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An experimental analysis of the fluid flow on performance and frost formation in exhaust air energy recovery heat exchanger

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Abstract. In the present paper, results for fluid flow, temperature and air humidity experimental measurements for innovative energy recovery counterflow air-to-air heat exchanger have been shown. For the low outdoor air temperatures case, frost formation is also observed and analysed. Base on the results of analysis the temperature, humidity and total efficiency of the exchanger are presented. The analysis showed that fluid flow rate, humidity and system efficiency significantly drop down under unfavourable conditions in the winter period when the outdoor temperature decrease below -5°C. In the present system, the heat exchanger equipped with a set of opposing air dampers can use intake air to absorb the moisture from the exhaust air. This solution has the advantage to prevent the exchanger frosting as well as melt ice layer if any growth on heat exchanger walls.

1 Introduction

In 2010 the Energy Performance of Buildings Directive (EPBD) [1] had been introduced by the European Commission. This document states that from 2019 all public buildings in UE will have to meet the requirements for nearly zero-energy buildings.

Heating, as well as air conditioning systems, are responsible for substantial energy consumption. In many cases, this consumption exceeds 60% of the total energy in operated buildings. Due to new regulations, such systems have to be designed to meet the requirements for the maximum use of non-renewable energy for heating, ventilation, cooling and hot water purpose. On the other hand, heating/cooling and ventilation units are often increasingly applicable in the domestic application as well as in industry [2-5]. Public buildings as also quite often with modern ventilation systems [6,7].

With increasing share of ventilation, the efficient energy recovery appears to be an essential issue and the unique solutions for energy saving [7-9]. But such ventilation type is necessary to keep certain indoor air quality [10-13]. With the implementation of energy recovery exchanger, it is a possibly significant decrease building energy consumption. The typically used for this purpose heat exchanger (HE) are characterised by high (often above 90%) recuperation efficiency [14]. Catalogue sheets of heat exchangers typically provide the temperature efficiency under optimum fluid flow conditions. Such high-efficiency also results from the fact that it is usually determined under laboratory conditions and for very low fluid flow velocity through the heat exchanger. However, these relatively high-efficiency values are usually evaluated without taking into account a dynamic change of fluid flow velocity or flow rate as well as outdoor and indoor air conditions which significantly affecting the reduction of heat recovery efficiency.

Additionally during the winter air temperature in cold and moderate climate zones may drop below minus 5°C which results in danger for HE icing. This phenomenon is caused by water dropping out from the exhaust air and occurs at the contact of the heat exchanger surface with cold air drawn from the outside [15,16]. Under the temperatures below zero Celsius, the condensate deposited in HE change its phase and cause a significant decrease in the heat recovery and finally increase the flow resistance. During low outdoor air temperatures, there is a risk of frost large formation on the heat exchanger surface which can lead to high-pressure drop, flow velocity decrease or even serious unit damage. To prevent heat exchanger from this situation and to keep constant fluid flow velocity, additional energy supply has to be implemented. Such a system is usually energy consuming and significantly reduce system performance. In the literature, various solutions have been proposed to melt ice deposited on HE surface. One of the most popular solutions includes the implementation of an electrical heater inside of HE in the supply air duct. Protection systems warm up the heat exchanger surface and melt the ice layer. The electrical heater significant increase the energy consumption and decrease central unit efficiency. Often a fresh air bypass is also applied. Different manufacturers also apply own solution, in which to warm-up the heat exchanger they turn-off the fresh air fans. However, the fresh air flow prevention

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fully disturbs the air flow in the entire building not ensuring acceptable comfort [17]. In many situations, the ice layer can also be melted by different the ratio of air supplied to the exhausted application. But such a solution reduces the amount of fresh air delivery to the building as well as create substantial negative pressure in the ventilated space.

In most of the central units, parallel plate counterflow air-to-air energy recovery heat exchanger are used. This type of heat exchanger was analysed in [18] in order to provide a guideline for optimal ventilation unit design. In their study two-dimensional model has was used in order to find analytical expressions. In other work [19] authors examined a new type of geometry for HE used in ventilation systems in cold and moderate climate zones. The methodology for system performance was presented base on the theoretical model and verified with experimental data. Fluid flow in parallel-plate turbulent open channel [20] has been studied successfully using Direct Numerical Simulation methods which provide very accurate results. In [21] the influence of channel geometrical configuration on the counter flow heat exchanger efficiency has been studied.

In this work, flow, temperature and humidity for innovative energy recovery counterflow air-to-air heat exchanger equipped with a set of opposing air dampers have been studied for the selected set of temperatures. Base on the results of analysis the temperature, humidity and total efficiency of the exchanger is evaluated. For the low outdoor air temperatures case, frost formation is also analysed. The present study was aimed to implement this solution to large industrial units.

2 Methodology

The periodic-flow heat exchanger unit under consideration consists of a standard counter-flow exchanger equipped with a set of opposing air dampers with a short opening/closing time, used in order to cyclically modify air flow direction. With this solution, the heat exchanger can use intake air to absorb the moisture from the exhaust air. It has also advantage to prevent the exchanger frosting as well as melt ice layer if any appears. The analysed HE used four identical counterflow exchanger arranged in the right order.

Additionally, the central unit is equipped with four counter-rotating aluminium dampers controlled by the actuators. Switching position allows changing the direction of air in different part of the exchanger. The fourth tightness class (according to EN-1751) prevent fresh and used air mixing. The measurement was done to determine the efficiency of the air handling unit with a new generation of the high-performance periodic counter-flow air-to-air heat exchanger with dampers.

Table 1. Flow Conditions during the study.

Parameter	V_{21}	t_{21}	ϕ_{21}	V_{11}	t_{11}	ϕ_{11}
Unit	m^3/h	^{o}C	%	m^3/h	^{o}C	%
Value	2000	-18	70	2000	23	46

where V, t, ϕ are volume flow rate, air temperature and humidity respectively.

The experimental measurements were done under real conditions reproduced in the laboratory to generate low air temperature and the possibility of occurrence of the phenomenon of heat exchanger frosting (Table 1).

The test section consisted of the central unit with a control system, which activates the anti-icing mode when the fresh air temperature t_{21} was below zero Celsius. The air handling unit was also equipped with a fresh air bypass, which was closed and deactivated for the current analysis. The time of dampers switching was set to 300s. The central unit was placed in an insulated chamber, inside which the air temperature was about 20+/-1^{o}C. The air was supplied to the air handling unit by two ducts equipped with glycol heaters/coolers. Figure 1 shows the measurement section of the heat exchanger. The temperature of the exhaust air from the room was maintained on a constant level of 23^{o}C, while the temperature of the fresh air was equal to -18^{o}C. JUMO EE650-T2L200 airspeed converters were used to record the volume flow rates (V_{11} ,V_{12}, V_{21}, V_{22}). JUMO EE210-HT3xPBFxB hygroscopic humidity and temperature converters were used to measure the air temperature and humidity (t_{11}, t_{12}, t_{21}, t_{22} and ϕ_{12}, ϕ_{12}, ϕ_{21}, ϕ_{22}). The data acquisition from sensors was carried out using a Mitsubishi Electric FX5U module and a MAPS HMI 750 panel. The measured values were recorded with 1-second intervals during the time equal to 2000s. The data recording was activated at the time of receiving constant temperature of the fresh air.

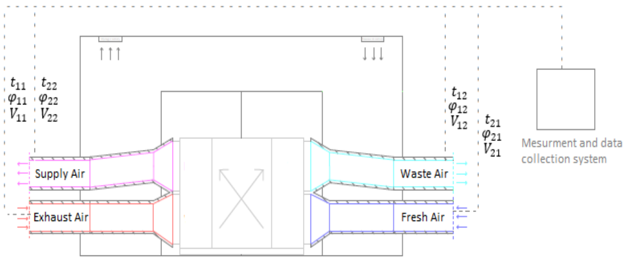

Fig. 1. Diagram of the test section.

Moisture content in the air:
The absolute humidity is defined as a ratio of water vapour mass in the air to the dry air mass. Using Dalton's law and the gas equation of state, it is possible to obtain a formula to evaluate the moisture content x in the air based on temperature and relative humidity as follows:

$$x = 0.622 \cdot \frac{\varphi \cdot p_{gs}}{p_b - \varphi \cdot p_{gs}} \tag{1}$$

where

$$p_{gs} = 6.1121 \cdot e^{\frac{17{,}502T}{T+240{,}97}} \tag{2}$$

$$p_b = 1013.25$$

Temperature efficiency:
The temperature η_t efficiency is calculated according to the following equations:

$$\eta_t = \frac{t_{22} - t_{21}}{t_{11} - t_{21}} \tag{3}$$

where t_{22}, t_{21}, are the temperature of supply and outdoor air, while t_{11} is exhaust air temperature.

3 Results and discussion

Figures 2 to 5 shows the experimental results of the air flow rate of fresh air V_{21}, and exhaust air V_{11}, temperatures t_{21}, t_{11} and relative humidity ϕ_{21}, ϕ_{11} of the air on each side involved in the energy exchange process. The volume flow rate of both flows was set-up to be 2000 m^3/h. On the basis of laboratory and experimental test measurements, the interval of rapid air flow damper position changes was set-up at the level of 300 s. Different the dumpers position results in different the direction of air flow through the air-to-air heat exchanger, enabling the condensate accumulated evaporation from the walls of the exchanger in both operating modes. The deposited at the wall surface water droplets are evaporated and absorbed by the stream of outside air. The results in Figure 2 shows that by switching the air damper position result in the air flow direction change through the heat exchanger. At the same time the resistance of the channel flows has changed which impact on the fluid flow velocity on both sides of the heat exchanger.

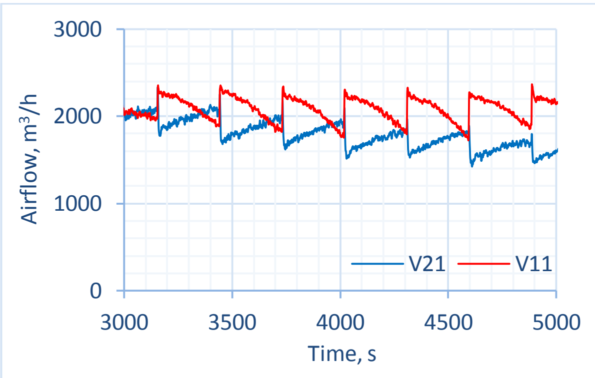

Fig. 2. Fresh V_{21} and exhaust V_{11} air volume flow rates.

The temperature of the supply air t_{22} presented in Figure 3 was about 14°C, with the temperature values for the intake t_{21} and extract air t_{11} stable all equal to -18°C (+/-0.5°C), and 23°C (+/-0.5°C), respectively. The above conditions result in the estimated temperature efficiency of the exchanger with dumpers in the range of 76-78% (see Fig. 6).

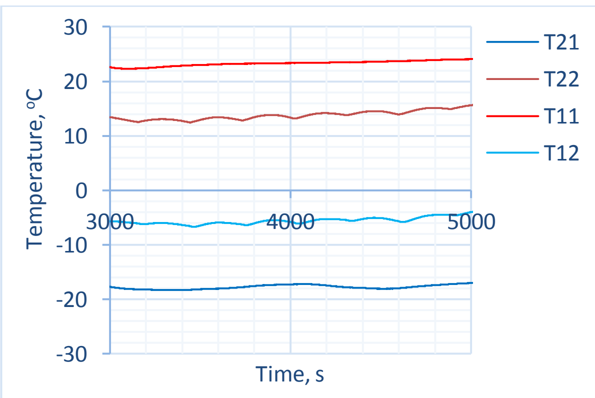

Fig. 3. Fresh t_{21}, supply t_{22}, exhaust t_{11} and waste t_{12} air temperature changes.

It is worth notice that despite critical air conditions due to dumpers implementation and flow direction variation, no frost layer was observed on the heat exchanger surfaces (see Fig. 7). Despite of not full water droplets evaporation (condensate), heat exchanger surface was at good condition. The average amount of condensed water from extract air was about 5.9 g/kg, and the evaporated water in supply air increase was about 4.72 g/kg. The deposited water content was observed as the iced surface of drip tray shown in Figure 8.

The relative humidity is presented in Figure 4. During the measurements, it changes dynamically between 40%–60% on supply air and 80–90% on waste air. During the study, the supplied air had the average humidity level higher than 50%, which effectively prevented the drying of the ventilated rooms, contributing to maintaining the feeling of thermal comfort for the users.

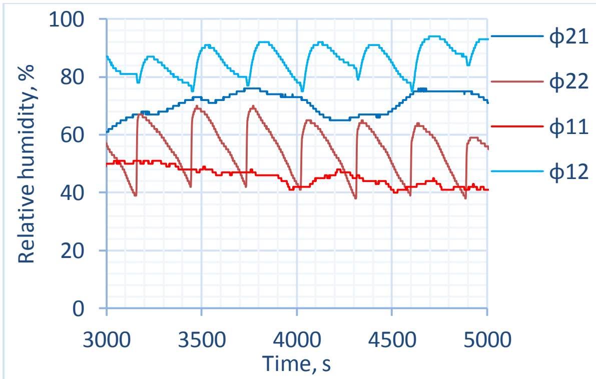

Fig. 4. Fresh φ_{21}, supply φ_{22}, exhaust φ_{11} and waste φ_{12} air relative humidity changes.

On the basis of the measurements of temperature and relative humidity values of the air flowing through the heat exchanger, the moisture content changes in each of the four air flow streams were evaluated. All these values, which contribute to the heat and moisture exchange processes, are presented in Figure 5.

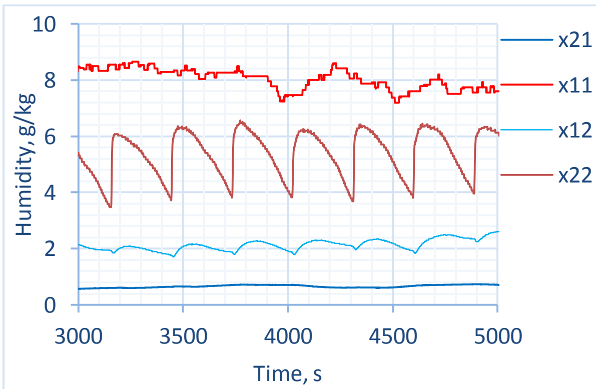

Fig. 5. Fresh x_{21}, supply x_{22}, exhaust x_{11} and waste x_{12} air humidity changes.

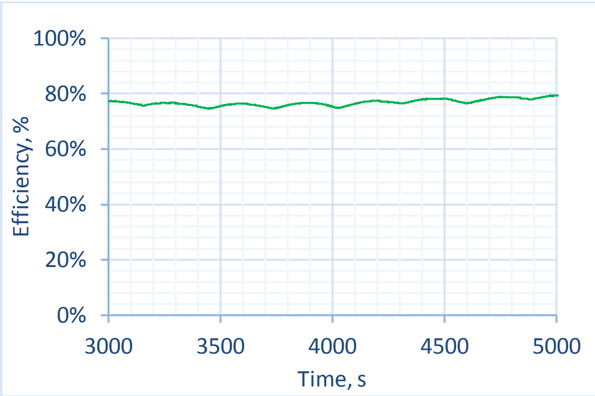

Fig. 6. The temperature efficiency over time.

Based on the experimental measurement the average humidity efficiency was evaluated to be equal to approx. 64%. According to Table 2 when humidity is not exchanged (as the case in traditional standard ventilation units), the process of heat exchange between fresh and exhaust air can be shown on Mollier chart - Figure 9. On these terms, the relative humidity would be only 10%.

Table 2. Average value of temperature, relative humidity and humidity.

t_{21}	−17.8°C	φ_{21}	70.7%	x_{21}	0.66 g/kg
t_{22}	13.8°C	φ_{22}	55.4%	x_{22}	5.38 g/kg
t_{11}	23.3°C	φ_{21}	45.6%,	x_{11}	8.04 g/kg
t_{12}	−5.6°C,	φ_{22}	85.7%	x_{12}	2.13 g/kg

Fig. 7. The heat exchanger surface at the end of measurements.

Fig. 8. Iced drip tray at the end of measurements.

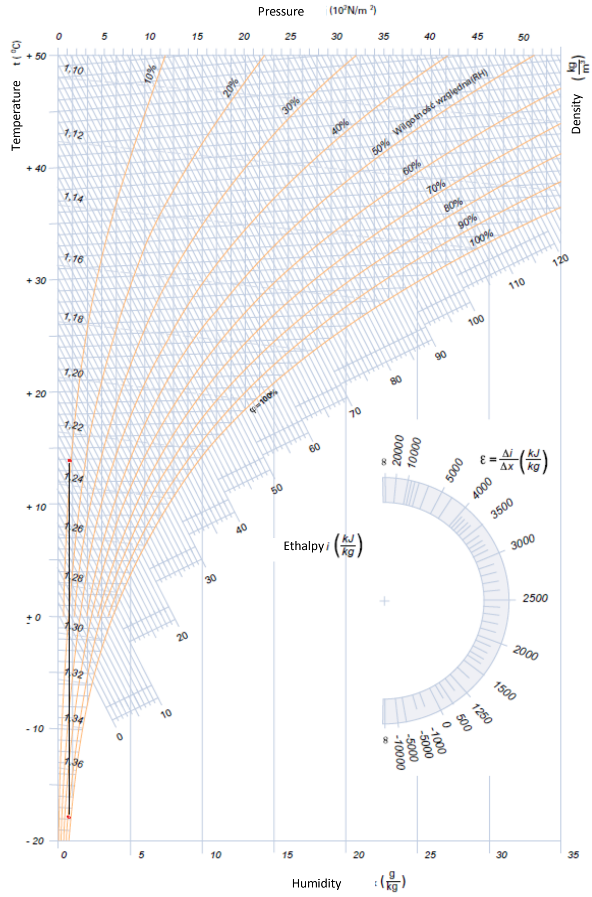

Fig. 9. Air process heating on Mollier chart (x=const).

4 Conclusions

In this research, the results of experimental measurements of an air handling unit equipped with an innovative periodic parallel-plate counterflow heat exchanger with dumpers are presented. Based on the analysis it is seen that traditional "anti-freezing" system which utilises different flow rates or even prevents fresh air flow to melt ice layer on heat exchanger surface should not be used at low-temperature conditions and can't be applied without an additional usually energy consuming protection method. Additionally, such a solution doesn't fulfil its primary role - proper building ventilation. The deficit of fresh air will result in significant growth of CO_2 concentration in the room as well as in the air temperature drop. The implementation of the heat exchanger with a system of air dampers which change air flow direction may solve wholly issue of heat exchanger icing. With dumpers, it is possible to achieve very high-efficiency values - not available by any other commercial unit. The proposed solution, remove anti-freeze systems (usually electrical heaters) completely. For the stable fresh air temperature equal to -18°C the evaluated temperature efficiency of the exchanger with dumpers was in the range of 76-78%.

In addition to that, based on the experimental measurement the average humidity efficiency is equal to approx. 64%. The mean amount of condensed water from extract air was 5.9 g/kg, while the evaporated water in supply air increase was 4.72 g/kg. During the analysis,

the supplied air the average humidity was higher than 50%, which entirely prevents the drying of the ventilated space. It is important to notice that low moisture content in air flow stream may lead to health problems, malaise and worsens the thermal comfort. At autumn and winter seasons there is even recommended to humidify the air in dry rooms. However using additional devices people are exposed to unnecessary investment, operational and maintenance costs. The proposed periodic-flow heat exchanger with flow direction switching using dampers may be an excellent solution for all types of buildings (public, private, schools or hospitals), allowing to keep the necessary measure at a comfort level.
It has been found that it is important to precisely determine the time of changing the direction of the fluid flow (the positions of the air dampers) with correlation to the outside and indoor conditions thus enabling a controlled recovery of moisture from the extract air.

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