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Original Research

Experimental and Numerical Study of an Earth-to-Air Heat Exchanger in Northeastern Poland

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Abstract

Our paper presents empirical data from a laboratory experiment investigating the performance of an air-to-soil heat exchanger between July and August 2016. Measurements were performed in a laboratory of the Department of Civil Engineering and Building Engineering Physics of the University of Warmia and Mazury in Olsztyn. Empirical data were compared with the results of analytical calculations based on meteorological data for a typical meteorological year.

Keywords: air-to-soil heat exchanger, watt-hour efficiency

Introduction

In earth-to-air heat exchangers (EAHE), atmospheric air flows through a system of pipes buried in the ground, which acts as an energy buffer [1-2]. Throughout the year, soil temperature remains relatively constant below a certain depth (usually 2-3 m). The constant temperature is known as earth's undisturbed temperature, and it is lower than ambient temperature in summer and higher in winter. Undisturbed ground temperature in different geographical locations is determined by short-term weather variations, seasonal variations, soil moisture content, and thermal conductivity of soil [3].

In summer, EAHE systems cool the air that enters a ventilation unit [4]. Ground-coupled duct systems are researched extensively in countries with a subtropical climate, such as Brazil [5-6], a hot and arid climate [7], the hot and humid climate of Mexico in zones 2A and 3A [8], and in Italy [9], Turkey [10], and Egypt [11].

The performance of EAHE systems for pre-cooling air in mechanical ventilation systems in summer and pre-heating air in winter has been investigated in Central-Eastern Europe which is characterized by cold winters and hot summers [12]. Ground heat exchangers minimize energy use and supply ventilated premises with fresh, hygienic, and filtered air [13]. A review study by Tan and Love (2013) indicates that much of the literature focuses on cooling applications, systems with a smaller (approximately 300 mm) diameter, and mild-to-hot climates. Research into EAHE systems for heating purposes in cold climates is less extensive, but its results are promising. According to numeric simulations performed for residential buildings in Norway [14] and

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Montreal in northern Canada [15-16], EAHE installations can increase the temperature of the supplied air by up to 12ºC (from -7ºC to +5ºC). Energy gains are even higher when the temperature of ambient air is very low [17]. In the temperate climate of Germany, empirical data acquired over a period of one year indicate that the temperature of air can increase by 16ºC between the inlet and outlet of a ground heat exchanger [18]. In Warsaw, where the average annual temperature is 8.1ºC, the relevant increase in air temperature in winter approximated 15ºC [19]. The results of the above studies indicate that EAHE systems are comparatively efficient in heating supply air in cold climates [20]. Researchers and designers have a growing interest in EAHE systems, which offer a promising solution for improving thermal comfort at low cost [21]. In studies evaluating the performance of EAHE systems, empirical data are compared with the results of numerical analyses [8]. Research methods and one-dimensional numerical models have been developed to analyze the performance of EAHE systems based on the energy conservation equation [22] [23]. Computer programs supporting multi-dimensional simulations of the thermal performance of EAHE are being developed [24]. Mathematical models are validated based on experimental results [25-26]. Numerical methods are used to evaluate and optimize the parameters of EAHE installations (pipe diameter, pipe material, pipe space, pipe length, and flowing fluid velocity) [27].

Earth-to-air heat exchangers can be further divided into open-loop and closed-loop systems. Open-loop installations are used in buildings with a high demand for fresh air, such as hospitals, industrial plants, and public utility buildings. In these systems, air is drawn from an outdoor inlet and supplied to the building via a pipe system. Closed-loop systems that recover heat from spent air can be used for ventilation in residential buildings. Closed-loop systems increase the energy efficiency of buildings [8, 28]. The performance of EAHE systems is analyzed in exergetic and economic assessments [29-30]. Ozgener et al. (2011) found that in EAHE systems for greenhouse heating, exergy destruction results mainly from blower losses and heat exchange losses [31]. The efficiency of EAHE is also tested in specific locations because their thermal performance can be substantially overestimated when the dynamic interactions between a heat exchanger and the environment are neglected [24, 32-33].

A dedicated laboratory station was developed at the University of Warmia and Mazury in Olsztyn, Poland, to investigate the energy efficiency of EAHE. A measurement system was designed for analyzing changes in the temperature and volume of air passing through the EAHE. Measurement data were registered to determine the actual transfer of energy from the ground to the ventilation system for heating purposes in winter and for cooling purposes in summer. This paper analyzes the results of measurements conducted between 1 July and 30 September 2016 and compares them with the results of theoretical calculations based on the International Ground Source Heat Pump Association (IGSHPA) method [34]. (Data were not recorded between 6 and 11 July 2016 due to technical problems.)

Laboratory Station

The laboratory station comprised the AwaduktThermo system of ground-coupled pipes buried in the ground at a depth of 2.10 m (at the point of intersection with the building's cellar wall) to 2.28 m (rainwater tank). The pipes had a downward slope in the direction of the rainwater tank in the vicinity of the AwaduktThermo air inlet tower. The pipeline had a total length of 41 m, with an external pipe diameter of 0.2 m and four 90ºC elbows pipes.

The measuring system comprised resistance temperature detectors mounted on the external northern wall of the building and by the EAHE outlet supplying air to the ventilation unit. In the EAHE, the air flow rate was measured with a detector installed inside the pipeline by the inlet to the ventilation unit in the cellar. The measurements were registered by a Siemens controller in real time and were averaged in hourly intervals.

Analyzing Measured Data

We used a database of hourly air temperature and air flow rate measurements conducted between 1 July and 30 September 2016. The heat gain from the EAHE was determined on an hourly basis during the analyzed period with the use of the following formula [35]:

$$Q_w = \frac{\dot{m} \cdot c_p \cdot (T_w - T_e) \cdot z}{3{,}6} \quad \text{Wh} \tag{1}$$

…where:
Q_w – heat gain from the EAHE (Wh)
$\dot{m}$ – the mass flow rate of air (kg/s)
c_p – specific heat of air determined based on the formula kJ/(kg·K)
T_w – air temperature measured at the EAHE outlet (ºC)
T_e – air temperature measured at the air inlet (ºC)
z – averaging interval (1 hour)

Theoretical Calculations for a Typical Meteorological Year

Theoretical heat gain from the EAHE was calculated with the IGSHPA method, which is used to select ground-coupled heat exchangers for heat pump systems [34]. Heat gain in every hourly interval of the analyzed period was determined with the use of the IGSHPA method based on average hourly temperatures of ambient air T_e in a typical meteorological year (according to mr.gov.pl). The method of determining the above values was described by Nawarowski [36]. The average hourly temperatures of air at the EAHE outlet T_w were determined based on

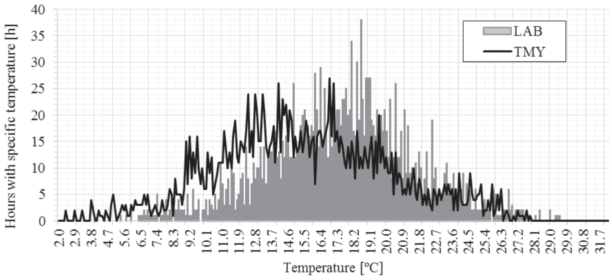

Fig. 1. Distribution of air temperatures between July and September 2016 in Olsztyn based on the performed measurements and a meteorological database (TMY). (Source: own elaboration)

the IGSHPA method [34]. The measured parameters were used in calculations according to the method described by Biernacka [37-38].

Results and Discussion

Weather Conditions

The frequency distribution of average hourly temperatures of ambient air measured between 1 June and 30 September 2016 and calculated based on data for a typical meteorological year [39] is presented in Fig. 1. A comparison of the data in Fig. 1 indicates that ambient temperatures in the evaluated period differed from a typical meteorological year. The lowest recorded temperature of 5.4ºC occurred for only one hour, whereas in a typical meteorological year the lowest temperature (5.4ºC) lasted two hours. In a typical meteorological year, the lowest temperature was 2.4ºC, and it lasted for two hours, whereas temperatures below 5.4ºC were recorded over a period of 30 hours. The average temperature of ambient air measured between July and September 2016 was 17.5ºC, whereas the average temperature in a typical meteorological year was 15.5ºC-2.0ºC lower than the measured temperature. The highest air temperature in the evaluated period was 29.5ºC and it occurred for one hour, whereas the highest temperature in a typical meteorological year was 27.9ºC, which lasted one hour and was 1.6ºC lower than the measured temperature. In the experiment, temperatures higher than 29.5ºC occurred for three hours. The most frequently registered (38 hours) temperature in the evaluated period was 18.6ºC, whereas the most frequent (27 hours) temperature in a typical meteorological year was 16.9ºC.

Amount of Heat Transferred by the Ground Exchanger to Flowing Air

Daily heat gains from a ground exchanger calculated based on laboratory measurements and a database for a typical meteorological year are presented in Fig. 2 and Table 1. Heat gain was determined at 182.07 kWh based on the measurements conducted between July and September 2016, and it was calculated at 197.49 kWh (15.42 kWh higher) based on the database for a typical meteorological year. Cooling load was determined at -12.22 kWh in the analyzed period and at -225.82 kWh (213.60 kWh higher) based on data for a typical meteorological year. The average daily heat gain determined in the experiment during the analyzed period was 1.63 kWh with maximum heat gain of 4.69 kWh and maximum cooling load of -2.52 kWh. The calculations based on data for a typical meteorological year revealed average daily heat gain of -0.33 kWh (cooling), with maximum heat gain of 10.34 kWh and maximum cooling load of -11.99 kWh. Monthly heating and cooling loads in the analyzed period are presented in Table 1.

Distribution of Air Temperatures Measured at the Air Inlet and the EAHE Outlet and Calculated with the use of the IGSHPA Method

The distribution of air temperatures measured at the air inlet and the EAHE outlet and calculated based on the database for a typical meteorological year is presented in Fig. 3. A comparison of temperatures measured at the EAHE outlet and the air inlet indicates that fluctuations in ambient temperature induced changes in the temperature measured at the EAHE outlet and the air inlet, although the corresponding changes were less extensive due to the thermal behavior of soil. The minimum temperature at the EAHE outlet was 9.3ºC, and the maximum temperature was 27.1ºC. The difference in air temperature between the EAHE outlet and the air inlet ranged from -2.4ºC (cooling) to 4.4ºC (heating). The smallest difference was observed when the temperature at the air inlet suddenly increased by 9.9ºC (from 19.6ºC to 29.5ºC) on 2 July between 5 a.m. and 5 p.m., and when the temperature at the EAHE outlet

Table 1. Monthly heating and cooling loads between July and September 2016.

	Laboratory measurements		Theoretical calculations for a typical meteorological year	
	Cooling load (kWh)	Heat gain (kWh)	Cooling load (kWh)	Heat gain (kWh)
July 2016	-6.42	37.24	-57.58	44.00
August 2016	-4.45	62.42	-79.92	58.27
September 2016	-1.35	82.41	-88.32	95.22

(Source: own elaboration)

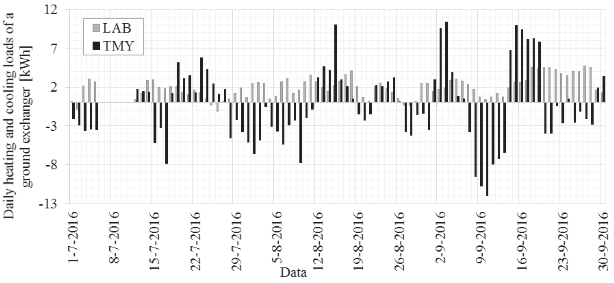

Fig. 2. Daily distribution of heating and cooling loads from a ground heat exchanger between July and September 2016 measured in the laboratory of the Department of Civil Engineering and Building Engineering Physics of the University of Warmia and Mazury in Olsztyn (source: own elaboration).

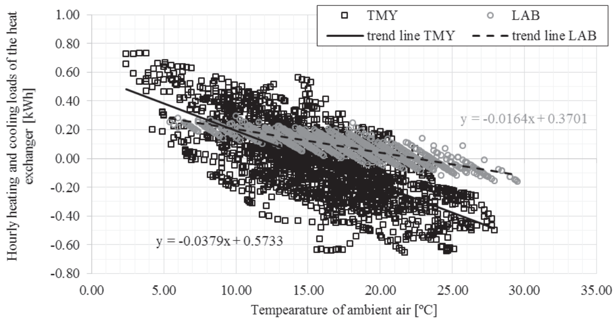

Fig. 4. Hourly heating and cooling loads measured in the experiment (LAB) and calculated based on mean hourly data for a typical meteorological year (TMY) (source: own elaboration).

increased by 7.1ºC in the corresponding period (from 19.9ºC to 27.1ºC). The greatest difference in temperature was noted during the steepest decrease in ambient temperature of 8.9ºC (from 18.9ºC to 10.0ºC) between 3 p.m. on 17 September and 7 a.m. on 18 September. During that period, the temperature at the EAHE outlet decreased by only 5.1ºC (from 19.5ºC to 14.4ºC).

The distribution of temperatures at the EAHE outlet for a typical meteorological year revealed lower temperatures than the measured data. The fluctuations in ambient temperature during a typical meteorological year were similar to those noted within the measured range. In the calculations, the temperature difference between the air inlet and the EAHE outlet ranged from -10.3ºC to 11.0ºC. The lower limit was approximately 4.3-fold higher than the measured values, whereas the upper limit was approximately 2.5-fold higher than the measured values.

The noted differences can be partially attributed to variations in the analyzed data. In the experiment, the minimum temperature of 5.4ºC was determined at 07:00 on 27 September. The temperature at the EAHE outlet reached 9.3ºC during the above measurement. Based on data for a typical meteorological year, the corresponding temperature was 10.8ºC, and the temperature at the EAHE outlet reached 11.4ºC. The differences in the temperature of ambient air were not extensive enough to justify such considerable variations in temperature at the EAHE outlet.

Heat gains measured in the experiment and calculated with the use of the IGSHPA method based on data for a typical meteorological year.

In Fig. 4, the trend lines representing hourly heat gains measured in the experiment and calculated based on mean hourly data for a typical meteorological year are similar, although laboratory results deviate toward higher average values of hourly temperatures. The maximum hourly heat gain was determined at 0.29 kWh in the experiment and at 0.73 kWh in theoretical calculations. The maximum hourly cooling load was determined at -0.16 kWh based on measured data and at -0.65 kWh based on data for a typical meteorological year. The average heat gain was 0.08 kWh in the experiment and the average cooling load was -0.01 kWh for a typical meteorological year.

An analysis of trend lines in Fig. 5 indicates the greatest discrepancy between heat gains relative to air temperature at the EAHE outlet. Laboratory measurements with a near-horizontal line and significant scatter of measurement points demonstrate weak correlations between heat gains with a decreasing trend in the direction of higher air temperature at the EAHE outlet. The highest hourly heat gain (0.29 kWh) was determined when air temperature at the EAHE outlet reached 14.4ºC, whereas the highest hourly cooling load

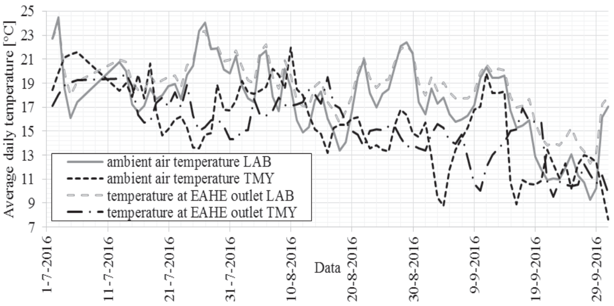

Fig. 3. Distribution of average daily temperature measured at the air inlet and the EAHE outlet (LAB) and calculated based on data for a typical meteorological year (TMY) (source: own elaboration).

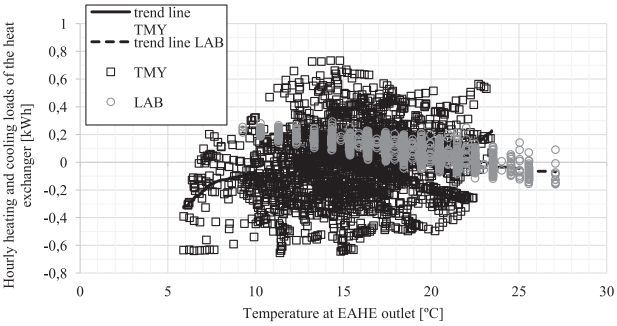

Fig. 5. Heating and cooling loads from the ground heat exchanger based on data for a typical meteorological year (TMY) and the values measured in the experiment (LAB) relative to air temperature at the EAHE outlet (source: own elaboration).

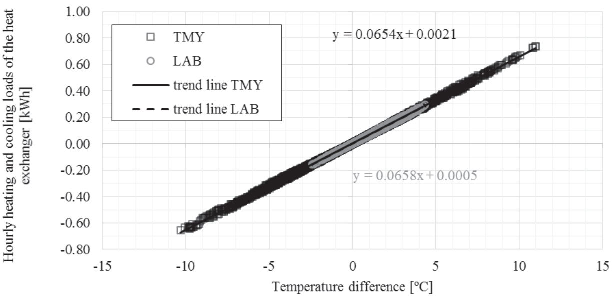

Fig. 6. Heating and cooling loads from a ground heat exchanger based on data for a typical meteorological year (TMY) and the values measured in the experiment (LAB) relative to differences in air temperature between the EAHE outlet and the air inlet (LAB) (source: own elaboration).

(-0.16 kWh) was observed for the highest temperature at the EAHE outlet of 27.1ºC.

The curves in Fig. 5 were fitted with the application of GMDH Shell software, a professional neural network software that solves time series predicting and data mining tasks by building artificial neural networks and applying them to the input information [40].

In the results calculated based on data for a typical meteorological year, the trend line slopes downward in the direction of lower air temperature at the EAHE outlet. The highest hourly cooling load (-0.65 kWh) was noted when the temperature at the EAHE outlet reached 11.4ºC. The highest hourly heat gain (0.73 kWh) was determined when the temperature at the EAHE outlet reached 14.8ºC.

Heating and cooling loads from the ground heat exchanger calculated based on data for a typical meteorological hear and data measured in the experiment based on the difference between air temperature at the EAHE outlet and the air inlet are presented in Fig. 6. Trend lines are similar, and data scatter relative to trend lines is not significant. The greatest differences were observed in the temperature at the EAHE outlet and ambient air temperature. The difference in measured data ranged from -2.42ºC (with the highest hourly cooling load of -0.16 kWh) to 4.36ºC (with the lowest hourly heat gain of 0.29 kWh). In the calculations based on data for a typical meteorological year, the smallest difference in temperature of -10.31ºC was similar to that noted in the experiment (with the highest hourly cooling load of -0.65 kWh), whereas the greatest difference of 11.0ºC significantly exceeded the measured results (with the highest hourly heat gain of 0.73 kWh).

Conclusions

1) The analyzed period (July-September 2016) was unusually warm in comparison with data for a typical meteorological year. The average temperature of ambient air measured in the experiment was 2.0ºC higher than the 30-year average. The maximum measured temperature (29.5ºC) was 1.6ºC higher than the maximum temperature in the corresponding period of a typical meteorological year. An analysis of temperature frequency distributions revealed that the measured temperatures in the range of 13-22ºC and the calculated temperatures in the range of 9-20ºC occurred for more than 10 hours. The most frequently measured temperatures were around 3ºC higher than the temperatures characteristic of a typical meteorological year. The most common measured temperature (38 hours) was 18.6ºC, whereas the most frequent temperature (27 hours) in a typical meteorological year was 1.7ºC lower.
2) A comparison of mean daily heating and cooling loads from the EAHE points to average daily heat gain of 1.63 kWh with maximum heat gain of 4.69 kWh and maximum cooling load of -2.52 kWh. The calculations based on the IGSHPA method produced an average daily cooling load of -0.33 kWh, with maximum heat gain of 10.34 kWh and maximum cooling load of -11.99 kWh. The total heat gain from the EAHE was only 8% lower than that determined in theoretical calculations. The greatest differences were observed in cooling loads. In the experiment, cooling load was determined at -12.22 kWh, and it accounted for only 5.4% of the cooling load calculated with the use of the IGSHPA method. The very low cooling load in the experiment could be attributed to round-the-clock operation of fans in spring, which increased ground temperature.

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