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Numerical Modeling and Experimental Studies of the Operational Parameters of the Earth-To-Air Heat Exchanger of the Geothermal Ventilation System

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Abstract: This article is devoted to the analysis of the heat engineering characteristics of the operation of an Earth-to-Air Heat Exchanger, EAHE, with a circular cross-sectional shape, which is a component of the geothermal ventilation system. The authors analyzed literature sources devoted to the research of heat exchangers of the soil-air type of various designs and for working conditions in various soils. Much attention is paid to the issues of modeling the operation of such heat exchangers and the distinctive features of each of these models. Also important are the results of experimental studies carried out on our own experimental bench and with the help of which the numerical model was validated. The results of these studies are the basis for the development of a method for determining the optimal diameter of an EAHE under operating conditions for soil in Kyiv, Ukraine.

Keywords: geothermal ventilation, earth to air heat exchanger, experimental studies, numerical modeling, renewable energy sources

1. Introduction

For a comfortable stay of people in buildings, an important condition is the availability of fresh air that complies with sanitary and hygienic standards, the supply of which is ensured by a forced ventilation system. Ventilation system performs the function of exchanging air in the room to remove excess heat, moisture, carbon dioxide, harmful and polluting substances in order to ensure an acceptable microclimate and air quality in the zone of human presence. Compliance with the normative air exchange in residential and administrative buildings, determined by the state building standards of Ukraine, is mandatory for new construction or reconstruction of existing buildings.

Increasing the energy efficiency of buildings standards complicates the design of ventilation systems due to with significant year-round costs of energy for heating and cooling the supply air. Air heating process requires a significant amount of energy (Cepiński et al. 2020). One of the solutions to the problem of reducing energy intensity is the use of a geothermal ventilation system, due to which it is possible to reduce the difference in the supply air temperature with the standard value and reduce the energy costs for heating (or cooling) before supplying air to the room.

The aim of this work is to develop a numerical model of the year-round operation of an Earth-to-Air Heat Exchanger, EAHE, with a circular cross-sectional shape with further its validation based on the obtained experimental data. We consider that these studies can form the basis for the development of methods for calculating and designing geothermal ventilation systems for climate conditions of Ukraine.

2. Background

To minimize the energy consumption of buildings, various systems have recently been used to extract low-grade soil heat. For example, vertical ground source heat pump heat exchangers (Dolan & Mikielewicz 2017a, 2017b), horizontal ground source heat pump heat exchangers (Díaz-Hernández et al. 2020), earth-to-air heat exchangers (Agrawal et al. 2019).

The main element of the geothermal ventilation system is an EAHE that is located in the soil mass at a certain depth – from 1.0 to 3.0 m, depending on the climatic conditions of a particular area. The EAHE usually has channels with a round cross-sectional shape and various lengths (see Table 1).

Article (Sakhri et al. 2020) shows main designs of typical EAHE. Operational parameters of these type heat exchangers have been widely studied throughout the world over the past decade. For example, studies conducted in Europe (Tzaferis et al. 1992, Badescu et al. 2007, Benkert et al. 1997, Congedo et al. 2019, Greco & Masselli 2019), CIS countries (Filatov & Volodin 2013), Africa (Sehli et al. 2012, Amara et al. 2011, Hamdi et al. 2018, Serageldin et al. 2016), Asia (Sanusi 2012, Ariffin et al. 2014, Misra et al. 2018, Agrawal et al. 2019, Verma et al.) and America (Díaz-Hernández et al. 2020, Krarti & Kreider 1996).

Ukraine also begins to carry studies in this direction (Basok & Novitska 2017, Nakorchevsky & Belyaeva 2005, Tkachenko et al. 2020, Basok et al. 2020), but their results are not enough to develop methods for calculating and designing geothermal ventilation systems for the corresponding climate conditions and local soils.

The active development of geothermal ventilation systems necessitates theoretical studies to understand the processes occurring in EAHE and to determine the quantitative effect of various parameters on the energy and economic efficiency of such a system. In general, the energy efficiency of a heat exchanger may depend on the following parameters (Ariffin et al. 2014):

- configuration and geometric dimensions of the heat exchanger,
- climatic conditions,
- thermophysical properties of the soil.

The consideration of these factors together or singly is a difficult task that modern researchers face. Recently were published in information sources several studies of the operation of EAHE using numerical simulation (Díaz-Hernández et al. 2020, Tzaferis et al. 1992, Badescu 2007, Greco et al. 2020, Serageldin et al. 2016, Rouag et al. 2018). An analysis of such heat exchangers usually involves either calculating the thermal conductivity of the soil mass to the wall of the heat exchanger or calculating the parameters of convective heat transfer between the air in the heat exchanger and the soil mass. Articles usually considered one, two- and three-dimensional numerical models of EAHE with various restrictions.

For example, article (Badescu 2007) describes a two-dimensional numerical model for calculating the parameters of an EAHE containing a single circular cross-section pipe with length of 36.0 m. The model is based on the determination of temperature values on the soil surface and in the vertical section of the soil mass. Calculations considered only the horizontal part of the heat exchanger, the influence of the vertical sections of the air inlet and outlet was considered insignificant. On the soil surface, the model takes into account convective heat flux, long-wave radiation from the soil surface, absorption of insolation energy by the surface of the soil, as well as latent heat of evaporation.

In (Tzaferis et. al. 1992), a comparison is made of eight existing at the time of publication of numerical models describing the heat exchange of air in the channel with the ground. The work describes an assessment of the sensitivity of methods to such parameters as inlet air temperature, air velocity, pipe length, radius and depth of the heat exchanger. In addition, the calculation results were compared with experimental data.

Table 1. Geometric characteristics of Earth to Air Heat Exchangers

Author	Cross-section shape	The size of the cross-section, m	Length of the EAHE, m	Depth of the EAHE, m	Links, notes
H.P. Díaz-Hernández et al.	circular	0.1016 (D)	12	2.5	Hernández et al. 2020
Tzaferis et al.	circular	0.125 (R)	30	1.5	Tzaferis et al. 1992
V. Badescu	circular	0.05-0.25 (D)	36	3.0	Badescu 2007
Benkert S et al.	circular	0.125 (D)	42	0.7-1.8	*Benkert et al.* 1997
P. Congendo et al.	circular	0.2 (D) 0.25 (D)	20 20	2.5; 3.0; 4.0; 3.0	*Congendo et al.* 2019
S. Filatov, V. Volodin	annular channel	0.54×0.05	4-17	vertical orientation	Filatov & Volodin 2013
A. Sehli, et al.	circular	0.110 (D)	53.16	3	Sehli et al. 2012
S. Amara, et al.	circular	0.21 (D)	60	1-5	Amara et al. 2011
Sanusi et al.	circular	0.076 (D)	25	0.5-1.5	Sanusi et al. 2012
NoorAziahMohd Ariffin	circular, pipe in pipe	0.05 (D)	25	1	Ariffin et al. 2014
M. Krarti, J. Kreider	circular	0.2 (D)	80	1.5	Krarti & Kreider 1996
Rouag, Amar et al.	circular	0.3 (D)	10	-	Rouag et al. 2018
B. Basok et al.	circular	0.16(D)	43	2.2	Basok et al. 2020

A semi-analytical model for determining the temperature of the soil near an EAHE with circular cross-section in long-term operation is shown in (Rouag et al. 2018). The aim of the work was to determine the optimal distance between the pipes of such a device, as well as between the devices themselves in the case of several heat exchangers located at a distance.

An original scheme for the removal of soil heat or cold by energy piles with air filling as a coolant was calculated based on numerical simulation in paper (Filatov & Volodin 2013). It was found, that when using energy piles as part of the supply ventilation system, in the warm season, the air temperature decreased by 3-6°C, and in the cold – it was heated by 6-9°C. At the same time, no more than 0.3% of energy was spent on air transportation from the energy of the heat flux of the energy pile.

In addition to works that are devoted to CFD modeling, articles describing experimental studies are also widely presented in the scientific literature (Cepiński et al. 2020, Díaz-Hernández et al. 2020, Hamdi et al. 2018, Serageldin et al. 2016, Misra et al. 2018). In these works, thermal performance of EAHE of different heating and cooling systems were analyzed. For example, article (Bonuso et al. 2020) shows ways for practical usage of EAHE in greenhouse and providing both the results of computational modelling and some experimental data of thermal performance of these EAHE.

Airflow in systems of this type is usually constant and selects at the discretion of the authors. Data on the flow rate or speed of air passing through the EAHE are shown in Table 2.

An important characteristic that used in the calculations is the climatic data on the temperature of the soil depending on the depth and its thermophysical properties (Table 3). In the literature, it is possible to find data on soil temperatures for a number of countries (Díaz-Hernández 2020, Benkert et al. 1997, Sanusi 2012), including and Ukraine (Nakorchevsky & Belyaeva 2005), as well as its thermophysical properties (Benkert et al. 1997, Congedo et al. 2019, Amara et al. 2011, Rouag et al. 2018, Basok et al. 2009). In the works it is usually accepted the assumption that soil is a homogeneous and isotropic medium. Several works also shows that the properties of the soil, namely its thermal conductivity, slightly affect the air temperature at the outlet of the EAHE. So, for example, in (Congedo et al. 2019), calculations of the parameters of an EAHE located at a depth of 3.0 m in soil with thermal conductivity in the range 1.49-2.1 W/(m·K) are presented, and it is concluded that such a range values does not significantly affect the air temperature at the outlet of the heat exchanger. The authors attribute this result to the low heat capacity of the air, which leads to a rapid decrease in air temperature to a value that is close to the soil temperature.

Table 2. Air velocity or flow rate in EAHE

Author	Cross-section shape	Air velocity or flow rate	Links, notes
Tzaferis et al.	circular	5 m/s	Tzaferis et al. 1992
Benkert S et al.	circular	140 m^3/h	*Benkert et al.* 1997
P. Congendo et al.	circular	450 m^3/h; 1200 m^3/h	Congendo et al. 2019
S. Filatov, V. Volodin	annular channel	0.073 kg/s	*Filatov & Volodin* 2013
A. Sehli et al.	circular	1-5 m/s	Sehli et al. 2012
S. Amara et al.	circular	3.79 m/s	Amara et al. 2011
Sanusi et al.	circular	5.6 m/s	Sanusi et al. 2012
NoorAziahMohd Ariffin et al.	circular, pipe in pipe	0.5 m/s	Ariffin et al. 2014
M. Krarti, J. Kreider	circular	3.5 m/s	*Krarti & Kreider* 1996
B. Basok, Novitska, M.	rectangular	natural convection	Basok & Novitska 2017

Table 3. Thermophysical properties of the soil

Author	Soil thermal conductivity, λ, W/(m·K)	Heat capacity of soil, C_p, kJ/(kg·K)	Soil density, ρ, kg/m^3	Links
V. Badescu	1.20	2.20	1800	Badescu 2007
S. Benkert et al.	1.50	1.30	1600	Benkert et al. 1997
P. Congendo et al.	1.49 2.30 1.24	1.34 2.85 1.65	1800 1650 1520	Congendo et al. 2019
S. Filatov, V. Volodin	2.00	1.10	1850	Filatov & Volodin 2013
A. Sehli et al.	2.01	1.38	2300	Sehli et al. 2012
S. Amara et al.	2.01	1.38	2300	Amara et al. 2011
Amar Rouag et al.	1.74 0.52	1.99 1.84	1868 2050	Rouag et al. 2018
B. Basok et al.	1.42	1.15	1840	Basok et al. 2009
B. Basok et al.	0.99	1.59	1920	Basok et al. 2020

Thus, the analysis of literature sources showed that now there are quite a lot of studies devoted to the issues of geothermal ventilation. The results of EAHE's modeling with various geometric data and which operate in their authentic soils under various hydraulic regimes and that are located at different depths are widely presented. However, these studies do not allow obtaining generalized patterns of heat transfer during the operation of soil-air heat exchangers and the influence of the geometric parameters of the heat exchanger on the operation of the geothermal ventilation system as a whole.

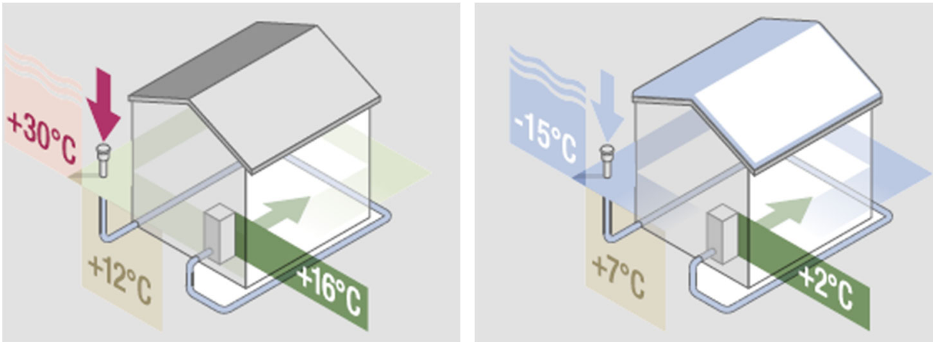
3. Description of the proposed numerical model

To solve the problems of heat accumulation by soil, it is necessary to know the depth of annual temperature changes in the soil H, which determines the soil layer that responds to changes in the temperature of the Earth's atmosphere. Below depth *H*, the temperature regime of the soil mass is stable and determined solely by the geological state. As shown in (Nakorchevsky & Belyaeva 2005), the values of *H* can vary from 3.9 m to 5.0 m, and the temperature of the soil mass below this depth can be from 5°C to 9°C, for different regions of Ukraine. Therefore, when fresh air passes through the EAHE, it heats in winter or cools in summer, as shown in Figure 1.

In this paper, to study the air flow in a pipe located in an array of soil, we used a numerical model based on the following assumptions:

- all materials used in the calculations were considered isotropic and homogeneous,
- in accordance with the data given in (Nakorchevsky & Belyaeva 2005), it is accepted that the temperature of the soil depends on the depth.

The calculations performed based on the system of equations for conservation of momentum, energy, kinetic energy of turbulence, and dissipation rate of kinetic energy of turbulence (1-8), which characterizes the processes of aerodynamics and heat transfer in an air-soil heat exchanger.



a) b)

Fig. 1. Schematic diagram of the operation of geothermal ventilation system: a) in summer; b) in winter

The continuity equation:

$$\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}+\frac{\partial w}{\partial z}=0\,. \tag{1}$$

The equations of conservation of momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right), \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right), \tag{3}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right). \tag{4}$$

Energy conservation equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right). \tag{5}$$

Equation of thermal conductivity of soil:

$$a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=0 \tag{6}$$

To close the system of equations of turbulent transfer, we use the k - ε model of turbulence. This model described by using equations for the kinetic energy and dissipation rate.

The equation of conservation of kinetic energy:

$$\frac{\partial uk}{\partial x}+\frac{\partial vk}{\partial y}+\frac{\partial wk}{\partial z}=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right]+G_k-\rho\varepsilon\,, \quad (7)$$

and the dissipation rate conservation equation:

$$\begin{aligned}&\frac{\partial u\varepsilon}{\partial x}+\frac{\partial v\varepsilon}{\partial y}+\frac{\partial w\varepsilon}{\partial z}=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right]+\\&+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right]+G_{1\varepsilon}G_k\frac{\varepsilon}{k}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}\end{aligned}, \quad (8)$$

The basic equations were solved using the finite volume method. In most areas, the computational grid consisted of elements in the form of prisms. The Navier-Stokes equations were calculated with the first order of accuracy.

The thermophysical properties of the materials, which we used in the calculations, are in Table 4.

Table 4. Thermophysical properties of soil and air that accepted in the numerical model

	Thermal conductivity, W/(m·K)	Heat capacity, kJ/(kg·K)	Density, kg/m^3
air	0.02420	1006.43	1.225
soil	0.99262	1059.87	1920

When performing calculations in the model, the following boundary conditions were used:

1) On the surface of the soil mass that is in contact with the environment, the heat transfer coefficient of 23.0 W/(m^2·K) and temperature equal to the value of the air temperature at the inlet to the EAHE were set.
2) On the sides of the soil massif, which is limited by the calculation area, the temperature of the soil (in Kelvin degrees) was set, which depended on the depth and time of the year:

mid-April: $T(z) = 0.16z^3 + 0.6899z^2 + 0.343z + 277.24$

mid-July: $T(z) = 0.431z^2 + 2.685z + 287.3$

mid-October: $T(z) = -0.245z^3 - 0.702z^2 - 0.494z + 285.1$

mid-January: $T(z) = -0.54392z^2 - 2.4523z + 277.54$

At the lower boundary of the region, the soil temperature T_S was constant and was according to (Sanusi 2012): April – 4°C; July – 13.0°C; October – 10.5°C; January – 4.75°C.

3) At the entrance to the EAHE air velocity v, m/s and air inlet temperature T_{in}, K were set. As turbulence parameters, we chose turbulence intensity of 10% and a hydraulic diameter corresponding to the diameter of the pipe.

4. Experimental studies of operation of EAHE for the geothermal ventilation system

To conduct experimental research on the operation of the geothermal ventilation system at the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine an experimental stand was created. This stand is designed to study thermophysical processes during the operation of a geothermal ventilation system elements.

The main element of the experimental stand is EAHE with a circular cross section and a total length of 43.0 m. The heat exchanger is made of PVC-U pipes Ø110 mm and located in the soil mass at a depth of 2.2 m (significantly lower than the seasonal depth of freezing in Kyiv). This heat exchanger is operated in two modes: in the warm season – air cooling mode, in the cold period – supply air heating mode for the supply and exhaust ventilation system.

The study of the geothermal ventilation system was carried out in two hydrodynamic modes: the supply air was pumped through the heat exchanger at a speed of 4.4 m/s and 5.5 m/s in the flow core. These speed values correspond to a volumetric air flow rate of 29.0 dm^3/s and 37.0 dm^3/s. The experimental stand is equipped with a measuring system – a Testo 405-V1 hot-wire anemometer, BME280 semiconductor temperature sensors (33 sensors in total, located in the soil mass near the heat exchanger), humidity and pressure sensors (at the inlet and outlet) and secondary computational device based on microprocessors.

The main parameters that were measured at the inlet and outlet of the heat exchanger and recorded by a special automated measuring system and testified to the efficiency of the heat exchanger – temperature, relative humidity and flow pressure. All measurements were carried out during the year (with short breaks for maintenance work) with a duty cycle of one survey of all sensors after a time period of 10 minutes. Also, the equipment used makes it possible to achieve a duty cycle of measurements up to measuring once every 1 second. Further, the data was archived and preprocessed on a computer. Uncertainties (random errors) of the experimental values were:

- for temperature – ±0.2°C,
- for absolute humidity – ±0.5-1%,
- for pressure – ±20 Pa,
- for air velocity – ±0.05 m/s.

Typical measurement results are shown in Figures 2-4. In particular, Figure 2 shows a complete generalized array of temperature measurement data for the total duration of the experiments from October 2018 to the end of September 2019. The abscissa axis shows the time of measurement of the experimental point parameter values, first obtained once every 1 minute, and starting from 10 800 minutes (75 days of operation of the heat exchanger) once every 10 minutes. The total measurement time – 516 240 minutes, that is, 358.5 days – almost the calendar year.

As we can see, the outdoor temperature fluctuated during the study period from +36°C to -14°C (weather data for Kyiv in 2018-2019). At the same time, the temperature of the air pumped through a horizontal heat exchanger was quasistationary (almost independent of the time of the current day) and varied from +18°C in summer to +2.5°C in winter.

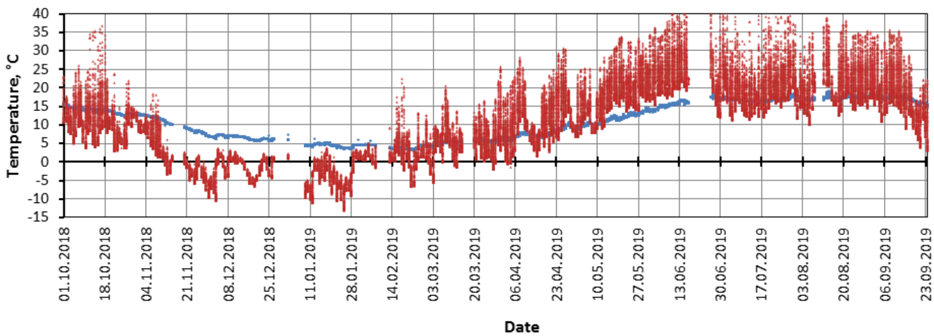


Fig. 2. Experimental data for ventilation air temperature (red drops – air inlet in EAHE; blue drops – air outlet from EAHE)

Ventilation air was almost not sensitive to local changes (daily, ten-day) in the ambient air temperature, and its temperature level was determined solely by the thermal regime of the soil mass surrounding the EAHE. That is, in the summer the air was cooled to a maximum of 18°C, and in the winter, it was heated to a maximum of 16°C to positive temperatures (which is important because there was no freezing of the soil at this depth). Air temperature was in the range of changes between the two red horizontal lines. In particular, in late spring, summer and early autumn, the temperature of ventilation air did not change much and amounted to 18°C. Due to this effect, the energy efficiency of the geothermal ventilation and air conditioning system of the house increased.

Fig. 3 shows detailed experimental studies of local changes in temperature, humidity and pressure for the day on August 18, 2018. The temperature difference reached almost 12°C (see Fig. 3a). At a midday temperature peak of the outdoor air at 29.5°C, the temperature of the soil mass near the heat exchanger barely changed after 3 hours – was observed temperature increase of 0.5°C.

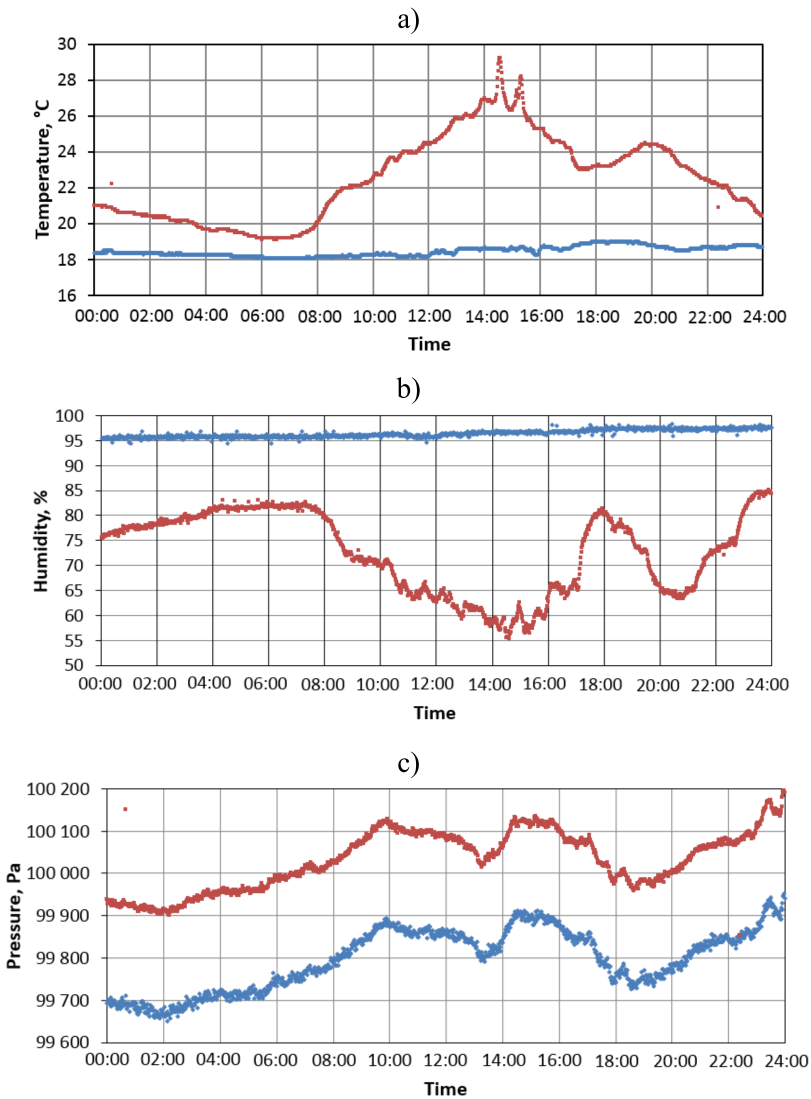
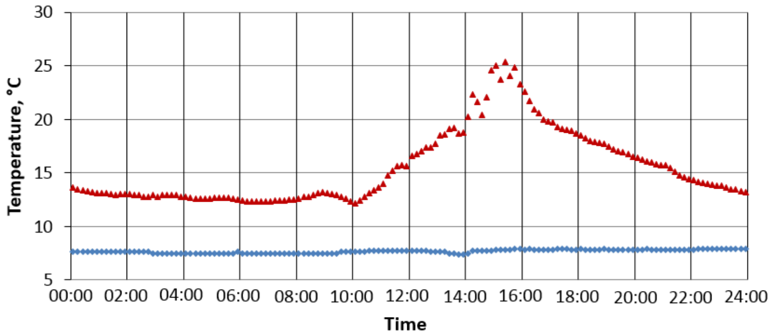


Fig. 3. Experimental data, obtained 18.08.2018: a) air temperature; b) air humidity; c) air pressure (red drops – air inlet in EAHE; blue drops – air outlet from EAHE)

Humidity of ventilation air (Fig. 3b) was quite high at the level of 95%. The ambient air humidity varied significantly from 55% at the peak of the noon temperature to 85% during the night cool. The time of minimum of the relative humidity of the outdoor air clearly coincided with the maximum of the dynamics of changes in its temperature.

The dynamics of pressure change of the airflow at the inlet and outlet of the EAHE correlated with the dynamics of changes in the external temperature. Both curves in Fig. 3c are clearly equidistant, the pressure drop over the entire measured period was 225 ... 235 Pa, which fully corresponds to the aerodynamic loss for the geometry of the heat exchanger channels.

a)



b)

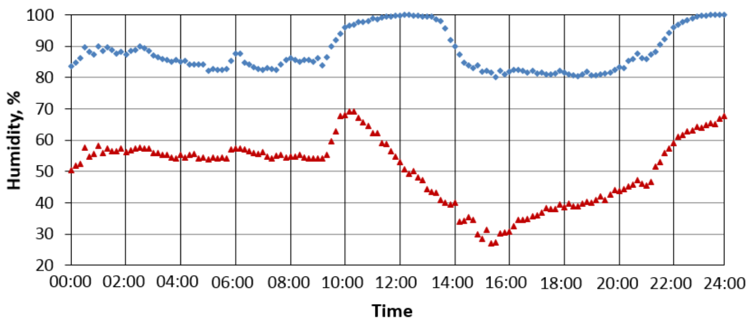


Fig. 4. Experimental data, obtained 09.04.2019: a) air temperature; b) air humidity (red drops – air inlet in EAHE; blue drops – air outlet from EAHE)

Fig. 4 shows effects of partial condensation of water vapor from outside air at the inlet to EAHE. Condensation of vapors occurred during the spring period of operation of the geothermal ventilation system, when the heating season was almost over.

The average daily ambient temperature almost coincided with the temperature of the soil mass near the heat exchanger (Fig. 4a). During this period, the humidity of the ventilation air was mainly dominated by the humidity of the outside air (Fig. 4b), and water vapor condensation occurred in some intervals.

5. Grid analysis and validation of a numerical model using experimental data

The calculation area was a parallelepiped with dimensions of 22.0 m *x* 4.0 m *x* 4.2 m (length *x* width *x* height), in which the EAHE pipe with a diameter of ∅ 110 mm was located. The domain was divided into cells by means of a pyramidal network with different thickening closer to the EAHE. Three mesh variants with different size of calculation cells were selected. The results of the comparison are presented in Fig. 5.

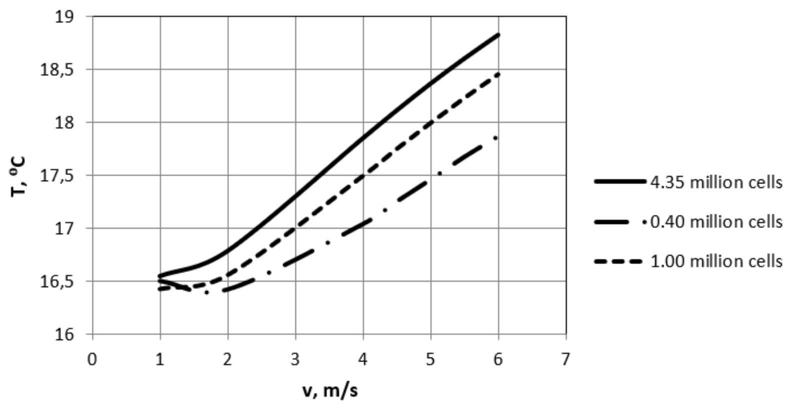
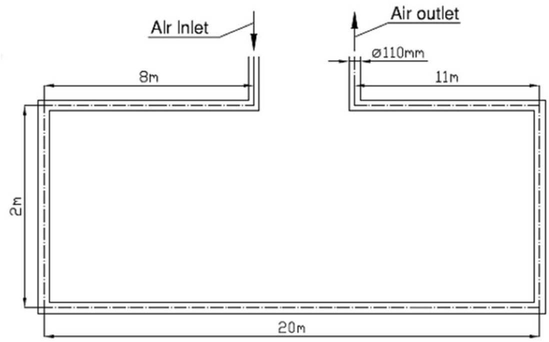


Fig. 5. Grid analysis

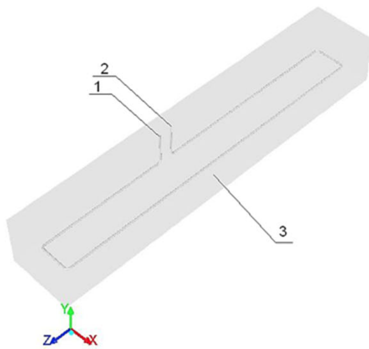
According to the results of comparison, for further calculations, a mesh with 1 million cells was selected. Since the difference between the calculation results between this and the grid with 4.35 million cells is less than 0.5°C (in contrast to the difference in the calculation of temperature between grids of 400 thousand and 1 million cells), this is only slightly more than the temperature measurement uncertainty at experimental research. The computational domain diagram is shown in Fig. 6.

We present the validation of the calculation results, which was carried out on the basis of the data obtained at the experimental stand. The data of a full-scale experiment are compared with the data of numerical simulation, provided that the stationary problem of air movement in an EAHE is solved at various average daily inlet air temperatures.

When the model was validated, the boundary temperature values in October and April, which were calculated according to (9), were set as boundary conditions on the lateral surface of the soil massif. On the upper surface the temperature equal to the temperature of the air entering the heat exchanger was set as a boundary condition.



a)



b)

Fig. 6. Geometric dimensions of the heat exchanger (b) and scheme of the calculation area (b): 1 – air inlet to the EAHE; 2 – air outlet from the heat exchanger; 3 – soil mass

Figure 7 shows a comparison of the experimental temperature data at the outlet of the EAHE and the results of numerical simulation.

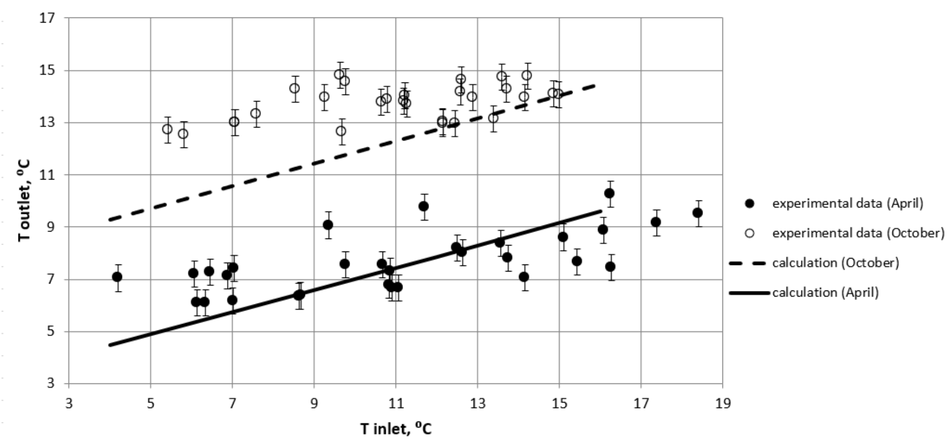


Fig. 7. Validation of numerical simulation using experimental data

As can be seen from Fig. 7, part of the experimental data coincides with the calculation within the experimental error. Some points lie above the calculated curve, this is because the calculation was carried out in a stationary setting, and cannot take into account the accumulation of heat in the soil with a sharp change in the temperature regime of inlet air. That is, if the average daily temperature during the previous days before the measurement time differed by several degrees compared with the day of measurement, then, thermal energy accumulated in the soil mass around the pipe of the EAHE and caused a higher air temperature at the outlet of the heat exchanger. These non-stationary process parameters were not taken into account in the model that was used in this case. But in general, in the absence of a sharp change in weather conditions, the model predicts the temperature at the outlet of the EAHE with the accuracy of experimental measurements.

For the obtained data, the calculation of the average relative error was performed by the formula:

$$\sigma = \frac{T_{outlet(\exp erimental)} - T_{outlet(numerical)}}{T_{outlet(\exp rimental)}} \cdot 100\% \tag{10}$$

Figure 8 shows the range of distribution of the relative error.

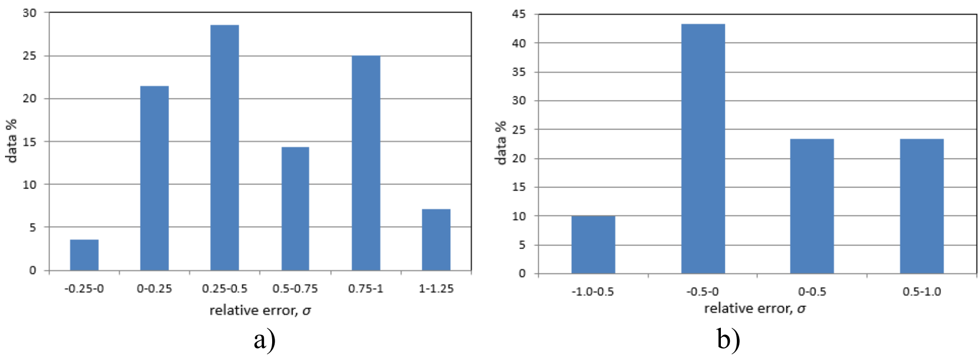


Fig. 8. Range of distribution of relative error for: a) October; b) April

The results of calculating the distribution of the relative error showed that it varies in the range from -0.25 to 1.25% (Fig. 9b). Most of the data for October 2018 (28%) has a relative error in the range of 0.25-0.5%. For April 2018, the range of relative error ranged from -1 to 1%. Most of the data for April (Fig. 9a) (40%) have a relative error from 0 to 0.5%.

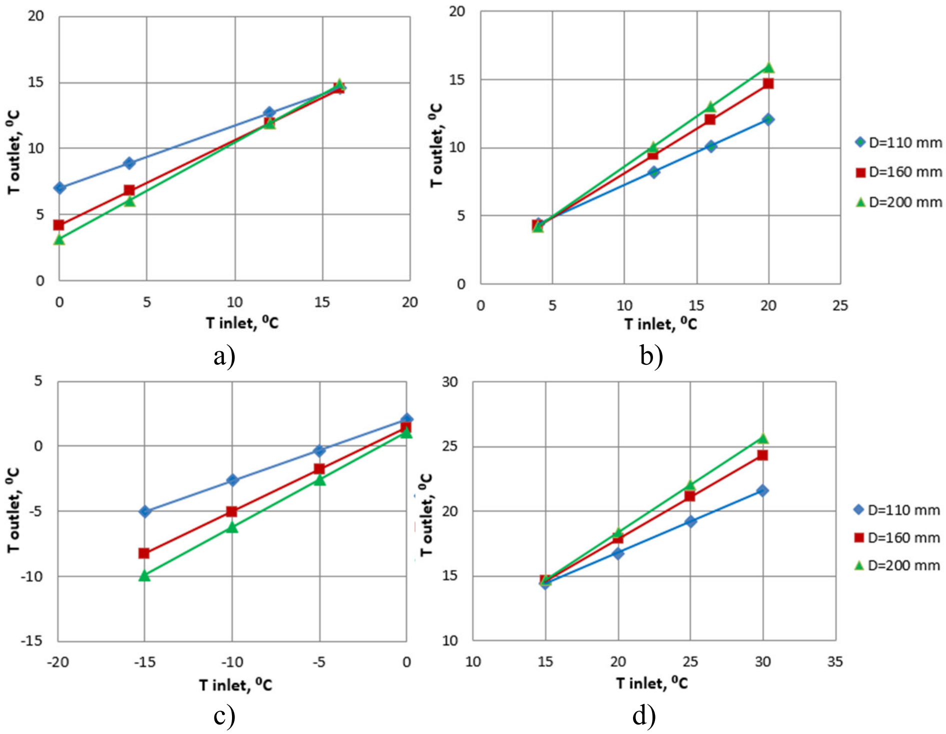


Fig. 9. Dependence of the air temperature at the outlet of the EAHE at various pipe diameters for: a) October; b) April; c) January; d) July

6. Results and discussion

Some researchers have investigated the diameter influences of EAHE on the performance of the whole system (Greco & Masselli 2020, Serageldin et al. 2016, Krarti & Kreider 1996). Krarti, M. and Kreider, J.F. (Krarti & Kreider 1996) developed a simplified analytical model of an underground air tunnel. The model was applied to a circular pipe buried at 1.5 m deep in ground. The ambient inlet temperature was assumed to vary sinusoidally within a 24 hour period, with an average value at 19°C and an amplitude of 9°C. The authors founded that outlet temperature depends significantly upon the pipe diameter. Increasing the pipe diameter results in a higher outlet air temperature.

(Serageldin et al. 2016) performed serpentine horizontal EAHE investigation in the weather conditions of Egypt. The results showed that with an increasing of the pipe diameter during EAHE operation in heating mode, the outlet air temperature decreases.

The authors of (Greco & Masselli 2020) optimized the parameters of the thermal performance of a horizontal single-duct heat exchanger on basis of the 2D numerical model. They founded that if the pipe is designed with smaller diameters and slower air flows, with other conditions that remain, the outlet temperatures come closer to the ground temperature. They proposed the combination that optimizes the performance of the EAHE system, with design condition for cooling and heating, is D = 0.1 m, v = 1.5 m/s; L = 50 m.

In our work, using the numerical model of the EAHE, that was described above, the operation parameters of the heat exchanger were calculated using pipelines with various typical outside diameters – 110, 160 and 200 mm. The initial temperature was the air temperature at the inlet to the heat exchanger and the air velocity, which was taken from the experimental data and amounted to 5.5 m/s.

Using the numerical model, the air temperature at the outlet of the EAHE and the linear density of the heat flux from the soil mass to the air flow that was pumped through the heat exchanger were calculated. Figures 7 and 8 show the corresponding data for the middle of four months – October, January, April and July. These months can be considered as those that generally characterizes climatic data that are relevant for the corresponding period of the year.

As can be seen from Fig. 9, the value of the outer diameter of the pipeline has a sufficiently significant effect on the difference in air temperature at the inlet and outlet of the EAHE. So, at the beginning (from October 15) and in the middle of the heating period (Fig. 9a and Fig. 9c), when the recuperative ventilation system has a significant contribution to the operation of the heating system, a pipeline with an outer diameter of 110 mm is optimal relative to the temperature head.

However, in the summer (Fig. 9d), to ensure air conditioning, without violating sanitary and hygienic and construction standards (State Building Regulations of Ukraine 2013), the outer diameter of the pipeline is 200 mm, at which the temperature difference between the outgoing and incoming air is kept at 5°C. With such a difference in air temperature, it is possible to abandon the use of additional devices for cooling the supply air and minimize energy costs for air conditioning.

Figure 10 shows the dependences of the influence of the outer diameter of the EAHE pipeline on the linear density of the heat flow.

We founded that the linear density of the heat flux during operation of the EAHE weakly depends on the outer diameter of the heat exchanger pipeline at the beginning and at the end of the heating period (April 15) (Fig. 10a and Fig. 10b).

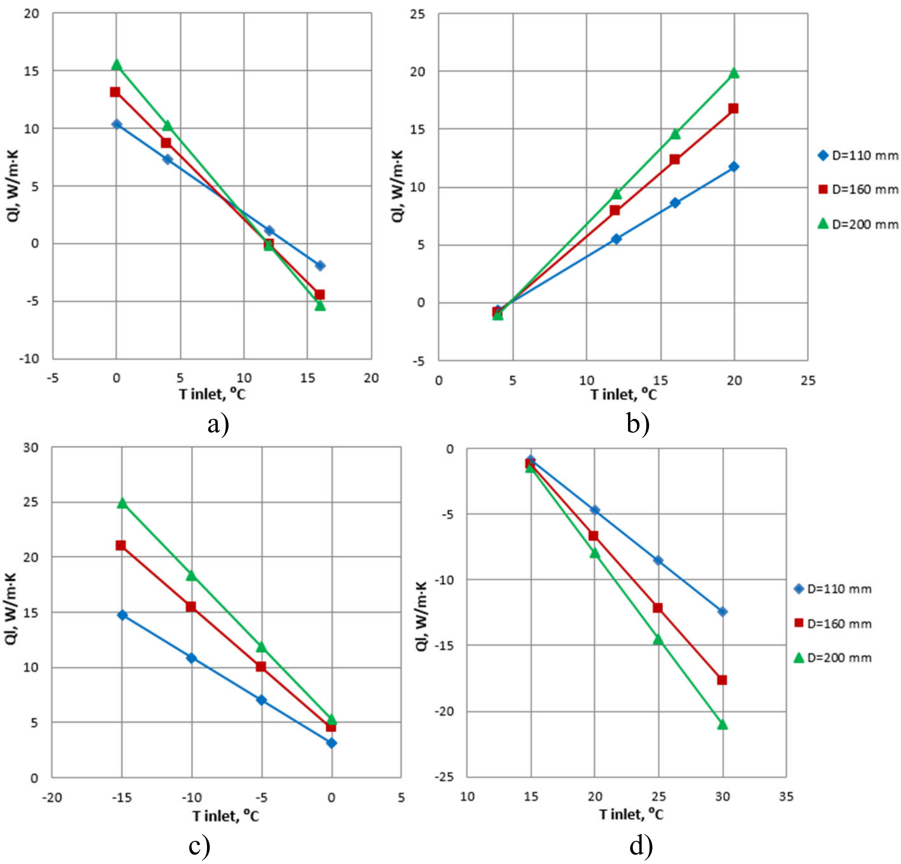


Fig. 10. Dependence of the linear heat flux density of the EAHE at different pipe diameters: a) October; b) April; c) January; d) July

In the middle of the heating period (Fig. 10c), the influence of the outer diameter of the pipeline on the linear heat flow is more significant. Thus, when switching from a diameter of 110 mm to 160 mm, the linear heat flux increases, on average, by 30%. In the transition from a diameter of 160 mm to 200 mm, the growth of the linear heat flux decreases and amounts to 16%.

In the summer (Fig. 10 d), a similar situation is observed. When there is the transition from a diameter of 110 mm to 160 mm, the linear heat flux increases, on average, by 32%, in the transition from a diameter of 160 mm to 200 mm, by 19%.

Thus, the optimal from the point of view of linear heat flow in a geothermal ventilation system is the use of an EAHE with an outer diameter of pipe of 160 mm.

7. Conclusions

Improving the energy efficiency of buildings using geothermal ventilation systems is currently an actual area of research.

The efficiency of heat transfer in the EAHE may be influenced by such parameters as the depth of placement, geometric size, shape of cross section, soil temperature, properties of heat exchanger materials, soil thermal and physical properties, mass flow through the system or its speed, climatic conditions, terrain features, etc.

A comparison of calculation results with experimental data showed that the proposed numerical model adequately describes the processes of aerodynamics and heat transfer in the EAHE.

Comprehensive experimental studies and comparisons of their data with the results of calculations using the developed numerical model of complex heat transfer processes made it possible to conduct a comparative analysis of the heat engineering parameters of air-ground heat exchangers with different pipe diameters.

Thus, for the operation of regenerative geothermal ventilation in winter and air conditioning in summer, for a given length of EAHE, corresponding to the thermal properties of the soil and airflow, it is optimal to use plastic pipes with an outer diameter of 160 mm.

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