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AIR, GROUND MASSIF LOW-TEMPERATURE ENERGY SOURCES

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Abstract
The aim of this study was to analyze and compare the impact of two low-temperature energy sources, air and linear horizontal ground heat exchanger (HGHE), on the energy effect of a heat pump and their contribution to fulfilling the objectives of reducing fossil fuel consumption. The results of operational verification and statistical analysis showed that linear HGHE is a more favorable low-temperature energy source for heat pumps than air in terms of expected energy effects. The set of temperatures of the heat transfer fluid from a linear HGHE showed higher average and median values, and less variability in comparison with the corresponding set of air temperatures. Temperatures of the fluid in linear HGHE were positive over the entire heating period and more than 73% of the data were higher than the temperatures of air. A higher value of the energy effect of the linear HGHE expressed by a comparative coefficient of performance, ε_h *of reversed Carnot cycle, also showed higher benefits of this low-temperature energy source with more significant impact on consumption of fossil fuels.*

Key words: *low-temperature energy source; temperature; air; ground massif; heat pump; heating factor; Carnot cycle.*

INTRODUCTION

Water and air, and both ground and rock massifs are important and frequently used low-temperature energy sources for heat pumps. Exploitation of surface or underground water as low temperature heat source is very limited because of the nature of its availability, complex legislation, variability of water flow and instability in heating power. Installation of the energy system is easier and cheaper when using air. The environmental aspect of the use of air is also important. This system affects the heat balance of the surrounding environment minimally. The energy delivered from the air to the heat pump evaporator returns to the environment as thermal losses in the exchanger. Horizontal ground heat exchangers (HGHE) with different pipe configurations, most commonly linear and slinky types, installed at depths of 1 to 2 m are used in Europe to obtain thermal energy from the ground. In the rock mass, vertical heat exchangers, mainly in the form of single or double U-tubes, installed in boreholes of depths of 70 to 200 m, are used to obtain heat energy. The heat transfer fluid, which is heated and fed to the heat pump evaporator flows through both of the heat exchanger types.

By 2007, the most annually installed heat pump type in the Czech Republic were those for which the low-temperature source for the evaporator was ground or rock massif. In 2006 alone, 4.82% of installed heat exchangers were of air to air heat pumps, 38.07% of air to water, 53.79% of ground to water and 3.32% of water to water heat pumps. However, in subsequent years, sharp falls were recorded in the installation of ground to water heat pumps. In 2014, the shares in total heat pump installation of ground to water, water to water and air to water heat pump types were, respectively 19.58, 0.59% and 79.83% (Bufka, Rosecky, 2016). Similar trends in changes in the share of low-temperature energy sources for heat pumps were also reported by L u n d and B o y d (2015) in the global geothermal energy use report. The main reason why investors prefer air to water heat pumps is because of its significantly lower investment costs compared to other low-temperature sources. Furthermore, its installation is easy and simple. For this reason, manufacturers have payed exceptional care to innovations and expansion of the possibilities of using air to water heat pumps. Success has been particularly achieved in the use of air as a low temperature source. Contemporary heat pumps can work with air at temperatures -15 °C or lower without any problem and can be delivered as block, compact units already filled with refrigerant, which significantly simplifies installation.

The primary objective of using renewable energy sources is first of all to reduce fossil fuel consumption. The open question is how the above-mentioned low-temperature sources contribute to meeting the goals of reducing fuel and energy consumption.
Modelling of heat transfer fluid temperatures in HGHEs and VGHEs (Vertical Ground Heat Exchangers) was addressed by F l o r i d e s et al. (2013). In particular, they evaluated the effect of linear HGHE pipe spacing on the fluid temperature. Their results indicated that increase in the HGHE tube spacing caused decrease in the temperature of the heat transfer fluid. B a n k (2012) stated that the temperature of the HGHE heat transfer fluid varied between +5 and -5 ° C during operation. VDI (2001) recommended that the temperature of the heat transfer fluid from the heat pump into the ground loop should not differ by more than ± 12 ° C from temperature of ground mass without HGHE. The performance and economic comparison of low-temperature energy sources (VGHE, HGHE, air) for heat pumps were dealt with by P e t i t and M e y e r (1998) who pointed out that whereas VGHEs provided the best performance, HGHE achieved more favorable heating factor (COP) than VGHE compared to air and VGHE as well. Also HGHE appeared to be the most cost effective.
The aim of this article was to analyze and compare the influence of two low-temperature energy sources used in heat pumps on the energy effect of the heat pump and their contribution to meeting targets of reducing fossil fuel consumption. In terms of frequency of use, air and linear HGHE with configuration most commonly used in the Czech Republic were selected for analysis and comparison.

MATERIALS AND METHODS

Theoretical analysis
The energy effect of the ideal reversed Carnot cycle operating between the temperatures T_p and T_o at which we supply and dissipate the heat can be expressed by equations (1) and (2):

$$\varepsilon_c = \frac{T_p}{\left|T_p - T_o\right|} \quad (1)$$

$$\varepsilon_h = \frac{T_o}{\left|T_p - T_o\right|} \quad (2)$$

Factor ε_c (cooling) is used to express the energy effect during cooling and ε_h (heating) when expressing the effect during heating. It follows from both equations that the effects are dependent on the temperature difference between T_p and T_o. The smaller the temperature difference - which represents work input brought into the cycle - the greater the effect of the ideal Carnot cycle.
The use of the ideal Carnot cycle is advantageous in our case because it enables to express the energy effects only depending on the temperatures mentioned. At the considered constant temperature T_o, the energy effect evaluated when using the cycle for heating is dependent on temperature- T_p.

Materials and methods of measurement

The linear horizontal ground heat exchanger was made of a polyethylene tubing PE 100RC 40x3.7mm (LUNA PLAST a.s. Hořín, Czech Republic) resistant to point loads and cracking. It was not placed in a sand bed. Exchanger tubing with a total length of 330 m (41.473 m^2) is installed at a depth of 1.8 m in 3 loops with a spacing of 1 m. The length of each loop was 54.62 m. The heat transfer fluid flowing through the exchanger was a mixture of 33% ethyl alcohol and 67% water. The MTW 3 electronic heat meter (manufactured by Itron Inc., Liberty Lake, USA) was used to measure the total heat flow through the horizontal heat exchangers, recording the flow and temperature of the heat transfer fluid at the outlet t_{L1} and the inlet t_{L2} to the ground heat exchanger. The temperature of the ground massif t_g at a distance of 10 m from the linear HGHE was measured by the GKF 200 temperature sensor (manufactured by GREISINGER electronic GmbH, Regenstauf, Germany) and recorded by the ALMEMO 5990 measuring station. The subject of the evaluation and statistical analysis were the exit temperatures of the fluid from the linear HGHE t_{L2} and the ambient temperatures t_e, corresponding to the temperature T_p in equation (2). Ambient temperatures were measured at a height of 2 m above the ground surface and 20 m away from horizontal ground exchangers by the ALMEMO FHA646AG sensor (manufactured by AHLBORN Mess-und Regulungstechnik, Holzkirchen, Germany). All temperatures were recorded in quarter-hour intervals and an hourly average was calculated from these values. The test was conducted for 217 days in the heating period from 17 September 2012 to 22 April 2013, so the basic statistical set for the evaluation of individual low-temperature energy sources were 5,208 temperature values. The results were evaluated using STATISTICA (StatSoft, Inc. 2013) and MS Excel (Mošna, 2017). Basic descriptive characteristics of the location, variability and distribution of the data sets were determined. The energy effect of the comparative ideal reversed Carnot cycle expressed by the heating factor ε_h according to (2) was also evaluated, where a constant temperature T_0 = 55 °C was considered.

RESULTS AND DISCUSSION

Basic descriptive statistics of temperature data of two low-temperature energy sources are summarized in Tab. 1 and in box plots (Fig. 1).

Tab. 1 Basic statistical characteristics of the data sets

Characteristics	Low-temperature energy source	
	Air	Linear HGHE
Mean $\bar{x}$ (°C)	5.47	8.13
Standard deviation S (K)	6.35	4.51
Variation coefficient VK (%)	116.12	55.43
Minimum x_{min} (°C)	-15.80	1.67
Maximum x_{max} (°C)	28.60	17.82
Range R (K)	44.40	16.15
Median $\tilde{x}$ (°C)	5.10	6.37
Mode $\hat{x}$ (°C)	6.00	6.00
Lower quartile Q_1 (°C)	1.00	4.62
Upper quartile Q_3 (°C)	9.10	11.45
Interquartile range Q_3 - Q_1 (K)	8.10	6.83
Coefficient of skewness A (-)	0.55	-0.76

A considerable variance was observed in the air temperatures data set; the standard deviation S was greater than the arithmetic mean, and the variation coefficient VK thus exceeded 100%. On the other hand, the variance in the data of the linear HGHE was significantly lower; the standard deviation S was approximately half the arithmetic mean which corresponded to a VK of approximately 55%.

The high variation in air temperatures negatively affected the process of heat transfer in the evaporator particularly in terms of changes in differential temperatures of air supplied to the evaporator and the evaporation temperature of working fluid of the heat pump.

The box plot (Fig. 1) shows the medians, quartiles and extreme values and thus gives general information on the both data sets. Firstly, there is a clear difference in the range values R. It is also apparent that a half of the air temperature data are within the interval from 1.00 to 9.10 °C and half of the HGHE temperature data are within the interval from 4.62 to 11.45 °C. The values of the lower and upper quartiles Q_1 and Q_3 in the linear HGHE data are higher than the corresponding values in the air temperature data (by 3.62 and by 2.35 K, respectively). The interquartile ranges $Q_3 – Q_1$ in both data sets were not much different (about 1.3 K). In the air temperature data, the interquartile range represented only 18.24% of the range *R*, whereas the interquartile range in the linear HGHE data set corresponded to 42.29% of *R*. This comparison also demonstrated the lower temperature variability in the linear HGHE.

Both aspects, i.e. the position of the interquartile range towards higher temperatures and lower variability of temperatures, had a positive influence on the effect of the heat pump.

From the point of view of efficient use of low-temperature sources, the interval and temperature distribution between the lowest temperature x_{min} and the lower quartile Q_1, containing 25% of all temperature values, were also significant. In the air temperature data set, 25% of the data were within the interval from -15.80 to 1.00 °C; whereas in the linear HGHE temperature set within the interval from 1.67 to 4.62 °C. Low evaporation temperatures of the heat pump working medium, together with the high frequency of low-temperatures of air with high relative humidity caused freezing of the evaporator and consequently a more frequent defrosting of the equipment was necessary. Due to the increase in electric power consumption for reverse operation of the heat pump, the effect of the whole system decreased.

The large interval between upper quartile Q_3 and the highest air temperature x_{max} from 9.10 to 28.60°C can be explained by higher air temperatures at the beginning and at the end of the heating season. In the case of linear HGHE, this interval was significantly smaller, i.e. from 11.45 to 17.82 ° C.

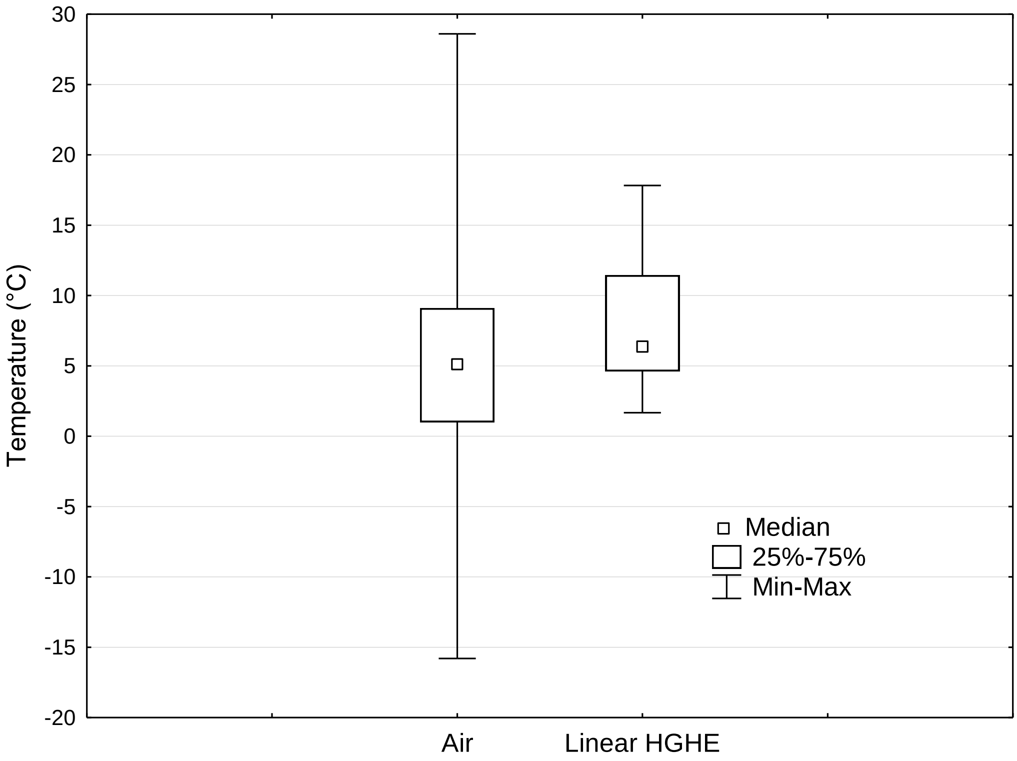

Fig. 1 Box-whisker plots of temperatures of the low-temperature sources

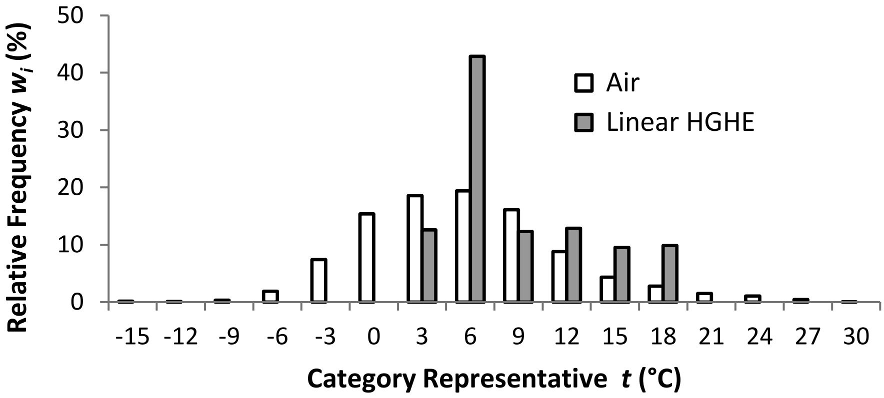

Fig. 2 Histograms of temperature relative frequencies in low-temperature sources

The distributions of the temperature data were further depicted in histograms (Fig. 2) generated from data sorted into intervals of length 3K. The mode $\hat{x}$ in both datasets was estimated as the center of the interval from 4.50 to 7.50°C with a frequency of 42.86% in the linear HGHE data set and a frequency of only 19.37% in the air temperature set. The histogram shape and the relations $\hat{x} \cong \tilde{x} \cong \bar{x}$, they both indicated a symmetric distribution of the air temperature data. On the other hand, the data of linear HGHE were mostly concentrated to the left of the mean and $\hat{x} < \tilde{x} < \bar{x}$ (see Fig. 2 and Tab. 1), hence the data distribution can be considered as left-handed asymmetric one. Nevertheless, a right-handed skewness has not been proven (see coefficient *A* close to zero in Tab. 1).
Temperatures of the heat transfer fluid in the linear HGHE were positive with the average value of 8.13°C which was about 3 K greater than stated by B a n k s (2012). With respect to HGHE pipe spacing, the temperature of the heat transfer fluid were in agreement with results presented by F l o r i d e s et al. (2013). When the temperatures of the heat transfer fluid in the linear HGHE and air systems throughout the measured period were compared, 73.6% of the HGHE temperatures were observed to be higher than the air temperatures. This corresponded to the significantly higher average of HGHE data than the average of the air data (confirmed by t-test on common level of 5%).
Higher temperatures of the heat transfer fluid are associated with higher heating factor ε_h (2). Therefore, the frequency of higher temperatures in the linear HGHE confirmed greater energy effects of this low-temperature source. For both low-temperature sources, the heating factors ε_h were calculated according to (2) and evaluated throughout the monitored heating period and especially in the reduced part where the air temperatures were less or equal to zero, which represented 20.12% of the data. The results, i.e. the heating factor averages ε_h and standard deviations *S*, are summarized in Tab. 2.

Tab. 2: Heating factors ε_h and standard deviations *S* during the whole heating period and from reduced data at ambient temperatures $t_e \leq 0$ °C

	Whole heating period		Reduced data, $t_e \leq 0$ °C	
	ε_h (-)	*S* (-)	ε_h (-)	*S* (-)
Air	6.75	1.00	5.71	0.22
Linear HGHE	7.07	0.74	6.59	0.28

The energy effect of air was influenced by higher air temperatures at the beginning and at the end of the heating period when almost 10% of the data exceeded the maximum temperature of the HGHE heat transfer medium. At negative air temperatures, the heating factor dropped below to the average value of 5.71±0.22. Mean values of heating factor ε_h of air were lower than at linear HGHE and that difference was more pronounced in the reduced data (t-tests also confirmed significant differences).
In the context of the recommendation of the German standard VDI (2001) cited earlier, the temperature differences t_{L1} of heat transfer fluid exiting the heat pump and the temperatures t_g of the ground

massif measured outside HGHE at the same depth of the massif were evaluated. The statistical analysis revealed that the average temperature difference $\Delta t_{\phi} = t_g - t_{L1}$ = 3.52±2.68 K, maximum difference Δt_{max} = 9.46 K. Hence, the temperature differences did not exceed the recommended range.

CONCLUSIONS

The results of the operational verification and analysis have shown that linear HGHE is a significantly more favorable low-temperature energy source for heat pumps than air in terms of the predicted energy efficiency benefit. The set of temperatures of heat transfer fluid of linear HGHE had less variability, the upper and lower quartiles and the median values were higher in comparison with the corresponding air temperatures. Fluid temperatures were positive throughout the heating period and more than 73% of the values were higher than corresponding air temperatures. The higher value of the energy effect in the linear HGHE, expressed by the heating factor ε_h of the comparative reversed Carnot cycle, demonstrated higher benefits of this low-temperature energy source. These favorable characteristics of a fluid temperature set from linear HGHE had a positive effect on the operation of the heat pump and on reduction of fossil fuels consumption both in the heating system and for the heat pump drive. The achieved results meet the objectives of the research papers presented in the introduction of the article. It is now necessary to seek ways to promote the application of low-temperature energy sources for heat pumps since they are more efficient than the currently widely used air.

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