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Efficiency of heat recovery unit in D-building

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DESCRIPTION

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Abstract

The main purpose of this thesis work is to consider how the heat recovery unit in D-building works and to search errors in the system (if any exist) and try to find methods to improve efficiency heat recovery system.

Analysis was performed according with database from automation in D-building. Database contains stored measurements of the temperatures before and after heat recovery unit, supply and exhaust air flows and heat electricity consumption. According this data it is possible to make diagrams and analyze functioning of the heat recovery unit,

Based on data from automation it can be concluded that the reason of malfunctioning of heat recovery unit is incorrect settings of automation system. Fluctuation in the diagram of the annual energy efficiency in the first part of the month the due to incorrect changing speed of the rotation wheel. It is necessary to fix settings to reach right functioning.

Subject headings, (keywords)

Ventilation, Air handling unit, heat recovery, heat exchanger

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Aki Valkeapää	

CONTENTS

Nomenclature

c_p	the specific heat capacity (kJ/kg K)
$h_{exhaust}$	enthalpy of exhaust air (kJ/kg)
$h_{outdoor}$	enthalpy of outdoor air (kJ/kg)
h_{rec}	enthalpy of mixed supply air (kJ/kg)
Q	amount of energy, which required to heat ventilation (kWh)
q	the volume flow of the air (m^3/s)
r	the factor takes into account the operation during the period of 24 hours
t_d	the operation time in hours per day (h/24h)
$t_{exhaust}$	temperature of exhaust air ($^\circ C$)
t_{HR}	temperature of air after heat recovery ($^\circ C$)
$t_{outdoor,crit,\max}$	outdoor temperature above that temp. efficiency of HRU should be reduce ($^\circ C$)
$t_{outdoor,crit,\min}$	outdoor temperature below that temp. efficiency of HRU should be reduce ($^\circ C$)
$t_{outdoor}$	temperature of outdoor air ($^\circ C$)
t_{rec}	temperature of mixed supply air ($^\circ C$)
$t_{\sup ply,crit}$	the maximum necessary temperature after heat recovery ($^\circ C$)
t_w	the number of days operation per week (d/7d)
Δt	difference between indoor and outdoor temperature ($^\circ C$)
V_o	the volume flow of the fresh air which comes from outdoor (m^3/s)
V_{return}	the volume flow of the air which return through the damper (m^3/s)
V_s	the volume flow of the air which supply to the room (m^3/s)
ϕ	momentary heating demand (kW)
ρ	density of air (kg/m^3)
η_T	temperature efficiency (%)
η_a	annual energy efficiency (%)
τ	the duration of certain outdoor temperature per year (h)

1. INTRODUCTION

Ventilation system is one of the most important parts of every building. Ventilation should meet the requirements of national building codes.

Ventilation is divided into two types: natural and mechanical ventilation. Airflow that occurs under the influence of the temperature difference and, consequently, the difference between the densities and pressures of internal and external air, is called natural ventilation. Natural ventilation doesn't need electricity because it doesn't need fans. Unfortunately it depends on weather. When you use natural ventilation it is not possible to use equipment which cause pressure losses (because driving forces at the flows are very small). Every unit increase pressure loses. This is one reason why mechanical ventilation is more popular. Using it you can change flow, velocity, quality, temperature and humidity of air. Supply and exhaust systems can be turned on and off at any time. Unfortunately mechanical ventilation needs more energy than natural ventilation. Heat recovery unit can help to reduce energy demand.

Heat recovery units are used to maintain health and comfortable indoor climate with as low energy consumption as possible. It means that money is saved. In Finland annual efficiency of the heat recovery unit should be more than 45%.

The main purpose of this thesis work is to consider how the heat recovery unit in D-building works. In my analysis I use database of the automation system. The target of this work is to search errors in the system (if any exist) and try to improve efficiency of the heat recovery system.

In the part of theoretical background I describe types of the ventilation systems, units which are used in different cases. Process, which are needed to provide good indoor air. And the most popular heat exchangers types in Finland.

2 VENTILATION SYSTEMS

2.1 Conditioning of supply air

In addition to the supply fresh air to the rooms, ventilation should ensure the required air quality. The energy, which is necessary to maintain health are comfortable indoor climate in building can divided into three categories:

-Heating energy. Heating of outdoor air to the supply temperature during periods when the outdoor temperature is low.

-Cooling energy. Cooling of outdoor air to the supply temperature during periods when the outdoor temperature is high.

-Electric energy. Fan electricity, which is needed to move air.

Some times, it may be necessary to humidify (or dehumidify) the supply air, besides heating (or cooling). For example in hospitals or museums, where is needed special microclimate. Humidifying may be necessary also in climates with cold winter because low outdoor temperature means small amount of water in the air (low absolute humidity). When supply air is only heated, it will result in low relative humidity. Humidification of supply air complicates the HVAC system and increases considerably the heat supply needs. Also humidifying unit should be served very carefully to avoid bacteria growing.

2.2 Air handling units

Air handling unit is the element of the ventilation system which main function is derive needed amount of the filtered air to the building. It can also contain devices for air treatment. Usually air handling unit includes heat recovery unit. It passes heat energy from exhaust air to supply air. It means that demand of energy (or other resources) for heating (or cooling) supply air are reduced.

The six basic processes of air conditioning are cleaning of both particulate matter and gases from air, cooling air, heating air, humidifying air, dehumidifying air and mixing of air streams. /2. p389/

2.2.1 Filtration

Filter is the device which removes solid particulates such as dust, mold, pollen and bacteria from the supply air. Usually outdoor air contains these pollutions. Therefore filters are necessary for maintain good air quality and indoor environment in buildings. Filters are usually made of cloth, a special paper or electrostatic cloth. Air passes through a layer of filter material with small holes. Solid particulates which contains in the air has bigger diameter than holes and trapped in the filter. Cloth filters provide a good enough clean air only at low speeds of motion. Therefore surface of the filter should be big. To achieve a compact size of the filter, cloth usually pull a zigzag. For that vertical strut are used. This method of installation allows simple change of the filter.

Figure 1. Air filter /9/

For dust removal electrostatic forces can also be used. In electrostatic cloth filters special materials are used. When air goes through the filter dust rubs against the fabric and creates electric charge. This properties increase efficiency of the filter, because electrostatic forces can also trapped small particles which diameter smaller than holes.

There are two reasons for using filters. Preventing of penetration pollutions into the building and protecting parts of the ventilation system from impurity. Sometimes in industry filters are used to clean exhaust air.

Pressure drop of the clean filter is between 80 Pa and 120 Pa. Gradually filter becomes dirty. Pressure drop increasing therefore air flow decreasing. Finally a pressure drop reach value, which makes the filter more unfit for use and it should be changed. Usually filters include control device which automatically measure pressure drop in a filter. This unit can send a signal when pressure drop achieve certain value. Anyway filter should be changer at least twice a year even if pressure drop is not so high to prevent bacteria on a dirty filter. /10 p218/

2.2.2 Cooling

Cooling air is the automatic reducing indoors indoor air temperature to ensure optimal conditions for the well-being of people are safeguard valuables. There are many methods that are used for cooling.

Direct expansion uses energy of latent heat of the refrigerant. After expansion, pressure of the liquid refrigerant is reduced and it change phase to the saturated vapor. Refrigerant spent a lot of heat energy for phase changing and therefore cooled. Heat from air transfer to the refrigerant and temperature in the room become lower. /11 p2.3/

A **fluid-filled cooling coil** works without any phase change. Air is cooled only by the heat transfer between supply air and chilled liquid refrigerant in the pipes. If temperature in the pipes higher than dew point of the air where will be no condensation. Therefore humidity stay the same. **Chilled beams** work on the same principle. Usually they are located under the ceiling and cooling indoor air by transfer heat from it to the liquid flow.

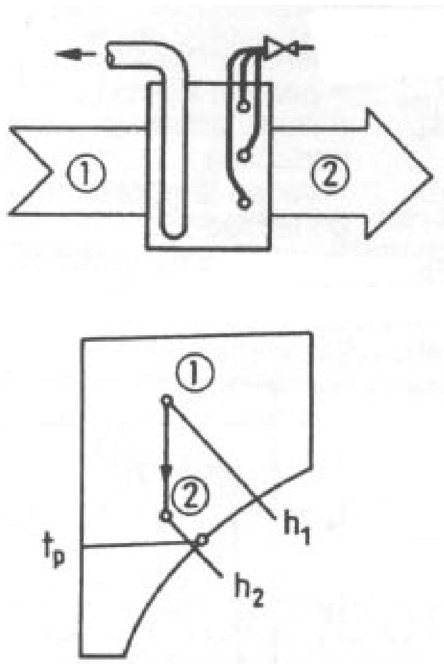

Figure 2. Process of the chilled air flow in the cooling coil on the Mollier diagram without condensation /12/

If surface temperature of the pipes, which are located in the cooling coil, is lower than the dew point water vapor will be condensed on the surface. If all the amount of the supply air will be in contact with chilled surface then state of air will be at point 3 (Figure 3). But it is impossible. Part of air transfers through the coil without contact with surface. Therefore air conditions should be on the line between point 1 and 3 (Figure 3) after mixing process. /12/

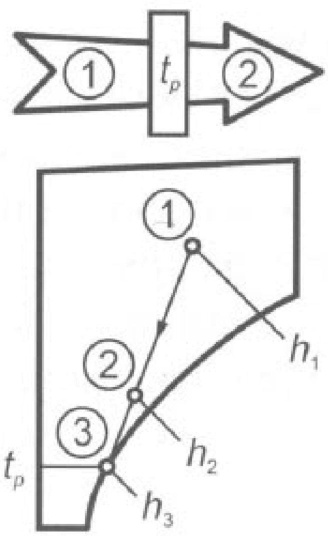

Figure 3. Process of the chilled air flow in the cooling coil on the Mollier diagram with condensation /12/

Some times surface temperature of cooling pipes is not constant water coil and it varies by temperature of the refrigerant. In this case the direction of the process is not straight line. It is changed step by step according with changing surface temperature./12/

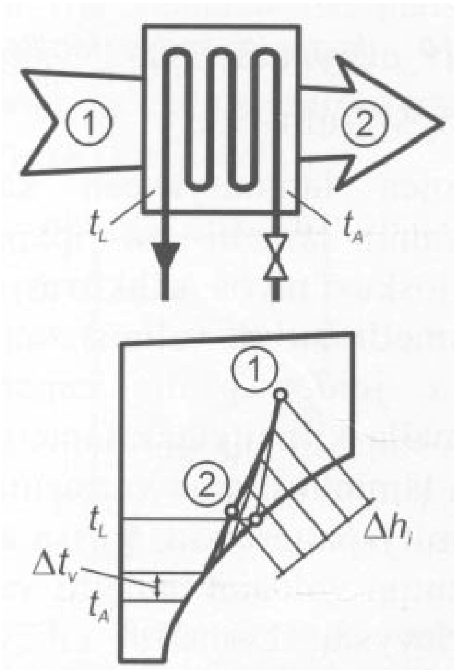

Figure 4. Process of the chilled air flow in the cooling coil on the Mollier diagram. With changing surface temperature at the coil /12/

“Direct spray of water in the airstream, an adiabatic process, uses the latent heat of evaporation of the water to reduce dry-bulb temperature while increasing moisture content.”/11 p2.3/ During this process sensible and latent cooling are used. This method is also used for humidifying supply air . Water is sprayed into the duct and part of the water evaporate and cool air. Water drops which has not evaporated goes to the conditioned space. It evaporate in the room space and carry out additional cooling and humidifying. It means that amount of needed air can be reduced. /11 p2.3/

Indirect evaporative cooling can be carried out by cooling exhaust air from the room space by spraying water. Then chilled exhaust air goes to the heat exchanger where takes heat from the supply air. In this method is used sprayed water for cooling air, but humidity of supply air don’t increase if heat exchanger is recuperative. Anyway if heat recovery unit is regenerative the humidity ratio increase less than with direct cooling by water spray) /11 p 2.3/

2.2.3 Heating

Heating coils are divided into two types. Heating coils with water circulating in the pipes and electric air heaters. First type use copper pipes through which flows hot water. The same principle as radiator. Other materials can also be used. Usually heating coil is equipped with fins. They increase surface of the heating parts. Air passes through the coil and heated. Electric air heaters are used the same, but except pipes with hot water they contain electric wires, which are heated when current goes through it. /3 p 414/

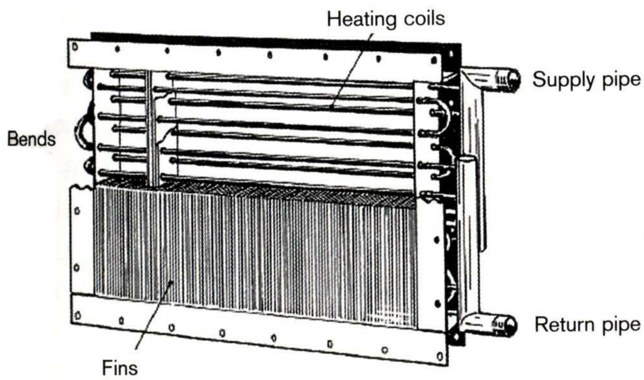

Figure 5. Heating coil (with circulation water pipes) /3. p413/

During the heating absolute humidity stays constant. Therefore line of the process goes straightly up. Figure 6 shows how it looks on the Mollier diagram. The same principle as in fluid-filled cooling coil but vice versa.

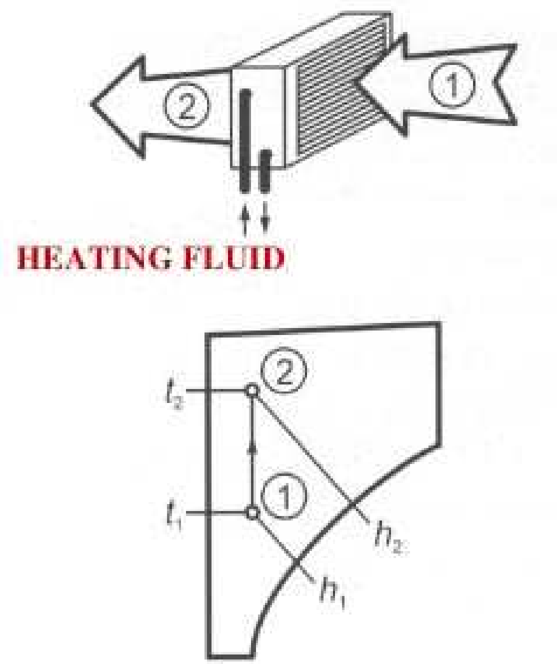

Figure 6. Process of the heating air flow in the heating coil on the Mollier diagram /12/

Another way is to the **heat supply air is by steam**. This method use latent heat of the fluid. When steam condensing, it gives up energy equal energy which was expended to the evaporation. Also steam moistens air. If should be heated and humidified it is most efficiency method.

2.2.4 Humidification

"The air flow can be humidifying using circulating water so that no heat transferred into or from the process in the humidifier. The system is insulated from the surroundings (adiabatic), so the enthalpy of the air will stay constant."/12/ Heat energy for evaporation water is taken from air. That why temperature of the air is reduced. In practice the process is not ideal and enthalpy slightly change. Using this method there is a risk to keep biological contaminants. Therefore it requires careful monitoring of the water conditions.

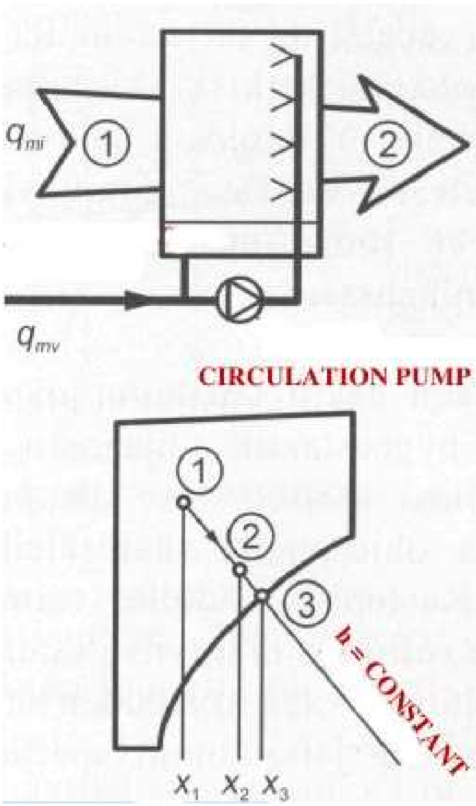

Figure 7. Process of the humidifying air flow on the Mollier diagram /12/

Humidification air by steam is more secure, in terms of biological contaminant risk. When steam is condensate it also passes heat to the air.

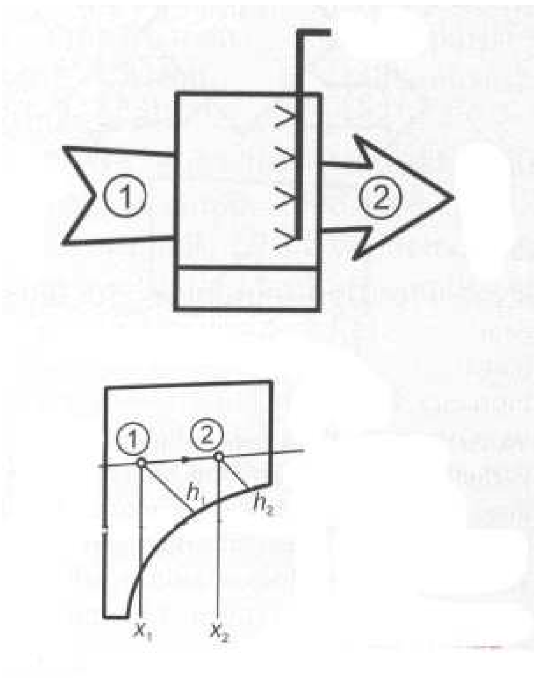

Figure 8. Process of the humidifying air flow by steam on the Mollier diagram /12/

2.2.5 Dehumidification

Wet air creates good conditions for bacterial and viruses. Also the best relative humidity of the indoor air for human being is 40-60%. Therefore in some cases is needed to decrease water content in the supply air. Moisture condenses on the surface which temperature lower than dew point of the air. Another way of dehumidification air is to spray into the airstream fluid with temperature below supply air. There are some chemical dehumidification methods are also used. /11 p2.5/

2.2.6 Different air handling unit

All those process can be illustrated on the Mollier diagram. In the basic air handling unit supply air is just filtered and heated. Also there are supply and exhaust air fans. This system can only clean and heat supply air when outdoor temperature is lower than recuired.
/2. p391/

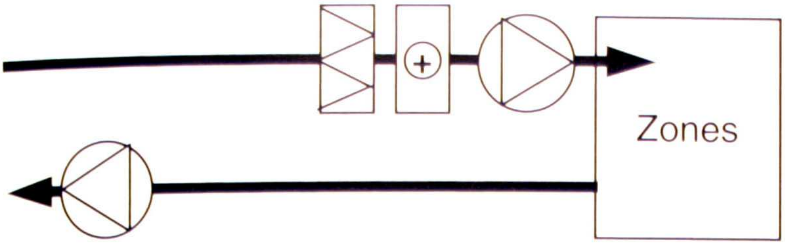

Figure 9. Air handling unit with heating coil and filters /2. p391/

More complex air handling unit is air handling unit with a cooling coil. Except heating it can cool supply air, when outdoor temperature is higher than required. Cooling coils are the same as heating coils, but they are used chilled water for cooling. /2. p391/

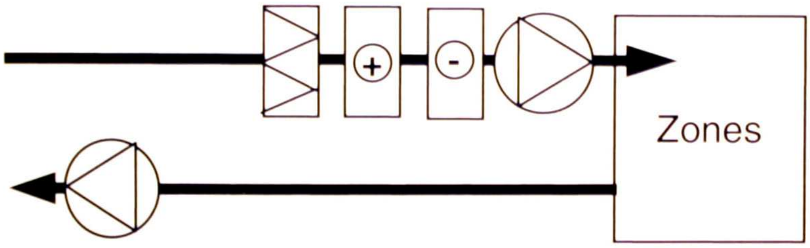

Figure 10. Air handling unit with heating and cooling coils /2. p391/

Air handling unit with heating coil, cooling coil and humidifier can maintain needed temperature and change humidity ratio. Air can be humidified by water or by steam. During the humidification by steam air is heated also. For humidification air by water is possible to use spray mist units or units of a porous material which is saturated with water.

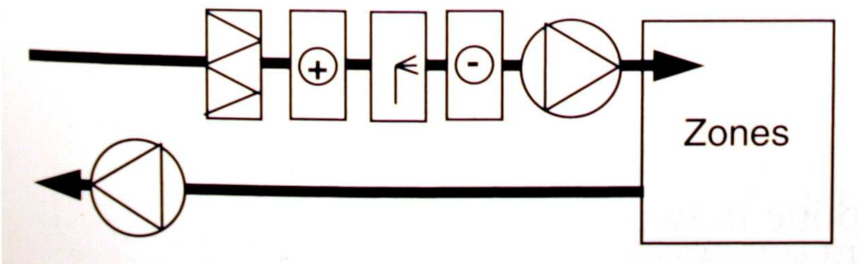

Figure 11. Air handling unit with heating, humidifying and cooling /2. p391/

Air handling unit in figure 12 has also reheating air coil. After humidifier temperature of supply air can be less than require. Reheating coil increases it to needed value. This air handling unit can achieve a fixed supply air temperature and humidity during the whole year. /2. p392/

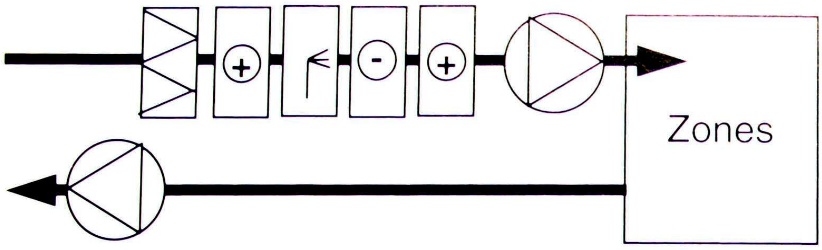

Figure 12. Air handling unit with Heating, humidifying, cooling and reheating /2. p392/

Figure 13 shows air handling unit with heat recovery and heating coil. This system can maintain the temperature if outdoor temperature is lower than needed with or without heating coil. But it is possible to add any needed device to this system. In previous cases system can works without exhaust fan, but when, heat recovery is used, exhaust air fan is required. If only supply fan is used, there is a rise that moisture penetrate to the constructions of envelope.

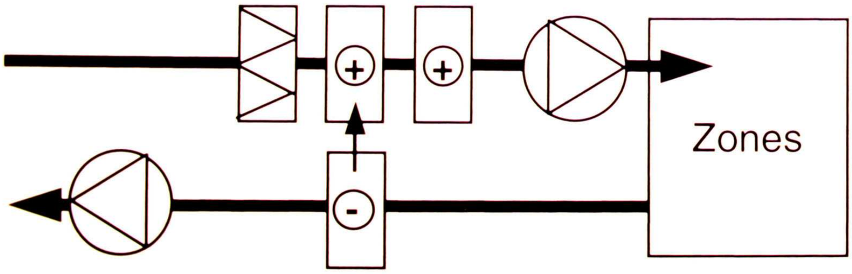

Figure 13. Air handling unit with heat recovery unit and heating coil /2. p392/

Usually air handling unit looks like big metal box which is connected with ducts. AHU is a part of mechanical ventilation system.

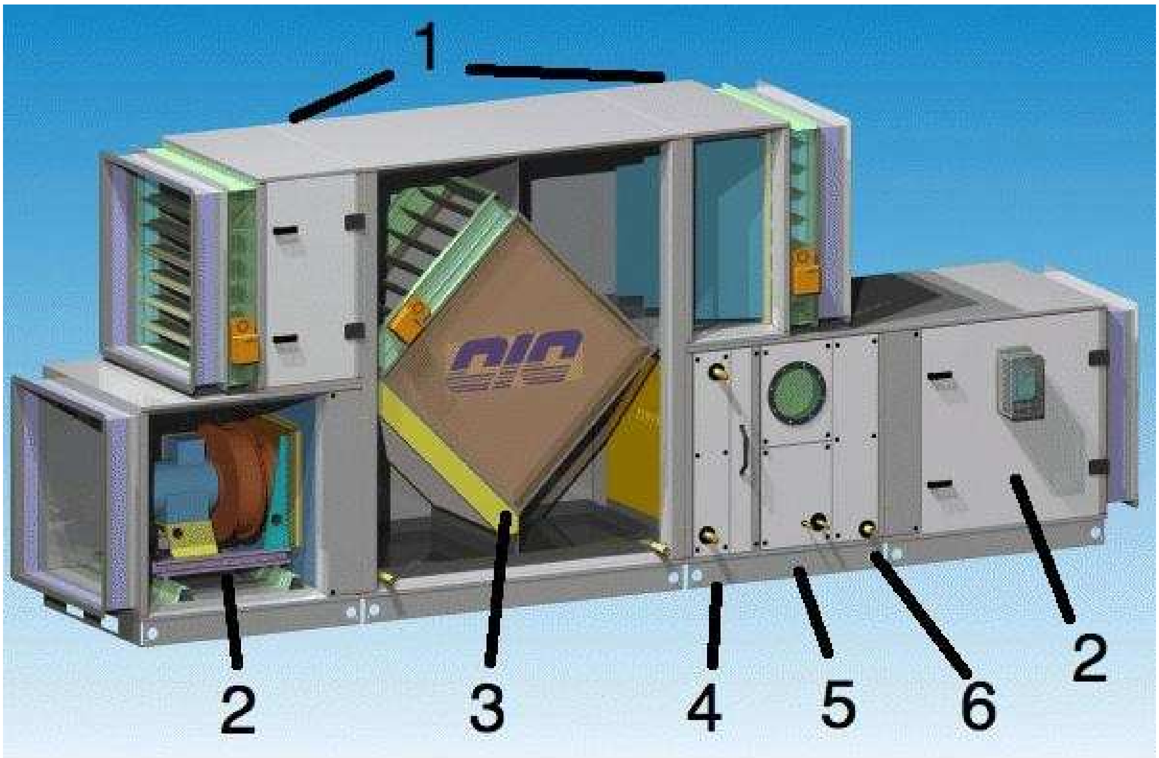

Figure 14. Air handling unit with cross flow heat exchanger (1. filters, 2. fans, 3. cross flow heat exchanger, 4. heating coil, 5. humidifier, 6. cooling coil) /7/

Figure 15 shows air handling unit without metal sheets and connection with ducts.

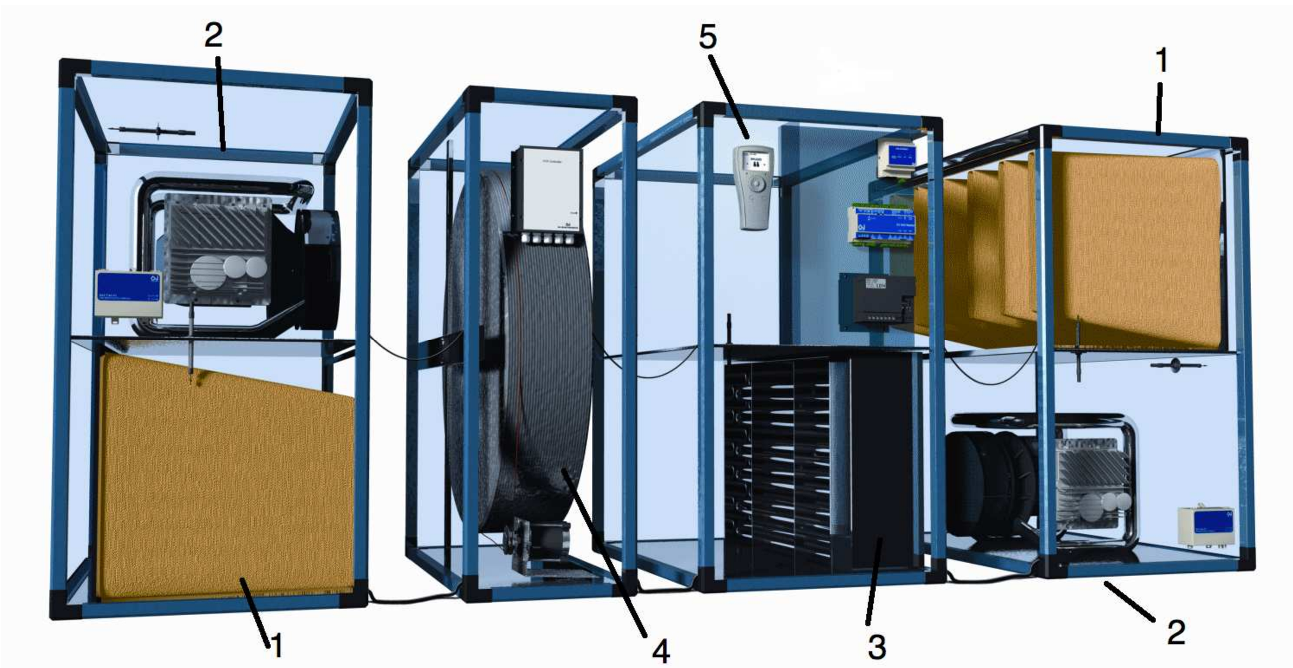

Figure 15. Air handling unit with rotary heat exchanger (1. filters, 2. fan, 3. heating coil, 4. rotary heat exchanger, 5. measuring unit) /8/

3 HEAT RECOVERY FROM EXHAUST AIR

3.1 Heat recovery from exhaust air by damper

To heat the air requires a lot of energy. The need of energy can be reduced by adding to system a heat recovery unit. It takes heat energy from exhaust air and gives it to supply air. The simplest way is just to provide damper between supply and exhaust air ducts. /2. p334/

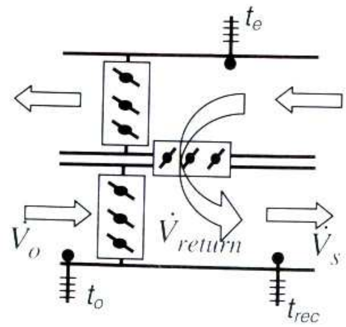

Figure 16. Heat recovery from exhaust air by damper /2.p 334/

Part of exhaust air goes through the duct and is mixed with supply air. The amount of return air is controlled by damper and can be expressed by a *return air factor* ***k*** **/2.p 334/**

$$k = \frac{V_{return}}{V_s} = \frac{V_s - V_o}{V_{supply}} \tag{1}$$

, where V_{return} is the volume flow of the air which return through the damper (m^3/s), V_o is the volume flow of the fresh air which comes from outdoor (m^3/s), V_s is the volume flow of the air which supply to the room (m^3/s) and V_{supply} is the volume flow of the air which supply to the rooms(m^3/s).

The total heat is sum of sensible heat and latent heat. The sensible heat is amount of energy released or absorbed by a substance during a change of temperature. (e.g. when you heat dinner it takes sensible heat). Latent heat is amount of energy released or absorbed by a substance during a phase change. It is called latent because when substance is getting or taking heat the temperature is not change. The total content of heat may be described by the enthalpy. The heat balance (enthalpy balance) for the mixing of air flows is

$$V_{Outdoor} \cdot \rho \cdot h_{outdoor} + V_{return} \cdot \rho \cdot h_{exhaust} = V_{\sup ply} \cdot \rho \cdot h_{rec} \quad (2)$$

Where

$$V_{outdoor} = V_{\sup ply} - V_{return} \quad (3)$$

And consequently the enthalpy of mixed supply air h_{rec} is

$$h_{rec} = h_{outdoor} + k(h_{exhaust} - h_{outdoor}) \quad (4)$$

,where ρ is density of air (kg/m^3), $h_{outdoor}$ is enthalpy of outdoor air (kJ/kg) and $h_{exhaust}$ is enthalpy of exhaust air (kJ/kg).

If the air is not change humidity content in the building and the supply air is not humidified or dehumidified, the enthalpy is about proportional to the temperature ($h \approx c_p t$). The temperature at the mixed air t_{rec} (no phase chase)

$$t_{rec} = t_{outdoor} + k(t_{exhaust} - t_{outdoor}) \quad (5)$$

where $t_{outdoor}$ is temperature of outdoor air ($^\circ C$) and $t_{exhaust}$ is temperature of exhaust air ($^\circ C$)

Heat recovery units are needed to minimize the input of energy to the whole system by the exchange of energy from exhaust air to supply air. They reduce heat demand and electricity consumption (if electric heaters (or chillers) are used). Therefore, amount of energy which needed to reheat air to required value is reduced. For than is possible to use smaller unit with lower cost. It considerably decrease investment cost.

The most popular heat exchangers in Finland are cross flow heat exchanger, heat recovery based on liquid circulation and rotating storing heat recovery. First two units are recuperative heat exchangers and the last one is regenerative.

3.2 Cross flow heat exchanger

In **Cross flow heat exchanger** heat is transferred **directly** from exhaust air to outdoor air through a plate that separates the air flows from one another. i.e. both ducts cross to each other in recovery unit. There is no mixing between the air flows. Both sensible and latent heat may be transferred latent heat when moisture in the exhaust air condensates on the heat exchanger. Moisture is not transferred to the supply air. Only fresh outdoor air goes to the rooms heated by exhaust air. The efficiency of the heat exchanger mostly depends on the size of the heat transfer surface area. Typical temperature efficiency η for cross flow heat exchanger is 0,5-0,8 /3 p.407/ In figures 17 and 18 there are examples of the cross flow heat exchangers.

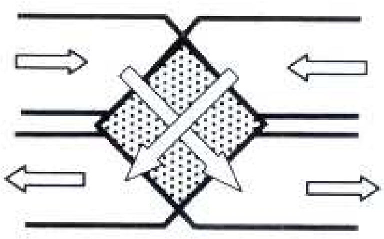

Figure 17. Principal scheme of cross flow heat exchanger /2.p 333/

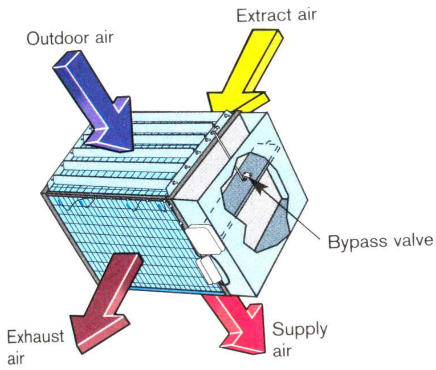

Figure 18. Cross flow heat exchanger /3.p 407/

This type of heat exchanger is recuperative, therefore humidity value stay constant. The supply air will receive the same amount of heat, which recovered from exhaust air. It can be calculated using formula 6. Figure 19 shows heat exchange process on the Molier diagram.

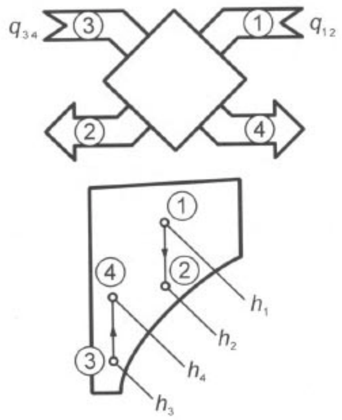

Figure 19. Heat exchange process on the Mollier diagram without condensation /12/

$$q_{4-3}(h_4 - h_3) = q_{1-2}(h_1 - h_2) \tag{6}$$

where q_{4-3} and q_{1-2} are exhaust and supply air flows and h are enthalpy of different flows.

If supply air is colder than exhaust air dew point temperature water vapor will be condensate in the heat exchanger. Except heat transfer exhaust air will be drying. The temperature rise of the supply air will be more than in the process without condensation.

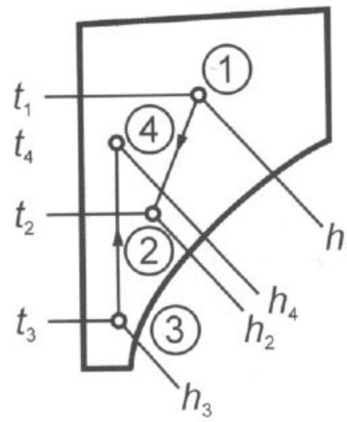

Figure 20. Heat exchange process on the Mollier diagram. With condensation /12/

3.3 Heat recovery based on liquid circulation

In **heat recovery based on liquid circulation** heat from the exhaust air is transferred to the supply air via circulating fluid. The circulating liquid consists of a 30-40% mixture of water and ethylene glycol. This type of heat exchanger can be used when impossible to cross ducts. Heat transfer is carried out by pipes with liquid, which can transport heat at some distance to other duct. Therefore it is indirect **recuperative** heat exchanger. Typical temperature efficiency η for indirect recuperative heat exchanger is $0{,}55-0{,}65$. /3, p. E407/

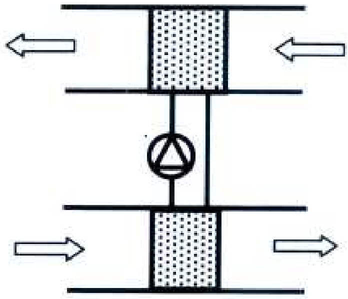

Figure 21. Principle scheme of heat exchanger based on liquid circulation /2.p 333/

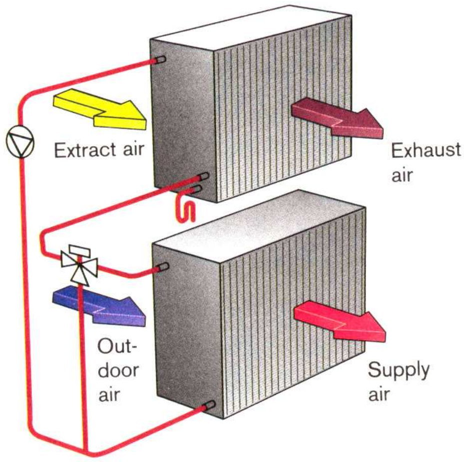

Figure 22. Heat exchanger based on liquid circulation /3.p 407/

This type of heat recovery is also recuperative and it has the same characteristics on the Mollier diagram.

3.4 Rotating storing heat recovery

Rotating storing heat recovery is **regenerative** heat exchanger containing a wheel which transfers heat from the exhaust air to the supply air (both sensible and latent heat). Hygroscopic wheels can also transfer moisture. For exchangers without hygroscopic wheels, the condensate is drained out. "The supply air flows through one half of the heat exchanger, and the exhaust air flows in counterflow through the other half. Supply and exhaust air goes through small holes in the wheel in opposite directions." /4 p.3/. If supply air must be humidified, rotating heat recovery reduce consumption for humidification, because moisture is also recovered. Times this type of heat recovery system is not always suitable for special places for example in hospitals or laboratories because this type heat recovery device also transfers small amounts of impurities. Typical temperature efficiency η for rotating is $0,5-0,85$. /3, p. E407/

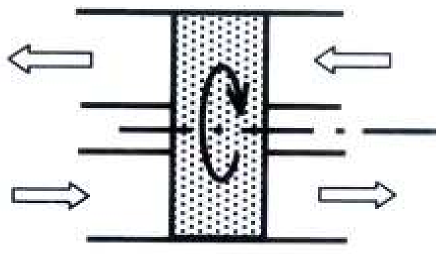

Figure 23. Principal scheme of rotary heat exchanger /2.p 333/

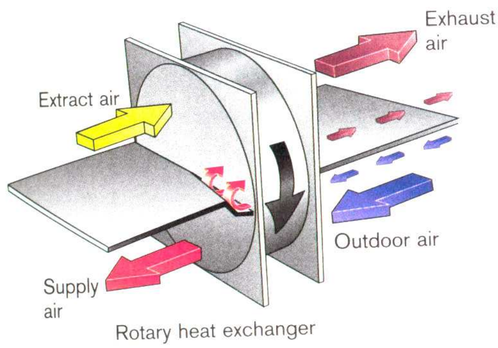

Figure 24. Rotary heat exchanger /3.p 407/

This type of heat exchanger is regenerative and it means that some amount of humidity from exhaust air transfer to the supply air.

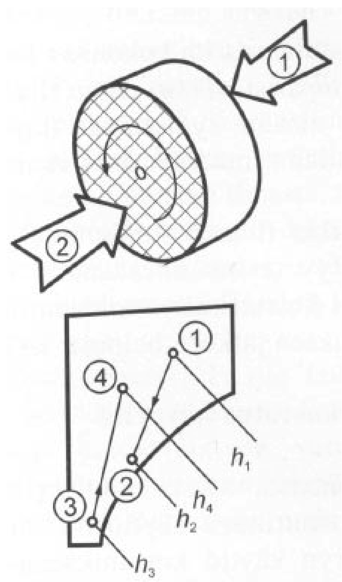

Figure 25. Heat exchange process on the Mollier diagram with moisture transfer /12/

3.4 Control of heat exchangers

There are some restrictions for the efficiency of heat recovery unit. If heat exchanger works with maximum performance When the temperature of outdoor air is high, the temperature of supply air will rise more than necessary. Therefore after certain temperature the efficiency should start to reduce.

Ways of reducing efficiency depends on type of heat exchanger:

- If we use **damper system** percentage of exhaust air should be reduced by regulating the dampers.
- Efficiency in **cross flow heat exchanger** can be adjusted by bypass which connects duct with outdoor air and duct after heat recovery.
- Efficiency in **heat recovery based on a liquid circulation** can be adjusted by reducing flow of liquid which transfer heat, usually with 3-way valve.
- Efficiency in **rotating storing heat recovery** can be adjusted by reducing speed of the wheel.

The highest outdoor temperature, when efficiency of the heat recovery may be maximum is with dampers /2. 336/

$$t_{outdoor,crit,\max} = \frac{(t_{supply,crit} - kt_{exhaust})}{1-k} \tag{7}$$

and with heat recovery unit

$$t_{outdoor,crit,\max} = \frac{(t_{supply,crit} - \eta_T t_{exhaust})}{1-\eta_T} \tag{8}$$

where $t_{supply,crit}$ is the maximum necessary temperature after heat recovery and $t_{outdoor,crit,\max}$ is the outdoor temperature above that temperature efficiency of heat recovery should be reduces.

When outdoor temperature is low, the supply air can take too much heat energy from exhaust air and temperature of exit air can decrease below zero. Because exit air consist some water, the water can condensate on surface of the heat exchanger, and if temperature is too low water will freeze. It is not permissible. According with D5 /1/ minimum allowed temperature for the t_{exit} is $t_{exit} = 0^{\circ}C$ for the offices and $t_{exit} = 5^{\circ}C$ for the dwellings.

To avoid freezing it is necessary to control efficiency of heat recovery. The ways are the same as in the previous chapter, but there are some additional methods for cross flow heat exchanger. In cross flow heat exchanger it is possible to pre-heat air before heat exchanger or turn-off supply air fan temporary.

The critical outdoor temperature can be found from the equation (with dampers)

$$t_{outdoor,crit,\min} = \frac{t_{exh}(k-1)+t_{exit}}{k} \tag{9}$$

with heat recovery

$$t_{outdoor,crit,\min} = \frac{t_{exh}(\eta-1)+t_{exit}}{\eta} \tag{10}$$

where $t_{outdoor,crit,\min}$ is the outdoor temperature when that temperature efficiency of heat recovery should be start to reduce. Between these two critical temperatures heat recovery may work with maximum efficiency. When outdoor temperature is more than temperature of exhaust air, heat recovery can be used for cooling supply air (night cooling). Heat recovery units are used almost during the whole year. Figure 26 shows useability of them.

In the figure 26 temperature efficiency of heat recovery is 75%, extract air temperature $24^{\circ}C$ and supply air temperature is $17^{\circ}C$. Air flows are constant. Heat is needed, when outdoor temperature is between -$30^{\circ}C$ and -$5^{\circ}C$. When outdoor temperature achieve approximately -$5^{\circ}C$ efficiency is start to reduces. When outdoor temperature is between 17 $^{\circ}C$ and $24^{\circ}C$ heat exchanger is turned off. When outdoor air temperature raises over $24^{\circ}C$, heat recovery unit is used to cooling building.

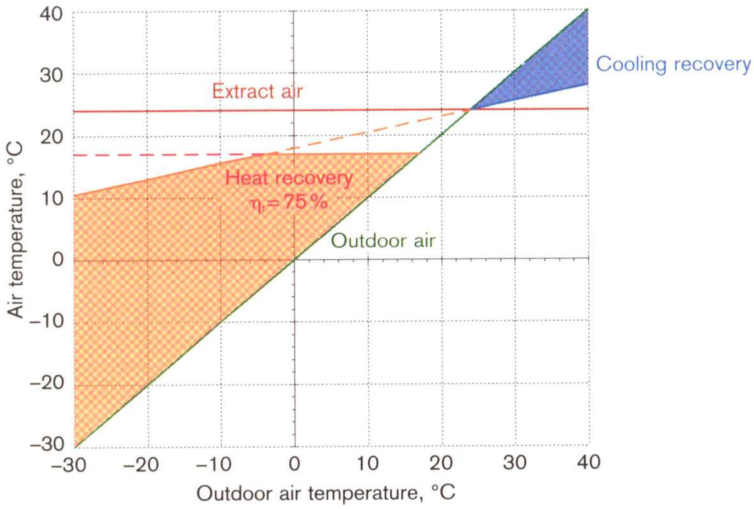

Figure 26. Temperature rise across the heat recovery unit as a function of the outdoor air temperature without preheating /3.p 408/

4. TEMPERATURE EFFICIENCY

Temperature efficiency can be calculated from the equation /3. p390/

$$\eta_T = \frac{t_{HR} - t_{outdoor}}{t_{exhaust} - t_{outdoor}} \qquad (11)$$

,where $t_{outdoor}$ is temperature of outdoor air ($^\circ C$), $t_{exhaust}$ is temperature of exhaust air ($^\circ C$) and t_{HR} is temperature of air after heat recovery ($^\circ C$). If the temperature efficiency is known the supply air temperature after heat recovery can be calculated from the equation

$$t_{HR} = t_{outdoor} + \eta_T (t_{exhaust} - t_{outdoor}) \qquad (12)$$

In figure 27 left diagram shows temperature changes during the year in chronological order. Right one shows the duration of specified temperature or less during the year.

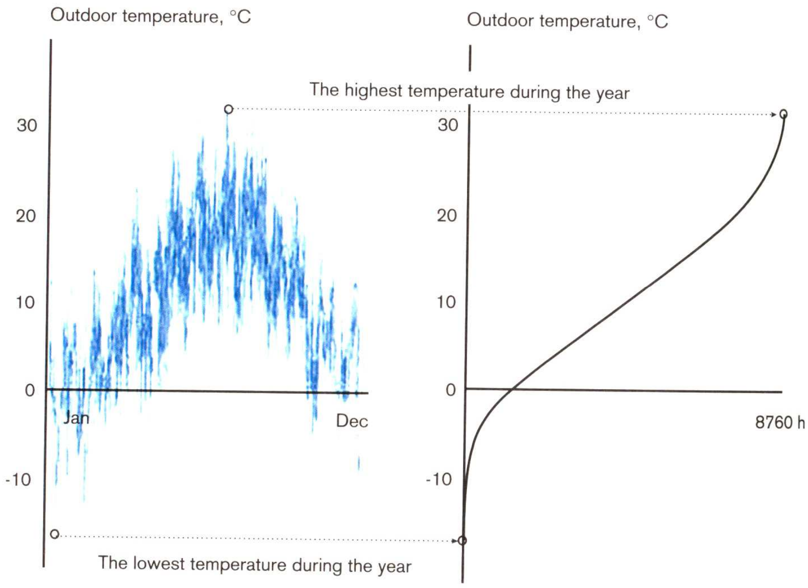

Figure 27. Example of Outdoor temperature chronological and duration curves /3.p 388/.

5. DURATION CURVE, VENTILATION HEAT DEMAND AND ANNUAL EFFICIENCY

The annual efficiency of heat recovery (η_a) depends of climate and may be calculated by outdoor temperature duration curve. According the Finnish norms minimum annual efficiency of heat recovery is 45%. The annual efficiency of heat recovery can be calculated from the temperature efficiency η_T .

Outdoor temperature duration curve can be drawn using the data of outdoor temperature values during the whole year, where we know number of hours during which the outdoor temperature is the same or lower than the specified value. If the values for the duration are plotted as a function of time, a duration curve will be obtained. Different geographical regions have different curves". /4, p 8/

Using duration curve (figure 28) it is possible to calculate the amount of energy requirement (needed to heat the outdoor air to the room temperature)

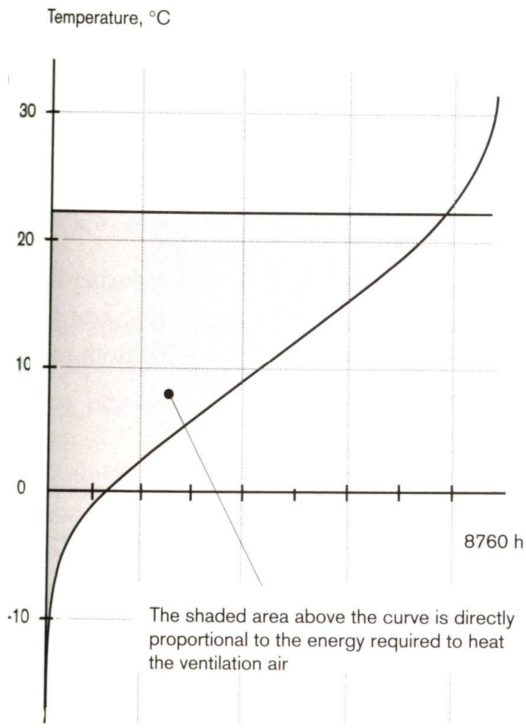

Figure 28. A graphical illustration of energy required to heat ventilation air /3.p 389/

The vertical distance between horizontal line and the curve in the graph is the difference between indoor and outdoor temperature. It is proportional to heating demand of the ventilation

$$\phi = q \cdot c_p \cdot \rho \cdot \Delta t \tag{13}$$

,where ϕ is momentary heating demand of (kW), ρ is density of air (kg/m^3), c_p is the specific heat capacity (kJ/kg$^\circ K$), Δt difference between indoor and outdoor temperature and q is the volume flow of the air (m^3/s). If we consider very short time period, we can suppose that the outdoor temperature is constant and we cant calculate energy of the time period. If we know the volume flow, using this graph we can calculate power requirement in every point with certain temperature difference

$$Q = c_p \cdot \rho \cdot q \cdot \Delta t \cdot \tau \tag{14}$$

,where τ is the time period, when the outdoor air temperature is supposed to be constant. By this way with short time period we can calculate the annual heat energy demand (kWh) at the ventilation (summing short time periods)

If the system contains heat recovery unit supply is air heated by the exhaust air and heating demand of supply air is reduced. This is illustrated in the figure 29.

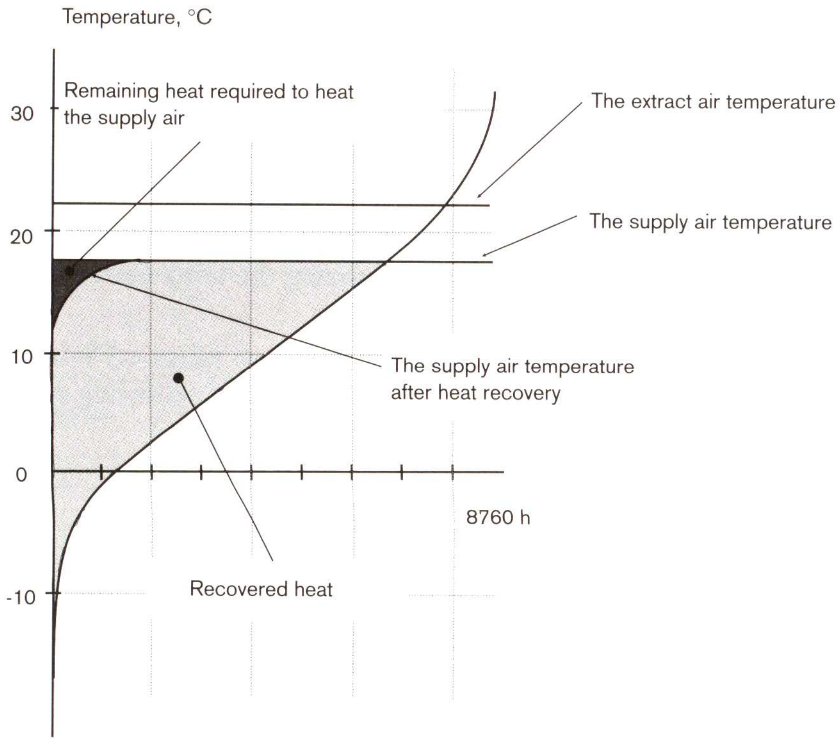

Figure 29. Energy requirement for heating air after heat recovery /3.p 392/

In the figure 29, the dark area represents amount of heat which is needed to heat after tha heat recovery. The light shaded area shows amount of heat which is recovered from the exhaust air with the heat exchanger. Annual efficiency in this diagram is 75%. Also it means, of course, money saving.

5.1 The calculation of annual energy efficiency of heat recovery

There are different ways to calculate annual energy efficiency of heat recovery. The first method is simple and rough. Manufacture which produce heat recovery unit should gives temperature ratio (temperature efficiency η_t) of heat recovery according to EN 308. Annual efficiency should be at least than 45%. The annual efficiency according to national building code can be calculated from equation /6/

$$\eta_a = 0{,}6 \cdot \eta_t \qquad (15)$$

The other method based on the duration curve /6/

$$\eta_a = \frac{Q_{HR}}{Q_{vent}} \tag{16}$$

, where Q_{HR} is the heat energy utilized from heat recovery (kWh) and Q_{vent} is the energy demand for ventilation (kWh)

Energy demand of ventilation is

$$Q_{vent} = c_p \cdot \rho \cdot q_{exhaust} \cdot (t_{exhaust} - t_{outdoors}) \cdot \tau \tag{17}$$

And heat energy utilized from heat recovery

$$Q_{HR} = c_p \cdot \rho \cdot q_{\sup ply} \cdot (t_{HR} - t_{outdoors}) \cdot \tau \tag{18}$$

or

$$Q_{HR} = c_p \cdot \rho \cdot q_{exhaust} \cdot (t_{exhaust} - t_{exit}) \cdot \tau \tag{19}$$

6. MEASUREMENTS

Building automation system in the D-building stored measurements of the temperatures before and after heat recovery unit, supply and exhaust air flows and heat and electricity consumption. According this data it is possible to analyze functioning of the heat recovery unit.

Figure 30 shows changing of annual energy efficiency during the whole October. Automation log data every hour and therefore it is reasonably accurate diagram. In the first half of the month the system is not stable. After two weeks efficiency become approximately stable, except some days, when its too low. According of the figure 30 it is difficult to determine the cause of the fluctuation, and it is necessary to analyze other characteristics of the heat recovery.

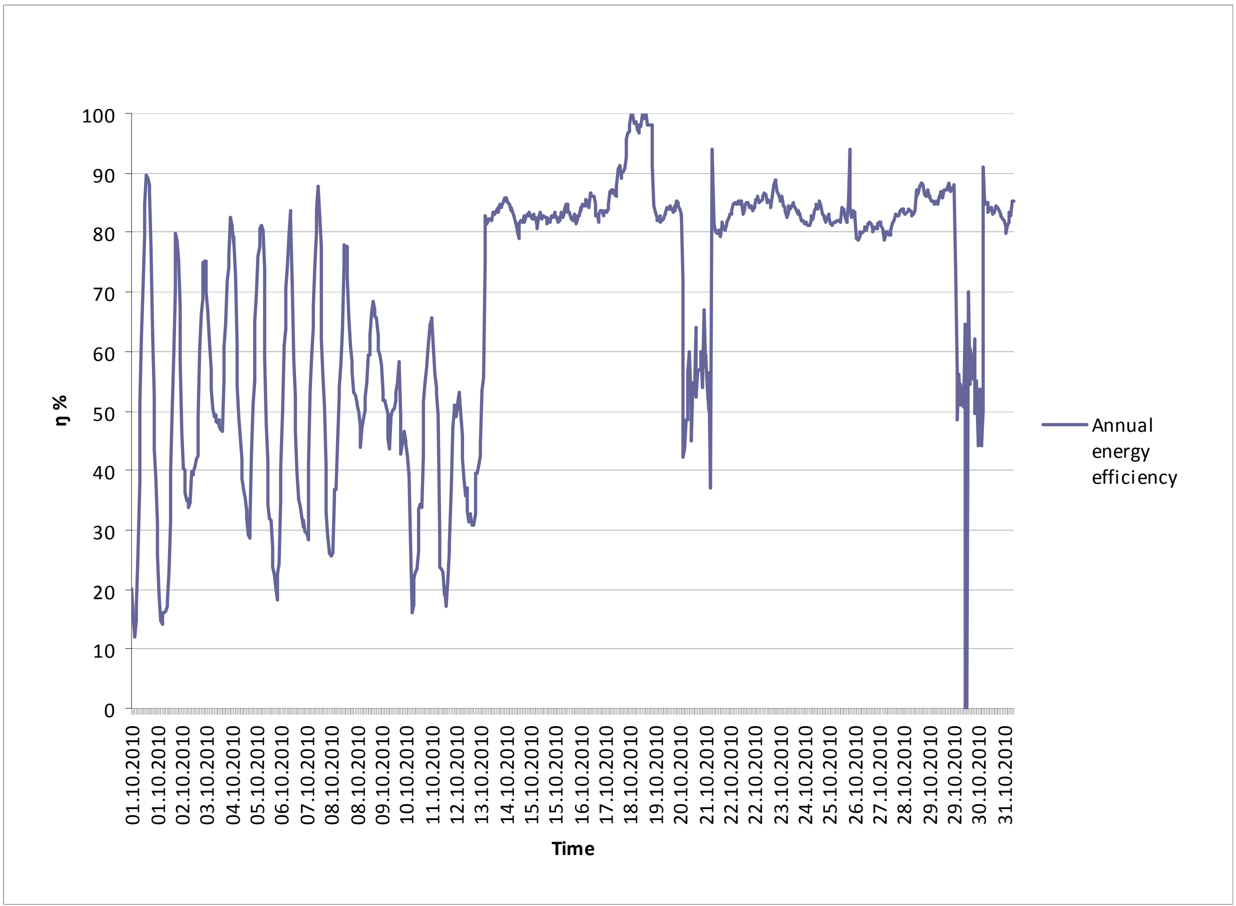

Figure 30. Annual energy efficiency of the heat recovery unit in October

Figure 31 shows heat energy demand for ventilation and utilized energy from heat recovery. In the first part of the month vibration of the Q_{HR} curve is bigger than Q_{vent} curve especially first three days. In the second part of the month wavering is also big but curves do it approximately equal.

According to this it is possible that rapidly fluctuation annual energy efficiency of the heat recovery unit (vibration at the beginning of the month) is due with Q_{HR}. According with equation (18) Q_{HR} depends on t_{HR}, $t_{outdoor}$ and q_{supply} (except constant c_p and ρ).

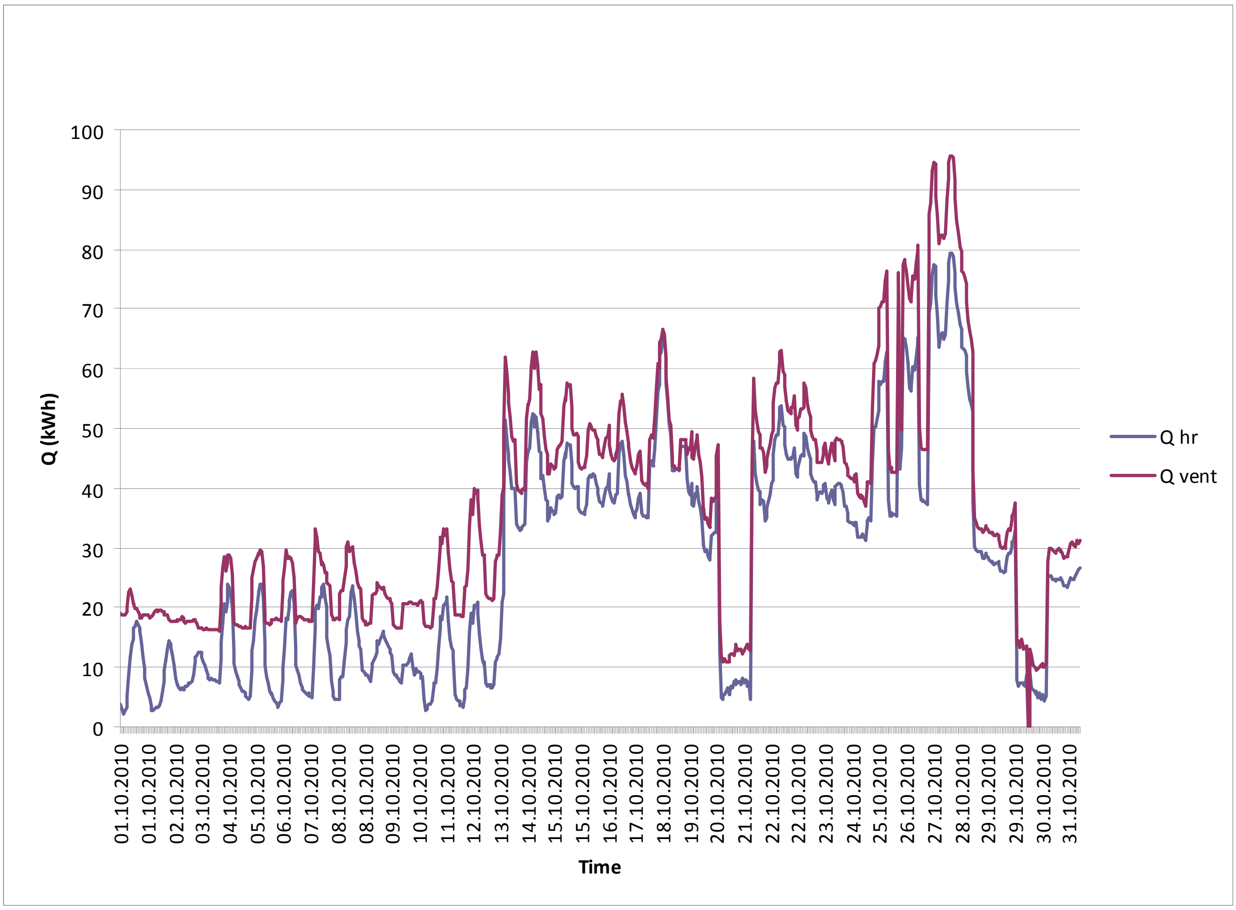

Figure 31. Heat energy demand for ventilation (Q_{vent}) and utilized energy from heat recovery (Q_{HR})

The air flows changes synchronously during whole month (Figure 32). Some first days they are approximately constant, that why $q_{\sup ply}$ can't be the reason vibration of the annual energy efficiency at the beginning of the month. At 20 and 21 of October air flows are too low and at 30 of October the flows become zero. Annual energy efficiency decreasing approximately at the same time.

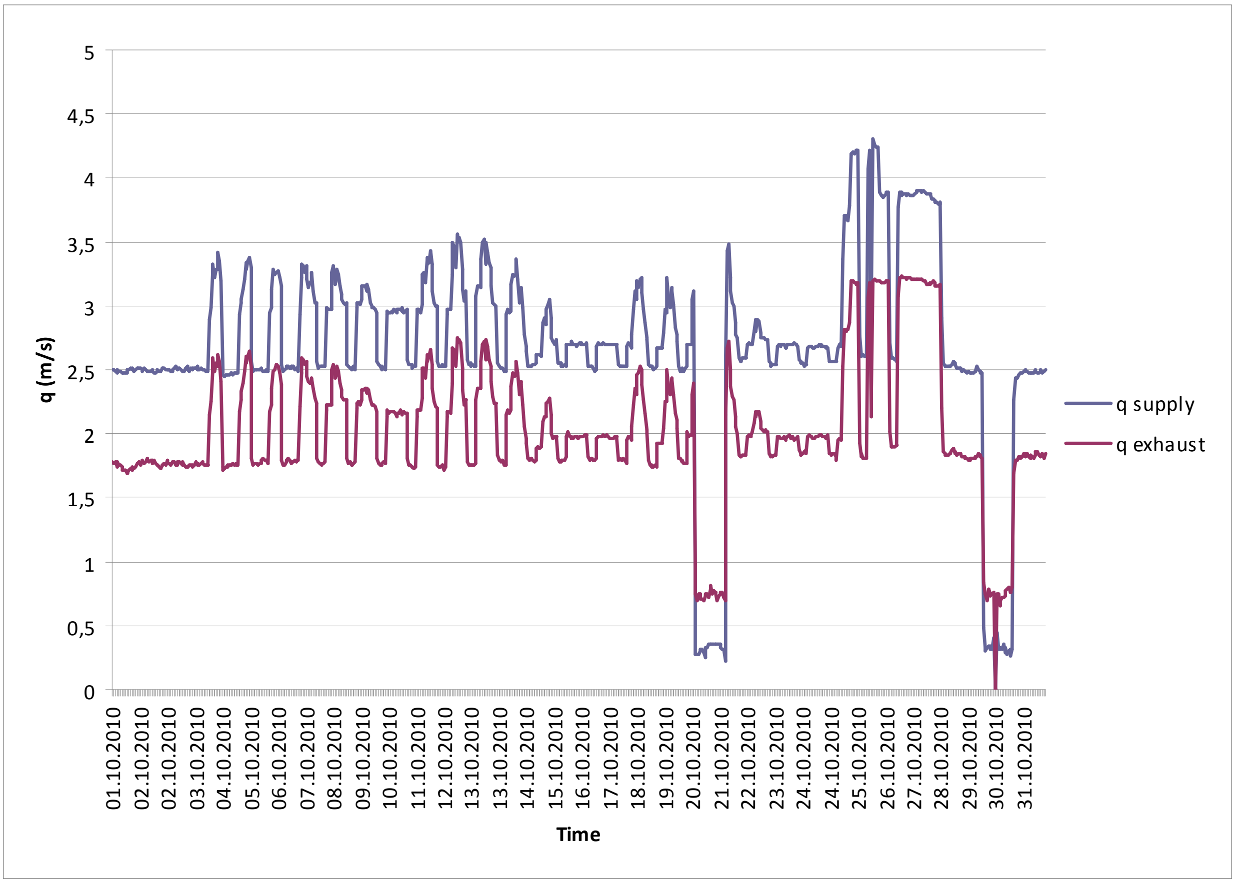

Figure 32. Supply and exhaust air flows

In figure 33 there are curves of the temperature of air after heat recovery (t_{HR}) and outdoor temperature ($t_{outdoor}$). There is also curve which shows difference between this both and the calculated exit air temperature (t_{exit}). First 13 days of the October outdoor temperature difference is low, but temperature after heat recovery is changing rapidly. This fluctuation is the reason of changing heat energy utilized from heat recovery Q_{HR} and energy efficiency η_a. It can be happened because of wrong automation settings. At the beginning of the month when temperature of supply air achieved maximum value automation changed speed of the rotation wheel. It helps to reduce temperature after heat recovery and annual energy efficiency. But after that t_{HR} had reached too low value, before automation increased rotation speed again. During October 20-21 supply temperature achieved 23 $^\circ$C and 30 of October 24 $^\circ$C. Air flows reduced at the first case and reached 0 $^\circ$C at the second. It is not possible with the correct settings of the automation system. Usually supply air temperature should not exceed 17-18$^\circ C$. It is possible that the settings are changed manually in these days.

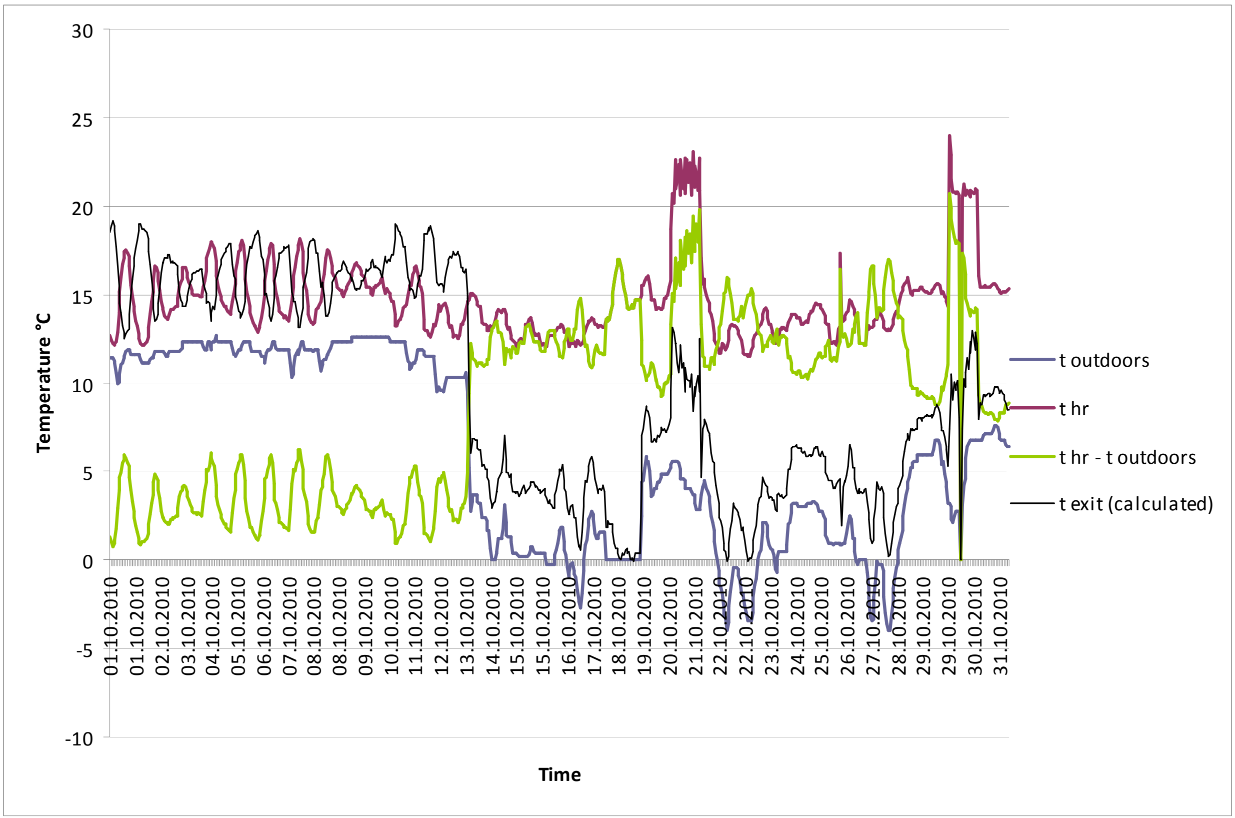

Figure 33. Outdoor temperature $t_{outdoors}$, temperature after heat recovery t_{HR}, difference between temperature after heat recovery $t_{HR} - t_{outdoors}$ and outdoor temperature and calculated temperature of exit air t_{exit}

6. CONCLUSION

Based on data from automation it can be concluded that the reason of malfunctioning of heat recovery unit is incorrect settings in automation systems. Fluctuation in the diagram of the annual energy efficiency in the first part of the month is the reason of incorrect changing speed of the rotation wheel. The change in itself is not a problem, because there is a limit of the supply air temperature. But after reduce temperature efficiency of the heat exchanger supply air temperature become too low value. It is a reason of big vibration at the beginning of the month.

After 13th of October annual energy efficiency of the heat exchanger is exceeds 80% and did not fall below, except for short periods. It is explained by the fact that at the same time, the outdoor temperature dropped down and supply air temperature didn't reach limit temperature anymore. Functioning of the system was correct during the second part of the October (except for short periods).

Main reason for wrong functioning of the heat recovery is the incorrect automation system settings. So, it can happen at high outdoor temperatures (at least higher than 10 °C). It is necessary to correct settings to reach right functioning during whole year.

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