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EFFICIENCY OF AIR HANDLING UNIT IN X-BUILDING

Bachelor's Thesis

Building Services Engineering

April 2012

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DESCRIPTION

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Date of the bachelor's thesis

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Degree programme and option

Building Services Engineering

Name of the bachelor's thesis

Efficiency of air handling unit of X-building

Abstract

The subject of this thesis is energy efficiency of air handling unit in X-building of MUAS. One of the aims of this work is to describe different equipment, which is in common to use in air handling. Some processes, which take place in air handling unit, will be described. Next, and main aim is to compare existing AHU with alternatives and define the most effective configuration.

It was necessary to make some measurements and calculations to compare AHUs. All measurements are described and calculations were made according to the National Building Code of Finland D5 and Ministry of environment of Finland.

As a result of comparison AHU equipped with counter-flow plate heat recovery was defined as the most effective variant with annual energy efficiency of whole ventilation system almost 63%.

Subject headings, (keywords)

Ventilation, heat recovery unit, efficiency of heat recovery, air handling

Pages	**Language**	**URN**
30	English	

Remarks, notes on appendices

Tutor

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CONTENTS

NOMENCLATURE

c_p	specific heat capacity;
d	internal diameter of the duct
η_t	temperature ratio
$\eta_{t\ a}$	actual temperature ratio
ΣQ_{LTO}	sum of heat recovery energy for all outdoor temperatures
Q_{LTO}	energy recovered from ventilation
$\Sigma Q_{exhaust}$	sum of energy needed for ventilation
Q_{iv}	net heating energy for ventilation
$Q_{iv,\ make-up}$	heating make up air in a space
$Q_{iv,\ supply}$	heating of supply air in a space
q_v	volume flow of air stream
$q_{v\ make-up}$	make-up air volume flow
ρ	density of the air
t_d	operation time during the day
T_{ib}	temperature of inblown air
T_{out}	mean outdoor air temperature during month (given in D5)
t_{pLTO}	temperature of exhaust air after heat recovery unit
t_s	indoor air temperature
t_{tLTO}	temperature of supply air after heat recovery unit
t_u	outdoor air temperature
t_v	operation days during the week.
τ	duration of certain outdoor temperature in hours
V	velocity of air stream

1. INTRODUCTION

To achieve comfortable indoor climate, it is very important to have good designed ventilation system according to all requirements.

There are two main types of ventilation systems: natural and mechanical ventilation. To choose one of them you should make a chose about your priorities like efficiency or economy. For example natural ventilation is low cost system but it can work in wrong direction because it is based on pressure difference between indoor space and outdoor conditions. This kind of system has not any fan or other forcing mechanisms. So in case of unsatisfying weather conditions natural ventilation may works wrong. If you need good performance ventilation system your chose should be - mechanical ventilation. This type of ventilation is divided into two: mechanical exhaust, mechanical supply and exhaust ventilation. The first one is cheaper than last, but it may not meet requirements. Mechanical exhaust and supply ventilation systems are the most expensive (as an investments, as an operation costs), but it has the best performance. It is very useful to use heat recovery in air handling unit. It is a special equipment which allows save a lot of energy on heating and cooling of supply air. There are a lot of different kinds of heat recovery unit. One of it is applied in air handling unit of X-building.

This thesis work consists of three main parts: theoretical research, measurements of parameters of the air handling unit (AHU) in X-building and calculation of existing heat recovery system as well as other type of heat recovery.

In theoretical part reader can familiarize with a review about main parts of ventilation systems, which exactly handle the air and make it up. Some processes of air conditioning are described. This part is necessary for understanding how different types of heat recovery units work and what kind of equipment is better to use in some special cases.

In next part of this thesis it is possible to find out information about measurements, which were made during the work. It is also described in this part how much results of measurements are different from data given by automation of air handling unit of X-building. Certainly all reasons of differs are explained.

The last part of my thesis work is about calculations. All calculations are necessary to get the values of annual energy efficiency. After all explanations two examples are described: existing heat recovery applied in X-building and alternative type of heat recovery as well. And finally it was found out what kind of these two systems is more efficient

.

2. THEORETICAL BACKGROUND

To rich certain air conditions for supply air specialists use different kinds of air handling units. There are often several ways to get required temperature and humidity. It is also in common to use special devices for energy saving. All these points are described in following paragraphs.

2.1 Air filters

Nowadays indoor air quality (IAQ) means a lot and there is a lot of attention paid for this criteria. One of the most important things of IAQ is cleanliness of supply air. That is why most of ventilation systems are equipped with air filters. There is also other reason to install air filters in the system: to minimize risk of break moveable parts of system like fans or heat recovery units due to dust, small leaves etc. /1 p.372./

There are some different types of air filters used in ventilation systems: bag or pocket filters, pad filters, panel filters, roll filters, particulate air filters etc. Every kind of filters has a range of size of particles, which are removed by this equipment. It is also possible to use one-stage or several-stage cleaning. Obviously several-stage cleaning provides better purification, but bigger operation and investment costs as well. It is usual to have several stage air filtering. Every next stage’s filter removes less size particles comparing with previous one. There are three stages defined:

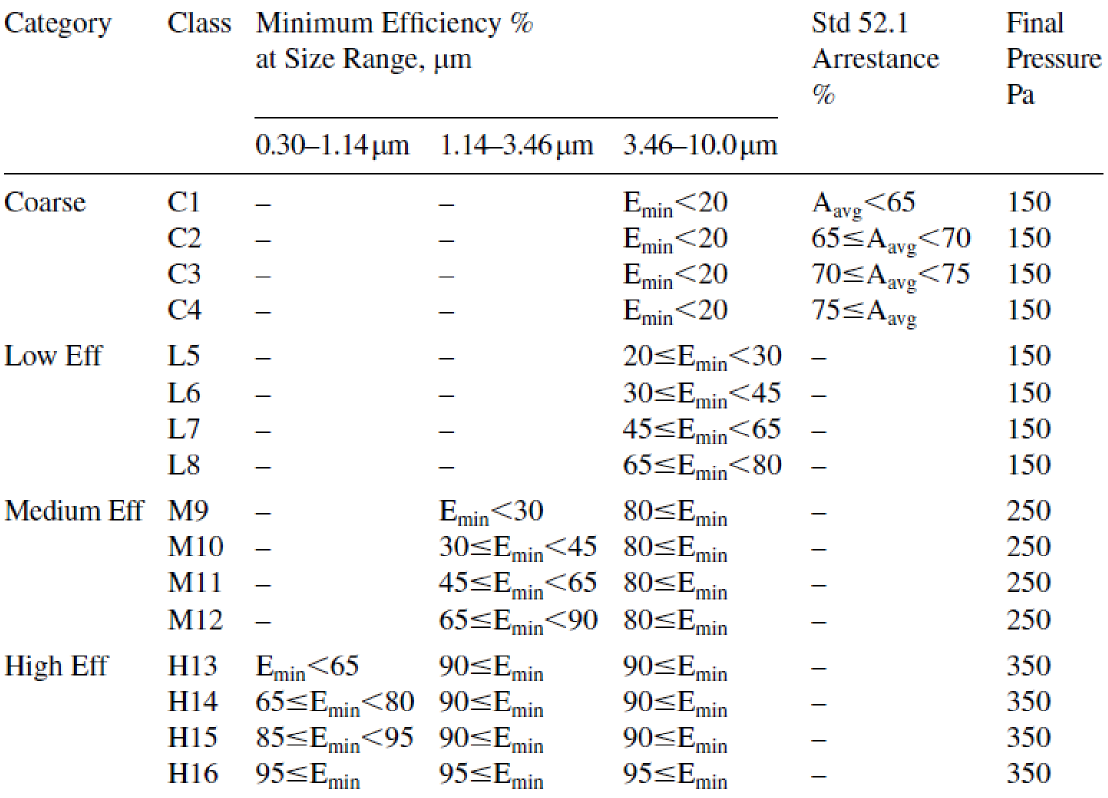
- primary stage filters remove majority of particles with size of 5-10 μm;
- next stage filters provide cleanliness from particles of 0,5-5 μm size;
- last stage is provided with low air velocity high efficiency particulate air HEPA-filters./1 p.372./

Special electrostatic equipment could be also used to remove low-size dust from the air stream. It is possible to use it effectively with much higher air velocity comparing with HEPA-filters. /1 p. 373./

But if we are talking about energy efficiency of air handling unit it is necessary to mention about pressure drop of air during the way through the filters. Higher pressure drop means more energy needed to blow air through the system. And according to

ASHRAE 52.2 classification, which is described in table 1, high efficiency filters have high value of pressure drop. That is why to provide good IAQ more energy is needed.

Table 1. ASHRAE 52.2 classification of filters / 1 p.374./



Category	Class	Minimum Efficiency % at Size Range, µm			Std 52.1 Arrestance %	Final Pressure Pa
		0.30–1.14 µm	1.14–3.46 µm	3.46–10.0 µm		
Coarse	C1	–	–	$E_{min}<20$	$A_{avg}<65$	150
	C2	–	–	$E_{min}<20$	$65\leq A_{avg}<70$	150
	C3	–	–	$E_{min}<20$	$70\leq A_{avg}<75$	150
	C4	–	–	$E_{min}<20$	$75\leq A_{avg}$	150
Low Eff	L5	–	–	$20\leq E_{min}<30$	–	150
	L6	–	–	$30\leq E_{min}<45$	–	150
	L7	–	–	$45\leq E_{min}<65$	–	150
	L8	–	–	$65\leq E_{min}<80$	–	150
Medium Eff	M9	–	$E_{min}<30$	$80\leq E_{min}$	–	250
	M10	–	$30\leq E_{min}<45$	$80\leq E_{min}$	–	250
	M11	–	$45\leq E_{min}<65$	$80\leq E_{min}$	–	250
	M12	–	$65\leq E_{min}<90$	$80\leq E_{min}$	–	250
High Eff	H13	$E_{min}<65$	$90\leq E_{min}$	$90\leq E_{min}$	–	350
	H14	$65\leq E_{min}<80$	$90\leq E_{min}$	$90\leq E_{min}$	–	350
	H15	$85\leq E_{min}<95$	$90\leq E_{min}$	$90\leq E_{min}$	–	350
	H16	$95\leq E_{min}$	$95\leq E_{min}$	$95\leq E_{min}$	–	350

2.2 Fans

Fans are one of the main parts of every mechanical ventilation system. It is the very device which blows air through the whole system. There are five types of fans which are mostly used in ventilation systems:

- axial flow;
- centrifugal flow;
- mixed flow;
- tangential flow;
- ring shaped. /2 p. 22./

All these types of fans are described on figure 1.

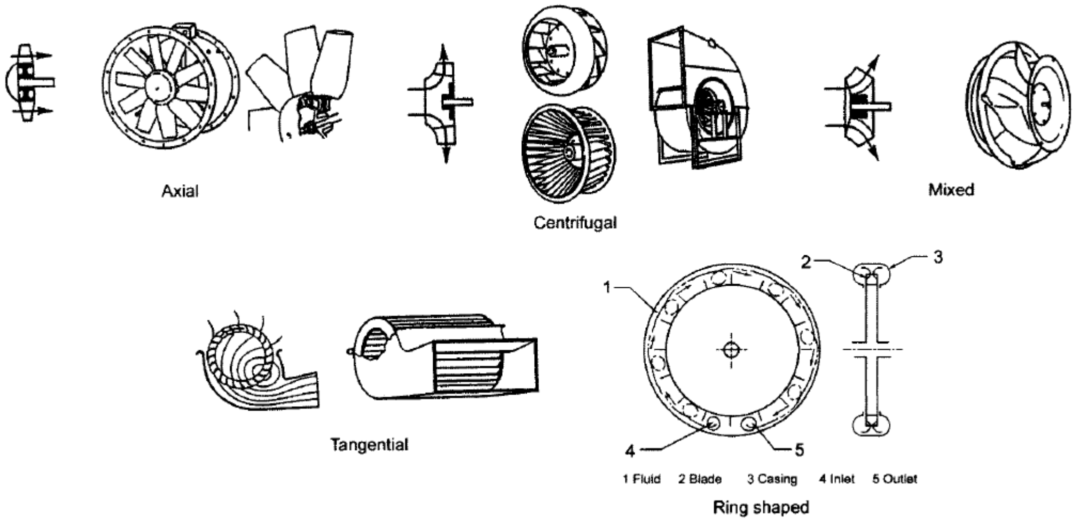


Figure 1. Types of fans /2 p. 22./

However in application to air handling units first three types are mostly in use. That is why more attention will be paid to them in the next paragraphs.

2.2.1 Axial flow

Axial flow is one of the most used in ventilation. It is common to install axial flow fans on round duct because of shape. This kind of fan mainly consists of two parts: impeller and electrical motor. Impeller may have different number and shape of blades. Mostly this amount is from 3 up to 12 blades. Figure 2 describes that blades are turned that way to push air stream in direction, which parallel to the axis of impeller’s spinning. This kind of fan is cheap to produce, moreover it has great efficiency up to 85%, if it is equipped with special cylindrical case around the impeller. /11 p. 22, 26-30./

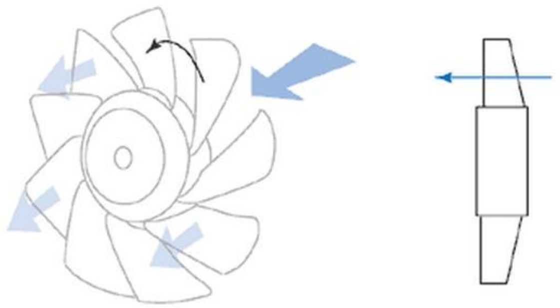


Figure 2. Impeller of axial flow fan / 3./

2.2.2 Centrifugal or radial flow

This kind of fans is mostly used in systems with high pressure drop, because special construction of impeller, which provides very high pressure. Special characteristics of radial flow fan depend on impeller and blades shape. It may be bent backward, forward, may be straightly radial or straight tilted backwards.

Bent backwards type of impeller makes centrifugal fans very efficient (up to 80%) at the low noise level, however it is not recommended to use it with dirty air. It is mostly in common to use straight blades tilted backwards to blow dirty air. Maximum efficiency of this kind of equipment is 70%. Straightly radial blades reduce collecting dust and dirt on the impeller, it reduces maintenance cost, but its efficiency is about 55%. And last type of impeller with blades bended forwards makes possible to reduce size of fan and motor. Efficiency of this kind of fan is up to 60%. /3./

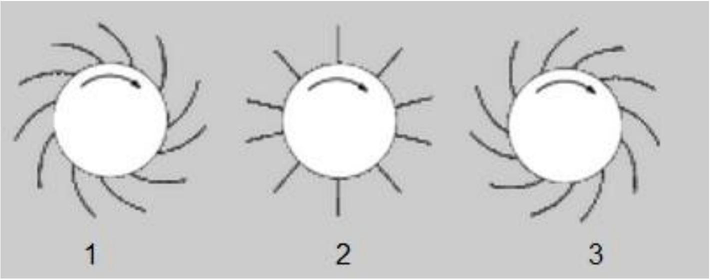


Figure 3. Impeller shape for centrifugal fan / 3./

2.2.3 Mixed flow

This kind of impeller combines principle of work of both axial and centrifugal flow fans. Impeller with blades is described on figure 4. Blades with angle of 45 degrees increase static pressure due to centrifugal force. Efficiency of mixed flow fans is up to 80%.

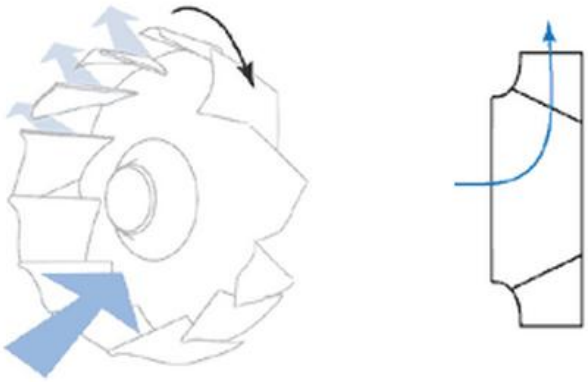


Figure 4. Impeller of mixed flow fan / 3./

2.3 Heating coils

This type of equipment is used to warm up air from outdoor in cold seasons. Nowadays heat for heating coil could be gotten by means of electricity, hot water and steam.

Electrical heating coils, which are shown on figure 5, are mostly connected to 3/380V/50 Hz electrical network. This type of construction makes it easier to uninstall or repair coil. This type of coil is also equipped by safety thermostat, which prevents excessive heating of the system and switch coil of in case of air flow stops. /4 p.188./

Figure 5. Electrical heater / 5./

Effective area of hot water heating coils described on figure 6 mainly made of copper because of its perfect thermal conductivity. It consists of tubes with aluminum fins, which increase heating effect by increasing usable area. This type of coil is also equipped by safety devices to prevent accidents. /4 p.188./

Figure 6. Hot water heater / 5./

It is also common to use in steam as a medium heating coils. This way of air heating is very useful because of two steps of heating: directly by heat of steam and also by heat emitted by condensation of steam.

Choice of heaters type depends on the client's desires and circumstances. For example, if client is limited of electrical power the only way is to use hot water heating coil. The heating process is clearly seen in id-diagram in figure 7.

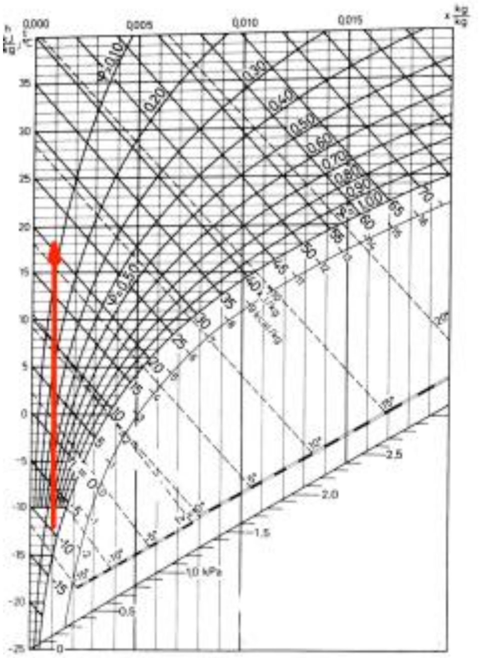


Figure 7. Electrical and hot water heating coil

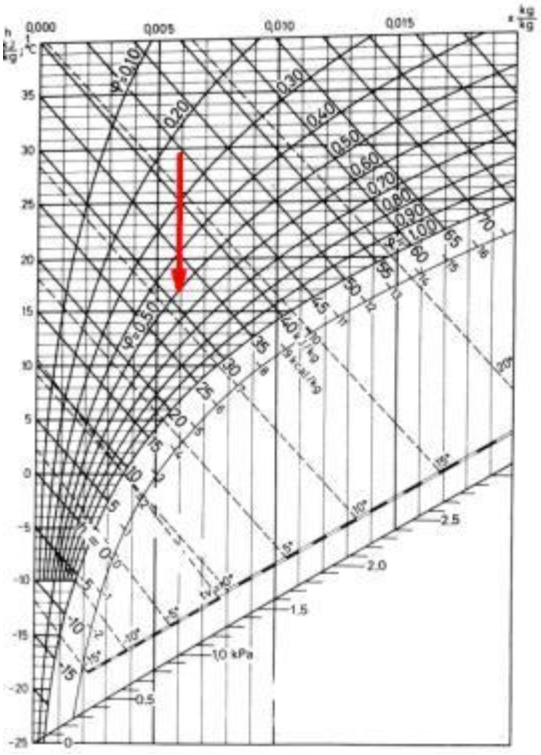
It is obvious according to figure 7 that heating coils do not change moisture content.

2.4 Cooling coils

Cooling coils could use gases, water-glycol mixture and water as a refrigerant. Designer often makes projects with two steps of air cooling. First one is precooling and it reduces loads on the cooling equipment. This step may be provided by cold water cooling coil. Second one is properly cooling with resort to refrigerating equipment. There are two ways of cooling process: with and without condensation. /4 p.187./

If evaporation of refrigerant occurs in cooling coil, it is considered that temperature of cooling surface is constant. That is why there is no condensation from the air in the cooling coil and moisture content is constant as well. This process is shown on figure 8. /4 p.187./

There is other kind of cooling coils with cooling surface with constant temperature under the dew point. Figure 9 describes this process. In this case condensation occurs, that’s why moisture content of air reduces. /1 p.187./



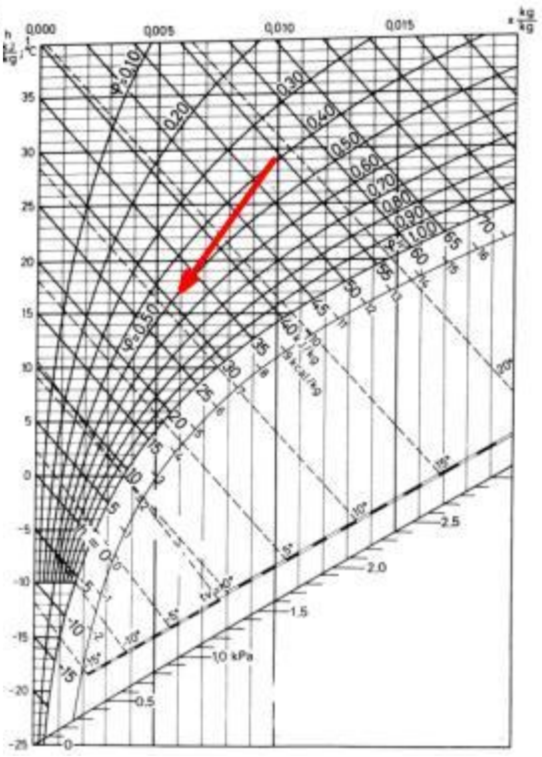


Figure 8. Cooling without condensation **Figure 9. Cooling with condensation**

2.5 Humidifiers

There are two types of humidifiers, which are mostly used in AHU. Principle of their operation is different. The first one humidifies air by spraying cold water to keep fog conditions in humidifier. Air adiabatically absorbs moisture from fog by going through it, what is clearly shown on figure 10. This kind of equipment costs less comparing with another, but hygienic risks are very high, therefore it is common to use steam humidifiers. This kind of equipment has some advantages:

-dry steam could be easily and quickly mixed with air

-dry steam does not contain any microorganisms and minerals

-low cost maintaining of this system. /4 p.188-189./

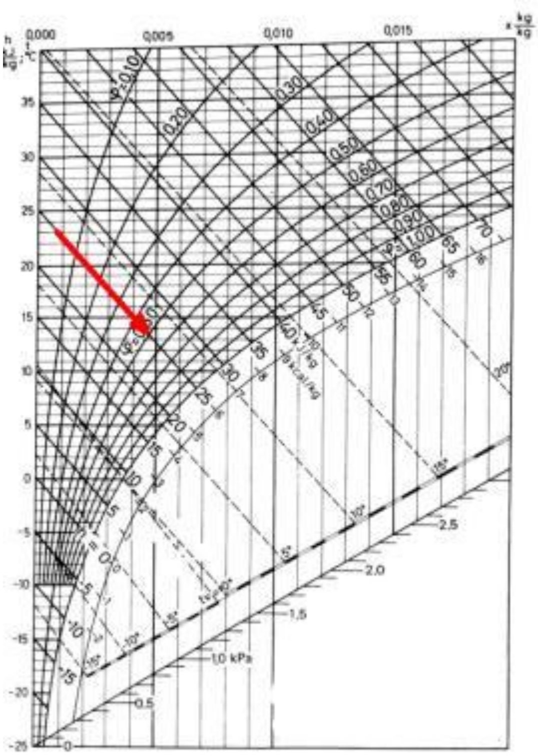


Figure 10. Cold water humidifier

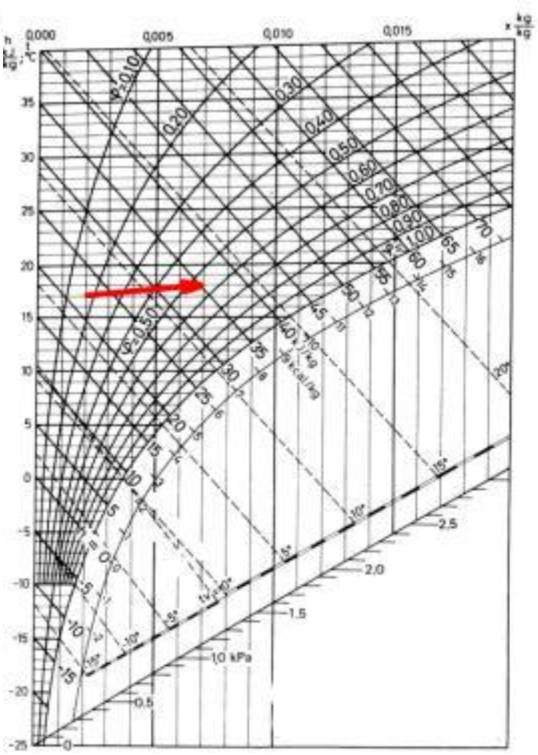


Figure 11. Steam humidifier

2.6 Dehumidifiers

In some regions there is a great likelihood of high humidity of outdoor air. So sometimes it is necessary to dehumidify air. Different ways can be chosen to reach certain level of humidity. HVAC designers usually use cooling-dehumidifying coils, which mostly the same as cooling coil with condensation shown on figure 9. In some cases chemical compounds can be also used to absorb moisture from the air. /3./

2.7 Energy recovery ventilation systems

These systems are used to reduce operation costs for ventilation by exchanging sensible and latent heat from exhausted air to outdoor air. There are two types of these systems:

-heat recovery ventilators (HRV),

-energy recovery ventilators (ERV).

Heat recovery ventilators transfer sensible heat only, what is described on figures 12 and 13. HRV systems are subdivided on different types: plate heat recovery, water-glycol double coil system, heat pipe heat exchanger, two-phase thermosiphon heat exchanger. Plate heat recovery and double coil system are more common in use comparing with last two. /2 p. 11-18./

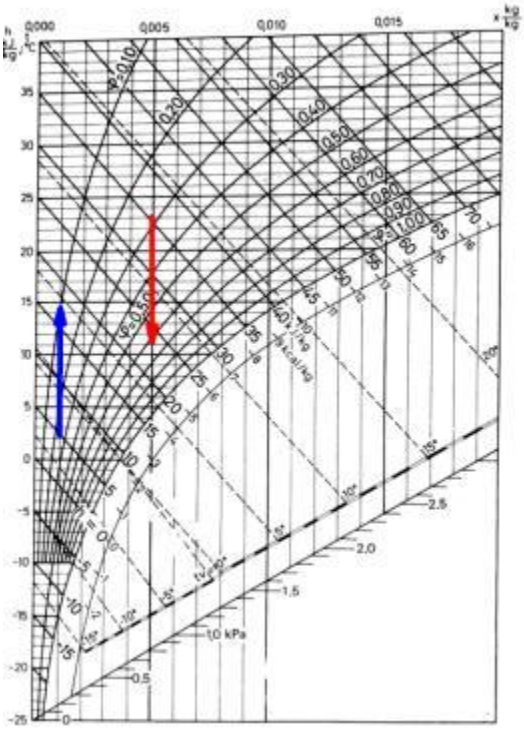


Figure 12. HRV without condensation

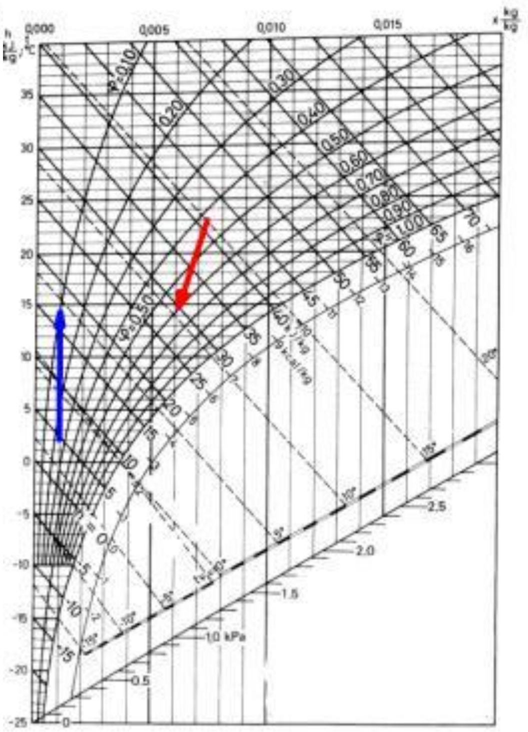


Figure 13. HRV with condensation

2.7.1 Heat recovery ventilators

2.7.1.1 Plate heat recovery

Operation principle of this system is pretty simple. Figure 14 simply shows it. This equipment consists of only stationary parts. It has a lot of layers separated from each other by plates.

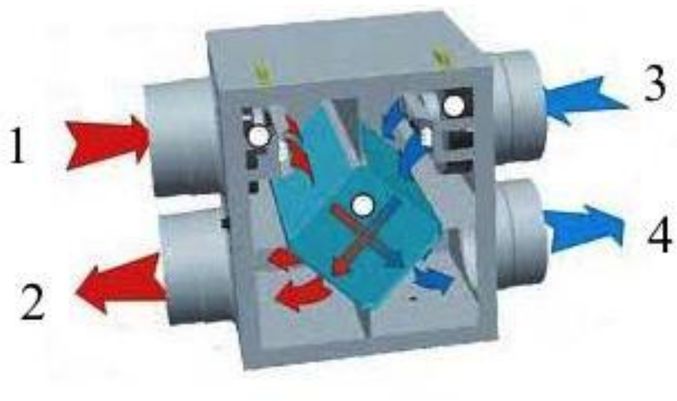


Figure 14. Cross-flow plate heat recovery/ 7./

For winter case as example: cold outdoor supply air (3) comes between plates and warmed up (2) straightly by heat transferred from warm exhaust air (1) by plates. Warm exhaust air is cooled down during this process and blown out as cold exhaust air (4). Sometimes it is very useful to put few cross-sections one after another to improve efficiency. Because of small cross-leakage (0 to 5%) value it is possible to use as exhaust wasted air, for example, from WC's, according to Finnish National Building Codes D2. But in special buildings for example in hospitals any cross-leakages are totally restricted, so it is impossible to use plate heat recovery in these cases. /8 p.11-13./

The advantages are lack of moving parts, low pressure drop (5 to 450 Pa) and simplicity of cleaning. All these points make low operation cost for plate heat recovery. Efficiency of plate heat recovery is from 50% up to 80%, depends on plates spacing and construction. /8 p.12./

2.7.1.2 Double coil heat recovery

This kind of system is very common in use for special buildings like hospitals, where any cross-leakages are restricted. It compensates rather small efficiency (45 to 60%) comparing thermal weal and plate heat recovery.

Operation principle of double coil system is shown on Figure 15. There are two heat exchangers for supply and exhaust air ducts. These coils are connected with each other by pipes. Water or other liquid is pumped over heat exchangers. For winter case media gets heat from exhaust air and goes to supply air coil, where it warm up outdoor air.

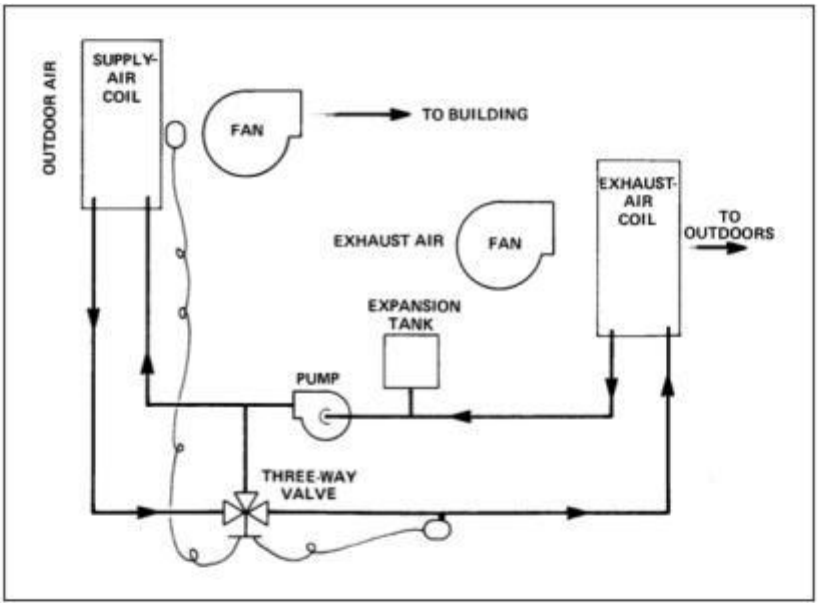


Figure 15. Double-coil heat recovery /8 p.15./

Efficiency of this system is regulated by three-pot valve controlled by two sensors. This valve is also used to prevent freezing of moisture in exhaust air coil. Usually ethylene glycol is added in water to prevent freezing of media in supply air heat exchanger. Expansion tank is necessary to allow media to contract and expand. /8 p.15./

Double coil system allows to separate exhaust duct from supply. It could be very useful in case of limited space or in case of necessity to make it separate. This solution is applied for example in Central Hospital of Mikkeli.

2.7.1.3 Heat pipe heat recovery

Heat pipe heat recovery looks like ordinary water coil, except for tubes separated from each other. This kind of heat recovery unit has two sides: evaporation side and condensing side. There is partition wall between these parts. It narrows cross leakage down to 0% (if pressure difference between two parts less than 12 kPa). /8 p.16./

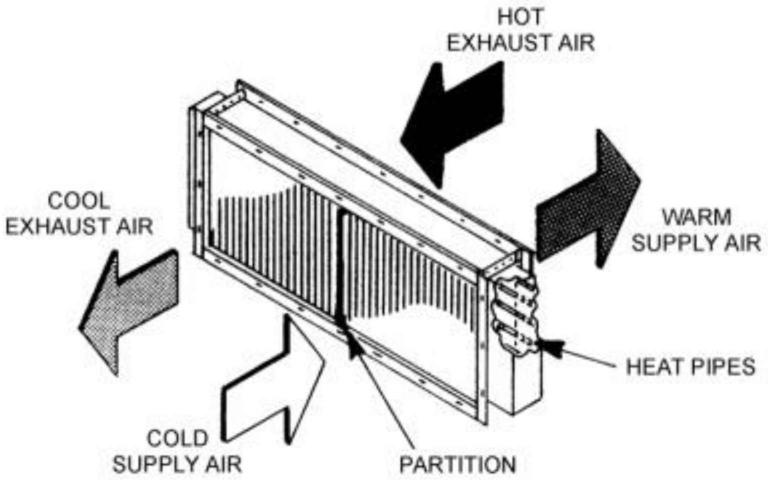


Figure 16. Heat pipe heat recovery/8 p.16./

Main principle of operation (Figure 17) is as cooling machine. Hot air goes through the evaporation part and evaporation of working fluid occurs. Vapor goes up in condensing part of exchanger, through which cold air goes. In this side vapor cools down and flows in the bottom of heat pipe to evaporation side. When fluid vaporizes, it takes a lot of energy from the air stream by its cooling. During the condensation of fluid emitting of heat occurs. Cold air gets warmer by passing through condensation side./2 p.16./

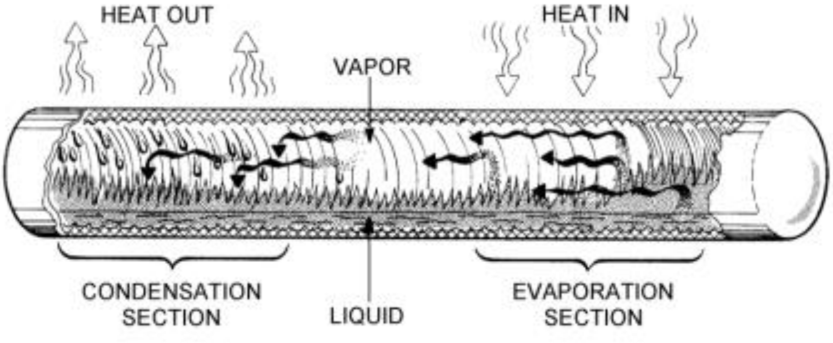


Figure 17. Heat pipe/8 p.16./

Affective area made of copper or aluminum as well due to good thermal conductivity. To improve the efficiency heat pipes covered with fins. Fins usually made of the same material as heat pipes to avoid problems with different thermal expansion. Spacing between fins depends on application of this heat recovery unit. For ventilation it is common to use spacing of 1.8 to 2.3 mm. /8 p.16-17./

Efficiency of heat pipe heat recovery is in linear dependence on number of rows of heat pipes. For example: in case of 7 rows efficiency is 66%, but heat exchanger with 14 rows of heat pipes has 83% efficiency with the same mass flow, face velocity 2 m/s and same fin spacing 1.8 mm. Efficiency is also depends on inside diameter of heat pipes. For instance heat transfer increases squarely if it is used heat pipes with inside diameter 25 mm instead of 16 mm. But increasing number of rows and diameter of heat pipes draws big values of pressure drop on heat exchanger and more powerful fan is needed. /8 p.17./

During the operation effectiveness is changed by changing the slope to the horizontal. Value of this slope is regulated by tilt controller, which works automatically. Because of changing the slope there is a necessity of flexible connections with ducts. It is obvious that heat pipe heat exchanger may operate in both directions: in summer and winter as well. Direction of operation could be also changed by tilt controller. /8 p. 17./

2.7.2 Enthalpy recovery ventilators

ERV recover sensible and latent heat as well (Figure 18). There are two types of ERV: rotating wheel heat recovery and special kind of plate heat recovery. Enthalpy wheel is one of the most common in use heat recovery units. It is used for example in X-building.

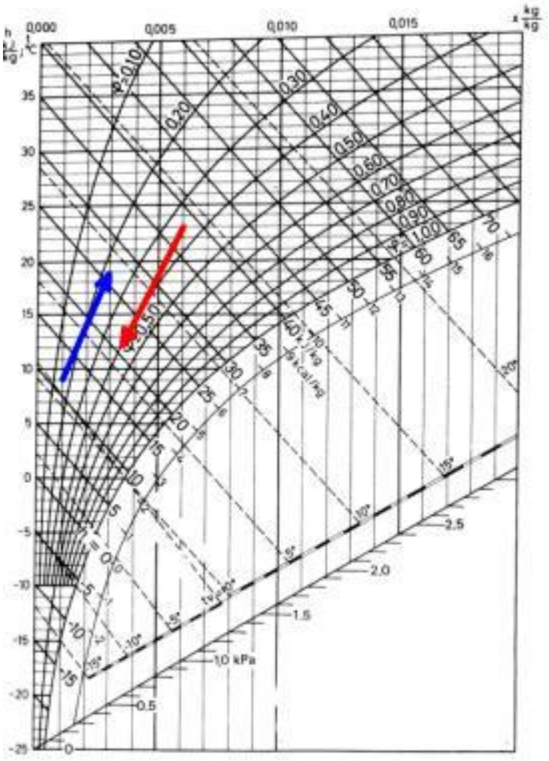


Figure 18. Energy recovery ventilator

But ERV's have one important disadvantage – big value of cross-leakages (up to 10%). That's why using of ERVs is limited by cleanliness of exhaust air. According to National Building Code D2 it is restricted to use air from waste spaces (WC's for example) as exhaust air. So volume flow of supply air is bigger than volume flow of exhaust air. Because of this inequality efficiency of enthalpy wheel is much less than announced by manufacturer. /8 p.12-13./

2.7.2.1 Rotating wheel heat recovery

Figure 19 describes construction of the Rotating wheel heat recovery unit. It consists of three main parts: frame made of steel, rotating wheel and electrical motor with belt-transmission. Wheel is made of aluminum and composed of big amount of cells or meshed wire. These constructions allow to increase operating area and therefore effectiveness (up to 90% with equal volume flows of both supply and exhaust air streams). /9./

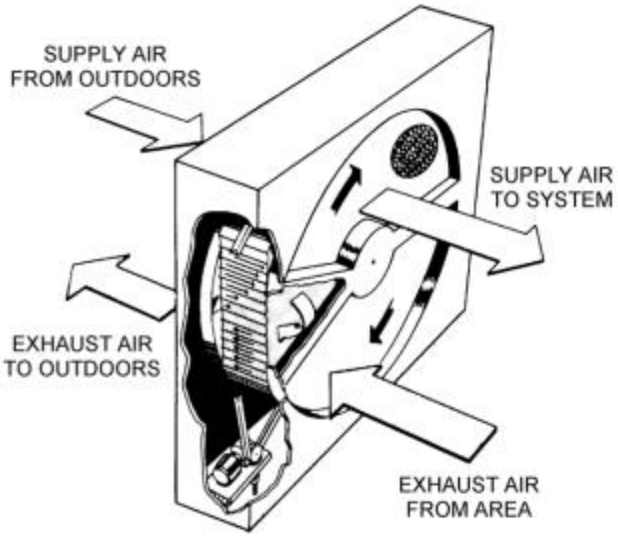


Figure 19. Rotating wheel heat recovery/8 p.13./

There are three types of rotating wheel heat recovery:

- RRS, RRT – common model, which is used to utilize sensible heat from warm air stream. Wheels of RRT-type transfer moisture only in cases when temperature of cold air stream is under the dew point. Thermal wheel is made of aluminum, which is resistant with salt water.

- RRH – high temperature thermal wheels, which are used to transfer sensible heat from air with temperature of 250°C

- RRSE, RRTE – enthalpy wheels, which are used to utilize total heat (sensible and latent heat as well). /9./

2.7.2.2 Permeable membrane plate heat recovery

This kind of ERV is mostly the same as normal plate heat recovery except one thing – the plates, which separate air streams from each other, are made of materials are permeable by moisture. It is common to use some polymers and cellulose to make membranes. Construction and composition of these heat and moisture exchangers are developed that way to minimize cross-leakage and prevent any air transfer through the plates. /8 p.12./

3. MEASUREMENTS AND COMPAIRING

The main point of following paragraph is to describe methods of measuring applied during this thesis work and to compare results of measurements with values which are given by automation system of air handling unit of X-building.

3.1 Measurements made by data loggers

To get value of energy efficiency of heat recovery it is absolutely necessary to measure temperatures before and after recuperator for both supply and exhaust air streams. Also the values of supply air temperature are also needed. That is why there are five points where data loggers were installed. All points are shown black on figure 20. One logger should be put after fan for supply air because of small rise of the temperature, but due to impossibility of installing logger on that place, it was put just before fan. This figure was screen-shouted from special program, which monitors and controls and collects all characteristic points of the system. It is possible to get values of temperature or humidity of air, energy consumption of fans, volume flow etc. After month ends, all data of each hour exports to special document.

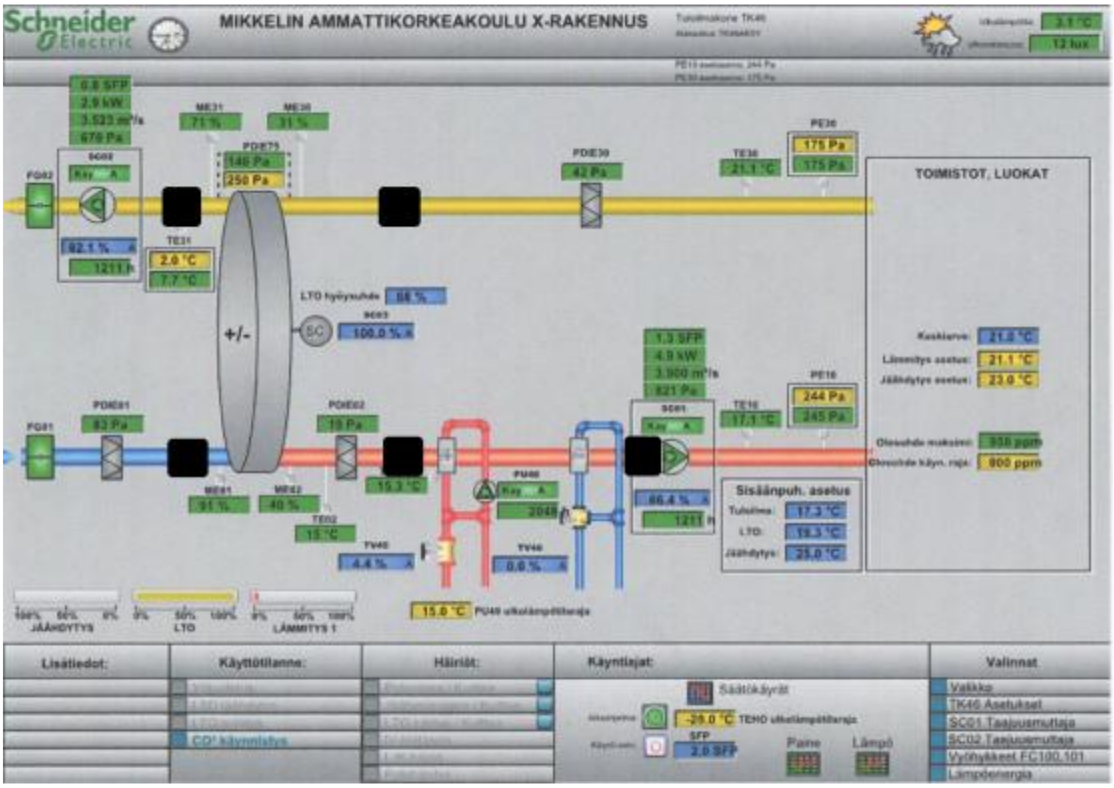


Figure 20. Loggers location in the air handling unit of X-building

There is a table in appendix 1, where data from loggers and AHU-automation are compared. Last four columns describe difference between values from different sources. According to this table most values of divergence are less than two degrees, but the biggest divergence is 4,8 degrees of Celsius, which is really huge. It can be explained by location of loggers in the AHU. Because of high volume flow, ducts with high dimensions are needed (cross section is more than one square meter). To get really adequate values it is necessary to have several points of measuring. It was impossible to put 25 to each of five points due to technical reasons. Moreover most of loggers were placed near the wall of duct because the only place to fix it safely is near the wall.

3.2 Measuring of volume flow from WCs

Other point to measure was volume flow of air going from WCs straightly to the roof. Due to zero-efficiency this value has great influence on the annual energy efficiency for whole ventilation system. It was decided that the easiest available method to make this kind of measurements is to measure velocity of air stream in the duct.

Because of this system was new some preparations were needed. Firstly it was necessary to make a small opening to make possible to put sensor inside of duct. Next thing to do was to measure diameter of the duct, as a result of 315 mm was gotten. Usually air velocity is measured by five-point method for this duct size. Cross section of duct with points of measuring are shown schematically on figure 21.

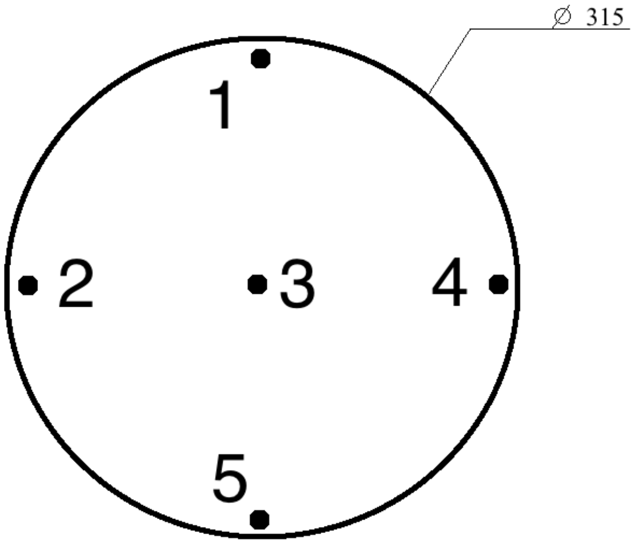


Figure 21. Cross section of duct with points of measuring

“Swema ” measuring instrument equipped with hot wire sensor was used. After all preparation processes air velocity was measured. But fluctuations of values given by anemometer were quite big ($up\ to\ 15\%$). However according to measurements average velocity of air stream in the duct is 3,57 m/s. It is easy to find out value of volume flow:

$$q_v = V \cdot \frac{\pi \cdot d^2}{4} \tag{1}$$

where V is velocity of air stream, d is internal diameter of the duct. As a result volume flow of 0,278 m^3/s was gotten. According to data from automation system of AHU in X-building, difference between supply and exhaust air volume flows is about 0,32 m^3/s. But this value is not exactly for moment of measuring, so it is quite difficult to judge if measuring results are true or not.

As a result for this paragraph it becomes obvious that incompleteness of measuring provided with results, which are not exactly right. Moreover air handling unit was designed the best way to make monitoring and control of system perfect by providing objective and trough values like temperature, humidity, volume flow of air, energy consumption etc. So it is better to use values given by automation of system to make following calculations.

4. CALCULATIONS AND COMPARING

Main idea of this paragraph is to familiarize reader with process of calculating annual energy efficiency. This value is very important and may be it can determine choice of customer what kind of heat recovery is better to use in air handling unit.

4.1 Order and description of calculations

First of all, it is necessary to calculate temperature ratio of existing air handling unit from data loggers. It can be easily calculated by formula 2. Only point to remember is to use in this formula data for outdoor temperatures between -5°C and +17°C. According to data temperature ratio for supply air is about 76%. But in following calculations it is necessary to know value of temperature ratio for equal volume flows, so in our case this value is 84%.

$$\eta_{t\ a} = \frac{t_{tLTO} - t_u}{t_s - t_u} \tag{2}$$

Annual energy efficiency can be calculated by creating table, which is shown in appendix 2 and 3. A lot of different values are necessary for that. Firstly duration curve is needed. Example of duration curve is shown on figure 19. It is a graph which describes how much time (given in axis of abscissas in percent from whole year) outside temperature is below given one (given in axis of ordinate in degrees of Celsius). Table form of duration curve is more useful to our purposes.

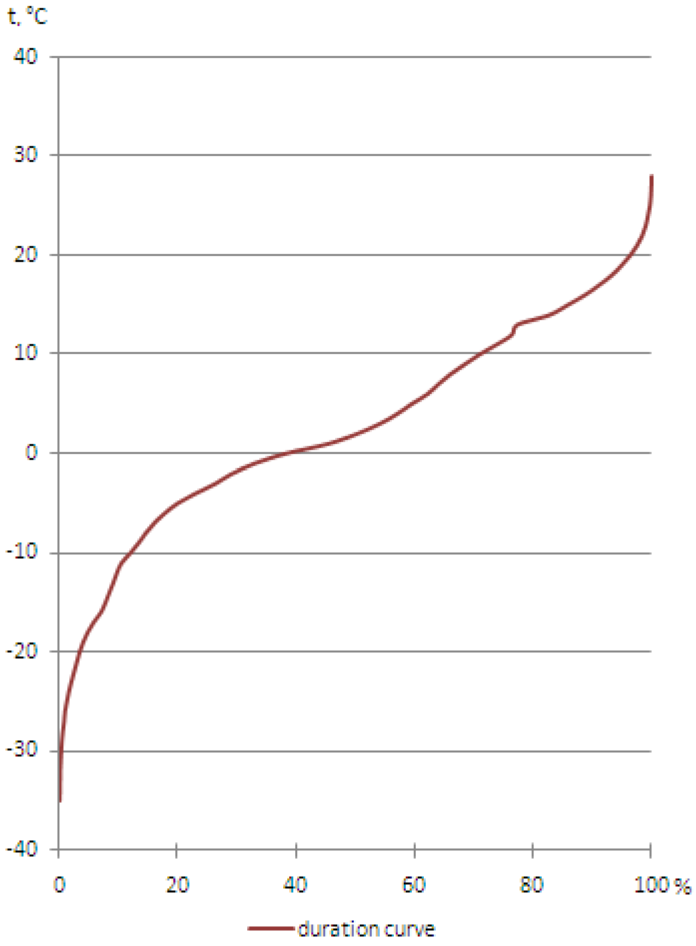


Figure 19. Duration curve

Calculation of the table begins from getting ratio between supply air volume flow and exhaust air volume flow.

$$R_{LTO} = \frac{q_{v\,supply}}{q_{v\,exhaust}} \tag{3}$$

According to requirements R_{LTO} must be more than 1 for energy recovery ventilators. This is exactly case of HRV for X-building, because rotating weal heat recovery is used in that AHU. Real temperature ratios for HR in cases like this are different from values which given by manufacturer, however it can be calculated by following formulas:

$$\eta_{t\,actual} = \frac{2}{(1+R_{LTO})} \cdot \eta_t \tag{4}$$

$$\eta_{p\,actual} = \eta_{t\,actual} \cdot R_{LTO} \tag{5}$$

where η_t is value of temperature ratio given by manufacturer, $\eta_{t\,R}$ is temperature ratio of supply air for actual value of R_{LTO}, $\eta_{p\,R}$ is temperature ratio for exhaust air for actual value of R_{LTO}.

Next point to calculate is temperature of exhaust air:

$$t_{pLTO} = t_s - \eta_{p\,R} \cdot (t_s - t_u) \tag{6}$$

where t_s is temperature of indoor air, t_u is outdoor air temperature.

But according to National Building Codes of Finland exhaust air temperature must not be less than 5°C due to risk of frozen in heat recovery ventilator. Indoor air temperature must be in range of +21°C$\leq t_s \leq$+23°C to meet requirements of D2, but it is in common to use in calculations value of t_s =+21°C. Because of these points actual temperature ratios must be reduced:

$$\eta_{p\,actual} = \frac{t_s - t_{pLTO\,actual}}{t_s - t_u} \tag{7}$$

$$\eta_{t\,actual} = \frac{\eta_{p\,actual}}{R_{LTO}} \tag{8}$$

where $\eta_{p\,actual}$ is an actual temperature ratio for exhaust air, $\eta_{t\,actual}$ is actual temperature ratio for supply air, $t_{pLTO\,actual}$ is temperature of exhaust air (not less than +5°C)./ 10./

Next step is to get value of actual temperature of supply air after heat recovery. It can be easily calculated by formula:

$$t_{tLTO\,actual} = t_u + \eta_{t\,actual} \cdot (t_s - t_u) \tag{9}$$

But $t_{tLTO\,actual}$ must not be more than +17°C because of providing indoor air temperature +21°C during the hot season. This is another reason to reduce efficiency of heat recovery ventilator.

One of the last points to calculate is heat recovery energy.

$$Q_{LTO} = c_p \cdot q_{v\,supply} \cdot \tau \cdot \rho \cdot t_d \cdot t_v \cdot (t_{tLTO} - t_u) \tag{10}$$

Where $c_p$is a specific heat capacity, τ is duration of certain outdoor temperature in hours, ρ isdencity of the air, t_d is operation time during the day, t_v is operation days during the week.

t_d and t_v values were defined from schedule of AHU, given by automation.

Also it is necessary to find out value of energy needed for ventilation:

$$Q_{exhaust} = c_p \cdot q_{v\,exhaust} \cdot \tau \cdot \rho \cdot t_d \cdot t_v \cdot (t_s - t_u) \qquad (11)$$

It is needed to make all these calculations for each outdoor temperature (from -35°C up to +28°C). It is easier to collect all that information in table. After that sum of heat recovery energy and separately energy for ventilation is needed.

Finally it becomes possible to get annual energy efficiency of AHU:

$$\eta_a = \frac{\Sigma Q_{LTO}}{\Sigma Q_{exhaust}} \qquad (12)$$

Where $\Sigma Q_{LTO}$is a sum of heat recovery energy for all outdoor temperatures, $\Sigma Q_{exhaust}$ is sum of energy needed for ventilation.

Firstly it was necessary to get this value for existing system. Because now rotating weal is used there are different air flows. In X-building special exhaust system for WCs was created. It is obvious that efficiency of this special system is η_{WC}=0%. This factor must be noticed in calculations: it is also calculated for each outdoor temperature with volume flow which was measured in the duct from WCs. Because of permanent work of WCs fan, t_d=t_v=1.

Value of annual energy efficiency of AHU is not enough to full comparing, so value of total annual energy efficiency of whole ventilation system of building. To get this value it is necessary to calculate according to formula 13:

$$\eta_{a\,vent} = \frac{Q_{LTO}}{Q_{LTO} + Q_{iv} + Q_{iv,make-up} + Q_{iv,\ supply}} \qquad (13)$$

where Q_{LTO} is an energy recovered from ventilation can be estimated using the equation 14, Q_{iv} is net heating energy for ventilation could be found by formula 15, $Q_{iv,\ supply}$ is heating power of supply air in a space was calculated by equation 16, $Q_{iv,\ make-up}$ is power needed for heating of make-up air in a space.

$$Q_{LTO} = \Sigma c_p \cdot q_{v\,supply} \cdot \tau \cdot \rho \cdot t_d \cdot t_v \cdot (T_{tLTO} - T_{out}) \cdot \Delta t / 1000 \qquad (14)$$

$$Q_{iv} = c_p \cdot q_{v\,supply} \cdot \tau \cdot \rho \cdot t_d \cdot t_v \cdot (T_{ib} - T_{tLTO}) \cdot \frac{\Delta t}{1000} \qquad (15)$$

$$Q_{iv,\ supply} = c_p \cdot q_{v\,supply} \cdot \tau \cdot \rho \cdot t_d \cdot t_v \cdot (T_{ind} - T_{ib}) \cdot \frac{\Delta t}{1000} \qquad (16)$$

$$Q_{iv,\ make-up} = c_p \cdot q_{v\,make-up} \cdot \tau \cdot \rho \cdot t_d \cdot t_v \cdot (T_{ind} - T_{out}) \cdot \frac{\Delta t}{1000} \qquad (17)$$

where T_{out} is mean outdoor air temperature during month (given in D5), T_{ib} is temperature of inblown air, , $q_{v\,make-up}$ is make-up air volume flow, T_{tLTO} is supply air temperature after HR could be calculated using formula 19.

$$q_{v\,make-up} = \Sigma(q_{v\,exhaust} - q_{v\,supply}) \cdot t_d \cdot t_v \qquad (18)$$

$$T_{tLTO} = T_{out} + \eta_a \cdot (T_{ind} - T_{out}) \qquad (19)$$

where T_{ind} is indoor air temperature. /11 p.19-21./

4.2 Comparing of existing HRU with alternative

Counter-flow plate heat recovery with announced temperature ratio of 70% was found. Exactly this value is recommended to use in calculations according to National Building Code of Finland D5. It is also useful to compare results with values of cross-flow HR with temperature ratio of 55% according to D5. /11 p.20/

It is allowed to blow exhaust air from WCs through heat recovery. In spite of lower temperature ratio comparing with rotating weal energy recovery plate heat recovery can have better annual energy efficiency due to equal volume flows for both supply and exhaust air streams. But there is a factor, which reduces total efficiency: building must have some ventilation during night time and weekends. In calculations value equal existing volume flow from WCs is used.

One of the main point to define in this thesis work is to find out what kind of system has better annual energy efficiency existing rotating weal with R_{LTO}=1,11 or plate heat recovery with R_{LTO}=1. Other point to mention is that according to D5 National Building Code of Finland minimum temperature of exhaust air must be limited by 0°C.

All calculations shown in application 2, 3, 4, 5, 6, 7 for both of these systems were made according formulas 3 - 19. Results are close to each other, but using plate heat recovery has a bit bigger value of annual energy efficiency of whole ventilation system (63.4% - for counter-flow plate heat recovery, 52.8% - for cross-flow plate heat recovery, 55.3% - for rotating weal heat recovery).

Moreover less investment for ducting and additional fan needed in case of plate heat recovery. But it also has some disadvantages, and one of the most important from them is risk of cross leakages. In spite of permission of requirement documentation it can cause some problem. It can be solved by keeping certain pressure drop in the system special way to provide cross leakage going from supply air stream to exhaust and to prevent it in opposite direction.

5. CONCLUSION

First part of this thesis mostly consists of information about different parts of air handling units. There are the most important processes, which take place in air handling, described there. That information was mentioned to make it easier to understand next paragraphs for non-specialized at HVAC-systems reader.

Next part is about measurements with results, calculations and comparing. It was necessary to make some measurements to calculate annual energy efficiency of the existing air handling unit. There some documents were used to base calculations of energy efficiency for other types of heat recovery units.

So as a result of this thesis work it is possible to say that designers of air handling unit in X-building had some alternative ways to reach efficient way of energy usage. Their choice was applying rotating weal heat recovery in the system. As an alternative way case of cross flow heat recovery was calculated. Both of these two variants have more or less the same results, however the second type has bigger value of annual energy efficiency. But designers chose more healthy and safety way. .

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10. D2 National Building Code of Finland

11. D5 National Building Code of Finland. Draft 28.09.2010.

Appendix 1. Data comparision

Date/Time	loggers				AHU-automation				difference			
	t_{out}	t_{tLTO}	t_s	t_{pLTO}	t_{out}	t_{tLTO}	t_s	t_{pLTO}	t_{out}	t_{tLTO}	t_s	t_{pLTO}
	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
2.12.2011 9:00:00	4	17	21,2	9,4	2,99	15,3	21,02	7,76	-1,01	-1,7	-0,18	-1,64
2.12.2011 10:00:00	4,3	17,1	21,4	9,8	3,53	15,4	21,12	8,05	-0,77	-1,7	-0,28	-1,75
2.12.2011 11:00:00	4,3	17,1	21,4	9,7	3,98	15,6	21,18	8,22	-0,32	-1,5	-0,22	-1,48
2.12.2011 12:00:00	4,5	17,1	21,4	9,8	3,98	15,6	21,18	8,3	-0,52	-1,5	-0,22	-1,5
2.12.2011 13:00:00	4,4	17,1	21,4	9,8	3,98	15,6	21,13	8,3	-0,42	-1,5	-0,27	-1,5
2.12.2011 14:00:00	4,2	17,1	21,4	9,7	3,98	15,6	21,17	8,13	-0,22	-1,6	-0,23	-1,57
2.12.2011 15:00:00	4,1	17	21,4	9,6	3,88	15,5	21,15	8,09	-0,22	-1,5	-0,25	-1,51
2.12.2011 16:00:00	4,2	16,8	21,1	9,6	3,69	15,4	21,05	8	-0,51	-1,4	-0,05	-1,6
2.12.2011 17:00:00	3,8	16,7	21	9,3	3,68	15,3	20,9	7,86	-0,12	-1,4	-0,1	-1,44
2.12.2011 18:00:00	4,1	16,8	21,1	9,4	3,69	15,3	20,84	7,82	-0,41	-1,5	-0,26	-1,58
2.12.2011 19:00:00	3,7	17	21,1	8,8	3,69	15,5	20,85	7,46	-0,01	-1,5	-0,25	-1,34
2.12.2011 20:00:00	3,5	17	21,1	8,6	3,69	15,5	20,91	7,28	0,19	-1,5	-0,19	-1,32
2.12.2011 21:00:00	3	21,1	17,7	13,5	3,4	18,5	20,03	11,4	0,4	-2,6	2,33	-2,08
2.12.2011 22:00:00	2,4	20,9	17,7	15,2	2,87	19,1	19,57	14,4	0,47	-1,8	1,87	-0,83
2.12.2011 23:00:00	2,1	20,8	17,9	15,9	2,83	19,3	19,53	15,3	0,73	-1,5	1,63	-0,64
3.12.2011	1,9	20,9	18,1	16,2	2,16	19,6	19,53	15,7	0,26	-1,3	1,43	-0,55
3.12.2011 1:00:00	1,6	21	18,2	16,5	1,81	19,8	19,53	15,9	0,21	-1,2	1,33	-0,57
3.12.2011 2:00:00	1,2	21,2	18,4	16,6	0,9	20	19,52	16	-0,3	-1,2	1,12	-0,59
3.12.2011 3:00:00	1,1	21,4	18,5	16,7	0,39	20,2	19,54	16,2	-0,71	-1,3	1,04	-0,53
3.12.2011 4:00:00	1,1	21,5	18,6	16,8	0,39	20,3	19,56	16,3	-0,71	-1,2	0,96	-0,54
3.12.2011 5:00:00	1,1	21,6	18,7	17	0,39	20,4	19,67	16,4	-0,71	-1,2	0,97	-0,6
3.12.2011 6:00:00	1,1	21,7	18,8	17,1	0,39	20,6	19,69	16,5	-0,71	-1,2	0,89	-0,58
3.12.2011 7:00:00	1,6	21,8	19	17,3	0,78	20,7	19,71	16,7	-0,82	-1,1	0,71	-0,62
3.12.2011 8:00:00	1,9	22	19,2	17,5	0,91	20,8	19,77	16,9	-0,99	-1,2	0,57	-0,58
3.12.2011 9:00:00	1,8	22,1	19,2	17,7	1,08	20,9	19,7	17	-0,72	-1,2	0,5	-0,7
3.12.2011 10:00:00	1,7	22,1	19,3	17,7	1,25	20,9	19,53	17,1	-0,45	-1,2	0,23	-0,6
3.12.2011 11:00:00	1,6	22,1	19,3	17,7	1,24	20,9	19,36	17,1	-0,36	-1,2	0,06	-0,61
3.12.2011 12:00:00	1,9	22,1	19,2	17,7	1,25	20,8	19,27	17	-0,65	-1,3	0,07	-0,68
3.12.2011 13:00:00	1,8	22,1	19,2	17,6	1,25	20,8	19,27	17	-0,55	-1,3	0,07	-0,63
3.12.2011 14:00:00	1,3	22,1	19,2	17,6	1,09	20,8	19,28	17	-0,21	-1,3	0,08	-0,64
3.12.2011 15:00:00	0,4	22	19,1	17,4	0,53	20,8	19,26	16,8	0,13	-1,2	0,16	-0,61
3.12.2011 16:00:00	-0,3	22,1	19	17,4	-0,59	20,8	19,28	16,8	-0,29	-1,3	0,28	-0,6
3.12.2011 17:00:00	-0,9	22	18,9	17,1	-1,13	20,8	19,42	16,6	-0,23	-1,2	0,52	-0,51
3.12.2011 18:00:00	-1,5	22,1	19	17,2	-1,32	20,8	19,45	16,6	0,18	-1,3	0,45	-0,63
3.12.2011 19:00:00	-1,5	22,1	19	17,3	-1,61	20,8	19,57	16,7	-0,11	-1,3	0,57	-0,59
3.12.2011 20:00:00	-0,8	22,1	19,1	17,5	-2,06	20,9	19,65	16,9	-1,26	-1,3	0,55	-0,65
3.12.2011 21:00:00	-0,2	22,2	19,2	17,7	-1,48	20,9	19,71	17	-1,28	-1,3	0,51	-0,7
3.12.2011 22:00:00	1,1	22,3	19,3	17,8	-0,69	21	19,81	17,2	-1,79	-1,3	0,51	-0,63
3.12.2011 23:00:00	1,6	22,3	19,3	17,9	0,33	21	19,87	17,3	-1,27	-1,3	0,57	-0,56
4.12.2011	1,9	22,4	19,4	18,1	0,8	21,1	19,88	17,5	-1,1	-1,3	0,48	-0,64
4.12.2011 1:00:00	2,4	22,4	19,5	18,2	1,1	21,2	19,9	17,6	-1,3	-1,2	0,4	-0,64

4.12.2011 2:00:00	2,4	22,5	19,5	18,3	1,32	21,2	19,92	17,7	-1,08	-1,3	0,42	-0,64
4.12.2011 3:00:00	2,2	22,5	19,7	18,5	1,72	21,3	19,93	17,8	-0,48	-1,2	0,23	-0,71
4.12.2011 4:00:00	2,1	22,6	19,7	18,5	1,72	21,4	19,94	17,9	-0,38	-1,3	0,24	-0,65
4.12.2011 5:00:00	1,9	22,6	19,8	18,6	1,72	21,4	19,92	17,9	-0,18	-1,2	0,12	-0,66
4.12.2011 6:00:00	1,7	22,7	19,8	18,6	1,72	21,4	19,99	18	0,02	-1,3	0,19	-0,57
4.12.2011 7:00:00	1,4	22,7	19,9	18,7	1,72	21,5	20,03	18	0,32	-1,2	0,13	-0,66
4.12.2011 8:00:00	1	22,7	19,9	18,6	1,63	21,5	20,01	18	0,63	-1,2	0,11	-0,58
4.12.2011 9:00:00	0,9	22,7	19,9	18,5	1,2	21,5	20,02	17,9	0,3	-1,2	0,12	-0,61
4.12.2011 10:00:00	1,1	22,7	19,9	18,4	1,2	21,5	20,03	17,8	0,1	-1,2	0,13	-0,62
4.12.2011 11:00:00	1,4	22,7	19,8	18,2	1,2	21,5	20,02	17,7	-0,2	-1,2	0,22	-0,51
4.12.2011 12:00:00	1,5	22,7	19,8	18,2	1,2	21,5	20,02	17,7	-0,3	-1,2	0,22	-0,54
4.12.2011 13:00:00	1,2	22,7	19,7	18,1	1,43	21,5	19,99	17,6	0,23	-1,2	0,29	-0,52
4.12.2011 14:00:00	1,9	22,7	19,5	17,9	1,55	21,5	19,92	17,4	-0,35	-1,2	0,42	-0,54
4.12.2011 15:00:00	2,2	22,7	19,5	17,8	1,53	21,4	19,91	17,3	-0,67	-1,3	0,41	-0,55
4.12.2011 16:00:00	2,8	22,7	19,4	17,7	1,89	21,4	19,91	17,1	-0,91	-1,3	0,51	-0,63
4.12.2011 17:00:00	3	22,7	19,4	17,5	2,08	21,4	19,94	17	-0,92	-1,3	0,54	-0,54
4.12.2011 18:00:00	3	22,7	19,4	17,9	2,11	21,4	20	17,2	-0,89	-1,3	0,6	-0,7
4.12.2011 19:00:00	2,7	22,7	19,5	18	2,35	21,5	20,01	17,4	-0,35	-1,2	0,51	-0,59
4.12.2011 20:00:00	2,6	22,7	19,7	18,1	2,43	21,5	20,03	17,5	-0,17	-1,2	0,33	-0,56
4.12.2011 21:00:00	2,2	22,7	19,7	18,2	2,38	21,5	20,03	17,6	0,18	-1,2	0,33	-0,62
4.12.2011 22:00:00	1,7	22,8	19,7	18,1	1,61	21,6	20,02	17,6	-0,09	-1,3	0,32	-0,52
4.12.2011 23:00:00	1,9	22,8	19,8	18,2	1,22	21,5	20,03	17,6	-0,68	-1,3	0,23	-0,62
5.12.2011	2,1	22,8	19,8	18,2	1,29	21,6	20,03	17,7	-0,81	-1,2	0,23	-0,55
5.12.2011 1:00:00	1,2	22,8	19,8	18,2	1,81	21,6	20,12	17,7	0,61	-1,2	0,32	-0,49
5.12.2011 2:00:00	1,6	22,8	19,9	18,4	0,86	21,6	20,15	17,7	-0,74	-1,2	0,25	-0,67
5.12.2011 3:00:00	1,8	23	19,9	18,5	1,24	21,7	20,16	17,8	-0,56	-1,3	0,26	-0,7
5.12.2011 4:00:00	1,8	23	19,9	18,4	1,27	21,7	20,15	17,8	-0,53	-1,3	0,25	-0,58
5.12.2011 5:00:00	1,8	23	19,9	18,4	1,27	21,7	20,18	17,7	-0,53	-1,4	0,28	-0,68
5.12.2011 6:00:00	1,7	23	19,9	18,4	1,27	21,7	20,21	17,7	-0,43	-1,3	0,31	-0,67
5.12.2011 7:00:00	1,5	23	19,9	18,4	1,27	21,7	20,2	17,7	-0,23	-1,3	0,3	-0,68
5.12.2011 8:00:00	0,8	16,4	21,4	7,5	1,24	15,5	21,15	7,01	0,44	-0,9	-0,25	-0,49
5.12.2011 9:00:00	0	16,2	21,5	6,9	0,51	14,4	21,29	5,4	0,51	-1,8	-0,21	-1,5
5.12.2011 10:00:00	-0,2	16,2	21,5	6,6	-0,17	14,2	21,42	5,01	0,03	-2	-0,08	-1,59
5.12.2011 11:00:00	0,5	16,4	21,6	7,3	-0,28	14,4	21,55	5,29	-0,78	-2,1	-0,05	-2,01
5.12.2011 12:00:00	0,3	16,1	21,4	7,1	-0,28	14,3	21,31	5,45	-0,58	-1,8	-0,09	-1,65
5.12.2011 13:00:00	0,2	16	21,2	6,9	-0,01	14,2	21,19	5,32	-0,21	-1,8	-0,01	-1,58
5.12.2011 14:00:00	0,3	16	21,2	7	0,13	14,1	21,11	5,22	-0,17	-1,9	-0,09	-1,78
5.12.2011 15:00:00	0,7	16,1	21,2	7,3	0,18	14,2	21,14	5,38	-0,52	-2	-0,06	-1,92
5.12.2011 16:00:00	0,7	16	21,1	7,1	0,43	14,2	21,11	5,57	-0,27	-1,8	0,01	-1,53
5.12.2011 17:00:00	0,6	15,9	21	7,1	0,24	14,1	20,99	5,39	-0,36	-1,8	-0,01	-1,71
5.12.2011 18:00:00	1,2	16	21	7,5	0,38	14,2	20,86	5,71	-0,82	-1,8	-0,14	-1,79
5.12.2011 19:00:00	1	16,5	21,1	6,9	0,44	14,5	20,82	5,36	-0,56	-2	-0,28	-1,54
5.12.2011 20:00:00	0,7	16,5	21,4	6,8	0,44	14,7	21,1	5,24	-0,26	-1,8	-0,3	-1,56
5.12.2011 21:00:00	1,1	24,2	17,1	12,4	0,44	20,1	20,32	9,91	-0,66	-4,1	3,22	-2,49
5.12.2011 22:00:00	0,8	22,8	17,5	14,4	0,44	20,4	19,95	13,5	-0,36	-2,4	2,45	-0,86
5.12.2011 23:00:00	0,5	22,1	17,9	15,3	0,44	20,2	19,95	14,8	-0,06	-2	2,05	-0,53

6.12.2011	-0,3	21,7	18,1	15,8	-0,1	20,1	19,94	15,3	0,2	-1,6	1,84	-0,55
6.12.2011 1:00:00	-0,2	21,6	18,4	16,2	-0,66	20,1	19,88	15,7	-0,46	-1,5	1,48	-0,54
6.12.2011 2:00:00	0,3	21,6	18,6	16,6	0,05	20,2	19,83	16	-0,25	-1,4	1,23	-0,61
6.12.2011 3:00:00	0,6	21,7	18,7	16,8	0,05	20,4	19,8	16,2	-0,55	-1,4	1,1	-0,6
6.12.2011 4:00:00	0,6	21,8	18,8	17,2	0,05	20,5	19,82	16,5	-0,55	-1,3	1,02	-0,66
6.12.2011 5:00:00	0,6	22	19,1	17,4	0,3	20,6	19,86	16,8	-0,3	-1,4	0,76	-0,59
6.12.2011 6:00:00	0,5	22,1	19,2	17,6	0,4	20,7	19,95	17	-0,1	-1,4	0,75	-0,58
6.12.2011 7:00:00	0,6	22,2	19,3	17,7	0,37	20,8	19,95	17,1	-0,23	-1,4	0,65	-0,62
6.12.2011 8:00:00	0,2	16,5	21,6	7,1	0,37	15,2	21,19	6,44	0,17	-1,3	-0,41	-0,66
6.12.2011 9:00:00	0,1	16,5	21,7	7	0,37	14,6	21,53	5,38	0,27	-2	-0,17	-1,62
6.12.2011 10:00:00	-0,1	16,4	21,7	6,9	0,37	14,5	21,54	5,3	0,47	-1,9	-0,16	-1,6
6.12.2011 11:00:00	0,2	16,5	21,7	7,1	0,37	14,5	21,53	5,32	0,17	-2	-0,17	-1,78
6.12.2011 12:00:00	0,3	16,5	21,7	7,2	0,37	14,6	21,51	5,48	0,07	-1,9	-0,19	-1,72
6.12.2011 13:00:00	0,2	16,4	21,6	7,1	0,37	14,6	21,5	5,48	0,17	-1,8	-0,1	-1,62
6.12.2011 14:00:00	0,1	16,4	21,6	7	0,37	14,4	21,42	5,39	0,27	-2	-0,18	-1,61
6.12.2011 15:00:00	0,1	16,2	21,6	7	0,37	14,4	21,4	5,32	0,27	-1,8	-0,2	-1,68
6.12.2011 16:00:00	-0,3	16,2	21,5	6,8	0,37	14,4	21,39	5,22	0,67	-1,8	-0,11	-1,58
6.12.2011 17:00:00	-0,5	16,1	21,5	6,6	0,37	14,3	21,38	5,1	0,87	-1,8	-0,12	-1,5
6.12.2011 18:00:00	-0,5	16	21,4	6,6	0,05	14,1	21,27	4,88	0,55	-1,9	-0,13	-1,72
6.12.2011 19:00:00	-0,2	16,2	21,2	6,1	0,05	14,3	21,09	4,48	0,25	-1,9	-0,11	-1,62
6.12.2011 20:00:00	0,1	16,4	21,2	6,4	0,01	14,4	21,12	4,73	-0,09	-2	-0,08	-1,67
6.12.2011 21:00:00	0,5	22,9	17,1	12,1	0	19,2	20,25	9,77	-0,5	-3,7	3,15	-2,33
6.12.2011 22:00:00	0	21,9	17,3	14,2	0	19,6	19,82	13,4	0	-2,3	2,52	-0,76
6.12.2011 23:00:00	-0,1	21,4	17,8	15,3	0	19,6	19,81	14,7	0,1	-1,9	2,01	-0,65
7.12.2011	-0,1	21,2	18,1	15,9	0	19,7	19,79	15,4	0,1	-1,5	1,69	-0,53
7.12.2011 1:00:00	-0,3	21,4	18,2	16,2	0	19,9	19,7	15,7	0,3	-1,5	1,5	-0,47
7.12.2011 2:00:00	-0,5	21,4	18,4	16,4	-0,79	20	19,7	15,9	-0,29	-1,4	1,3	-0,55
7.12.2011 3:00:00	-1,5	21,5	18,5	16,5	-1,15	20,2	19,68	16	0,35	-1,3	1,18	-0,55
7.12.2011 4:00:00	-2,6	21,6	18,6	16,7	-2,83	20,3	19,73	16,1	-0,23	-1,3	1,13	-0,58
7.12.2011 5:00:00	-2,2	21,7	18,7	16,8	-3,16	20,4	19,78	16,3	-0,96	-1,3	1,08	-0,53
7.12.2011 6:00:00	-2,5	21,8	18,9	17	-2,83	20,5	19,84	16,4	-0,33	-1,3	0,94	-0,57
7.12.2011 7:00:00	-2,4	22	19,1	17,2	-3,05	20,6	19,93	16,6	-0,65	-1,4	0,83	-0,58
7.12.2011 8:00:00	-3	15,5	21,5	5	-3,04	14,2	21,24	4,47	-0,04	-1,3	-0,26	-0,53
7.12.2011 9:00:00	-3,8	15,4	21,7	4,4	-3,86	13,2	21,55	2,83	-0,06	-2,2	-0,15	-1,57
7.12.2011 10:00:00	-4,1	15,2	21,5	4,1	-4,67	12,8	21,55	2,36	-0,57	-2,4	0,05	-1,74
7.12.2011 11:00:00	-3,4	15,3	21,5	4,5	-4,48	12,8	21,53	2,42	-1,08	-2,6	0,03	-2,08
7.12.2011 12:00:00	-2,9	15,4	21,6	5	-3,1	13,1	21,54	3,03	-0,2	-2,3	-0,06	-1,97
7.12.2011 13:00:00	-3,2	15,4	21,6	4,8	-2,7	13,1	21,51	3,08	0,5	-2,3	-0,09	-1,72
7.12.2011 14:00:00	-3,3	15,3	21,5	4,7	-2,7	13	21,51	2,83	0,6	-2,3	0,01	-1,87
7.12.2011 15:00:00	-2,9	15,4	21,5	4,9	-2,7	13,1	21,47	3,03	0,2	-2,3	-0,03	-1,87
7.12.2011 16:00:00	-2,3	15,5	21,5	5,3	-2,7	13,2	21,47	3,3	-0,4	-2,3	-0,03	-2
7.12.2011 17:00:00	-2	15,4	21,3	5,3	-2,7	13,3	21,34	3,54	-0,7	-2,1	0,04	-1,76
7.12.2011 18:00:00	-1,9	15,4	21,1	5,4	-1,96	13,3	21,2	3,62	-0,06	-2,2	0,1	-1,78
7.12.2011 19:00:00	-1,3	15,5	21	5,1	-2,4	13,4	20,94	3,31	-1,1	-2,1	-0,06	-1,79
7.12.2011 20:00:00	-0,7	15,7	20,9	5,5	-1,84	13,5	20,84	3,63	-1,14	-2,2	-0,06	-1,87
7.12.2011 21:00:00	-0,1	20,2	18,7	10,6	-1,29	15,4	20,67	6,36	-1,19	-4,8	1,97	-4,24

7.12.2011 22:00:00	0,1	20,6	17,5	13,8	-0,91	18,3	19,64	12,9	-1,01	-2,3	2,14	-0,9
7.12.2011 23:00:00	0,2	20,3	17,7	15,1	-0,78	18,6	19,49	14,5	-0,98	-1,8	1,79	-0,65
8.12.2011	0,3	20,4	17,9	15,8	-0,46	18,8	19,49	15,3	-0,76	-1,6	1,59	-0,54
8.12.2011 1:00:00	0,5	20,6	18,1	16,4	0,19	19,2	19,55	15,8	-0,31	-1,4	1,45	-0,6
8.12.2011 2:00:00	0,6	20,8	18,4	16,7	0,18	19,5	19,56	16,1	-0,42	-1,3	1,16	-0,63
8.12.2011 3:00:00	0,6	21	18,5	17	0,19	19,8	19,57	16,4	-0,41	-1,2	1,07	-0,63
8.12.2011 4:00:00	0,6	21,2	18,6	17,1	0,18	20	19,58	16,5	-0,42	-1,2	0,98	-0,58
8.12.2011 5:00:00	0,7	21,5	18,7	17,2	0,18	20,2	19,59	16,6	-0,52	-1,3	0,89	-0,58
8.12.2011 6:00:00	0,8	21,6	18,8	17,4	0,41	20,3	19,61	16,8	-0,39	-1,3	0,81	-0,61
8.12.2011 7:00:00	1	21,7	19	17,5	0,52	20,5	19,67	16,9	-0,48	-1,2	0,67	-0,57
8.12.2011 8:00:00	0,8	16,2	21,2	7,4	0,52	15,2	21,05	6,67	-0,28	-1	-0,15	-0,73
8.12.2011 9:00:00	0,7	16,2	21,4	7,4	0,52	14,4	21,27	5,71	-0,18	-1,8	-0,13	-1,69
8.12.2011 10:00:00	0,8	16,5	21,6	7,6	0,52	14,5	21,48	5,84	-0,28	-2	-0,12	-1,76
8.12.2011 11:00:00	1	16,4	21,5	7,5	0,51	14,5	21,41	5,92	-0,49	-1,9	-0,09	-1,58
8.12.2011 12:00:00	0,8	16,4	21,5	7,4	0,52	14,5	21,41	5,78	-0,28	-1,9	-0,09	-1,62
8.12.2011 13:00:00	0,6	16,2	21,5	7,3	0,76	14,4	21,45	5,69	0,16	-1,8	-0,05	-1,61
8.12.2011 14:00:00	0,7	16,2	21,5	7,4	0,83	14,4	21,48	5,7	0,13	-1,8	-0,02	-1,7
8.12.2011 15:00:00	0,5	16,1	21,5	7,1	0,79	14,3	21,38	5,65	0,29	-1,8	-0,12	-1,45
8.12.2011 16:00:00	0,1	16	21,4	6,8	0,37	14,1	21,26	5,29	0,27	-1,9	-0,14	-1,51
8.12.2011 17:00:00	0,3	15,9	21,2	6,9	-0,33	14	21,16	5,15	-0,63	-1,9	-0,04	-1,75
8.12.2011 18:00:00	0,3	15,9	21,1	6,9	-0,34	14	21,03	5,29	-0,64	-1,9	-0,07	-1,61
8.12.2011 19:00:00	0	16	21,1	6,1	-0,33	14	20,85	4,56	-0,33	-2	-0,25	-1,54
8.12.2011 20:00:00	-0,1	16,1	21,1	6,1	-0,28	14,2	20,95	4,51	-0,18	-2	-0,15	-1,59
8.12.2011 21:00:00	0,4	22,1	17,3	12,4	-0,29	18,6	20,06	10,1	-0,69	-3,5	2,76	-2,29
8.12.2011 22:00:00	0,5	21,4	17,6	14,6	-0,27	19,2	19,68	13,9	-0,77	-2,2	2,08	-0,75
8.12.2011 23:00:00	0,4	21	17,9	15,7	0,5	19,3	19,67	15,1	0,1	-1,7	1,77	-0,57
9.12.2011	0,5	21	18,2	16,2	0,47	19,5	19,67	15,7	-0,03	-1,5	1,47	-0,54
9.12.2011 1:00:00	0,6	21,1	18,5	16,7	0,47	19,7	19,68	16,1	-0,13	-1,4	1,18	-0,59
9.12.2011 2:00:00	0,6	21,4	18,7	17,1	0,51	20	19,69	16,4	-0,09	-1,5	0,99	-0,66
9.12.2011 3:00:00	0,6	21,5	18,8	17,2	0,5	20,2	19,7	16,7	-0,1	-1,4	0,9	-0,53
9.12.2011 4:00:00	0,7	21,6	19	17,4	0,54	20,3	19,72	16,8	-0,16	-1,3	0,72	-0,58
9.12.2011 5:00:00	0,8	21,8	19,1	17,5	0,47	20,5	19,73	17	-0,33	-1,3	0,63	-0,55
9.12.2011 6:00:00	0,5	22	19,2	17,7	0,54	20,6	19,75	17,1	0,04	-1,4	0,55	-0,63
9.12.2011 7:00:00	0,7	22,1	19,4	17,9	0,57	20,7	19,86	17,2	-0,13	-1,4	0,46	-0,71
9.12.2011 8:00:00	0,4	16,5	21,6	7,3	0,57	15,2	21,26	6,59	0,17	-1,3	-0,34	-0,71
9.12.2011 9:00:00	0,3	16,2	21,6	7	0,57	14,4	21,58	5,45	0,27	-1,8	-0,02	-1,55
								MAX	0,87	-0,9	3,22	-0,47
								MIN	-1,79	-4,8	-0,41	-4,24

Appendix 2. Annual energy efficiency of rotating wheel heat recovery

t_u	Time period	Time in hours	t_{pLTO}	$t_{tLTO\ actual}$	t_{tLTO}	R_{LTO}	η_t	η_p	$Q_{exh\ air}$	Q_{LTO}	Q_{wc}
°C	%	h	°C	°C	°C				kWh	kWh	kWh
-35	0,00	0	-5,0	-11,6	-11,6	1,11	0,42	0,46	0	0	0
-34	0,06	5	-5,0	-10,6	-10,6	1,11	0,43	0,47	424	200	132
-33	0,08	2	-5,0	-9,6	-9,6	1,11	0,43	0,48	168	81	52
-32	0,09	1	-5,0	-8,6	-8,6	1,11	0,44	0,49	79	39	25
-31	0,17	7	-5,0	-7,6	-7,6	1,11	0,45	0,50	562	281	175
-30	0,26	8	-5,0	-6,6	-6,6	1,11	0,46	0,51	634	323	197
-29	0,38	10	-5,0	-5,6	-5,6	1,11	0,47	0,52	770	401	240
-28	0,55	15	-5,0	-4,6	-4,6	1,11	0,48	0,53	1132	601	352
-27	0,75	18	-5,0	-3,6	-3,6	1,11	0,49	0,54	1330	720	414
-26	0,90	13	-5,0	-2,6	-2,6	1,11	0,50	0,55	946	524	294
-25	1,21	27	-5,0	-1,6	-1,6	1,11	0,51	0,57	1915	1082	596
-24	1,55	30	-5,0	-0,6	-0,6	1,11	0,52	0,58	2086	1205	649
-23	1,98	37	-5,0	0,4	0,4	1,11	0,53	0,59	2510	1483	781
-22	2,43	40	-5,0	1,4	1,4	1,11	0,54	0,60	2656	1606	826
-21	2,91	42	-5,0	2,4	2,4	1,11	0,56	0,62	2719	1683	846
-20	3,37	40	-5,0	3,4	3,4	1,11	0,57	0,63	2532	1606	788
-19	3,98	54	-5,0	4,4	4,4	1,11	0,59	0,65	3330	2165	1036
-18	4,75	67	-5,0	5,4	5,4	1,11	0,60	0,67	4032	2688	1255
-17	5,73	86	-5,0	6,4	6,4	1,11	0,62	0,68	5043	3451	1569
-16	6,96	108	-5,0	7,4	7,4	1,11	0,63	0,70	6161	4329	1917
-15	7,74	68	-5,0	8,4	8,4	1,11	0,65	0,72	3781	2730	1176
-14	8,40	58	-5,0	9,4	9,4	1,11	0,67	0,74	3132	2326	974
-13	9,06	58	-5,0	10,4	10,4	1,11	0,69	0,76	3042	2326	946
-12	9,68	54	-5,0	11,4	11,4	1,11	0,71	0,79	2747	2165	855
-11	10,45	67	-5,0	12,4	12,4	1,11	0,73	0,81	3330	2706	1036
-10	11,95	131	-5,0	13,4	13,4	1,11	0,75	0,84	6285	5271	1955
-9	13,32	120	-5,0	14,4	14,4	1,11	0,78	0,87	5555	4814	1728
-8	14,51	104	-4,6	15,1	15,1	1,11	0,80	0,88	4664	4124	1451
-7	15,96	127	-3,8	15,3	15,3	1,11	0,80	0,88	5487	4852	1707
-6	17,71	153	-2,9	15,5	15,5	1,11	0,80	0,88	6386	5647	1987
-5	19,90	192	-2,0	15,7	15,7	1,11	0,80	0,88	7696	6805	2394
-4	22,91	264	-1,1	15,9	15,9	1,11	0,80	0,88	10170	8993	3164
-3	26,29	296	-0,2	16,1	16,1	1,11	0,80	0,88	10964	9694	3411
-2	29,10	246	0,7	16,3	16,3	1,11	0,80	0,88	8735	7724	2718
-1	32,93	336	1,5	16,5	16,5	1,11	0,80	0,88	11388	10069	3543
0	38,18	460	2,4	16,7	16,7	1,11	0,80	0,88	14901	13175	4636
1	45,47	639	3,3	16,9	16,9	1,11	0,80	0,88	19705	17424	6131
2	50,21	415	4,2	17,0	17,1	1,11	0,79	0,88	12172	10677	3787
3	54,03	335	5,1	17,0	17,3	1,11	0,78	0,86	9293	8031	2891
4	56,95	256	6,0	17,0	17,5	1,11	0,76	0,85	6709	5701	2087
5	59,39	214	6,9	17,0	17,7	1,11	0,75	0,83	5276	4397	1642
6	62,07	235	7,7	17,0	17,9	1,11	0,73	0,81	5433	4427	1690
7	63,95	165	8,6	17,0	18,1	1,11	0,71	0,79	3557	2823	1107
8	65,96	176	9,5	17,0	18,3	1,11	0,69	0,77	3532	2717	1099
9	68,37	211	10,4	17,0	18,5	1,11	0,67	0,74	3909	2895	1216
10	70,88	220	11,3	17,0	18,8	1,11	0,64	0,71	3732	2639	1161
11	73,74	251	12,2	17,0	19,0	1,11	0,60	0,67	3865	2577	1203
12	76,39	232	13,0	17,0	19,2	1,11	0,56	0,62	3223	1990	1003

13	79,26	251	13,9	17,0	19,4	1,11	0,50	0,56	3103	1724	965
14	82,74	305	14,8	17,0	19,6	1,11	0,43	0,48	3292	1568	1024
15	85,79	267	15,7	17,0	19,8	1,11	0,33	0,37	2473	916	769
16	88,69	254	16,6	17,0	20,0	1,11	0,20	0,22	1960	435	610
17	91,07	208	17,5	17,0	20,2	1,11	0,00	0,00	1287	0	400
18	93,24	190	18,3	17,0	20,4	1,11	0,00	0,00	880	0	274
19	94,90	145	19,2	17,0	20,6	1,11	0,00	0,00	449	0	140
20	96,35	127	20,1	17,0	20,8	1,11	0,00	0,00	196	0	61
21	97,52	102	21,0	17,0	21,0	1,11	0,00	0,00	0	0	0
22	98,39	76	21,9	17,0	21,2	1,11	0,00	0,00	0	0	0
23	99,00	53	22,8	17,0	21,4	1,11	0,00	0,00	0	0	0
24	99,35	31	23,7	17,0	21,6	1,11	0,00	0,00	0	0	0
25	99,69	30	24,5	17,0	21,8	1,11	0,00	0,00	0	0	0
26	99,86	15	25,4	17,0	22,0	1,11	0,00	0,00	0	0	0
27	99,95	8	26,3	17,0	22,2	1,11	0,00	0,00	0	0	0
28	100,00	4	27,2	17,0	22,4	1,11	0,00	0,00	0	0	0
		8760							**241340**	**188830**	**75084**

$$\eta_{t,a} = \mathbf{59,7}\%$$

Appendix 3. Total annual efficiency of ventilation equipped with rotating wheel heat recovery

Month	Mean t_u	Time in hours	t_{tLTO}	Q_{iv}	$Q_{iv,\ supply}$	$Q_{iv,\ make\text{-}up}$	Q_{LTO}
	°C	h	**°C**	**kWh**	**kWh**	**kWh**	**kWh**
January	-3,97	650	10,93	6762,43	4457,14	2782,37	16604,14
February	-4,50	602	10,72	6483,61	4128,00	2631,60	15704,39
March	-2,58	607	11,49	5731,83	4162,29	2453,67	14642,56
April	4,50	354	14,35	1610,25	2427,43	1001,31	5975,46
May	10,76	117	16,87	25,90	802,29	205,39	1225,66
June	14,23	9	18,27	0,00	61,71	10,45	62,33
July	17,30	0	19,51	0,00	0,00	0,00	0,00
August	16,05	31	19,00	0,00	212,57	26,31	156,98
September	10,53	161	16,78	61,24	1104,00	288,97	1724,48
October	6,20	331	15,03	1116,65	2269,71	839,79	5011,57
November	0,50	495	12,73	3620,33	3394,29	1739,57	10381,10
December	-2,19	595	11,65	5458,11	4080,00	2365,38	14115,69
				30870,36	27099,43	14344,81	85604,37

$$\eta_a = \mathbf{54{,}21}\%$$

Appendix 4. Annual energy efficiency of counter-flow plate heat recovery

t_u	Time period	Time in hours	t_{pLTO}	$t_{tLTO\ actual}$	t_{tLTO}	R_{LTO}	η_t	η_p	$Q_{exh\ day}$	$Q_{exh\ night}$	$Q_{exh\ we}$	$Q_{LTO\ day}$	$Q_{LTO\ night}$	$Q_{LTO\ we}$
°C	%	h	°C	°C	°C				kWh	kWh	kWh	kWh	kWh	kWh
-35	0,00	0	0,0	-14,0	-14,0	1	0,38	0,38	0	0	0	0	0	0
-34	0,06	5	0,0	-13,0	-13,0	1	0,38	0,38	471	47	38	180	18	14
-33	0,08	2	0,0	-12,0	-12,0	1	0,39	0,39	187	19	15	73	7	6
-32	0,09	1	0,0	-11,0	-11,0	1	0,40	0,40	88	9	7	35	3	3
-31	0,17	7	0,0	-10,0	-10,0	1	0,40	0,40	625	62	50	252	25	20
-30	0,26	8	0,0	-9,0	-9,0	1	0,41	0,41	705	70	56	290	29	23
-29	0,38	10	0,0	-8,0	-8,0	1	0,42	0,42	856	86	68	360	36	29
-28	0,55	15	0,0	-7,0	-7,0	1	0,43	0,43	1258	126	101	539	54	43
-27	0,75	18	0,0	-6,0	-6,0	1	0,44	0,44	1478	148	118	646	65	52
-26	0,90	13	0,0	-5,0	-5,0	1	0,45	0,45	1052	105	84	470	47	38
-25	1,21	27	0,0	-4,0	-4,0	1	0,46	0,46	2128	213	170	971	97	78
-24	1,55	30	0,0	-3,0	-3,0	1	0,47	0,47	2318	232	185	1082	108	87
-23	1,98	37	0,0	-2,0	-2,0	1	0,48	0,48	2788	279	223	1331	133	106
-22	2,43	40	0,0	-1,0	-1,0	1	0,49	0,49	2951	295	236	1441	144	115
-21	2,91	42	0,0	0,0	0,0	1	0,50	0,50	3021	302	242	1511	151	121
-20	3,37	40	0,0	1,0	1,0	1	0,51	0,51	2814	281	225	1441	144	115
-19	3,98	54	0,0	2,0	2,0	1	0,53	0,53	3700	370	296	1943	194	155
-18	4,75	67	0,0	3,0	3,0	1	0,54	0,54	4480	448	358	2413	241	193
-17	5,73	86	0,0	4,0	4,0	1	0,55	0,55	5604	560	448	3097	310	248
-16	6,96	108	0,0	5,0	5,0	1	0,57	0,57	6845	685	548	3885	389	311
-15	7,74	68	0,0	6,0	6,0	1	0,58	0,58	4201	420	336	2450	245	196
-14	8,40	58	0,0	7,0	7,0	1	0,60	0,60	3479	348	278	2088	209	167
-13	9,06	58	0,0	8,0	8,0	1	0,62	0,62	3380	338	270	2088	209	167
-12	9,68	54	0,0	9,0	9,0	1	0,64	0,64	3053	305	244	1943	194	155
-11	10,45	67	0,0	10,0	10,0	1	0,66	0,66	3700	370	296	2428	243	194

-10	11,95	131	0,0	11,0	11,0	1	0,68	0,68	6983	698	559	4730	473	378
-9	13,32	120	0,0	12,0	12,0	1	0,70	0,70	6172	617	494	4320	432	346
-8	14,51	104	0,7	12,3	12,3	1	0,70	0,70	5182	518	415	3628	363	290
-7	15,96	127	1,4	12,6	12,6	1	0,70	0,70	6097	610	488	4268	427	341
-6	17,71	153	2,1	12,9	12,9	1	0,70	0,70	7096	710	568	4967	497	397
-5	19,90	192	2,8	13,2	13,2	1	0,70	0,70	8551	855	684	5986	599	479
-4	22,91	264	3,5	13,5	13,5	1	0,70	0,70	11300	1130	904	7910	791	633
-3	26,29	296	4,2	13,8	13,8	1	0,70	0,70	12182	1218	975	8527	853	682
-2	29,10	246	4,9	14,1	14,1	1	0,70	0,70	9706	971	776	6794	679	544
-1	32,93	336	5,6	14,4	14,4	1	0,70	0,70	12653	1265	1012	8857	886	709
0	38,18	460	6,3	14,7	14,7	1	0,70	0,70	16556	1656	1325	11589	1159	927
1	45,47	639	7,0	15,0	15,0	1	0,70	0,70	21895	2189	1752	15326	1533	1226
2	50,21	415	7,7	15,3	15,3	1	0,70	0,70	13524	1352	1082	9467	947	757
3	54,03	335	8,4	15,6	15,6	1	0,70	0,70	10326	1033	826	7228	723	578
4	56,95	256	9,1	15,9	15,9	1	0,70	0,70	7455	745	596	5218	522	417
5	59,39	214	9,8	16,2	16,2	1	0,70	0,70	5863	586	469	4104	410	328
6	62,07	235	10,5	16,5	16,5	1	0,70	0,70	6037	604	483	4226	423	338
7	63,95	165	11,2	16,8	16,8	1	0,70	0,70	3953	395	316	2767	277	221
8	65,96	176	11,9	17,0	17,1	1	0,69	0,69	3924	392	314	2717	272	217
9	68,37	211	12,6	17,0	17,4	1	0,67	0,67	4343	434	347	2895	290	232
10	70,88	220	13,3	17,0	17,7	1	0,64	0,64	4146	415	332	2639	264	211
11	73,74	251	14,0	17,0	18,0	1	0,60	0,60	4295	429	344	2577	258	206
12	76,39	232	14,7	17,0	18,3	1	0,56	0,56	3582	358	287	1990	199	159
13	79,26	251	15,4	17,0	18,6	1	0,50	0,50	3448	345	276	1724	172	138
14	82,74	305	16,1	17,0	18,9	1	0,43	0,43	3658	366	293	1568	157	125
15	85,79	267	16,8	17,0	19,2	1	0,33	0,33	2748	275	220	916	92	73
16	88,69	254	17,5	17,0	19,5	1	0,20	0,20	2177	218	174	435	44	35
17	91,07	208	18,2	17,0	19,8	1	0,00	0,00	1430	143	114	0	0	0
18	93,24	190	18,9	17,0	20,1	1	0,00	0,00	978	98	78	0	0	0
19	94,90	145	19,6	17,0	20,4	1	0,00	0,00	499	50	40	0	0	0
20	96,35	127	20,3	17,0	20,7	1	0,00	0,00	218	22	17	0	0	0
21	97,52	102	21,0	17,0	21,0	1	0,00	0,00	0	0	0	0	0	0

22	98,39	76	21,7	17,0	21,3	1	0,00	0,00	0	0	0	0	0	0
23	99,00	53	22,4	17,0	21,6	1	0,00	0,00	0	0	0	0	0	0
24	99,35	31	23,1	17,0	21,9	1	0,00	0,00	0	0	0	0	0	0
25	99,69	30	23,8	17,0	22,2	1	0,00	0,00	0	0	0	0	0	0
26	99,86	15	24,5	17,0	22,5	1	0,00	0,00	0	0	0	0	0	0
27	99,95	8	25,2	17,0	22,8	1	0,00	0,00	0	0	0	0	0	0
28	100,00	4	25,9	17,0	23,1	1	0,00	0,00	0	0	0	0	0	0
		8760							**268156**	**26816**	**21452**	**170329**	**17033**	**13626**
									316424			**200988**		

$$\eta_{\boldsymbol{t,a}} = \mathbf{63,5}\%$$

Appendix 5. Total annual efficiency of ventilation equipped with counter-flow plate heat recovery

Month	Mean t_u	Time in hours	t_{tLTO}	Q_{iv}	$Q_{iv,\ supply}$	Q_{LTO}
	°C	h	°C	kWh	kWh	kWh
January	-3,97	650	11,89	5693,30	4457,14	17673,27
February	-4,50	602	11,70	5472,41	4128,00	16715,59
March	-2,58	607	12,40	4789,01	4162,29	15585,38
April	4,50	354	14,98	1225,49	2427,43	6360,22
May	10,76	117	17,26	0,00	802,29	1304,58
June	14,23	9	18,53	0,00	61,71	66,35
July	17,30	0	19,65	0,00	0,00	0,00
August	16,05	31	19,19	0,00	212,57	167,09
September	10,53	161	17,18	0,00	1104,00	1835,51
October	6,20	331	15,60	793,96	2269,71	5334,27
November	0,50	495	13,52	2951,89	3394,29	11049,54
December	-2,19	595	12,54	4549,21	4080,00	15024,59
				25475,28	27099,43	91116,38

$$\eta_a = \mathbf{63,4\%}$$

Appendix 6. Annual energy efficiency of cross-flow plate heat recovery

t_u	Time period	Time in hours	t_{pLTO}	t_{tLTO} actual	t_{tLTO}	R_{LTO}	η_t	η_p	$Q_{exh\ day}$	$Q_{exh\ night}$	$Q_{exh\ we}$	$Q_{LTO\ day}$	$Q_{LTO\ night}$	$Q_{LTO\ we}$
°C	%	h	°C	°C	°C				kWh	kWh	kWh	kWh	kWh	kWh
-35	0,00	0	0,0	-14,0	-14,0	1	0,38	0,38	0	0	0	0	0	0
-34	0,06	5	0,0	-13,0	-13,0	1	0,38	0,38	471	47	38	180	18	14
-33	0,08	2	0,0	-12,0	-12,0	1	0,39	0,39	187	19	15	73	7	6
-32	0,09	1	0,0	-11,0	-11,0	1	0,40	0,40	88	9	7	35	3	3
-31	0,17	7	0,0	-10,0	-10,0	1	0,40	0,40	625	62	50	252	25	20
-30	0,26	8	0,0	-9,0	-9,0	1	0,41	0,41	705	70	56	290	29	23
-29	0,38	10	0,0	-8,0	-8,0	1	0,42	0,42	856	86	68	360	36	29
-28	0,55	15	0,0	-7,0	-7,0	1	0,43	0,43	1258	126	101	539	54	43
-27	0,75	18	0,0	-6,0	-6,0	1	0,44	0,44	1478	148	118	646	65	52
-26	0,90	13	0,0	-5,0	-5,0	1	0,45	0,45	1052	105	84	470	47	38
-25	1,21	27	0,0	-4,0	-4,0	1	0,46	0,46	2128	213	170	971	97	78
-24	1,55	30	0,0	-3,0	-3,0	1	0,47	0,47	2318	232	185	1082	108	87
-23	1,98	37	0,0	-2,0	-2,0	1	0,48	0,48	2788	279	223	1331	133	106
-22	2,43	40	0,0	-1,0	-1,0	1	0,49	0,49	2951	295	236	1441	144	115
-21	2,91	42	0,0	0,0	0,0	1	0,50	0,50	3021	302	242	1511	151	121
-20	3,37	40	0,0	1,0	1,0	1	0,51	0,51	2814	281	225	1441	144	115
-19	3,98	54	0,0	2,0	2,0	1	0,53	0,53	3700	370	296	1943	194	155
-18	4,75	67	0,0	3,0	3,0	1	0,54	0,54	4480	448	358	2413	241	193
-17	5,73	86	0,1	3,9	3,9	1	0,55	0,55	5604	560	448	3082	308	247
-16	6,96	108	0,6	4,4	4,4	1	0,55	0,55	6845	685	548	3765	376	301
-15	7,74	68	1,2	4,8	4,8	1	0,55	0,55	4201	420	336	2310	231	185
-14	8,40	58	1,8	5,3	5,3	1	0,55	0,55	3479	348	278	1914	191	153
-13	9,06	58	2,3	5,7	5,7	1	0,55	0,55	3380	338	270	1859	186	149
-12	9,68	54	2,9	6,2	6,2	1	0,55	0,55	3053	305	244	1679	168	134
-11	10,45	67	3,4	6,6	6,6	1	0,55	0,55	3700	370	296	2035	204	163
-10	11,95	131	4,0	7,1	7,1	1	0,55	0,55	6983	698	559	3841	384	307

-9	13,32	120	4,5	7,5	7,5	1	0,55	0,55	6172	617	494	3395	339	272
-8	14,51	104	5,1	8,0	8,0	1	0,55	0,55	5182	518	415	2850	285	228
-7	15,96	127	5,6	8,4	8,4	1	0,55	0,55	6097	610	488	3353	335	268
-6	17,71	153	6,2	8,9	8,9	1	0,55	0,55	7096	710	568	3903	390	312
-5	19,90	192	6,7	9,3	9,3	1	0,55	0,55	8551	855	684	4703	470	376
-4	22,91	264	7,3	9,8	9,8	1	0,55	0,55	11300	1130	904	6215	622	497
-3	26,29	296	7,8	10,2	10,2	1	0,55	0,55	12182	1218	975	6700	670	536
-2	29,10	246	8,4	10,7	10,7	1	0,55	0,55	9706	971	776	5338	534	427
-1	32,93	336	8,9	11,1	11,1	1	0,55	0,55	12653	1265	1012	6959	696	557
0	38,18	460	9,5	11,6	11,6	1	0,55	0,55	16556	1656	1325	9106	911	728
1	45,47	639	10,0	12,0	12,0	1	0,55	0,55	21895	2189	1752	12042	1204	963
2	50,21	415	10,6	12,5	12,5	1	0,55	0,55	13524	1352	1082	7438	744	595
3	54,03	335	11,1	12,9	12,9	1	0,55	0,55	10326	1033	826	5679	568	454
4	56,95	256	11,7	13,4	13,4	1	0,55	0,55	7455	745	596	4100	410	328
5	59,39	214	12,2	13,8	13,8	1	0,55	0,55	5863	586	469	3224	322	258
6	62,07	235	12,8	14,3	14,3	1	0,55	0,55	6037	604	483	3320	332	266
7	63,95	165	13,3	14,7	14,7	1	0,55	0,55	3953	395	316	2174	217	174
8	65,96	176	13,9	15,2	15,2	1	0,55	0,55	3924	392	314	2158	216	173
9	68,37	211	14,4	15,6	15,6	1	0,55	0,55	4343	434	347	2389	239	191
10	70,88	220	15,0	16,1	16,1	1	0,55	0,55	4146	415	332	2280	228	182
11	73,74	251	15,5	16,5	16,5	1	0,55	0,55	4295	429	344	2362	236	189
12	76,39	232	16,1	17,0	17,0	1	0,55	0,55	3582	358	287	1970	197	158
13	79,26	251	16,6	17,0	17,4	1	0,50	0,50	3448	345	276	1724	172	138
14	82,74	305	17,2	17,0	17,9	1	0,43	0,43	3658	366	293	1568	157	125
15	85,79	267	17,7	17,0	18,3	1	0,33	0,33	2748	275	220	916	92	73
16	88,69	254	18,3	17,0	18,8	1	0,20	0,20	2177	218	174	435	44	35
17	91,07	208	18,8	17,0	19,2	1	0,00	0,00	1430	143	114	0	0	0
18	93,24	190	19,4	17,0	19,7	1	0,00	0,00	978	98	78	0	0	0
19	94,90	145	19,9	17,0	20,1	1	0,00	0,00	499	50	40	0	0	0
20	96,35	127	20,5	17,0	20,6	1	0,00	0,00	218	22	17	0	0	0
21	97,52	102	21,0	17,0	21,0	1	0,00	0,00	0	0	0	0	0	0
22	98,39	76	21,6	17,0	21,5	1	0,00	0,00	0	0	0	0	0	0

23	99,00	53	22,1	17,0	21,9	1	0,00	0,00	0	0	0	0	0	0
24	99,35	31	22,7	17,0	22,4	1	0,00	0,00	0	0	0	0	0	0
25	99,69	30	23,2	17,0	22,8	1	0,00	0,00	0	0	0	0	0	0
26	99,86	15	23,8	17,0	23,3	1	0,00	0,00	0	0	0	0	0	0
27	99,95	8	24,3	17,0	23,7	1	0,00	0,00	0	0	0	0	0	0
28	100,00	4	24,9	17,0	24,2	1	0,00	0,00	0	0	0	0	0	0
		8760							**268156**	**26816**	**21452**	**141765**	**14176**	**11341**
									316424			**167283**		

$$\eta_{t,a} = \mathbf{52,9}\%$$

Appendix 7. Total annual efficiency of ventilation equipped with cross-flow plate heat recovery

Month	**Mean t_u**	**Time in hours**	**t_{tLTO}**	**Q_{iv}**	**$Q_{iv, supply}$**	**Q_{LTO}**
	°C	h	**°C**	**kWh**	**kWh**	**kWh**
January	-3,97	650	9,23	8657,10	4457,14	14709,47
February	-4,50	602	8,98	8275,61	4128,00	13912,39
March	-2,58	607	9,89	7402,67	4162,29	12971,72
April	4,50	354	13,22	2292,10	2427,43	5293,61
May	10,76	117	16,17	165,76	802,29	1085,80
June	14,23	9	17,81	0,00	61,71	55,22
July	17,30	0	19,26	0,00	0,00	0,00
August	16,05	31	18,67	0,00	212,57	139,07
September	10,53	161	16,07	258,02	1104,00	1527,70
October	6,20	331	14,02	1688,52	2269,71	4439,71
November	0,50	495	11,34	4804,90	3394,29	9196,53
December	-2,19	595	10,07	7068,83	4080,00	12504,97
				40613,51	27099,43	75836,20

$$\eta_{a} = \mathbf{52,8}\%$$