EXPERIMENTAL AIR GROUND HEAT EXCHANGER AND ITS CONSTRUCTION

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The article reports on a newly realized experimental ground heat exchanger (GHE), which has been built up as an accessory of an experimental low-energy dwelling of Faculty of Mechanical Engineering, Brno University of Technology (FME BUT), and analyzes some aspects of its project, especially the choice of proper tubing. Based on a simplified computational model, the impact of four most employed tubing types on a performance and an effectiveness of the GHE has been judged and benefits of particular tubing types were compared with their investment costs. Finally, using of KG-Systém (PVC)® SN4 was evaluated as the best variant.

Keywords: *ground heat exchanger, ventilation, energy savings, anti-frost protection*

1. Introduction

Ground heat exchangers (GHE) exploit a relatively stable temperature distribution in adequate depth under the ground level. Temperature changes that proceed on the Earth's surface are attenuated with increased depth and in the level of 2–2.5 m are relatively low. Furthermore, the thermal lag of the soil induces the time shift of the temperature course, and so the maxima (or minima) of ground temperature are delayed in comparison to annual course of average air temperatures.

These effects enable using the ground for pre-heating of ventilating air during winter and transitional seasons, and for its cooling in summer, respectively. This principle brings not only energy savings; it is often used for anti-frost protection of consequent HVAC devices (e.g., the channel heat recovery exchanger) and as auxiliary air condition as well.

At present, two variants of GHEs are employed: the *air GHE* is created as simple air tubing embedded in the ground (with adequate air inlet and outlet arrangement), and the passed air is warming up directly, with the heat transferred from the surrounding soil. Alternatively, the *brine GHE* consists of the ground pipeline arrangement, which is passed with non-freezing liquid; consequently, the heat (or cold) acquired is transferred to the air using common liquid/air heat exchanger (which is usually placed in the building). Both types of GHEs can be arranged in circulation configuration, which is very useful for summer cooling of interior air.

2. Experimental air ground heat exchanger of the FME BUT

Ground heat exchangers represent relatively novel component of HVAC systems (at least in the Czech Republic), and an experience with its operation, its benefits, as well as potential

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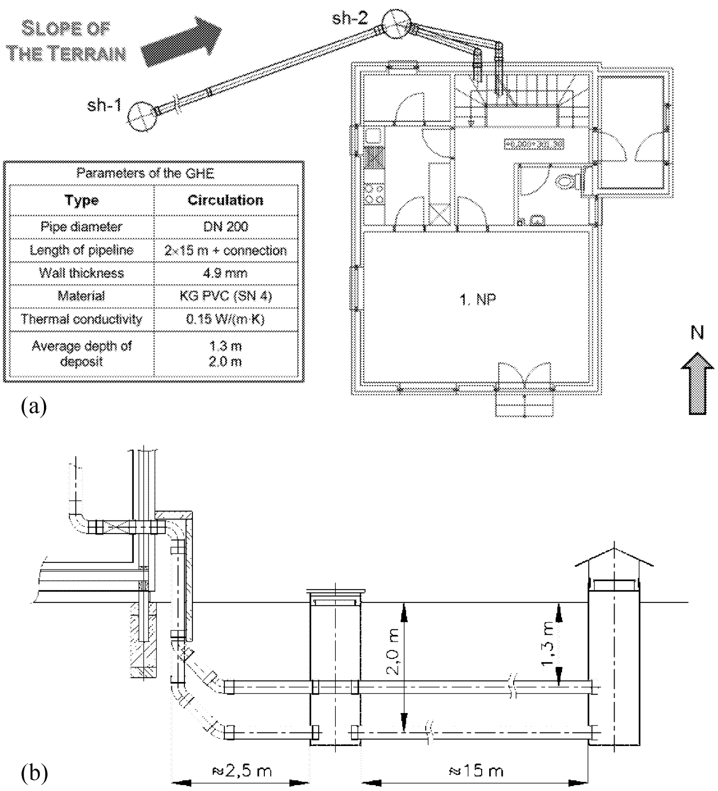
hazards is very poor. The students of HVAC specialization at the FME BUT have not yet had an opportunity to familiarize with it.

Therefore, a project of own experimental air GHE in circulation configuration was designed at the department of thermodynamics and environmental engineering of the Energy Institute FME BUT, and was realized under the grant No. 3206/2011/G1 provided by Universities Development Fund of Ministry of Education, Youth and Sports CR in 2011.

Geometry of the ground heat exchanger (Fig. 1a) is conformed to the free exploitable area surrounding the experimental low-energy dwelling at the FME BUT, where it was connected. The GHE consists of two pipes of DN 200 diameter, which are dug one over the second in depths (measured to the center line) of 1.3 and 2.0 m, respectively, under the ground level (Fig. 1b). The direct parts of both pipes are attached on both ends to chambers (the connecting one in the edge of the pipelines, and the reversing one at the end). Both parts of the upper pipeline, which is intended for forward stream of air, are in the connecting chamber join with flexible connection, fitted with a syphon for drainage of condensed water. The bottom pipeline (for backward stream) is connected simply with the chamber. The air is moved with a fan installed at the piping outlet in the building. The flow rate is regulated using a stepwise controller.



Parameters of the GHE

Type	Circulation
Pipe diameter	DN 200
Length of pipeline	2×15 m + connection
Wall thickness	4.9 mm
Material	KG PVC (SN 4)
Thermal conductivity	0.15 W/(m·K)
Average depth of deposit	1.3 m 2.0 m

Fig.1: Ground and profile plane of described GHE

In this configuration, the air is sucked from the building façade or, in the circulating mode (optional using switchable T-valve), directly from the upper part of the building. The total air path in the ground is then approx. 35 m (2×15 m direct pipes + edged parts of the pipelines). However, this configuration can be relatively easily changed for suction of air from the reversing chamber (through one or both pipelines). In this case, an inlet slot with a net would be installed in the chamber. This way, 7 operating regimes of the GHE can be realized in total.

As a part of the project, a monitoring system of the GHE was installed. Temperature and relative humidity of passed air is measured in 6 points (at the inlet and outlet, and in four intermediate points). The flow rate is calculated from the flow velocity within the pipe, measured with the thermo-anemometer AHLBORN. Besides, four ground temperature probes are embedded, which measure the temperature stratification of soil in affected, as well as in unaffected area. The detailed description of whole plant can be found in [1].

3. Design of the GHE

The factors that influence operating parameters of the GHE and its energy benefit can be sorted into two groups. The first group contains the factors, which are determined by extrinsic conditions: the type of soil, the bedding depth (with respect to feasibility of excavation commonly chosen about 2 m), required airflow rate and working period, and climatic conditions. In the second group there are the parameters, which can be chosen: the length of the GHE, a material and a diameter (and a number, respectively) of pipes, and the airflow velocity. Thus, the latter ones could be a matter of the design. However, it should be noted that the number and the diameter of tubes (which both determine the total flow cross-section), the airflow rate, and air velocity, respectively, are mutually coupled, and so only two of them can be chosen; the third quantity results from the rest.

3.1. Computational model of the GHE

Simplified computational model of air ground heat exchanger was developed for numerical simulation of its operation and asset of energy savings [2]. The GHE is considered as a simple circular tube with constant wall temperature, equal to the actual temperature of the surrounding soil, T_S, which is passed with an air. The inlet and outlet parts, as well as possible condensation of water vapor on walls, are neglected.

Under these simplifying assumptions, the outlet mean air temperature, $\overline{T_\mathrm{a,OUT}}$, would be

$$\overline{T_\mathrm{a,OUT}} = T_\mathrm{S} - (T_\mathrm{S} - T_\mathrm{a,IN}) \exp\left(-\frac{\bar{h}_\mathrm{a}\, S_\mathrm{p}}{\dot{m}_\mathrm{a}\, c_\mathrm{p,a}}\right) \tag{1}$$

where $\bar{h}_\mathrm{a}$ stands for mean value of heat transfer coefficient (HTC) between the tube wall and the air.

However, this relationship does not take into account the thermal resistance of a tube wall. Therefore, the Eq. (1) was modified using overall HTC, $\bar{h}_\mathrm{o}$, due to equations

$$\frac{1}{\bar{h}_\mathrm{o}\, \pi\, D_\mathrm{i}} = \frac{1}{\bar{h}_\mathrm{a}\, \pi\, D_\mathrm{i}} + \frac{\ln \dfrac{D_\mathrm{o}}{D_\mathrm{i}}}{2\pi\, k_\mathrm{t}}\ , \tag{2a}$$

$$\frac{1}{\bar{h}_\mathrm{o}} = \frac{1}{\bar{h}_\mathrm{a}} + \frac{D_\mathrm{i}\, \ln \dfrac{D_\mathrm{o}}{D_\mathrm{i}}}{2\, k_\mathrm{t}} \tag{2b}$$

instead of simple wall-air HTC, $\bar{h}_\mathrm{a}$. Here, the first right-hand term represents the thermal resistance of the convective boundary layer, and the second one the thermal resistance of the tube wall.

The value of $\bar{h}_{\mathrm{a}}$ is due to

$$\bar{h}_{\mathrm{a}} = \frac{\overline{\mathrm{Nu}}_{\mathrm{D}}\, k_{\mathrm{a}}}{D_{\mathrm{i}}} \tag{3a}$$

where an average Nusselt number, $\overline{\mathrm{Nu}}_{\mathrm{D}}$, can be enumerated using common relationships for internal flow. Because Reynolds numbers in the range of 22,000 to 28,000 can be supposed (for air flow rate of $200\,\mathrm{m}^3/\mathrm{h}$, inner tube diameters according Tab. 1 and air temperatures, that can be taken into account), the Dittus-Boelter equation [3] for turbulent flow was applied:

$$\overline{\mathrm{Nu}}_{\mathrm{D}} = 0.023\,\mathrm{Re}_{\mathrm{D}}^{0.8}\,\mathrm{Pr}_{\mathrm{a}}^{n} \ . \tag{3b}$$

Here, the exponent n acquires the value of 0.4 for winter regime (air heating), and $n = 0.3$ for summer operation (cooling of air).

Further simplification relates to the temperature of surrounding soil, T_{S}. Its exact determination (including the impact of the GHE operation) is possible by numerical simulation only. However, its implementation is conditioned by detailed knowledge of boundary conditions on the ground surface (i.e., not only air temperatures, but solar radiation intensities, rainfall or thickness of snow mantle etc. as well).

Therefore, the simplified model based on the conception of the ground as a semi-infinite solid, which is subjected to year-long sinusoidal variation of average air temperatures, was adopted [4], [5]. Accordingly, the soil temperature, T_{S}, in the depth of z under ground level is calculated as

$$T_{\mathrm{S}}(z,t) = T_{\mathrm{M}} - T_{\mathrm{A}}\,\exp\left(-\frac{z}{z_{\mathrm{p}}}\right)\cos\left(\frac{2\pi}{\tau}\,(t-\tau_{\mathrm{S}}) - \frac{z}{z_{\mathrm{p}}}\right) \ . \tag{4}$$

Here, the time t [s] accounts from the year beginning; T_{M} and T_{A} stand for average yearly air temperature and amplitude of sinusoidal approximation of daily mean air temperatures, respectively, and τ means its period in [s]. The τ_{S} is the time shift of the sine minimum from the year beginning (accounted in [s] as well). Finally, the s.c. depth of penetration, z_{p}, depends on the thermal diffusivity of the soil, $\alpha_{\mathrm{g}} = k_{\mathrm{g}}/(\varrho_{\mathrm{g}}\,c_{\mathrm{p,g}})$, due to relationship

$$z_{\mathrm{p}} = \sqrt{\frac{\alpha_{\mathrm{g}}\,\tau}{\pi}} \ . \tag{5}$$

It means that both the ratio of attenuation of outer temperature changes with increasing depth and the time shift of sinusoidal course of soil temperature to outer, exciting temperature variations, depend on soil properties.

3.2. An influence of the piping material and airflow velocity

Many different types of tubing can be used for the GHE construction: concrete, ceramic, metal, or, most frequently, plastic. Usually used materials are polyvinyl chloride (PVC), polyethylene (PE), and polypropylene (PP). These materials differ not only in mechanical properties (particularly, in the load-bearing capacity) and the price, but also in the thermal conductivity, k_{t}, which secondarily affects an outlet air temperature and an effectiveness of the GHE.

Therefore, an analysis of an influence of the tubing type on these parameters has been carried out. Four most common types of solid-wall plastic tubing employed for the GHEs have been considered (Tab. 1); the first three types (KG-Systém, KG 2000) are primarily intended for sewage systems, whilst the REHAU AWADUKT Thermo® is an tubing especially designed for GHE applications (with two-stage sealing and embedded Ag-particles for the sake of an elimination of possible microbiological contamination).

However, the thermal resistance of the tube wall does not affect the overall HTC, $\bar{h}_o$, by oneself, but in combination with the convection HTC, $\bar{h}_a$ (see Eqs. 2a, 2b). Therefore, its impact depends on actual values of both terms, which have to be assessed simultaneously.

Parameter	Unit	KG-Systém (PVC)		KG 2000 Polypropylen	AWADUKT Thermo
Circular load-bearing capacity (SN)	kN/m^2	4	8	8	8
Wall thickness, d	mm	4.9	5.9	6.2	7.3
Thermal conductivity, k_t	W/(m K)	0.15	0.15	0.22	0.29
Overall HTC, $\bar{h}_o$ *)	$W/(m^2 K)$	7.58	7.24	7.86	8.05
Effectiveness of the GHE, e **)	—	0.905	0.892	0.910	0.913
	rel. ±%	—	−1.46	+0.55	+0.88
Price for 1 bm ***)	CZK/m	389.30	592.10	836.90	704.00
	rel. ±%	—	+52.1	+115.0	+80.8

*) for convective HTC 10 $W/(m^2 K)$, which is due to airflow rate 220–230 m^3/h (in detail see Tab. 2);
**) for tubing length 35 m and airflow rate 200 m^3/h (at 20 °C);
***) incl. VAT; recalculated from prices of 5 m long pipes (except the AWADUKT Thermo, which was recalculated from 6 m tubing) [6, 7].

Tab.1: Parameters of selected types of DN200 tubing, proper for construction of GHEs

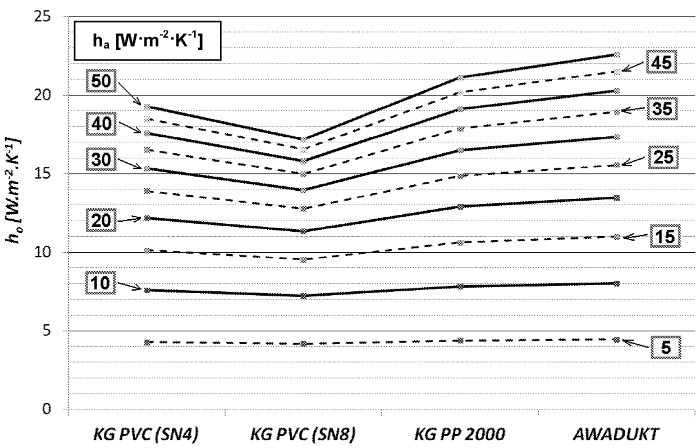


Fig.2: Overall ground-air HTC, $\bar{h}_o$, in relation to type of tubing (DN200) and convective HTC value, $\bar{h}_a$

The values of $\bar{h}_a$ that have been taken into consideration with respect to possible airflow rates, $\dot{V}$, are enumerated in Tab. 2. Their impact on overall HTC, $\bar{h}_o$, for tubing types taken into account is graphically represented in Fig. 2.

Finally, the effectiveness of the GHE, ε (which corresponds to that used in heat exchangers theory, see e.g. [3]), has been evaluated accordingly to the relationship

$$\varepsilon = \frac{\overline{T_{\mathrm{a,OUT}}} - T_{\mathrm{a,IN}}}{T_{\mathrm{S}} - T_{\mathrm{a,IN}}} = 1 - \exp\left(-\frac{\bar{h}_{\mathrm{o}}\, S_{\mathrm{p}}}{\dot{m}_{\mathrm{a}}\, c_{\mathrm{p,a}}}\right) . \tag{6}$$

All significant quantities for different types of GHE tubing are compared in Tab. 1.

4. Discussion

As can be seen in Fig. 2, the overall HTC differs only slightly for particular variants, when the airflow rate is low. Higher differences (20 % or more) appear from the values of $\bar{h}_{\mathrm{a}} = 30\,\mathrm{W\,m^{-2}\,K^{-1}}$. However, the airflow rate affects not only the convective and the overall HTCs, but also the pressure drop in the piping (see the last row in Tab. 2), which should be hold on an acceptable level. From this viewpoint, the airflow velocity in the tube should not exceed values of 2–3 m/s [8], which correspond to convective HTC about $10\,\mathrm{W\,m^{-2}\,K^{-1}}$ (see Tab. 2). Therefore, such high values of $\bar{h}_{\mathrm{a}}$ as mentioned above could not be really expected, and a choice of a tube material is not crucial.

$\dot{V}$	$\mathrm{m^3/h}$	100	**200**	300	400	**500**	750	1000
h_{a}	$\mathrm{W/(m^2.K)}$	5.1	**8.9**	12.3	15.4	**18.5**	25.5	32.1
w_{a}	m/s	0.98	**1.96**	2.93	3.91	**4.89**	7.33	9.78
p_{z}	Pa/m	0.09	**0.31**	0.62	1.03	**1.53**	3.14	5.27

Tab.2: An influence of airflow rate, $\dot{V}$, on other airflow parameters (for the KG-Systém (PVC)-SN4-DN200 tubing; assumed parameters for ventilating and circulating regime, respectively, are boldface printed)

With respect to this fact, the tubing KG-Systém (PVC)® SN4 was selected for the newly built experimental GHE. This choice represents the best price/power ratio (and it should be noted that it is the most employed type of GHE tubing in the CR as well). The adopted type of tubing also guarantees tight joints, even when the tubing would be misshaped or skewed. As far as the investment costs are concerned, the worst choice is the KG 2000 Polypropylen® tubing; the specialized GHE tubing AWADUKT Thermo lies in the middle of price margins (however, it is still more than 80 % costly).

5. Conclusion

As it is evident from foregoing analysis, the choice of tubing material does not have a decisive influence on GHE performance. More precise assessment, in combination with an influence of airflow rate (or airflow velocity, respectively), would require a detailed all-year energy simulation. However, its performance is conditioned by knowledge of applied ventilation regime (which is not known at stage of design). Moreover, operation of GHE depends on actual outer temperatures. Therefore, the presented simplified methodology appears to be sufficient for the given purpose.

With respect to abovementioned conclusion, the type of GHE tubing has been selected according to the required investment costs. However, an application of the tubing primarily assigned for sewage systems could bring possible microbiological hazards and potential pollution of ventilating air. Further proposed research will be therefore focused on these aspects of GHE operation.

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Nomenclature

$c_{\mathrm{p,a}}$	$[\mathrm{J\,kg^{-1}\,K^{-1}}]$	specific heat capacity of an air
$c_{\mathrm{p,g}}$	$[\mathrm{J\,kg^{-1}\,K^{-1}}]$	specific heat capacity of a ground
D_{i}	[m]	inner diameter of a tubing
D_{o}	[m]	outer diameter of a tubing
k_{a}	$[\mathrm{W\,m^{-1}\,K^{-1}}]$	thermal conductivity of an air
k_{g}	$[\mathrm{W\,m^{-1}\,K^{-1}}]$	thermal conductivity of a ground
$\dot{m}_{\mathrm{a}}$	$[\mathrm{kg\,s^{-1}}]$	mass flow of an air
$\mathrm{Pr_a}$	[–]	Prandtl number of an air
p_{z}	$[\mathrm{Pa\,m^{-1}}]$	specific pressure loss
S_{p}	$[\mathrm{m^2}]$	inner surface of a pipe
$T_{\mathrm{a,IN}}$	[°C]	inlet air temperature
w_{a}	$[\mathrm{m\,s^{-1}}]$	air velocity inside the pipe
ϱ_{g}	$[\mathrm{m^3\,kg^{-1}}]$	density of a ground

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