

PAPER • OPEN ACCESS

Cooperation of a Horizontal Ground Heat Exchanger with a Ventilation Unit During Winter: A Case Study on Improving Building Energy Efficiency

To cite this article: Anna Romanska-Zapala *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 092075

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.

Cooperation of a Horizontal Ground Heat Exchanger with a Ventilation Unit During Winter: A Case Study on Improving Building Energy Efficiency

**Anna Romanska-Zapala¹, Marcin Furtak¹, Malgorzata Fedorczyk-Cisak¹,
Mirosław Dechnik²**

¹ Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland

² AGH University of Science and Technology, Mickiewicza 30, 30-059 Kraków, Poland

a.romanska@pk.edu.pl

Abstract. Renewable energy sources have a significant impact on improving a building's energy balance. These sources are increasingly used in modern construction. One such source is a ground air heat exchanger (earth-air heat exchanger – EAHX), which is used in a building's mechanical ventilation system. This solution allows for the initial preparation of inlet air in a ventilation unit prior to the exhaust air energy recovery process (recuperation). As a result, the solution reduces the energy demand for the heating or cooling of rooms. This article expands upon a previous study on the possibilities of improving energy efficiency of a horizontal earth-air heat exchanger (EAHX) working in cooperation with a ventilation unit. This study adds to the knowledge gained in the previous study (Romańska-Zapała et al., 2017) performed during the summer of 2016. This previous study found that, in the summer, the continuous operation of these exchangers is not optimal; therefore, 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. The thesis statement of this previous paper emphasized 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 exchanger work (summer and winter). This article presents the results of *in situ* measurements of the horizontal, tubular ground air heat exchanger which supports building heating by preheating the inlet air of the cooperating ventilation unit in the winter season, in southern Polish climatic conditions. In particular, this article provides details on the experimental verification of the previous paper's thesis regarding the possibility of sub-optimal performance of an EAHX exchanger subject to continuous operation during the winter season. The experiment in this paper was performed using a ventilation unit (intake – exhaust) connected to three independent fresh air sources: a direct external air intake located on the wall, and two air intakes located outside of the building that directs air into the pipes of two earth-air heat exchangers. This article illustrates how the exchanger's work changes the ventilation unit's inlet air temperature. For a majority of the experiment, the exchanger – ventilation unit system was working optimally. Therefore, the system did not require intervention of the control system. However, due to several temporary increases in outdoor temperature, the occasional cooling state operation of the EAHX exchanger was also recorded. Even before the occurrence of these undesirable states, an exchanger should be switched off and a bypass should be used to directly collect external air and reduce the unnecessary load of electric fan drives. Considering the results of this study, it



can be concluded that in the winter, it is favorable to automatically control the selection of a ventilation unit's fresh air source depending on external conditions. However, in the winter, the energy effect of the control is comparatively lower than in the summer.

1. Introduction

Reducing energy consumption is the key challenge for construction today. It is estimated that, worldwide, 30 to 40% of total energy consumption is in buildings [1]. In the EU, buildings consume as much as 40% of the energy produced (of which 63% is for residential buildings), while transport consumes 32% and industry 25% [2, 3].

The use of renewable energy resources has a significant impact on improving a building's energy balance. Therefore, renewable energy sources are increasingly used in modern construction. One such source is a ground air heat exchanger (earth-air heat exchanger – EAHX, EAHE, ETAHE, ATEHE), which is used in a building's mechanical ventilation system [4, 5, 6, 7, 8]. The external air flows through the exchanger's underground pipe, warming in the winter and cooling in the summer. This physical phenomenon depends on the temperature difference between the ambient air and the soil (which is approximately constant throughout the year at a given depth below ground level) [9]. This solution allows for the initial preparation of inlet air of an air handling unit, prior to the exhaust air energy recovery process (recuperation). As a result, the solution reduces the energy demand for heating or cooling rooms [7]. The concept of ground pre-heating was used in ancient Greece and Persia [4, 5, 10]. In modern times, the first application of pre-heating was in glasshouses. In more recent years, these systems have been used in many types of buildings located in different climatic zones [4, 5].

2. Methodology

Existing literature shows a number of studies of ground heat exchangers used in ventilation systems in buildings. Mostly these cases involve simulation calculations [5, 11]. For example, study [4] addresses the energy efficiency of EAHX where the interaction between the heat exchanger, soil, and ambient air is discussed. Another study [12] shows the application of CFD simulation to calculate the efficiency of EAHX in the summer and winter in a Mediterranean climate, while [9] discuss the EAHX energy efficiency in arid climates in the summer. The potential, cost, benefit, and drawbacks of ground heat exchangers, as well as the negative consequences of their incorrect selection were presented in [6, 7, 8]. In turn, [13] proposes a new simulation method to assess the energy potential of ground heat exchangers. Less popular methods are experimental evaluations. The performance of EAHX, using a laboratory simulator, was reported in [14]. Article [15] reports the one-year experience from 3 ground heat exchangers in an office building in Germany, while [16] reports the same for Bangladesh. Several studies show a field assessment of EAHX in Polish climatic conditions, during the winter [17, 18], summer [19], or both [20]. Moreover, [20] compares the performance of two heat exchangers, one of which is located under the building and the other outside of the building. The aforementioned reported cases permit us to draw the conclusion that ground heat exchangers are characterized by a large potential for energy saving, through the pre-conditioning of air used to ventilate a building.

The previous study [19] of this article's authors, 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 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 outdoor temperature fluctuations. Furthermore, the thesis statement of this previous paper emphasized 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 exchanger's work (summer and winter).

This article continues the study on improving energy efficiency of a horizontal earth-air heat exchanger working in cooperation with an air handling unit. This study adds to existing knowledge

gained in the previous study [19], 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 building heating by preheating the inlet air of the cooperating air handling unit in the winter season, in southern Polish climatic conditions. In particular, this article provides details on the experimental verification of the previous paper's thesis regarding the possibility of sub-optimal performance of an EAHX subject to continuous operation during the winter season.

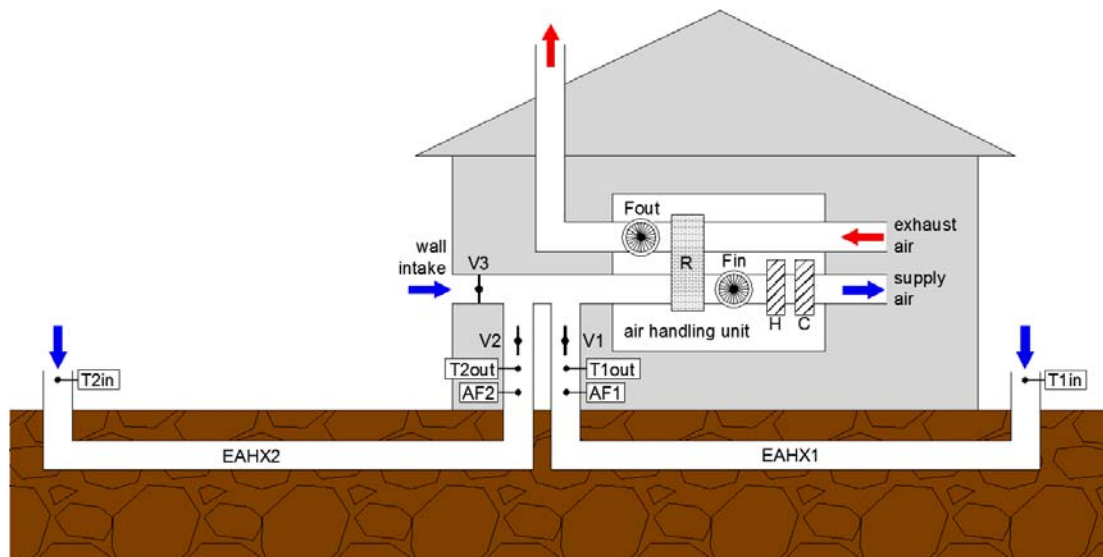


Figure 1. Scheme of the experimental set-up: horizontal ground heat exchangers' channels connected with the air handling unit (in the real system, the exchanger's inlets are next to each other). EAHX₁ – horizontal ground heat exchanger channel placed under the building; EAHX₂ – horizontal ground heat exchanger channel placed outside of the building; V₁, V₂, V₃ – air valves with actuators; T_{1in}, T_{2in} – inlet air temperature sensors; T_{1out}, T_{2out} – outlet air temperature sensors; AF₁, AF₂ – air flow meters; air handling unit's elements: Fin – supply fan, Fout – exhaust fan, R – recuperator, H – water heater, C – water cooler.

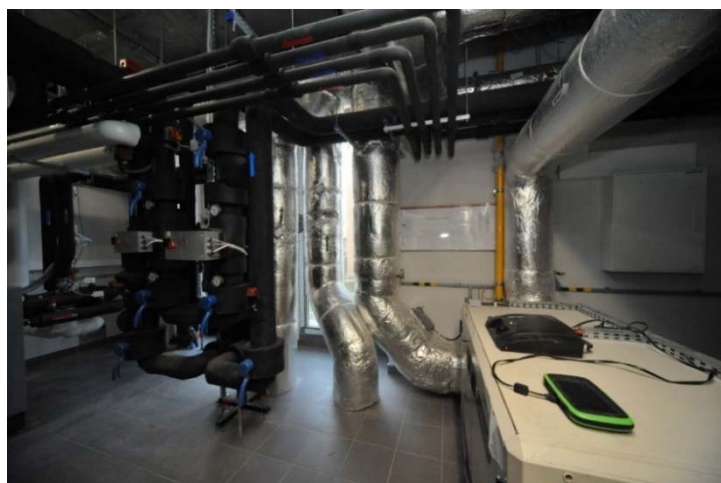


Figure 2. Mechanical room of the MLBE: ventilation unit and air channels covered with a shiny aluminium cladding; from the left: air wall intake (invisible, behind black water pipes), two ground heat exchangers' outlets passing through the floor, intake manifold, and exhaust).

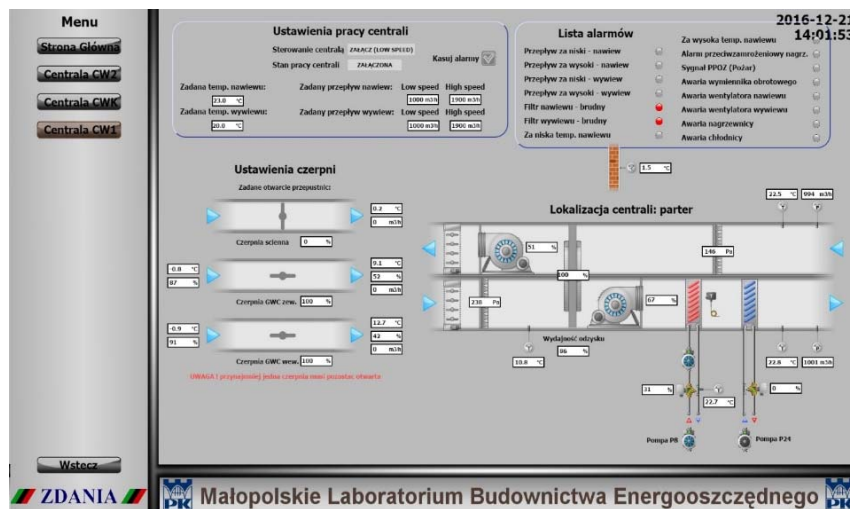


Figure 3. Operator panel of the integrated MLBE building automation and control system.

The experiment was performed using a part of the ventilation system of the Malopolska Laboratory of Energy Efficient Building (MLBE) at the Cracow University of Technology. The machine setup consists of a ventilation unit (intake – exhaust) connected to three independent fresh air sources: a direct external air intake located on the wall (EAHX bypass), and two air intakes located outside of the building that directs air into the pipes of two earth-air heat exchangers (see figures 1 and 2). All three air sources' inlets are on the north side of the building. One of these ground heat exchangers is located under the building and the other outside of the building. The heat 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 handling unit is located on the main floor and supports the ground, first, and second floor (without toilets and communication rooms) of the MLBE building. It is equipped with a rotary heat exchanger (heat or cold recovery from exhaust air with an efficiency of 80%), water heater and cooler, with nominal power of 3,25 kW and 4,22 kW, respectively. The air handling unit can deliver 1850 m³/h and is equipped with its own built automation controller connected with the integrated control system. The exhaust is channelled through the roof exhaust [19]. The measuring system includes temperature sensors (with accuracy of $\pm 0.3^{\circ}\text{C}$ over the range -25°C to 0°C and $\pm 0.1^{\circ}\text{C}$ over the range 0°C to 40°C) at the inlets and outlets of both exchangers, air flow meters, and a weather station that senses the local weather conditions. The integrated MLBE building automation and control system (BACS) is responsible for supervision of ventilation system operation, as well as acquiring and archiving of measurement data (see figure 3). The experimental set-up enables the assessment of the cooperation of a ground heat exchanger with an air handling unit for real conditions. The *in-situ* measurements were performed during the 2016/2017 and 2017/2018 winter seasons. 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 processing of the measurement data.

During the experiment, two solutions for horizontal ground heat exchangers were used, differing in the position of the exchanger relative to the building. Both types of exchangers show similar performance, but have slightly different characteristics throughout the year [20]. In the summer, the EAHX placed under the building has somewhat lower output temperatures than the one placed outside of the building, while in the winter this relation is reversed. 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 m³/h), the average temperature at the exit of both heat exchangers was determined in accordance with:

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

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 later part of this study will be referred to as a single exchanger. The reference outdoor air temperature was calculated in accordance with:

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

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.

This temperature can be considered as the temperature of air supplied directly to the ventilation unit when the heat exchangers are switched off and external air is taken from the wall intake. The temperature performance of the exchanger expressed as the temperature difference at the inlet and outlet of the exchanger was determined using the formula:

$$\Delta T_{EAHX} = T_{EAHXoutlet} - T_{EAHXinlet}$$

with: $T_{EAHXoutlet}$ – outlet air temperature of the EAHX, $T_{EAHXinlet}$ – inlet air temperature of the EAHX.

3. Results and discussion

Figures 4 and 5 show the air temperatures at the inlet (outdoor air) and outlet of the ground heat exchanger, during the winter. These figures allow one to consider two cases of system operation: using the EAHX and not using the exchanger (using external air intake on the wall). In the first case, the ventilation unit inlet air temperature is the same as the outlet EAHX air temperature. In the second case, the ventilation unit inlet air temperature is the same as the temperature of outdoor air. Air at the same temperature would be collected by the air intake, in the case of the ventilation system without any ground heat exchanger. Figures 4 and 5 illustrate how the exchanger's work changes the ventilation unit's inlet air temperature. The EAHX provides a stabilization of the air temperature upon entry to the ventilation unit, in comparison to the outdoor temperature. If the air temperature at the EAHX outlet is lower than the air temperature at its inlet (the ΔT_{EAHX} sign is negative), 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 ΔT_{EAHX} sign is positive), the exchanger heats the outside air. During the winter of 2016/2017, the exit temperature of the exchanger was not continuously recorded, but due to its relative stability, its general trend is clearly visible. It should be emphasized that the operation of an EAHX increases the electric power consumption of a ventilation unit's fan drives, because an additional amount of energy is needed to force the air through the exchanger channel, which has a higher air flow resistance than a direct external air intake. In the winter, it is necessary to heat the building. For a majority of the experiment, the EAHX supported the building's heating process and the exchanger – ventilation unit system was working optimally. Therefore, the system did not require intervention of the control system. The maximum temperature efficiency of the exchanger was registered in the morning of January 7, 2017, when the air temperature was raised by 26°C. However, due to several temporary increases in outdoor temperature, the occasional cooling state operation of the EAHX was also recorded. Changes in the inequality relation between air temperatures at the inlet and outlet of the EAHX are visible, especially in the second half of both winter seasons.

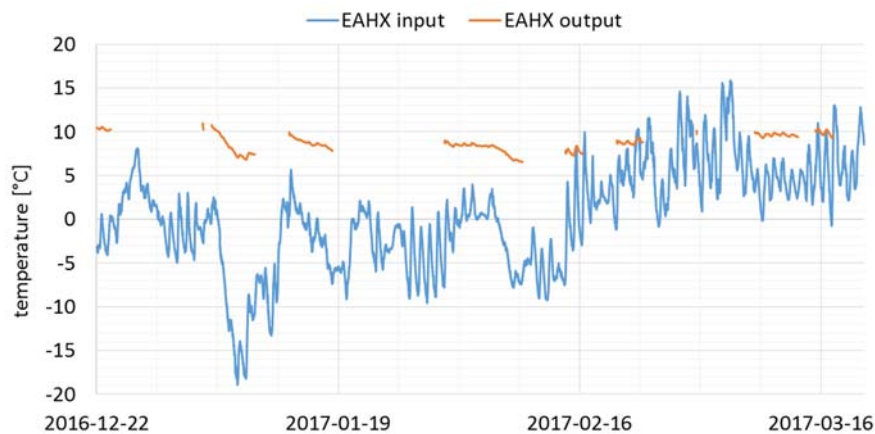


Figure 4. The winter of 2016/2017 overview graph of air temperatures upon entry and exit from the ground heat exchanger.

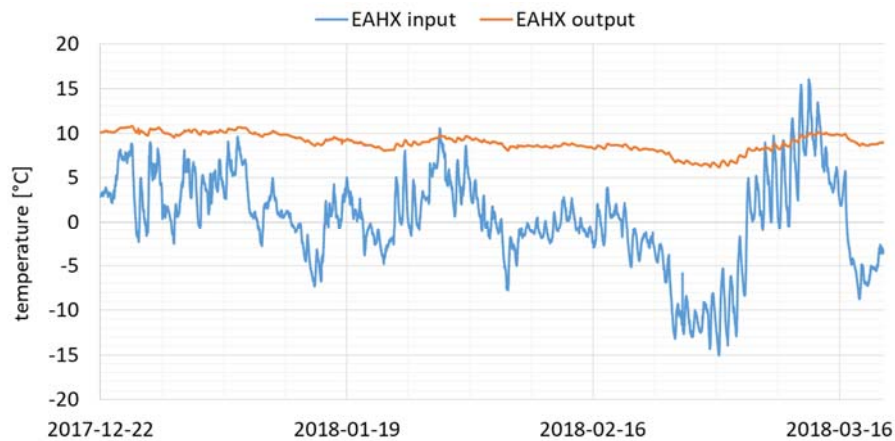


Figure 5. The winter of 2017/2018 overview graph of air temperatures upon entry and exit from the ground heat exchanger.

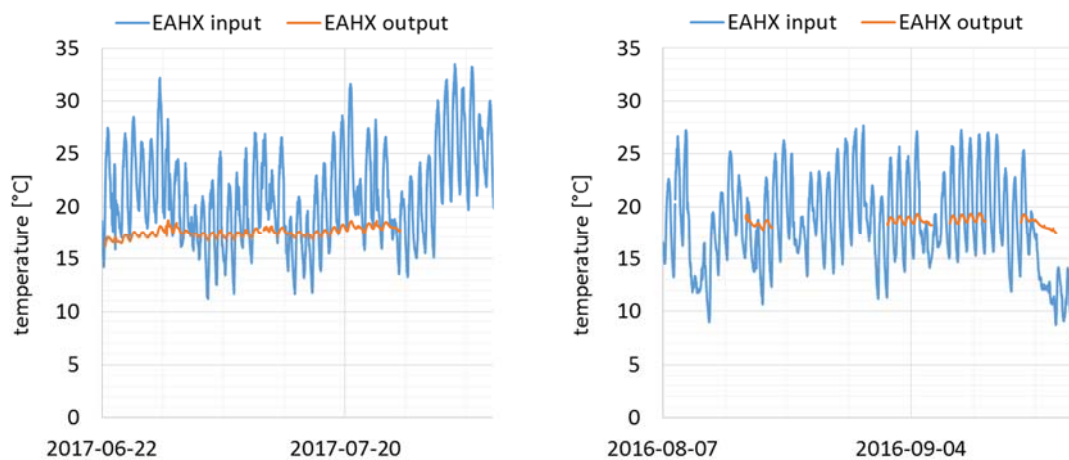


Figure 6. The first half of the summer of 2017 (on the left) and the second half of the summer of 2016 (on the right). Overview graphs of air temperatures upon entry and exit from the ground heat exchanger.

An example of an unfavorable cooling state operation of EAHX during winter is shown in figures 7 and 8. This state of the heat exchanger's work leads to an increase in energy consumption for the preparation of the desired building's supply air temperature. Thus, experimental verification confirmed the truth of the previous paper's [19] thesis regarding the possibility of sub-optimal performance of an EAHX subject to continuous operation during the winter season. An example of an unfavorable cooling state operation of EAHX during winter is shown in figures 7 and 8. This state of the heat exchanger's work leads to an increase in energy consumption for the preparation of the desired building's supply air temperature. Thus, experimental verification confirmed the truth of the previous paper's [19] thesis regarding the possibility of sub-optimal performance of an EAHX subject to continuous operation during the winter season. Compared to the summer (see figure 6), the winters (see figure 4 and 5) were characterized by lower daily fluctuations in the outside temperature, as well as, for a majority of the experiment, a significant higher absolute value of the temperature difference at the inlet and outlet of the exchanger ($|\Delta T_{\text{EAHX}}|$), while its favorable inequality relation ($T_{\text{EAHXoutlet}} > T_{\text{EAHXinlet}}$ during winter; $T_{\text{EAHXoutlet}} < T_{\text{EAHXinlet}}$ during summer). As a result, in the winter, unfavorable temperature relations at the outlet and inlet of the exchanger occur less frequently than in the summer, which results in rare transfers of an exchanger into an undesired cooling operation state.

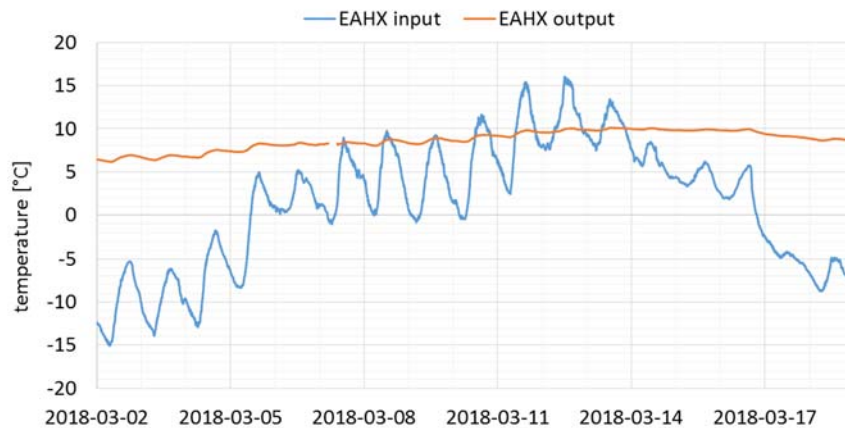


Figure 7. A detailed daily graph of air temperatures upon entry and exit from ground heat exchanger, during an example period of the second half of the winter of 2017/2018.

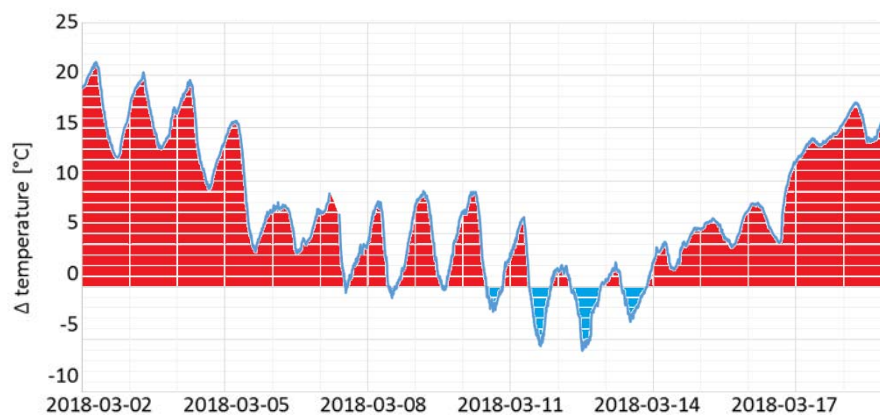


Figure 8. A detailed daily graph of the ground heat exchanger input and output temperature difference, during an example period of the second half of the winter of 2017/2018;
red – air heating effect; blue – air cooling effect.

In general, in the winter, there are more favorable conditions for the continuous operation of an EAHX, than in the summer. Therefore, this season is characterized by a lower potential to improve the energy efficiency of an EAHX - ventilation unit system, through adequate a fresh air source control, compared to the summer season. To ensure optimal operation of an EAHX – air handling unit system in the winter, the EAHX operation states in the cooling mode should be detected and eliminated by an automatic control system. 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.

A control algorithm, constantly monitoring the temperature parameters of an exchanger's operation, should be oriented towards achieving the maximum possible energy efficiency. Assuming that the outdoor temperature is higher than the temperature at an exchanger's outlet, to ensure the highest available inlet air temperature for an air handling unit, an exchanger should be turned off by switching the valves, and a bypass (external air intake) should be used to directly collect outdoor air. This intervention should be taken even before the occurrence of undesirable cooling states of an EAHX, to additionally reduce the unnecessary load of electric fan drives. As soon as the outside temperature drops again, the EAHX should return to normal operation by restoring the valves' position. In summary, as in the summer, in the winter the adequate automatic control the selection of a ventilation unit's fresh air source has an influence on improving energy efficiency of a horizontal earth-air heat exchanger working in cooperation with a ventilation unit, but the energy effect of the control is comparatively lower than in the summer. One can notice that in the winter, similar to in the summer, to optimize the interaction of a ground heat exchanger with an air handling unit, the control algorithm should include:

- outdoor air temperature,
- air temperature upon exit from ground heat exchanger,
- air temperature upon exit from ventilation unit (set temperature of the air supplied to a building),
- additional electrical load of fan drives to force air flow through EAHX.

4. Conclusions

The increasing requirements of energy efficiency forces us to use alternative energy sources and integrated automation and control systems. One such source is a ground air heat exchanger which, when used in a mechanical ventilation system, can reduce the energy demand for heating or cooling rooms by the pre-adjustment of the supply air temperature.

This article presents the field study of a horizontal, tubular ground air heat exchanger (EAHX) which supports a building heating by preheating the inlet air of the cooperating ventilation unit. Furthermore, it provides considerations on the functioning of the actual implementation of the EAHX in the winter season, in southern Polish climatic conditions.

Considering the results of this study, it can be concluded that, in the winter from the point of view of a building's energy efficiency, the continuous use of these exchangers is not optimal, a point that validates the previous paper's [19] thesis. For improving the energy efficiency of an EAHX – a ventilation unit system, it is favourable to automatically control the selection of a ventilation unit's fresh air source, (EAHX or direct air intake), depending on the relation between the outdoor air temperature and the air temperature achieved by the exchanger. Thanks to this, it is possible to ensure the most suitable air temperature at the ventilation unit's inlet, before using other methods of its conditioning (recuperation or conventional heating and cooling). Such prepared air supplied to the mechanical ventilation system should reduce the energy inputs necessary to achieve the desired temperature in each room of a building. However, in the winter, the energy effect of the exchanger's activity control is comparatively lower than in the summer.

This study indicates the significance of the interaction and integration of different elements, such as a ground heat exchanger, direct fresh air inlet, and a mechanical ventilation unit in a low energy building. The integration of an exchanger control with other functionalities of an intelligent building,

such as the detection of an occupant's presence or of a rooms' intensity of use, can provide the maximum energy efficiency of an EAHX – ventilation unit system. The presented results form the basis for further research on control algorithms of a horizontal ground heat exchanger cooperating with a ventilation unit, as well as their integration with a building automation and control system. Such an algorithm will be universally applicable to all buildings with mechanical ventilation that are equipped with ground heat exchangers.

References

- [1] M. Manic, D. Wijayasekara, K.Amarasinghe, J. J. Rodriguez-Andina, "Building Energy Management Systems: The Age of Intelligent and Adaptive Buildings", *IEEE Industrial Electronics Magazine*, vol. 10, iss. 1, pp. 25–39, 2016.
- [2] H. Wicaksono, S. Rogalski, E.Kusnady, "Knowledge-based intelligent energy management using building automation system", *IPEC, 2010 Conference Proceedings*, 2010.
- [3] 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.
- [4] 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.
- [5] 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.
- [6] 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.
- [7] 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.
- [8] 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.
- [9] 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.
- [10] 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.
- [11] Maneesh 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.
- [12] 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.
- [13] G. Chiesa, "Climate-potential of earth-to-air heat exchangers", *Energy Procedia*, vol. 122, pp. 517–522, 2017.

- [14] 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.
- [15] J. Pfaffertott, “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.
- [16] 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.
- [17] A. Skotnicka Siepsiak, M. Wesołowski, “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.
- [18] 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.
- [19] 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.
- [20] 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.