1  Definition and concept of energy recovery ventilation system for buildings

There are a lot of different concepts for energy recovery ventilation (ERV) systems and different approaches. The definition of ERV varies in the literature; this section defines the understanding of ERV in this paper and explains the general concept.

1.1 Definition

Sometimes we distinguish between: a) heat recovery ventilation (HRV), which can recover only the sensible heat of the exchanged air, and b) (ERV), that can recover sensible heat and latent heat from the exchanged air. ERV is also referred to as enthalpy recovery. Sensible heat is the temperature of the fluid, which can be measured with a thermometer, and latent heat is the energy needed for the phase transition of the humidity in the air, which cannot be measured with a thermometer. In a hot climate, the term HRV is misleading because the indoor temperature is kept cool to ensure a healthy indoor environment. In this section, the term “energy recovery ventilation” is used even if only the sensible heat can be recovered.

The term “energy recovery” refers to the depth of a air-to-air heat or energy recovery system. These systems recover energy (heat/mass) from an air flow at a higher energy level by exchanging this energy to another air flow at a lower energy level. The energy recovery process can maintain a comfortable temperature level in a room between $-6$ to $-10^{\circ}$C. Additional energy is only needed at extreme external temperatures to keep the comfortable difference between the internal and external temperature. [1]

In extreme weather conditions, i.e. extreme cold and low humidity or extreme heat and high humidity, ERV is not sufficient to ensure a comfortable indoor environment. If the temperature difference and/or the humidity variation are too high, the sensible heat and/or the latent heat needs to be adjusted by using a heating, a cooling, or an air conditioning system, which would be added to the ERV.

1.2 Concept

The concept of ERV is based on the thermodynamic equilibrium, which any physical system tries to reach. For example, if ten litres of water at a temperature of $30^{\circ}$C and ten litres of water a temperature of $40^{\circ}$C are mixed, the twenty litres of water reach a temperature of $35^{\circ}$C, which is an equilibrium. If the ten litre buckets are now refilled, the temperature in both buckets will be $35^{\circ}$C. This equilibrium will be a 50 percent energy recovery, described in more detail in subsection 4.5.2.1.

In an ERV, the two fluids are the air leaving the building and the air entering the buildings. These fluids try to reach a thermodynamic equilibrium. The stale air and fresh air are kept separated by a medium in the ERV unit, which can transfer the sensible heat and/or the latent heat. If the
stale air and the fresh air are kept next to each other, without moving it, the thermal equilibrium would be reached after some time. This equilibrium will be a 50 percent energy recovery. Higher energy recovery is possible with smart designs of the ERV-unit, which will be described in subsection 4.5.2. The degree of efficiency declines with a higher air flow rate. ERV recovers up to 95 percent of the heat. There are many concepts and ways to recover heat; the right decision is based on the individual situation. In some cases, a simple system is sufficient, whilst high-tech is the best choice in other instances. [1] [2]

1.2.1 Centralized and decentralized systems

ERV can be distinguished as centralized and decentralized systems. Diverse operating principles are known as exhaust air systems, supply air systems, and systems that combine supply and exhausted air. Most ERV have filters, and this can be seen as standard. The quality of an ERV in this paper is defined by the efficiency of the heat exchanger. If the heat exchanger has a higher efficiency, the indoor temperature will be more stable. [1] [3]

Decentralized systems are more suitable for retrofitting as an add-on for rooms that have high moisture loads, like a kitchen or a bathroom. These systems have multiple units; each unit can switch from intake to exhaust so that they can recover the temperature and the thermal mass via switching. This recovery principle is similar to the rotary wheel, which is explained in section 1.5.2.2. Decentralised systems will not be explained further in this paper. [1] [3]

Centralized ERV systems have two air cycles. Each of the two air cycles has a blower fan - one to exhaust stale air and one to draw fresh air into the building. Centralized systems are complex. The air channels need to be connected to the one central unit. Two ways of connecting the ducts are possible:

- The simpler version connects the bedrooms and living rooms to the air supply outlets, and the kitchen and bathrooms to the stale air intake, as shown in Figure 1-1. The outlets and intakes between the rooms need to be connected by soundproof holes in walls and doors.
- The more complex version has each room separately connected to intakes and outlets. [1]
1.2.2 Energy recovery ventilation units

The ERV unit distinguishes ERV systems. The quality of the ERV system is the energy recovery efficiency degree of the ERV unit. The ERV unit is the heart of the ERV system. All ERV units have two outputs and two intakes, as shown in Figure 1-2. The outputs consist of one which extracts the used air to outside, and one which draws the fresh air into the room. The intakes consist of one which intakes fresh air from the outside, and one which intakes stale air from the room. Inside the energy recovery unit, the fresh air stream that enters the building is pre-conditioned by the stale air stream leaving the building. This energy recovery is done by using the energy difference between the fresh air and the stale air, which try to reach a thermodynamic equilibrium. The principle of the ERV unit is shown in Figure 1-2. [1] [2] [4]
As described before, new buildings have a high level of airtightness and therefor a lack of air exchanges by coincidental ventilation. This lack of ventilation causes a rise in carbon dioxide ($CO_2$) and other air pollution levels and can cause moisture problems. The necessary air exchanges can be provided by ERV, and reduce the pollution and adjust the relative humidity level to an acceptable level. The energy efficiency and the air quality are contradictive. If the air exchanges are low, the air quality and the energy demand is low, and if the air exchanges are high, the air quality and the energy demand is high. The lowest acceptable level of air exchanges depends on the occupancy of the building. For one person, $30 \, m^3/h$ is needed according to the DIN 1946 standard. If provided for one person: the fresh air is $30m^3/h$, the living space would be about $30 \, m^2$ and a room height is about $2.9$ meter, the air exchange per hour is $0.35$. This way of calculating may be not accurate because it does not take into account that people may gather in one room, and so further research is needed. Most likely, a $CO_2$ level based air exchange using a sensor will be the best energy efficient and healthiest approach for the future. An often suggested $CO_2$ level for mechanically ventilated buildings is $800 \, ppm$. Carbon dioxide controlled ventilation systems could improve the energy efficiency, comfort level and health requirements in buildings. [5] [2] [6]
1.4 Temperature and clothing factor

The temperature in a building should be between 20 – 26°C, corresponding to the RH level. Residential buildings and offices are designed for a clothing factor (Clo) of one. The thermal insulation needed for one Clo relates to the value of clothing required to keep a person comfortable whilst sitting at rest in a room at 21°C with air movement of less than 0.1 m/s and a relative humidity of 50 percent. A typical measure of one Clo is a person wearing a business suit. A clothing factor of 1 clo gives a person a thermal insulation of 0.155 m²K/W. [30] [31]

Figure 1-3 shows a type of psychrometric chart with the comfort zones for the clothing factor of one and a half. Depending on the individual, the ideal comfort zone will be different and so the indoor conditions need to be adjusted to the occupants needs. [7]

![Figure 1-3 Necessary clothing factor in an indoor environment. [7]](image-url)
1.5 Energy recovery ventilation systems for buildings

This subsection gives a short overview of the most common air to air energy recovery ventilation units. The function of the units is explained and the conditions in which they can be used in buildings.

1.5.1 Different types of energy recovery

The systems can be categorized into three different applications:

- Process to process, where the energy difference is recovered from the process exhaust stream and transmitted to the process supply stream. These systems only transfer sensible heat and can handle high temperature levels.
- Process to comfort recovers the heats (latent and sensible) from the process exhaust stream and transmits latent heat to the process supply stream. This process is only used in cold winters.
- Comfort to comfort recovers and transfers both latent and sensible heat between the processes and also adjusts the relative humidity level. [1]

There are many types of energy recovery methods that can be distinguished by size, configuration, used fluids and geometry. In this paper, it will be categorized by the construction of the heat exchanger; the ERV unit.

1.5.2 Overview of different energy recovery units

The extracted air needs to be the same amount as the fresh air in order to avoid creating over or under pressure in the building. Each ERV unit has two different efficiencies. One for running the fans, which gives the amount of electricity needed for moving one cubic meter of air in watt-hours per cubic meter. The other is the energy recovery efficiency of the ERV unit as a percentage. The following sections refer to the recovery efficiency.

1.5.2.1 Fixed-plate

Fixed-plate energy recovery is the most common setup of energy recovery ventilation units for buildings. Thin plates are stacked, while leaving gaps between them, so that the air can circulate in the gaps. The principle is shown in Figure 1-4. The thin plates separate the exhaust air and the supply air. The energy between the streams is transferred via the plate heat exchanging surfaces. The reached efficiency is between 50-85 percent of sensible heat. The high effectiveness of fixed plate recovery is due to the high heat transfer coefficients in conjunction with the principle of the counter-current streams. [1]
The principle of the countercurrent stream needs to be explained by an example. To start, there is bucket A, with ten liters of water at a temperature of 100°C, and bucket B, with ten liters of water at a temperature of 0°C. The water is always in liquid form.

The water is exchanged without mixing and energy losses. Bucket A will hold the water with 0°C and bucket B the water with 100°C. The water changes location, and the energy recovery is 0 percent.

If the water is mixed in a third bucket and then filled back into A and B, the water will have the temperature of 50°C, an energy recovery of 50 percent.

If these two liquids were in an endless long tube, separated by a thin air layer and moving contrary, the temperature for both liquids would be the same at the respective end. The temperature at B would be 100°C and at A 0°C. The ten liters of hot water would be cooled down to 0°C and the cold water heated up to 100°C, so that the water in A stays at 100°C and in B at 0°C. This is an energy recovery efficiency of 100 percent. Because of the losses and the particular length of the fixed-plates, only an efficiency of up to 85 percent is possible.

The outdoor temperature and humidity conditions have an impact on the performance of fixed-plate systems. A study showed that the efficiency of the fixed-plate type is higher in the winter time than in the summer time due the heat gain of the fan in the ERV unit. [1]

Diverse studies have shown that the efficiency of cross-flow membrane based ERV unit only achieves a recovery of 55 to 60 percent of the total heat. Improvements were obtained by a Z-flow configuration to approximately 75 percent sensible heat and 60 percent for latent heat. [1] [8]

![Fixed-plate energy recovery](image)
Different studies were carried out by changing the membrane material and properties. Thin plastic film plates under the cross-flow mode achieved an effectiveness of 65-85 percent by allowing the plates to be vibrated by the flowing air. Sensible polymer for a balanced ventilation system results in a drop of RH level from 95 percent to 34 percent and a thermal efficiency of 80 percent. The layout of the experimental facility of the sensible polymer fixed plate is shown in Figure 1-5. [9] [8]

1.5.2.2 Rotary wheel

The rotary wheel method has a turning disk with air tubes, as shown in Figure 1-6. The tubes are heated up by the hot air that is moving through the tubes. By turning the wheel, the heat from the tubes conducts from the pre-heated tubes to the cold air. The wheel transfers latent and sensible heat from one air flow to the other air flow. The rotation happens about 3 to 25 times in a minute and achieves efficiency of up to 80 percent. The advantages include high effectiveness, trouble-free operation and self-cleaning as well as the ability to use the energy of the latent and sensible heat and outweigh the disadvantages. The weaknesses are cross-contamination of the air flows, higher energy consumption, wearing of seals and a lifetime of 10 years. The disadvantage of mixing exhaust and fresh air can only be minimized but not eliminated because the air tubes are filled with air during the rotation process and are therefore moved to the other air flow. The rotary wheel approach is also really effective for dehumidifying, and can therefore be an excellent solution for a hot and humid climate. [1] [10] [11]

Many studies have been undertaken regarding the rotary wheel system. The different setups achieve diverse results. Overall, it can be expected that some improvements will be made in the near future. [1] [10]
1.5.2.3 Run-around

Run-around systems, as shown in Figure 1-7, use a fluid to transfer the energy between exhaust and fresh air. This fluid circulates between two heat exchanging coils. One loop cools the bypassing air, and the other one heats the bypassing air. Each coil could be placed in the building separately and only needs to be connected by pipes, which gives the system high flexibility for installation. The separated units of the inflow and the outflow guarantees no cross-contamination. The thermal efficiency is about 45 to 65 percent and does not achieve the 75 percent for the passive house standard. The main disadvantages are the energy required for pumping the three different mediums and the low energy recovery efficiency caused by the side step; a fluid for transferring heat. A higher efficiency is not expected due to the physical boundaries of exchanging heat twice. [1] [12]
Heat pipe units have a separate cycle with a cooling fluid for transferring heat, similar to the run around ERV unit as shown in Figure 1-8. The cooling fluid condenses under pressure and evaporates at a lower pressure. This mechanism is used to exchange energy between the exhausted air and the supply air. Heat is conveyed by the hot gas to the condenser and is transferred to the surrounding air. If the temperature is below operation temperature, the pipe is inactive making it ideal for heating. In this case, it should be used for cooling as the outside temperature needs to drop below the boiling point of the fluid in the tube. As soon as the outdoor temperature is above the boiling point, the heat pipe is not cooling and could even have an unwanted heating effect. The thermal efficiency is about 45-55 percent. The effectiveness of this system decreases at higher fan speeds. The advantages of this system include: no moving parts, ability to be used for cooling and heating, no cross-contamination, compact and suitable for different climate conditions. [1]

This system can also be integrated into HVAC in hot and humid climates for pre-cooling the air before entering the refrigerator of the HVAC system. A typical heat pipe for this function is shown in Figure 1-9. [13]
As described before, the heat pipe can be inactive if the temperature is below operation temperature. This is the case if it is used for heating. If it is used for cooling, the condensation temperature will be below 25°C. On a hot day, the fluid will stay evaporated and may cause a heating effect. Furthermore, the system can only work in a limited temperature range and can only be used one way; for cooling or heating.

Cooling is only possible if the outdoor temperature is below the indoor temperature. If cooling is needed, and the outdoor temperature is below the indoor temperature, it is better to use the fresh air without the ERV unit. In this case, a bypass would be the best choice like described in subsection 1.5.4.1. [14]
1.5.3 Heat pump

Heat pumps are not ERV units. They are reversed heat engine or reversible vapor-compression refrigeration devices. Heat pumps are optimized for high efficiency in both directions of thermal energy transfer and can be an efficient way of heating or cooling a building. Just like the heat pipe and the run-around unit, a heat pump uses a fluid for transferring the energy between the two air flows. [15] [16]

Figure 1-10 shows the refrigeration cycle of a heat pump. The working fluid has a liquid form in the high-pressure part of the condenser. The high-pressure part is separated from the low-pressure part by the expansion valve. As soon the fluid has a lower pressure, its starts to evaporate and cools down. The air flow around the evaporator heats the working fluid and speeds up the evaporation. The gaseous working fluid is compacted in the compressor, and the fluid becomes liquid and hot. The air flow around the condenser cools the working fluid before it reaches the expansion valve. [15]

The whole process can be reversed by changing the direction of the compressor. The condenser becomes the evaporator and vice versa. [17]

The thermal efficiency of heat pumps can be up to 90 percent and they could be used for a passive house. A combined solution using one heat pump for ventilating and heating the domestic hot water is possible, the potential is shown in section 1.6.5. [17]
1.5.4 Improvements for energy recovery units

Different add-ons to ERV systems can improve the efficiency of the system. The two most common ones are explained next.

1.5.4.1 Bypass for an ERV unit

A bypass is not an ERV unit, but it is an inexpensive tool that can improve an ERV system dramatically. The bypass is a tube that takes one air stream around the ERV unit. This tube is used if the outdoor temperature is beneficial for the indoor environment. For example, after a hot day the indoor temperature could be higher than the outdoor night time temperature. In this case, it is better to use a ventilation system without the ERV unit. A bypass in an ERV unit is shown in Figure 1-11. [18] [19]

Figure 1-11 Bypass of an ERV unit. [19]
1.5.4.2 Ground heat exchanger

A ground heat exchanger is not an ERV unit, but it is an addition to improve the efficiency of ERV systems. The ground heat exchanger and the bypass are the most common add-ons to ERV systems to improve the effectiveness.

The ambient earth temperature is typically $10 \sim 23^\circ C$ all year round and becomes more stable with depth. In the winter, the outdoor temperature can be lower than the ground temperature and so can pre-heat the fresh air. In the summer, the ground can be used for cooling. The ERV system can operate in a more extreme climate without additional energy needed for cooling or heating, by using a ground heat exchanger. In this case, a heating or cooling device is still needed, but the ground heat exchanger can reduce the energy demand. The layout of an ERV system including a ground heat exchanger is shown in Figure 1-12. [20]
1.6 Integrated use of energy recovery to ventilate houses

If the ERV system is not sufficient to keep the indoor environment at a comfortable level, the ERV system needs to be combined with other elements. By integrating different systems and using their synergy effects, ERV can be improved. The energy recovery ventilation unit can be combined with passive, active, conditioning and dehumidifying appliances. [1]

1.6.1 Energy recovery in passive ventilation systems

Early attempts to integrate energy recovery in passive ventilation used the stack effect. Stack effect pressure is generated by differences in air density with temperature, i.e. hot air rises and cold air sinks. This effect was used in a vertical counter flow air-to-air heat exchanger, achieving an efficiency of 40 percent. Although houses are only three to nine meters tall, a stack effect can be a major driving force to the airflow. The stack effect is high in climates with a temperature difference of $25^\circ C$ across the enclosure, or higher. This force can be used for cooling during the night time, as shown in Figure 1-13. [1] [21]

Others attempted to use a glazed solar chimney in conjunction with a heat pipe and achieved efficiency of 4 percent. [1] The effect of a solar chimney can be accomplished by creating a tall space vented at the top, allowing warm air to rise and flow out. Using sunlight to heat up the air within the chimney could further increase the temperature, resulting in the hot air rising and flowing out faster. A sun-exposed glazed chimney with dark surface materials would be ideal. Figure 1-14 shows the functions of a solar chimney; it shows how the movement of the hot air above creates a draught causing an infiltration of cooler fresh air below. [1] [22]
Figure 1-14 Solar Chimney Air Movement. [22]
1.6.2 Energy recovery in active ventilation systems

A traditional mechanical ventilation system can consume up to 33 percent of the household electricity consumption [1]. Implementing an ERV unit can reduce this consumption. Three different studies were undertaken using a heat recovery in an active ventilation system:

One showed that double recovery using sensible heat recovery and a heat pump is the most efficient way to save energy [23].

Another one showed that a total heat recovery (latent and sensitive) can increase thermal efficiencies up to 78 percent in a single room approach [24].

A cost-efficient study using available components in Finland showed that a traditional exhaust ventilation system uses about 67 percent more energy than an ERV system with 80 percent thermal efficiency. In this study, two heat recovery systems were compared as well. It showed that the systems with 80 percent thermal efficiency use 11 percent less energy than one ERV system with a 60 percent thermal efficiency. [25]

1.6.3 Conditioning of air with energy recovery

HVAC systems take the heat from the conditioning mode in the summer directly into the environment. Traditionally, the hot humid air is cooled below the dew point, and then reheated to the intended supply temperature and humidity. This cooling and reheating uses a lot of energy and could be reduced by using a heat pipe to pre-cool the air before entering the refrigerating unit of the HVAC system. Studies have been carried out on the cooling mode of HVAC, experimenting with a porous hydrophilic membrane - a phase changing material transferring heat and humidity from the intake to the exhaust stream. [1]

1.6.4 Combined use of energy recovery ventilation and building appliances

There are many appliances that create a local thermal difference. Most appliances create a positive thermal load, such as all electrical devices, cooking and baking equipment, refrigerators. All of these appliances are potential thermal sources. The biggest heating source is the waste water from the dishwasher, laundry, bath and shower. This heat could be used for preheating the domestic hot water as shown in Figure 1-15, but not for heating the air in the room. All the other heat sources transmit the heat to their environment and heat the air in the room, as shown in Figure 1-16. [26]

Only a few appliances create a negative thermal load, and they are normally all related to the cold water supply, as the toilet flushing tank. The most promising cooling potential is offered by the heating system for the domestic water if a heat pump is used. A heat pump is the same device as found in a refrigerator, only that it is used in reverse if a heat pump is used for heating water. The exhaust air is hot from a fridge and the exhaust air is cold from a heat pump.
Figure 1-15 Pre-heating of water for hot shower use. [26]

Figure 1-16 Internal thermal loads of buildings. [27]
1.6.5 Calculation of the cooling potential of a heat pump used for the hot water supply

The hot water demand is usually calculated as 25 litres of 60°C hot water per person and day. For the calculation of the cooling potential, 20 liters of 60°C hot water per person per day is used. The water supply temperature is calculated with the Passive House Planning Package (PHPP) at 19.2°C for the winter and 23.9°C for the summer. In the following calculation, a temperature of 25°C is used. 4,182 kilojoules is needed to heat one liter of water by one Kelvin.

\[
\text{Temperature differential} = \Delta T = 60°C - 25°C = 35 K
\]

\[
\text{Heating demand} = \frac{20 \times \text{water}}{ \text{(person \times day)}} \times 35 K \times \frac{4,182 \text{ kJ}}{K \times \text{water}} = 2927.4 \frac{\text{kJ}}{\text{person \times day}}
\]

\[
\text{Heating demand} = \frac{2927.4 \frac{\text{kJ}}{\text{person \times day}}}{3600 \text{ Sec}} = 0.813 \frac{\text{kWh}}{\text{person \times day}} = \frac{813 \text{ Wh}}{\text{person \times day}}
\]

The performance coefficient of a typical air-water heat pump is about 3.4, as it is for the LWP 300W of Dimplex. The LWP 300W is a hot water heat pump with an integrated ventilation system, as shown in Figure 1-17. It is usually installed as an exhaust-air system, but can also be integrated into an ERV-system or be installed separately, as shown in Figure 1-17. The cooling capacity is the heating demand for heating water minus the energy demand for running the heat pump. [28]

\[
\text{Energy demand} = \frac{813 \text{ Wh}}{\text{person \times day}} \times 3.4 = \frac{239 \text{ Wh}}{\text{person \times day}}
\]

\[
\text{Cooling capacity} = \frac{813 \text{ Wh}}{\text{person \times day}} - \frac{239 \text{ Wh}}{\text{person \times day}} = \frac{573 \text{ Wh}}{\text{person \times day}}
\]

One cubic meter of air needs 0.33 Wh to be heated by one Kelvin. Each person needs 30 cubic meters of fresh air per hour.

\[
\text{Air cooling capacity} = \frac{573 \text{ Wh}}{\text{person \times day}} \times \frac{1 \text{ m}^3}{0.33 \text{ Wh}} = \frac{1727 \text{ m}^3 K}{\text{person \times day}}
\]

\[
\text{Air cooling capacity} = \frac{1727 \frac{\text{m}^3 K}{\text{person \times day}}}{30 \text{ m}^3 \text{ person}} = \frac{57.7 K}{\text{day}}
\]

\[
\text{Air cooling capacity} = \frac{57.7 \frac{K}{\text{day}}}{24 \frac{h}{\text{day}}} = 2.4 K
\]
According to this calculation, it is possible to cool the 30 cubic meters of fresh air per person an hour by about 2.4 Kelvin. This cooling capacity can be sufficient to eliminate the cooling needs. If the cold exhaust air cannot be extracted directly to the outside in winter, it could cause a heating demand.

Figure 1-17 Ventilation system with a hot water heat pump. [29]
Sources


