Numerical modeling of underfloor heating system using CFD procedures with Elmer software

Daniel Kucharski, Marcin Wesołowski, Ryszard Niedbała
Warsaw University of Technology
00-662 Warszawa, ul. Koszykowa 75, e-mail: Daniel.Kucharski@ien.pw.edu.pl

Jacek Hauser
Poznan University of Technology
60-965 Poznań, ul. Piotrowo 3A, e-mail: Jacek.Hauser@put.poznan.pl

In the paper, the usage of multiphysical simulation software Elmer for simulating underfloor heating systems in a building is presented. Calculations were carried out in areas of solid elements of the model of the room, with the behavior of air and its temperature distribution was also taken into account. Results were compared with those obtained from other model based on a study of the temperature field only in solids, where the room's temperature is known, or its change is given.

1. Introduction

Numerical simulation allows observation of physical phenomena on a computer screen, with a possibility of detailed analysis of each of the parts of the modeled world. To achieve desired results of calculations, two approaches are used – creating your own computational procedures and using commercial programs like Ansys, Flow 3D, or Nisa. The first method gives a possibility of experiencing the wealth of numerical algorithms, which allows us to simulate our physical world, to understand the beauty of mathematical formulas, and to feel both their complexity, and also simplicity and elegance of form. Unfortunately, creating your own algorithms and their programming is very time consuming. The prices of commercial computational systems that use the best available models describing the physical phenomena are very high. Consequently, small research teams or individual scientist cannot afford them.

The solution to this problem that combines the two mentioned above methods are programs released under GNU General Public License (http://www.gnu.org/). The user receives not only the executable program, but also its source code. That gives the possibility of making modifications in software and of implementing your own procedures without having to write that program from scratch. However, the most important reasons for using GNU GPL programs are that they are often free of charge and at the same time, they have similar computation potential like commercial programs.

This paper proposes the usage of finite element software package Elmer [2, 7]. The creation of this program has been started in 1995 in Finland. It is a result of a scientific project for the development of a research tool for solving Computational Fluid Dynamics problems. Nowadays, further development of Elmer is in the hands of CSC - IT Center for Science, and their distribution is based on the GNU license, under which Linux operating system is also released. Initially, the program was intended only for the CFD problems, but it has been expanded over time to describe the thermal, electrostatic, and electromagnetic phenomena, diffusion, mechanical deformations, acoustics and even quantum processes [7]. Elmer has been verified in many simulation problems, such as Magnetic Czochralski method for monocrystalline silicon growth [8]. From mathematical point of view, it is a very a complicated process, which combines mass transfer, temperature field and crystallization of the material from liquid silicon, and also magnetic field affecting the crystallization process.

Many researchers have worked on the problem of numerical simulation of heating entire buildings or individual rooms [1, 4, 5, 6]. In simplified calculation models, this problem is reduced to determining only the temperature distributions in solid elements (walls, floors, ceilings) of the building. Newton's Law of Cooling equation (4) is used to describe heat transfer between solid elements and ambient air [4]. Advanced model describes also the temperature field of air in the room, with its movement, according to location of heat source and ventilation efficiency. Moreover, this model was presented in many scientific works [1, 5, 6]. The disadvantages of this approach are: complexity of the model, which forces you to use highly advanced computer systems, and the fact that its solution is extremely time consuming.

The design of the underfloor heating system is usually based on the determination of energy balance in a steady-state in different areas of the building, assuming minimum outside temperature for a given area of the country. This method might be insufficient for heating systems that are characterized by slowly response of the temperature field to changing weather conditions. Storage underfloor heating systems, which works intermittently and accumulates heat at certain times of the day, while in the remaining periods use this energy to heat, are particularly this types of systems.

2. Mathematical models

The geometry of the modeled object has been based on typical construction of buildings, heated by a heat source located under the floor surface. Two-dimensional model of the room was considered, without any windows or doors. There was not any force ventilation in room, so air movement was solely the result of a natural convection. Heat was transferred through the exterior wall, which was composed of two materials - styrofoam and cellular concrete. Used materials, together with their thermal parameters, are listed in Table 1.

The geometry of the sample object was created using Gmsh software (http://www.geuz.org/gmsh/) [3]. This free program is a finite element mesh generator with very interesting capabilities. The reason for using this program is lack of this type of advanced software in the Elmer system. Fortunately, one of the Elmer programs, ElmerGrid to be exact, was designed to transform one of several popular mesh file formats created in other programs (inter alia Ansys or Gid) to the one that is understood by ElmerSolver.

Gmsh works on a similar principle as interpreted programming language. It is possible to define the variables that describe the model width, height or diameter of the heating cables. The existence of a loop conditional is a very interesting feature. Model of an element could be created with that feature, in the way a computer program is normally created, for example: ten cables of the same shapes, which are located in close distance. It allows you to apply modifications to the structure of geometry quickly, without having to make many operations as in typical GUI type programs. It is possible to generate mesh using various algorithms (Delaunay, Frontal). Gmsh can generate mesh with various polygon sizes in different areas of the model of the room, as can be seen in Fig. 1.

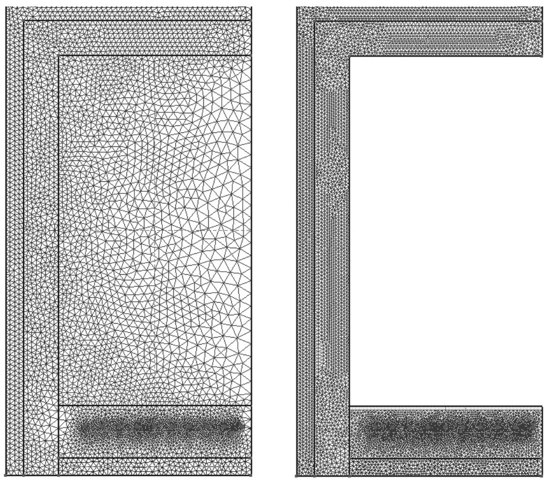

Fig. 1. Model geometry created with Gmsh

After creating the model geometry and its polygon mesh, solver input file (file extension is *sif*) needs to be created. That requires selecting mathematical equations that govern physical phenomena. The definition of parameters of all materials is also required. Very interesting feature of Elmer is that one can have influence on the way in which Elmer procedures of solving differential equations actually work. It is possible to use direct linear system solvers that use Umfpack or Lapack libraries, iterative Krylov solvers, multigrid solvers, and many more [2, 7]. Multitude of Elmer's options is really overwhelming.

Calculations were performed in transient state. The calculations were carried out in steps of 1 s for the first 3600 s of simulation time, the rest of the simulation uses step of a 2 s range. The calculation that was run on PC Intel Quad Duo lasted approximately 200,000 s, so more than two days. An important advantage of Elmer is its ability to interrupt the calculations and run them again from the moment they were interrupted.

Table 1. Materials used in calculations

Material	c_w	k	ρ
-	[J/kgK]	[W/mK]	[kg/m$^{3]}$
Floor concrete F311 Knauf	837	1,660	2100
Cellular concrete Ytong 700 type (for wall)	840	0,200	700
Styrofoam PS-E FS 15 (thermal insulation of the wall)	1500	0,042	15
Styrofoam PS-E FS 20 (thermal insulation of the floor)	1500	0,038	20

It was mentioned in the preface that two different methods of solving the problem have been applied in this research. Figure 1 shows both geometry of the same room model connected with these two approaches. On the left side of Figure 1, shape of the model with its polygon mesh for solving coupled velocity and temperature field were presented. In the area defined as air, the program will solve the Navier-Stokes equations (velocity and pressure fields) and Fourier-Kirchoff equation in solid elements of room. On the right side of Figure 1 is the same model, however without mesh in the air area of the room. The result of these calculations is the temperature field only in solid elements.

Three different equations are required for finding velocity, temperature, and pressure fields in air: continuity equation, Navier-Stokes equation (2), and Fourier-Kirchoff, which is also called heat equation (1). Elmer can perform calculations for three compressibility model of simulated flow: incompressible, artificial compressible and perfect gas [2]. Thermal incompressible flow of Newtonian fluid was chosen, because it models well the airflow in a heated room. In incompressible flow, fluid density ρ=const is assumed and conservation of mass (the continuity equation) simplifies to form of $\nabla \cdot \vec{u} = 0$. Temperature field is a result of Fourier-Kirchoff equation, given in form:

$$c_p \rho \left(\frac{\partial t}{\partial \tau} + (\vec{u} \cdot \nabla) t \right) - \nabla \cdot (k \nabla t) = \rho \cdot p_v \tag{1}$$

where: c_p – specific heat for given pressure, ρ - density, u – velocity vector, k – thermal conductivity, p_v – heat source density, t – temperature field, τ - time.

$$\rho\left(\frac{\partial \vec{u}}{\partial \tau}+(\vec{u}\cdot\nabla)\vec{u}\right)-\nabla\cdot\left(2\mu\overline{\mathbf{T}}\right)+\nabla p=\vec{f} \tag{2}$$

Boussinesq approximation is very important for presented calculations (3). We assumed thermal incompressible that ρ=const, but of course when we think about natural convection, density of the fluid needs to be changing with temperature, which cause buoyancy force. Equation (3) requires knowledge of the value of volume expansion coefficient β, which was defined for air in 273 K, β = 0,00343 1/K. Another simplification of these very complicated and time-consuming calculations is that it was assumed that the air is a Newtonian fluid, which means that the dynamic viscosity is constant, independent of the speed of fluid motion. It was also assumed constant with temperature.

$$\vec{f}=\rho_0 g(1-\beta(t-t_0)) \tag{3}$$

In case of calculations that were performed only for solid elements, temperature field cannot be solved for air. Typical way to approach in this case is to use Newton's Law of Cooling (heat transfer is proportional to temperature difference between surface and ambient temperature) (4). We assume that the surfaces of walls and floors are exchanging heat with ambient air, and rate of this process is described by heat transfer coefficient α. This is a very basic approach with computation time very short if compared to second method, but ambient temperature has to be assumed, which is in some way wrong. Calculation of this temperature is the main issue of many scientific problems. For example, this temperature might be an unknown in a given shape of a room, structure of the wall, used materials, and heat system efficiency.

$$q=\alpha\cdot(t-t_p) \tag{4}$$

One of many interesting feature of Elmer is the possibility of using internal programming language for mathematical operations called Matc. Values of material parameters or the power of the heat source can be a function of every physical quantity, which are the results of a calculation. That gives a possibility of defining thermal conductivity as a function of temperature or the heat source value as an impulse function:

```
Body Force 1
Name = "cables"
Heat Source = Variable Time
matc "if ( tx >0  & tx<25000 )    300;   else 0;"
End
```

In above example of part of *sif* file, the manner in which the heat source works is defined. Between 0 s and 25,000 s of calculation time, heat source (electric underfloor heating cables) generates 300 W per 1 kg of mass. For the rest of simulation time, heat was not provided. In the same way, the temperature controller can be modeled, defining value of generated heat as a function of temperature of heat source.

3. Results

Although calculations of an advanced model are extremely time-consuming, a number of them were carried out. In case of calculations of a simpler model, in which air behavior was not considered, equations (1) and (4) were used. This approach was marked by the "FK", the abbreviation of the name of the Fourier-Kirchoff equation. The second approach is governed by the equations (1) and (2), and it was marked by the “FK-NS”, because it uses both Fourier-Kirchoff and Navier-Stokes equations. Two-dimensional distribution of thermal, velocity and pressure fields was a solution for this model. Temperature field of the model is presented in Fig. 2 for different time moments. At first, the air temperature was uniform, which cause irregular flow of mass of air. It can be see in Fig. 2 in moments 400 s and 1600 s.

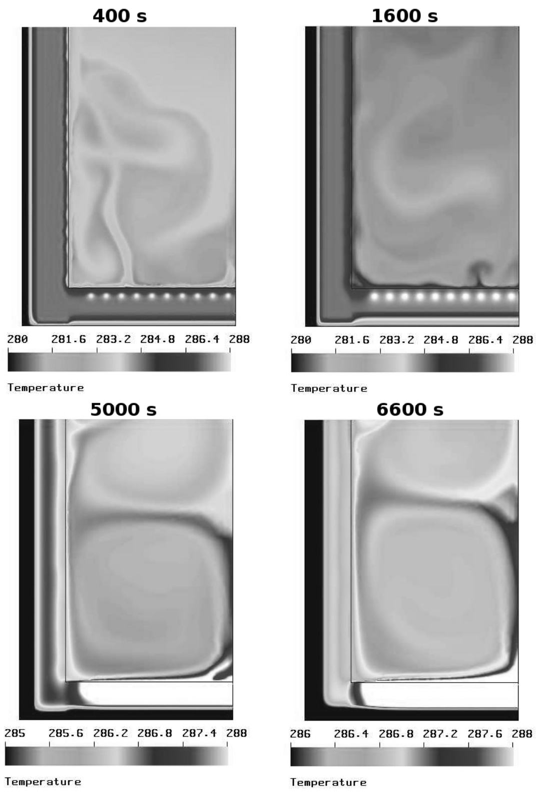

Fig. 2. Temperature distributions obtained for the FK-NS model, at various moments in time

The main mass of air flowed alongside walls and heated the air located in close distance of the ceiling. Thus, the air located near the ceiling has slightly higher temperature than the air near the floor. This observation is illustrated in a more readable way in Fig. 4, where temperature distribution in height was presented. In next moments (5000 s and 6600) the flow of air created a several vortexes. They were directing the flow of air alongside the floor and to the wall, and then to the ceiling. It is a balanced flow, but unfortunately it cannot be achieved by using computations in steady-state mode, which should greatly reduced computation time.

Comparison of both of these approaches (FK and FK-NS) in a form of temperature change in time for the point on the surface of the floor was presented in Fig. 3. The functions marked by numbers 4 and 5 are a result of using the FK-NS model. Temperature change presented as a line without any shapes (4) is for the point located on the surface of the floor. Temperature change presented as a line with wheels (5) is for the point located 1,5 m above the floor. In case of the FK-NS model, average temperature of air does not need to be assumed, as it is in the FK model. Thus, significant differentials between solutions of these two approaches can be seen (1, 2 and 3 functions on Figure 3). Small modification of the FK model was also tried. The first was to assume that average temperature of air in the room is changing during simulation, and it is defined as a linear function of time, for 0 s temperature equals 280 K, and for 20000 s equals 290 K. In the result of this modification, temperature change marked by 1 (Fig. 3) was obtained. The second modification was to use exponential function as a description of change of average temperature of air in the room (graph number 2 and 3 in Fig. 3) for different functions.

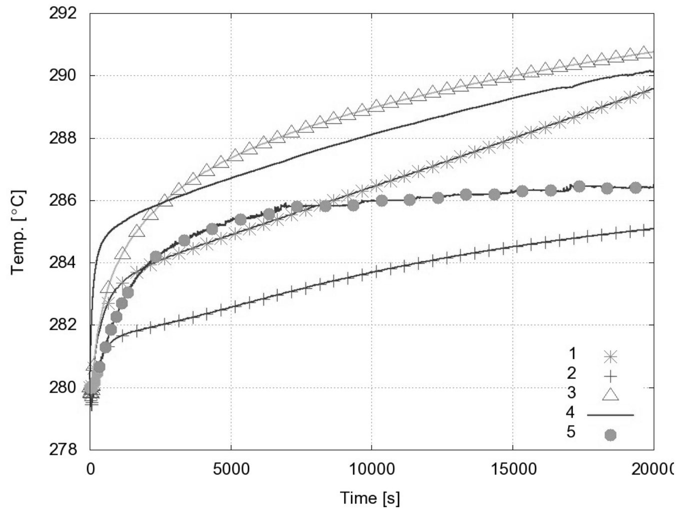

Fig. 3. Temperature change of one of the point on floor surface, calculated using different methods

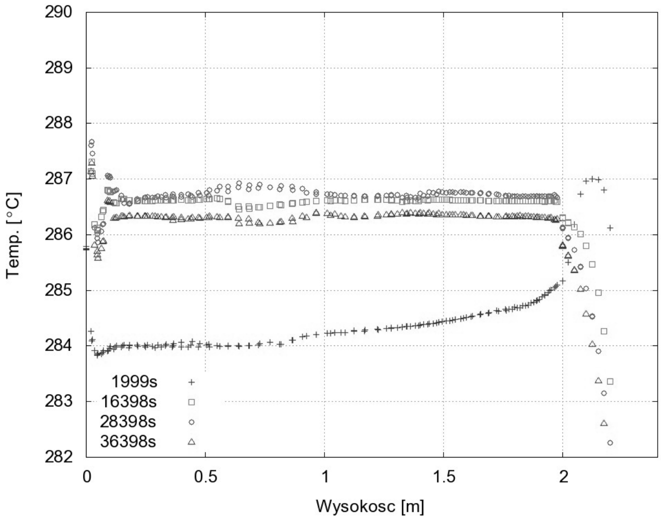

Fig. 4. Temperature distribution with height of the model of the room, for different moment of time

The temperature change in case of intermittently heated room was presented in Fig. 5. Temperatures of three locations were presented for location of heating cables, for a point located on the floor surface and for a point located 1,5 m above the floor. After 10000 seconds, the generation of heat has been off. Thermal inertia of the floor is significant, thus causing temperature rising even then. Even one hour after the generation of heat has been off, temperature of air in a point 1,5 m above the floor does not change significantly. This could not be observed without the use of the FK-NS model for numerical simulation.

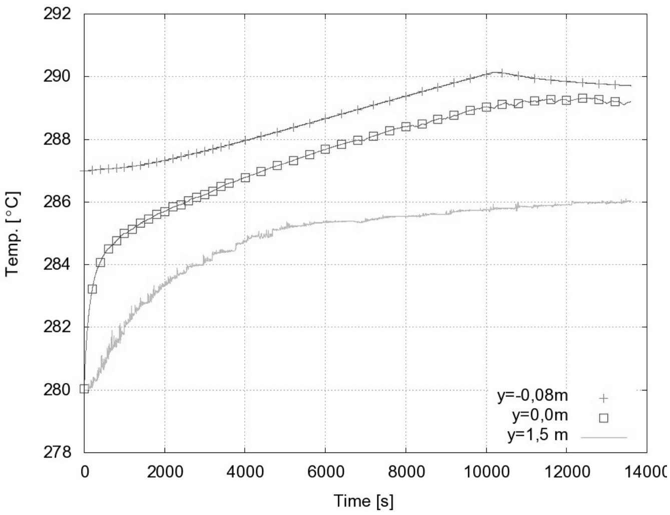

Fig. 5. Temperature change in different location of intermittently heated room

4. Summary

Many interesting programs with very high computational capability can be found among commercially available engineering software. Unfortunately, their costs often exceed the financial capabilities of a small research team, which does not have enough money to buy any software needed for performing numerical simulations of physical phenomena. Elmer capabilities allow simulating many different phenomenon easily, even in case of coupled field problems.

In the paper, many of Elmer system capabilities were presented. We have been using this software for numerical simulation of underfloor heating system, which is a very interesting and popular building heating system in many countries. Heat equation and Navier-Stokes equation were used in those simulations, but Elmer provides more various mathematical models. Transient state analysis of underfloor heating system in an exemplary room was conducted. Unfortunately, such calculations are very time-consuming, they can last even a couple of days. It depends on the grid density and computer speed. Hence, it may seem that this approach better suits researchers' purposes than designers'. However, even designers can effectively use Elmer in their work. The big advantage of the system is the capability of using multi-core processors, which nowadays are standard. In this case, the mesh of the model was divided into several parts, which were run as separate Elmer problems on every core of the processor.

Two methods of numerical simulation of thermal properties of the room heated with underfloor heating system were compared. The solution of the FK model, based on the heat equation, was the distribution of temperature in the solid elements of the room. The solution of this model was based on knowledge or assumption of average temperature of air in the room. Thus, this model is more suitable to studies of temperature field of floors, walls and ceilings. Although these are very important issues, various others treat temperature field of air in the room as an unknown. Hence, the FK-NS model, should be used. The solution of this model is the temperature field in air and solid elements, but also the velocity and pressure distribution.

Presented software allows defining the value of the heat power dependent on the value of temperature of air in the room or on simulation time. It is possible to simulate the use of the temperature controller to control underfloor heating system. This allows examining the impact of the thermal dynamics on the control of the room's temperature, which is an important in case of underfloor storage heating system.

To sum up, multiphysical simulation software Elmer is worth a closer look.

References

[1] Bartosiak A., Petera J., *Zastosowanie oprogramowania ANSYS do modelowania numerycznego wentylacji wyporowej pomieszczeń biurowych*, Ciepłownictwo, Ogrzewnictwo, Wentylacja nr 12 (441) grudzień 2006.

[2] Elmer finite element software http://www.csc.fi/english/pages/elmer strona domowa programu Elmer, data uzyskania dostępu 31.01.2010.

[3] Geuzaine C., Remacle J.-F. *Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities*. International Journal for Numerical Methods in Engineering, Volume 79, Issue 11, pages 1309-1331, 2009.

[4] Gołębiowski J., Kwiećkowski S., *Analytical and numerical modelling of a stationary temperature field in a three dimensional electric heating system*, Electrical Engineering, Vol 81, No 2 May 1998, p 69-76.

[5] Nadolna M., Ziembicki P., Malinowski P., *Zastosowanie modelowania numerycznego do prognozowania pionowego rozkładu temperatury w obiekcie z ogrzewaniem podłogowym,* Ciepłownictwo Ogrzewnictwo Wentylacja, nr 10 (415), październik 2004.

[6] Nielsen P. V., *Computational fluid dynamics and room air movement,* Indoor Air International Journal of Indoor Environment and Health, Vol. 14 Issue s7, 2004, pp. 134-143, Blackwell Munksgaard 2004.

[7] Overview of Elmer, CSC – IT Center for Science, http://www.csc.fi/english/pages/elmer/documentation dostęp 31.01.210.

[8] Savolainen V., Heikonen J., Ruokolainen J., Anttila O., Laakso M., Paloheimo J., *Simulation of large-scale silicon melt flow in magnetic Czochralski growth,* J. Crystal Growth 243 (2002), 243-260.