

PAPER • OPEN ACCESS

## Need for Automatic Bypass Control to Improve the Energy Efficiency of a Building Through the Cooperation of a Horizontal Ground Heat Exchanger with a Ventilation Unit During Transitional Seasons: A Case Study

To cite this article: Anna Romanska-Zapala *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 092076

View the [article online](#) for updates and enhancements.



**IOP | ebooks™**

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

# Need for Automatic Bypass Control to Improve the Energy Efficiency of a Building Through the Cooperation of a Horizontal Ground Heat Exchanger with a Ventilation Unit During Transitional Seasons: A Case Study

Anna Romanska-Zapala <sup>1</sup>, Marcin Furtak <sup>1</sup>, Malgorzata Fedorczyk-Cisak <sup>1</sup>,  
Miroslaw Dechnik <sup>2</sup>

<sup>1</sup> Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland

<sup>2</sup> AGH University of Science and Technology, Mickiewicza 30, 30-059 Kraków, Poland

a.romanska@pk.edu.pl

**Abstract.** One of the ways to improve the energy balance of buildings is through the use of local, renewable energy sources, for example, ground air heat exchanger. This article continues the study on improving energy efficiency of an EAHX working in cooperation with a ventilation unit. In the previously reported study (Romańska-Zapala et al., 2017), performed during the summer of 2016, it was found that in the summer, the continuous operation of these exchangers is not optimal. Furthermore, there is a need for dynamic control of the ventilation unit's fresh air source. This is due to changes in the exchanger's operating status between heating and cooling, as a result of external temperature fluctuations. This article presents the results of *in situ* measurements of the horizontal, tubular EAHX which supports maintaining the desired temperature in a building by preheating or precooling the inlet air of the cooperating ventilation unit during transitional seasons of the climatic conditions of southern Poland. In particular, this article provides details on the experimental verification of the 2017 thesis regarding the ineffective work of an EAHX during transitional seasons. The influence of the exchanger on changes in the ventilation unit's inlet air temperature is presented. Numerous, unfavorable changes were registered in the state of the exchanger's work, either heating or cooling the flowing air, depending on the relation of outside air temperature to the achieved output air temperature. This indicated that the work of the exchanger was ineffective for buildings. The key to optimal, energy efficient EAHX – ventilation unit system operation during transitional seasons is the dynamic selection of a fresh air source depending on external conditions and the required output air temperature of the ventilation unit (air supplied to rooms), accounting for the increase of electric energy consumption for the fan drive during EAHX operation.

## 1. Introduction

Buildings are one of the largest energy consumers in the world. It is estimated that 30-40% of the total world energy production is used in buildings [1]. One of the ways to improve the energy balance of buildings is through the use of local, renewable energy sources. An example of such a source is a ground air heat exchanger, also referred to as an earth-air heat exchanger (EAHX EAHE, ETAHE, ATEHE) [2-6]. The idea of the exchanger's work is based on the physical phenomenon of heating or cooling the air flowing through a buried pipe, depending on the relationship of the ambient air and the



ground temperatures. While the air temperature is characterized by a relatively high variability, the ground temperature (at a depth of a few meters below ground level) is approximately constant throughout the year [7]. This idea has been known since ancient Greece and Persia [2, 3, 8]. Currently, the exchangers are used in mechanical ventilation systems in various types of buildings located in different regions of the world [2, 3]. As a result, it is possible to reduce the energy demand for the heating or cooling of a building interior by pre-conditioning the inlet air of a ventilation unit [5].

## 2. Methodology

A literature review shows a number of studies of ground heat exchangers used in a building's ventilation system. These studies are based mainly on simulation calculations [3, 9]. For example, the influence of the interaction between the heat exchanger and its surroundings on the energy efficiency of an EAHX is discussed in [5]. Study [10] evaluates the exchanger's efficiency in the summer and winter in a Mediterranean climate, while [7] discusses the cooling efficiency of an exchanger in arid climates. In turn, a new simulation method was shown in [11]. Several studies [4, 5, 6] discuss the advantages and disadvantages of ground heat exchangers, including the negative effect associated with an incorrect selection. Field evaluations are less popular methods for assessing EAHXs. Study [12] describes the performance of an EAHX in laboratory conditions, using a simulator. Article [13] evaluates the one-year experience from three ground heat exchangers in an office building in Germany, while [14] evaluates the same for Bangladesh. Several studies show a field evaluation of an EAHX in Polish climatic conditions, during the winter [15, 16], summer [17] or both [18]. Furthermore, [18] compares the performance of two heat exchangers, one of which is located under the building and the other outside of the building. In summary, it can be concluded that a ground heat exchanger is characterized by a large potential for energy saving, through pre-conditioning of air used to ventilate a building. In the previously reported study [17] of this article's authors, it was found that, in the summer, the continuous operation of an EAHX is not optimal. Therefore, to ensure optimal cooperation of an EAHX with a ventilation unit, there exists a need for dynamic control of the ventilation unit's fresh air source. This is due to changes in the exchanger's operating status between heating and cooling, as a result of the external temperature fluctuations. Furthermore, the previous paper's thesis stated that this relationship is not only appropriate on an annual basis for the transitional seasons (spring and autumn), but also on individual days during the potentially most favorable seasons of the EAHX's work (summer and winter).

This article expands upon a previous study [17] on the possibilities of improving energy efficiency of a horizontal earth-air heat exchanger working in cooperation with a ventilation unit, performed during the summer of 2016. This article presents the results of *in situ* measurements of the horizontal, tubular ground air heat exchanger which supports maintaining the desired temperature in a building by preheating or precooling the inlet air of the cooperating ventilation unit during transitional seasons of climatic conditions in southern Poland. In particular, this article provides details on the experimental verification of the 2017 thesis regarding the ineffective work of an EAHX during transitional seasons. The experimental setup consists of a ventilation unit (intake – exhaust) connected to three independent fresh air sources, which is a part of the ventilation system of the Malopolska Laboratory of Energy Efficient Building (MLBE) at the Cracow University of Technology. Fresh air can be delivered to the air handling unit either from the direct external air wall intake (EAHX bypass) or from two air intakes, located outside of the building, that are integrated with two separate ground heat exchangers' pipes (see figure 1). One of these ground heat exchangers is placed under the building, while the other is placed outside of the building. Both exchangers are made of 200 mm diameter PVC pipe with 59 or 60 m length, located at a depth of 1.5 to 2.5 m, with a 2% slope. The selection of the source of fresh air is performed using valves with actuators. The air sources' inlets are on the north side of the building. The ventilation unit is equipped with a rotary recuperator (efficiency of 80%), water heater and cooler, with nominal power of 3,25 kW and 4,22 kW, respectively. The ventilation unit can deliver 1850 m<sup>3</sup>/h and is equipped with its own built automation controller connected with the integrated control system. The exhaust is channelled through the roof exhaust [17]. The measuring system is composed of

temperature sensors (with accuracy of  $\pm 0.3^\circ\text{C}$  over the range  $-25^\circ\text{C}$  to  $0^\circ\text{C}$  and  $\pm 0.1^\circ\text{C}$  over the range  $0^\circ\text{C}$  to  $40^\circ\text{C}$ ) at the air inlets and outlets of both EAHXs' channels, air flow meters, and a weather station that senses the local weather conditions. Supervision of ventilation system operation and recording of measurement data were carried out using the integrated MLBE building automation and control system (BACS). The experimental set-up enables the evaluation of the interaction between a ground heat exchanger and a mechanical ventilation system. The *in-situ* measurements were carried out during the spring of 2017 and the autumn of 2016 and 2017. Measurement data was collected every 5 min. Incorrect temperature readings registered during shutdowns and restarts of the ventilation unit or BACS system controllers, as well as during system reconfiguration works were removed during the data processing.

During the experiment, two types of horizontal EAHXs' were used, differing in the position of the exchanger relative to the building. Both types of exchangers show similar performance, but display slightly different characteristics throughout the year [18]. For the purpose of this study, both independent EAHXs were included as a common system preparing the air for the ventilation unit. Because the amount of air flowing through each exchanger was the same ( $400\text{ m}^3/\text{h}$ ), the average temperature at the exit of both heat exchangers was determined in accordance with formula (1):

$$T_{EAHXoutlet} = \frac{T_{1out} + T_{2out}}{2} \quad (1)$$

with:  $T_{1out}$  – outlet air temperature of the EAHX placed under the building,  $T_{2out}$  – outlet air temperature of the EAHX placed outside of the building.

This temperature is the effect of the connected EAHXs operation from the ventilation unit's point of view. Therefore, the heat exchangers system in the further part of this study will be referred to as a single exchanger. The reference outdoor air temperature was calculated according to formula (2):

$$T_{EAHXinlet} = \frac{T_{1in} + T_{2in}}{2} \quad (2)$$

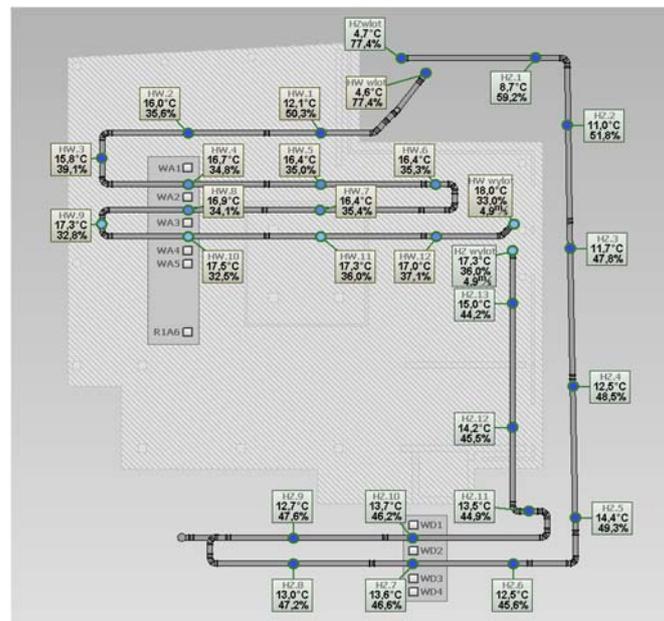
with:  $T_{1in}$  – inlet air temperature of the EAHX placed under the building,  $T_{2in}$  – inlet air temperature of the EAHX placed outside of the building.

The temperature performance of the exchanger expressed as the temperature difference at the inlet and outlet of the exchanger was determined using the formula (3):

$$\Delta T_{EAHX} = T_{EAHXoutlet} - T_{EAHXinlet} \quad (3)$$

### 3. Results and discussion

The influence of the exchanger on changes in the ventilation unit's inlet air temperature is presented in figures 2 (spring) and 3 – 4 (autumn). These figures allow one to consider two cases of the ventilation system operation: using the EAHX and not using the exchanger (using external air intake on the wall). In the first case, the air handling unit inlet air temperature is the same as the outlet EAHX air temperature. In the second case, the air handling unit inlet air temperature is the same as the temperature of the outdoor air. Air at the same temperature would be collected by the air intake, in the case of the ventilation system, without any EAHX. During the experiment the EAHX exit temperature was not recorded continuously, but due to its relative stability, its general trend is clearly visible.



**Figure 1.** Schematic layout of two horizontal EAHXs' channels; lighter gray indicates the area of building; the blue dots indicate the sensors of the parameters of air flowing through the channels.

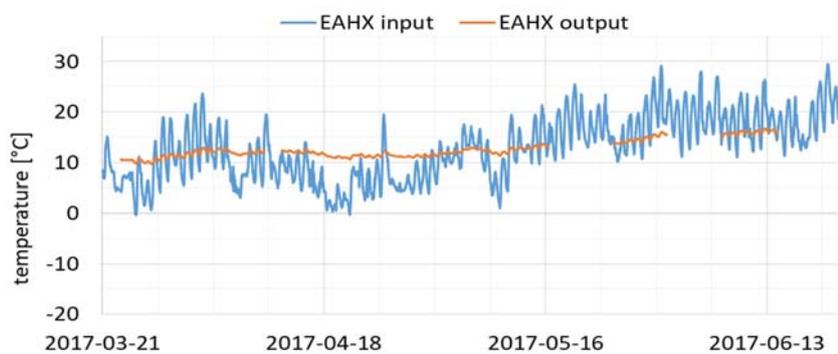
Figures 2 – 4 illustrate how the exchanger's work changes the ventilation unit's inlet air temperature, during transitional seasons. If the air temperature at the EAHX outlet is lower than the air temperature at its inlet (the  $\Delta T_{\text{EAHX}}$  sign is negative), it means that the air is cooled by the exchanger. However, if the temperature at the outlet of the EAHX is higher than the air temperature at its inlet (the  $\Delta T_{\text{EAHX}}$  sign is positive), it means that the exchanger heats the outside air. One may observe that the EAHX stabilizes the air temperature upon entry to the ventilation unit, in comparison to the outdoor temperature. The temperature obtained at the outlet of the EAHX changes throughout the year. During the spring, this temperature steadily increased from about 10°C to 16°C, while in the autumn this temperature steadily decreased from about 17°C to 10°C. The registered winter minimum temperature was around 6°C, while the summer maximum was around 19°C.

Considering the possibility of energy efficient operation of the EAHX – ventilation unit system during transitional seasons, it is necessary to analyze the relations of temperatures at the inlet and outlet of the EAHX that were recorded during the experiment. On the basis of the presented graphs (see figures 2 – 4), one may notice that the transitional seasons are characterized by a similar average daily temperature of the outdoor air to the outlet EAHX's temperature. This relationship is particularly strong in the spring. Comparing the seasonal overview graphs (figures 2 – 6), the spring and summer were characterized by higher daily fluctuations in outside temperature than the autumn and winter. For example, in the spring, in the morning of January 7, 2017, the EAHX heated the outside air by ca. 8°C. On the same day at noon, the EAHX cooled it by ca. 7°C, while the next day at noon it heated it again by ca. 5.5°C. During these days, the EAHX constantly supplied the air handling unit air with, a stable ( $\pm$  ca. 0.5°C), temperature of ca. 11.5°C. figures 2 – 4 show numerous changes in the inequality relation between air temperatures at the inlet and outlet of the EAHX during the transitional seasons. This means that numerous, unfavourable changes were registered in the state of the exchanger's work, either heating or cooling the flowing air, depending on the relation of outside air temperature to the achieved EAHX's outlet air temperature. The transfers of the exchanger between heating and cooling states were many times more frequent in the spring than in autumn. These changes occur most often in the spring and summer. Examples of a variable EAHX's operation state are shown in figures 7 – 8 (the spring) and 9 – 10 (the autumn). In transitional seasons, the unstable EAHX's operation mode, during its continuous use, leads to temporary, unnecessary increases in a building's energy consumption due

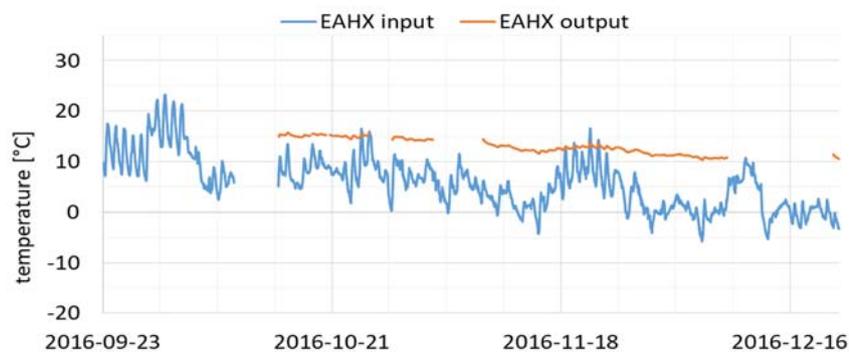
to the unfavorable ventilation unit's inlet air temperature. This means that the continuous operation of an EAHX is ineffective in regards to the building's energy efficiency. Thus, this study validates the previous paper's [17] thesis regarding the possibility of an EAHX's poor performance subject to continuous operation during transitional seasons. The simplest, but least effective, solution to eliminate the adverse impact of the EAHX on a building's energy consumption is the seasonal bypassing of an exchanger (switching off the exchanger during transitional seasons and using it only in the summer and winter).

The evaluation of the EAHX energy efficiency, in transitional seasons, is more complex than in the winter or summer, during which the building's needs for heating and cooling are obvious. In the winter, it is necessary to heat the building, and in the summer, it is necessary to cool the building. However, during transitional seasons a building's needs for heating and cooling are not clearly defined and can change over time. These needs result from the thermal dynamics of buildings as well as internal and external factors. One may notice that, in conditions of high solar irradiance and low outside temperature, a building with large glazed areas may require cooling, while a building with full walls may require heating. Therefore, the assessment of exchanger work during transitional seasons can only be made by accounting for the building's needs. In an EAHX – air handling unit system, the current needs of a building (desired temperature in a building) should be expressed by means of a set temperature at the outlet of the ventilation unit (supply air to the rooms of the building). Thus, in transitional seasons, the key to assessing and optimizing the energy efficiency of an EAHX – ventilation unit system is the relation between the temperatures:

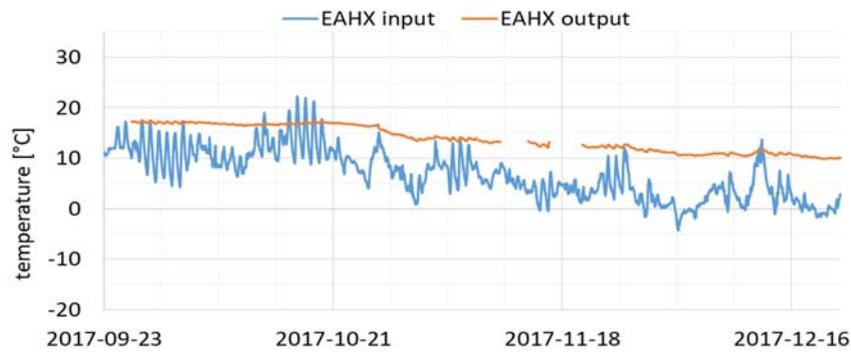
- outdoor air temperature,
- air temperature at an EAHX outlet,
- set temperature of air at a ventilation unit outlet.



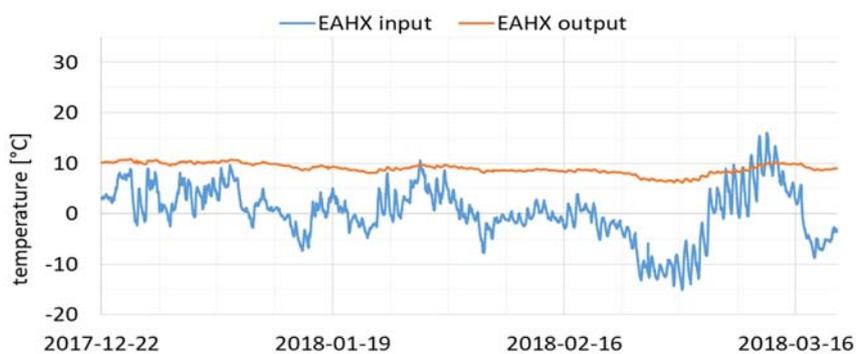
**Figure 2.** Spring 2017 overview graph of the EAHX's inlet and outlet air temperatures.



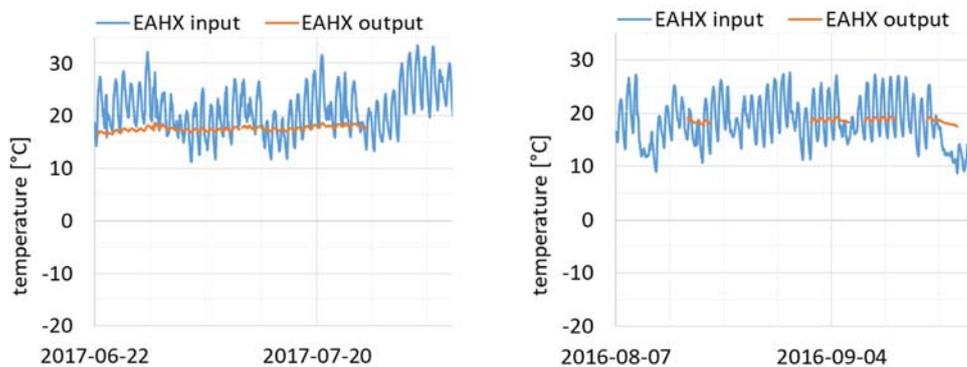
**Figure 3.** Autumn 2016 overview graph of the EAHX's inlet and outlet air temperatures.



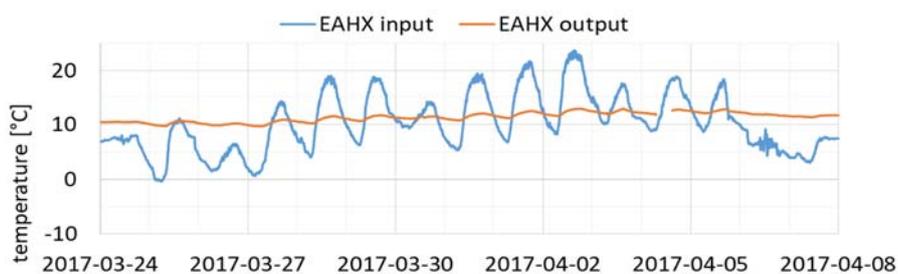
**Figure 4.** Autumn 2017 overview graph of the EAHX’s inlet and outlet air temperatures.



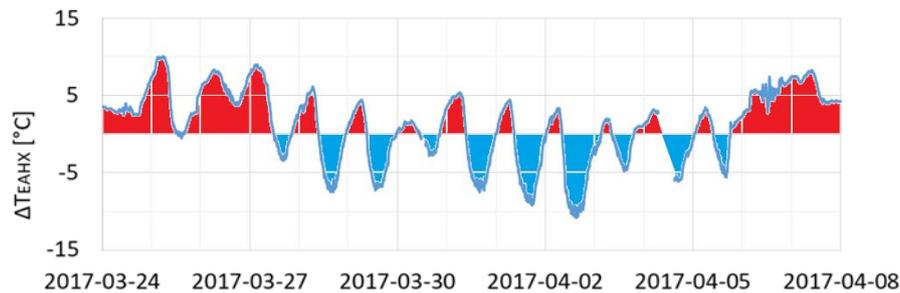
**Figure 5.** Winter 2017/2018 overview graph of the EAHX’s inlet and outlet air temperatures.



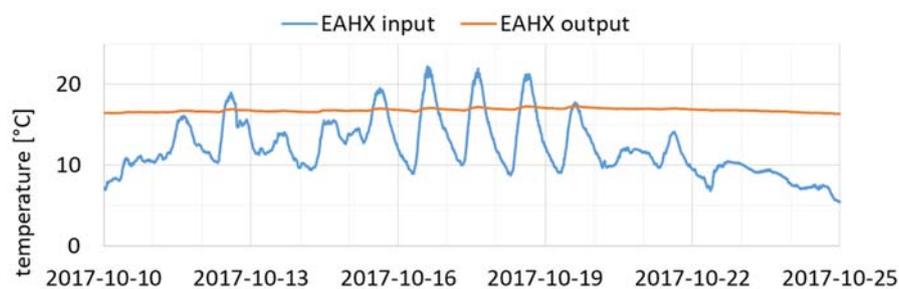
**Figure 6.** Overview graphs of the EAHX’s inlet and outlet air temperatures. The first half of the summer of 2017 (on the left) and the second half of the summer of 2016 (on the right).



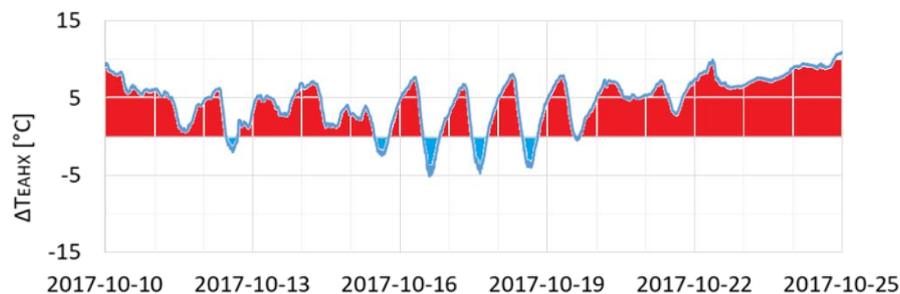
**Figure 7.** A detailed daily graph of the EAHX’s inlet and outlet air temperatures, during an example period of the spring of 2017.



**Figure 8.** A detailed daily graph of the EAHX inlet and outlet temperature difference, during an example period of the spring of 2017; red – air heating effect; blue – air cooling effect.



**Figure 9.** A detailed daily graph of the EAHX's inlet and outlet air temperatures, during an example period of the autumn of 2017.



**Figure 10.** A detailed daily graph of the EAHX inlet and outlet temperature difference, during an example period of the autumn of 2017; red – air heating effect; blue – air cooling effect.

The control system's goal is to support maintaining the desired temperature in a building by preheating or precooling the inlet air of the cooperating air handling unit. For this purpose, the EAHX – air handling unit system should be equipped with an independent fresh air source (bypass), valves positioned by actuators, and a set of temperature sensors. The temperature of the air supplied to a building by a ventilation unit can be set manually by an operator or automatically selected, depending on the needs of a building (variable set point). A control system should constantly monitor the temperature parameters of an exchanger's operation and compare them with the set temperature, to ensure optimal operation of an EAHX – ventilation unit system. Let's assume that the set temperature is marked as  $T_{\text{setpoint}}$  and outlet and inlet air temperature of an EAHX markings are  $T_{\text{EAHXoutlet}}$  and  $T_{\text{EAHXinlet}}$ , respectively. Considering the inequality relation between the instantaneous values of these air temperatures, ignoring the possibility of equal temperatures, there are 6 possible cases (permutation without repeating the 3-element set). These cases are shown in Table 1. It is worth mentioning that the EAHX has a higher air flow resistance than a direct external air intake; therefore, its operation leads to an increase in electric power consumption by a ventilation unit's fan drives.

This additional electric load to force air flow through EAHX, can be expressed using formula (4):

$$\Delta P_{el} = P_{elEAHX} - P_{el} \quad (4)$$

with:  $P_{elEAHX}$  – the electric power of the fan drives when using EAHX,  $P_{el}$  – the electric power of the fan drives when using a direct external air intake (bypass).

**Table 1.** Possible operating conditions of the fresh air source control system depending on the set air temperature at the outlet of the ventilation unit.

	Temperature relation	The preferred source of the ventilation unit's inlet air	Restrictions due to $\Delta P_{el}$ if:
<b>1</b>	$T_{setpoint} > T_{EAHXinlet} > T_{EAHXoutlet}$	bypass <sup>a</sup>	$T_{EAHXinlet} \approx T_{EAHXoutlet}$
<b>2</b>	$T_{setpoint} > T_{EAHXoutlet} > T_{EAHXinlet}$	EAHX	$T_{setpoint} \approx T_{EAHXoutlet}$
<b>3</b>	$T_{setpoint} < T_{EAHXinlet} < T_{EAHXoutlet}$	bypass <sup>a</sup>	$T_{EAHXinlet} \approx T_{EAHXoutlet}$
<b>4</b>	$T_{setpoint} < T_{EAHXoutlet} < T_{EAHXinlet}$	EAHX	$T_{setpoint} \approx T_{EAHXoutlet}$
<b>5</b>	$T_{EAHXinlet} > T_{setpoint} > T_{EAHXoutlet}$	bypass <sup>a</sup> and EAHX	$T_{setpoint} \approx T_{EAHXoutlet}$
<b>6</b>	$T_{EAHXoutlet} > T_{setpoint} > T_{EAHXinlet}$	bypass <sup>a</sup> and EAHX	$T_{setpoint} \approx T_{EAHXoutlet}$

<sup>a</sup> bypass = direct external air intake.

The first two cases listed in Table 1 relate to the situation when an EAHX and external air intake are able to provide air with excessively low temperatures, in relation to the set temperature at the outlet of a ventilation unit. In this situation, a control system should switch the valves to choose a source that supplies air with a higher temperature compared to the other, to ensure the highest available inlet air temperature for an air handling unit. For example, assuming that the outdoor air temperature is higher than an EAHX's outlet air temperature, an exchanger should be turned off by switching the valves, and a bypass (external air intake) should be used to directly collect outdoor air. The next two listed cases (3 and 4) concern the situation when both air sources can provide air with too high temperature, in relation to the preset temperature at the outlet of a ventilation unit. Then, the valves should be switched to draw air from a lower temperature source. The last two cases relate to the situation when the set temperature at the outlet of the ventilation unit is lower than the temperature of one of the sources and higher than the other one. In this situation, a control system should use both air sources and, by adjusting the valve opening, aim to obtain the set temperature. A control algorithm should be constantly oriented towards achieving maximum possible energy efficiency. Thus, when the EAHX is even partially open and the air temperature at its outlet is close to the set temperature, the restrictions resulting from electrical power losses ( $\Delta P_{el}$ ) should be taken into account to additionally reduce the unnecessary load of electric fan drives. For the same reason, if the air temperatures of both sources are similar, the control algorithm should select direct external air intake (with lower airflow resistance). Thus, to optimize the interaction of an EAHX with an air handling unit, in addition to outdoor air temperature, air temperature at an EAHX outlet and set temperature of air at a ventilation unit outlet, a control algorithm should include:

- additional electrical load of fan drives to force air flow through EAHX ( $\Delta P_{el}$ ),
- building's exhaust air temperature and the necessity of a ventilation unit's rotary heat exchanger (recuperator) operation,
- additional energy to heat or cool the ventilation air,
- the necessary air flow.

In summary, during transitional seasons (especially in the spring) the automatic control of a ventilation unit's fresh air source can have a significant impact on improving the energy efficiency of a horizontal earth-air heat exchanger working in cooperation with a ventilation unit.

#### 4. Conclusions

Currently, control systems and local, renewable energy sources are increasingly used in buildings to improve their energy balance. In this paper, the actual implementation of a horizontal, tubular ground air heat exchanger was investigated. The exchanger supports maintaining the desired temperature in a building by preheating or precooling the inlet air of the cooperating ventilation unit, during the transitional seasons (spring and autumn) of climatic conditions in southern Poland.

The results show that transitional seasons are characterized by a high potential, compared to other seasons, for effective operation of the automatic control system for the selection of a fresh air source (EAHX or bypass). This is due to the variability of the effect of the exchanger's work between heating and cooling of the supply air, as well as the varying needs of the building for cooling or heating, depending on external weather conditions and heat gains. The presented analysis shows that in transitional seasons, when considering a building's energy efficiency, the continuous use of EAHX is not optimal. Thus, this study validates the previous paper's [17] thesis. The key to optimal, energy-efficient system (EAHX – ventilation unit) operation during these seasons is the dynamic selection of a fresh air source (EAHX or bypass) depending on the external conditions and the required output air temperature of the ventilation unit (air supplied to rooms), accounting for the increase of electric energy consumption for the fan drive during EAHX operation. As a result, the system can reduce the energy demand for the heating or cooling of a building interior, by supplying air at a suitable temperature, before using other methods for its conditioning (recuperation or conventional heating and cooling). Furthermore, the results indicate the importance of the interaction and integration of devices in a low energy building. Future research by the authors will focus on the development of universally applicable control algorithms of an EAHX – ventilation unit system.

#### References

- [1] M. Dechnik, S. Moskwa, „Smart House – intelligent building – the idea of the future” (Smart House - inteligentny budynek - idea przyszłości), *Przegląd Elektrotechniczny*, vol. 9, pp. 1–10, 2017.
- [2] G. Gan, “Dynamic interactions between the ground heat exchanger and environments in earth–air tunnel ventilation of buildings”, *Energy and Buildings*, vol. 85, pp. 12–22, 2014.
- [3] C. Peretti, A. Zarrella, M. De Carli, R. Zecchin, “The design and environmental evaluation of earth-to-air heat exchangers (EAHE). A literature review”, *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 107–116, 2013.
- [4] Ż. Mirosław, “Assessment of Potential Applicability of Ground Air Heat Exchanger (GAHE) in Białystok” (Ocena potencjalnych możliwości zastosowania GPWC na terenie Politechniki Białostockiej), *Ciepłownictwo, ogrzewnictwo, wentylacja*, vol. 8/2012, pp. 323–346.
- [5] M. Szymański, J. Wojtkowiak, “Analysis of Year-Long Operation of RGWC Ground Pipe Heat Exchanger in Mechanical Ventilation System of Apartment Building” (Analiza całorocznej pracy rurowego gruntowego wymiennika ciepła RGWC w układzie wentylacji mechanicznej budynku mieszkalnego), *Ciepłownictwo, ogrzewnictwo, wentylacja*, vol. 11/2008, pp. 36–38.
- [6] M. Szymański, J. Wojtkowiak, “Simplified method of dimensioning and cost-effectiveness evaluation of earth-to-air heat exchanger in building ventilation system” (Uproszczona metoda wymiarowania i oceny opłacalności gruntowego wymiennika ciepła w układzie wentylacji budynku), *Ciepłownictwo, ogrzewnictwo, wentylacja*, vol. 7-8, pp. 55–63, 2007.
- [7] D. Belatrache, S. Bentouba, M. Bourouis, Numerical analysis of earth air heat exchangers at operating conditions in arid climates, *International Journal of Hydrogen Energy*, vol. 42, iss. 13, pp. 8898-8904, 2017.
- [8] C. Ionescu, T. Baracu, G-Elena Vlad, H. Necula, A. Badea, “The historical evolution of the energy efficient buildings”, *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 243–253, 2015.

- [9] M. Kaushal, “Geothermal cooling/heating using ground heat exchanger for various experimental and analytical studies: Comprehensive review”, *Energy and Buildings*, vol. 139, pp. 634–652, 2017.
- [10] P. M. Congedo, C. Lorusso, M. Grazia De Giorgi, R. Marti, D. D’Agostino, “Horizontal Air-Ground Heat Exchanger Performance and Humidity Simulation by Computational Fluid Dynamic Analysis”, *Energies*, vol. 9, iss. 11, 2016.
- [11] G. Chiesa, “Climate-potential of earth-to-air heat exchangers”, *Energy Procedia*, vol. 122, pp. 517–522, 2017.
- [12] T. M. Yusof, H. Ibrahim, W. H. Azmi, M. R. M. Rejab, “Thermal analysis of earth-to-air heat exchanger using laboratory simulator”, *Applied Thermal Engineering*, vol. 134, pp. 130–140, 2018.
- [13] J. Pfafferoth, “Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency”, *Energy and Buildings*, vol. 35, iss. 10, pp. 971–983, 2003.
- [14] Md. Shazib Uddin, A. Raju, R. Masudur, “Performance evaluation and life cycle analysis of earth to air heat exchanger in a developing country”, *Energy and Buildings*, vol. 128, pp. 254–261, 2016.
- [15] A. Skotnicka Siepsiak, M. Wesółowski, “Efficiency of Tubular Ground-Air Heat Exchanger in Winter Season in the Light of Laboratory Empirical Measurement Data” (Wydajność rurowego gruntowego powietrznego wymiennika ciepła w świetle laboratoryjnych danych pomiarowych w okresie zimowym), *Ciepłownictwo, ogrzewnictwo, wentylacja*, vol. 2, pp. 71–75, 2016.
- [16] A. Flaga-Maryńczyk, J. Schnotale, J. Radon, K. Was, “Experimental measurements and CFD simulation of a ground source heat exchanger operating at a cold climate for a passive house ventilation system”, *Energy and Buildings*, vol. 68, Part A, pp. 562–570, 2014.
- [17] A. Romańska-Zapała, M. Furtak, M. Dechnik, “Cooperation of Horizontal Ground Heat Exchanger with the Ventilation Unit During Summer – Case Study”, *WMCAUS 2017, IOP Conference Series: Materials Science and Engineering*, vol. 245, 2017.
- [18] A. Romańska-Zapała, M. Bomberg, M. Fedorczak-Cisak, M. Furtak, D. Yarbrough, M. Dechnik, “Buildings with environmental quality management (EQM) Part 2.: Integration of hydronic heating/cooling with thermal mass”, *Journal of Building Physics*, vol. 41(5), pp. 397–417, 2018.