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Experimental investigation of a decentralized heat recovery ventilation system

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ABSTRACT
Indoor air quality is an important issue for improving and maintaining the indoor environment because it is directly related to people’s health and work performance. These days, in many settlements, the applicability of natural ventilation is limited in the face of the decreasing infiltration loads, increased atmospheric pollution, and the climatic conditions. Therefore, the use of mechanical systems that are designed to ensure proper ventilation is becoming widespread. This paper presents full-scale experimental research of a wall-integrated decentralized ventilation system with heat recovery in the laboratory conditions. The heat recovery unit includes a ceramic block for sensible thermal energy storage. Parametric experimental studies were carried out to obtain the temperature distributions and the thermal capacity of the ceramic block during the supply and exhaust modes of working. In order to simulate the winter and summer conditions, two large scale temperature-controlled rooms are built up. The duration of the ventilation period is varied to be 1, 2, 5, 7.5 and 10-min. Experimental measurements indicate that 2 min of operation time shows the best thermal performance in terms of maintaining a comfortable indoor temperature with the least energy consumption. And some shortcomings were observed about the fan and thermal storage limitations.

1. Introduction

The social and economic transformation of society brought a change in living spaces. Places of living affected the spread of the COVID-19 virus [1] despite the fact that many measures are described by scientists and paramedics for preventing the spread of the virus. Thus, it was seen that humanity is not technologically, economically, or scientifically ready for that kind of crisis [2]. The importance of indoor air quality was once again remembered during the 2020 crisis. Therefore, it is essential to carry out scientific and technological studies for the revision and development of both existing and new ventilation systems. During the COVID-19 pandemic period, the importance of choosing correct filters and HVAC systems operating with 100% fresh air became significantly evident [3].

The supply of fresh air is very important for human comfort to lead healthy and productive lives. The air leakages from building elements caused by pressure differences between inside and outside occur to some degree. But these leakages are mostly uncontrolled; therefore, they induce significant energy losses. Besides, they are a probable cause for polluted air to come indoors since they are unfiltered. As a commonly accepted principle, the infiltration loads are kept as low as possible in building codes to reduce energy consumption. All-air systems are used to supply the required fresh air to the indoors; however, they are not usually considered as a proper solution in all kinds of ventilation practices due to their high investment costs and large volume requirements. The utilization of heat recovery ventilation systems with installed all-water systems and/or direct expansion systems are becoming more widespread applications. These types of systems are either placed within the ventilated space or mounted on a suitable place outside the volume to meet the indoor fresh air requirements. Another mechanical ventilation system as a decentralized heat recovery unit integrated within room walls has the potential to become a notable alternative and is the topic of this study.

It is necessary to provide sufficient air from outside to ensure indoor air quality. Supplying fresh air helps to (i) limit the concentration of pollutants such as CO₂ and cigarette smoke, (ii) keep the temperature and humidity at the comfortable levels, and (iii) reduce the number of harmful microorganisms such as viruses and bacteria. Buildings that do not have proper and sufficient ventilation systems can become...

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uninhabitable due to low indoor air quality and low thermal comfort conditions. Increasing the thermal insulation in buildings and using airtight construction reduce the air leakage through the building envelope. The amount of infiltration depends on the climatic features of the location of the building, the type of ventilation system, and the airtightness of the building. Homeowners can improve indoor air conditions with regular maintenance in cooling and heating systems and with the help of natural ventilation [4]. However, the relationship between the spread of serious acute respiratory diseases such as COVID-19 and the rate of transmission is shown [5]. Indoor air quality does not only depend on indoor sources, but it also depends on the air quality provided from the external environment through doors, windows, and building structural cracks [6]. Therefore, proper ventilation is necessary, and it is possible to improve indoor air quality with a decentralized ventilation system using an appropriate filter.

Today, it is imperative to install mechanical ventilation systems in new buildings, especially in cold climates. According to Buildings Performance Institute Europe [7,8], mechanical ventilation is mandatory for high-rise residences and buildings in some cold climatic countries such as Denmark and Poland. Additionally, in some mild climate European countries, mechanical ventilation systems are increasingly used in parallel with the reduction of infiltration loads [8]. As a result of the necessity and requirement of mechanical ventilation, many studies were performed to assess the current and potential technologies according to ventilation system classifications [9,10]. There are several studies in the literature on centralized and decentralized ventilation systems based on computational fluid dynamics (CFD) simulation, basic theoretical analysis (TA), or experimental measurements (EM) (Table 1). The recent review studies on centralized (CVS) or decentralized ventilation methods (DVS) are summarized, and an overview of their general inferences is also presented in Table 1.

Table 1 depicts that a wide range of energy-efficient systems have been developed for the buildings, and studies on recovery of waste energy from buildings are evaluated within this scope [12,16,17]. Another important drawback in buildings is that in most of the ventilation solutions in the literature, the systems occupy a significant amount of place in the conditioned environment [10]. In many studies, decentralized ventilation systems have been compared with centralized systems under various climatic conditions. Their results show that decentralized ventilation systems cause lower pressure losses, and these systems save much more energy as they reduce energy losses due to heating and ventilation. Moreover, heat recovery units make it possible to regulate the thermal balance in rooms and provide thermal comfort enhancement [18]. Heat recovery ventilation systems ensure the efficient use of energy due to their working principle of transferring the heat from exhaust air to the fresh air supplied to indoors [13]. These systems typically recover approximately 60%–95% of the energy in the exhaust air and significantly improve the energy performance of buildings [19]. There are various concepts for heat recovery from exhaust air for ventilation applications. Besides, there are many studies according to building typologies, and studies that examine the performance and potential of reducing the energy consumption of decentralized ventilation units integrated into the facade of offices [20,21]. In some studies, wall-integrated heat recovery ventilation systems or single-room ventilation systems, especially for decentralized ventilation, were mentioned, and their potential applications for residential ventilation were evaluated [16,22,23]. Although there are several studies on the heat recovery systems, there are still shortcomings in the research and development of the use of decentralized ventilation systems in building applications [22,24].

Storing thermal energy in the sensible form is one of the most widely used techniques that is preferred in the wall-integrated decentralized heat recovery ventilation systems [25]. These systems usually involve electronically driven two-way fans. The working principle of the ventilation unit with heat recovery is simple. The indoor air that is discharged to the outdoor flows through a ceramic material and transfers the useful energy to the ceramic block. The temperature variations within the ceramic block correspond to the sensible heat storage. After completing the discharging process, the fan works in the opposite direction, and it transfers the fresh outdoor air to the indoor. Energy stored inside the ceramic material is transferred to the air coming from the outside, thus delivering fresh pre-heated/cooled air into the indoor environment. Removable filters in the system prevent the entrance of outdoor contaminants. The number of units applied to a build environment is typically depending on the volume to be ventilated since two units should also run asynchronously with each other to prevent pressure imbalance.

The aforementioned decentralized heat recovery ventilation systems can be applied by using one of the many different wall-integrated products from the market. The structure of these products generally consists of an air supply grill, an air filter, an axial fan, and a ceramic heat exchanger. Depending on the size of the space to be ventilated and the desired air change rate, the number of systems is determined, and the homogeneous fresh air distribution in the space is taken into consideration for the placement of the systems. In small spaces, a single system divided into two can be also used with double axial fans. These decentralized systems offer advantages of integration with architectural design and adding aesthetic value, being less noisy and easier to control than centralized systems. However, the proper design, selection, and implementation of energy-efficient ventilation systems require a holistic approach to the buildings and the users in the applications.

Decentralized heat recovery ventilation systems can meet sufficient fresh air with less energy and space loss, and are easily adaptable; in other words, they can be installed where they are needed and as much as required. On the other hand, there is still a lack of design guidelines for

| Nomenclature | Definition |
|--------------|------------|
| $m$ | mass (kg) |
| $c_p$ | specific heat capacity (J kg$^{-1}$ °C$^{-1}$) |
| $\Delta T$ | temperature difference (°C) |
| $T$ | temperature (°C) |
| $R$ | total uncertainty of the value |
| $x_i$ | independent variables |
| $W_R$ | uncertainty in the independent variables |
| $m$ | mass flow rate (kg s$^{-1}$) |
| $\rho$ | air density (kg m$^{-3}$) |
| $V_0$ | air velocity (m s$^{-1}$) |
| $A_c$ | cross-sectional area (m$^2$) |
| $Q$ | heat transfer rate (W) |
| $Q$ | thermal energy (J) |

| $\Delta t$ | time (s) |

| Abbreviation | Description |
|--------------|-------------|
| DVS | Decentralized Ventilation System |
| CVS | Centralized Ventilation System |
| CFD | Computational Fluid Dynamics |
| EM | Experimental Measurements |
| EN | European Standards |
| PWM | Pulse Width Modulation |
| TA | Theoretical Analysis |

| Subscript | Description |
|-----------|-------------|
| in | inlet |
| out | outlet |
Table 1
Overview of the past reviews.

| DVS | CVS | Climate | TA | CFD | EM | Investigation Approach |
|-----|-----|---------|----|-----|----|------------------------|
| ✓   | –   | –       | ✓  | ✓   | ✓  | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| ✓   | ✓   | ✓       | ✓  | ✓   | ✓  | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| ✓   | ✓   | ✓       | ✓  | ✓   | ✓  | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| ✓   | ✓   | ✓       | ✓  | ✓   | ✓  | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| ✓   | ✓   | ✓       | ✓  | ✓   | ✓  | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| ✓   | ✓   | ✓       | ✓  | ✓   | ✓  | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |

- [11] is a review of the recent development of air-to-air heat and mass recovery technologies.
- Extensive research was conducted on passive systems, mechanical ventilation systems, defrosting methods, dehumidification systems, and heat and mass exchangers integrated into the energy-efficient systems of buildings.
- The applications, advantages, disadvantages, and basic performance criteria of each system are detailed.
- [12] decentralized ventilation systems were evaluated according to European climatic conditions compared with central systems.
- Decentralized systems cause lower pressure losses.
- The fan speed and airflow rate can be adjusted simply and effectively depending on indoor climate and thermal conditions.
- Radiant panel with a decentralized ventilation system was found to have the lowest energy consumption for heating, ventilation, and air conditioning.
- Information is available in the paper.
- Information is not available in the paper.

The correct design recommendation in implementing the wall-integrated units according to the set temperature values and incoming-exhaust air exchange periods for energy issues. In addition, to the best of the authors’ knowledge, there is also a lack of studies in the literature on experimental analysis of decentralized mechanical ventilation with sensible heat recovery systems under laboratory conditions. Hence, the authors aimed to carry out a detailed experimental study by combining and critically reviewing the current work in the public domain and investigating the effects of operation time during the heat storage on efficiency and heat gain/loss from the ceramic. Therefore, to achieve this goal, this paper does the following:

(i) Builds up a large-scale experimental setup to characterize thermally a decentralized heat recovery ventilation unit with sensible heat storage working under controlled conditions,
(ii) Investigates experimentally how the different cycle periods affect the energy consumption by heat recovery ventilation.

2. Methods

The performance of the wall-mounted single-room ventilation unit with ceramic heat exchanger was studied. Firstly, on-site measurements were performed in laboratory conditions. The next step was to calibrate the laboratory measurements according to measured indoor and outdoor temperature, air velocity data. In experimental studies, uncertainties affect the accuracy of the data. So, the uncertainties were calculated. Then the fan performance and the performance of the heat recovery unit are calculated according to calibrated and measured data. Lastly, the results of the single-room ventilation unit with ceramic heat exchanger were analyzed and the conclusions on the performance of this unit were given. Also, the heat exchanger efficiency was calculated. In Appendix, Fig. A shows the flow chart of the main steps of the study.

2.1. Experimental setup

The experimental study was carried out in the Building Physics Laboratory of Izmir Institute of Technology, Faculty of Architecture. The setup previously used for the thermal performance of the double-skin facade [26–28] and was redesigned and prepared for this study. The experimental setup includes two temperature-controlled volumes, which correspond to indoor and outdoor environments, and an aerated concrete wall separates these two environments. Parametric experimental studies were carried out to determine the performance of two wall integrated heat recovery ventilation systems.

The experimental setup shown in Fig. 1 consists of seven components. There is a constant temperature bath (I) to meet the heating/cooling load of the indoor ambient. Two rooms are separated from each other with an aerated concrete wall (II). In the setup, both the indoor (III) and the outdoor (IV) environments are simulated. Two air ducts (V)
are mounted inside the aerated concrete wall. A cooling group (VI) and an electric heater (VII) are used to control the temperature of the outdoor environment.

A room with dimensions of 2.7 m in-depth, 1.5 m in width, and 3 m in height is used to simulate the indoor environment (III). The walls of the room are insulated with 10 cm thick polyurethane thermal insulation panels. The indoor air temperature is controlled with the water flow from the constant temperature bath (I). The heating/cooling serpentines are placed on the long walls of the room. The flow rate of water is measured by a rotameter located outside the indoor environment (Fig. 1).

The room representing the outdoor environment (IV) is 2 m deep, 1.5 m wide, and 3 m high. It is directly cooled with a refrigerant-based cooling system. The cooling unit (VI) is located outside of the laboratory, and the refrigerant directly circulates through the heat exchanger that is located inside the room. An electrical heater (VII) that is controlled by a digital thermostat is placed inside the room to represent summer conditions. The temperatures of the indoor and outdoor rooms are adjusted with thermostats. The room temperatures, the flow rate of the water coming from the constant temperature bath, and the inlet/outlet temperatures of the water are recorded in 5-s intervals.

Fig. 1. Plan (a) and section (b) of the experimental setup (not in scale).

Fig. 2. Positions of the ventilation channels on the aerated wall.
2.2. Channel setup

Two prototypes of the heat recovery ventilation systems are integrated into the aerated concrete wall that separates the indoor and outdoor environments. The Channel-1 and Channel-2 in Fig. 2 are placed 1 m above the ground and have a cross-sectional area of 0.175 m × 0.175 m. The air inside the channels flows in opposite directions. While Channel-1 works in exhaust mode, the Channel-2 works in supply mode. Fans work simultaneously in opposite directions to minimize the pressure imbalances in the rooms that represent indoor and outdoor environments. Thermocouples are placed within the channels to monitor the temperature variations of air and the ceramic materials.

2.3. Measurement devices

2.3.1. Air velocity measurement

One of the key parameters to evaluate the functional capacity of an HVAC system is the volumetric flow rate of air. A parabolic velocity profile occurs inside the duct section due to the viscous fluid flow within the channels; therefore, measurement of air velocity at a single point is not sufficient to determine the mean velocity. Different standards can be used to accurately measure the airflow rate. EN 12599 [29] is used in Germany and most of Europe; in addition, EN 16211 [30] and ASHRAE 111 [31] can be used. The common point of all these standards is that measurement points must be distributed inside the cross-section of the duct. EN 12599 [29] recommends using the Trivial linear equation solution method while measuring the air velocity in these air ducts. According to this method, the first step is to divide the velocity field in the channel section into equal-sized measurement areas. Then, measurements are taken from the midpoint of each section, and finally, the resultant arithmetic mean value represents the result.

Blitz Sens VS-C2-1-A air velocity transmitter is used to measure the air velocity inside the ducts at specified positions. The measurement range of this device is 0–1 m/s. This thermal anemometer, also called velocity meter works on the principle of measuring the airspeed and volumetric flow via heating and cooling of the sensor by electricity [32]. Its highly precise thin-film sensor is 180 mm long and is produced for use in narrow spaces. Table 2 represents the characterization test results for supply (out to in) and exhaust (in to out) channels of Channel 1 by the Trivial method [29]. According to the measurement results, the points that gave the closest values to the average were determined, and the measurements were taken from those points at the cross-section of the duct (shown in Table 2) during the experimental studies. The results for average supply airspeed are 0.215 m/s, and the exhaust speed is 0.165 m/s. These average values were measured at two different positions in the channels due to the airflow direction because of providing fully developed flow.

2.3.2. Temperature measurements

The positions of thermocouples inside the test rooms are shown in Fig. 1. The number and placement of thermocouples are as follows; one thermocouple measures the laboratory environment, in which the experimental setup is placed, five thermocouples provide the temperature values of the indoor environment, and three thermocouples represent temperature for the outdoor environment. In the indoor environment, one thermocouple is placed at the midpoint of the exit sections of the two channels to measure the air temperature inside the channel for determining the air density. In the outdoor environment, for each channel, three thermocouples measure the system inlet temperature in front of the filter, and three thermocouples measure the system outlet temperature (Fig. 3). As shown in Fig. 4, a total of eight thermocouples are placed in the ceramic heat exchangers in each channel to measure temperature changes along the channels and mean temperatures of each ceramic material. Thermocouple positions within the ceramic heat exchangers are indicated as G1 and G2-1 to 4, for Channel-1 and Channel-2, respectively.

2.4. Calibration process and uncertainty analysis

All thermocouples with data logger used in the experimental setup are calibrated in the calibration laboratory of the Izmir Chamber of Mechanical Engineers. The calibration is performed by immersing the temperature sensors (including a reference sensor) into a constant temperature bath. The temperatures measured by the calibrated sensor and the reference thermometer are taken as the basis, and the results of each thermocouple measurements are fit to the line to ensure high accuracy.

The air velocity measurement probe was calibrated in a wind tunnel by comparison method in which the reference sensor and the test instrument were placed in the test section of the tunnel. The uncertainty of the measurement value of the test instrument was calculated by using 5 data in a series measured in 30 s.

2.4.1. Uncertainty analysis

In experimental studies, some uncertainties affect the accuracy of the data. Uncertainty calculations were made within the scope of the method followed by Holman [33] and Tokuc et al. [34], which is also provided in ISO “Guide to the Expression of Uncertainty in Measurement” as the uncertainty analysis method for errors caused by an experimental set and measurement tools [35]. For a measurement with n variables, the result R is a function of the independent variables $x_1, x_2, x_3 \ldots x_n$ whereas $w_1$, $w_2$, $w_3$ \ldots $w_n$ are uncertainties in the independent variables. $R$-value is expressed based on independent variables as

$$R = R(x_1, x_2, x_3, \ldots x_n)$$

If $W_k$ is defined as the uncertainty value in the result, the uncertainty of all independent variables are given with the same odds, then Eq. (2) is used:

$$W_k = \left[ \left( \frac{\partial R}{\partial x_1} \right)^2 + \left( \frac{\partial R}{\partial x_2} \right)^2 + \left( \frac{\partial R}{\partial x_3} \right)^2 + \ldots + \left( \frac{\partial R}{\partial x_n} \right)^2 \right]^{1/2}$$

For the experimental studies, the uncertainty analysis of the mass flow rate (Eq. (3)), and heat transfer rate (Eq. (4)) in the channel were calculated. Accordingly;

$$\dot{m} = \rho V_c A_c$$

$$\dot{Q} = \dot{m} c_p \Delta T$$

The uncertainty in Eq. (3) is caused by the density of the air ($\rho$), the cross-sectional surface area through which the air passes ($A_c$), and the average velocity of the air ($V_c$). The heat transfer rate uncertainty value in Eq. (4) depends on the mass flow rate ($\dot{m}$), the specific heat of air at constant pressure ($c_p$) and temperature difference ($\Delta T$). Accordingly,
parameters affecting the mass flow rate and the heat transfer rate for the air in the equations are defined as

\[
\dot{m} = f(\rho_a, A_c, V_a) \tag{5}
\]

\[
\dot{Q} = f(\dot{m}, c_p, \Delta T) \tag{6}
\]

The uncertainty values of each independent variable are given in Table 3. The uncertainty of the mass flow rate is calculated according to the parameters defined in Eq. (3). For the measured air velocity values obtained in the experiments, the uncertainty value was taken from the catalog value of the manufacturer. And later, it was determined to be approximately 5.94% by interpolation. The uncertainty of the mass flow rate of air calculated for each independent variable given in Table 3 is 6.27%.

The uncertainty of heat transfer rate during the experiments is calculated based on the parameters defined in Eq. (6). The total uncertainty value of thermocouples with data logger was evaluated in accordance with the uncertainty of the devices used during the calibration. And the uncertainty of heat transfer rate is calculated as 6.35% based on the mass flow rate, specific heat, and temperature uncertainty values.

3. Results and discussion

The decentralized heat recovery ventilation systems, which store sensible energy into the ceramic material, exhaust air from the inside and supply fresh air from the outside during the working cycles in this experimental study. During the experiments, the fan performance of the exhaust and supply is observed to be different in the measurements. This is due to the design of the fan blades in the experimental system, therefore the suction fan worked with a lower flow rate than discharge. For this reason, in this study, a new fan characteristic was obtained by making measurements at manufacturing speed settings.

3.1. Evaluation of the fan characteristics

The axial fan, which is installed inside the ventilation unit, can work in two flow directions. The fans of commercial products have limited speed, and their exhaust-supply times are also limited (Fig. 5). Therefore, a fan control system was developed in the current study. This interface was used to control the desired speed and working period of the fans on the heat recovery system. Before running the experiments, fan characteristic of the system was obtained, and the common points in the direction of supply and exhaust were determined according to the normalized air velocity and the pulse width modulation (PWM). Also, it is seen that from Fig. 5, the fan operates with 47% efficiency.

3.2. Charging and discharging experiments

In this study, seven experiments are detailed for two decentralized heat recovery units operating simultaneously, the channel and the

![Fig. 3. Channel setup and measurement points (not in scale).](image)

![Fig. 4. Thermocouple layout inside the ceramic heat exchanger (not in scale).](image)

| Table 3 | Uncertainty values of each independent variable measured in the experimental studies. |
|---------|-----------------------------------------------------------------------------------|
| Variables | Value | Uncertainty | Specifications |
| Air density, \(\rho_a\) | 1.184 kg/m³ @ 25°C | ±0.02% | Manufacturer: BLITZSENS, Type: VS-C2-1-A, (2pcs) |
| Air velocity, \(V_a\) | 0-1 m/s | ±5.94% | |
| The cross-sectional area which the air passes, \(A_c\) | 0.0225m² | ±2% | |
| Temperature, \(T\) | 0-42°C | ±1% | Data logger manufacturer: HIOKI, Type: LR8402-20 (K/T), (37pcs of Thermocouples) |
| Specific heat of air, \(c_p\) | 1007 J/kgK @ 25°C | ±0.02% | |
simulation rooms were monitored until steady-state conditions were attained before recording measurements for each experiment. For the simulation of summer conditions, the indoor environment is kept at around $20^\circ$C, and the outdoor environment is kept at approximately $35^\circ$C, while in winter conditions, the indoor environment is kept constant at around $20^\circ$C and the outdoor environment approximately at $5^\circ$C. The heat recovery units were operated for specific cycles of; 1-min, 2-min, 5-min, 7.5-min, and 10-min.

The temperature measurements of thermocouples in ceramics are given in Figs. 6–12. The graphs on the left side of Figs. 6–12 belong to Channel 1 (C1) and the graphs on the right side belong to Channel 2 (C2). These graphs show the temperature distribution when two units are operated simultaneously for different time periods defined above. Values from the thermocouples placed in 3 cm, 6 cm, 9 cm, and 12 cm depths inside the ceramic material show that a temperature gradient occurs inside the heat exchanger during the experiments. The depths of the thermocouples are coded as follows; 1-1 and 2-1 represent the thermocouples at 12 cm, while 1-2 and 2-2 at 9 cm, 1-3 and 2-3 at 6 cm, 1-4, and 2-4 represent the thermocouples at 3 cm depth for C1 and C2, respectively, in Figs. 6–12. These four thermocouples are also mentioned as two groups numbered G1 and G2 separately. $T_{\text{inside}}$ and $T_{\text{outside}}$ given in Figs. 6–12 are indoor temperature and outdoor temperature, respectively. The average of the three thermocouples placed before the filter in the unit and the average of the three thermocouples placed after the ceramic heat exchanger are coded as $C_{1T_{\text{In}}}$ and $C_{2T_{\text{In}}}$, $C_{1T_{\text{Out}}}$, and $C_{2T_{\text{Out}}}$ in C1 and C2, respectively.

Fig. 6 shows the temperature data taken from the thermocouples in the ceramic heat exchangers from the two channels for the experiment conducted in simulated winter conditions operating for 10 min with 1-min cycles. In other words, each 1-min, the operating direction is changed via the fan controller interface. During the experiment, the indoor average temperature ($T_{\text{inside}}$) was measured from five points and was kept around $20^\circ$C, while the outside average temperature ($T_{\text{outside}}$) was calculated approximately $3^\circ$C by using data from three thermocouples. Average air temperatures measured by the three thermocouples placed at the inlets ($T_{\text{in}}$) and the outlets ($T_{\text{out}}$) of the heat recovery system fluctuated by as much as $3^\circ$C during the experiment because of the thermal inertia of the ceramic heat exchangers. Ceramic materials

![Fig. 5. Calculated normalized air velocity.](image)

![Fig. 6. Heat recovery system operating for 10 min with 1-min cycles in simulated winter conditions for Channel 1 and 2.](image)
were heated by indoor air and their temperatures increased between 1 °C and 3 °C depending on the position of the thermocouples in the ceramics. Temperatures of the inside part of the ceramic materials close to the indoor environment had a relatively higher temperature increase, therefore they stored more thermal energy. On the other hand, temperatures of the outer part of the material were close to the outside temperature and their fluctuations were about 1 °C, with less thermal energy storage, yet all of the energy stored in the system was discharged at the end of each cycle.

Fig. 7 gives the results for the simulated winter conditions, and the values of the units working for 6 min with a 2-min cycle can be seen. Inside and outside temperatures were almost constant during the experiment, and the two ventilation systems worked synchronously but with different airflow directions. Since the working period was changed to a 2-min cycle, temperatures of the ceramic materials increased by up to 7 °C, depending on the measurement positions. The material temperatures were close to the outside temperature at the outer part of the ceramic and the temperature fluctuations were less than the inner part of the ceramic. The 2-min cycles also showed that the thermal energy charged was able to be discharged from the ceramic material.

Fig. 8 shows 5-min cycles in simulated winter conditions, for a total of 20 min. In general, the indoor environment remained constant and there was a fluctuation of approximately 1 °C at the outdoor temperature. When the system was operated for 5 min, the temperatures at the inner part of the ceramic became close to the indoor temperature. Besides, depending on the thermocouple locations, there was a temperature difference up to 10 °C inside the ceramics.

In Fig. 9, there are 2 cycles of 7.5 min, in total 15 min in simulated winter conditions, and units are operated by changing direction after each cycle. This experiment shows a fluctuation up to 2 °C at the outdoor temperature. Besides, when the system is operated for 7.5 min, the ceramic temperatures next to the indoor and outdoor sides are approximately equal to indoor and outdoor temperatures at the end of the cycle. The results shown in Fig. 10 belong to Channel 1 and 2, 2 cycles are shown for the 7.5-min cycle of simulated summer conditions. When the outdoor temperature remained constant at approximately 34 °C, the indoor environment was stable at 23 °C. The temperature values at the inside of the ceramics increased to around 8 °C. When the system was operated in the opposite direction, the thermocouple values reached the indoor temperature approximately at the end of the cycle.

In Figs. 11 and 12, the units were operated for 10 min, in simulated winter and summer conditions, respectively. The indoor environment is generally stable at 20 °C and the outdoor environment varies between 3 °C and 5 °C in Fig. 11. Considering temperature distribution inside the ceramic at the end of the cycle process, almost all the temperature values are equal to the outdoor temperature or the indoor temperature depending on the airflow direction. Fig. 12 shows that the outdoor temperature fluctuates up to 2 °C and the indoor temperature is generally stable at 21 °C. There is a decrease or increase of approximately 12 °C in the ceramics temperatures during the 10-min cycles. Temperature values at the ceramics change significantly in the first part of the periods, after that there are not remarkable temperature alterations in the ceramic material which indicates that the most of thermal energy storage rate decreased gradually during a 10-min cycle.

3.3. Data reduction

The amount of heat stored in/released from the ceramics is calculated by using Eq. (7),

\[ Q = mc_p \Delta T \]  

where \( Q \) is the thermal energy (J), \( m \) is the mass of the ceramic (kg), \( c_p \) is the specific heat capacity of the ceramic (J/kg°C) and \( \Delta T \) is the change in temperature (°C) of the ceramic material. Specific heat is the amount of heat required to change the temperature of the unit mass of a substance and the differential scanning calorimeter method is used to measure specific heat. This method measures the amount of energy absorbed or released while the sample taken from the ceramic material is heated and cooled for a few cycles [36] between 5 °C and 35 °C. The specific heat value of the ceramic material was measured to have an average value of 0.725 kJ/kg°C.

The results of the heat recovery ventilation system with a ceramic heat exchanger for C2 are tabulated in Table 4. These results are for a working cycle when the system operated from the indoor to the outdoor environment and from the outdoor to the indoor environment. Table 4 indicates that the result of the air energy change obtained to the weighted averages of C2-T_{in} and C2-T_{out} data and air velocity data measure during different time steps.

The maximum possible heat transfer capacity, \( Q_{\text{max}} \) is defined in Table 5 for the given set of operating conditions and it is calculated by using Eq. (8) as;

\[ Q_{\text{max}} = \dot{m} \Delta h c_p \Delta T \]  

where \( \dot{m} \) is the mass flow rate of air (kg/s), \( c_p \) is the air specific heat capacity (J/kg°C), \( \Delta h \) is the temperature change of air (°C) and \( \Delta T \) is the cycle period in second. Table 5 gives the results for the thermal energy storage in the ceramic, as well as the energy from the fan and the maximum energy values that can be stored. According to the fan manufacturer’s catalog data [37], power consumption is 3.4Watt when the nominal voltage is 12.0 V. Therefore, there is an energy gain/loss of approximately 0.2–2 kJ from the fan during a cycle period. When the

![Fig. 7. Heat recovery system operating for 6 min with 2-min cycles for Channel 1 and 2.](image-url)
data from Channel 2 are calculated; while the system is operated in winter conditions for 1 min from outdoor environment to indoor environment, 4.478 kJ heat release occurs, when it is operated for 2 min, 10.762 kJ energy is released.

As seen in Table 5, as the system’s operating time increases, heat transfer also increases. However, when looking at the storage per unit time, the best performance can be seen by operating the system for 2 min. When the fan runs for a long time period, the cost of electrical energy increases. The fan is more advantageous when the system operates in a short period.

The efficiency of the sensible heat recovery ventilation system with a ceramic heat exchanger is obtained by using the data in Tables 4 and 5.
The efficiency is calculated [25] as the ratio of stored/released energy from the ceramic unit ($\sum q_1$) to the maximum amount of energy considering outdoor and indoor temperature ($\sum q_2$):

$$\eta = \frac{\sum q_1}{\sum q_1 + \sum q_2}$$  \hspace{1cm} (9)

According to calculations via Equation (9), the supply efficiency for 2 min operation time is 82%, the result for 5 min is 76%, for 7.5 min the result is 73% and the winter condition average result is 77% and the exhaust efficiency is 65%. For summer conditions, when the unit is operated for 7.5 min, the supply efficiency is 89% and for 10 min, the exhaust efficiency is 45%. Table 6 shows the energy efficiency results according to different working times. Fan energy consumption is not considered for the efficiency calculations.

According to the average heat transfer rates in Fig. 13, the best result
was observed when the system was operated for the 2-min cycle. The reason for the difference in the exhaust (in to out) and supply (out to in) values for heat transfer rates is due to the thermal energy stored in the ceramic from the previous cycle or prolonged waiting time between the cycles.

4. Conclusions and recommendations

This study critically reviewed the current work in the public domain and carried out laboratory measurements with changing indoor-outdoor temperatures and operation times during winter and summer conditions. The performance of the ceramic heat recovery ventilation unit with sensible energy storage and its axial fan were experimentally investigated under different working conditions. Ventilation performances for supply and exhaust were also analyzed to provide new experimental data under controlled environment conditions.

For this case of the studied heat recovery ventilation unit, the airflow caused large differences in the supply and exhaust efficiencies. Also, the pressure differences were affected by the airflow rates in this ventilation system. And, the pressure was affected by the airflow balance of the unit. Thus, the stack effect pressure this resulted in a change in heat recovery system efficiency. The simulation results showed that the best heat transfer result was observed when the system operated for the 2-min cycle in winter conditions. In addition, the best performance according to efficiency results was also the 2 min of operation time. This experiment allowed for the calculation of the actual efficiency of the ceramic unit and the calculations show that there was no significant difference between the efficiency value given by the manufacturers and the calculated value. Yet, in the airflow measurements, the fan operates with 47% efficiency according to the measurement results for the exhaust mode. The findings and important conclusions of this study and related recommendations can be defined with the following items:

- Decentralized heat recovery units, which make it possible to regulate the exchange of thermal balance, to reduce heat losses caused by ventilation for supplying fresh and filtered air, are a viable choice in the room by recovering heat from the exhausted air in a heat exchanger. However, the fact that automation and fans perform the exhaust and supply functions together brings some disadvantages, like pressure unbalance for single system usage, choosing the correct working period for the individual ventilated environment, and the energy consumption of the fan for the working condition design.

- Considering that the products in the market operate for 70 s, their working time is not flexible to respond to the different working conditions. For this reason, adjustable automation should be added to the system according to the outdoor and indoor conditions and the ventilation demand of the built environment. It is possible to design a product that can be used in different climatic regions with more flexible working conditions and consider the volume of the ventilated environment and the necessary amount of air change.

- The fan operates in the supply direction with a lower flow rate than the exhaust direction. Due to the relatively higher flow rate, during the fresh air flow from the outdoor to the indoor environment, a more homogeneous distribution occurs in the heat exchanger, rather than during the air transfer from the indoor to the outdoor environment. Thus, the supply efficiency for 2 min operation time is 82%, while the efficiency of this unit for exhaust efficiency is 67% for the simulated winter condition. For this reason, the axial fan direction of airflow, and the direction of airflow should be controllable. A pitch control fan or two separate fans can generate better ventilation performance by ensuring these two operations.

| Working conditions | Time [min] | Exhaust efficiency [%] | Supply efficiency [%] |
|--------------------|-----------|------------------------|----------------------|
| Winter             | 1         | 73                     | 75                   |
|                    | 2         | 67                     | 82                   |
|                    | 5         | 73                     | 76                   |
|                    | 7.5       | 58                     | 73                   |
|                    | 10        | 52                     | 77                   |
| Summer             | 7.5       | 61                     | 89                   |
|                    | 10        | 45                     | 81                   |

Fig. 13. Comparison of average heat transfer rates on Channel 1 and 2.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Wall-mounted single-room ventilation units with ceramic heat exchanger analysis

Overview of the past research

Measurements in laboratory conditions
  Indoor temperature
  Outdoor temperature
  Ceramic temperature distribution
  Air temperature at channels
  Air velocity

Calibration of the measurements
  Air velocity measurement probe
  Thermocouples

Uncertainty analysis
  Air density, specific heat of air, air velocity, air temperature and cross-sectional area

Heat recovery unit thermal and flow calculations
  Charging/discharging experiments
  Evaluation of the fan characteristics
  Data Reduction

Conclusions on the performance of the unit

Fig. A. The flow chart of the studies to calculate heat recovery unit performance.
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