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Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency

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Abstract

In designing an earth-to-air heat exchanger (EAHX), a decision on design goals has to be made. If the air flow is given by the ventilation system and the construction site is known, the question is: is it more important to achieve a high specific energy performance based on the surface area of an EAHX, a high adoption of air temperature to ground temperature or a very small pressure loss? This paper deals with the performance of three EAHXs for mid European office buildings in service, with the aim of characterising their efficiency. A general method to compare EAHXs in operation will be introduced. First, the temperature behaviour is described by plots over time and characteristic lines, and compared by standardised duration curves. Second, the energy gain is illustrated by standardised graphs. Third, a parametric model is used to provide general efficiency criteria. Thermal efficiency should be defined by both the dynamic temperature behaviour and energy performance.

Keywords: Earth-to-air heat exchanger; Passive cooling; Evaluation; Parametric model; Energy performance; Efficiency criteria; Office buildings

1. Introduction

As the energy demand of new office buildings has been reduced during the last few years, there is a rising interest for heating and cooling systems based on renewable sources of energy. Because of the high thermal inertia of the soil, the temperature fluctuations at the ground surface are attenuated deeper in the ground. Further, a time lag occurs between the temperature fluctuations at the surface and in the ground. Therefore, at a sufficient depth, the ground temperature is lower than the outside temperature in summer and higher in winter. When ambient air is drawn through buried pipes, the air is cooled in summer and heated in winter, before it is used for ventilation. Thus, earth-to-air heat exchangers (EAHXs) can fulfil both purposes demanded above: (pre-)heating in winter and (pre-)cooling in summer.

The main advantages of the system are its simplicity, high cooling and pre-heating potential, low operational and maintenance costs, saving of fossil fuels and related emissions. Pre-heated fresh air supports a heat recovery system and reduces the space heating demand in winter. In summer, in combination with a good thermal design of the building, the EAHX can eliminate the need for active mechanical cooling and air-conditioning units in buildings, which will result in a major reduction in electricity consumption of a building if the EAHX is designed well. EAHXs are hence a passive cooling option in moderate climates.

The energy performance of EAHXs is described by the thermal interaction of heat conduction in the soil taking moisture in consideration, heat transport by flowing and ground water, heat transmission from the pipe to the air and changes in the air temperature and humidity. Different parametric and numerical models for EAHXs have been published in the last 12 years. Some of them are mentioned below in order of publication date. Simulation models can be classified as models with an analytical or a numerical solution of the ground temperature field, and mixed models:

- Albers [1] developed a parametric model for steady air flow based on a form factor to model the three-dimensional temperature profile in 1991. In 1992, Sedlbauer [2] published a model based on a heat-capacity model to take changes in air flow during operation into account. An evaluation of eight simulation models in 1992 by Tzaferis et al. [3] reached the conclusion that almost all proposed algorithms can predict the outlet air temperature with sufficient accuracy. A very new approach based on a parametric model using deterministic techniques is given by Mihalakakou [4].

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- Detailed simulation models of the energy performance of EAHXs are based on algorithms describing the coupled and simultaneous transfer of heat in soils under a temperature gradient. A complete numerical model for a single-pipe EAHX is introduced by Mihalakakou et al. [5] in 1994. This model is validated with long-term measurements and is used to describe the thermal influence of the key variables, pipe length, pipe diameter, air velocity and pipe depth [6]. A numerical model for a two-pipe EAHX is described by Bojic et al. [7]. A numerical model for multiple-pipe EAHXs was validated by Hollmuller and Lachal [8] in 2001.
- Mixed simulation models are resistance–capacity models based on a numerical solution for the earth temperature near the pipe and an analytical calculation of boundary conditions. In 1999, Evers and Henne [9] used such a model to predict the energy performance of EAHXs for different design parameters. In the framework of an EU project, a design tool was developed under the guidance of AEE Gleisdorf and Fraunhofer ISE by 15 engineering companies [10]. The simulation model is based on an extended, validated and well-tested resistance–capacity model by Huber [11].

The accuracy of parametric and numerical models can be tested against experimental data for the thermal performance (energy and temperature) of EAHXs by introducing a dimensionless temperature difference (in this paper: Eq. (6)). A comparison showed good agreement [12]. Against this background, a design tool based on four models with different levels of detail was developed and validated at Fraunhofer ISE [13]: the first model is a nomogram (set of characteristic curves) for design decisions without detailed information about the thermal soil properties and operation management, the second model is based on an analytical solution of the undisturbed three-dimensional temperature field with a form factor, the more detailed third model is based on a heat-capacity model and takes the operation time into account, and the most detailed fourth model is a complete numerical solution of the three-dimensional heat and moisture transfer and the changes in the air temperature and humidity. Starting from this design tool, an analytical model was enhanced by the author [14]: the model combines a form-factor model with a heat-capacity model and accurately predicts the thermal performance of EAHXs. This model (simplified in Eqs. (4) and (5)) will be used to compare the thermal performance of EAHXs in operation (Section 5).

As the ground temperature is dependent on many boundary conditions, its modelling is rather difficult. Mihalakakou et al. [15] used the energy balance equation to predict ground surface temperatures. In addition to this deterministic approach, a data-based approach is described by Mihalakakou [16]. The influence of the input climatic parameters on the ground surface temperature was investigated using a neural network approach. Starting with the calculated surface temperature, the ground temperature can be estimated [17]. The ground temperature profile is strongly influenced by the material parameters of the soil. Usually, determination of the heat conductivity, heat-capacity and density is difficult. A practical detailed summary is given by Dibowski and Rittenhofer [18]. In addition to the ground cover and the material parameters of soil, possible thermal influence of a building or ground water should be taken into account (see [14]). In this paper, a data-based model is used to predict the undisturbed ground temperature (Eq. (3)) according to [14,17].

There are some publications concerning the design and operation of EAHXs (see [10,19–21]). The heat and cooling energy gain by an EAHX should meet the actual energy demand of the building's ventilation system. If the heating or cooling energy gain is lower than the corresponding energy consumption, the supply air has to be heated up or cooled down additionally. If the energy gain is higher than the corresponding energy consumption, the supply air has to be cooled down or heated up, respectively, though this would not be necessary if the EAHX were not in operation. This means an unwanted energy dissipation. An additional demand on EAHXs in office buildings is that an EAHX should meet the complete cooling energy demand for sufficient thermal comfort. Santamouris et al. [22] presented an integrated method to calculate the energy contribution of EAHXs to the cooling load of thermostatically controlled buildings. Bojic et al. [23] introduces an energy ratio to calculate, whether an EAHX provides more or less heat or cooling energy than it needs to reach a given comfort temperature inside the building. Besides the heat gain, the electricity demand should be taken into account. In this paper, the contribution of an EAHX to the building energy consumption is characterised by a frequency distribution for the heating and cooling energy supply.

In spite of many publications and available design tools, there is a lack of comparative analysis. The presented method includes an evaluation of temperature behaviour, energy gain by standardised performance criteria and energy efficiency. In this method, the electricity demand for the fan is not considered, because the measured electricity for fans cannot be divided into the energy consumption for the building ventilation system in general and the EAHX easily. De Paepe and Janssens [24] developed a method to optimise the energy efficiency of an EAHX by reducing the pressure drop for a given thermal efficiency. According to this method, not the electricity demand but the dissipation energy caused by the pressure loss is used to calculate the coefficient of performance COP, the ratio of thermal energy supplied to mechanical dissipation energy (in this paper: Eq. (7)).

2. Description of evaluated earth-to-air heat exchangers

The thermal performance of three EAHXs located in Germany is compared. The projects are presented in detail in [25,26]. The ventilation system for the office building of DB

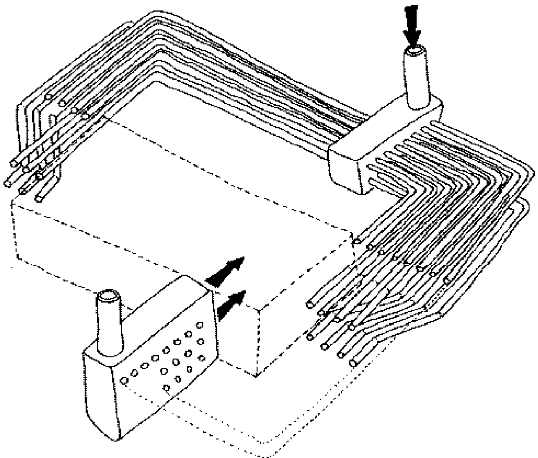

Fig. 1. Drawing of the earth-to-air heat exchanger, DB Netz AG (Hamm).

Fig. 3. Earth-to-air heat exchanger under construction, Lamparter (Weilheim).

Netz AG (Hamm) is designed for an air flow of 12,000 m^3/h. For cooling in summer, a maximum inlet temperature of 19 °C was nested during designing (independent of weather conditions). The total surface area was designed quite large to cool the air almost to the undisturbed earth temperature, which reaches approx. 18 °C in late summer. The large register had to be positioned in the small excavation at the construction site (Fig. 1). The EAHX at Fraunhofer ISE (Freiburg) is located left and right to the foundation slab of the building (see Fig. 2) and was designed for an air flow of 9000 m^3/h. The design idea was to achieve a high energy performance to assist the ventilation system with cooled or pre-heated air. The EAHX for the Lamparter Office (Weilheim) was designed for an air flow of 1200 m^3/h and for small pressure losses. It is installed around the office building (Fig. 3). In summer, cool air assists the passive cooling by night ventilation. In winter, pre-heated air supports the heat recovery system, reduces the heat energy demand and prevents freezing of the heat exchanger. In all three cases, no further active cooling is needed to achieve a sufficient thermal comfort.

Each EAHX is operated in an office building which is used as such. All projects were realised without any investment

Fig. 2. Earth-to-air heat exchanger under construction, Fraunhofer ISE (Freiburg).

subsidies. The demands on operating time are similar, but the design criteria are different (see above). For each EAHX, monitored data are available for a whole year in 5 min intervals. The EAHXs are described in [25]. The characteristic attribute is the surface area per air flow, it varies from 0.075 to 0.18 $m^2/(m^3\,h)$. All ducts are made of polyethylene.

The data evaluation (Sections 3 and 4) deals with 5 min data for air flow, ambient temperature, inlet and outlet air temperature and ground temperature. Hourly data are generated for the mean air flow, mean ambient temperature and mean ground temperature. Inlet and outlet air temperatures are averaged over the operating time. Operation is defined by a minimum air flow of 3000 m^3/h (DB Netz AG), 2500 m^3/h (Fraunhofer ISE) and 500 m^3/h (Lamparter).

3. Analysis of temperature behaviour

First, the temperature behaviour is described by plots over time and characteristic curves, separately for every project. The temperature behaviour of different projects can be compared with duration curves and a dimensionless ratio of temperature variation.

3.1. Ground temperature

In the design process, the undisturbed ground temperature is a main input parameter. However, its accurate modelling is difficult because the soil parameters are often unknown. Additionally, the definition of "undisturbed ground temperature" is problematic due to the thermal influence of a building or different soil properties at an EAHX. In the following, the undisturbed ground temperature is influenced by the building but not by the EAHX and is defined for mean soil properties. The undisturbed ground temperature is hence a hypothetical value because the register has non-negligible spatial dimensions. Fig. 4 shows that the monitored undisturbed ground temperatures are influenced both by the building and by the EAHX (in comparison to Figs. 5–7): at

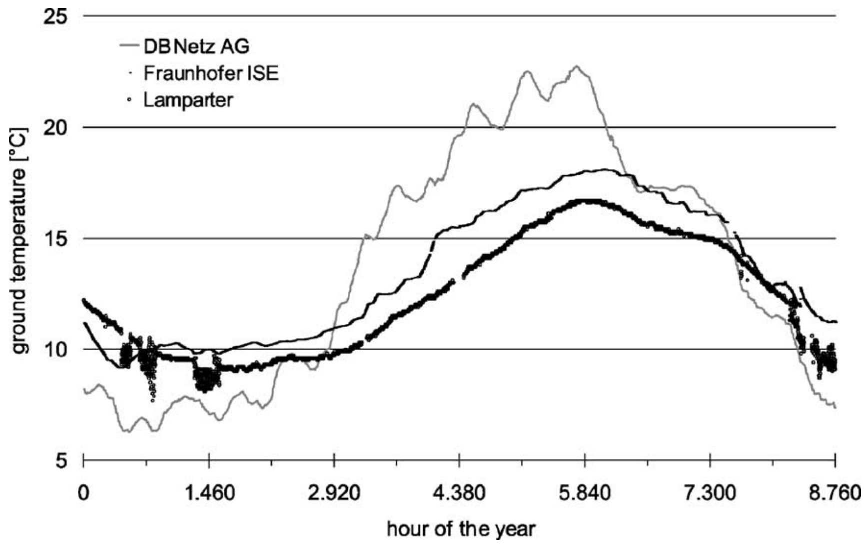

Fig. 4. Ground temperature profile, hourly data.

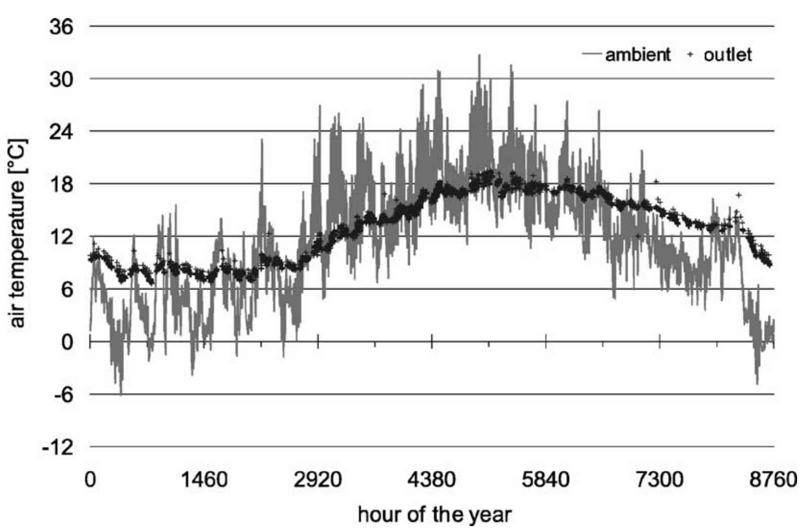

Fig. 5. Ambient and outlet air temperatures at DB Netz AG, hourly data.

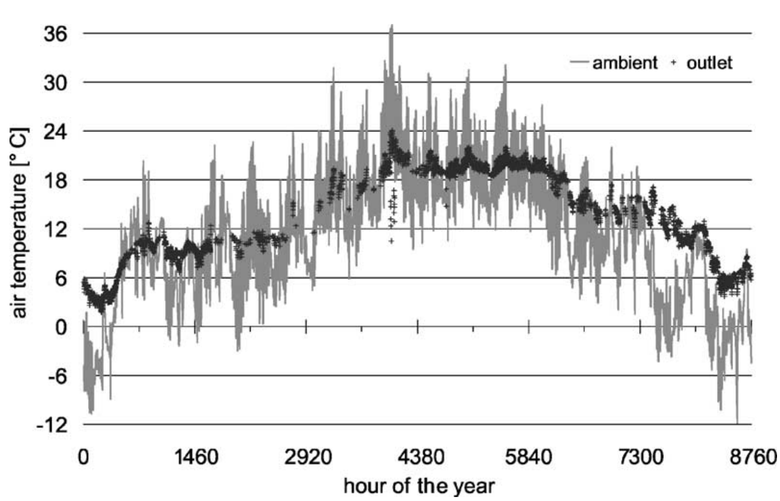

Fig. 6. Ambient and outlet air temperatures at Fraunhofer ISE, hourly data.

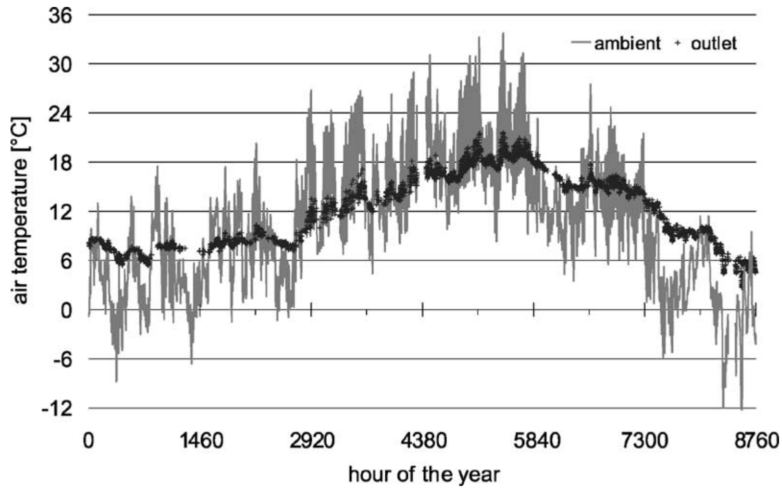

Fig. 7. Ambient and outlet air temperatures at Lamparter, hourly data.

DB Netz AG, the maximum ground temperature is higher than the maximum outlet air temperature; at Fraunhofer ISE, the outlet air temperature in summer is sometimes higher than the ground temperature; and at Lamparter, the outlet air temperature in winter is sometimes lower than the earth temperature. Obviously, these measurements cannot be used to evaluate the heat exchange efficiency (Section 5).

3.2. Time variation curves

Due to the damped periodic oscillation of the ground temperature, the outlet air temperature is higher than the inlet air temperature in winter and lower in summer. Figs. 5–7 show hourly mean air temperatures during operation for a whole year. These plots illustrate the working principle of EAHXs but a more significant conclusion is given by statistical analysis (Section 5).

3.3. Characteristic lines

Characteristic lines summarise the temperature behaviour of EAHXs. In Figs. 8–10, vertical lines divide the temperature field into three zones: the heating period for low energy office buildings with inlet temperatures below 12 °C, the cooling period with inlet temperatures above 22 °C and the passive period in between, without heating and cooling. Due to different energy concepts and ventilation strategies, there are different demands on the air flow rate and supply air temperature. Therefore, these temperature limits are defined only as a benchmark but not as a quality criterion.

According to the building energy demand for heating or cooling, at a certain ambient temperature the inlet air should be either heated or cooled. However, in operation, there is sometimes an unwanted temperature decrease in winter or increase in summer due to the non-ideal control. Limits

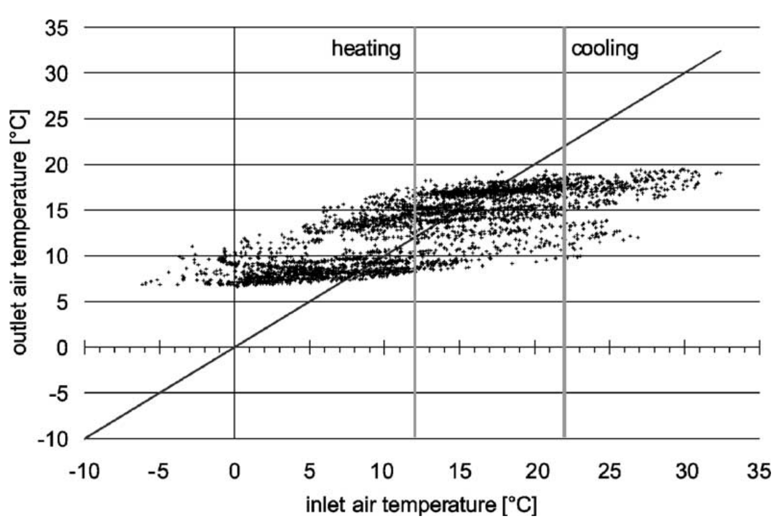

Fig. 8. Characteristic line for DB Netz AG, hourly data.

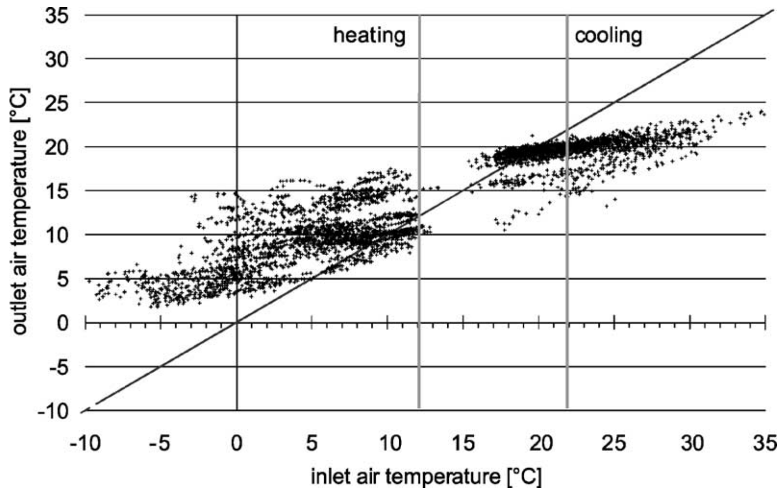

Fig. 9. Characteristic line for Fraunhofer ISE, hourly data.

derived from these demands are introduced for better comparison of EAHXs:

- The EAHX at DB Netz AG is operated during working days between 8 a.m. and 5 p.m. As the EAHX is operated without controls, there is a wide temperature range with both heat and cooling energy gain. The outlet air temperature is always between 20 and 5 °C.
- Due to the high specific air flow rate, the EAHX at Fraunhofer ISE has the highest range in outlet temperature. As the air flow through the EAHX at Fraunhofer ISE is controlled by the inlet air temperature, there is no operation between 12 and 16 °C. Due to the open loop control at Fraunhofer ISE, there is only a very small temperature overlap with both heat and cooling energy gain.
- The office rooms at Lamparter are ventilated with a constant supply air temperature of 22 °C during the working hours. Accordingly, the EAHX warms up or cools down the incoming air to 22 °C (without temperature hysteresis). Thus, the EAHX is operated at every ambient temperature though the air flow through the EAHX is controlled by the outlet air temperature. As the closed loop control at Lamparter has no hysteresis, there is a temperature overlap which is smaller than that at DB Netz AG but larger than that at Fraunhofer ISE.

3.4. Duration curve of outlet temperature

Time variation curves and characteristic lines illustrate the temperature behaviour of a single EAHX. Fig. 11 compares the outlet air temperatures for all of the three projects. The outlet air temperature is dependent on both the inlet air temperature and the ground temperature (not shown in Fig. 11). As the duration curve is not independent of the climate, a dimensionless ratio of temperature variation R_T is introduced. R_T is independent of the climate if the inlet air temperature is related to same limits ($T_{in,max}$ and $T_{in,min}$):

$$R_T = \frac{T_{out,max} - T_{out,min}}{T_{in,max} - T_{in,min}} \quad (1)$$

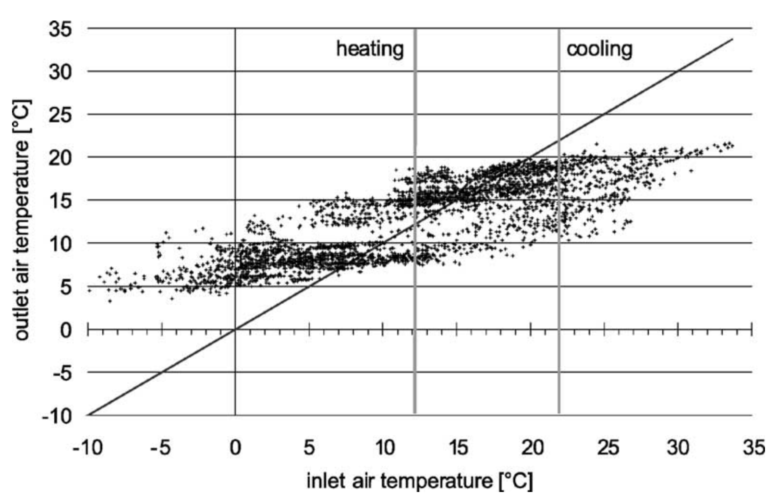

Fig. 10. Characteristic line for Lamparter, hourly data.

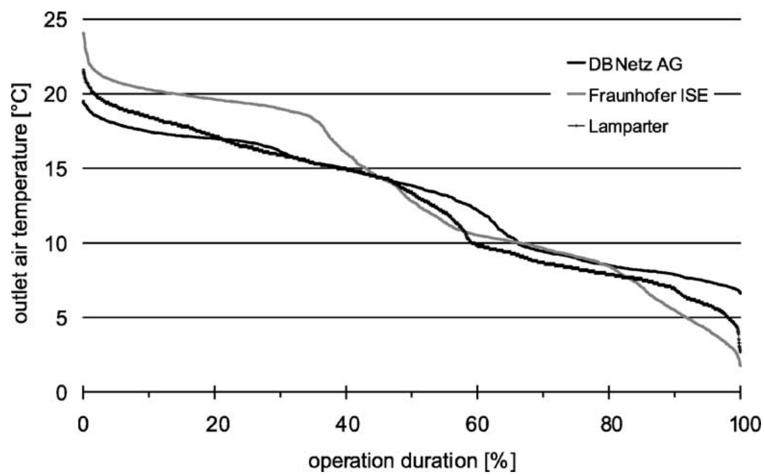

Fig. 11. Duration curve of outlet air temperature for all of the three projects, hourly data.

The inlet temperature range is defined from −10 to 35 °C. The minimum and maximum outlet temperature for each EAHX is derived from a compensation function for low and high inlet air temperatures in Figs. 8–10. The compensation function is the gradient for the minimum and maximum outlet temperature at high and low inlet temperatures (not drawn in Figs. 8–10). The ratio calculated with Eq. (1) increases with decreasing specific surface area (from Table 1). Therefore, the EAHX at DB Netz AG achieves the strongest and the EAHX at Fraunhofer ISE the smallest damping of inlet air temperature (see Table 5 in Section 5.3). The R_T-value can be used to estimate the effect of an EAHX on the thermal influence of a building and to design the thermal performance of additional heat exchangers for the ventilation system.

4. Energy gain and supply

Second, energy gain is illustrated by time variation curves and sorted according to ambient temperature, separately for every project. The energy gain from an EAHX is not identical with its utilised energy gain to a building due to non-ideal control of the operation. The energy gain of an EAHX can be derived from a frequency distribution for heat and cooling energy gain. Therefore, energy performance for each project is compared with a frequency distribution which takes temperature limits for heat and cooling energy demand into consideration. The usable energy supply for heating and cooling can be taken from this graph.

4.1. Yearly energy gain

The energy performance of an EAHX is given by

$$\dot{Q}_{air} = \dot{V}_{air}\rho_{air}c_{air}(T_{out} - T_{in}) \quad (2)$$

Taking the operation time into account, the heat and cooling energy gain can be calculated for certain periods from Eq. (2). The specific energy gain (in relation to surface area from Table 1) is compared for different EAHXs in Table 2. The specific energy gain increases with operation time and

Table 1
Description of evaluated earth-to-air heat exchangers

	DB Netz AG	Fraunhofer ISE	Lamparter
Number of ducts	26	7	2
Length of ducts (m)	67–107	Approx. 95	Each 90
Diameter (mm)	200 and 300	250	350
Depth of ducts (m)	2–4, around foundation slab	2, partly below foundation slab	2.3, around foundation slab
Mean air flow (m^3/h)	10300	7000	1100
Total surface area of ducts (m^2)	1650	522	198
Specific surface area (m^2/(m^3 h))	0.16	0.075	0.18
Air speed (m/s)	Approx. 2.2	5.6	1.6
Pressure loss at mean air flow (Pa)	40 (measured)	166 (measured)	12 (calculated)
Start of operation	October 1999	November 2001	September 2000
Soil type	Dry, rocky	Dry, gravel	Moist, clay
Ventilation system	Hybrid ventilation with supply and exhaust air	Hybrid ventilation with supply air	Hybrid ventilation with supply and exhaust air
Heat recovery system	Yes, 65% (design)	No	Yes, 80% (measured)
EAHX bypass	Yes, but not used	Yes	Yes
Control strategy	Time controlled	Temperature-controlled (open loop)	Temperature-controlled (closed loop)

Table 2
Heating and cooling energy gain

	DB Netz AG	Fraunhofer ISE	Lamparter
Period of measurement	1 January–31 December 2001	7 November 2001–6 November 2002	1 January–31 December 2001
Hours of operation (h)	3701	4096	3578
Heating energy gain (kWh per annum)	27700	26800	3200
Specific (kWh/(m^2 per annum))	16.8	51.3	16.2
Cooling energy gain (kWh per annum)	22300	12400	2400
Specific (kWh/(m^2 per annum))	13.5	23.8	12.1

the available temperature difference between earth and air but with decreasing specific surface area (from Table 1). Thus, the EAHX at Fraunhofer ISE has the highest specific energy gain. As the energy gain is dependent on climate and operation time of the EAHX, the specific energy gain is suitable to evaluate the energy saving potential of an EAHX but is not suitable as a general efficiency criterion (see Section 5).

4.2. Monthly energy gain

Depending on the operation time, ground temperature and inlet air temperature, there is a heating energy gain in winter and a cooling energy gain in summer which is illustrated in Figs. 12–14 (with different scaling of *y*-axis). Due to the warm May 2001 and the cold November 2001, there are comparatively high energy gains in these months because of the high temperature difference between the inlet air and ground.

4.3. Energy performance sorted by ambient air temperature

Each EAHX is integrated into a ventilation system. As an approximation, there is either a heating or a cooling energy demand at a given ambient air temperature. Depending on the ambient temperature, the supply air should be heated or cooled. If the energy performance of an EAHX is sorted by the ambient temperature, the performance at a certain temperature can be calculated. For better comparison, the mean energy performance is related to the total surface area (from Table 1). Figs. 15–17 (with temperature limits from Section 3) are used to estimate the maximum energy performance: for a certain ambient air temperature, the specific energy performance at Fraunhofer ISE is clearly higher than at DB Netz AG or Lamparter which are similar to each other.

4.4. Energy supply sorted by ambient air temperature

The energy gain by an EAHX does not necessarily save heating or cooling energy. Sometimes, an EAHX cools down the incoming air at low ambient temperatures and heats the incoming air at high ambient temperatures. This is contrary to the original aim of an EAHX. A control strategy is needed to supply energy when it is actually needed. Starting from fictitious temperature limits for heating and cooling energy demand, the effectively usable energy supply can be estimated from Fig. 18: at DB Netz AG (only time control), only 82% of heating energy is supplied below 12 °C and only 43% of cooling energy above 22 °C. If an EAHX is not only time-controlled but also temperature-controlled, more energy is supplied when it is actually needed. At Fraunhofer ISE (open loop control), 96% of heating energy is supplied below 12 °C and 72% of cooling energy above 22 °C. At Lamparter (closed loop control without hysteresis), 88% of

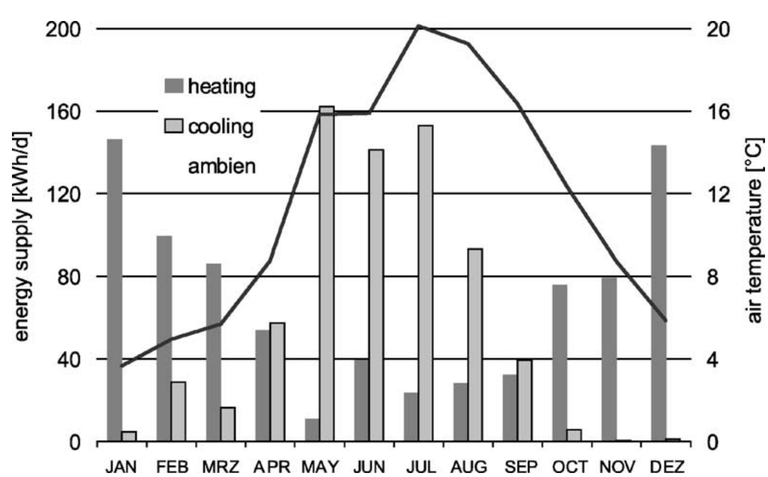

Fig. 12. Energy supply, DB Netz AG: 1 January–31 December 2001.

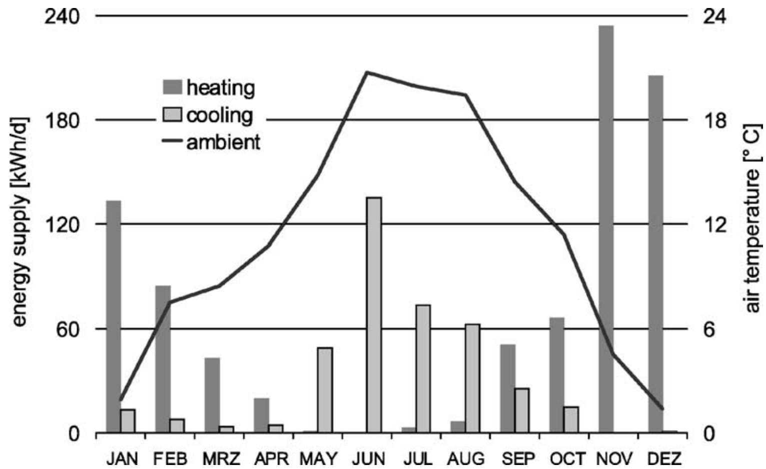

Fig. 13. Energy supply, Fraunhofer ISE: 7 November 2001–6 November 2002.

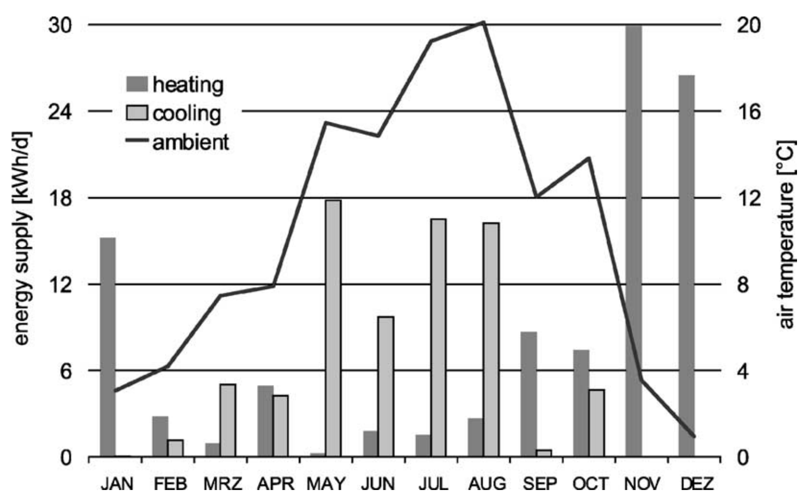

Fig. 14. Energy supply, Lamparter: 1 January–31 December 2001.

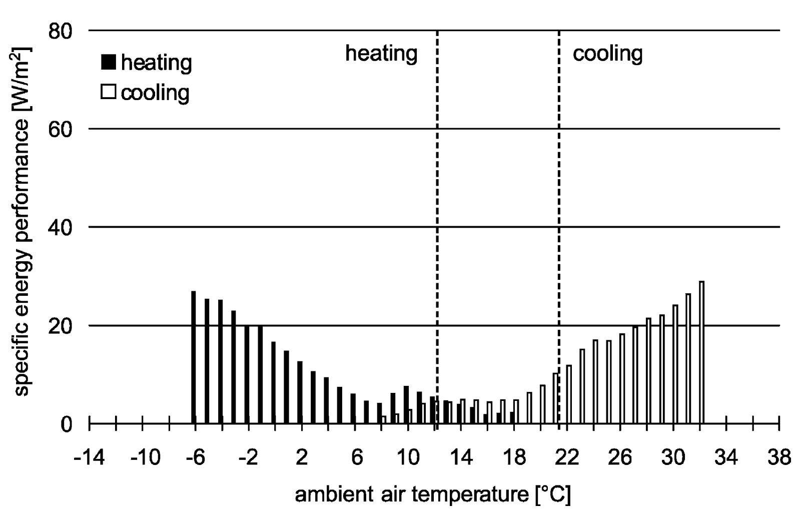

Fig. 15. Heating and cooling energy performance sorted by ambient air temperature, DB Netz AG.

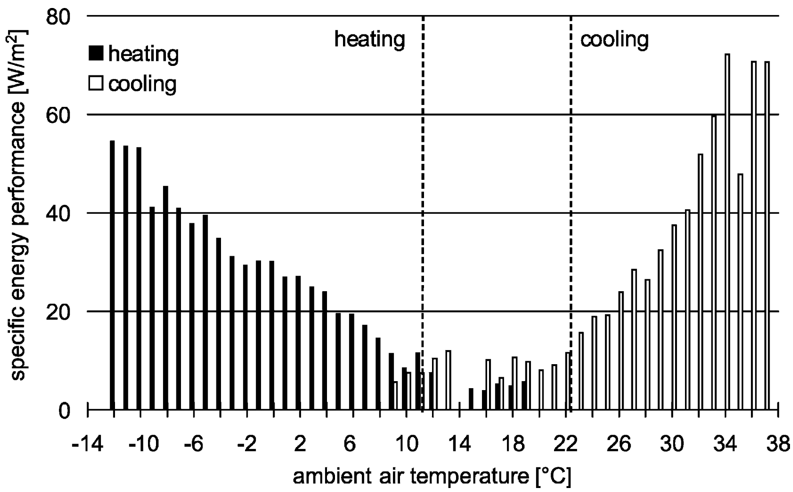

Fig. 16. Heating and cooling energy performance sorted by ambient air temperature, Fraunhofer ISE.

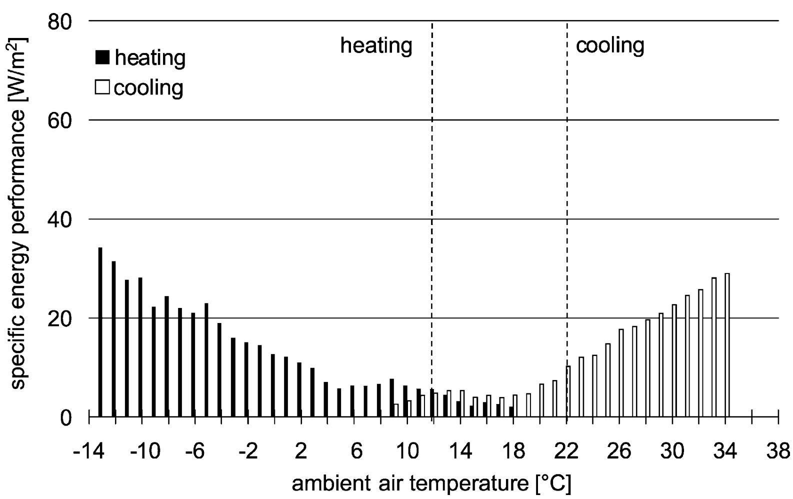

Fig. 17. Heating and cooling energy performance sorted by ambient air temperature, Lamparter.

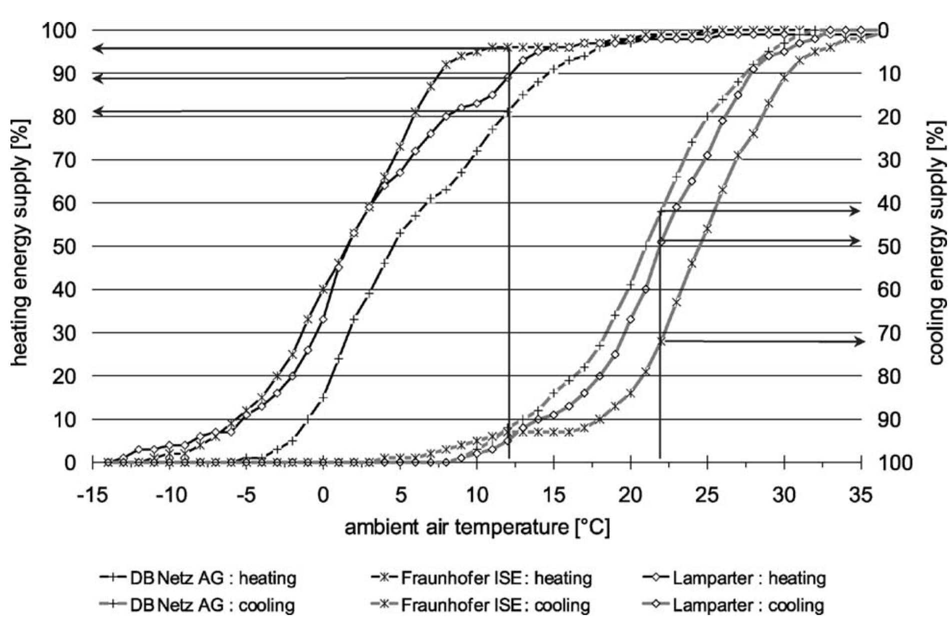

Fig. 18. Frequency distribution for heat and cooling energy supply.

heat energy is supplied below 12 °C and 48% of cooling energy above 22 °C.

5. A model for comparison of efficiency

Third, a parametric model is used to provide general efficiency criteria. Time variation curves for both inlet and outlet air temperatures and ground temperature $T(t)$ can be analysed by a regression function using a mean temperature T_{mean}, a temperature amplitude ΔT and a phase shift t_φ:

$$T(t) = T_{mean} - \Delta T \sin\left(\frac{2\pi(t + t_\varphi)}{8760}\right) \quad (3)$$

The outlet air temperature T_{out} can be calculated from the ground temperature T_{ground}, the inlet air temperature T_{in} and the dimensionless number of transfer units (NTU). The temperatures are time dependent and NTU is dependent on the operation time t_{op}:

$$T_{out}(t) = T_{ground}(t) + [T_{in}(t) - T_{ground}(t)]\exp[-\mathrm{NTU}(t_{op})] \quad (4)$$

During operation, the ground near the pipe is discharged thermally. Starting from the undisturbed ground temperature, the effective temperature difference between earth and air decreases with operation time. As NTU takes both the thermal capacity of the ground and the heat transfer from the ground to the air into account, it is dependent on operation time. After simplifying, a mean heat transfer with the air flow rate from measurements is used:

$$\mathrm{NTU}(t_{op}) = \frac{h_{EAHX}(t_{op})A_{surface}}{\dot{V}_{air}\rho_{air}c_{air}} = \mathrm{const.} \quad (5)$$

5.1. Energy performance of an earth-to-air heat exchanger

As the measured ground temperatures are obviously not undisturbed (Section 3.1), four parameters are unknown in Eq. (4) with Eq. (3). Using the least-squares method, these parameters can be calculated. The results are summarised in Table 3. The profiles of undisturbed ground temperatures are similar. However, due to the construction under the foundation slab, the undisturbed ground temperature at Fraunhofer ISE is higher and shows a shorter phase shift. The mean ground temperature and amplitude are mathematically correct results but not directly comparable with the undisturbed ground temperature (see Fig. 4). The regression function for the undisturbed earth temperature is based on the measured outlet air temperature. As the specific surface area at DB Netz AG is higher (small mass flow rate), its NTU is higher than the NTU at Fraunhofer ISE. The NTU at Lamparter is smaller than that at DB Netz AG because of its comparatively large pipe diameter (small convective heat transfer coefficient).

Table 3
Ground temperature and NTU sets from parameter identification

	DB Netz AG	Fraunhofer ISE	Lamparter
Mean earth temperature (°C)	12.8	13.8	11.9
Amplitude ΔT_{earth} (K)	5.1	5.9	5.3
Phase shift (days)	55	21	50
Mean NTU	2.59	1.57	1.74

The main characteristic describing energy performance is the overall heat transfer coefficient h. Using Eq. (5), the mean heat transfer coefficient can be calculated with the surface area and the air flow rate from measurements. The results are shown in Table 5. The overall heat transfer coefficient at Lamparter is smaller than at DB Netz AG and Fraunhofer ISE, though we expected a better heat transfer at Lamparter than at DB Netz AG or Fraunhofer ISE due to the higher heat conductivity of the moist earth (see Table 1). Obviously, the convective heat transfer between the piping and air dominates the overall heat transfer from the earth to the air.

5.2. Temperature ratio for an earth-to-air heat exchanger

Using Eq. (2) for a regression analysis, the time variation curves (Figs. 5–7) can be specified by a mean air temperature, an air temperature amplitude and a phase shift, with the results listed in Table 4. Using the results from Table 4 and the earth temperature from Table 3, a second temperature ratio can be calculated in addition to the temperature ratio R_T. The temperature ratio Θ is a “scale unit” for temperature behaviour:

$$\Theta = \frac{T_{in} - T_{out}}{T_{in} - T_{earth}} \quad (6)$$

Due to its large specific surface area, the temperature ratio Θ for the EAHX at DB Netz AG is higher than at Fraunhofer ISE (see results in Table 5). The temperature ratio Θ for the EAHX at Lamparter is smaller than at DB Netz AG though

Table 4
Regression analysis for inlet and outlet temperatures

	DB Netz AG		Fraunhofer ISE		Lamparter	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Mean air temperature (°C)	11.78	12.80	12.94	13.81	11.35	11.90
Amplitude ΔT_{air} (K)	8.00	5.27	11.21	6.77	6.05	5.30
Phase shift (days)	26	52	2	21	10	38

Table 5
Main characteristics for earth-to-air heat exchangers

	DB Netz AG	Fraunhofer ISE	Lamparter
R_T (K/K) (Section 3.4)	0.28	0.47	0.36
h_{mean} (W/(m^2 K)) (Section 5.1)	5.5	5.0	3.2
Θ (K/K) (Section 5.2)	0.944	0.766	0.804
COP (kWh_{th}/kWh_{mech}) (Section 5.3)	88	29	380

the specific surface area is similar: the heat transfer is worse because of the larger pipe diameter. As the heat transfer is poorer, the temperature ratio decreases in comparison to an EAHX with a similar specific surface area.

5.3. Thermal energy gain and mechanical dissipation energy

The energy gain of EAHXs is associated with an energy demand for the fan. The energy efficiency of an EAHX is the ratio between its energy gain and the fan electricity demand. As mentioned above, on the one hand the measured electricity demand for the fans is for both the EAHX and the ventilation system. On the other hand, not the fan but the mechanical dissipation energy is a characteristic parameter of an EAHX. Accordingly, the coefficient of performance COP is calculated with the overall energy gain (kWh_{th}) supplied by the EAHX (from Table 2) and the mechanical dissipation energy (kWh_{mech}) during operation time:

$$\mathrm{COP} = \frac{\sum_{t_{op}} (Q_{heat} + Q_{cool})}{\sum_{t_{op}} (\Delta p\, \dot{V})} \qquad (7)$$

The mechanical dissipation power at mean air flow is 114 W at DB Netz AG, 322 W at Fraunhofer ISE and only 4 W at Lamparter. The results for each EAHX are shown in Table 5. Due to the large pipe diameter and low air speed, the COP at Lamparter is very high. In contrast, the COP at Fraunhofer ISE is much smaller because the pressure loss is higher. As the EAHX at Fraunhofer ISE had to be integrated into the air-inlet, there are more flow resistances than at Lamparter. Due to the low air speed, the COP at DB Netz AG is high, too. Though there are large differences in COP, it should be mentioned that each COP is high enough to save both end and primary energy:

- Taking a typical fan efficiency of around 70% into account, the end energy saving is 70% smaller than the COP ($kWh_{electric\ energy}$/0.7 kWh_{mech}): 61.5 $kWh_{th}/kWh_{electric\ energy}$ (DB Netz AG), 20.1 $kWh_{th}/kWh_{electric\ energy}$ (Fraunhofer ISE) and 265.8 $kWh_{th}/kWh_{electric\ energy}$ (Lamparter).
- Starting from this end energy saving and taking a primary energy conversion factor for electric energy (approx. 3 $kWh_{primary\ energy}/kWh_{electric\ energy}$) into account, each EAHX leads to primary energy savings of 20.5 $kWh_{th}/kWh_{primary\ energy}$ (DB Netz AG), 6.7 $kWh_{th}/kWh_{primary\ energy}$ (Fraunhofer ISE) and 88.6 $kWh_{th}/kWh_{primary\ energy}$ (Lamparter), respectively.

5.4. Characteristics of an earth-to-air heat exchanger

Of course, the usable heat and cooling energy supply is the most important result from evaluation of the data. However, the energy supply is dependent on both the hours of operation and the climate. In order to characterise the thermal efficiency of an EAHX, the main characteristics of an EAHX should be independent of those changeable parameters. In addition to the energy gain in Table 2, Table 5 summarises the four main characteristics of EAHXs.

6. Conclusions

In the present paper, the thermal performance (temperature performance and energy efficiency) of EAHXs was calculated using four different approaches (R_T, h_{mean}, Θ and COP). But, which EAHX is the best concerning thermal performance? The application of passive heating and cooling is a multilayered process and there is a wide range of design criteria and demands on ventilation systems. Thus, the evaluation of an EAHX is dependent on project-specific criteria. Each of the evaluated EAHXs at DB Netz AG, Fraunhofer ISE or Lamparter is the best from a certain point of view: the EAHX at DB Netz AG narrows the outlet air temperature close to the undisturbed earth temperature. The EAHX at Fraunhofer ISE supplies the highest specific energy gain based on the total surface area. Taking a lower heat transfer into account, the EAHX at Lamparter has the highest COP.

An important characteristic for passive cooling applications is the temperature ratio R_T which describes the temperature damping between inlet and outlet temperature. The smaller R_T is, the more cooling energy is supplied to the building. As expected, the EAHX at DB Netz AG reaches the smallest R_T due to the high specific surface area (high conductive heat transfer between soil and pipe) and the comparatively small pipe diameter (high convective heat transfer between pipe and air).

The method for data evaluation of EAHXs in operation gives some noteworthy considerations for design and operation of EAHXs: the influence of earth parameters (soil and surface) and of the building on the earth temperature is as important as the pipe diameter on the thermal efficiency. In spite of a high heat flux density, the influence of the density of a pipe register on the energy gain is small: obviously, thermal regeneration is good enough to prevent a reduced energy performance. Pipe lengths up to 100 m and pipe diameters around 250 mm are profitable. If the EAHX aims at a high specific energy performance, a small specific surface area should be reached using fewer pipes. If the EAHX aims at a high temperature ratio, a high specific surface area should be reached using more pipes. However, the construction site itself often determines the dimensions of an EAHX.

The heating energy damned for ventilation is negligible if a heat recovery systems with high efficiency is operated (in this paper: Lamparter). But in heat recovery systems with high efficiency there is the danger of freezing because the humid exhaust air is cooled down under the freezing point at very low inlet air temperatures. If an EAHX is operated in series with a heat recovery system with high efficiency it should be large enough to prevent freezing at low ambient air temperatures in any case.

In operation, the control strategy plays a decisive role for the actually usable energy supply by the EAHX. A temperature control is important to prevent unwanted heating in summer and cooling in winter. Of course, a better utilisation of energy supply is achieved by a closed loop control but its programming is difficult because of long dead times in EAHXs. An open loop control runs robustly but usually its programming should be adjusted after the first year of operation, when the temperature behaviour is known. Though the operation of each evaluated EAHX could be improved, each EAHX supplies more heating and cooling energy than the primary energy it uses for fans. As assistance to night ventilation, each EAHX replaces an active mechanical cooling system in summer.

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