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Cold Climate Challenges: Analysis of Heat Recovery Efficiency in Ventilation Systems

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Abstract: As building energy consumption gains ever-increasing attention worldwide, the focus on addressing it through the examination and optimization of efficient heat recovery solutions continues to intensify. With well-insulated and airtight buildings, the proportion of heating needs attributed to ventilation is growing, leading to the widespread integration and optimization of heat recovery solutions in mechanical ventilation systems. Heat recovery in ventilation is a highly efficient strategy for reducing heat losses and conserving energy. This study involves the investigation of a ventilation unit installed in an apartment situated in Riga, Latvia, as a practical examination of heat recovery system efficiency within the Latvian climate conditions, representing a cold climate region. The objective of this study was to examine the heat recovery efficiency of the ventilation system in the Latvian climate with variable outdoor and exhaust air parameters, given that the dry heat recovery efficiency is different from the actual heat recovery efficiency. The ventilation unit was equipped with a plate heat exchanger at an airflow rate of 105 m^3/h. To evaluate heat recovery efficiency, extensive measurements of air temperature and relative humidity were conducted. The collected data was analyzed, employing statistical regression analysis to ensure measurement reliability and assess correlations. The findings indicated a strong correlation between variables such as heat content, moisture content, and sensible air parameters. It was observed that the actual heat recovery efficiency was 6% higher than the calculated dry efficiency, emphasizing the importance of considering real-world conditions in heat recovery assessments. Additionally, regression analysis demonstrated a positive linear correlation with a coefficient of 0.77, highlighting the dependency between actual measurements and the theoretical model. These quantitative outcomes provide essential insights for optimizing heat recovery systems and enhancing energy-efficient ventilation practices, especially in cold climate environments. Moreover, this study highlights the strong correlation between variables such as heat content, moisture content, and sensible air parameters. Findings offer essential insights for optimizing heat recovery systems and enhancing energy-efficient ventilation practices, especially in cold climate environments.

Keywords: heat recovery; mechanical ventilation; energy efficiency; cold climate; heat exchanger

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1. Introduction

The global energy market is facing increased volatility, particularly since 2020, accompanied by unprecedented surges in energy prices. In this context, the pursuit of building stock energy efficiency emerges as an increasingly pressing concern [1–6]. Building stock accounts for approximately 40% of total primary energy consumption worldwide and, therefore, has a large impact on total energy consumption across all sectors [7–9]. Moreover, the focus on building energy efficiency extends far beyond the boundaries of a building stock and plays a pivotal role in promoting long-term economic and social progress on both a national and regional scale, and serves as a catalyst for sustainable development, contributing to energy conservation, reduced environmental impact, and enhanced living standards within communities [10–13]. An extensive number of the current building stock across the

EU regions has been constructed before the 2000s and is in need of deep renovation [14–17]. Energy renovation and thermal retrofitting of these buildings could significantly enhance the overall energy efficiency of the building stock in the corresponding region [18,19]. In developed countries, the current building stock is expected to remain in use for many decades. However, there is a growing emphasis on substantial energy retrofitting initiatives for the existing structures, primarily due to the long-term cost-effectiveness of these measures [19–21] as the building stock energy efficiency is gaining more public attention, government support, and financial investment worldwide [22–24]. This investment encompasses a range of financial instruments, including grants, subsidies, tax incentives, and low-interest loans, all aimed at encouraging building owners and developers to undertake energy-efficient renovations. Moreover, institutional investors and private sector entities are also recognizing the potential for long-term returns on sustainable building projects, further fueling the flow of capital into the sector. This convergence of public and private funding underscores the critical role of the building sector in achieving broader energy efficiency and sustainability goals [25–27]. On the other hand, it is projected that by 2050, a substantial portion of the existing buildings in Europe and the United States will undergo renovation or be replaced by newly constructed buildings. Consequently, the emerging newly constructed built environment will take a leading role in shaping urban energy demand within these regions [21,28]. However, it is important to note that the adoption and practical implementation of energy efficiency policies are intricately linked to the social, economic, and technological development of the region. Moreover, the adoption of well-structured regional development programs plays a significant role in expediting the integration of these policies into real-world practice. The extent to which these factors align and are effectively leveraged can significantly influence the successful implementation of energy efficiency measures within a particular area [29,30]. In the EU-28 region, buildings represent a significant share of 50–55% of the total electricity consumption and approximately 40% of the overall final energy consumption, on average. This data underscores the importance of addressing energy efficiency in buildings as a means to achieve significant reductions in overall energy consumption and mitigate environmental impacts [31–33].

In the Baltic States, comprising Latvia, Lithuania, and Estonia, buildings account for an even greater proportion, approximately 45%, of the total energy consumption. This increased share can be attributed to the suboptimal energy performance of a substantial portion of the existing building stock, mainly constructed during the period between the 1960s and the 1990s when building energy efficiency was not among the priorities in building construction. As a result, these structures now fall short of modern energy performance standards. It is also important to note that until 2002, construction practices in Latvia adhered to regulatory codes that lacked stringency concerning thermal performance. Consequently, a significant share of the existing building stock, which has not undergone comprehensive renovation measures, features poor thermal resistance, excessive outdoor air infiltration, and the occurrence of condensation within the external wall structures, compromising the energy inefficiency and indoor environmental quality in these buildings [34–38].

Furthermore, a majority of these buildings are devoid of adequate mechanical ventilation systems, leading to a reliance on natural ventilation or outdoor air infiltration through building exteriors, such as walls and roofs. This, in turn, results in substantial thermal energy losses [39–44].

Aligned with a broader objective of mitigating environmental impact, the European Union has announced a target to reduce greenhouse gas emissions by no less than 55% by the year 2030, with a long-term vision to achieve climate neutrality by 2050. In order to reduce energy consumption, the EU has issued directive 2010/31/EU that all buildings built from 2021 must comply with near-zero energy building criteria, which encourages the use of heat recovery in ventilation systems since the combination of infiltration and ventilation is responsible for almost 50% of energy emissions for insulated buildings in temperate climates [45,46].

Heat recovery units are fundamental components in the mechanical ventilation systems to achieve sustainability and energy efficiency goals in both renovated and newly constructed buildings. They are instrumental in ensuring optimal indoor comfort while simultaneously reducing environmental impact. In line with the environmental awareness and energy efficiency imperatives, the integration of effective heat recovery solutions is crucial to meet the demands of the future. The potential energy savings from using heat recovery systems can vary widely depending on factors such as climate, building size, insulation, and the specific technology employed [47,48]. However, according to several studies, on average, heat recovery systems have the potential to save anywhere from 30% to 90% of the energy that would otherwise be lost in the ventilation process. This can lead to substantial reductions in heating and cooling costs, making it a cost-effective and environmentally friendly solution for improving energy efficiency in buildings. It is essential to conduct a thorough energy audit and analysis to determine the precise energy savings achievable in a particular building or context [49–51]. Zemitis et al. conducted simulations in IDA-ICE 4.8 software, demonstrating that for a specific single-family house, the adoption of ventilation with heat recovery can lead to an impressive reduction in heating energy consumption of up to 84%. This remarkable reduction underscores the efficiency gains achievable through heat recovery systems [52]. Additionally, Liu et al.'s research emphasizes the significance of optimal design in achieving energy savings. Their findings reveal that an annual net energy savings increase of up to 48% can be achieved when employing optimal rotary heat exchangers compared to baseline systems [53]. Accurate data on building occupancy and usage play a pivotal role in designing these systems to maximize energy savings and promote sustainability [54].

Several studies have demonstrated that amongst other intervention measures for a building's energy efficiency upgrade, integration of heat recovery systems presents the largest final operational energy savings for the buildings after façade insulation [12,49,55]. In the Northern European region, where the heating season lasts for 5–6 months, heat recovery systems are of particular importance [38,56–59]. Mechanical ventilation systems with heat recovery stand as a pivotal component in the operation of energy-efficient buildings, as they can lead to significant energy savings [38,60,61]. A study by Evola et al. (2017) emphasized that the adoption of CMV systems with heat recovery in residential units is a cost-effective and energy-efficient solution, offering significant energy savings and favorable payback periods, especially in cold climates, while addressing concerns related to indoor air quality and mold formation [62].

In this context, the aim of this paper is to examine heat recovery efficiency within ventilation systems, focusing specifically on cold climates pertaining to those in the Baltic States. This study seeks to demonstrate the discrepancies between the established [63] methodology and the practical performance of these systems, providing valuable insights into the factors that determine heat recovery efficiency. By conducting the experimental measurements and analyzing data, the study examines how temperature and relative humidity variations impact heat recovery in these systems. The findings address the established dry efficiency metrics and provide insight into the complex interactions among environmental variables. This sets the foundation for improved and more precise energy certification practices.

To attain these goals, the methodology is comprehensively outlined, the parameters under investigation are underscored, and the experimental approach is thoroughly elaborated upon. This research aims to bridge the divide between theoretical standards and their practical applicability, ultimately contributing to the development of more efficient and sustainable ventilation systems, especially in challenging climates.

2. Methodology

Ventilation is intended to ensure an air exchange and a comfortable and healthy indoor climate. Without proper ventilation, there is a risk of moisture accumulation in the premises, which can cause mold growth on the enclosing structures and deterioration of indoor air quality [49,64,65]. Building occupants are vulnerable to fluctuations in relative humidity in rooms, and according to the LVS EN 16798-1:2019 standard, the comfort relative humidity limits are between 30% and 60% at comfort air temperatures [66,67]. Moreover, if the occupant density is high, then the CO_2 concentration increases and may affect occupants' health and well-being. After the outbreak of COVID-19 in Latvia, a new norm was adopted regarding the limit value of the CO_2 level—ventilation in public buildings should be ensured so that the indoor concentration of CO_2 does not exceed 1000 ppm [12,68–70].

The study aims to provide insights into the efficiency of heat recovery systems in buildings located in cold or moderately cold climates. By conducting comprehensive simulations and analysis, the study anticipates revealing the potential energy savings achievable through the implementation of heat recovery systems.

The experimental study involved measuring the actual heat recovery efficiency to compare how it differs with the data provided by the manufacturer, taking into account changes in temperature and relative humidity.

EN308:1997 methodology stipulates a heat recovery process without water vapor condensation, i.e., dry efficiency. The heat exchanger has to be tested at the following air parameters: room air +25 °C, RH 27%, and outdoor air +5 °C. As with these temperature parameters, the dew point is not reached, and condensate does not fall on the surface of the heat exchanger. Thus, the dry efficiency is measured. Processing data from the Central Statistical Office for the last 5-year period from November to March, it was concluded that out of 22 months, only one had a temperature that exceeded the +5 °C outdoor air value of the EN308:1997 methodology (see Figure 1), that means that the dry efficiency does not correspond to the actual heat recovery efficiency in the climate of Latvia. The average air temperature for this period was +0.4 °C.

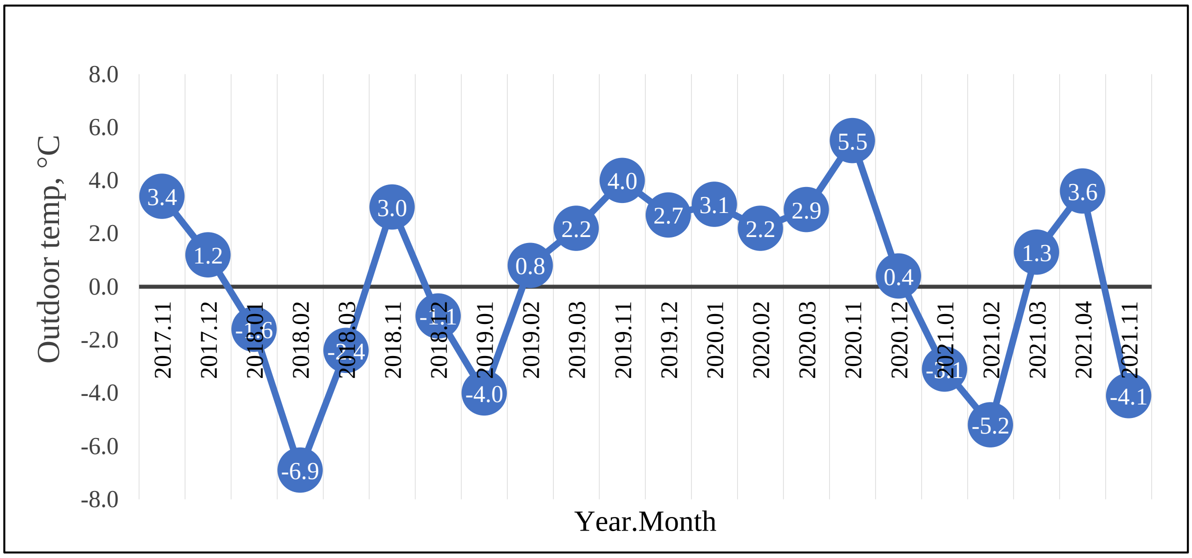

Figure 1. Average monthly air temperature in Latvia in the period from 2017 to 2021 throughout November–March (cold months season).

The selection of the heat recovery system was based on a comprehensive evaluation of its specifications and performance in the specific climatic conditions of Latvia. This system was chosen for its unique capacity to recover energy efficiently in cold climate regions, differentiating it from existing studies that primarily focused on theoretical models or warmer climate scenarios. The measurements took place at a test chamber with the possibility of controlling the necessary air parameters, such as temperature and absolute moisture content, which affect enthalpy and relative humidity. The test chamber and an air handling unit specification are shown in Table 1.

Table 1. Test chamber and AHU specifications.

Specification	**Value**
Test Chamber	
Width	4 m
Length	3 m
Height	2.8 m
Air Handling Unit	
Type of heat recovery unit	Aluminum, Plates
Maximum output	183 m^3/h at 100 Pa system pressure
Air duct connections	4 × Ø125 mm
Fan capacity	2 × 0.119 kW, 0.9 A
Electric after heater	0.9 kW
Heat recovery efficiency	84% (as per manufacturer's data)
Defrosting method	Contour line without preheating

The sensible and latent efficiency for the plate heat exchanger can be determined by Equations (1) and (2).

$$\varepsilon_{sensible} = \frac{m_2(C_{p,1}T_1 - C_{p,2}T_2)}{m_{\min}(C_{p,1}T_1 - C_{p,3}T_3)} \tag{1}$$

$$\varepsilon_{latent} = \frac{m_2(h_{fg,1}W_1 - h_{fg,2}W_2)}{m_{\min}(h_{fg,1}W_1 - h_{fg,3}W_3)} \tag{2}$$

where

m_n—mass flow at the measuring station n, kg/s;
$m_{\min}$—minimum supply or exhaust air mass flow, kg/s;
$C_{p,n}$—heat capacity of dry air at the station n, kJ/(kg·K);
h_{fg}—vaporization heat of water, kJ/(kg·K);
T_n—dry air temperature at the station n, °C;
W_n—humidity ratio at the station n, kg_w/kg_{da};
h_n—enthalpy at the station n, kJ/kg.

The total efficiency of the plate heat exchanger is determined by the following equation:

$$\varepsilon_{total} = \frac{m_2(h_1 - h_2)}{m_{\min}(h_1 - h_3)} \tag{3}$$

In order to measure the actual heat recovery efficiency of ventilation systems, combined sensors of air temperature and relative humidity were installed in a test plate heat exchanger. The air temperature sensor measured the current air temperature at different points (see Figure 2). Measurement of relative humidity was necessary to determine its effect on heat recovery efficiency and variation dynamic, as well as the effect on heat exchanger defrost interval and duration.

Measurements were taken every hour for one month in the period from December 2021 to February 2022 using the analog-type wireless combined sensors HOBO MX1104. This sensor type was chosen for its versatility, offering measurements of temperature, relative humidity, and light in a single device, which is essential for comprehensive environmental monitoring in our experimental setup. Additionally, its wireless feature allowed for easy data collection and real-time monitoring, which is especially valuable for present research focused on building energy efficiency and heat recovery systems. A more detailed specification of HOBO MX1104 is provided in Table 2.

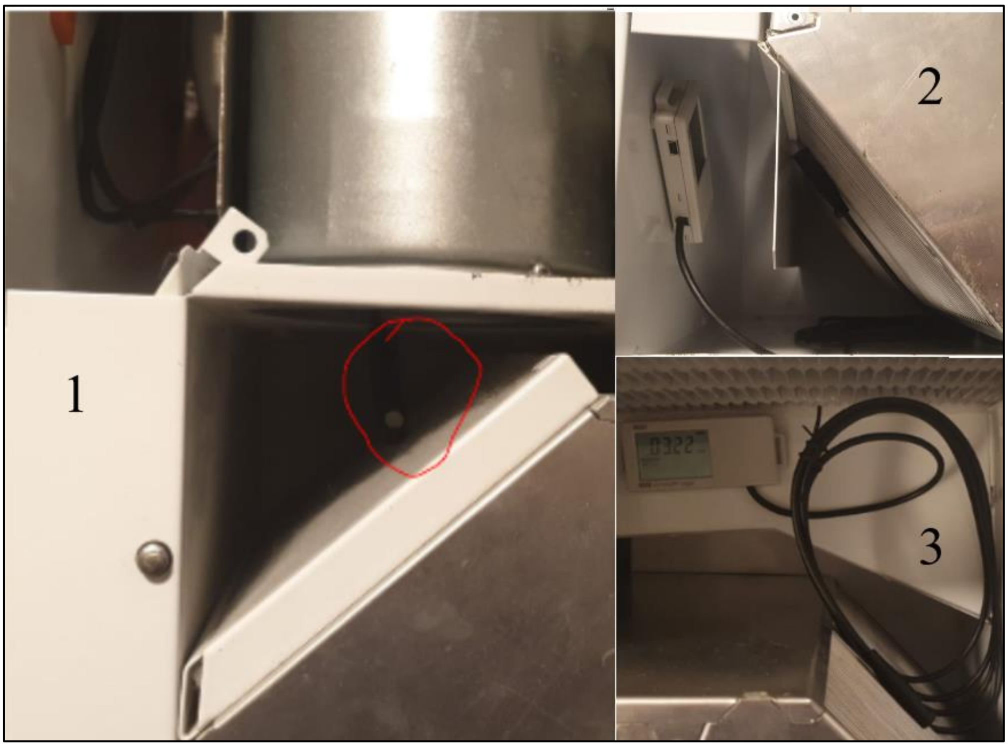

Figure 2. Placement of temperature—humidity sensors in the ventilation equipment. 1—exhaust air, 2—supply air, 3—outside air.

Table 2. Technical specification of HOBO MX1104 data logger.

Specification	**Value**
Measuring unit	HOBO MX1104 Data Logger
Manufacturer	Onset
Temperature:	
Measurement range	−20 °C to +70 °C
Accuracy	±0.20 °C from 0 °C to +50 °C
Measurement accuracy deviation	<0.1 °C per year
Relative humidity	
Measurement range	0–100% at −20 °C to 70 °C
Accuracy	±2.5% (10% to 90%) with a maximum of ±3.5%
Typical deviation (below 10% and above 90%)	±5%
Reading data	
Possible reading interval	1 s to 18 h
Reading modes	Fixed interval (normal and statistical)
Time accuracy	±1 min per month
Power source:	3× AAA 1.5 V Batteries

3. Results and Analysis

The experimental measurements were conducted in the period from 27 December 2021 to 10 February 2022. Measurements were taken every hour and totaled 769 data points. The representative period from 27 December 2021 to 9 January 2022 was used for detailed analysis, consisting of 305 data points. This period represented the coldest stretch with an average outdoor air temperature of +2.5 °C and a temperature variation of −3.3 °C to +7 °C. The temperature graph can be seen in Figure 3.

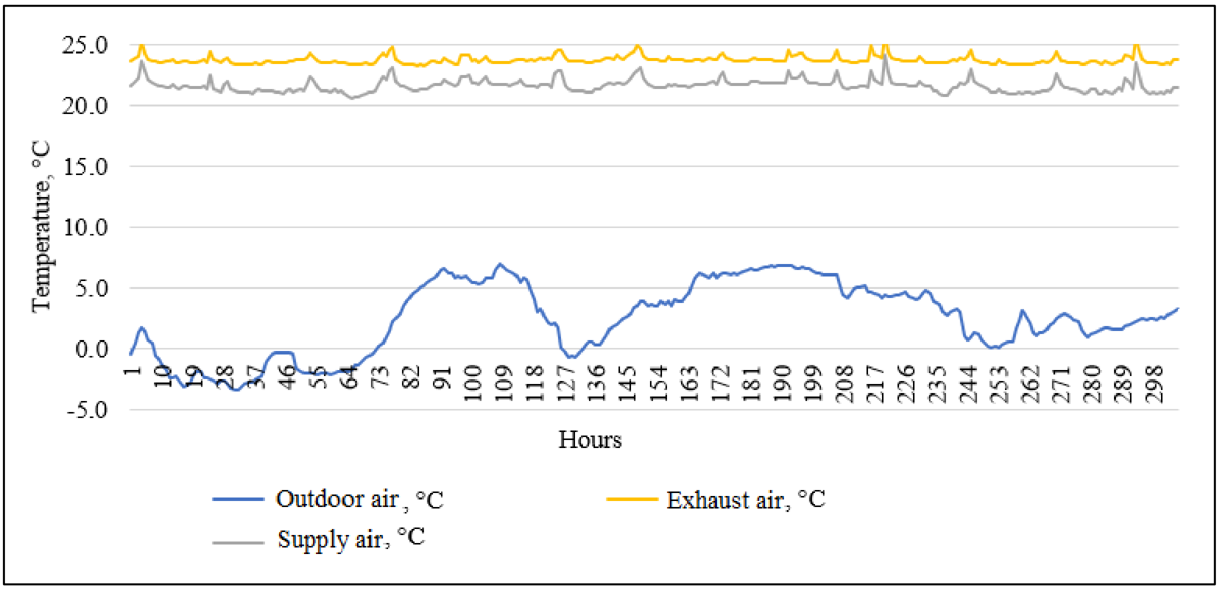

Figure 3. Outdoor, exhaust, and supply air temperature measurements.

The exhaust and supply air curves follow the same dynamic, suggesting that the supply temperature changes uniformly with the change in the exhaust air temperature, while changes in the outside air temperature do not affect the supply air temperature. It is important to point out that the outdoor air temperatures at which icing would form in the recuperator were not reached during the entire period of the experimental measurements, and only water vapor condensation occurred during this period (Figure 4).

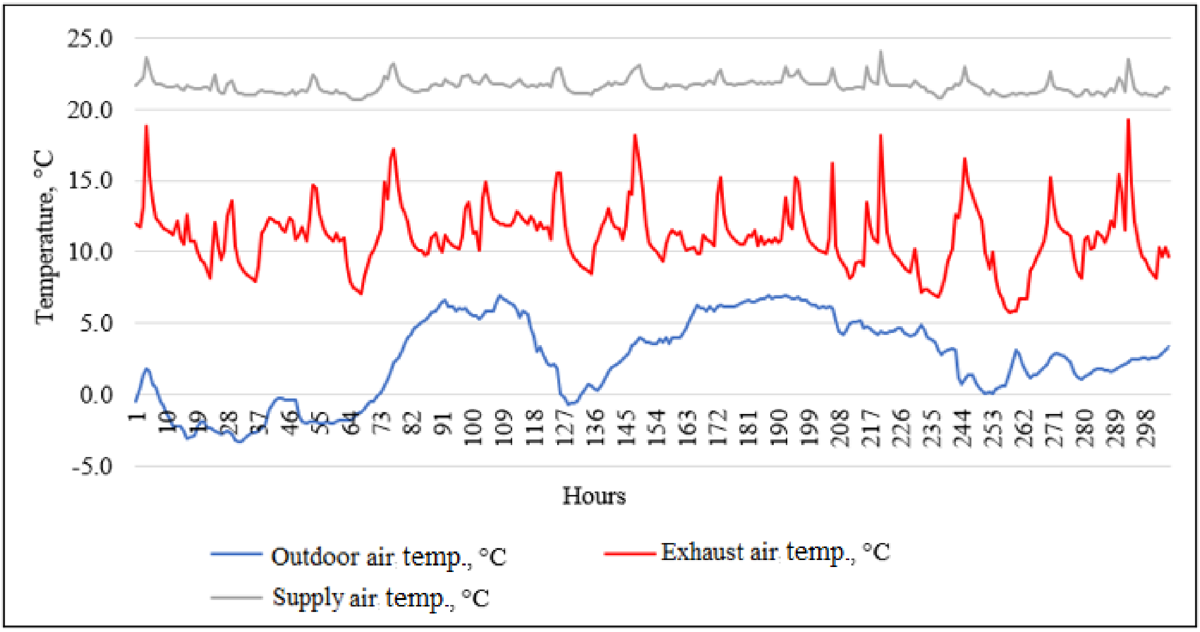

Figure 4. Exhaust air dew point variation graph.

The EN308:1997 methodology stipulates the validation of the heat exchanger using temperature–humidity regimes where water vapor condensation does not occur, but as it is seen, the outside air temperature remained lower than the dew point of the extract air. This suggests that the water vapor condensed in the recuperator constantly released additional heat. In addition, it is important to note that the supply air temperature fluctuated following the dew point curve dynamic. Increases in the exhaust air dew point peaks were also reflected in the supply air temperature, translating into a direct relationship between these values (Figure 5).

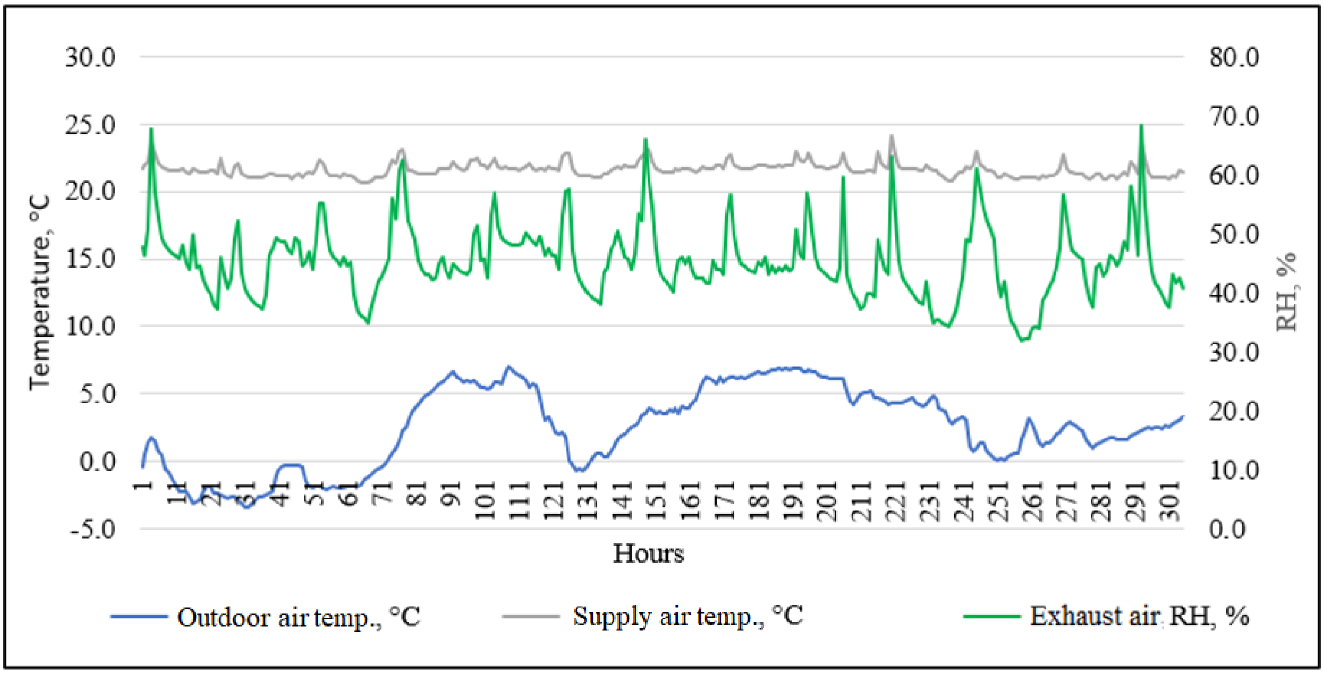

Figure 5. The change in the three studied quantities (outdoor air temperature, supply air temperature, relative humidity) over the time of the experiment.

As with the dew point, changes in the relative humidity of the exhaust air affect the supply air temperature. This indicates that the relative humidity of the exhaust air directly affects the efficiency of heat recovery (Figure 6).

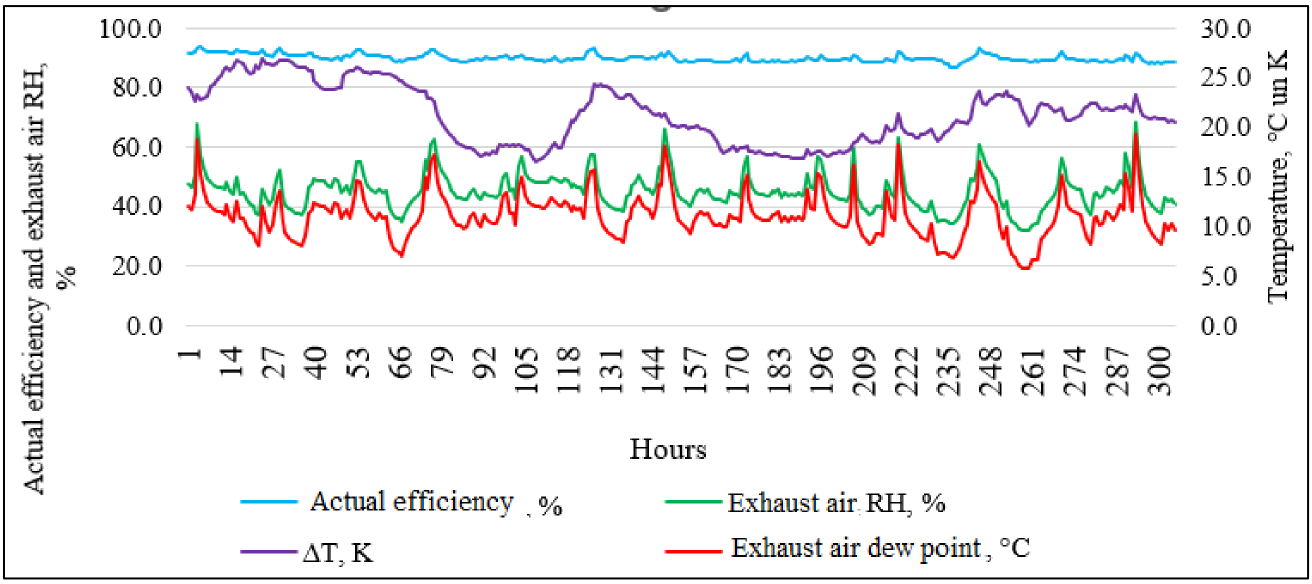

Figure 6. Changes in the efficiency of the heat recovery.

According to the graph shown, a significant connection between changes in dew point/relative humidity and heat recovery efficiency can be observed, while with regard to outdoor air and exhaust temperature, there is no particularly pronounced connection linked to heat recovery efficiency. Therefore, a regression analysis was performed to determine the relationship between actual and theoretical heat recovery efficiency (Figure 7).

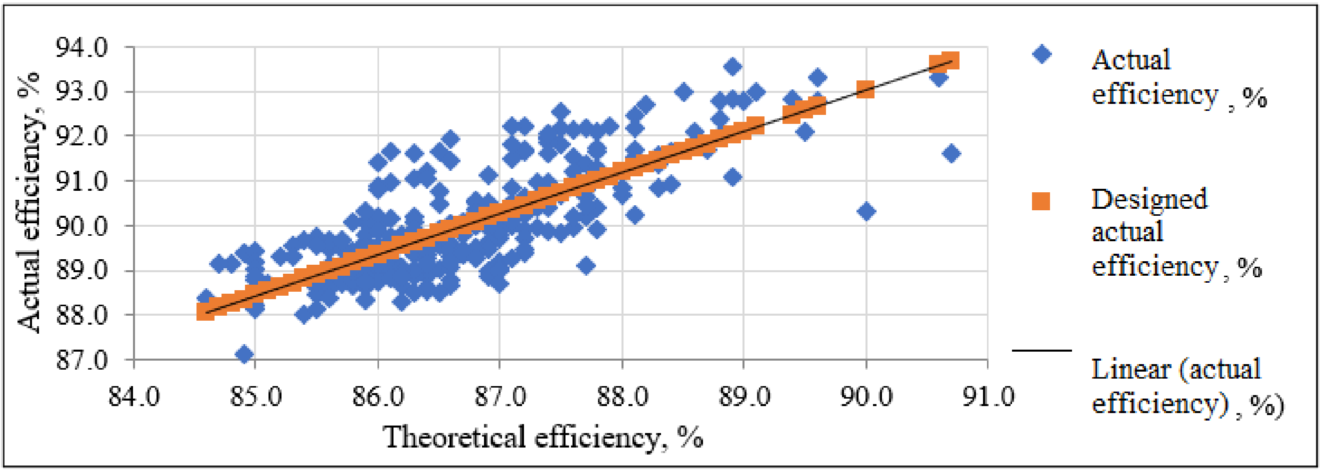

Figure 7. Regression model of the actual and theoretical heat recovery efficiency.

Regression analysis of the actual and theoretical heat recovery efficiency demonstrated a positive linear correlation with a coefficient of 0.77, indicating that there is a dependency between the variables between the actual measurements and the theoretical model. Although there are some points that significantly deviated from the total sample, their number is relatively insignificant. A positive trend can be seen when examining the regression analysis graph, showing a high agreement between the models.

The graph represents the heat energy recovered by the recuperator (Figure 8). The energy curves of recovered heat are uniform for all cases: actual, theoretical, and EN308:1997. Although the heat recovery efficiency, according to EN308:1997, is constant and is not affected by relative humidity fluctuations, the heat recovery curve repeats the actual measurement curve. Using the above-mentioned data, outdoor air temperatures at which recuperator icing begins were calculated using the manufacturer's computer program. The author performed a simulation with the average exhaust air temperature and relative humidity, lowering the outdoor air temperature one degree at a time to a temperature of −20 °C. The target supply air temperature was +20 °C. When the bypass valve is open, the supply air temperature drops proportionally to the outdoor temperature drop as it diverts part of the outdoor airflow through the bypass valve, and its volume depends on the exhaust air temperature, which must be above 0 °C so that the recuperator does not freeze. It is important to note that during bypass line defrosting mode, the efficiency of heat recovery increases proportionally to the decrease in outdoor air temperature. Analyzing the two defrosting methods (bypass and preheating), an energy balance can be drawn up for the ventilation system under study, i.e., the distribution of heat energy consumption for each method.

As the outdoor temperature drops (Figure 9), the amount of recovered heat recovery energy also decreases, indicating the logical correlation sequence. However, the amount of the recovered thermal energy is different under each of the applied methods. The thermal energy recovered from preheating is higher than for bypass defrosting. As the outdoor air temperature decreases, the heat recovery energy difference between the two methods starts to increase, and after −16 °C, the difference starts to gradually decrease. This is due to the fact that the preheating heat energy constantly increased by 0.04 kW with each lowering degree, while the post-heating thermal energy increased unevenly. This can be explained by the fact that in the case of bypass defrosting, the air coming out of the recuperator is a mixture of two air flows; therefore, the air density can be uneven as the airflow passing through the bypass also fluctuates in an uneven manner.

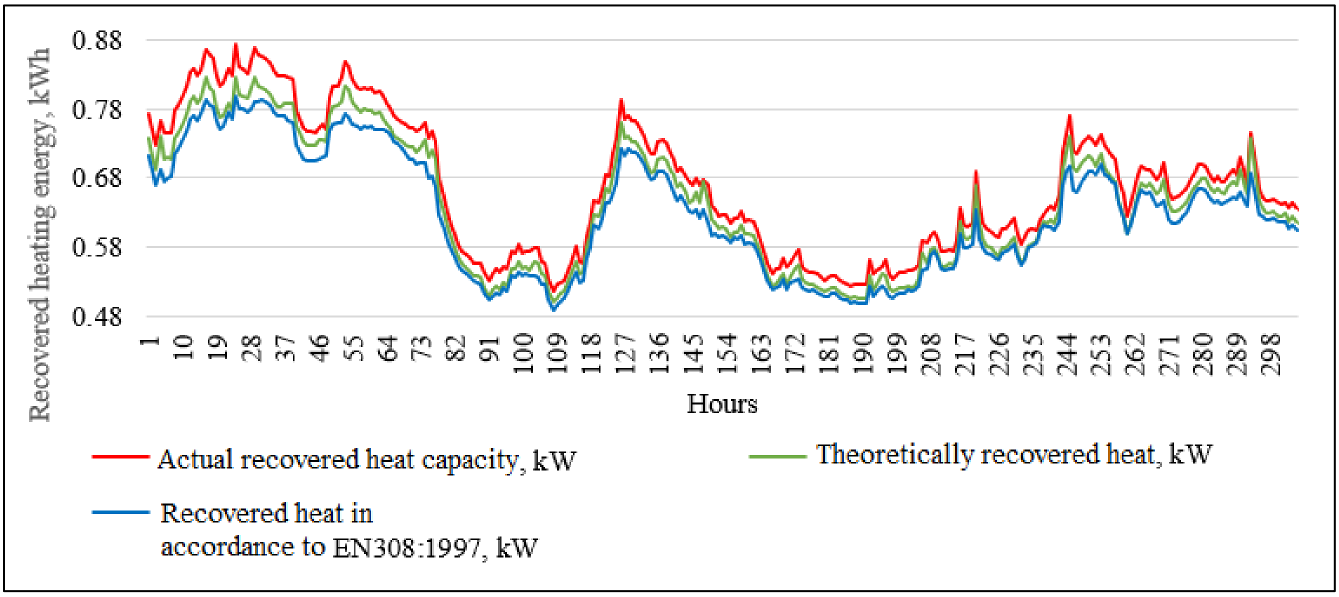

Figure 8. Recovered thermal energy (kWh).

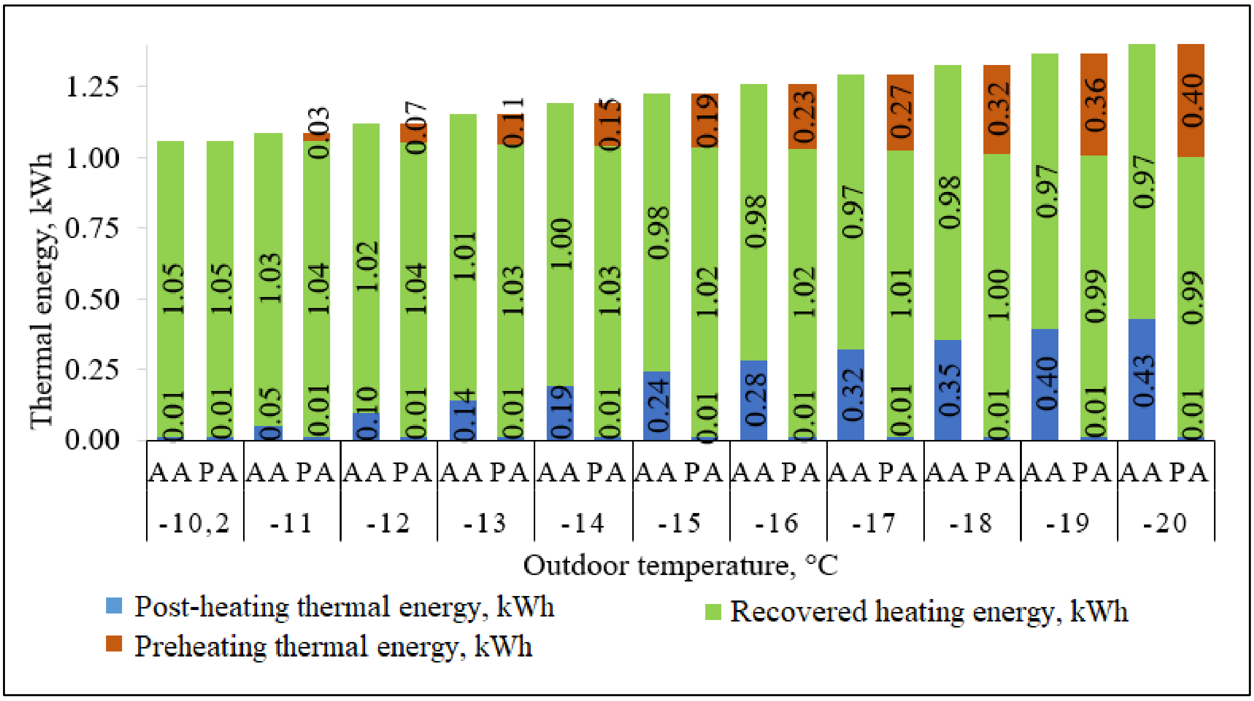

Figure 9. Energy balance of bypass (AA) and preheating (PA) defrosting methods, air volume 105 m^3/h.

In the case of bypass defrosting, the air coming out of the recuperator is a mixture of two air flows. Therefore, the air density can be uneven. The preheat defrosting method is deemed more efficient than the bypass defrosting method. This experiment is consistent with a previously described study comparing two defrosting methods [71]. It is important to add that preheating defrosting is more effective only at the beginning of the icing stage—as the outdoor air temperature drops, its efficiency decreases and almost aligns with bypass defrosting. In addition, if the ventilation unit is equipped with preheating defrost technology, it will require two heaters—for preheating and post-heating, which increases the capital costs of the ventilation unit and affects the overall dimensions of the ventilation unit. On the other hand, in the case of bypass defrosting, there is only one air heater, and the ventilation unit can be more compact. Insufficiency in heating capacity can be solved by temporarily reducing the airflow.

The findings indicate that the dry heat recovery efficiency, as per EN308:1997, is lower than both the actual performance and theoretically computed wet efficiency using the heat exchanger manufacturer's technical data. The disparity between outdoor air and exhaust air temperatures minimally affects heat recovery efficiency; instead, it predominantly influences water vapor condensation, thereby augmenting condensation-based heat recovery [72,73]. When evaluating dry conditions, the temperature differential demonstrates no noticeable impact on efficiency. The EN308:1997 dry efficiency solely reflects the intrinsic characteristics of the heat exchanger, considering factors such as materials, technology, and design without external influences. During the cold season in Latvia, it is highly likely that condensate will form within the heat recovery system. The absence of condensation at low external air temperatures suggests excessively dry indoor air, causing discomfort for occupants, who may resort to local humidification in this case [74]. Consequently, instances of excessively dry indoor air are extremely rare. Moreover, human activities generate moisture, and unless ventilation is exceptionally aggressive, excessively dry indoor air is nearly unattainable [75]. Considering this aspect, applying dry energy efficiency for energy certification yields a calculation result with a 5% buffer. Furthermore, dry efficiency precludes the risk of freezing in the recuperator, which could otherwise diminish heat recovery and increase auxiliary heating energy consumption.

The observed results presented in the study are supported by a rigorous examination of temperature and humidity measurements in the test plate heat exchanger. These measurements, conducted over a span of one month, provided substantial data to support the findings. The strong correlation between variables, such as heat content, moisture content, and sensible air parameters, underscores the significance of these factors influencing heat recovery efficiency within ventilation systems. This empirical evidence reinforces the discussion, highlighting the practical implications and complexities of heat recovery in cold climate environments.

As such, it is recommended to utilize the SEC (Specific Energy Consumption) energy efficiency calculation method prescribed by ventilation equipment manufacturers in accordance with Directive 1253/2014 for energy certification. This approach encompasses all conceivable operational scenarios of ventilation equipment across three climate zones: cold, temperate, and warm. A more precise energy efficiency calculation can facilitate resource allocation in construction and potentially reduce expenses.

Upon investigating factors impacting heat recovery efficiency, it can be inferred that alterations in exhaust air temperature and relative humidity independently affect heat recovery efficiency [47,48]. Nonetheless, when these alterations are examined individually, their influence appears negligible, resulting in an insignificant correlation. This is triggered by the fact that air conditions may undergo changes that are isothermal, adiabatic, or entail no moisture content modification, while enthalpy, representing heat content, experiences variations [48,76,77]. Consequently, it was observed that heat recovery is more responsive to enthalpy changes than the parameters of sensible air conditions. Higher enthalpy signifies greater energy potential in the air, and larger differences in energy potential translate to more efficient energy exchange.

4. Conclusions

The results of the study indicate that the dry heat recovery efficiency, according to EN308:1997, is lower than the actual and theoretically calculated wet efficiency. The difference between outdoor air and exhaust air temperatures has little effect on heat recovery efficiency, as it only affects the amount of water vapor condensation, which increases the efficiency of heat recovery by condensation.

In the cold season of the Latvian climate, there is a high probability that condensate may form in the heat exchanger. If no condensation is formed in the recuperator at low outdoor air temperatures, it indicates that the air in the premises is too dry. Investigating the factors affecting heat recovery efficiency, the study demonstrated that changes in exhaust air temperature and relative humidity affect heat recovery efficiency. The heat recovery is more affected by changes in heat content than by the parameters of the sensible air condition—the higher the heat content, the more potential energy mass is in the air volume.

When examining the recovered heat energy in the reviewed period, the study showed that the actual recovered heat energy is 6% higher than the heat energy calculated by EN308:1997 (204.19 kWh against 191.80 kWh). During the experimental measurements, it was observed that simultaneous changes in exhaust air temperature and relative humidity affect heat recovery efficiency. When performing the regression analysis, the correlation coefficient of those parameters reached 0.83, which indicates a high interrelationship. The regression analysis for separate exhaust air temperatures, relative humidity, and heat recovery efficiencies produced the correlation coefficient −0.56 and 0.61, respectively, which indicates that separate exhaust air temperature and relative humidity have less influence on heat recovery than combined.

In summary, the study emphasizes the dynamics within heat recovery efficiency, demonstrating the significance of factors beyond standard metrics. It showcases the impact of varying exhaust air temperature and relative humidity on heat recovery efficacy, validating the interaction between these variables. By revealing the complex correlations of heat content, moisture, and sensible air parameters, this research contributes essential insights for optimizing heat recovery systems and advancing energy-efficient ventilation practices, particularly in cold climate conditions.

For energy certification purposes, the utilization of the manufacturer's SEC (Specific Energy Consumption) calculation method is a more appropriate choice compared to relying on the EN308:1997 dry heat recovery efficiency metric. The SEC calculation provides a holistic and encompassing evaluation of ventilation equipment performance, taking into account all conceivable operational scenarios. Particularly, when dry efficiency is employed in the energy certification process, the resulting energy efficiency assessment demonstrates a modest 5% margin. This underscores the significance of adopting the SEC methodology for more accurate and comprehensive energy certification.

As a forward-looking proposition, the authors recommend conducting further research within a controlled climatic chamber environment. Such controlled conditions facilitate the measurement of a broader spectrum of temperature and relative humidity combinations, enabling a more comprehensive investigation across a wider range of operational scenarios with respect to ventilation units.

Furthermore, it is proposed that future research consider the incorporation of actual air density or the conversion of actual airflow into air mass flow during calculations. This would contribute to a more precise and scientifically rigorous assessment of ventilation equipment performance. In light of these considerations, the adoption of these methodologies and the pursuit of further research in these directions hold the potential to advance the field of energy efficiency assessment in ventilation systems attributed to cold climate environments.

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