CALCULATION TOOL FOR EARTH HEAT EXCHANGERS *GAEA*

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ABSTRACT

Earth heat exchangers are advantageous features to reduce energy consumption in residential buildings. In winter they pre-heat ventilation air with minimal operation costs - necessary for low energy architecture -, in summer they help to prevent passive houses with relevant solar gains from overheating by pre-cooling ventilation air.

The goal of *GAEA* (Graphische Auslegung von ErdwärmeAustauschern, German for Graphical Design of Earth Heat Exchangers) is to provide an easily usable calculation tool for to match earth heat exchangers and buildings. This may work well as a stand-alone tool but is also projected to be part of detailed building simulations to evaluate the potential of earth heat exchangers within the whole heating and ventilation system of houses.

KEY WORDS: earth heat exchanger, low energy architecture, passive solar architecture, building simulation

1 INTRODUCTION AND PURPOSE OF *GAEA*

For many years earth heat exchangers have been acknowledged to be useful tools for the climatization of buildings, both to decrease energy consumption and increase building comfort. For low energy houses in particular the fraction of heating demand or cooling load that can be avoided by earth heat exchangers is considerably large. Methods to adjust earth heat exchangers for individual projects are still lacking.

Similar to previously developed products at the Software Laboratory for Low Energy and Solar Architecture [1, 2] *GAEA* relies on a graphical user interface. All input values are preset to default values and may be edited by means of scroll bars. When one input is edited the result of this change is immediately visible in the presented output figures. Hereby a quick understanding of many questions may be obtained. Some topics of investigation may be:

- How do earth heat exchangers affect a building's energy demand?
- What are the optimum length and cross-section of air pipes for a given flow rate?
- What is the optimum depth and distance of several pipes for the layout of an earth heat exchanger?
- Which further effort is needed to condition pre-heated or pre-cooled air according to comfort standards required inside buildings?

2 THEORY OF EARTH HEAT EXCHANGERS

The principal process taking place in an earth heat exchanger is that ambient air flows through a system of pipes which is buried in the ground. The air exchanges heat through the pipe walls with the surrounding earth. At the outlet of the pipe system the air enters the ventilation system of a building and is usually conditioned for heating or cooling. The underlying theory therefore comprises mainly heat flow mechanisms and fluid dynamics.

The authors designed *GAEA* according to well known models of heat and mass transfer [3, 4, 5, 6]. An analytical model is used to determine the temperatures along one pipe constituting the earth heat exchanger. The calculations are based on approximations for the earth temperature which varies with the time of the year and depth under surface. Heat transfer coefficients for the heat flow between air, pipe wall and earth are estimated from material coefficients, flow properties and geometric parameters. The following restrictions are made for the current version of the program:

- Homogenous earth is situated above and around the earth heat exchanger, ground properties are constant;
- When calculating more than one pipe (e.g. parallel pipes in an earth heat exchanger) interference between different pipes is (preliminarily) assumed to be negligible.

2.1 Earth temperature

Earth temperature at the wall of the pipe depends firstly on the heat transfer from earth surface to deeper layers. Secondly when the earth heat exchanger is used the air

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in the pipe itself influences the earth temperature at the pipe wall.

A parameter U* is defined to measure the ratio of both effects taking into account thermal conductivity of the earth, heat transfer coefficient between the airflow and the earth at the pipe wall as well as the geometric configuration [7][1] :

$$U^* = 2\pi \frac{\lambda}{U_L} \cdot \frac{1}{\ln\left(\frac{S_0}{R_0} + \sqrt{\left(\frac{S_0}{R_0}\right)^2 - 1}\right)} \quad (1)$$

with:

U* = conductance ratio of heat transfer from earth surface to pipe and from airflow to pipe wall
λ = thermal conductivity of ground in W/(m K)
U_L = heat transfer coefficient per length of wall of pipe between bulk air and wall in W/(m K)
S_0 = depth of pipe center under surface in m
R_0 = radius of pipe in m
(R_0 is assumed to be small compared to S_0)

The earth temperature at the wall of the pipe not influenced by the pipe $\vartheta_{E,0}$ is calculated from the ambient air temperature with its mean value ϑ_m and its maximum value ϑ_{max}, assuming a sinusoidal temperature variation throughout the year. A parameter ξ describes the "thermal depth" of the pipe. Heat flows from air to earth surface without resistance [5]. The result is:

$$\vartheta_{E,0}(t) = \vartheta_m + \left(\vartheta_{max} - \vartheta_m\right) \cdot e^{-\xi} \cos\left(2\pi \frac{t}{t_0} - \xi\right) \quad (2)$$

with:

$\vartheta_{E,0}$ = earth temperature at the wall of the pipe not influenced by pipe in °C
ϑ_m = annual mean value of ambient air temperature in °C
ϑ_{max} = annual maximum value of ambient air temperature in °C
ξ = dimensionless parameter for "thermal depth" of pipe
t = time in s
t_0 = duration of year in s (1 a ≈ 31.5 x 10^6 s)
t/t_0 = fraction of year (with t/t_0 equal zero for maximum ambient air temperature)

The "thermal depth" ξ in which the earth heat exchanger is situated depends on the real depth under surface and on thermal properties of the earth above the pipe as follows:

$$\xi = S_0 \sqrt{\frac{\pi \rho c}{t_0 \lambda}} \quad (3)$$

with:

ρc = volumetric heat capacity of ground in J/(m³ K)

Typical values for ground properties may be extracted from literature [5, 8, 9].

Whereas v. Cube [5] introduces a correction factor to represent the influence of the pipe on the earth temperature Albers [7] separates the stationary and instationary terms of equation (2) and compares the heat flow from the earth surface to the pipe with the heat flow through the pipe wall. He then finds the corrected earth temperature at the wall of the pipe $\vartheta_{E,W}$ to be:

$$\vartheta_{E,W} = \frac{U^* \vartheta_{E,0} + \vartheta_{A,P}}{U^* + 1} \quad (4)$$

with:

$\vartheta_{E,W}$ = earth temperature at the wall of the pipe in °C
$\vartheta_{A,P}$ = air temperature inside the pipe in °C

This means that $\vartheta_{E,W}$ is the weighted arithmetic mean between the airflow temperature inside the pipe $\vartheta_{A,P}$ and the earth temperature at the wall of the pipe not influenced by the pipe $\vartheta_{E,0}$ with the thermal conductances from earth surface to pipe and from airflow to pipe wall as weighting factors.

2.2 Ambient air temperature

The ambient air temperature $\vartheta_{A,0}$ determines the inlet temperature for the earth heat exchanger, it indirectly also relates to the earth temperature (see equation (2)). A sinusoidal temperature profile throughout the year is assumed which provides sufficient accuracy for the purpose of the program [5, 7]:

$$\vartheta_{A,0}(t) = \vartheta_m + \left(\vartheta_{max} - \vartheta_m\right) \cdot \cos\left(2\pi \frac{t}{t_0}\right) \quad (5)$$

with:

$\vartheta_{A,0}$ (t) = ambient air temperature in °C at time t in s

2.3 Heat transfer in the earth heat exchanger

For to calculate the heat exchange in the pipe the total length of the heat exchanger is divided into 100 segments which are treated step by step. Each segment is supposed to carry air of constant temperature so that heat exchange in the segment leads to a jump in

[1] The parameter U* is also used to describe altered heat flow characteristics caused by nearby building structures or ground water.

temperature at the border between two segments. The heat exchange for each segment is:

$$\dot{Q}_W = \Delta z \cdot U_L \cdot \left(\vartheta_{E,W} - \vartheta_{A,P}\right) \qquad (6)$$

with:

$\dot{Q}_W$ = heat flow from earth through wall of pipe to air in pipe in W

Δz = length of segment in m

The heat transfer coefficient per length of wall of pipe U_L for pipes typically used with earth heat exchangers depends only on the heat transfer coefficient h_i at its inner surface:

$$U_L = 2\pi R_0 \, h_i \qquad (7)$$

with:

h_i = heat transfer coefficient at the inner surface of pipe in W/(m² K)

The heat transfer coefficient at the inner surface of the pipe h_i depends on flow properties, dimensions of the pipe and material properties of the air in the pipe [10]:

$$h_i = \frac{\lambda_{A,P} \, Nu}{2 \cdot R_0} \qquad (8)$$

with:

$\lambda_{A,P}$ = thermal conductivity of air in pipe in W/(m K)

Nu = Nusselt number of air in pipe

The Nusselt number Nu of air in a pipe depends on Reynolds number Re and thus on flow rate. For turbulent airflow in the temperature region relevant for earth heat exchangers Gnielinski [4] proposes the following approximation:

$$Nu = 0{,}0214 \cdot \left(Re^{0,8} - 100\right) \cdot Pr^{0,4} \qquad (9)$$

with:

Re = Reynolds number of air in pipe

Pr = Prandtl number of air (typically: Pr = 0,72)

2.4 Air temperature in the pipe

Now the air temperature throughout the total length of the earth heat exchanger can be calculated. Beginning with an inlet temperature equal to the ambient air temperature step by step, i.e. segment for segment, the air temperature is adjusted according to the heat flow in the segment and the heat capacity of the air.

3 DIMENSIONING OF AN EARTH HEAT EXCHANGER WITH *GAEA*

Albers [7] presents an experimental earth heat exchanger located in the south of Germany. For a first validation and verification of the program the authors entered the obtainable data into *GAEA* and compared the calculated results with measured values of temperatures and energy flows. Further evaluation is planned within the project NESA of the AG Solar NRW which investigates low energy and solar architecture and includes buildings with earth heat exchangers under operation [11].

3.1 Investigated system

The investigated earth heat exchanger system assists an undivided family house for heating in winter and cooling in summer. A single pipe winds around the foundation of the house to whose ventilation system it connects. The pipe extends to the length of 42 m, its inner diameter is 125 mm. The pipe is embedded in the ground in a depth of between 0.7 m and 1.8 m. To enable drainage of condensate the pipe has a slope of 2 % from air inlet to outlet.

The house is heated with a heat pump. The earth heat exchanger is operated in winter to preheat the ventilation air and in summer to lower the ventilation temperature. For moderate outside temperatures the ventilation system is switched to directly suck in air from an inlet located above the roof of the building.

For the system given hereby several calculations are performed within *GAEA*. Weather data are available as 20-year-averages from the weather station Stuttgart-Hohenheim lying close to the house [7].

3.2 Calculated results

Figure 1 shows the temperature at the outlet of the earth heat exchanger for an air flow of 140 m³ per hour. The amplitude is damped and shifted compared to the outside air temperature as expected. Figure 2 gives the local temperatures along the pipe for a warm summer day as calculated by *GAEA*. The program is also capable of specifying the heat flow for every segment of the pipe for a particular day (Fig. 3) as well as summing the total heat exchange in the system throughout the year (Fig. 4).

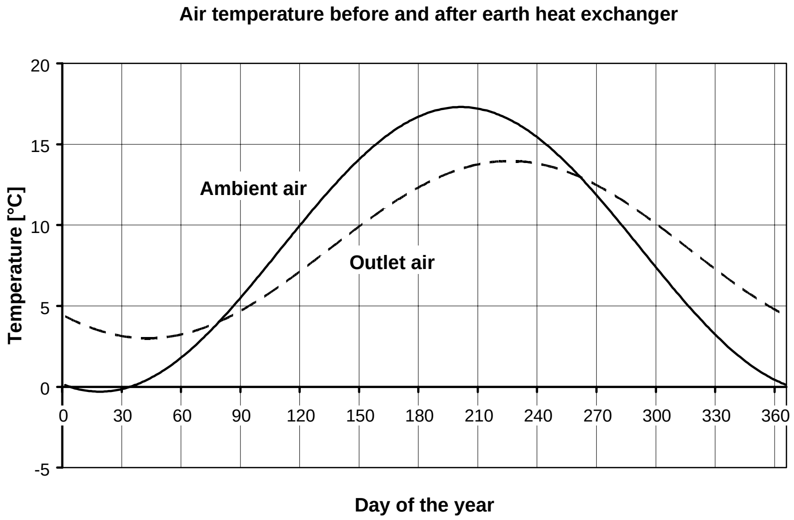

Figure 1: Ambient air temperature and temperature at the outlet of the earth heat exchanger throughout the year (calculated by *GAEA*)

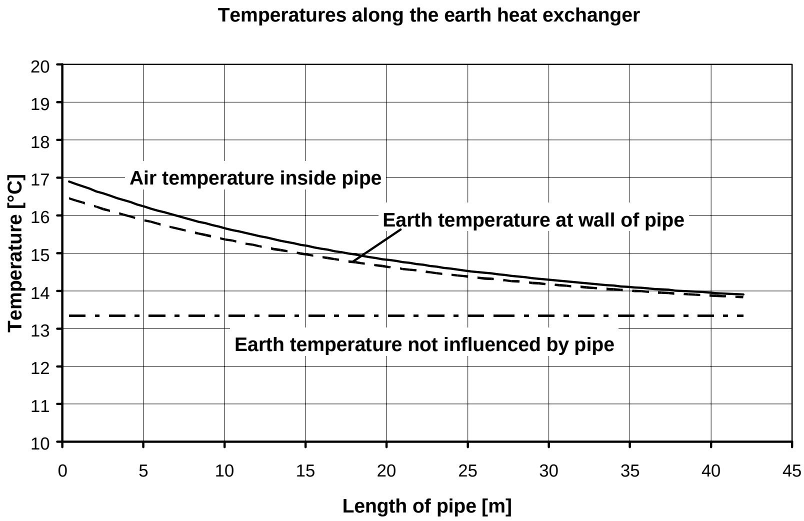

Figure 2: Temperatures along the pipe of the earth heat exchanger for a warm summer day (calculated by *GAEA*)

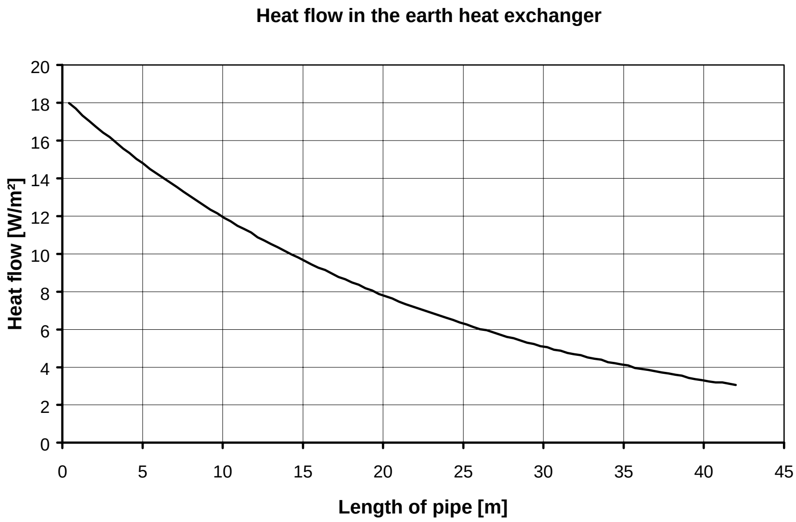

Figure 3: Heat flow along the pipe of the earth heat exchanger for a winter day (calculated by *GAEA*)

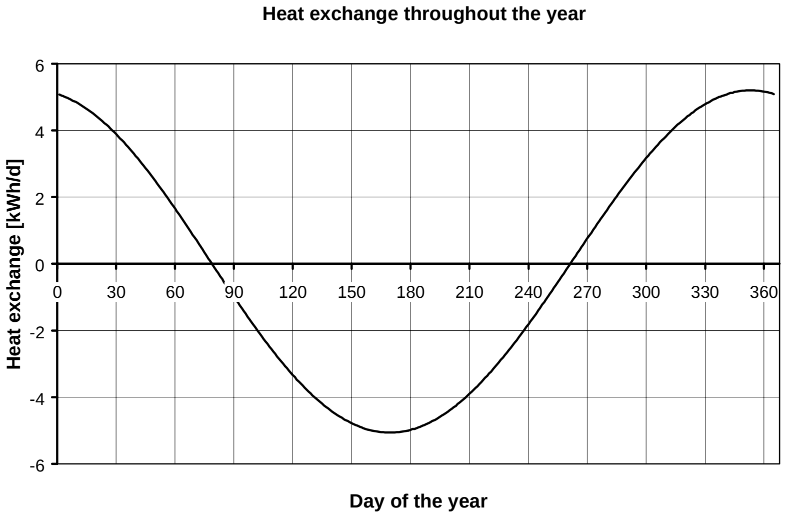

Figure 4: Heat exchange in the earth heat exchanger throughout the year (calculated by *GAEA*)

3.3 Heat gain during winter - cooling in summer

The integration of the heat exchange over time gives an estimate of the possibilities of the investigated heat exchanger system. In the described case *GAEA* predicts a heat gain in winter and a cooling effect in summer of about 600 kWh in each case.

The actually achievable energy flows may vary according to the following influences. Firstly the ambient air temperature distribution is not as smooth as the approximated sinusoidal curve used for the calculations. Therefore the usable energy flow tends to be higher since bigger temperature differences and hence bigger heating or cooling demands are correlated with higher energy flows in the earth heat exchanger. On the other hand especially during transition time the ambient air sometimes leads to a better room comfort then the air from the earth heat exchanger does. The system is therefore switched to circumvent the earth heat exchanger. Heating or cooling of air inside the pipe calculated by *GAEA* must then not be taken into account for the total heat balance.

Both corrections are to be considered when *GAEA* forms part of a detailed building simulation. Actual weather conditions may be used as input for the program. The calculation of heating demand according to e.g. EN 832 [12] allows to calculate a utilization factor for the output of the earth heat exchanger to better characterize its performance.

3.4 Comparison with experimental results

Figure 5 shows the air temperature in the segments of the investigated earth heat exchanger for a warm summer day as measured by Albers [7] and calculated by *GAEA*.

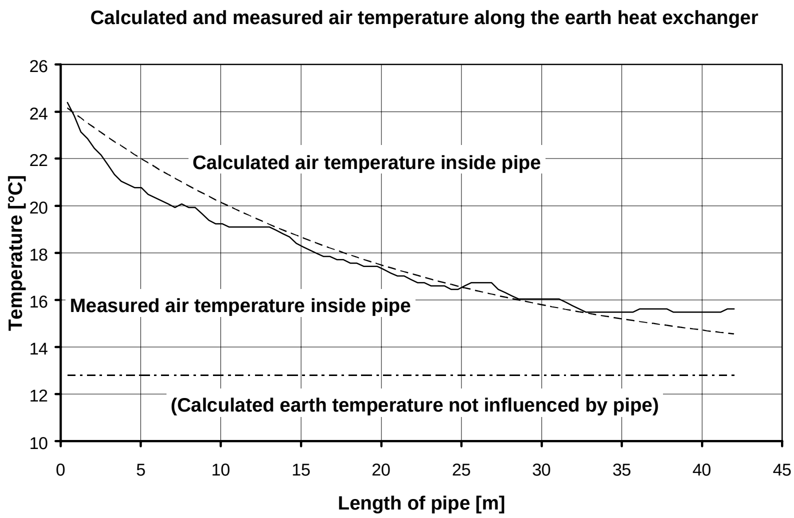

Figure 5: Comparison of measured and calculated air temperatures for a warm summer day along the earth heat exchanger

The parameters for the model were chosen as to represent the real weather conditions at the time of measurement, e.g. ambient air temperature was 25.3 °C and earth temperature at the depth of the pipe but not influenced by the pipe was 12.8 °C.

The main input values for the program *GAEA* are chosen according to the data provided by Albers [7]:

- annual mean value of ambient air temperature $\vartheta_m = 8.5$ °C
- annual maximum value of ambient air temperature $\vartheta_{max} = 26$ °C
- density of ground $\rho = 1600$ kg/m³
- heat capacity of ground c = 1300 J/(kg K)
- thermal conductivity of ground $\lambda = 1.5$ W/(m K)

The discrepancy of the temperatures may be explained largely by inhomogenous earth properties above the real pipe whereas the model assumes fixed values. In a refined version of *GAEA* it is planned to allow for different depths for each segment of the pipe.

With the model described above *GAEA* estimates a heat gain during winter and a cooling energy during summer of about 600 kWh in each case for the investigated earth heat exchanger. In the real world control strategies have an immense effect on the performance of the system. For the investigated house Albers measured a heat gain of 923 kWh during winter, of which 127 kWh stem from the ventilator needed to propel the air. In summer a cooling energy of 421 kWh was measured, here the ventilator produced waste heat of 36 kWh [7]. As Albers notes and as mentioned above monthly averages do not suffice for detailed calculation of the energy flows in an earth heat exchanger. The authors believe that *GAEA* will be more accurate when coupled to a building simulation program where more detailed temperature profiles and a realistic control strategy can be considered.

4 OPTIMIZATION OF AN EARTH HEAT EXCHANGER WITH *GAEA*

A main application of *GAEA* has to be the optimization of devices during the planning of buildings. Interesting parameters during the optimization process are the layout of pipes and the length and cross-section of pipes constituting the device.

One crucial point for an earth heat exchanger to operate satisfactorily is that only with turbulent airflow relevant heat exchange will take place. Figure 6 shows the correlation between the number of pipes and the diameter of each pipe for a system with an airflow of 140 m³/h (as in the layout calculated before) for the Reynolds number set to 2300, i.e. airflow is just starting to become turbulent.

Figure 7 shows the achievable heat gains of different layouts for an earth heat exchanger with a total air flow of 500 m³/h. The diameter of the pipes is chosen to ensure turbulent air flow at 140 m³/h according to figure 6. It can be seen that for this system a clear improvement in performance is reachable for the number of pipes to be two or three instead of one, but for more pipes no significant improvement is gained. Thinking of the costs for laying pipes [5] a probable compromise would be to use two pipes but not more. A refined version of the program *GAEA* will suggest a sensible solution for the number of pipes, its lengths and cross-sections according to given constraints by means of a mouse-click.

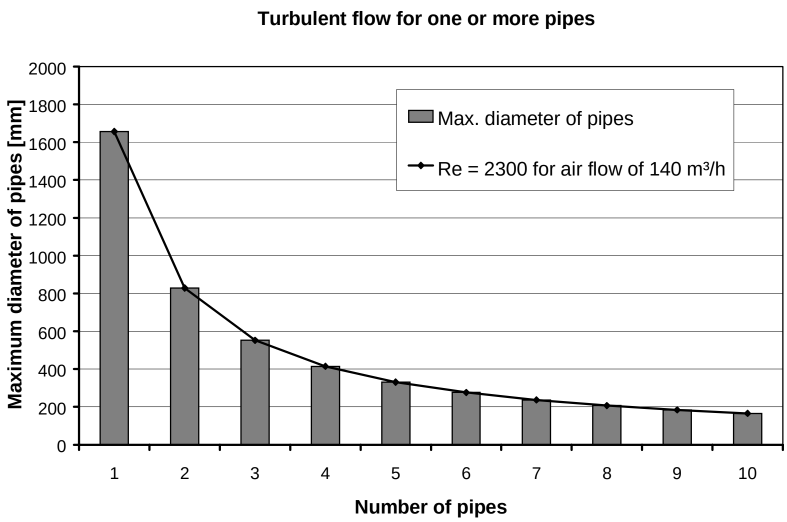

Figure 6: Conditions for turbulent flow in earth heat exchangers with one or more pipes

Heat gain of different layouts of earth heat exchangers

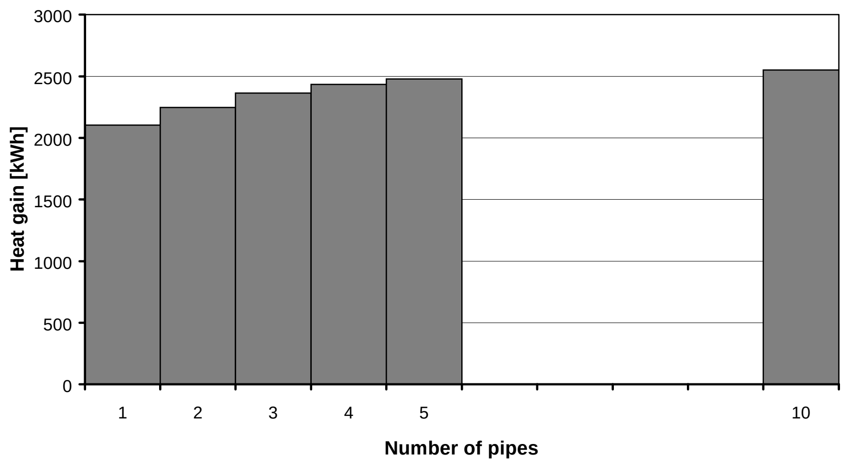

Figure 7: Comparison of different earth heat exchanger layouts

5 *GAEA* AND BUILDING SIMULATION

As a stand-alone tool *GAEA* serves the design and optimization of earth heat exchangers for buildings during the planning process. Yet especially for low energy houses the whole heating equipment is a complex system which must not be regarded in its parts only. Up to now the results of *GAEA* like the air temperature at the outlet of the buried pipe can be exported into files and be used as inputs of building simulation programs, e.g. to determine the inlet temperature of air used for ventilating rooms. It is projected to develop the program so that it can be linked together with simulation programs to integrate the calculations necessary for the characterization of the heating and ventilation of houses.

The combination of *GAEA* with a building simulation program also increases the accuracy of the earth heat exchanger calculation. Actual values for air properties can be used out of real weather profiles where up to now a rough sinusoidal approximation provides the input values. A monthly heating demand analysis e.g. using EN 832 [12] allows the determination of a utilization factor to characterize the performance of the earth heat exchanger in its interaction with the heating and ventilation system of the building.

6 CONCLUSION

GAEA still is in its first stage of development, but already it is a valuable tool to assist the design and calculation of earth heat exchangers forming part of the heating and ventilation system of houses. For different layouts of pipes the heat exchange, resulting temperatures and air flow properties can be calculated, both for the entire system and for individual segments in the course of the pipes. The results are written into output files that serve the input of building simulation programs for the calculation of heating and ventilation of buildings.

A refined version of the program will allow the input of more detailed ground coverings and earth structures above the earth heat exchanger. A better coupling with building simulation programs raises the possibility to use real weather profiles and hence make the calculation of air properties more accurate.

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NOMENCLATURE

h_i = heat transfer coefficient at the inner surface of pipe in W/(m² K)
Nu = Nusselt number of air in pipe
Pr = Prandtl number of air (typically: Pr = 0,72)
$\dot{Q}_W$ = heat flow from earth through wall of pipe to air in pipe in W
R_0 = radius of pipe in m
(R_0 is assumed to be small compared to S_0)
Re = Reynolds number of air in pipe
S_0 = depth of pipe center under surface in m
t = time in s
t_0 = duration of year in s (1 a ≈ 31.5 x 10^6 s)
t/t_0 = fraction of year (with t/t_0 equal zero for maximum ambient air temperature)
U_L = heat transfer coefficient per length of wall of pipe between bulk air and wall in W/(m K)
U* = conductance ratio of heat transfer from earth surface to pipe and from airflow to pipe wall
Δz = length of segment in m
$\vartheta_{A,0}(t)$ = ambient air temperature in °C at time t in s
$\vartheta_{A,P}$ = air temperature inside the pipe in °C
$\vartheta_{E,0}$ = earth temperature at the wall of the pipe not influenced by pipe in °C
$\vartheta_{E,W}$ = earth temperature at the wall of the pipe in °C
ϑ_m = annual mean value of ambient air temperature in °C
ϑ_{max} = annual maximum value of ambient air temperature in °C
λ = thermal conductivity of ground in W/(m K)
$\lambda_{A,P}$ = thermal conductivity of air in pipe in W/(m K)
ξ = dimensionless parameter for "thermal depth" of pipe
ρ c = volumetric heat capacity of ground in J/(m³ K)