

Performance of an earth-air heat exchanger (EAHE) in a heat recovery ventilation for residential buildings in severe cold regions

Xinyi Hu^{1*}, Juha Jokisalo^{2,3}, Risto Kosonen^{2,3,4} and Matti Lehtonen¹

¹EDP Sciences, Editorial Department, 91944 Les Ulis Cedex A, France

¹Department of Electrical Engineering and Automation, Aalto University, 02150 Espoo, Finland

²Department of Mechanical Engineering, Aalto University, 02150 Espoo, Finland

³Smart City Center of Excellence, TalTech, 19086 Tallinn, Estonia

⁴College of Urban Construction, Nanjing Tech University, 211899 Nanjing, China

Abstract. The prolonged duration of winter season and the occurrence of extreme low temperatures present significant challenges when implementing mechanical ventilation systems in severe cold regions. These challenges encompass substantial requirements for heating supply air and frequent operations for defrosting. Heat stored in the ground has the potential to be harnessed for pre-conditioning supply air through the utilization of an earth-air heat exchanger (EAHE). This study focuses on evaluating the heating performance of the EAHE when integrated into a heat recovery ventilation system. The energy model of a case building in Harbin and the proposed ventilation system were simulated in IDA ICE. The results show that as the outdoor temperature drops, the proportion of heat supplied by EAHE increases, leading to a decrease in reliance on reheater to heat supply air. This underscores the advantages of applying EAHE to preheat fresh air in colder climates.

1 Introduction

Natural ventilation via manually opened windows and envelope infiltration is the main method to ensure airflow rates in rural houses situated in China's severe cold regions. However, to avoid draughts and high energy consumption, residents tend to close windows during the prolonged winter season, leading to inadequate indoor air quality (IAQ). The severe cold region mentioned is defined as having an average temperature of less than -10 °C during the coldest month and more than 145 days with a daily average temperature of less than 5 °C [1].

Heat recovery (HR) ventilation system is a widely used method for effectively enhancing IAQ by extracting heat from exhaust air. However, implementing it in severe cold areas often encounters significant challenges, including intensive heating needs from

* Corresponding author: xinyi.hu@aalto.fi

supply air and frequent occurrence of frosting in HR. One commonly employed approach is preheating the supply air prior to its introduction into the HR [2]. The thermal energy existing in the ground can be utilized to pre-condition supply air by employing an earth-air heat exchanger (EAHE). The utilization of renewable energy makes this solution more attractive than conventional preheaters.

An EAHE typically consists of one or multiple ducts that are buried in the ground either horizontally or vertically at a predetermined depth. This depth assures a year-round, relatively undisturbed environment characterized by a nearly constant temperature [3]. Soil temperature below a specific depth is lower than ambient air temperature during the summer and higher during the winter due to the delayed response of the soil [4]. The underlying soil could thus be utilized as a thermal sink. Heat is transferred between the ventilation supply air and the soil as the air passes through the ground duct. Hence, an EAHE, which is typically situated upstream of HR, has the capability to precool incoming fresh air in summer and preheat it in winter.

Many scholars have studied the performance of EAHE in pre-conditioning the supply air. Chlela et al. [5] found that in central European climates, EAHE demonstrates superior performance in cooling supply air in summer compared to heating it in winter. Integrating EAHE into the heat recovery ventilation system results in only a marginal reduction of heat demand. Khabbaz et al. [6] reported that in a hot semi-arid climate, the supply air temperature leaving EAHE remains constant at approximately 25 °C during summer when the outdoor temperature exceeds 40 °C. Wei et al. [7] studied the effectiveness of a U-shape EAHE in cooling the incoming fresh air under hot and humid weather conditions. The results indicate that EAHE demonstrated effective cooling and dehumidification capabilities for the supply air with cooling coefficient of performance (COP) achieving 31.8 at maximum. However, current research focusing on the heating performance of EAHE is still limited, especially in the application and evaluation under severe cold climate conditions.

This paper seeks to assess the heating performance of EAHE when integrated with a heat recovery ventilation system under severe cold climate conditions.

2 Methods

2.1 Description of case building

The case building used is a single-family detached house located in the rural area of Harbin. Its heated net floor area is 54 m². The building model and detailed characteristics are presented in Fig. 1 and Table 1. The case building could represent the building layout, construction, energy, and ventilation systems of local rural houses.

The envelope renovation strategy has been determined by the previous study [8]. Its performance after energy-efficient renovation could meet the requirements of Chinese codes for rural houses [9].

The space heating need is met by a biomass pellet boiler and water radiators. The heating setpoint of the two bedrooms was set at 17 °C, and that of kitchen and storage was 14 °C. The heating system operates continuously during the heating season. The internal gains from lighting and equipment were 5 W/m² and 3.8 W/m², respectively [10].

There is no mechanical ventilation system in the case building. The air exchange is performed through envelope infiltration and manually opening windows. However, during the cold winter, residents are reluctant to open the window in order to maintain the indoor temperature and save energy costs. The previous study [8] has reported high CO₂ concentration levels in bedrooms, thus demonstrating the need for a mechanical ventilation system.

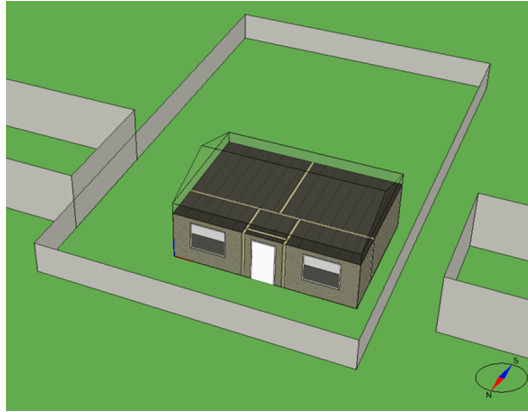


Fig. 1. IDA model of case building.

Table 1. Building characteristics.

Parameters	Unit	Value
Heated net floor area	m ²	54
Envelope area	m ²	177
Window/envelope area	-	9.1%
U-value of external wall	W/m ² K	0.17 (southern); 0.19 (others)
U-value of ground floor	W/m ² K	0.53
U-value of roof	W/m ² K	0.42
U-value of windows	W/m ² K	2.30
Heating usage time	h/d	24
Annual power demand for lighting	W/m ²	5

Annual power demand for equipment	W/m ²	3.8
Clothing level	clo	1.01±0.41
Activity	met	1.2

2.2 Proposed ventilation system

A balanced ventilation system with both EAHE and HR was applied in this study. This ventilation system only operated during heating season. At other times, the previous ventilation strategy was still used.

The EAHE was installed at the upstream of HR. The fresh air first went through the ground ducts in EAHE, transferring heat with soil, and then it entered HR to further absorb recovered heat from the exhaust air. If the supply air did not reach the pre-set ventilation setpoint of 17 °C, it would be heated by an electric heater before being supplied to the rooms. The HR has a 70% temperature efficiency of supply air, and the defrost protection threshold was set at 4 °C.

The supply terminals were in two bedrooms and the exhaust terminals were in the kitchen and storage. The air handling unit (AHU) including HR was placed in the storage room where HR connected with the ground duct buried in the yard. Fig. 2 presents a simplified sketch, revealing the relationship between EAHE and case building.

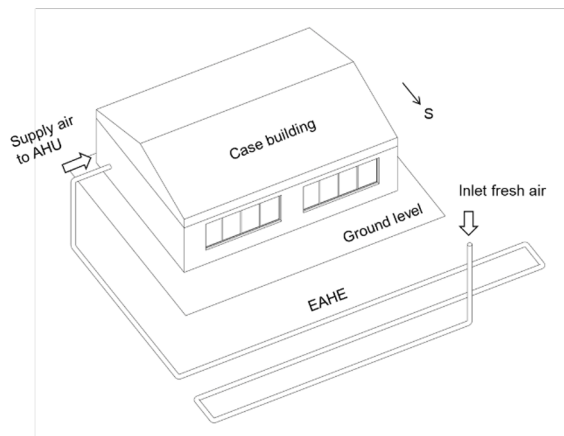


Fig. 2. Simplified sketch for EAHE and case building.

The ground duct was buried horizontally in the soil at a depth of 3 m from the ground surface. The depth was selected to maintain the soil temperature undisturbed and to roughly resemble the average yearly outdoor air temperature. The horizontal duct arrangement was applied because the rural houses usually have yards, which provides enough space for installing ground ducts and possesses advantages on excavation costs.

The explicit parameters of the EAHE are described as follows: duct length of 40 m, buried depth of 3 m, duct diameter of 80 mm, duct distance of 1.5 m, a horizontal serpentine arrangement, and the use of polyvinyl chloride (PVC) material.

The heating capacity of EAHE was calculated as follows:

$$\Phi = \dot{m}c_p(t_o - t_i) \quad (1)$$

$$\dot{m} = A\rho v \quad (2)$$

Where Φ is the heating capacity of EAHE (W), \dot{m} is the mass flow rate of air in ground duct (kg/s), c_p is the constant pressure specific heat of air (J/kg·°C), t_i and t_o are the supply air inlet and outlet temperature of ground duct (°C), A is the cross-section area of ground duct (m²), ρ is the air density (kg/m³), v is the air velocity (m/s).

The positive value of Φ refers to the absorbed heat from soil to air, which means that EAHE heats the supply air; the negative value refers to the transferred heat from air to soil, which means EAHE cools down the supply air.

2.3 Simulation tool

In this study, IDA Indoor Climate and Energy (IDA ICE) was used for establishing and simulating the building energy model as well as the proposed ventilation system. IDA ICE is a program that allows for simulating thermal indoor environments and energy consumption in buildings, which has been validated under EN 15255 and EN 15265 [11]. The building energy model without mechanical ventilation systems has been validated in the previous study [8].

The “Ground duct supply air” component was used for modeling the proposed balanced ventilation system with both EAHE and HR. The simulation theory utilized in this component drew inspiration from IDA Tunnel, a reliable algorithm known for its ability to simulate the heat exchange between the earth and air within ground ducts. The ducts can be installed in either shallow or deep soil. The algorithm has been validated and applied to numerous practical projects [12,13].

The following temperature fields were calculated [14]:

- One-dimensional heat transfer caused by conditions in the ground duct.
- One-dimensional heat transfer in an undisturbed ground field at ground surface and at a depth.
- One-dimensional heat transfer caused by geothermal effects.

The superposition process was conducted by combing the external temperature fields caused by undisturbed ground, geothermal effects and neighboring ducts with their contributions. The total field is then formed by the summation of the external temperature fields and the internal temperature field of ground duct.

The ground surface boundary condition was determined by the fluctuating ambient air temperature on an hourly basis.

2.4 Weather data and typical weeks

Harbin is a representative city located in the severe cold region of China. The duration of heating season in Harbin spans 183 days, commencing on October 20th and concluding

on April 20th of the following year. The average temperature throughout this period is $-7\text{ }^{\circ}\text{C}$. The depth of local frozen soil is 2.1 m.

Table 2 categorizes the entire heating season into three weather groups based on the weekly average outdoor temperature: slight cold, cold, and severe cold groups [15]. One typical week was selected in each group to represent the typical weather circumstances of that group. Fig. 3 shows the hourly outdoor temperature profile of Harbin and highlights the chosen typical winter weeks.

Subsequently, a comprehensive analysis was conducted to examine the performance of the proposed ventilation system during typical winter weeks. The analysis seeks to explain the impact of diverse weather conditions on the operational efficiency of the system.

Table 2. Weather condition groups and typical winter weeks.

Weather condition	Temperature range	Chosen typical week	Weekly average temperature
Slight cold	$> -5\text{ }^{\circ}\text{C}$	Mar 30 – Apr 5	$3.3\text{ }^{\circ}\text{C}$
Cold	$-5\text{ }^{\circ}\text{C} \sim -15\text{ }^{\circ}\text{C}$	Dec 1 – Dec 7	$-9.4\text{ }^{\circ}\text{C}$
Severe cold	$< -15\text{ }^{\circ}\text{C}$	Jan 19 – Jan 25	$-18.3\text{ }^{\circ}\text{C}$

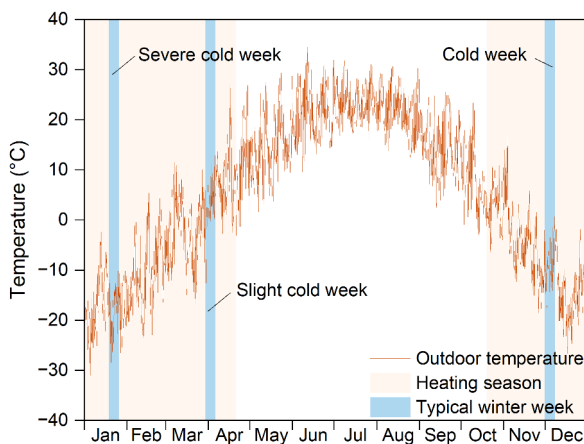


Fig. 3. Outdoor temperature and typical winter weeks in Harbin.

3 Results

3.1 Heating capacity

Fig. 4 presents the duration curve of AHU capacity when operating during the heating season. The peak power of EAHE, HR, and reheater are 904 W, 273 W, and 142 W,

respectively. Throughout the duration of the whole heating season, it is necessary for both the HR and the reheater to remain operating. During 88% of the heating season, the EAHE contributes to heating supply air. However, during the remaining time (12%), the heating capacity of EAHE exhibits negative values, implying that heat is being transferred from the air to the soil. This indicates that the EAHE is working to cool the supply air.

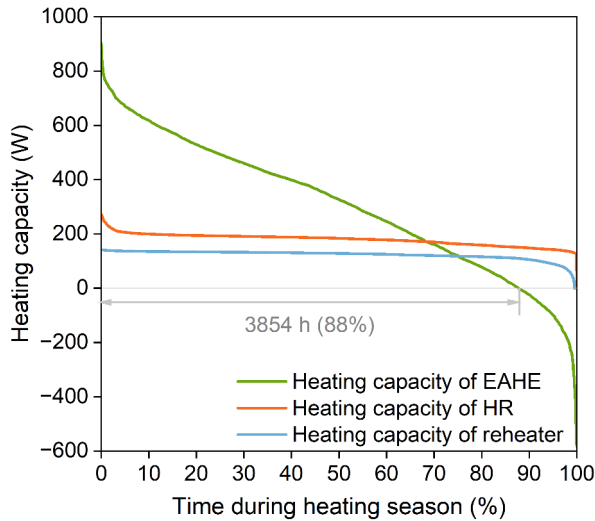


Fig. 4. Duration curve of AHU capacity during heating season.

3.2 Temperature and power variation

Fig. 5 shows the supply/exhaust air temperature variation curve and power profile of AHU during three typical winter weeks.

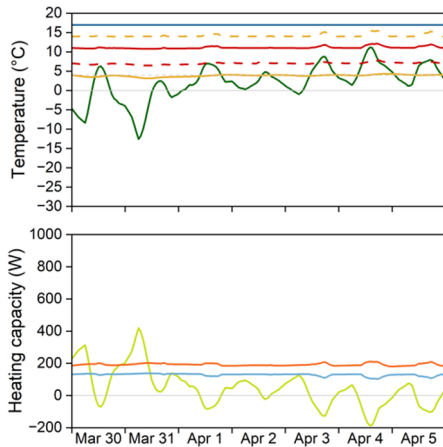
In all typical weeks, there is a pronounced opposite correlation between the supply air inlet temperature of EAHE (which is also the outdoor air temperature) and the heating capacity of EAHE. From the slight cold week to the cold week, and then to the severe cold week, the range of outdoor air temperature undergoes a gradual decrease, and simultaneously the range of heating capacity of EAHE gradually increases. Besides, during each typical week, the heating capacity of EAHE reaches its maximum value when the outdoor air temperature is at its lowest.

The heating capacity of EAHE exhibits noticeable variations in response to fluctuations in outdoor air temperature, suggesting a substantial influence of the outdoor temperature on this system. Regardless of the fluctuations in outdoor air temperature over three typical weeks, it is observed that the heating capacity of the HR and reheater remains relatively stable, at approximately 180 W and 130 W, respectively. This indicates that the heating capacity of the HR and reheater remains rather unaffected by variations in outdoor air temperature.

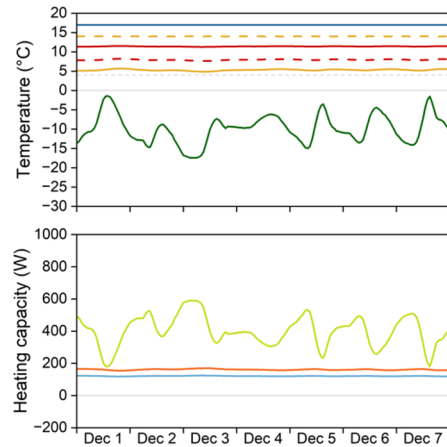
The supply air inlet temperature of HR is defined as the temperature at which the supply air enters HR after crossing through the EAHE. Throughout all three typical weeks, this temperature remains consistently above 0 °C (grey solid line). The exhaust air

outlet temperature of HR refers to the specific temperature at which the exhaust air departs from the HR system. It is a crucial factor in determining whether to activate defrost control. This temperature is always above the HR defrost limit of 4 °C (grey dash line). Based on the results above, it can be drawn that the risk of frosting in HR is significantly reduced during these three typical weeks. Hence, this proposed ventilation system is suitable for use in all three different weather conditions.

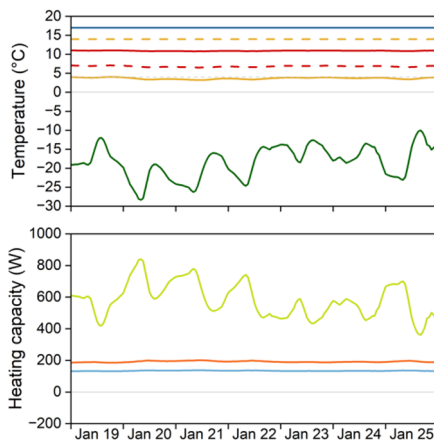
(a) Slight cold week



(b) Cold week



(c) Severe cold week



— Supply air inlet temperature of EAHE
 — Supply air inlet temperature of HR
 — Supply air outlet temperature of HR
 — Supply air outlet temperature of fan
 - - Exhaust air inlet temperature of HR
 - - Exhaust air outlet temperature of HR
 — Heating capacity of EAHE
 — Heating capacity of HR
 — Heating capacity of reheater

Fig. 5. Supply/exhaust air temperature variation and AHU power profile during typical weeks.

3.3 Heating power ratio

Fig. 6 presents the heating power ratio of EAHE, HR and reheater during typical winter weeks and the whole heating season. It analyses the heat supply contribution of each AHU component.

During slight cold weeks, it shows that HR provides 52% of heating power while EAHE only occupies 14%, the rest heat demand is compensated by the reheater. However, in the severe cold week, the heating power of HR decreases to 21% while EAHE and reheater account for 64% and 15%, respectively.

When the outdoor temperature decreases, there is a noticeable shift in the heat sources. The proportion of heat provided by HR decreases, while that of EAHE increases significantly, going from 13% in the slight cold week to 64% in the severe cold week. Additionally, the proportion of reheater supplementary heat is also reduced accordingly.

The analysis of the entire heating season shows that the EAHE is responsible for meeting half of the ventilation heating demands. HR contributes 30% of the heating needs by effectively recovering the heat from the exhaust air and the remaining 20% is fulfilled by the reheater.

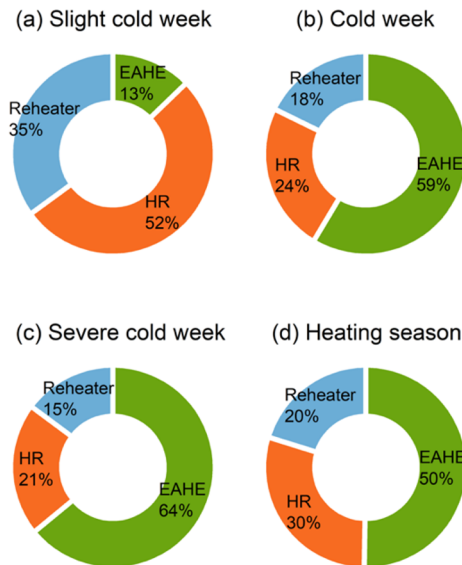


Fig. 6. AHU heating power ratio during typical weeks and heating season.

4 Discussion

The changes in the heat power ratio of EAHE over three typical weeks illustrate that EAHE has the ability to provide better heating performance and reduce the reliance on the reheater in colder weather conditions. While in a conventional mechanical

ventilation configuration, severe cold conditions are precisely the situations in which HR performance is frequently threatened by defrost.

During the slight cold week, EAHE occasionally cools rather than heats the supply air. EAHE transfers part of the heat away from the supply air, but the supply air temperature exiting EAHE has not yet reached the ventilation setpoint requirements. Therefore, the unnecessary cooling behavior of EAHE during the heating season actually leads to additional heating needs for the HR and reheater. To mitigate this phenomenon, one possible approach is to implement a bypass system.

If the temperature of the supply air gets close to the condensation temperature, condensation may occur inside the ground duct. However, due to the hydrophobic characteristic of the PVC material used for the ground duct, condensed droplets can be efficiently drained, and the likelihood of mold growth can be minimized [16].

The newly installed radiators in the kitchen and storage, where exhaust terminals are located, help to increase the exhaust air temperature, thus increasing HR efficiency and reducing defrost operation time. However, it should be mentioned that the heating setpoints in bedrooms (17 °C) and auxiliary rooms (14 °C) are derived from the thermal history of residents and the Chinese standard requirements for rural residential houses. If residents desire a higher indoor temperature, such as raising it to the heating setpoint specified in European codes (20 °C) [17], the HR's efficiency will be further enhanced.

5 Conclusion

This study aims to investigate the heating performance of earth-air heat exchanger (EAHE) when combined with a heat recovery (HR) balanced ventilation system and utilized in severe cold regions.

The key findings are as follows:

- During each typical winter week (slight cold, cold, and severe cold), the heating capacity of EAHE reaches its maximum value when the outdoor air temperature is at its lowest.
- EAHE provides better heating performance in colder weather conditions and reduces the reliance on the reheater.
- During the entire heating season, EAHE, HR, and reheater account for 50%, 30%, and 20% of ventilation heating needs, respectively.

The above results, which explored three different winter weather conditions, also hold reference significance for other climate regions. This includes cold regions as well as regions with hot summers and cold winters. Further studies will improve the performance of this ventilation system by optimizing its design parameters, including duct length, duct diameters, and buried depth. Other ventilation options, such as natural ventilation and exhaust ventilation, will be simulated and compared from more comprehensive aspects in the future.

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