EasyPipes *Basic*

Pre-dimensioning tool for air-soil heat exchangers

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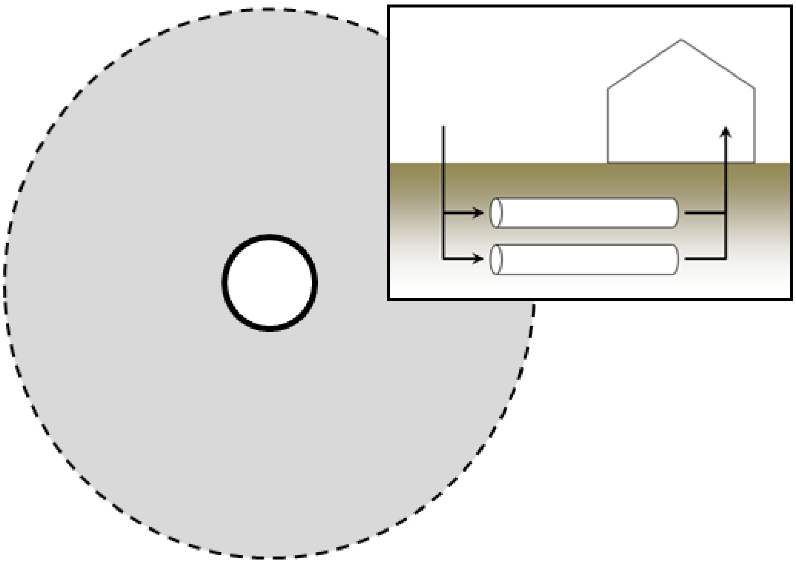

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General description

EasyPipes Basic is a pre-dimensioning tool for air-soil heat exchangers, which is based on an analytical solution of the heat equation, for the simplified case of a single pipe embedded in a cylindrical soil layer of given thickness.

The airflow, which is considered to be constant, is submitted to sinusoidal temperature oscillation at pipe inlet. The entire hourly dynamic over an entire year is constructed via Fourier analysis of the inlet temperature. This enables for very fast calculation and visualization of the fundamental behavior of the air-soil heat exchanger, in particular in terms of dampening of the inlet annual and daily temperature oscillations (linked to heat charge/discharge into the soil). It however doesn't take into account transient airflows, nor the interference with the upper surface.

The tool is driven by way of an Excel 2010 interface, and needs no other specific software.

Development of the tools originates from a PhD on air-soil heat exchangers elaborated by P. Hollmuller at University of Geneva. It further benefitted from following projects and funding:

- EasyPipes: Front/end numerical tool for simulation and dimensioning of air-soil heat exchangers, funded by the Swiss Federal Office of Energy.
- Stratégies alternatives à la climatisation (AlterClim), funded by Services Industriels de Genève (SIG).
- Building Energy Efficiency Project (BEEP), bilateral cooperation project between the Swiss Agency for Cooperation and Development of the Swiss Federal Department of Foreign Affairs and the Ministry of Power, Government of India.

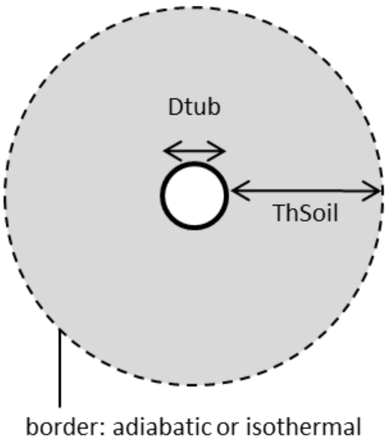
Disclaimer

The author, as well as the University of Geneva and the funding entities, deny any responsibility related to the use of this tool, in particular concerning the reliability of the results.

Geometry

The system is composed of a single pipe, embedded in a circular homogenous soil cylinder:

- The geometry is defined by the pipe length and diameter, as well as by the available soil layer.
- Border condition is either adiabatic or isothermal, and is set all around the soil cylinder.
- The soil characteristics (conductivity and heat capacity) are homogeneous, and the airflow is constant.
- The hourly inlet and outlet temperature dynamic is being constructed by summation of the most relevant oscillation frequencies: 0 (yearly average), 1 (yearly oscillation), 2 (yearly + daily oscillation), up to 4380 (all frequencies).



Parameters

The model is defined by following parameters.

Symbol	Unit	Description
<u>Geometry</u>		
Ltub	m	pipe length
Dtub	m	pipe diameter
ThSoil	m	Soil thickness
<u>Airflow</u>		
Fair	m3/h	air flowrate
<u>Soil</u>		
LamSoil	W/K.m	soil conductivity
CvSoil	kJ/K.m3	soil heat capacity
<u>Border conditions</u>		
Ibord	-	border condition (0: adiabatic, 1: isothermal)
Tbord	C	border temperature (if Ibord = 1)
<u>Simulation</u>		
Nfreq	-	Number of calculated frequencies (0-4380)

Inputs and outputs

The model requires following input:

- Outdoor (=inlet) temperature in hourly time step over an entire year (8760 values)
- Corresponding temperature amplitude and phase-shift for the 4380 associated frequencies. These values are obtained by way of Fourier analysis of the inlet temperature data, which is done via a specific tool (see below)

The model calculates the outlet temperature in hourly time step over the entire year.

Excel interface

The tool is embedded within an Excel 2010 interface (EP.Basic.xlsm).

EP.Basic.xlsm contains macros, which must be enabled when opening the workbook. Excel calculation is set to manual, so that the workbook is not constantly calculating when changing parameters. After use of EP.Basic.xlsm, beware to undo this option via the Excel Formula tab / Calculation options.

Cells with black font correspond to constants, cells in blue font to formulas. Except for the editable cells (grey brown background), the cells are protected against edition, so as to protect from miss-use. If needed, the sheets may be unprotected via the review tab (under responsibility of the user).

The excel workbook contains following sheets:

- Main: the top part of the sheet contains the action buttons and the parameters. The lower part contains the graphs:
  - The first graph concerns the daily mininma and maxima of the inlet and outlet temperature (red and blue lines), as calculated for the selected Nfreq frequencies. As a reference, the graph shows also the full dynamic of the inlet temperature (orange lines), as given by all the 4380 frequencies.
  - The second graph concerns the hourly dynamic over a month, which can be selected via the spin button.
  - The last two graphs concern the output versus input amplitudes of the yearly and daily oscillations, in both cases calculated on daily basis. For the yearly oscillation, the amplitude is defined as the difference between the average daily temperature and the yearly average temperature; for the daily oscillation, it is defined as the difference between the maximum and the minimum daily temperature.
- Data.t: hourly data over an entire year (8760 values per column)
- Data.w: frequency data (4380 values per column)
- Data.period: hourly data over an entire month (zoom of Data.t)
- Data.day: daily min/max values
- Data.reg: linear regression values for determination of daily/yearly amplitude dampening coefficients

- Data.other: other stuff

Action buttons

The main sheet contains two action buttons:

- Load: opening and loading of meteorological data (inlet temperature) that has previously been Fourier analyzed (see MeteoFourier tool further down). The hourly data is automatically pasted into the ‘Text’ range (in sheet ‘Data.t’), the frequency data is pasted into the ‘Freq’, ‘TextMod’ and ‘TextArg’ ranges (in sheet ‘Data.w’).
- Refresh: calculating/ refreshing of model, due to manual calculation mode.

MeteoFourier tool

Embedded within an Excel 2010 interface named ‘MeteoFourier.xlsm, this specific tool performs Fourier analysis of hourly meteorological temperature over one year, and stores it into an excel workbook with extension ‘.fourier.xlsx’. See the specific user guide of this tool.

Mathematical model

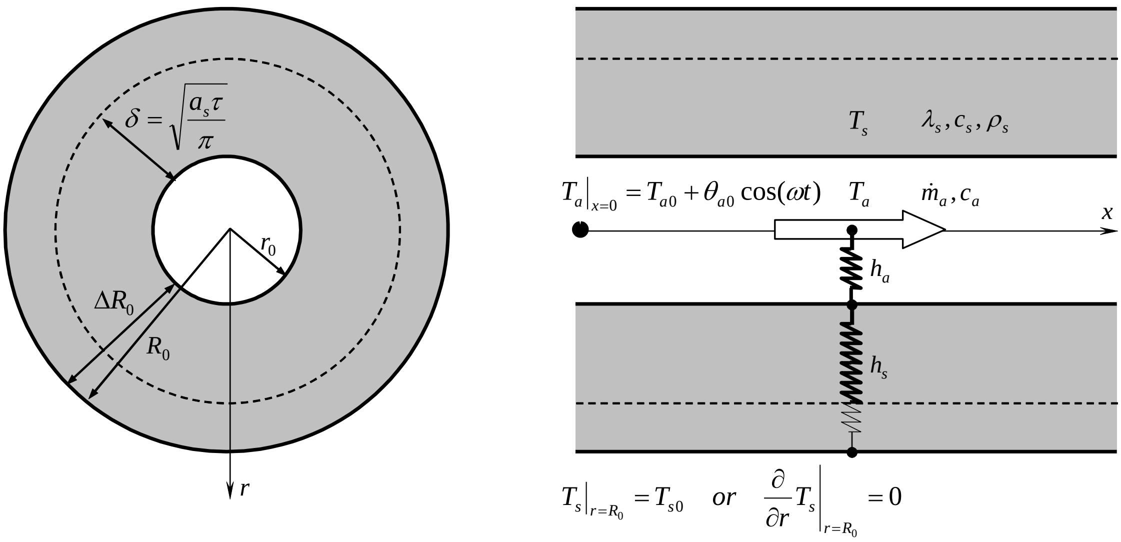
The formulation below is taken and adapted from (Hollmuller P., 2003). Only the problem definition and the main results are given here.

We consider a constant mass flow of air submitted to sinusoidal temperature oscillation at entrance of a cylindrical pipe, itself embedded in a finite cylindrical soil layer with adiabatic or isothermal boundary condition. Following hypothesis will further be made:

- In relation to perpendicular heat diffusion, longitudinal one is considered to be secondary and will hence not be accounted for. As will be seen by comparison with numerical simulation, this hypothesis will be more than good enough, at least as long as the characteristic length of amplitude-dampening or phase-shifting remains larger than the natural penetration depth.
- Within a given section air is considered to be homogenous, so that the dynamic of convective air/soil heat exchange will not be described in detail but by means of a unique convective heat exchange coefficient between airflow and pipe, supposed to be constant over the whole pipe length. Velocity profile is furthermore supposed to be uniform, so that bulk and average temperatures in a pipe section can be said to coincide. Comparison with experimental data as well as with a numerical model (itself validated against several in situ monitored real scale systems) should support for these assumptions to cause negligible errors in practical applications.

- Soil thermal conductivity and capacity are considered to be homogenous and constant, variation of soil type and water content not being accounted for. Nor is being considered any water movement inducing convective heat exchange within the soil.
- The pipe itself is not taken into account. In first approximation this hypothesis could if necessary be corrected by : 1) including the conductivity of the pipe into the convective heat exchange coefficient between airflow and pipe ; 2) considering an effective soil radius which takes into account the pipe's thermal capacity.
- Possible latent heat exchanges are not accounted for, which means that no water infiltration is at work and that the air temperature is supposed to remain above its dew point.
- Thermal effect of charge losses are not taken into account.

Cross-section — Longitudinal section



The thermal exchanges of the system are governed by the following three differential equations, which respectively describe cylindrical heat diffusion in the soil, convective air/soil exchange and the link between both at the pipe's level :

$$a_s \left(\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r} \frac{\partial T_s}{\partial r} \right) = \frac{\partial T_s}{\partial t}$$

$$c_a \dot{m}_a \left(\frac{\partial T_a}{\partial x} + \frac{1}{v_a} \frac{\partial T_a}{\partial t} \right) = 2\pi r_0 h_a \left(T_s\big|_{r=r_0} - T_a \right)$$

$$\lambda_s \frac{\partial T_s}{\partial r}\bigg|_{r=r_0} = h_a \left(T_s\big|_{r=r_0} - T_a \right)$$

The system is resolved for the particular case of stationary harmonic input, with adiabatic or isothermal boundary conditions:

$T_a\big|_{x=0} = \theta_{a0} \cos(\omega t)$

$$T_s\big|_{r=R_0} = 0 \quad \text{or} \quad \left.\frac{\partial T_s}{\partial r}\right|_{r=R_0} = 0$$

It is shown that the resulting temperature along the pipe corresponds to an exponentially dampened and phase-shifted oscillation of the form:

$$T_a(x,t) = \theta_{a0} \cdot \exp\left(-\frac{2\pi r_0}{c_a \dot{m}_a} hx\right) \cdot \cos\left(\omega(t - \frac{x}{v_a}) - \frac{2\pi r_0}{c_a \dot{m}_a} kx\right)$$

Explicit calculation of the h and k coefficients, which imply modified Bessel functions, are given in (Hollmuller P. 2003).

By way of Fourier analysis, above calculation can be extrapolated to any periodic input signal:

References

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- Hollmuller P., Lachal, B. (2008). Air-soil heat exchangers: dimensioning guidelines for dampening of day/night or summer/winter temperature oscillation, in: Eurosun 2008, 1st International Conference on Solar Heating, Cooling and Buildings, 7-10 October 2008, Lisbon, Portugal.
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