An experimental investigation of the thermal efficiency and pressure drop for counterflow heat exchangers intended for recuperator

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Abstract. Ventilation systems are responsible for a large part of total energy consumption in operated buildings. The possibility of significant energy savings has been noticed when using mechanical ventilation. In order to decrease energy consumption, devices called recuperators are used and their main element responsible for heat recovery is the heat exchanger. In this work, thermal efficiency and pressure drop at individual heat exchangers designed for recuperators were examined. The results of the analysis and the influence of parameters on the device operation are presented. Finally, the thermal efficiency of the entire unit was evaluated. The results were compared and the phenomena occurring in the device itself affecting the differences in calculated efficiency were described.

1 Introduction

Ventilation is a process designed to bring fresh air into rooms while extracting used air. Due to deterioration of the microclimate, including air quality inside the residential and commercial buildings, the application of mechanical ventilation becomes necessary. However, typical ventilation and air conditioning systems can consume as much as 50% of the total electricity demand [1]. By increasing the number of air changes in a ventilated space, the quality of air inside it is significantly improved but at the expense of increased energy requirement for cooling and heating. The two main strategies to reconcile these contradictions are the use of heat recovery and the implementation of controlled ventilation [2-4]. By increasing global energy consumption, legal regulations and environmental protection, manufacturers of ventilation devices are forced to use energy-savings solutions [5].

One of the solutions to fulfil current energy efficiency requirements is to use heat exchangers in air distribution devises. Thanks to this approach, along with energy-saving, we provide sufficient fresh air, better microclimate control and high energy efficiency [6]. Studies show that using heat recovery equipment, total annual energy consumption can be reduced in cold climates by up to 20% [7]. A typical mechanical ventilation system consists of air ducts, fans and a heat exchanger in which thermal energy is transferred between streams. Fans ensure air movement through the exchanger ensuring proper flow. They also give the possibility to regulate the mass flow and thus the number of air changes in the building.

Current heat recovery systems are able to recover around 60-95% of the energy contained in waste air, which is a significant value. This shows huge potential for reducing the heat needs of buildings incurring relatively low investment costs [8]. At present, plate heat exchangers are very popular due to their compactness and high heat transfer coefficient [9]. They form the basis for very efficient heat recovery because their high efficiency in combination with counter-flow allows obtaining temperatures close to the final values which is the temperature of the air in ventilated space [10-13].

Heat recovery efficiency is defined in standard rated conditions for a given device. Usually specified in relevant standards. E. Juodis [14] noticed that the actual efficiency of heat recovery depends not only on the heat recovery unit, but also on the heat loss and gain ratio in the building.

In [15] as much as 13 ventilation units were tested and the 3 best cases the actual heat efficiency was in the range of 60-70% and concerned units with a nominal efficiency of 80%. For the 3 worst results, the actual efficiency was less than 10%, so the system consumed more energy than recovered. The differences were mainly caused by leaks both inside the building and in the ventilation unit itself. M.K. Drost [16] conducted an analysis of the thermal efficiency of heat recovery systems in 38 houses. During studies, it was estimated that the devices worked on average about seven hours a day with an average thermal

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efficiency of 52%. Such a low value suggests that design ventilation indicators were not provided.

Research carried out by Shah and Skiepko [17] clearly showed that even with relatively small leaks (around 5%), a significant reduction in heat exchange between cold and warm air could be observed. In [18] experimental and numerical studies were carried out to determinate the relationship between various heat exchanger parameters. It has been shown that the flow conditions and heat transfer coefficient, which depend on the geometry of the exchangers, affect the efficiency of devices. The thermal efficiency of plate heat exchanger decreases as the flow rate increases. In similar research studies [19], authors noted that when the flowrate increase from 50 m^3/h to 175 m^3/h, the efficiency decreased from 94% to 78%. When the air velocity through the exchanger increases, the air resistance increases as well. Pressure loss as a function of flow directly depends on the geometry of the exchanger.

Based on the literature review it can be concluded that the heat exchange efficiency and airflow resistance are affected not only by the unit design (geometrical parameters) but also depends on unit operating parameters. In addition, counterflow heat exchangers have the highest heat recovery potential. For this reason, presented research in this work focuses on this type of heat exchangers. However, counterflow heat exchangers varies considerably depending on the design, material used and method of manufacture. In this work, the main attention is paid to thermal efficiency, which directly affect the thermal comfort of people in the ventilated space. In addition to that, the focus is on the pressure drop, which causes a significant increase in energy need to be supplied to the system. Industrial companies are interested in solutions improving the efficiency of energy systems without significant investments. They are also aimed at minimizing energy losses and maximizing energy efficiency [20,21]. The paper presents the results for two different counterflow heat exchangers produced by the same manufacturer. One of the analysed exchangers was installed and tested in a real system device unit. The presented measurements were carried out according to 13141-7 and PNEN 308 standard.

2 Experimental methodology

The experimental measurement was performed to determinate the temperature and sensible efficiency of the heat exchanger. The measurement procedure has been done under conditions presented in PNEN 308 standard (Table 1). The test was carried out on the test stand presented in Figure 1 according to Figure 2.

Table 1. Measurement conditions.

Extract air		Outdoor air	
T_{11} [°C]	T_{w11} [°C]	T_{21} [°C]	T_{w21} [°C]
25	< 14	5	-

In Tab.1. the T_w is the wet-bulb temperature of the air while indexes are as follows:

22 - the supply air	11 - the extract air (room)
21 - the fresh air	12 - the exhaust air

Parameters such as temperature (T_{21}, T_{22}, T_{11}, T_{12}) were measured using PT1000 sensors and pressure (p_{21}, p_{22}, p_{11}, p_{12}) by using PT2500 – R8 sensor. The air flowrates (V_{21}, V_{22}, V_{11}, V_{12}) were measured by using the Venturi tube. During experiments, the flow was set to 600 kg/h. The measurement was recorded by Jumo Logoscreen and the Mitsubishi Electric FX5U acquisition system with the MAPS HMI 750 panel. The measurements were recorded with time step 1 second and averaged every 60 seconds.

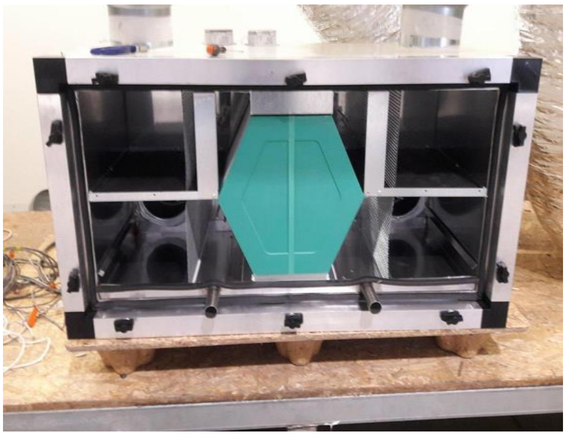

Fig. 1. Photo of test section.

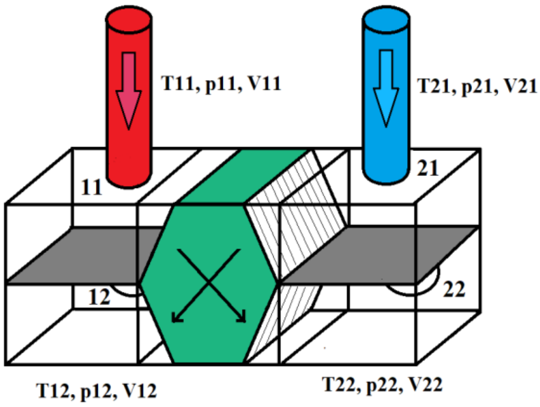

Fig. 2. Diagram of the test section.

The outdoor air was drawn to the section presented in Figures 1-2 by channel 21, and the warm air which simulated the conditions inside the ventilated space was drawn by channel 11. Respectively the channel 22 contains the fresh air while channel 12, waste air. The temperature efficiency of a heat exchanger was calculated as the ratio of the heat flux recovered by the heat exchanger transferred to or extracted from the supply air in reference to the total heating power required to heat the outside air to indoor air temperatures.

Efficiency ratio on the supply air side can be calculated using the following equation:

$$\eta_{t,su} = \frac{T_{22}-T_{21}}{T_{11}-T_{21}} \cdot \frac{q_{m22}}{q_{m11}} \quad (1)$$

where T is the temperature of air and q_m is the mass flow of air (for well-balanced units, the flow ratio of q_{m22} and q_{m11} should be up not higher than 3%).

3 Results and discussion

The experimental measurements were carried out in order to evaluate key thermal and fluid flow parameters and select the appropriate heat exchanger device for the newly designed system unit. Two different exchangers from the same manufacturer were tested. The primary to evaluate parameters were temperature efficiency and pressure drop.

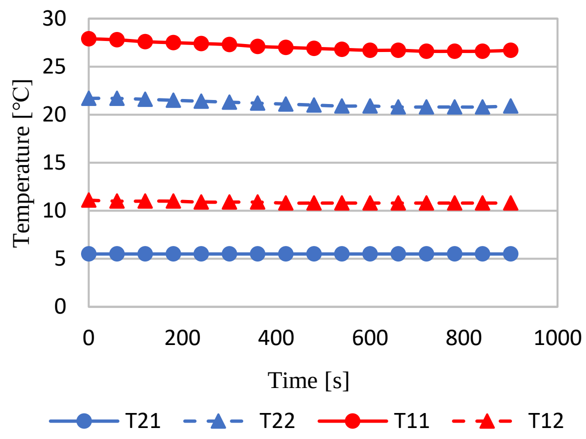

Fig. 3. The air temperature through the heat exchanger HEX1.

Based on the measured pressure, Figure 4 was plotted showing the pressure drop in the exchanger. It can be noticed that the airflow is asymmetrical, higher resistance is generated on the fresh-supply channel than on the exhaust-extract section.

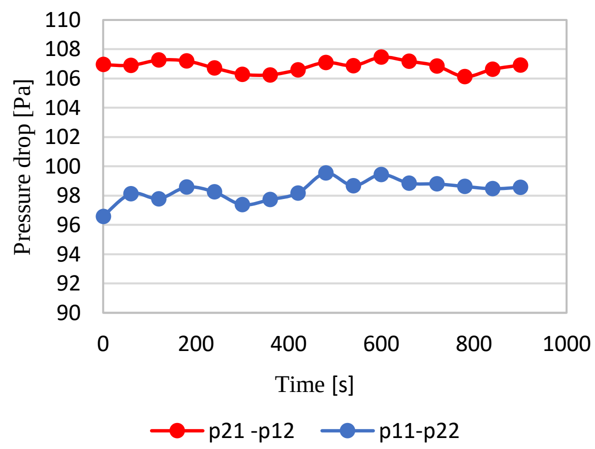

Fig. 4. Pressure loss through the heat exchanger HEX1.

Figure 3 shows all 4 streams (22 - the supply air; 11 - the extract air; 21 - the fresh air; 12 - the exhaust air) temperature during the experimental measurement. The first analysed heat exchanger HEX1 obtain an average thermal efficiency about 72.5% with a mass flow equal to 600 kg/h.

For the second heat exchanger HEX2, the same analysis was carried out. The evaluated average temperature efficiency in this case about 83.3% was achieved for the same mass flow rate. Figure 5 presents the air temperature for the heat exchanger HEX2.

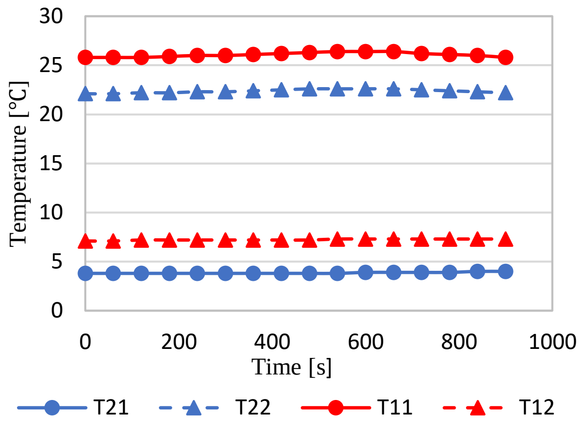

Fig. 5. The air temperature through the heat exchanger HEX2.

Also, in the case of this exchanger, the flow turned out to be asymmetrical, and the pressure difference between the inlet of supply air and exhaust air was about 30 Pa. The measurement results are presented in Figure 6.

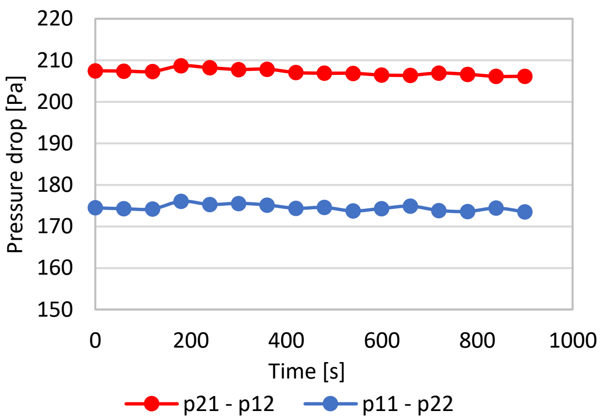

Fig. 6. Pressure loss through the heat exchanger HEX2.

Due to the two times lower pressure loss in the exchanger, the HEX1 heat exchanger was selected for assembly in the prototype system unit. This choice was caused by a significant energy saving during the operation of fans installed in the device. After assembly of the selected heat exchanger, the entire device was tested according to 13141-7 standard.

During the experimental measurement, the device was not completely sealed. Figure 7 shows the mass flow of the air over time. The ratio of q_{m22} and q_{m11} is equal to 0.995. However, the $q_{m21} \neq q_{m22}$ and the $q_{m11} \neq q_{m12}$ what suggests the internal leakage in the manufactured unit equal to $q_{ml} = 40.8(m^3/h)$.

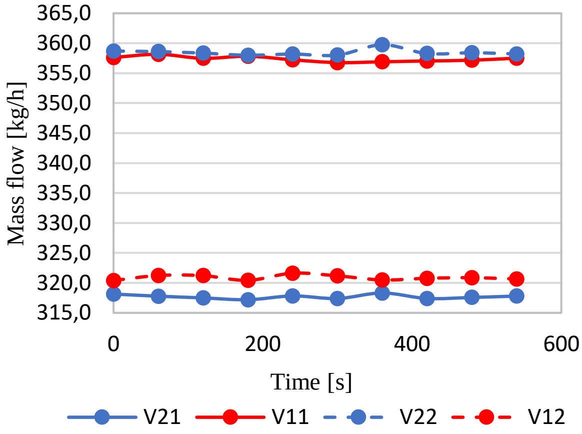

Fig. 7. The airflow through the recuperator.

There are two possible reasons for internal leakages. The first one is from room air to the fresh air and second from waste air to ambient air. According to Tab. 2, the leakage from waste to ambient air is more likely due to occurring pressure on each side of the heat exchanger unit.

Table 2. Measure pressure on each side of the heat exchanger.

P_{11} [Pa]	P_{12} [Pa]	P_{21} [Pa]	P_{22} [Pa]
-28.3	26	-31.2	19.1

Despite the internal leakage, it was decided to continue the research. Figure 8 presents the temperature course overtime during the test.

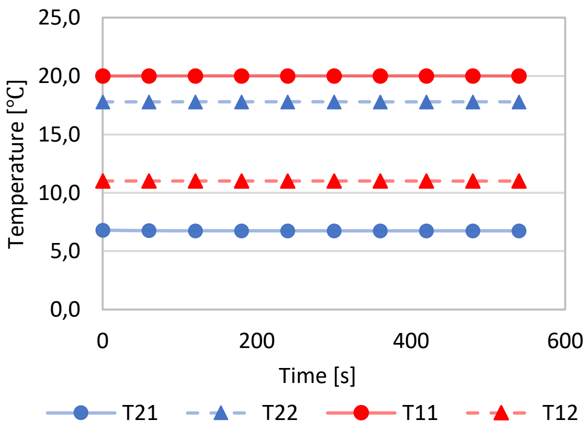

Fig. 8. The air temperature through the recuperator.

The temperature efficiency of heat exchanger and the unit was calculated on the basis of equation (1). The results are shown in Figure 9. It is easy to see that despite the use of lower efficiency, the device has achieved higher efficiency than anticipated. The average efficiency of the unit oscillates around 83.5% and this value is about 10 p.p. (percentage points) higher than the values obtained from the study of exchanger HEX1. The occurrence of the internal leakage presented above had the greatest impact on this phenomenon.

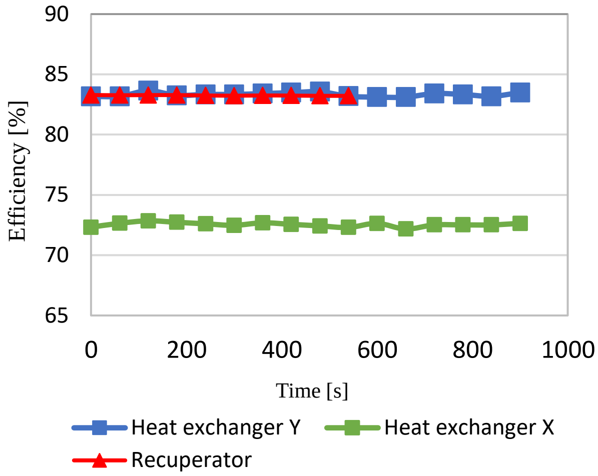

Fig.9. The efficiency over time.

4 Conclusion

One of the assumptions for designing the device was the mass flow equal to 600 kg/h. To fulfil this assumption two exchangers were preselected and tested. The most important from the efficiency point of view parameters were evaluated i.e., temperature efficiency and pressure drop across the exchanger. Despite the fact that one of the heat exchangers had a thermal efficient higher by about 10 p.p. the pressure losses generated by it almost doubled caused the decision to abandon this solution. The complete system unit thermal efficiency obtained from experimental measurement is 83.5%. From the analysis of (internal) heat exchanger, it has been calculated that the thermal efficiency is equal to 72.5% (Fig. 9).

The results can be explained by the following phenomena:

- based on the experimental measurement some internal leakage was observed which artificially raised this parameter,
- it can be assumed that other physical phenomena such as heat convection through the steel layer increase the overall efficiency of the unit,
- due to lack of space, smaller fans were used, therefore the mass flow of the tested device was lower,
- the results obtained may be affected by the fact that PNEN 308 and 13171-7 standard indicate different temperatures for testing heat exchangers and equipment.

To sum up, when specifying the parameters of the designed device, detailed tests confirming its parameters should be performed. It is not possible to rely only on the data presented by the manufacturer. A separate examination of the exchanger itself is recommended. During the operation of the device, various physical phenomena occur that may affect energy and temperature efficiency. The tested prototype must be redesigned due to the fact that there is not a possibility to evaluate the precise efficiency of the unit where the (internal or external) leakage is observed. In the first step for the accurate determination of the unit efficiency the devices should be tested on tightness and then if all streams are equal the unit is ready for final efficiency test.

During system design, one should also pay attention to the asymmetrical airflow through the exchanger. At the same power delivery to the fans, quite different airflow rates are possible. As a result, this situation may significantly disturb the air exchange in the building and increase or decrease (depends on case) the efficiency of the device.

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