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PERFORMANCE EVALUATION OF A 3D-PRINTED HEAT RECOVERY VENTILATION SYSTEM (HRVS)

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Abstract: *Heat Recovery Ventilation Systems (HRVS) provide an effective solution by recovering energy from exhaust air to preheat incoming fresh air. This study evaluates the performance of a 3D-printed HRVS prototype manufactured from PLA. The system's efficiency was tested under natural indoor and outdoor conditions. Simulations using ANSYS and experimental measurements were conducted to determine heat recovery efficiency at various airflow rates. Results indicate that the HRVS achieves an efficiency of up to 87%, demonstrating its potential for improving energy performance and thermal comfort in buildings while maintaining Indoor air quality (IAQ).*

Key words: *HRVS Assembly, HRVS efficiency, performance of HRV, experimental results of HRV system, simulated results of HRV system.*

1. INTRODUCTION

Nowadays, building sector is induced by saving energy policies to decrease energy consumptions with great improvement of the insulation envelope. Indoor air quality (IAQ) and energy consumption are extreme worries. Most of old mechanical ventilation systems have a significant loss in energy and compromised IAQ. HRVS provides the solution by improving IAQ without heat loss by preheating the incoming fresh air by the exhaust air which is of high temperature. Though, the performance of HRVS varies significantly due to many factors such as design, installation, and working conditions.

In cold weather conditions, it is a necessary to use mechanical ventilation systems in new buildings. Mechanical ventilation is required in high-rise buildings in a number of cold climatic countries [1]. When the ventilation rate increases the IAQ improves, in addition the increasing of ventilation will also increase the heating and the cooling. HRVS award recovering energy and controlled ventilation which are very important [2-7].

In addition, heat recovery unit allow for the regulation of thermal conditions in indoor spaces, thus enhancing overall comfort [2]. This ventilation system maximizes energy efficiency by transferring heat from outgoing exhaust air to the incoming fresh air supplied to the interior [3]. Generally, such systems are capable of recovering around 60%–95% of the energy contained in the exhaust air, contributing significantly to the improved energy performance of buildings [4].

There are several approaches for recovering heat from exhaust air in ventilation systems. Various studies have explored different building types and looked at the performance and potential energy savings of decentralized ventilation units integrated into office facilities [2, 3]. Some research focuses on wall-integrated heat recovery ventilation systems and single-room solutions, particularly for decentralized setups, evaluating their suitability for residential ventilation [4-6]. Even with extensive studies on heat recovery systems, there are still gaps in the research and development of decentralized ventilation systems for building applications [5, 7].

These decentralized heat recovery ventilation systems can be implemented using various wall-integrated products available on the market. Usually, these include an air supply grid, air filter, axial fan, and heat exchanger. The number of systems required is determined based on the

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size of the space and the preferred air exchange rate, ensuring even fresh air distribution within the area. For smaller spaces, a single unit divided into two sections with dual axial fans can be employed. These systems are beneficial due to their unified integration with architectural design, aesthetic appeal, less noise levels, and ease of control compared to centralized systems. However, effective design, selection, and implementation of energy-efficient ventilation require a comprehensive approach, considering both the building's characteristics and the occupants needs.

The performance of an HRVS is evaluated based on its efficiency or effectiveness. Usually, enthalpy efficiency is determined through laboratory testing under specific indoor and outdoor conditions, using steady-state scenarios. This efficiency is often considered a constant value when evaluating ventilation systems' impact on heating and cooling energy needs. Though, in real-world applications, within actual homes, enthalpy efficiency is not a fixed value, as it is influenced by varying indoor and outdoor air conditions [8-12].

2. PROTOTYPE OF THE HRVS

2.1 HRVS mechanical system

The heat recovery ventilation system (HRVS) with dimensions 115 × 113.05 × 220 mm was 3D-printed using PLA material with a PRUSA MK4 3D printer.

The manufacturing process includes the fabrication of key mechanical components such as the heat exchanger, air distributors, nozzle, and diffuser, along with the integration of the necessary electronic devices to ensure proper HRVS functionality. Figure 1 illustrates the mechanical components of the HRVS.

The heat exchanger consists of multiple channels arranged in rows and columns. Some channels carry warm air out, while others bring fresh air in, facilitating heat exchange. Heat transfer occurs through conduction across the channel walls, allowing the warm outgoing air to transfer energy to the incoming cold air. As illustrated in Figure 2, the red zones represent the channels carrying warm air, whereas the blue zones indicate the channels carrying cold air.

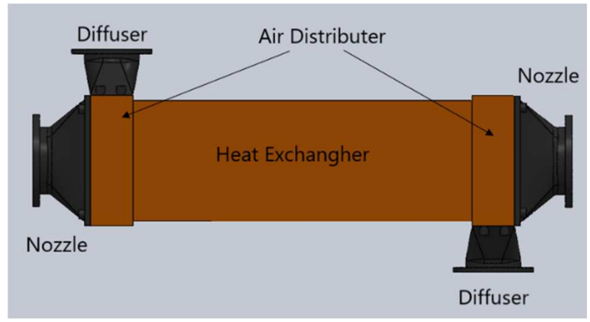

Fig. 1: Mechanical parts of HRV system

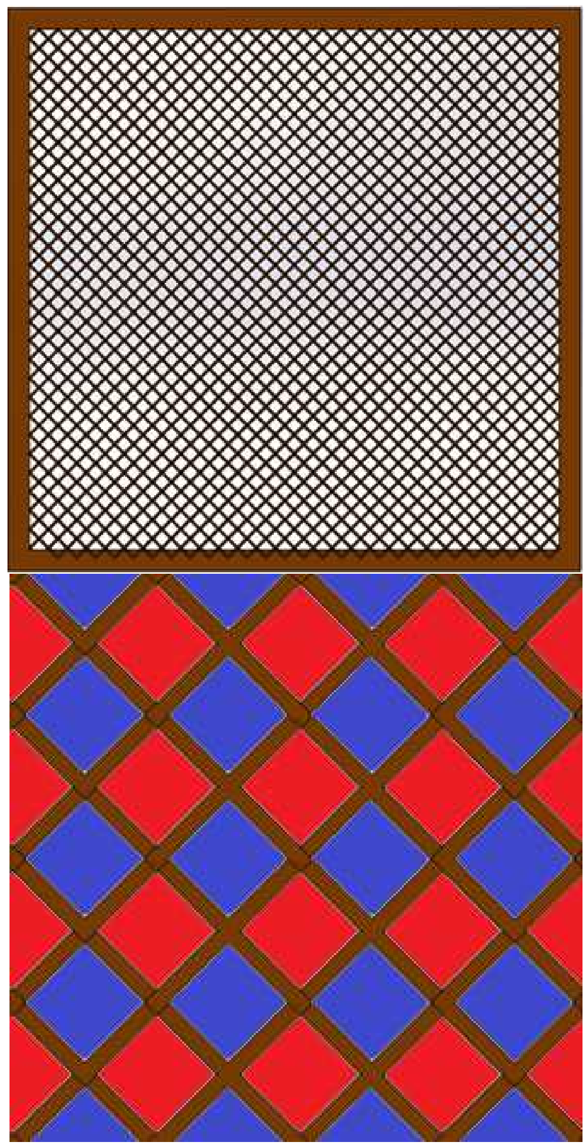

Fig 2: Scheme of HX shows the hot and cold areas

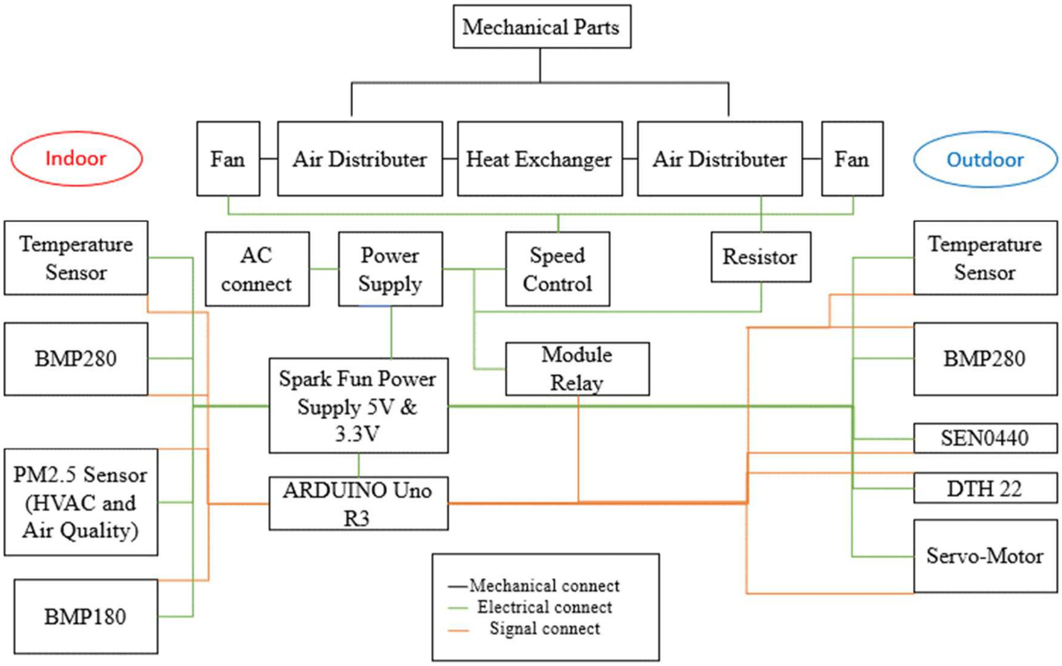

Fig. 3: Scheme of the connected HRV system

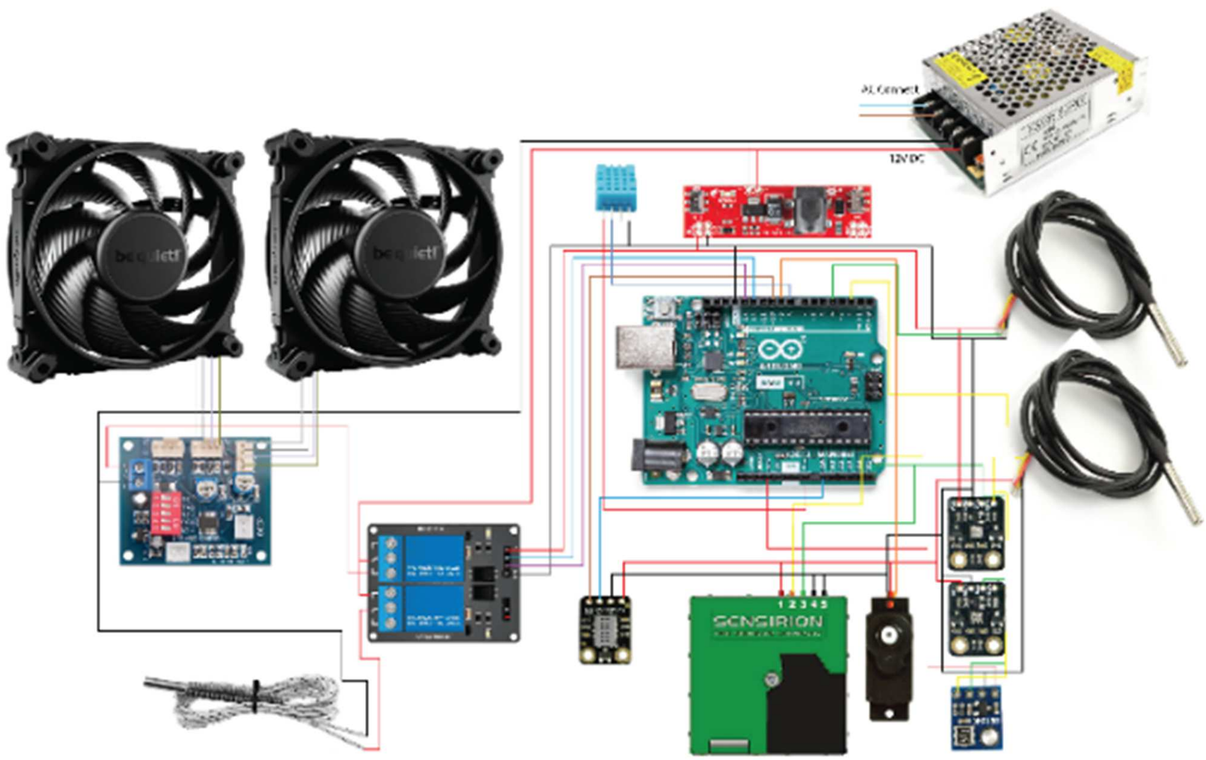

Fig. 4: Scheme of the connected control system

2.2 HRVS Control system

The block diagram of the HRVS control system is presented in Figure 3. The system operates by regulating the flow of hot and cold air through the heat exchanger (HX), requiring fans and a speed controller to adjust the airflow. To power the circuit, a power supply is essential. The system also requires sensors to monitor key environmental parameters:

- Temperature and humidity sensors – Measure indoor and outdoor conditions.
- Gas sensors – Detect the presence of toxic gases. If hazardous gases are detected, the system automatically shuts down using a servo motor, which acts as the main component of the actuator.
- Pressure sensors – Monitor indoor and outdoor air pressure to determine the pressure difference.

Resistor – Placed outside the HRVS to heat incoming air and prevent freezing of water vapor at extremely low temperatures, ensuring unobstructed airflow.

The components of the control system are:

- **LCD module 16x2**

The LCD - electronic display module used to display needed values such as air temperature.

- **DTH 22**

DHT22 is a temperature and humidity sensor that gets its data from Arduino Serial Monitor. Its humidity range is 0-100% and its temperature range is -40°C to 125°C.

- **Silent Wings 4 120mm PWM high-speed**

The fan "Silent Wings 4 120mm PWM high-speed" combines all features of a virtually inaudible with an extremely performant fan for the most demanding applications.

- **PM 2.5 Sensor**

PM 2.5 sensor used for HVAC and air quality applications SPS30, that enable the implementation of innovative air quality monitoring devices that prevent air pollution damage.

- **SKU: DFR0198**

The SKU: DFR0198 is a waterproof Arduino Temperature Sensor that can measure the temperature of something far away or in wet conditions. This sensor used in HVAC environmental controls that can sense the temperature in buildings, machinery or equipment.

- **BMP280 Sensor**

BMP280 is a digital pressure sensor, that can be used to measure temperature and atmospheric pressure accurately. As the atmospheric pressure changes with altitude, it can also measure approximate altitude of a place.

- **BMP180 Sensor**

BMP180 is a digital pressure sensor, that measure pressure with an accuracy down to 0.02 hPa in advanced resolution mode.

- **SEN0440 Sensor**

The SEN0440 sensor is a gas sensor that uses MEMS technology to detect the gas concentration of CO, CH4, C2H5OH, C3H8, C4H10, H2, H2S and NH3.

- **Power HD Micro Servo HD-1800A**

POWER HD MICRO SERVO HD-1800A is a servo motor which is a part of actuator. It converts the control signal of the controller into the rotational angular displacement or angular velocity of the motor output shaft.

- **Arduino Uno R3**

The Arduino Uno R3 is a microcontroller board based on a removable, dual-inline-package (DIP). It is able to control relays, LEDs, servos, and motors as an output.

- **Spark Fun Breadboard Power Supply**

Spark Fun Breadboard Power Supply Stick 5V/3.3V is a power supply that takes power from a DC wall wart and outputs a selectable 5V or 3.3V regulated voltage.

- **Speed Controller**

Speed controller which is a 12V PWM PC CPU fan temperature control speed controller module and high-temp alarm.

- **Power Supply**

The mean well rs-50-12 switched mode power supply converts that electric current from a source to the needed voltage or current.

- **Resistor**

The resistor "12V/50W 1M Wire Cartridge Heater" used in industry, that provides localized and precise heating, used to heat the air avoiding freezing of water vapor.

- **Module Relay 12V of two Channels**

The Module relay 12V of two channels used to control high voltage and high current load to the motor.

After identifying the required electronic components, the next step is to connect them using appropriate wiring to ensure proper functionality without errors. The final wiring setup is presented in Figure 4, and the system was thoroughly tested over an extended period without any detected malfunctions.

Fig. 5: Prototype of the HRVS

By integrating these components, the HRVS ensures efficient ventilation, real-time monitoring, and automatic control, optimizing indoor air quality (IAQ) and energy efficiency. In Figure 5 is presented the prototype of the HVRS.

3. RESULTS

The simulation and the experimintal study of the HRVS were performed in a conditioned area at a constant pressure (1001.09 hPa), humidity (45%_50%), altitude (101.75 m) and several values of fan speed 255 rpm that affects the air flow rate and indoor and outdoor temperatures as shown in the table 1.

Table 1

Inlet Temperatures at different Fan Speeds

Fan speed	T cold, in °C	T hot, in °C
100%	1.5	20.6
90%	1.5	21.2
80%	1.5	20.25
70%	1.5	22
60%	1.5	22

3.1 Simulated Results

Based on previously published works [13-15], PLA material is the most convenient material to use in HX. The simulation of the performance of the system was done using ANSYS. The performance tested at five different flow rates with mentioned indoor and outdoor conditions as shown in figures 6,7 and table 2.

Table 1

Simulated *Temperature*

Fan speed %	T cold, out °C	T hot, out °C
100%	18.00	4.00
90%	18.50	3.70
80%	19.50	4.00
70%	19.50	3.00
60%	20.00	2.80

3.2 Experimental Results

After assembling all the mechanical and electronic parts of the HRVS prototype, the HRVS was placed in wall between outdoor and indoor (the conditioned area) to test its performance.

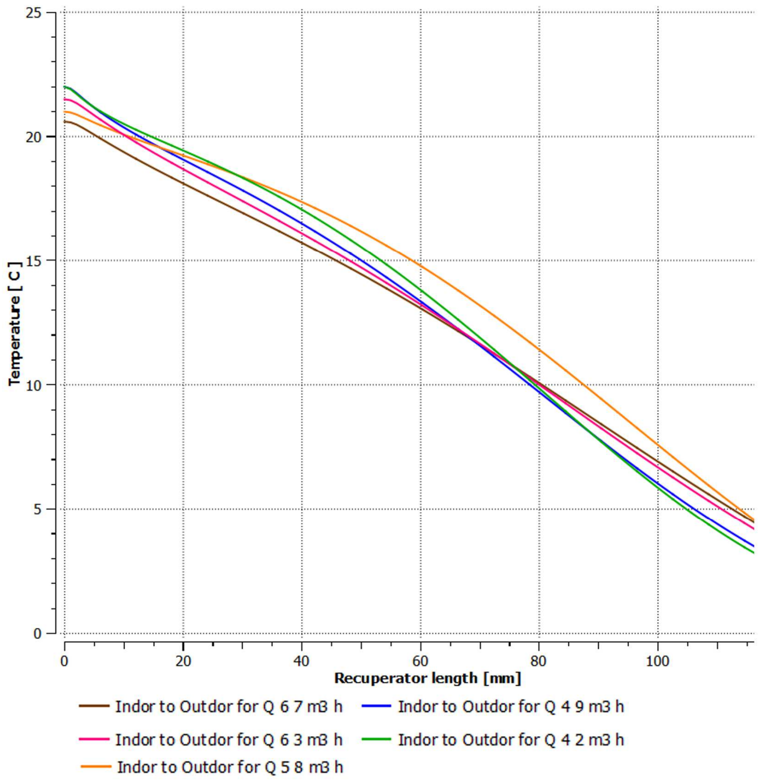

Fig. 6: Simulated results for hot air flow

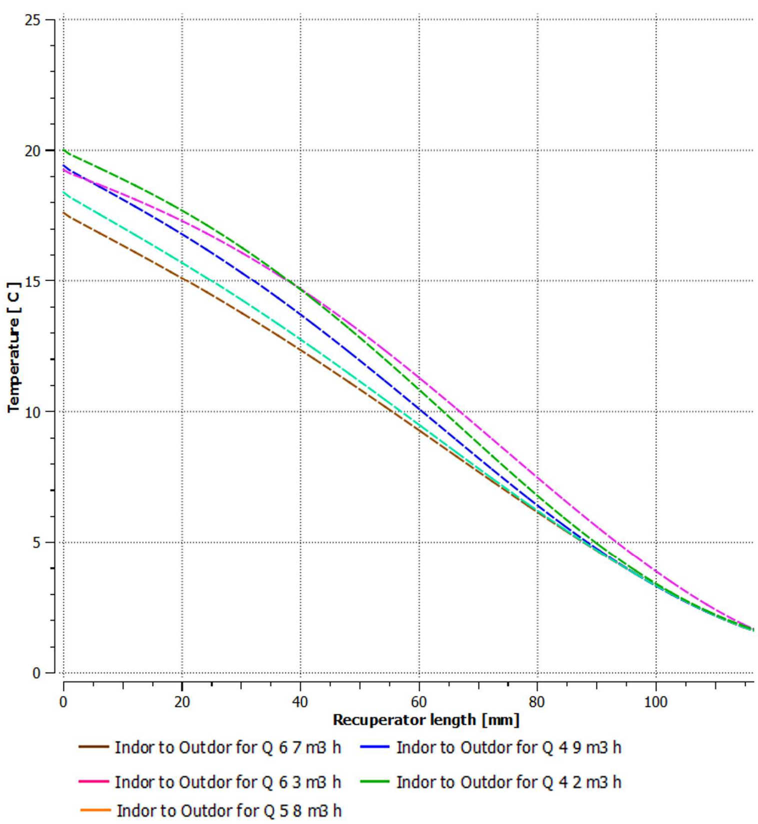

Fig. 7: Simulated results for cold air flow

The field of measurement were done in winter in Oradea (Romania) also at five different values of air flow rate. The results are shown in table 3.

Table 2

Experimental Results

Fan speed %	T cold, out °C	T hot, out °C
100%	18.1	3.9
90%	17.8	3.7
80%	17.9	3.8
70%	18.2	3.5
60%	18.2	2.94

3.3 Simulated vs. Experimental Results

As shown in the simulated and experimental results, the difference between the two results is very small specially at high flow rate which is less than 1°C as shown in table 4.

Table 3

Differences between simulated and experimental temperatures

Fan speed %	T cold, out °C (Sim – Exp)	T hot, out °C (Sim – Exp)
100%	-0.1	-0.1
90%	0.7	0
80%	1.6	-0.2
70%	1.3	0.5
60%	1.8	0.14

3.4 HRVS Efficiency

The efficiency of the HRVS is calculated using the following equation:

$$\eta = \frac{T_{cold,out} - T_{cold,in}}{T_{hot,in} - T_{cold,in}} * 100$$

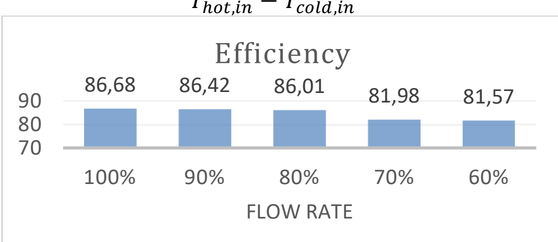

Fig 8: Efficiency variation with flow rate

The study of the performance of the HRVS done at five different values of air flow rate, for a long interval of time (around 2 hours) for each air flow rate, as shown in Figure 8 the efficiency variation.

As we can see, as the air flow increases the efficiency increase when the system said to be in steady state. The maximum efficiency is observed at maximum air flow rate which is around 87%.

4. CONCLUSION

This study highlights the effectiveness of HRVS in enhancing indoor air quality while minimizing energy losses in mechanical ventilation systems. Experimental and simulated results showed minimal discrepancies, reinforcing the accuracy of the proposed system's design and efficiency. The prototype achieved a maximum efficiency of 87%, proving its viability for energy-efficient ventilation in cold climates. Moreover, the HRVS can also be utilized in warm seasons to enhance ventilation and maintain comfortable indoor conditions without excessive cooling demands. Future research should focus on optimizing materials, improving system integration, and investigating the long-term durability of 3D-printed components. Implementing such decentralized HRVS solutions in modern buildings can contribute significantly to energy savings and improved occupant comfort throughout the year.

5. ACKNOWLEDGMENT

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EVALUAREA PERFORMANȚEI UNUI SISTEM DE VENTILAȚIE CU RECUPERARE DE CĂLDURĂ

Sistemele de ventilație cu recuperare de căldură (HRVS) reprezintă o soluție eficientă pentru îmbunătățirea performanței energetice a clădirilor, prin recuperarea căldurii din aerul evacuat pentru a preîncălzi aerul proaspăt admis. Acest studiu analizează performanța unui prototip HRVS realizat prin imprimare 3D din material PLA. Eficiența sistemului a fost evaluată în condiții reale de mediu, atât în interior, cât și în exterior. Simulările realizate cu ANSYS, alături de măsurătorile experimentale, au permis determinarea eficienței recuperării căldurii la diferite debite de aer. Rezultatele obținute arată că sistemul poate atinge o eficiență de până la 87%, evidențiind astfel potențialul său de a optimiza consumul de energie și confortul termic al clădirilor, fără a compromite calitatea aerului interior.

Cuvinte cheie: *Asamblarea HRVS, eficiența HRVS, performanța HRV, rezultatele experimentale ale sistemului HRV, rezultatele simulate ale sistemului HRV*

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