An analysis of the innovative exhaust air energy recovery heat exchanger

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Abstract. Heating, ventilation and air conditioning systems are responsible for a nearly 50% of total energy consumption in operated buildings. One of the most important parts of the ventilation system is an air handling unit with a heat exchanger for energy recovery which is responsible for effective and efficient energy recovery from exhaust air. Typically heat exchangers are characterised by the producers by heat and humidity recovery efficiency up to 90% and 75% respectively. But these very high values are usually evaluated under laboratory conditions without taking into account a dynamic change of outdoor and indoor air conditions significantly affecting the recovery efficiency. In this paper, results of thermal, humidity and enthalpy recover efficiency of innovative energy recovery exchanger have been presented. The analysed system allows adjustment of the humidity recovery especially useful in the winter period and forefends energy use for an anti-froze system of energy exchanger. Presented result show that analysed innovative system can achieve the value of thermal efficiency recovery higher than 90% and efficiency of humidity recovery about 80%. This is possible because the analysed system is able to work without the use of any primary source energy or other anti-freeze systems. Presented in this research unique solution is able to work without external anti-freeze systems even in extremely adverse outdoor air conditions such as minus 20°C and humidity 100% RH.

1 Introduction

The construction sector is the largest source of energy consumption in the European Union economy, accounting for almost 40% of total energy demand in the EU-28 countries. This is more than transport (32%) or even whole industry sector (26%) [1]. This sector has been classified as one of the key sectors that should meet the 20-20-20 requirement: to reduce greenhouse gas emissions by 20% compared to 1990, to increase energy savings by 20% and increase the share of renewable energy sources by 20% by 2020. Also, the reduction of greenhouse gas emissions from the construction sector by the year 2050 is planned in the range of 88-91% compared to 1990 [2].

To decrease energy consumption in the construction sector in 2010, the European Union (EU) has introduced the directive EPBD [3] on the energy efficiency of buildings, which assumes that from 2019, all public buildings, and then from 2021, all newly constructed buildings, will have to meet the requirements for nearly zero-energy buildings (nZEB) [3]. In Poland, the EPBD directive was implemented in 2014, specifying in the national conditions the definition and requirements for this type of building [4].

It is known that the ventilation, heating, hot water and cooling systems in a typical building account for about 50% of the total energy consumption in the construction sector. Due to the national requirements, these systems have to be designed to meet the criteria for the maximum use of non-renewable primary energy for ventilation, heating/cooling and domestic hot water [5]. Nowadays the growing share of heating loads and ventilation the heat recovery appears as one of the important solutions able to decrease heat losses and create significant energy savings [6-8].

In almost all houses (depends on region) ventilation plays a significant role in the total heat losses. Heat loss due to ventilation is responsible for about 25-55% total heat loss. Taking into account this fact it is recognised that it is practically impossible to achieve a high energy-efficient house without adequately designed mechanical ventilation [9].

The main unit of mechanical ventilation system consists of air-to-air heat exchanger responsible for exhaust air energy (and humidity) recovery. Most manufacturers used of counterflow heat exchangers and declare temperature efficiency values above 90%. However, such high (reported by producers) efficiency results from the fact that it is usually determined in laboratory conditions with minimum values of air flow velocity through the heat exchanger and usually overestimating the results observed during the real operation of the heat exchanger [10]. In fact, during the

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year-long operation of the heat exchanger with non-constant parameters (temperature and relative humidity), a significant fall in performance is seen, getting up to 20% of the declared for laboratory measurement efficiency [11]. In addition to that, in locations where the outside temperature in winter falls below minus 5°C, there is a risk of icing on the heat exchanger surface.

The icing on the exchanger surface is caused by the condensation of the incoming from outside air as a result of the temperature fall on the heat exchange surface below the dew point temperature [12]. As a result, the condensate change phase due to the low temperature of the air flowing through the heat exchanger. With the time the ice layer increases significantly reducing the heat exchange surface area. This cause additional resistance of the air flow and leads to an increase in electricity consumption by fans as well as to a meaningful drop in the heat recovery performance. This phenomena in extreme situations can cause the complete destruction of the heat exchanger deactivating the operation of ventilation and air-conditioning systems.

The aim of the study is to evaluate the temperature, humidity and total efficiency of the air handling unit with a new proposed type of high-performance periodic counter flows air-to-air heat exchanger. This work presents the results of studies of the efficiency of recovery of sensible, latent and total heat for a periodic heat exchanger. An analysed heat exchanger significantly gain the energy efficiency of the ventilation as well as comfort air-conditioning system. The proposed system can be also implemented with the recovery of moisture from the used air. The presented solution prevents the heat exchanger icing without increasing its primary energy demand. As a result, very high and regular seasonal performance of heat and humidity recovery, independent of outside air parameters, can be expected.

2 Methodology

The periodic-flow heat exchanger unit consists of a standard counterflow exchanger and a set of opposing air dampers with a short opening/closing time, used to appropriately cyclically modify the direction of air flow through the heat exchanger, allowing the intake air to absorb the moisture from the cold side of the heat exchanger. This solution not only changed flow direction but also protects the exchanger against frosting.

The experimental measurement for the analysed system was done to determine the temperature, humidity and total efficiency of the air handling unit with a new generation of high-performance periodic counterflow air-to-air heat exchanger. The tests were carried out under conditions which, based on experience, were considered to be extremely unfavourable for the possibility of occurrence of the phenomenon of heat exchanger frosting. The details about flow conditions during the study are presented in Table 1.

Table 1. Airflow conditions during the study.

V_{cz} m³/h	T_{cz} °C	ϕ_{cz} %	V_w m³/h	T_w °C	ϕ_w %
670	-20	-70	680	20	-50

The fluid flow and heat transfer experimental measurement of the new type of air-to-air heat exchanger was carried out in the Polish National Research Radom Institute. Two independent calorimetric chambers allowed for precise control of climatic conditions and simulating the desired parameters of the intake air and the parameters of the extract air. The unit, in which the periodic-flow heat exchanger was installed, was placed in the chamber in which the air temperature was maintained at the level of 20.0 +/-1°C, thus reducing possible heat losses through the unit housing.

In the calorimetric chamber which simulated winter conditions, there was a connection of the intake and exhaust air to the unit with the periodic-flow heat exchanger, while in the warm chamber which simulated the conditions inside the ventilated rooms, there was a connection of the extract and supply air to the unit. A diagram of the analysed system is presented in Figure 1.

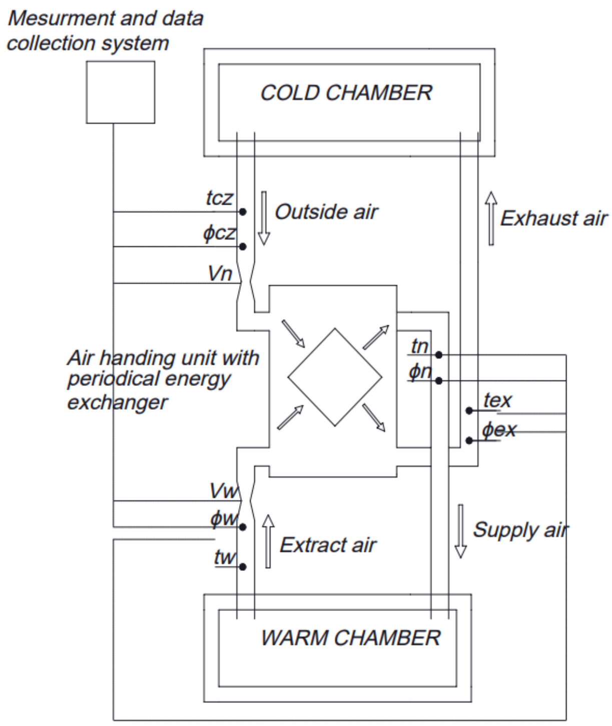

Fig. 1. Schematic diagram of the test section.

Air temperatures T_{cz}, T_{ex} (outside and exhaust air) and T_n, T_w (supply and extract air) were measured by using Geneza GPE-D-A-160-Pt100-klA sensors with 0.1K accuracy. Measuring of air relative humidity ϕ_{cz}, ϕ_{ex}, ϕ_n, ϕ_w were performed by using Introl EE31 transducers with 1% measurement uncertainties. Volume flow rates V_n, V_w (supply and extract air) were measured by using Venturi tube in accordance with PN-81/M-42364 standard.

A data logger (APAR AR207) was used to acquire individual air fluid flow and thermal parameters (air temperatures, volume flow rates, relative humidity). All monitored air thermal parameters and air flow parameters were acquired with a temporal resolution equal to 5 seconds and for a period of 5100 s. Regardless of the configuration, the temperature and humidity of the outside and extract air were stabilized for the period of about 1500 s.

2.1 Air moisture content

The air moisture content is the ratio of the mass of water vapour contained in the air to the mass of dry air. By transforming the gas state equations and using Dalton's law [13], the following equation can be used to determine the air moisture content on the basis of the value of the air temperature and relative humidity:

$$x = 0{,}622 * \frac{\phi * p_{gs}}{p_b - \phi * p_{gs}} \tag{1}$$

where

$$\mathrm{p_{gs}} = 6.1121 * \mathrm{e}^{\,17{,}502\mathrm{T}/(\mathrm{T}+240.97)} \tag{2}$$

$$\mathrm{p_b} = 1013.25$$

2.2 Air enthalpy

Humid air enthalpy *h* with moisture content *x* is the enthalpy of a mixture of 1 kg dry air and *x* kg water vapour. Assuming that for such a mixture of dry air and the total moisture content in the liquid form at 0ºC, the enthalpy equals zero, the following relationship is obtained:

$$h = c_{pg}T + x\left(c''_{pp}T + r_o\right) \tag{3}$$

2.3 Temperature efficiency of the heat exchanger

The temperature efficiency of a heat exchanger is calculated as the ratio of the heat flux recovered by the heat exchanger transferred from the extracted air to the supply air in reference to the total heating power required to heat the outside air to indoor air temperature. The efficiency of the recovery of sensible heat can be determined using the following equation:

$$\eta_t = \frac{(T_n - T_{cz})}{(T_w - T_{cz})} * 100\% \tag{4}$$

2.4 Humidity efficiency of the heat exchanger

The humidity efficiency of a heat exchanger is defined as the ratio of the moisture flux recovered by the heat exchanger transferred from the extracted air to the supply air compared to the total moisture demand that would have to be met in order for the humidity of the outside air to be increased to the level of humidity of indoor air. The efficiency of the recovery of latent heat (the so-called humidity efficiency) can be determined using the following equation:

$$\eta_w = \frac{(x_n - x_{cz})}{(x_w - x_{cz})} * 100\% \tag{5}$$

2.5 Total efficiency of the heat exchanger

The overall efficiency of the heat exchange can be defined as the ratio of the heat flux recovered in the heat exchanger system to the potentially recoverable heat flux. The efficiency of the total heat exchange can be determined from the following equation:

$$\eta_t = \frac{V_n * (h_n - h_{cz})}{V_w * (h_w - h_{cz})} * 100\% \tag{6}$$

3 Results and discussion

Figures 2-5 present the results of the flow rate measurements of supplied air V_n, and extracted air V_w, temperatures *T* and relative humidity ϕ of the air on each side of the heat exchanger. On the basis of laboratory and experimental test measurements, the interval of rapid air damper position changes was assumed to be 300 s. Changing the position of the dampers results in changing air flow through the exchanger direction, enabling evaporation of the condensate accumulated on the side walls of the exchanger in both operating modes. This condensate is then absorbed by the stream of outside air. The results in Figure 2 shows that by switching the air damper position resulting in a change in the direction of air flow through the heat exchanger and the resistance of the flowing air on both sides of the heat exchanger is changed. This causes a decrease in the extract air flow rate and an increase in the supply air flow rate by a constant value of about 60 m^3/h, which represents 8% of the respective initial rates. The total difference between the supply and extract air balance increases from the initial value of 5% to 15%.

The temperatures of the supply air are presented in Figure 3. It is worth to notice that none of the temperatures did not fall below the value of 18ºC during the entire period of the study, with the temperature values for the intake and extracted air stable and amounting to -20ºC (+/-0.5ºC), and 20ºC (+/-0.5ºC), respectively. The maximum temperature of the supply air was 18.9ºC, and the minimum was 18.2ºC, which results in the temperature efficiency of the exchanger in the range of 95-97.5%. The maximum exhaust temperature was -6.2°C and the minimum was -9.1°C. One can infer from the figure that despite critical air conditions, no frost was observed on the heat exchanger surfaces. This was caused by the complete evaporation of the condensate as a result of periodic changes in the direction of air flow through the heat exchanger.

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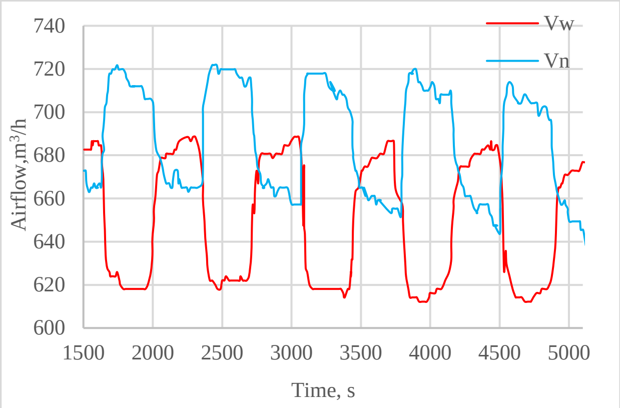

Fig. 2. Supply V_n and extract V_w air volume flow rates.

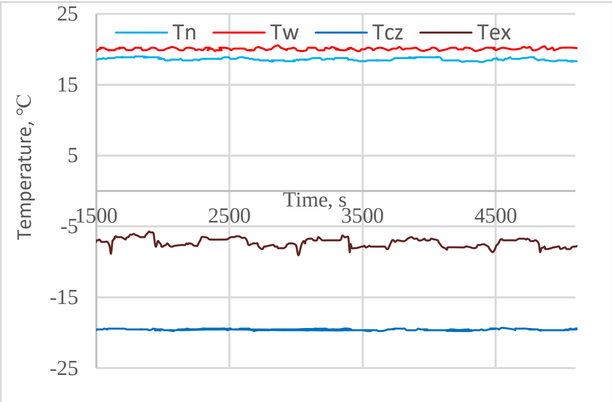

Fig. 3. Outside T_{cz}, supply T_n, extract T_w and exhaust T_{ex} air temperature.

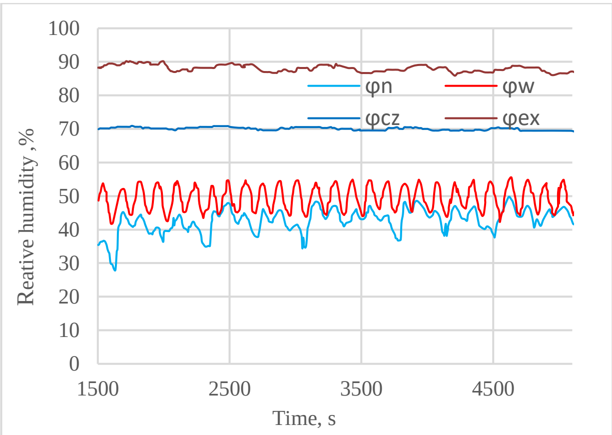

Fig. 4. Outside ϕ_{cz} , supply ϕ_n, extract ϕ_w and exhaust ϕ_{ex} relative humidity.

The humidity of the supply and extract air is presented in Figure 4. During the measurements, humidity changed dynamically between 30%–48% and 44–54% respectively. During the study, the supplied air had the humidity level higher than 30%, which effectively prevented the drying of the ventilated rooms, contributing to maintaining the feeling of thermal comfort for the users of the building.

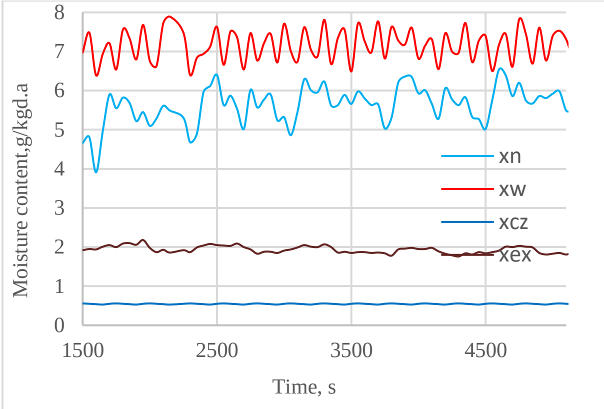

Fig. 5. Outside x_{cz}, supply x_n, extract x_w and exhaust x_{ex} air moisture content.

On the basis of the measurements of temperature and relative humidity of the air flowing through the air-to-air heat exchanger, the moisture content in each of the four air streams was evaluated. All these values, which contribute to the heat and moisture exchange processes, are presented in Figure 5. During the first 150 s of the changes in the working cycles of the quick-acting dampers, the most intensive process of evaporation of the condensate accumulated on the heat exchanger plates is observed, during the following 150 s, the moisture content x_w in the supply air drop as a result of the complete evaporation of moisture located on one side of the heat exchanger.

Table 2. Average temperature and efficiency of the heat exchanger.

V_n m³/h	V_w m³/h	T_{cz} °C	T_n °C	T_w °C	T_{ex} °C	N_t %	Q_t kW
685	651	19.8	18.6	20.1	-7.3	96.3	8.80

Based on the experimental measurement, it was evaluated that the average humidity efficiency is about 79.8%, while the average humidity capacity of the air handling unit with a periodic-flow heat exchanger is 2.96 kW. The detailed results for this case are presented in Tables 2-3. The average overall efficiency of the analysed in this work new heat exchanger type is about 91.4%, which translates into a total capacity of 11.76 kW (see Table 4).

Table 3. Average humidity and efficiency of the heat exchanger.

V_n m³/h	V_w m³/h	x_{cz} x/kg	x_n x/kg	x_w x/kg	x_{ex} x/kg	N_w %	Q_u kW
685	651	0.56	5.82	7.15	1.93	79.8	2.96

Table 4. Average total and efficiency of the heat exchanger.

V_n m³/h	V_w m³/h	h_{cz} kJ/kg	h_n kJ/kg	h_w kJ/kg	h_{ex} kJ/kg	N_c %	Q_c kW
685	651	18.2	33.35	38.2	-2.52	91.4	11.76

4 Conclusions

This work the results of experimental measurements conducted in order to determine the temperature, humidity and total efficiency of an air handling unit equipped with an innovative periodic counter-flow heat exchanger are shown. The analysis indicates that due to the appropriate design of the heat exchanger equipped with a system of air dampers, it is possible to achieve high system performance. The sensible and latent heat recovery at extremely unfavourable simultaneous values, amounting to 96.3% and 79.8% respectively. At the same time an overall heat recovery value is about 91.4% which is unusual for this type of devices. An advantage of the proposed heat exchanger solution is its unique property, which results in the fact that during the experimental measurement, despite low an average air temperature of -7.3°C on the exhaust side, no frost forming has been observed on the heat exchanger side walls or fins. With the proposed system, it is possible to eliminate additional typically implemented in this type of unit the anti-freeze systems that use an electrical heater, which requires high amounts of energy. To achieving the average air temperature of about 18.6°C and the supply air moisture content of 5.82 g/kg, it is unnecessary to use energy-consuming auxiliary heaters and air humidifiers.

Systems with periodic-flow heat exchangers can be recognised as a very good solution to the requirements of nearly zero-energy buildings.

The periodic operation of the heat exchanger should be sought primarily in the optimisation of its design to equate the air resistance on both sides of the exchanger and to minimise the difference in the balance of the supply air and extract air flow during changing the air damper position. It has been recognised that it is essential to carefully evaluate the time of changing the air dumpers positions with relation to the indoor and outside conditions, thus enabling a controlled recovery of moisture from the extract air.

In order to fully implement the proposed solution on a macro scale, it is required to create a numerical model of the air-to-air heat exchanger, which allows for accurate computational fluid dynamics analysis and for the optimisation.

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