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PRAKTYCZNA IMPLEMENTACJA PERIODYCZNEGO MODELU TRANSMISJI CIEPŁA, JAKO SYMULACJI W 4D

IMPLEMENTATION OF A PERIODIC THERMAL CONDUCTION MODEL IN A 4D SIMULATION PROGRAM

Summary

Using the periodic calculation approach allows to capture heat conduction and heat storage effects in three-dimensional models. It is necessary to use this calculation approach if there is a considerable influence of heat storage capacity while calculating thermal bridges. A three-dimensionally, periodically working thermal-bridge-analysis software will be presented, as well as possibilities to visualize results dependent on 4 dimensions. The practicability is exemplified by an earth-coupling system.

Keywords: thermal bridges, heat storage capacity, 3D calculation, periodic calculation

Abstract

The paper outlines the possibilities of capturing thermal behavior of thermal bridge regions with considerable heat storage capacity using a three-dimensional, periodic approach. The problems of earth-coupling systems will be addressed in this context.

Keywords: transient thermal bridge analysis software

1. Introduction

In the course of thermal bridge calculations the capture of a multidimensional heat conduction process is generally based on steady-state, i.e. time-independent boundary conditions. In this calculation approach, the heat storage capacity of analyzed constructions has no influence on calculation results.

The steady state calculation will therefore only provide useful approximation results, when the heat storage capacity of the investigated building construction is to be neglected. Old and historic buildings, with massive masonry and thick walls, will not comply with these requirements. The heat storage capacity of earth coupled systems is of utmost importance. In these cases the calculation has to be transient, i.e. time-dependent.

The theoretical basis for a multi-dimensional, transient calculation of heat conduction and heat storage operations - for the special case of time-dependent periodic boundary conditions - is known for some time [1, 2]. The main results of this theory will be briefly recapitulated here.

During the implementation of the periodic theory into the thermal bridge calculation software AnTherm [3,4], the presentation of calculation results proved a major challenge. Reason is the time as an additional fourth dimension to the three spatial coordinates in comparison to steady state calculations. In this paper solutions for the visualization of two- and three-dimensional, transient calculations are shown, discussed and complemented with examples.

2. Periodic calculation approach

It is known for some time that the heat conduction equation can be solved for each harmonic in the special case of periodic set boundary conditions. This means that there is no need for time discretization [1]. Further the problem of unknown starting conditions does not arise.

The theory of thermal conductances was developed for the steady state case and has been presented in the book "Wärmebrücken" (Thermal Bridges) [5]. It proved to be a special case of the more common periodic theory [1]. The fundamental relations are same for the steady state case as well as for the periodic theory. Those are outlined below.

The complex amplitude of the heat loss of an *i* indexed room $\hat{\Phi}_i$ to all neighboring rooms can be described as

$$\hat{\Phi}_i = -\sum_j \tilde{L}_{i,j} \cdot \hat{\Theta}_j \qquad (1)$$

The exterior is involved into this model in kind of "external rooms". Thus, there is a linear relation between the complex amplitude of the heat loss $\hat{\Phi}_i$ of room *i* and the complex amplitudes of the transient behavior of the air temperatures $\hat{\Theta}_j$ of all rooms adjacent to the construction. The complex harmonic thermal conductances $\tilde{L}_{i,j}$ act as proportionality factors. In equation (1) it has to be summated over all rooms including room *i* itself. This approach (1) is part of the international standard EN ISO 13786 [6] for the special case of construction components that are adjacent to two rooms only ("interior" and "exterior"). It is the basis for the definition of the effective heat storage capacity[1]. In the steady state i.e. time-independent case relation (1) can be described as [2]

$$\bar{\Phi}_i = -\sum_j L_{i,j} \cdot \bar{\Theta}_j \qquad (2)$$

$\bar{\Phi}_i$ and $\bar{\Theta}_j$ are the zeroth harmonic of their respective Fourier-Series and are real numbers (the mean value of the heat loss and the mean value of the air temperature profiles). In the steady state case the thermal conductances $L_{i,j}$ are real numbers, as well.

Due to the conservation of energy, for the steady state case (only) is

$$\sum_j L_{i,j} = 0 \quad . \qquad (3)$$

By using relation (3) equation (2) can be altered to

[1] Despite several requests to correct, there is still a sign-error in equation (4) of EN ISO 13786.

$$\bar{\Phi}_i = \sum_{\substack{j \\ j\neq i}} L_{i,j} \cdot (\bar{\Theta}_i - \bar{\Theta}_j) \tag{4}$$

This basic relation of the theory of thermal conductances is part of the standard EN ISO 10211 [7]. According to [1] the calculation of the temperature distribution inside the construction is resulting in a linear relation, as well. The complex amplitude $\hat{\Theta}$ of the temperature of any point of a construction can be determined by using

$$\hat{\Theta}(x,y,z) = \sum_j \tilde{g}_j(x,y,z) \cdot \hat{\Theta}_j \tag{5}$$

Thus, $\hat{\Theta}(x,y,z)$ is linearly dependent on the complex amplitudes of the air temperature profile $\hat{\Theta}_j$ of each of the rooms adjacent to the construction component. The complex dimensionless harmonic temperature-weighting-factors $\tilde{g}_j(x,y,z)$ act as proportionality factors. Again, it has to be summated over all rooms adjacent to the construction using equation (5). For the zeroth harmonic, that is the steady state case, equation (5) keeps its structure:

$$\Theta(x,y,z) = \sum_j g_j(x,y,z) \cdot \Theta_j \quad . \tag{6}$$

The temperature-weighting-factors g_j are real numbers in case of the zeroth harmonic. Θ_j are the mean values of the temperature profiles of each of the rooms adjacent to the construction. Θ is the temperature on the position marked by (x,y,z) .

Like the thermal conductances and the temperature-weighting-factors, the harmonic thermal conductances and the harmonic temperature-weighting-factors are independent of the air temperatures, as well. That's why they are ideally suited for acting as indicators of the construction. They can be calculated by suitable thermal bridge analysis software without the need of defining boundary conditions. According to EN ISO 10211 [7] the steady state conductances and the temperature-weighting-factors state the result of a thermal bridge calculation as significant indicators.

At given conductances and temperature-weighting-factors the thermal conduction - and heat storage processes can be described three-dimensionally for variously shaped and arbitrary composed constructions– by using the basic relations of (1), (4), (5) and (6). Further there is no limitation regarding the amount of interior and exterior rooms adjacent to the construction. The construction may be a section of the building envelope or the entire building envelope; even the totality of all construction components of a building can be considered to be a construction.

The following procedure is required for the calculation of the temperature profile and/or the heat flows: In the first step the mean values and complex amplitudes of the given temperature profiles and/or given heat flow profile is calculated using Fourier-Analysis. The amount of harmonics is depending on the question to be answered and the accuracy requirements of the result. In the second step the complex amplitudes of the variable to be found is calculated for each harmonic by using the relations of (1) and/or (5). The likewise required mean values can easily be calculated by equations (4) and (6). Of course the thermal conductances and the temperature-weighting-factors have to be determined beforehand using a periodic thermal bridge calculation. A final Fourier-Synthesis leads to the parameter varying in time.

For instance the temperature-profile of any point of the construction component can be calculated in this way. Thus, the temperature field of a three-dimensional construction component can be calculated including its changes in time. Likewise the varying-in-time heat losses of each room adjacent to the construction component can be determined.

3. Visualization of calculation results

The three-dimensional, periodic calculation on the basis of the conductance theory is already implemented in the thermal bridge program AnTherm [3]. While implementing the calculation module especially the visualization of the calculation results turned out to be a special challenge. Since the calculation result is dependent on four dimensions which are three spatial coordinates and the time it cannot be visualized right away. However, there are various possibilities to show the calculation results, by using appropriate visualizations in a smaller dimension. The applicable choice of visualization is highly depending on the question to be answered.

Even in a steady state case it is sophisticated to clearly visualize the calculated temperature distribution in three-dimensional models. To avoid this problem, it is possible to reduce the dimension by laying flat sections trough the construction. On these sections, the calculated temperature distribution can be shown by using a false-color image or/and isotherms. By moving the section plane along an axis it gives an impression of the temperature distribution inside the construction component.

By calculating the temperature distribution on a specific section plane for a certain point of time, it is now possible to show it in the manner of a slide show. This type of visualization may give the user an impression of the effects of heat conduction and heat storage inside the component; however, it is very unlikely that it will lead to usable quantitative conclusions.

In order to obtain more usable information, it is necessary to reduce the visualization to two dimensions. Through this kind of visualization most questions will be answered the best. An example may be the heat loss varying in time of one room to another room or to the outside. In this case, the result of a three-dimensional, transient simulation can easily be presented using diagrams.

Regarding the temperature distribution, it is often more useful to focus on specific points, than trying to visualize it in a more complicated way. Thus, according to EN ISO 10211[7] it is reasonable to check the point of minimal surface temperature of each room only. However, the search for this point, regarding the transient case, is more complicated. Beforehand, the minima of the temperature profiles of each point have to be determined and compared.

The totality of points of equal temperature is another very important task in practice.

One possibility to visualize the result of this question is to draw isotherms on cutting planes running through the model at a certain time. Sometimes it is more useful to visualize an isosurface into a three-dimensional model at a specific time.

An example of this matter would be the determination of the frost line in the ground close to buildings, to be able to proof a frost-free foundation.

4. Example of application

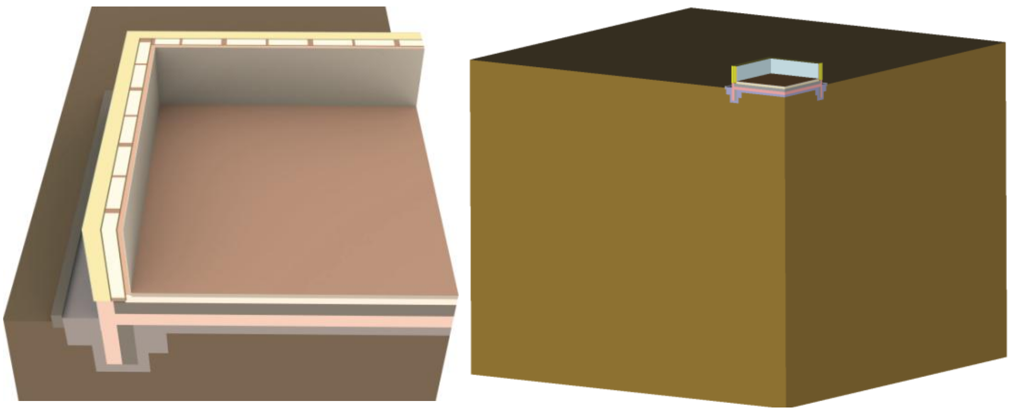
While assessing the thermal performance of the building envelope the description of heat losses of earth coupled components takes a special position for two reasons:

1.) A one-dimensional approach that is often used for air-touched components to calculate partial conductances by multiplying heat-transfer coefficients and the respecting component surface areas would not make any sense. The two-dimensional calculation of heat loss does not bring any useful results of practical relevance because the influence of the corners cannot be ignored [8].

2.) In connection with heat loss through earth coupled components, wide areas of the ground surrounding the building are affected by the heat flow.

Most steady state or quasi-steady state calculations neglect the effects of heat storage. This leads to major misjudgments, because of the great influence of heat storage effects [9]. Therefore the thermal behavior of earth coupled components has to be calculated in transient way. In most cases the thermal behavior of a building over the long time average is of interest. This means that the periodic steady state calculation approach on the basis of the annual period is perfectly suited for describing the thermal behavior of earth coupled components. For this reason, the foundation slab of a detached house in passive house standard will serve as an example of a three-dimensional periodic calculation in the following section.

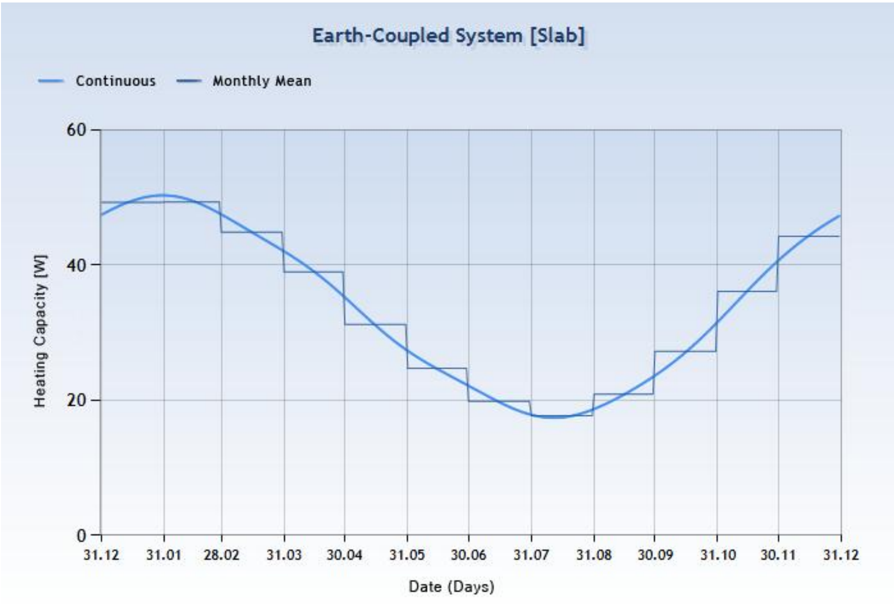
Under consideration falls a square cut-out of the foundation slab including one meter of the rising external wall. Figure 1 shows the structure and the three-dimensional calculation model. Besides the building construction of interest, according to EN ISO 10211, large areas of the surrounding soil are included in the model.



Ryc. 1: Szkic konstrukcji i model obliczeniowy

Fig.1: Construction and calculation model

As a result of the three-dimensional, periodic calculation AnTherm [3] provides an immediate thermal conductance between the inside and outside as well as the matrices of the harmonic thermal conductances for the 6 considered harmonics. The heat loss during the course of the year through the section as shown in figure 1, is calculated by the three-dimensional, periodic based thermal building simulation program Thesim [10] using equations (1) and (4). Assuming a constant inside air temperature of 20°C and a long-time, smoothed annual profile of the outside temperature for the meteorological station in Vienna, Hohe Warte, results in an annual course of heat loss output as shown in figure 2.

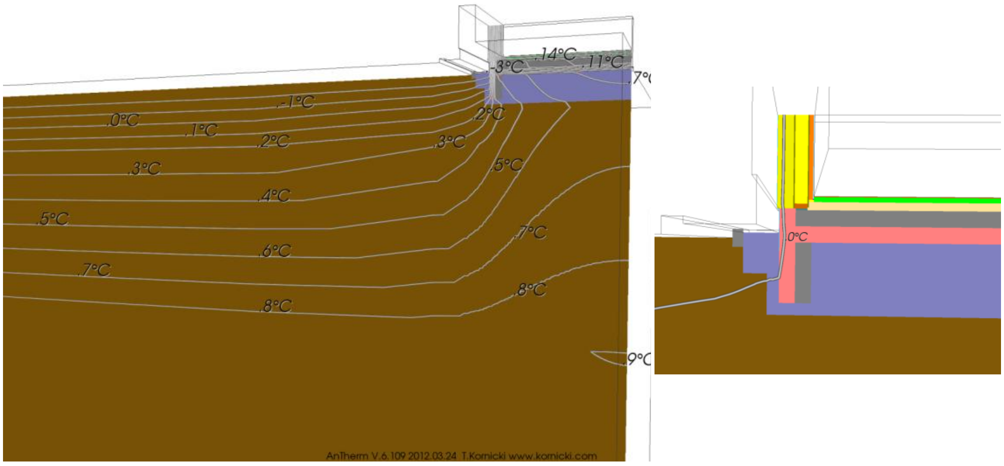


Ryc. 2: Roczny przebieg strat energii cieplnej [10]

Fig.2: Annual course of heat loss [10]

In addition to the correct evaluation of heat loss trough earth coupled components, the frost line in the ground plays an important role. The calculation of heat loss, based on long-term mean values, cannot be used to ensure a frost-free foundation. To obtain realistic results, it is necessary to apply extreme winter conditions. The present case is based on the year with the most extreme winter outdoor temperatures out of a 50-year time series (1960 - 2009 Vienna, Hohe Warte). Hence, the year 1966 was chosen, the only year with monthly mean values below freezing point for December, January and February.

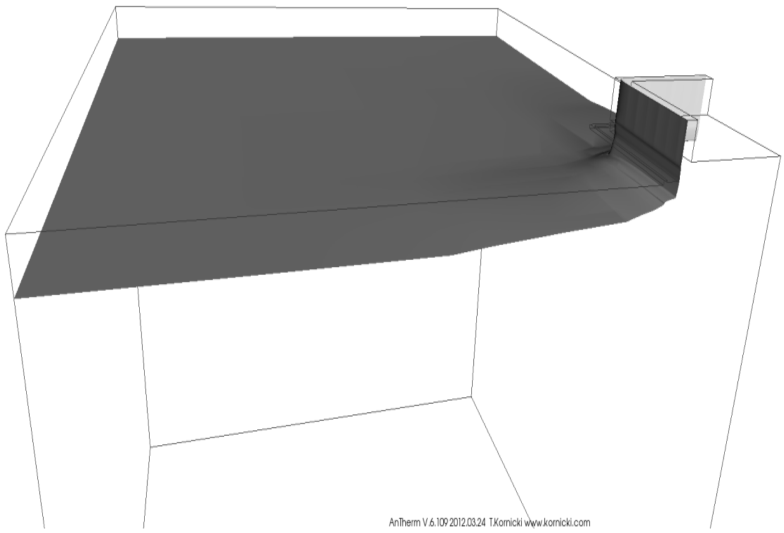
The following figure shows the calculated temperature field on the section plane running through the exterior wall and foundation slab for February, 8th, 8:00. More information about the frost-resistance of the structure located in Vienna provides the following figure on the right side of fig. 3.



Ryc. 3: Wizualizacja rozkładu temperatury (izotermy) w dniu 8 lutego, $8^{\underline{00}}$, przekrój poprzez ścianę zewnętrzną i płytę fundamentu.

Fig.3: Isotherm visualization of temperature distribution on February, 8^{th}, $8^{\underline{00}}$, section plane running through external wall and foundation slab. Right side: zero-Grade Isotherm

It turns out, that a strip foundation remains frost-free in the area of the selected section even during extreme winter frost. The question, whether the foundation remains frost-free in the area of the edge of the building, is not answered yet. This gets revealed by the visualization of the isosurface for 0°C in the following figure.



Ryc. 4: Izo-powierzchnia dla temperatury 0°C w dniu 8 lutego, $8^{\underline{00}}$

Fig.4: Isosurface for 0 °C, February, 8^{th}, $8^{\underline{00}}$

Figure above shows that the foundation keeps frost-free for the Viennese site and locations with similar exterior climate conditions. When interpreting this result it has to be considered that AnTherm [3] uses non-time-varying material parameters. The effects of moisture transport and ground freezing are neglected. Analyzing the influence of these effects on the temperature field [11] in detail reveals that a consideration leads to slightly elevated temperatures. Thus, the temperature fields calculated by AnTherm [3] are on the safe side.

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