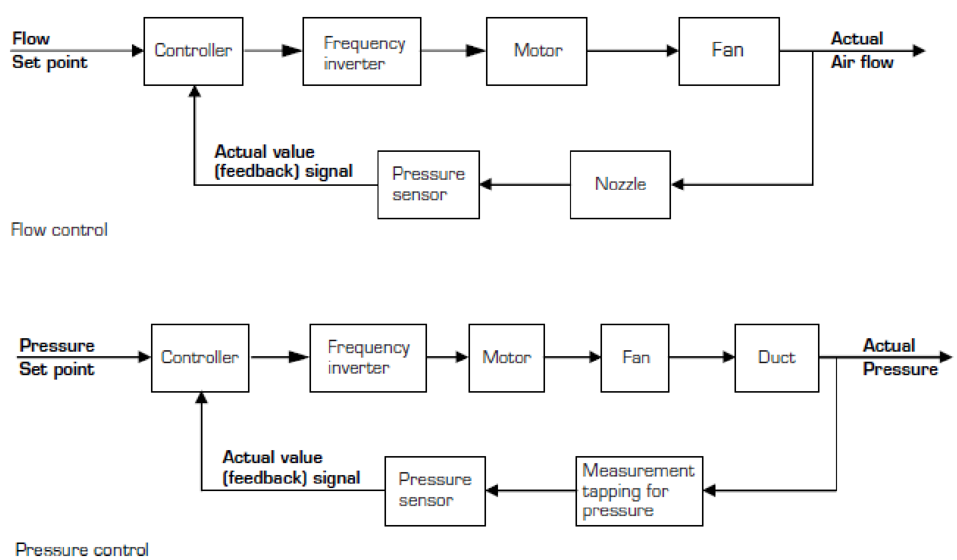

Figure 14 VAV and CAV
working principle /10/

The sequence control system, which is especially relevant to the topic of this thesis, is used for regulating the supply air temperature to an appropriate level. Heating or cooling is required as the outdoor ambient temperature is usually never the same as the setpoint temperature. As, nowadays, the regulations for

AHU requires to have heat recovery unit equipped, this control system plays the main role for utilizing as much recovered energy as the needed (though not exceeding the theoretical potential). Figure 15 describes the idea of the working principle in the sequence controller.

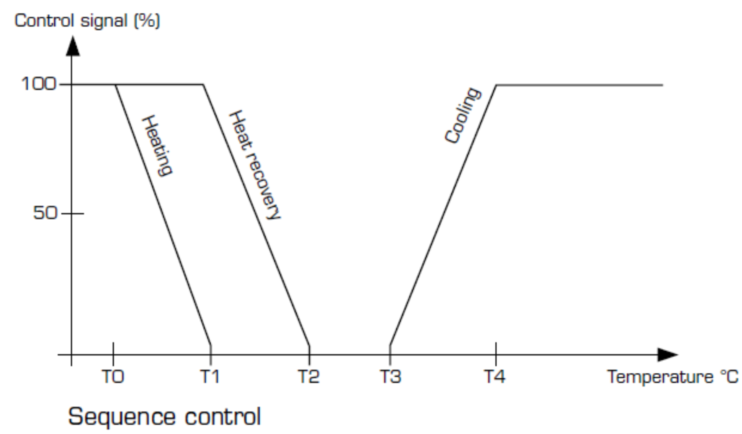

Figure 15 The principle of the right supply air to achieve /10/

The graph shows the inputs from the controller to the different units of the AHU at setted different temperatures. T2 and T3 stands for the set point for the supply air in winter time and for the supply air in summer time, respectively 18 ˚C and 22 ˚C (typically). As long the setted values for supply air temperature satisfies the comfort for people inside, those two temperature values – T2 and T3 – should not be the same. It serves in energy saving because no heating or cooling is required as long as supply air do not drops below T2 or exceeds T3. In the case of temperature goes down the T2 (18 ˚C), the heat recovery unit starts to work by utilizing the inside air heat to supply air side. If the temperature continues in falling down, the output signal transmitted from the controller will increase what will lead to have more energy recovered. When the signal strength reaches 100 %, the heater will be switched on and both HRU and heater will continue the heating process. In the case of temperature exceeds T3 (22 ˚C), cooling would be required. The control system would operate analogically (as long as outdoor air is higher than the extract air).

4 PRACTICAL PART

4.1 Air handling unit system in H-building

As an object for my research was chosen the H-building in the campus of South-Eastern Finland University of Applied Sciences – XAMK. It is a two-storey administrative type building.

The reason why this building was chosen for this investigation is because of its unconventional air handling unit system. The key factor of such system includes 3 boreholes drilled on the northern side of the building – Figure 16:

Figure 16 Site plan with locations of the boreholes /11/

The idea of this investment was to utilize the direct heat of the ground for supply air. In other words, applying the positive temperature which is taken from the profoundness of the earth, supply air is preheated during the cold season and (pre)cooled during the warm season. In this studies, focus will be concentrated on the system in winter time.

As it was already mentioned, the first stage of heat transfer process appears between the liquid inside the underground pipes and the soil. This heat then is given to the outside air through a needle heat exchanger (Figure 17) which is produced by the RETERMIA manufacturer.

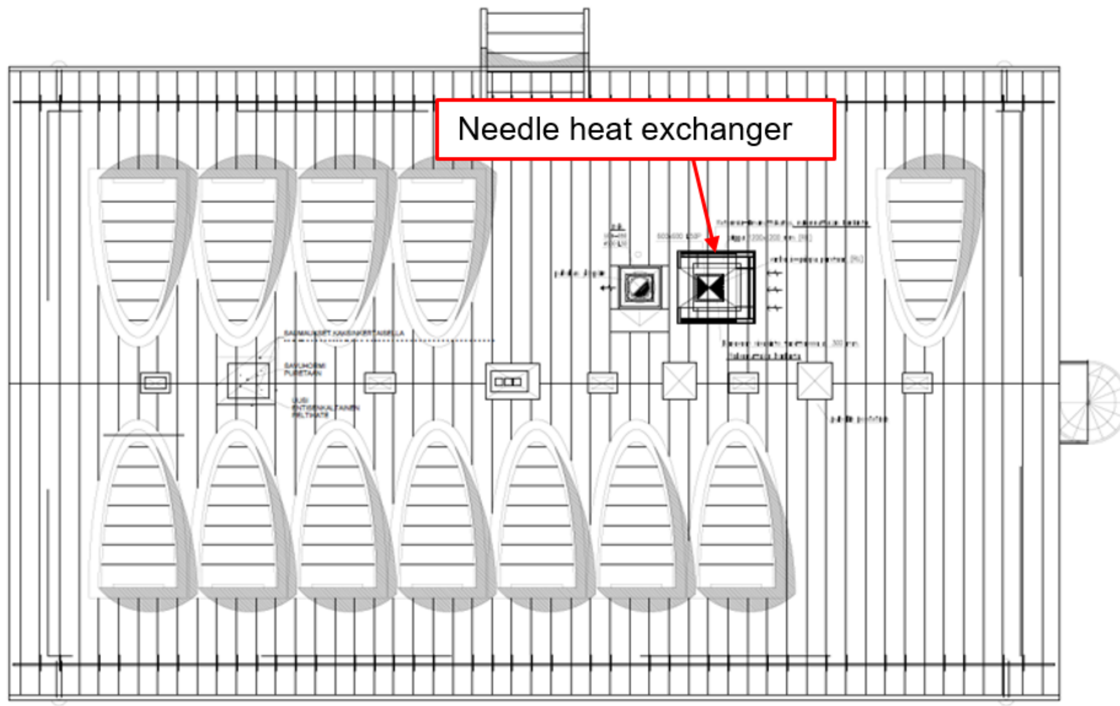

Figure 17 The top view of the H-building roof with the indicated needle heat exchanger location /16/

This equipment is the solution for the especially efficient heat transfer to happen.

The reason of its efficiency is the design of itself. Unit is supplied with a 1-2 cm needles to maximize possible surface for heat transferring as much as possible. While outdoor air is being blown in through this device, the ground source heat is transmitted through the walls of needles and enters air handling unit already in higher temperature. In order to maintain the heat transfer between mediums, the fluid inside pipes must be running as long as there is a need for this system to work.

For this reason, a circulating pump, presented in Figure 18, is installed on the supply side of the pipes. Furthermore, the climate of Finland requires one more device for liquid flow adjustment in the pipes.

Figure 18 Circulating pump for borehole system /11/

As the capacity of power to be transferred to the outdoor air must be regulated according to weather temperature (in winter, spring, summer or autumn, in whole year, temperature varies in a large range, from -29 ˚C to +32 ˚C), 3-way valve (might be seen from the schematic control drawing of the borehole energy system in Figure 19) should be installed, also. This valve provides the system with option of by-pass, which means the part of the liquid flow is recirculated.

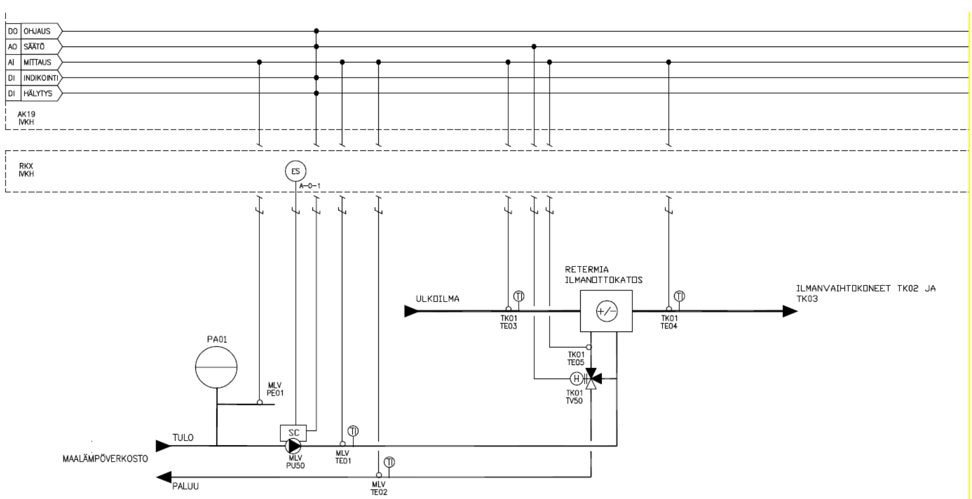

Figure 19 The scheme of the control system of the borehole energy system in the H-building /16/

When there is no need for complete utilization of the ground source heat (almost no preheating/precooling required), the valve is opened at 80 %. It means, 20 %

of the dimensioned flow reaches needle heat exchanger unit and gives only a slight influence on outdoor air temperature changes. This operation is mainly applied during the spring and autumn seasons and for summer and winter period, the 3-way valve is closed. By regulating such valve, it is possible to prevent the energy waste on electricity for the extra heating or cooling, which would truly happen if ground source energy would be transferred at full capacity - more than the demand is. The system would have had been even more efficient if the regulation of 3-way valve would not have had any faults (in 2015 for some time 3-way valve was not operating smoothly. When having outdoor temperature higher than the temperature of the circulated fluid, the valve was fully closed and as a consequence the air had been cooled down.

The capacity of power gained from the borehole system does not only depend on the size of the flow but on the type of the medium, also. As it was noticed from the collected data, when the outdoor air temperature drops lower than -7 or -8 C, the borehole liquid starts to operate in negative temperature. According to such working conditions, the fluid must characterize itself in untifreeze properties and as high specific heat capacity as possible. Therefore, the chosen liquid to circulate in the system is 30 % ethylene. During the long operating time of the system and under some other circumstances, the amount of liquid is tended to decrease. For this reason, the tank for refilling is located in the technical room (Figure 20). If it is necessary, the borehole system is manually re-pumped with a few litters until the required amount (1500 liters) is again in the system and capable to transfer the required amount of energy.

Figure 20 Information about the circulating liquid in the borehole system /11/

The following components of the AHU are a damper, a filter and a heat recovery unit. Only the later one has a significant impact on the amount of heat transfer. At extremely cold weather, the fluid capacity between supply air side heat exchanger and exhaust air side heat exchanger should be optimal, do not recover too much heat as the frost on the cooling side heat exchanger may occur. In accordance with the manufacturer‘s recommendations, the exhaust temperature of the HRU is limited to 0 ˚C (having in mind that temperature difference between the air and the refrigerant in the HRU is considered to be $\Delta t = 5\ ^\circ C$, the minimum return refrigerant temperature follows to be at -5 ˚C). As extract air temperature is considered to maintain the constant (22 ˚C) and the limited exhaust air temperature is constant (0 ˚C), the maximum amount of temperature taken from the extract air is fairly steady and would be 22 ˚C (the difference between 22 ˚C and 0 ˚C), theoretically. In real life, the amount of transferred heat would be even lower because of a natural heat losses to the surrounding (even though the HRU pipes are insulated well) and the temperature difference between fluids (air-refrigerant).

In order to have the effective heat transfer, the temperature between fluids must differ at least 5 ˚C. It means, that the fluid running inside the liquid-coupled heat recovery unit must be at -5 ˚C in return pipe side and around 17 ˚C in supply pipe side (and also have the specific characteristics similar to borehole system liquid for untifreeze purpose). It means, similarly with the boreholes system, the capacity of energy must be adjustable to the outdoors conditions. Following this, the purpose of installed circulating pump is not only to ensure liquid is running but to adapt the right size and speed of the flow, also. GRUNDFOS pump (Figure 21) is connected to the frequency converter, which ensures that the speed of the flowing liquid only convey the amount of capacity which is needed at the certain weather temperature (because of the frequent converter's sensibility to the outdoor air temperature). Though, according to the measurements, the pump is working all the time same, at 100 %. Apparently, there is no need for customizing the pump speed (flow rate) with the regards to the effect (preheating) the needle heat exchanger provides.

Figure 21 Circulating pump of the HRU system /11/

The last heat exchanger supply air needs to go through is a heating coil. District heating system serves as the heat source there. The temperature rise demand in heating coil mostly depends on the temperature of the exhaust air. In other words, at extremely low outside air temperature, the amount of the heat that might be potentially recovered from the extract air is limited because of the risk of the frostiness. At those days, heating coil plays especially important role. That follows to the key point of such AHU system, that because of the needle heat exchanger the supply air temperature is not extremely low (for instance, at -23 ˚C) when entering the HRU system, what leads to have more effective heat recovery and reduces the need for a heating coil. And that gives heat and money savings.

It is worth mentioning that supply and extract air flow rates are not uniform. Even though supply air flow rate is variable as an air damper is controlled by the CO_2 sensor, there is quit fixed amount of workers (from 8 to 10 people) in the building, it means CO_2 might vary with the correspondence of the visitors, guests and activity of the people. When damper is more open, pressure drop decreases what leads to more intensive fan work. Also, while analysing data, it was noted that night time rates exceeds the day times rates. Apparently, the system was mistaken set to work at summer time regime, to serve to cool down the building. It needs to be added that in the calculations part the supply and extract air flow rates were estimated to be equal.

4.2 Calculations

The main idea of this research was to compare the capacities of the energy supplied by the borehole system, by the heat recovery unit and the heating coil unit to the total amount the air handling unit of H-building requires. For this purpose, the power $[kW]$ that each heat exchanger unit is capable to provide was estimated according to the equation 1:

$$\phi = q_v \cdot \rho \cdot c_p \cdot \Delta t \qquad (1)$$

Where q_v is a volume flow rate, $[m^3/s]$;

ρ is a density, $[kg/m^3]$;

c_p is a specific heat capacity, $[kJ/kg \cdot K]$;

Δt is temperature difference, $[°C]$.

The AHU is equipped with a liquid-coupled heat recovery unit. On the supply air side of the HRU is heating coil and on the exhaust air side – cooling coil. If during the heat recovery process the exhaust air temperature drops below the temperature of the dew point, condensation may occur. At this point, the moisture content of the air must be taken into account, also. The amount of the water vapour is evaluated by following:

$$x = q_{m\,wv}/q_{m\,da} \quad (2)$$

Where $q_{m\,wv}$ is a mass flow rate of water vapour, $[kg/s]$;
$q_{m\,da}$ is a mass flow rate of dry air, $[kg/s]$.

It is completely enough to take into calculations only the sensible heat of the air because of following reasons. To begin with, the needle heat exchanger preheats incoming air by lowering the maximum temperature difference between outdoor and indoor air. Secondly, during cold season, water vapour amount in the outdoor is at low level. In addition, there are barely 8 -10 workers inside the H-building and their breathing, the use of kitchen would not have a huge influence on the water vapour amount changes inside the building. These facts let assume that during the heat recovery process in the HRU, the amount of moisture is not sufficient to condensate. The extract air temperature after HRU? never reaches wet bulb temperature and water vapour do not condensate in investigated period.

The processes are shown in psychrometric chart below (Figure 22):

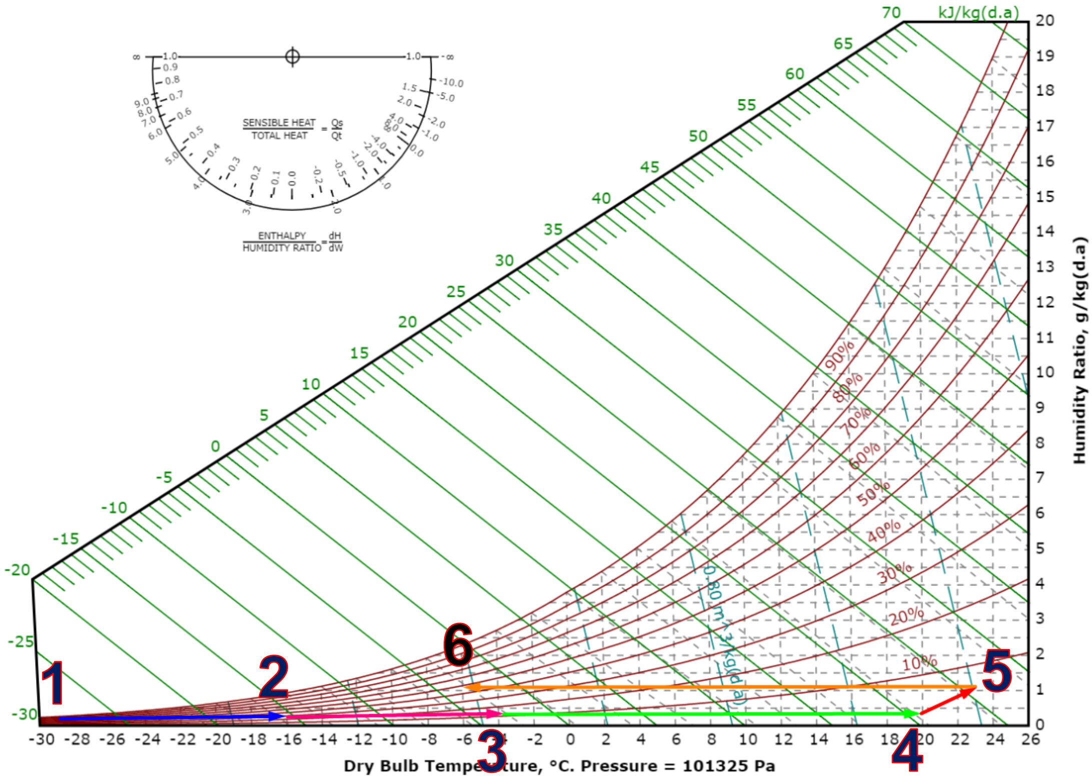

Figure 22 Temperature and moisture content changes of the supply-exhaust air when outdoor air is at -29 ˚C /11/, /17/

The 1-2 process represents the changes of air properties between outdoor air and supply air after the needle heat exchanger. The 2-3 process shows the difference between supply air after the needle heat exchanger and supply air after the HRU. The 3-4 process indicates changes that heating coil gives to supply air. All changes from 1 to 4 represent the temperature growth at the same stable water amount in the air. The amount, that incoming outdoor air already had. An arrow 4-5 shows a small change of air temperature and a significant increase of humidity ratio. Which is because of the people inside the building. The last 5-6 segment indicates air changes before and after heat recovery unit on the extract-exhaust air side. According to the figure, during the heat recovery process, the water vapour does not condensate.

With accordance to no changes of water vapor state (no latent heat), the AHU working is assessed because of sensible heat, only. In other words, heat transfer between mediums is based on flow rates, specific heat capacity and last but not least, the temperature difference. The highest amount of power capacity fluids (extract air, glycothylen, supply air) are conveying between each other is determined according general equation 3. It must be pointed out that the maximum amount of capacity fluid can transfer from cooling coil to heating coil is defined with the temperature of extract air and the recommended exhaust air temperature the manufacturer of the liquid-coupled heat recovery unit provides in the specification sheet. Formula below explains about the heat transfer at this stage in more particular way:

$$\Phi_{cooling\ coil\ lim.} = q_{v\ ext} \cdot \rho_a \cdot c_{p\ a} \cdot (t_{ext} - t_{exh\ lim.}) \tag{3}$$

Air density is $\rho_a = 1{,}2\ kg/m^3$ and specific heat capacity is $c_{p\ a} = 1{,}0\ kJ/kg \cdot K$.

According to KOJA, the manufacturer of the HRU, the temperature limitation for preventing of frostiness on the exhaust air side should be 0 ˚C. Values for volume air flows and extract air temperatures are taken as a constant value and is equal to 0,9 m/s^3.

$$\Phi_{cooling\ coil\ lim.} = \Phi_{supp-return\ fluid} = \Phi_{heating\ coil} \tag{4}$$

At the last stage, calculations of the coefficient of performance for the installed borehole system were obtained. Further formula gives a ratio between the amount of power capacity investigated system provides and the power demand of the electricity driven elements in the system:

$$COP = \frac{W}{P} \tag{5}$$

Where W is power provided by the system, $[kW]$;
P is power used by the system, $[kW]$.

When defining the power demand for the borehole system to work, a couple of aspects must be considered. Both the motor efficiency of the pump and the pressure difference the supply air must overcome in the passage of the needle heat exchanger play an essential role in the final determination of the COP:

$$P = P_p + \Delta P_{FAN} \tag{6}$$

Where P_p is power consumed by a circulating pump, $[kW]$;

ΔP_{FAN} is lost power in the needle heat exchanger, $[kW]$.

According to this, the eventual power demand for the pump is perceived according to the:

$$P_p = \frac{q_v \cdot \Delta p}{\eta_{el.m}} \tag{7}$$

Where q_v is the flow rate of supply air, $[m^3/s]$;

Δp is power of consumed electricity, $[kW]$;

$\eta_{el.m}$ is the efficiency of the electrical motor, estimated to be 50 %.

and the load of the electricity power of the fan gained with respect to the pressure drop in needle heat exchanger:

$$\Delta P_{FAN} = \frac{q_{m\,supp} \cdot \Delta p_{RET}}{\eta_{FAN}} \tag{8}$$

Where $q_{m\,supp}$ is the mass flow of supply air, $[kg/s]$;

Δp_{RET} is pressure drop in the needle heat exchanger, $[Pa]$;

η_{FAN} is the efficiency of the fan, [%].

The system of an air handling unit is being mentored by using the software provided by SCHNEIDER company. All concerning readings of the air handling unit equipment are displayed on this schematic drawing (Figure 23):

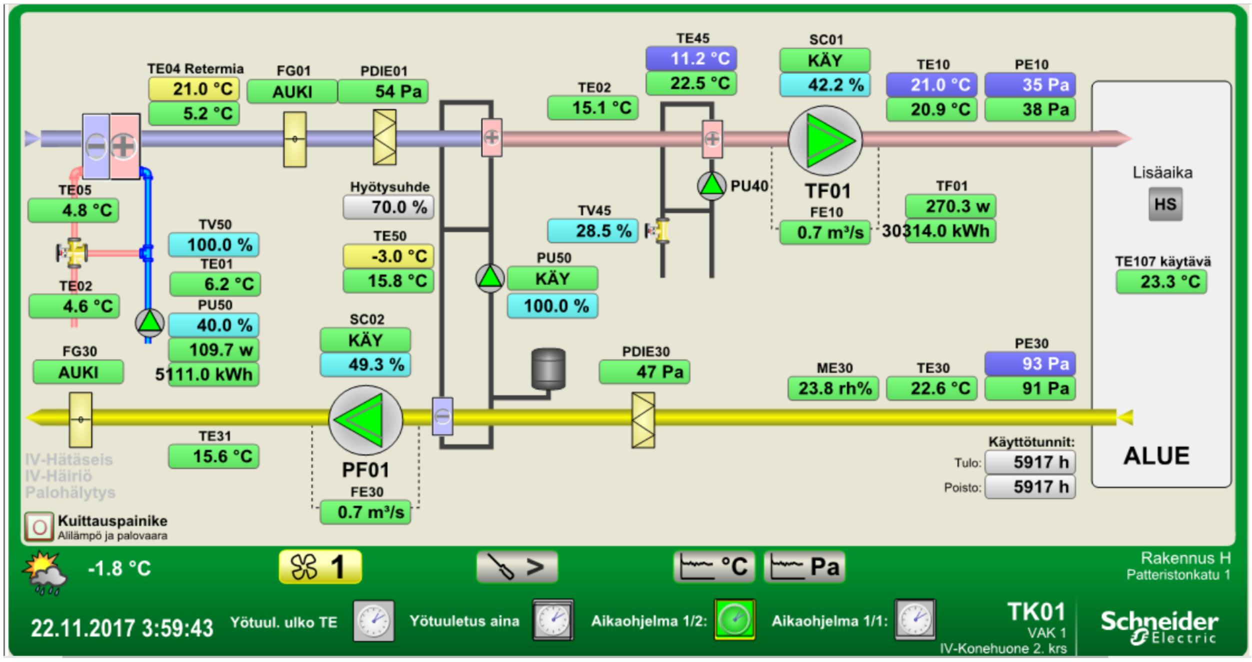

Figure 23 Schematic drawing of the AHU
system in the H-building /16/

Analysis was made according to the measurements collected by the software. Among all the parameters shown in figure above the most relevant to this thesis include not all of them. The temperatures of the coming circulating liquid inside borehole system TE01 and returning circulating liquid after the needle heat exchanger TE05, the opening of the control valve TV50 and the circulating pump PU50 parameters indicated about the borehole energy system. Outside air temperature TE00 (shown on the left side of the lower part of the scheme), supply air temperatures after needle heat exchanger TE04, supply air temperatures after heat recovery unit TE02, supply air temperatures after heating coil TE10 imply about the air condition on the supply air side. On the exhaust air side most important readings are the extract air temperature TE30 and relative humidity ME30. It is important to note that there was no exhaust air temperature TE31 indicator in the data collected at the investigated period. The air flow rates in supply and exhaust air sides (respectively FE10 and FE30) and the lowest permissible temperature of the liquid in the HRU return side TE50 give significant importance in the calculations.

In order to investigate the effectiveness of the system during the whole year, the annual energy efficiency of the ventilation might be estimated. For this purpose the annual outdoor temperature data with the time periods is used.

Table 2 Weather data for the climatic zone 1 and zone 2 in Finland /18/

	1	2	3	4	5	6	7	8	9	10	11	12	vuosi	talvi	kesä	
	744	672	744	720	744	720	744	744	720	744	720	744	8760	6552	2208	
-21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-21
-20	0.0027	0.0074	0	0	0	0	0	0	0	0	0	0	0.0008	0.0011	0	-20
-19	0.0067	0.0238	0.0067	0	0	0	0	0	0	0	0	0	0.003	0.004	0	-19
-18	0.0202	0.0417	0.0081	0	0	0	0	0	0	0	0	0	0.0056	0.0075	0	-18
-17	0.0309	0.0536	0.0094	0	0	0	0	0	0	0	0.0056	0	0.008	0.0107	0	-17
-16	0.0444	0.0729	0.0148	0	0	0	0	0	0	0	0.0097	0	0.0114	0.0153	0	-16
-15	0.0766	0.1086	0.0202	0	0	0	0	0	0	0	0.0139	0	0.0177	0.0237	0	-15
-14	0.0927	0.1682	0.0323	0	0	0	0	0	0	0	0.0361	0.0081	0.0272	0.0363	0	-14
-13	0.1089	0.2024	0.0376	0	0	0	0	0	0	0	0.0528	0.0242	0.0344	0.0459	0	-13
-12	0.1358	0.2292	0.0511	0	0	0	0	0	0	0	0.0722	0.0376	0.0426	0.0569	0	-12
-11	0.1492	0.2426	0.0591	0	0	0	0	0	0	0	0.0931	0.0538	0.0485	0.0649	0	-11
-10	0.1613	0.2649	0.0712	0	0	0	0	0	0	0	0.1042	0.0645	0.0541	0.0723	0	-10
-9	0.1868	0.2768	0.0806	0	0	0	0	0	0	0	0.1097	0.0793	0.0597	0.0798	0	-9
-8	0.2151	0.2932	0.1089	0	0	0	0	0	0	0	0.1264	0.0941	0.0684	0.0914	0	-8
-7	0.2567	0.3244	0.1599	0	0	0	0	0	0	0	0.1431	0.125	0.0826	0.1105	0	-7
-6	0.2796	0.369	0.2191	0	0	0	0	0	0	0	0.1681	0.1747	0.0993	0.1328	0	-6
-5	0.3199	0.4048	0.2728	0	0	0	0	0	0	0	0.1875	0.2567	0.1186	0.1586	0	-5
-4	0.3737	0.4405	0.3118	0	0	0	0	0	0	0	0.2111	0.3427	0.1385	0.1851	0	-4
-3	0.4261	0.4792	0.3723	0.0083	0	0	0	0	0	0	0.2319	0.4261	0.1605	0.2146	0	-3
-2	0.4718	0.5313	0.4422	0.0347	0	0	0	0	0	0.0013	0.2708	0.4866	0.1849	0.2473	0	-2
-1	0.5874	0.558	0.5	0.0694	0	0	0	0	0	0.0108	0.3028	0.5323	0.2119	0.2833	0	-1
0	0.6492	0.6265	0.6089	0.1097	0	0	0	0	0	0.0228	0.3528	0.6062	0.2463	0.3294	0	0
1	0.8266	0.7128	0.8011	0.1778	0.0081	0	0	0	0.0028	0.0484	0.4278	0.6801	0.3055	0.4084	0	1
2	0.9664	0.7798	0.914	0.3153	0.0188	0	0	0	0.0083	0.1022	0.4903	0.7675	0.3619	0.4838	0	2
3	1	0.8795	0.9637	0.4472	0.0309	0	0	0	0.0222	0.1976	0.5486	0.9073	0.4144	0.554	0	3
4	1	0.939	0.9812	0.5708	0.0457	0.0028	0	0	0.0514	0.3091	0.6167	0.9691	0.4548	0.6078	0.0009	4
5	1	0.9583	0.9879	0.6597	0.0685	0.0097	0	0	0.0903	0.3898	0.7069	1	0.4868	0.6497	0.0032	5
6	1	0.9866	0.9973	0.7278	0.1129	0.0167	0	0	0.1236	0.504	0.8181	1	0.5212	0.6951	0.0054	6
7	1	0.9926	1	0.7681	0.1895	0.0292	0	0.004	0.1833	0.6062	0.8944	1	0.553	0.7357	0.0109	7
8	1	0.9985	1	0.8111	0.2876	0.05	0.0027	0.017	0.2694	0.6882	0.9528	1	0.5872	0.7773	0.0231	8
9	1	1	1	0.8375	0.371	0.0861	0.0067	0.039	0.3597	0.7608	1	1	0.6192	0.8132	0.0435	9
10	1	1	1	0.8583	0.4785	0.1403	0.0215	0.067	0.4472	0.836	1	1	0.6517	0.8458	0.0756	10
11	1	1	1	0.8833	0.5632	0.2028	0.0336	0.121	0.5583	0.8831	1	1	0.6848	0.8758	0.1182	11
12	1	1	1	0.9111	0.6532	0.2764	0.0739	0.183	0.6361	0.9113	1	1	0.7183	0.9008	0.1766	12
13	1	1	1	0.9292	0.7191	0.3889	0.1156	0.23	0.7014	0.961	1	1	0.7517	0.9231	0.2432	13
14	1	1	1	0.9431	0.7782	0.4833	0.1828	0.31	0.7861	1	1	1	0.7885	0.9451	0.3238	14
15	1	1	1	0.9556	0.828	0.5819	0.2473	0.425	0.8514	1	1	1	0.8224	0.9592	0.4162	15
16	1	1	1	0.9625	0.8602	0.6681	0.3522	0.531	0.9111	1	1	1	0.8556	0.9702	0.5154	16
17	1	1	1	0.9778	0.9046	0.7528	0.4987	0.616	0.9556	1	1	1	0.8909	0.9818	0.6209	17
18	1	1	1	0.9889	0.9274	0.8097	0.6008	0.688	0.975	1	1	1	0.9148	0.9878	0.6984	18
19	1	1	1	1	0.9422	0.8611	0.6761	0.763	0.9917	1	1	1	0.9354	0.9925	0.7659	19
20	1	1	1	1	0.9583	0.9194	0.7608	0.813	1	1	1	1	0.9537	0.9953	0.8302	20
21	1	1	1	1	0.9704	0.9625	0.8441	0.867	1	1	1	1	0.9699	0.9966	0.8904	21
22	1	1	1	1	0.9879	0.9806	0.9059	0.902	1	1	1	1	0.9811	0.9986	0.9289	22
23	1	1	1	1	0.9933	0.9917	0.9328	0.925	1	1	1	1	0.9866	0.9992	0.9493	23
24	1	1	1	1	1	1	0.953	0.945	1	1	1	1	0.9913	1	0.9656	24
25	1	1	1	1	1	1	0.9772	0.96	1	1	1	1	0.9946	1	0.9787	25
26	1	1	1	1	1	1	0.9973	0.984	1	1	1	1	0.9984	1	0.9937	26
27	1	1	1	1	1	1	1	0.989	1	1	1	1	0.9991	1	0.9964	27
28	1	1	1	1	1	1	1	0.993	1	1	1	1	0.9994	1	0.9977	28
29	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29

This table specifies how long particular temperature last each month. In the following calculations /19/ values in percentage from “vuosi” (means “year”) section for the $\Delta\tau_n$ determination was used:

$$Q_{AHU} = \rho \cdot c_p \cdot q_s \cdot \sum_n (t_s - t_{out}) \cdot \Delta\tau_n \tag{9}$$

Where Q_{AHU} is the energy need in AHU without HR in AHU, $[kWh]$;
ρ is the density of the supply air, $[kg/m^3]$;
c_p is a specific heat capacity of air, $[kJ/kg \cdot K]$;
q_s is the volume flow rate of the supply air, $[m^3/s]$;
t_s is the set point for the supply air temperature, 18 $^\circ C$;
t_{out} is the outdoor air temperature, $[^\circ C]$;
$\Delta\tau_n$ is the time period when temperature difference $(t_s - t_{out})$ occurs, $[h]$.

While formula above indicates the energy need for AHU when there is no heat recovery, equation 10 represents the amount of energy recovered from the extract air when the heat recovery unit is installed:

$$Q_{HR} = \rho \cdot c_p \cdot q_s \cdot \sum_n (t_{sHR} - t_{out}) \cdot \Delta\tau_n \tag{10}$$

Where Q_{HR} is the energy recovered from the extract air in the HRU, $[kWh]$;
ρ is the density of the supply air, $[kg/m^3]$;
c_p is a specific heat capacity of air, $[kJ/kg \cdot K]$;
q_s is the volume flow rate of the supply air, $[m^3/s]$;
t_{sHR} is the supply air temperature after HRU, $[^\circ C]$;
t_{out} is the outdoor air temperature, $[^\circ C]$;
$\Delta\tau_n$ is the time period when temperature difference $(t_{sHR} - t_{out})$ occurs, $[h]$.

After determining the energy demand in AHU without HR and the energy recovered from the extract air in the HRU, the annual energy efficiency of the ventilation is gained from the formula below:

$$\eta_{a,\ AHU} = \frac{Q_{HR}}{Q_{AHU}} \cdot 100\ \% \tag{11}$$

4.3 Results

The general understanding about the benefits Retermia unit is able to provide to the AHU system is illustrated below. Figure 24 shows the amount of heat gained in all three – needle heat exchanger, heat recovery unit and heating coil - units at different weather temperatures. Between all the investigated months of 2016, the most coldest was January ($t_{min} = -29{,}14\ °C,\ t_{avrg} = -14{,}25\ °C,\ t_{max} = 2{,}13\ °C$). In order to understand the trend of the influence of the preheater for the HRU, the research was mostly carried on at the outdoor temperature points of -29 ˚C , -25 ˚C, -20 ˚C, -15 ˚C, -10 ˚C, -5 ˚C, 0 ˚C, 5 ˚C, 10 ˚C and 15 ˚C, respectively. Values were estimated as an average of all possible hourly data within the interval of ± 0,5 ˚C. Picture below represents the energy repatriation according to the data of the 2016:

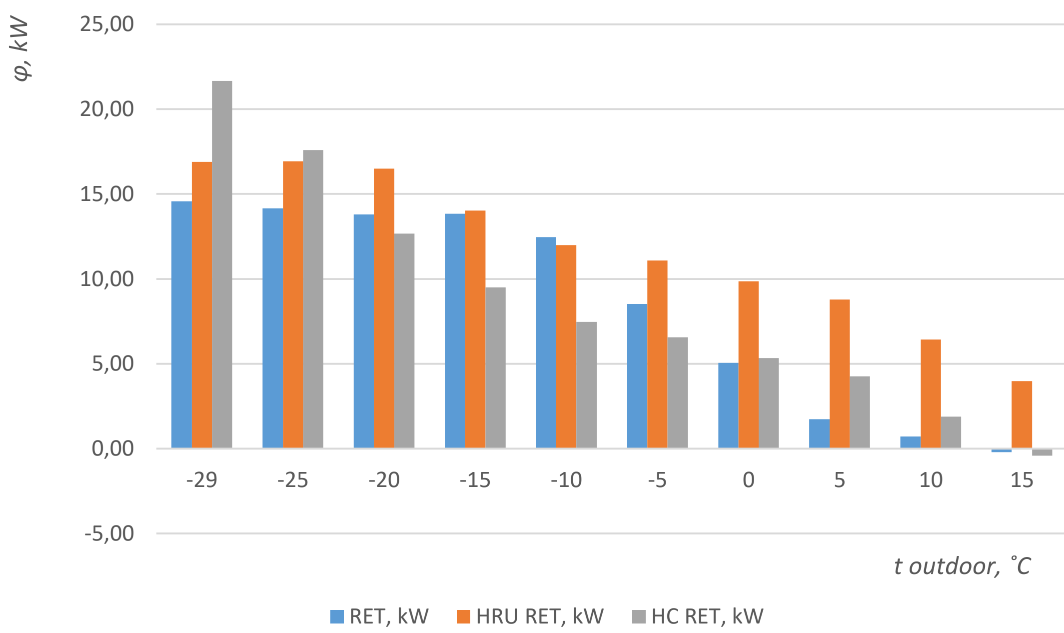

Figure 24 Amounts of power produced in
different heat exchangers of the AHU (with needle HE)

According to the chart above, the Retermia unit gives pretty stable amount of power when outdoor temperature varies between -29 ˚C and -15 ˚C. In other words, this is the maximum power the needle HE unit is able to give to the supply air side. From the outdoor temperature of -10 ˚C, the energy the needle HE unit gives to the supply air, starts to reduce. It is because the outdoor temperature rises but demand for energy, reduces. The amount of energy the HRU produces, gradually decreases in the all range of outdoor temperature. Lastly, the HC ensures the supply air side was provided with the full amount of energy required for achieving the desired temperature for the supply air (18 ˚C). As it is seen, these numbers are reducing with accordance to outdoor air. When investigating such systems, it is important to understand that energy provided by the needle HE and HRU is commonly perceived as free or almost free energy. And the idea is to find out at what conditions HC needs to give the lowest part of required energy.

Illustration below helps to understand the results of the points at 10 ˚C and 15 ˚C outdoor temperature.

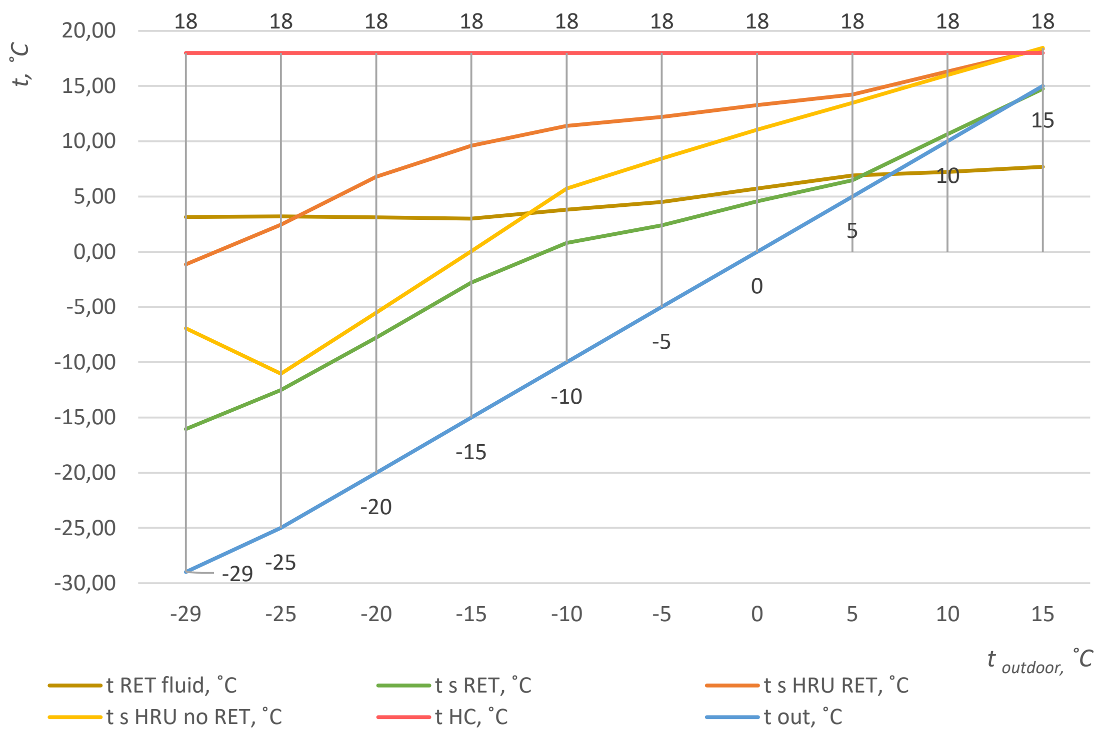

Figure 25 The most important temperatures of the AHU system during this investigation

According to the graph above, it is possible to determine at what outdoor air temperature the preheater is not able to provide the incoming supply air with any heat. Logically, as long as outdoor air temperature is lower than the temperature of the fluid circulating in the borehole, the preheater system is working profitable.

From the Figure 25 it is seen that having outdoor air temperature at app. 7 ˚C, the temperature of the circulating fluid in the borehole system is at app. 7 ˚C, also. That follows, that at this point the system is not able to preheat the supply air anymore.

In addition, this graph tells that having outside temperature at 10 ˚C and circulating fluid in the boreholes at 7 ˚C, the preheater is still managing to warm up the outdoor air app. 1 ˚C. This is incorrect. Probably, because of the inaccuracies the monitoring system gives. Another thing worths mentioning is when having outside temperature at 15 ˚C, the temperature of the supply air after the HRUs are exceeding the set point for supply air to building (18 ˚C). This explains why in Figure 24 at $t_{out} = 15$ ˚C the power from the HC is negative (HC is cooling the air). Following that, there should be no additional HC operation (the valve on heating side must be closed, as the amount of heat the HRU is able to recover is enough for achieving the set point value for the supply air).

After the simulation was applied (after eliminating needle HE), there are only two heat exchangers in the AHU – HRU and HC. As the comparison shows (Figure 26), firstly, supply air is being heated by the HRU. Second ly – in the HC. As the illustration shows the energy that HC recovers gradually decreases when outdoor air becomes warmer.

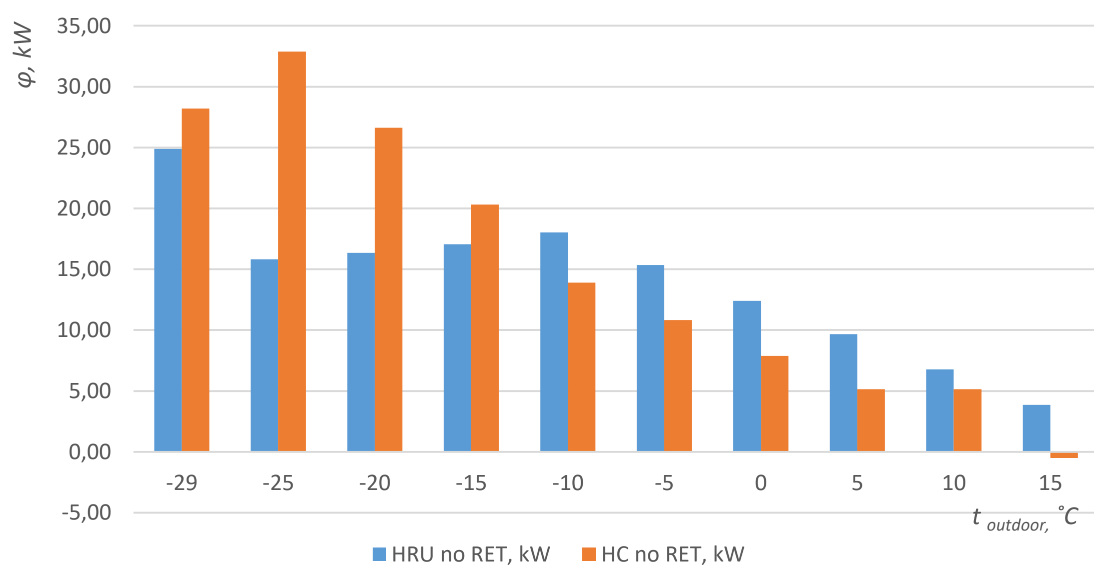

Figure 26 Amounts of power produced in different heat exchangers of the AHU, no RET

When outdoor temperature rises from -10 ˚C to 15 ˚C, amount of energy HRU transfer takes the major part. It might be explained because it was determined that at the outdoor air temperature of -10 ˚C there is no more need for limiting the exhaust air, it means, the HRU operates fully.

According to the diagram (Figure 27), when having needle HE, HRU provides the systems with the highest amount of energy ($9008\ kW < 9793\ kW > 8355\ kW$). Then follows heating coil (*9008 kW*) and needle HE (*8355 kW*). When there is no preherater in the AHU system, heating coil provides the systems with the higher amount of power than the HRU does ($16559\ kW > 10597\ kW$). While comparing power demands in heating coil with installed RET and without, the total power difference for January of 2016 would be $16559\ kW - 9008\ kW = 7551\ kW$. This is the amount of power saved during the January of the 2016 because of the preheater installed in the beginning of the air handling unit.

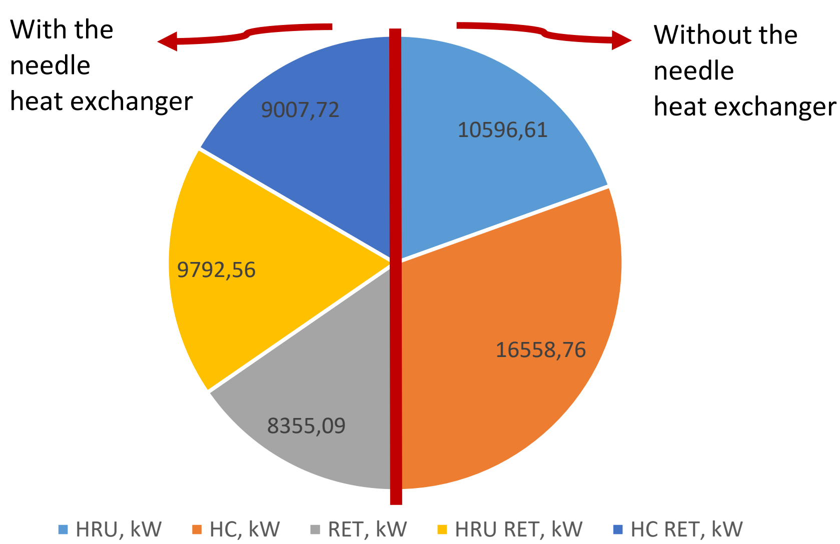

Figure 27 Comparison of the power produced in different heat exchangers of the AHU system in January of 2016

Figure 28 compares the amount of power the heating coil gives at certain outdoor temperatures when there is installed needle HE in the AHU system and when there is not.

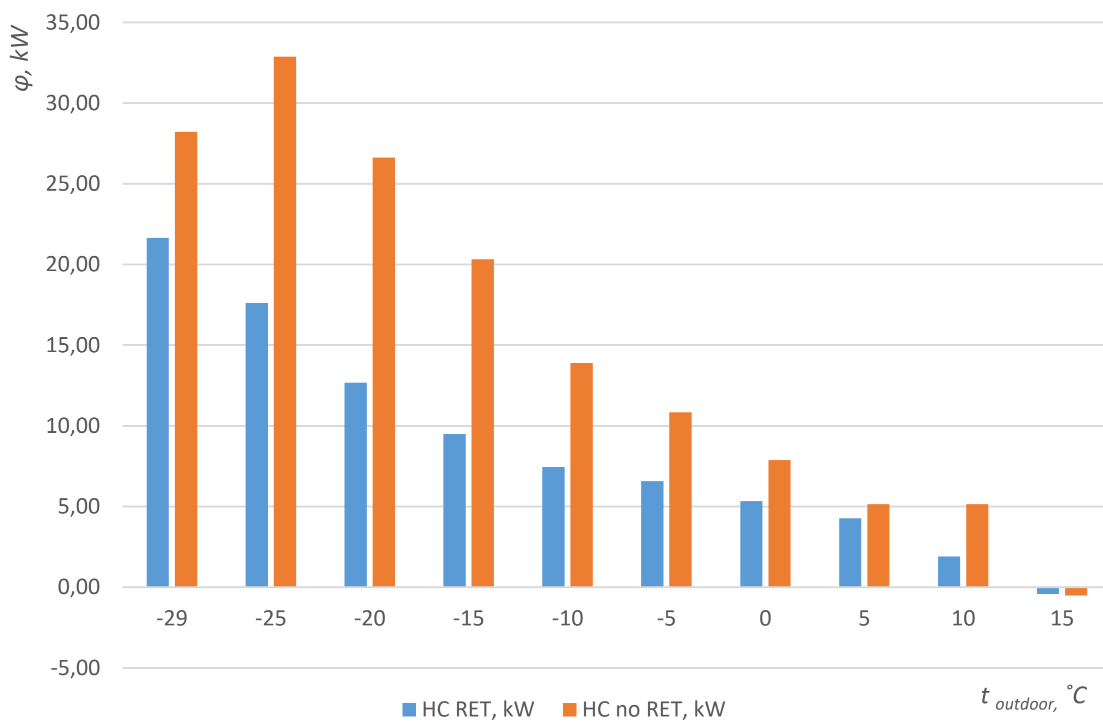

Figure 28 Amounts of power produced in heating coil with RET and without RET

Is it easy to notice that in all range of the outdoor temperature RET gives a significant impact for heat concerns. Roughly, from 1,2 to 2,71 times heating coil needs to warm up the supply air more when there is no needle HE than when there is. More precise numbers at each temperature rate are given below:

Table 3 Needle heat exchanger influence on the heating coil work

t out, ˚C	-29	-25	-20	-15	-10	-5	0	5	10	15
HC_{RET}, kW	21,66	17,60	12,68	9,50	7,46	6,57	5,34	4,27	1,90	-0,42
$HC_{no\ RET}$, kW	28,21	32,88	26,63	20,31	13,90	10,83	7,87	5,14	5,14	-0,52
RATIO	1,30	1,87	2,10	2,14	1,86	1,65	1,47	1,20	2,71	1,24
ΔHC, kW	6,56	15,29	13,95	10,81	6,44	4,26	2,53	0,87	3,24	-0,10

4.3.1 Analyze of the fluid inside the HRU

In order to understand the impact of the needle HE to an air handling unit, the meaning of the mixing valve was investigated, also. New results were gained as the needle HE unit was eliminated and bypass option was “installed” in the HRU system. In order to remain with the same speed of the ethylene glycol flow in HRU pipes (as a prevention of the laminar flow for ensuring the heat transfer between fluid and air is effective) as having Retermia unit, bypass option was applied. Having this supplementary shaft pipe it is possible to control the amount of heat recovered from extract air for avoiding frostiness on the exhaust air side outlet of the HRU cooling coil.

Figure 29 shows which part (in percentage) of the ethylene glycol flow from the HRU cooling coil (exhaust air side) needs to be recirculated in the system instead of entering the HRU heating coil (supply air side). These two graphs proves that having the RET unit installed in the AHU, it is possible to recover more power from the extract air because the liquid is being recirculated less in cold weather when compared with no having RET.

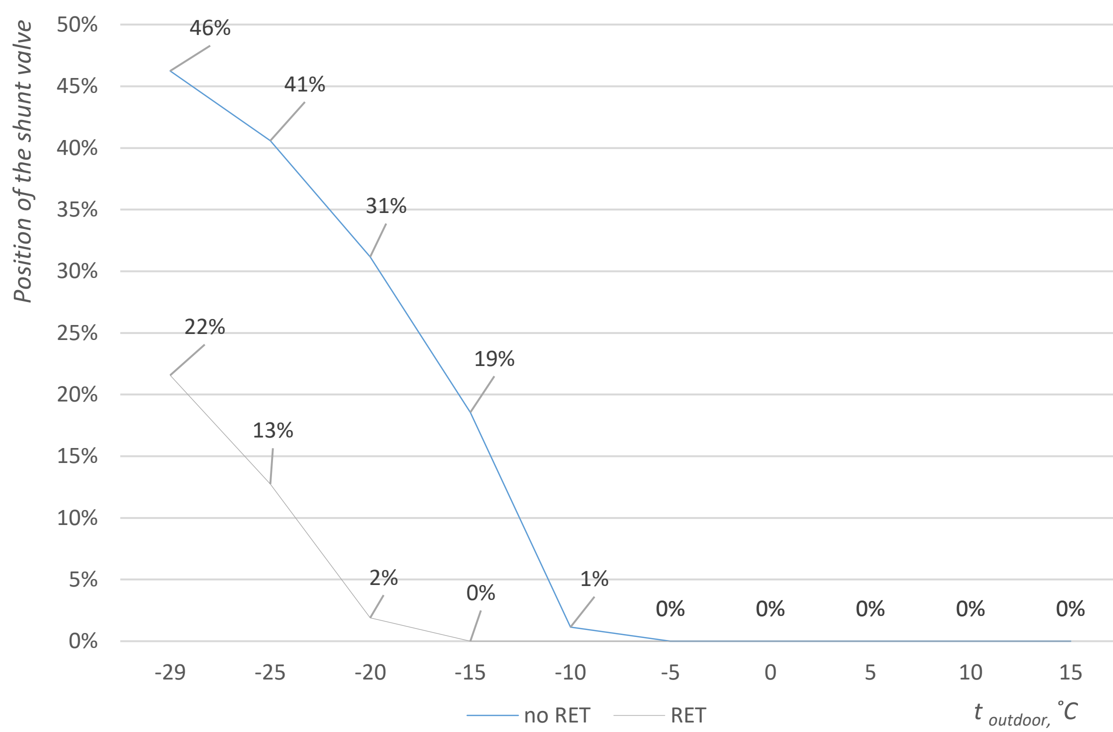

Figure 29 Comparison of the position of the shunt valve and outdoor air temperature

To be more precise, the need for shunting the significant part of the flow for recirculation starts at different outdoor temperatures when having RET unit installed and when having not. In the case of needle HE unit is installed in the AHU, at the outdoor temperature of -20 ˚C, the flow decreases from the 0,286 kg/s to 0,281 kg/s., like graph below represents:

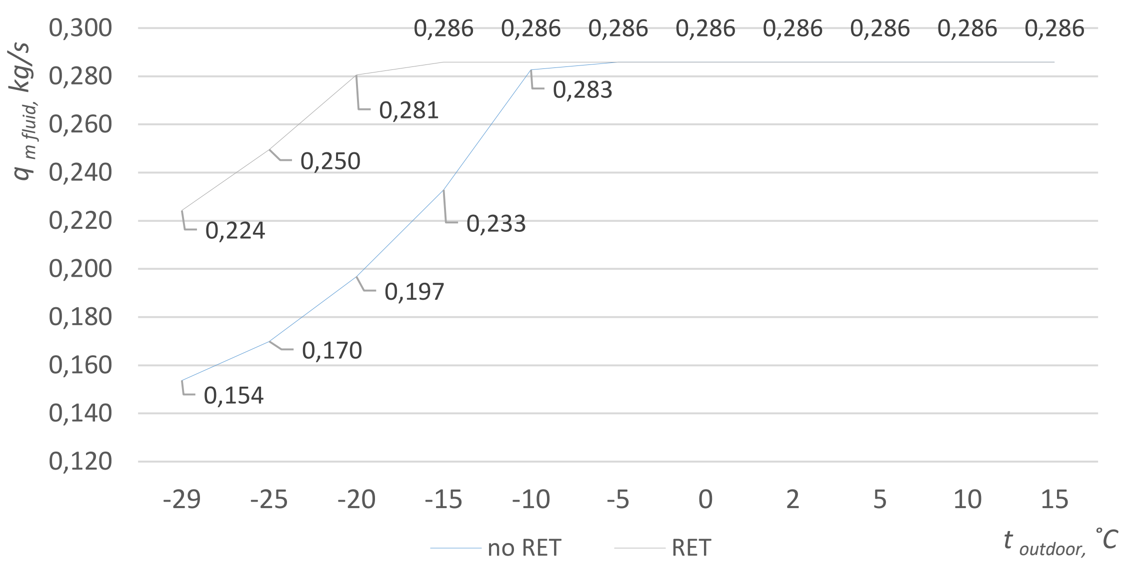

Figure 30 Comparison of the ethylene glycol flow in the HRU pipes (to supply air side coil) and outdoor air temperature

When temperature drops to -29 ˚C, the flow reaches 0,224 kg/s (app. 22 % of possible heat is being lost because of the prevention for the frost possibility). In the case when AHU is not equipped with the RET unit, the outdoor temperature of -10 ˚C is too low (exhaust air temperature already needs to be limited) and flow here is reduced from 0,286 kg/s to 0,283 kg/s. When outdoor temperature reaches -29 ˚C, the flow going from cooling coil to heating coil is being cut by more than 46 % of the full (0,286 kg/s) flow.

4.3.2 Determining the COP for the needle HE

The summarization is given in Table 4. By having amount of power produced in the needle HE and by knowing how much power is lost in the preheater because of pressure losses that a fan needs to compensate (0,054 kW), and by knowing how much electricity power the circulation pump for needle HE is consuming

(0,110 kW), the conclusion containing COP – coefficient of performance – value for the needle HE can be drawn:

Table 4 Figures for COP determination

t_{out}, ˚C	-29	-25	-20	-15	-10	-5	0	5	10	15
ΔRET, kW	14,57	14,16	13,80	13,84	12,47	8,52	5,06	1,74	0,73	-0,20
$\Delta P_{FAN\ in\ RET}$, kW	0,054	0,054	0,054	0,054	0,054	0,054	0,054	0,054	0,054	0,054
W_{PUMP}, kW	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11
COP	88,8	86,3	84,1	84,4	76,0	52,0	30,9	10,6	4,4	-1,2

Coefficient of performance varies, of course, in accordance with outdoor temperature. A graph below shows how COP alters with different outdoor conditions.

According to the Figure 31, the COP decreases as the outdoor temperature increases. To be more precise, the COP varies very slightly as long as outside air temperature is from -29 ˚C to -10 ˚C. It is noticed from the graph, that temperature difference the needle HE provides supply air with is directly related to its COP. Grey and red lines represent the $t_{s\ RET}$ and t_{out}, respectively. From the $t_{out} = -10$ ˚C and warmer, the COP is drastically reducing. And that is because the temperature difference between outdoor air and supply air after needle HE is getting smaller.

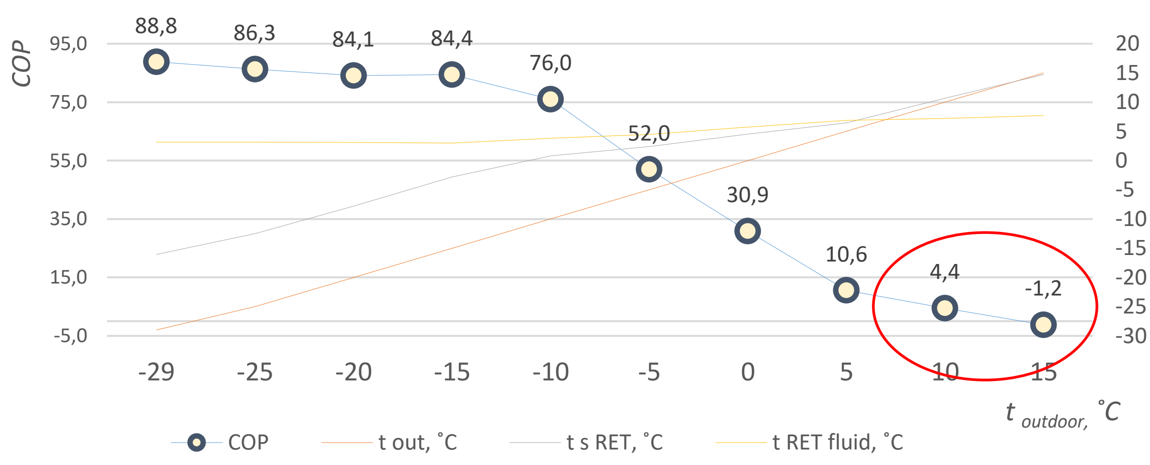

Figure 31 The relation between coefficient of performance of the needle HE and outdoor temperature

It needs to be mentioned that at outdoor temperature of 10 ˚C and 15 ˚C, the COP values are inaccurate as needle HE stops making any benefits at the outdoor air of app. 7 ˚C (that was explained in Figure 25). Indeed, it is making even a small negative impact because of the pressure loss the supply air needs to experience in the needle heat exchanger and because of the running circulation pump in the borehole system which consumes some power, also.

An illustration below shows how energy demands are distributed in different heats exchangers. As bars of January are the tallest it refers to the highest amount produced in all coils. Following that, the outdoor temperature of January was the lowest between all the investigated months. It was noticed that when there is a needle HE, the highest amount of power is being produced in HRU. In simulated case, when there is no needle HE installed, the higher amount of power is produced by HC only in January, when there was extremely cold days (roughly, -25 ˚C and lower).

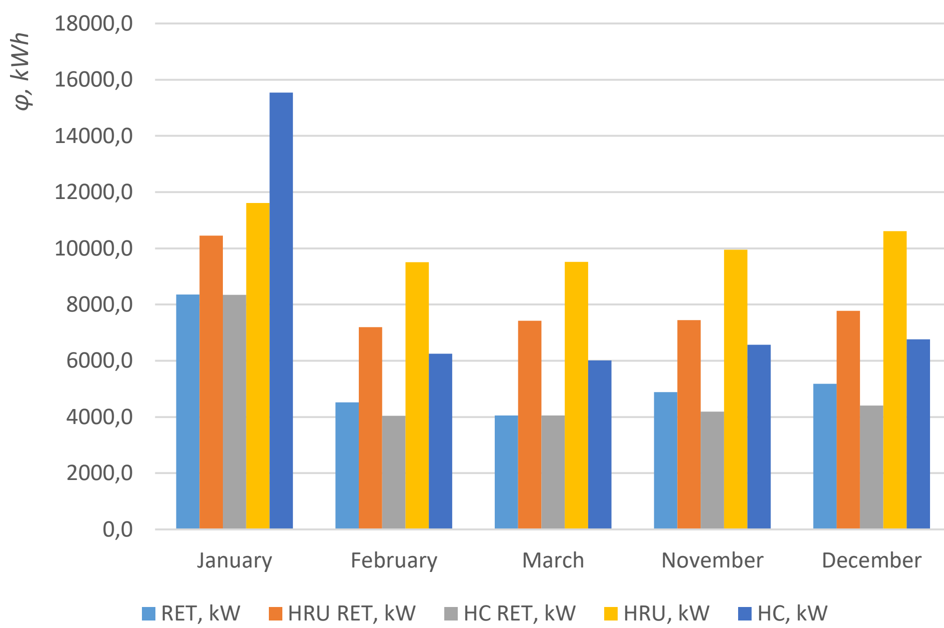

Figure 32 Amounts of power produced in different heat exchangers of the AHU during the cold season of 2016

During the research it was estimated that 7199 kWh, 2205 kWh, 1960 kWh, 2382 kWh and 2352 kWh, respectively for January, February, March, November and December, would be saved in heating coil if having the needle HE installed for preheating purpose in the beginning on the air handling unit.

4.3.3 Sensibility test for the HRU

For the reason to perceive the operation of the HRU better, the sensibility test for the January of 2016 was carried out. Such variables as the temperature difference between fluids in HRU (ethylene glycol and air) and the temperature limitation for exhaust air were slightly changed (chart Figure 33 shows):

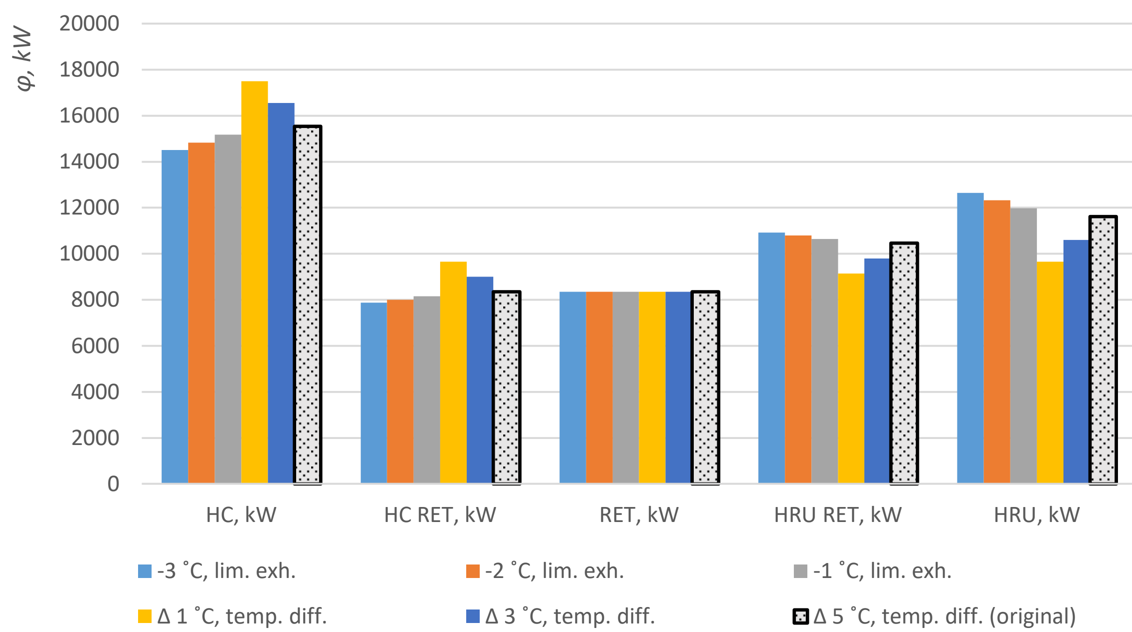

Figure 33 Results after the sensibility test
for the January of 2016

The illustration above explains how much minor changes are influential for the AHU system operation. As both the temperature difference between fluids and the temperature limitation for exhaust air changes are made to be applicable to the HRU only, no alterations in the needle HE unit should be noticed (the possible temperature difference changes between the fluid circulating in the borehole and air was not investigated). Keeping the 5 ˚C temperature difference between the fluids and 0 ˚C for limited exhaust air as the initial (original) values, variations will be discussed. If temperature difference between fluids would be 3 ˚C instead of 5 ˚C, more power should be recovered in the HC and, following that, less amount in HRUs (darker blue color represents in the graph such situation).

In the case of using 1 ˚C as the temperature difference between fluids, the results would be worse (as the HC should produce the system with the highest amounts). The HRU would be able to retrieve less energy and HC should cover the rest (yellow color represents in the graph this situation).

It worths mentioning that in order to improve the heat transfer between fluids while consuming the same amount of time, heat exchangers must be dimensioned to be longer. And that means the larger space demand for the equipment footprint what leads in not saving space.

When simulating with the limitation temperature for the exhaust air, it was spotted to have the positive influence on the AHU. After changing the limited exhaust air temperature from 0 ˚C to -1 ˚C or to -2 ˚C, or to -3 ˚C, the results were especially influential for the HRU. The most inevitable disadvantage here is the risk of having condensate frozen in the cooling coil of the HRU. And that would cause the HRU operation to be not so fluent and efficient.

4.3.4 Estimated savings

Final aspect that needs to be discussed is benefits for the economical perspective. As the total amount of saved energy in the heating coil for 2016 is 16098 kWh (7199 kWh, 2205 kWh, 1960 kWh, 2382 kWh and 2352 kWh, respectively for January, February, March, November and December), it would lead to a great cost savings as heating coil warms the supply air by the heat transfer from the district heating fluid to the supply air.

By referring to the district heating prices used for the XAMK campus maintenance /16/, it is possible to save up to:

$$16{,}098\ MWh \cdot 47{,}6\ eur/MWh \cdot 1{,}24 = 950\ eur/2016\ year.$$

Where 16,098 MWh stands for the saved energy in HC (when needle HE is used);

47,6 eur/MWh is the price for 1MWh for the district heating energy (without taxes);

238,40 eur/month is app. fixed monthly price for contractor fee (without taxes); it is not taken into account at this point as this fee serves for both space heating and ventilation. It follows that it is inevitable fee and should not be included in this savings calculations;

1,24 is a coefficient that gives a final costs including 24 % taxes.

In order to have even more precise number, the costs for needle HE operation must be taken into account, also. The amount of energy lost in the RET unit (because of pressure losses) is $198{,}29\ kWh/2016\ year$ and amount of electricity energy consumed by a circulation pump for this preheater is $403{,}92\ kWh/2016\ year$. The sum of these figures reaches $602{,}21\ kWh/2016\ year$. As the energy source now is used electricity (not district heating), it means that calculations for savings are slightly different:

$$602{,}21\ kWh/2016\ year \cdot 0{,}08\ eur/kWh \cdot 1{,}24 = 59{,}74\ eur/2016\ year.$$

Where 0,08 eur/kWh includes both consumption and contractor fees;

1,24 is a coefficient that gives a final costs including 24 % taxes.

That follows to the final savings of:

$$950\ eur/2016\ year - 59{,}74\ eur/2016\ year = 890\ eur/2016\ year.$$

4.3.5 Annual efficiency of the AHU system

Figure 34 compares the achieved supply air temperatures after the HRU when there is needle HE and when there is not. The higher temperature is reached with no installed preheater. However, that does not follow to higher power demand in the heating coil.

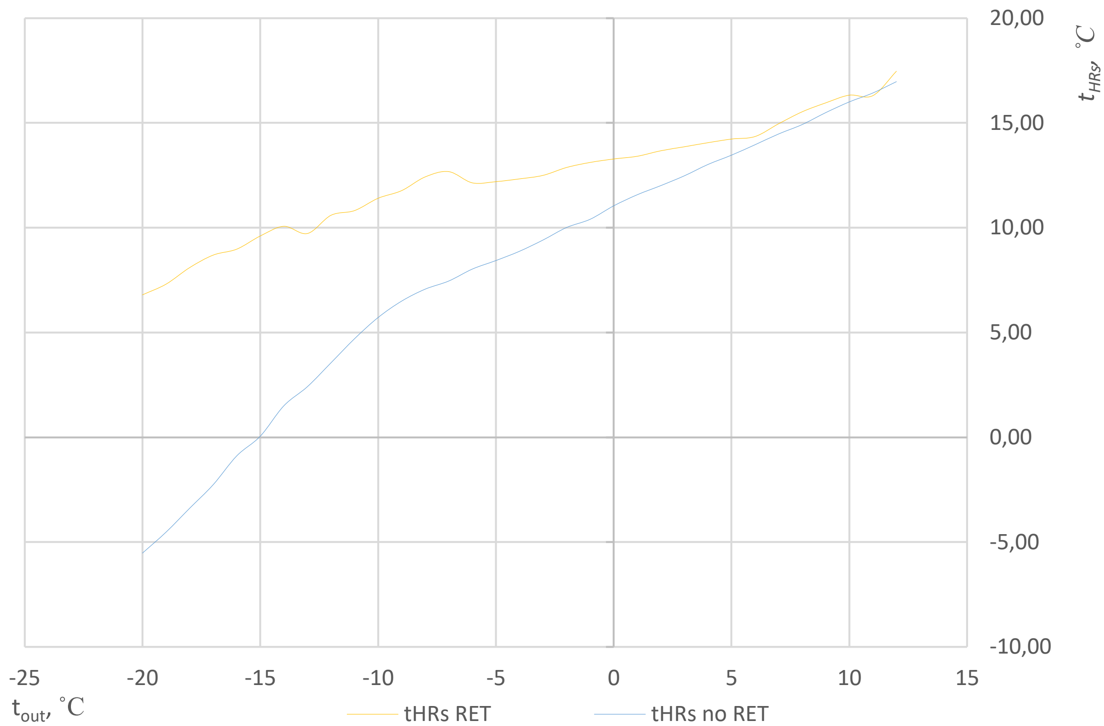

Figure 34 Comparision of the supply air temperatures after the HRU at different types of estimations

In the illustration below there is shown the effectiveness of the liquid coupled heat recovery unit at different outdoor air temperatures. There are two graphs in the Figure 34 representing two different operations of the HRU. The blue line shows the effectiveness of the HRU with no preheater and red line represents the case when there is a preheater. As it was noticed that at the outdoor air temperature of -10 ˚C, the limitation for the exhaust air should be applied. According to this condition, the supply air after the HRU at -10 ˚C and lower temperature was estimated with the maximum possible power in the cooling coil. Having t_{out} above -10 ˚C, the supply air after the HRU was determined with $\eta_s = 50\ \%$ (temperature ratio) of the liquid coupled heat recovery unit. The reason why there is no such drastic changes in the case with needle HE because the outdoor air enters the HRU warmer and that leads in smaller theoretical possible temperature difference.

It is worth mentioning that Figure 35 might be deceptive. It is can not be guided for the final annual understanding whether the preheater system is profitable or it is not.

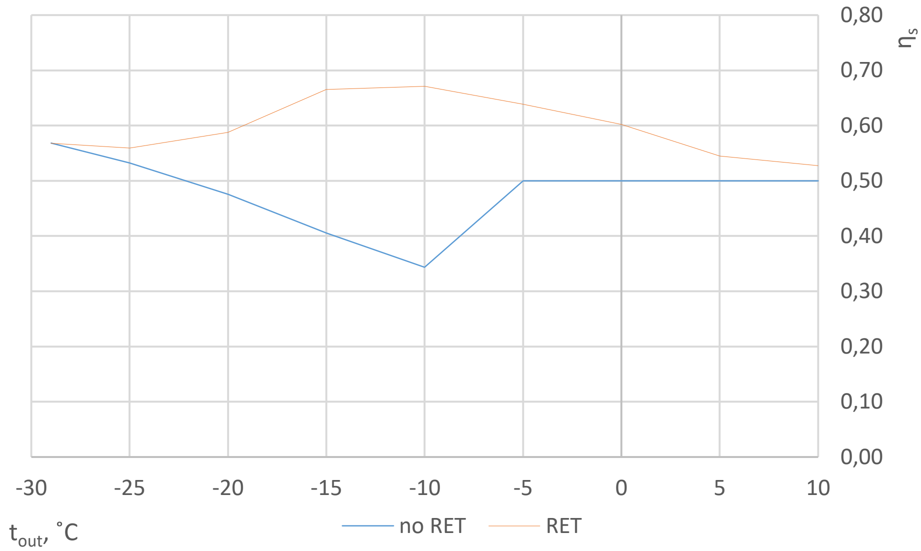

Figure 35 The effectiveness (temperature ratios) of the HRU at different outdoor temperatures

As a ensuring values for the latter remark, Table 5 is given. The ratio between the amount of annual energy recovered in the HRU and the amount of energy demand in the AHU (the energy required to heat up the outdoor air until the preset 18 ˚C) provides the annual energy efficiency of the air handling unit. Technically, the higher supply air temperature after the HRU is, the better annual energy efficiency of the system is achieved.

Table 5 Figures for the annual energy efficiency of the AHU

Q_{vent}, kWh	$Q_{HRU\ no\ RET}$, kWh	$Q_{HRU\ RET}$, kWh	
116995,6	67347,5	81840,6	
$\eta_{a\ AHU}$, %	**57,6**	**70,0**	
	$Q_{HC\ no\ RET}$, kWh	$Q_{HC\ RET}$, kWh	ΔQ_{HC}, kWh
	42811,7	28318,6	14493,1

There are presented different variations of the HRU system operation in the table – both when supply air temperature after the HRU is gained with accordance to no preheater and when supply air temperature after the HRU is obtained according to operation of preheater:

Numbers in the table show that installed preheater can increase the annual energy efficiency of the AHU about 22 % (from the 57,6 % to the 70,0 %).

The more efficient the AHU system is the less energy demand in the heating coil is. The lowest row of the table shows that having increased the annual energy efficiency of the AHU 22 %, the energy demand in heating coil was reduced up to 34 %.

When looking financially, it is possible to save:

$$14{,}5\ MWh \cdot 47{,}6\ eur/MWh \cdot 1{,}24 = 855{,}9\ eur/year.$$

Where 14,5 MWh stands for the saved energy in HC (when needle HE is used);

47,6 eur/MWh is the price for $1\ MWh$ for the district heating energy (without taxes);

1,24 is a coefficient that gives a final costs including 24 % taxes.

It is useful to evaluate the energy losses because of the needle HE here, as well. Using the annual data (the amount of hours at the specific outdoor air temperature) it was calculated that the costs for needle HE operation reaches:

$$1031{,}94\ kW/year \cdot 0{,}08\ eur/kWh \cdot 1{,}24 = 102{,}37\ eur/\ year.$$

Where 0,08 eur/kWh includes both consumption and contractor fees;

1,24 is a coefficient that gives a final costs including 24 % taxes.

That follows to the final savings of:

$$855{,}9\ eur/year - 102{,}4\ eur/\ year = 753{,}5\ eur/year$$

Illustration below – Figure 36 – compares both cases when annual savings were based on the particular months of the 2016 (January, February, March, November and December) and when saving were estimated according to the annual energy efficiency of the AHU:

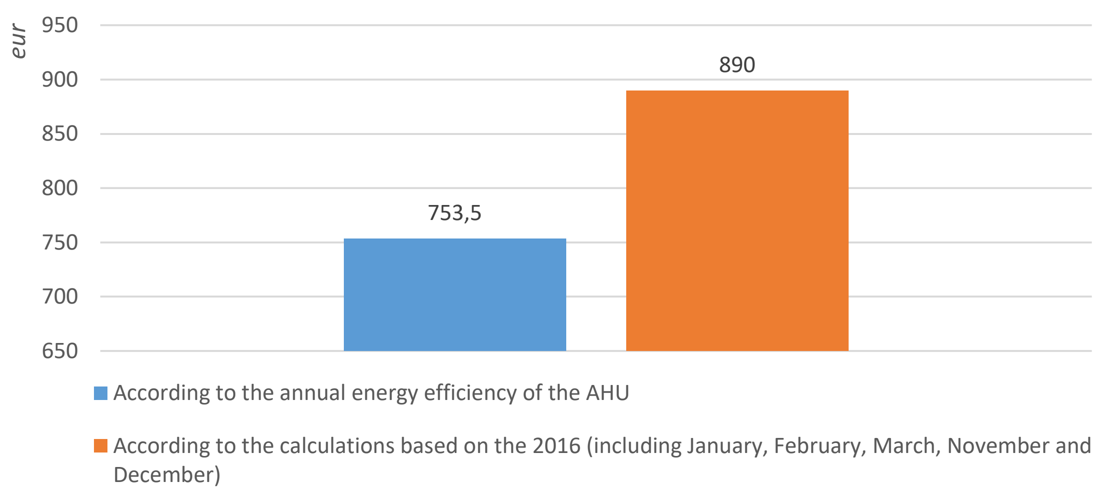

Figure 36 The amount of saved money during the year

There are some explanations why calculated savings during the year varies more than 100 eur. The evaluation of the annual energy efficiency of the AHU includes outdoor temperatures in a range from -21 ˚C to 12 ˚C. For instance, in the January of 2016 lower outdoor air temperature than -21 ˚C was for 223 hours (out of the 744 hours). And that means 30 %. In addition, in the calculations for the 2016 there were taken only January, February, March, November and December. That means that other hours which fits in a range from -21 ˚C to 12 ˚C of the rest months of the year were not taken into account. These are the reasons making some inaccuracies in the calculations.

5 DISCUSSION

After the investigation of the AHU system of the H-building was made, some important results were gained. As this study was designed to investigate the real AHU system in the H-building for cold period, the following results might have some reasonable value.

The main results has shown that having preheater in the beginning of the AHU system can lead to some savings. Specifically, when the system was investigate for the year of 2016, the possibly amount for savings reaches 890 eur per year. It worth mentioning that this number was gained by simulating the HRU system to work with the temperature difference between mediums (fluid and air) ar the 5 ˚C.

In addition, having increased the annual energy efficiency of the AHU by 22 %, the energy demand in heating coil was reduced app. by 34 %.

According to the sensibility results, even better numbers might be achieved if the AHU system would work at lower limited exhaust air temperature – at -1 ˚C, -2 ˚C or -3 ˚C. Unfortunately, that would lead to experience bigger risk of condensation to freeze.

Less important results but still worth mentioning revealed that the COP of the needle heat exchanger reaches more 88 % at the outdoor air of the -29 ˚C. It need to be added, that pretty stable value remains until the outdoor air drops till -10 ˚C. Above this temperature, the temperature difference between the liquid inside the borehole system and the outdoor air, starts to reduce and that leads to decreasing COP.

In conclusion, this component of the AHU system not only provides the supply air with some free energy retrieved from the ground but helps in filtering the supply air from variety of the impurities, also.

In addition to the beneficial results obtained during the cold period, the needle heat exchanger serves as a precooler at the summer time, as well. According to the Anastasia Bykova research, the COP of the borehole system reaches nearly 100 during the really hot summer days. Thats proves that the main purpose of this borehole energy system is to utilize ground source energy for the pre-cooling purposes. In addition for profitable operating in the summer time, this report ensures the borehole energy system make a valuable impact on the winter time, also.

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