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The modelling of thermal conductivity measurements using “FEMM” application

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ABSTRACT

Purpose: of this paper is to show a virtual model of thermal conductivity measuring station.

Design/methodology/approach: Simulation has been made using finite element methods program called FEMM (Finite Elements Method Magnetics) ver. 4.2. Program has been created by David Meeker.

Findings: Virtual model based on real measuring station is very helpful tool for engineering approach. Virtual model gives the possibilities of quick examinations of experiment, fast errors correction and possibilities of various experimentation without any cost losses.

Research limitations/implications: The program for finite element methods modelling has its limitation. Boundary conditions and material properties has to be precisely given. Also heat losses has to be consider at all cost.

Practical implications: The method applied in this work is also shown the capabilities, limitation and possibilities of this program. The prove of correctness of measuring station and simulation has been shown.

Originality/value: The whole process of creating the model (drawing elements, defining materials, defining boundary condition and setting parameters of experiment) and running the simulation of thermal conductivity process has been presented. There is also shown the possible errors during model creation and its possibility of elimination.

Keywords: Thermal conductivity; FEMM; Virtual modelling; Heat flow; Finite Elements Method

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

In the project: "Non destructive method in evaluation of the thermal degradation and structural testing of polymer composites" [3] the station to thermal test has been built [1, 2]. The measurements of thermal conductivity were carried out. An attempt was made to create a virtual station model and simulation of thermal conductivity measurement. Virtual examination aims to compare the results of the simulation to results received at the measuring station. Measurements on the station occur errors due to the finite precision of measuring temperature, the accuracy of the thermocouple, the direct contact, etc. These errors are minimized when calibration of the station is made [2]. In a study of thermal conductivity should be noted that the thermal conductivity are primarily intended for building engineering (materials with a low coefficient of thermal expansion), which provides the satisfactory results of the measurements. However, in examining the materials of a coefficient of thermal expansion (e.g. laminates), this expansion is the source of the measurement errors.

In the virtual model errors in form:

- the lack of direct contact,
- errors resulting grid elements of the finite,
- the precision of the calculations, etc.

Knowing the source of the errors we can minimize them. In the article are shown potential sources of modelling errors and ways to minimize them.

A Program that was used to build the model and the same for the simulation is called "FEMM" (Finite Elements Method Magnetics). FEMM is a suite of programs for solving problems in flat, two-dimensional (and 3D) problems with a range of issues:

- magnetic,
- electrostatic,
- steady-state heat conduction,
- and current flow problems.

FEMM allows you to make calculations for material on any of the characteristics declared by the user. FEMM offers 3D built models by declaring "depth" of the project. The most important advantage of the FEMM is its accessibility and versatility. This software is available on the home page (www.femm.info). The author is David Meeker.

The heat flow problems address by FEMM are essentially steady-state heat conduction problems. These problems are represented by a temperature gradient, G and heat flux density, F. The heat flux density must obey Gauss’ Law, which says that the heat flux out of any closed volume is equal to the heat generation within the volume [6].

Many scientific investigations concerning these methods for engineering materials testing have been carried out in recent years [8-15].

2. Finite Element Analysis in FEMM

Although the differential equations of interest appear relatively compact, it is typically very difficult to get closed-form solutions for all but the simplest geometries. This is where finite element analysis comes in. The idea of finite elements is to break the problem down into a large number regions, each with a simple geometry (e.g. triangles). For example, Figure 1 shows a some region broken down into triangles [6].

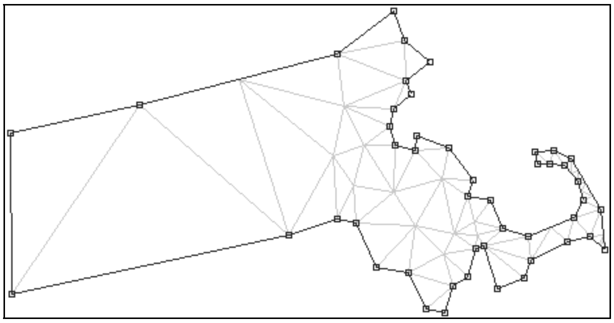


Fig. 1. Triangulation of a chosen region [6]

Over these simple regions, the “true” solution for the desired potential is approximated by a very simple function. If enough small regions are used, the approximate potential closely matches the exact solution.

The advantage of breaking the domain down into a number of small elements is that the problem becomes transformed from a small but difficult to solve problem into a big but relatively easy to solve problem. Through the process of discretizaton, a linear algebra problem is formed with perhaps tens of thousands of unknowns. However, algorithms exist that allow the resulting linear algebra problem to be solved, usually in a short amount of time.

Specifically, FEMM discretizes the problem domain using triangular elements. Over each element, the solution is approximated by a linear interpolation of the values of potential at the three vertices of the triangle. The linear algebra problem is formed by minimizing a measure of the error between the exact differential equation and the approximate differential equation as written in terms of the linear trial functions.

This article shows the modelling of the transmission of heat issues.

3. Measuring station and the virtual model

Sketch of the measuring station on which they were carried out the studies of thermal conductivity shows Figure 2. An investigation was carried out on samples of known thermal conductivity (sample glass).

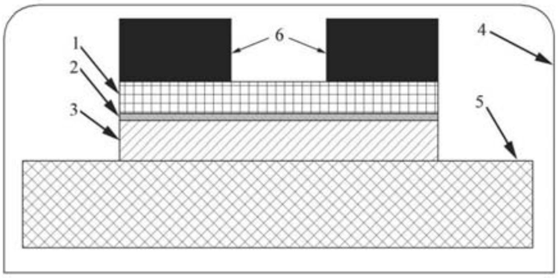


Fig. 2. Scheme of the measuring station: 1) isolation of heating elements; 2) heater; 3) glass sample; 4) glass globe; 5) radiator; 6) weights

The thermal conductivity measurements on the station (Fig. 2) were carried out in vacuum. To obtain the vacuum the glass globe has been used (4) tightly covering station. There were no uses of any coupling means on the heater and radiator surfaces. It is because the sample will be subjected to further examination, and the application of lubricating oils or pastes may diffuse in the sample (giving the wrong results of thermal conductivity) [3].

The only means of coupling was use of silicone (1 mm layer on the cooler and heater), in which included thermocouples. Rigid samples during the examination might not contact everywhere to the heater and radiator surfaces, so the weights have been applied. Measurements were carried out by quasi-stationary method. Quasi-stationary of the station is that the temperature of the steady-state is unknown. Time of measurement of the sample was determined experimentally-600s. [3]. Before the measurement the calibration of the station had to be made. Calibration considers heat losses on heater radiation and direct contact of the sample surfaces between the heater and cooler (Fig. 3) [1]. Then the losses are taken into account in calculating the thermal conductivity. Note that in the measurements of thermal conductivity the preconditions and boundary conditions are fundamental.

Modelling and measuring using FEMM are in stationary condition.

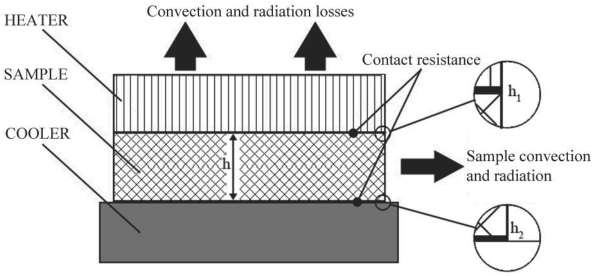
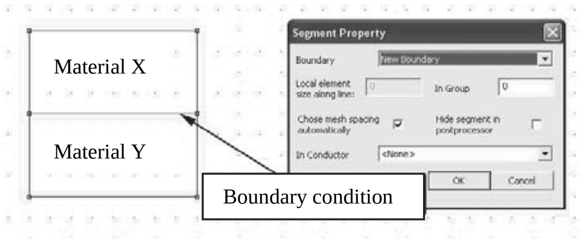


Fig. 3. Heat losses during measurements [1]: h – sample thickness, h_1, h_2 – contact thickness

4. Modelling

Process of modelling in FEMM includes drafting a graphical model, dividing the area under consideration on the finite elements and carry out calculations. When modelling needed to be taken into account, inter alia:

1. Declaration of the border condition of each block of the material. However, you cannot declare more than one condition to one block of material (Fig. 4).



Boundary: New Boundary
Local element size along line: 0
In Group: 0
Chose mesh spacing automatically ☑
Hide segment in postprocessor ☐
In Conductor: <None>

Fig. 4. Determination of the boundary between two materials

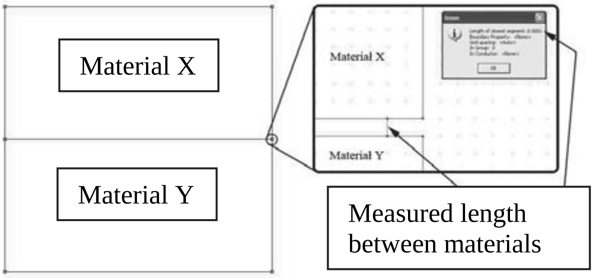


Fig. 5. Model of two blocks of distant from each other

If the material, which must have a different values such as: isolation and test sample, you may receive a problem in which the ability to declare only one boundary. It can be resolved by creating a single block for each material and making distance between them (the distance were experimentally chosen). In this case, each material has its own boundary condition (Fig. 5).

2. When you try to make the grid, it appeared that, since the distances between materials were 0.1 µm, program begins to create the grid. The upper limit at which the program will compute (at the distance of 0.1 µm errors appeared) was 0.8 µm. Setting the automatic size of elements, increases density of the grid in narrower places (Fig. 6):

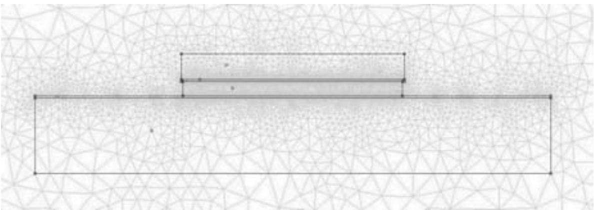


Fig. 6. Automatic grid size and its density

3. When determining the minimum distance between elements, program does not connect two points directly. At a distance between materials 0.3 µm points 1 and 2 (Fig. 7) has not been combined – program link point 1 and point 3 (Fig. 7). Block of length 20 mm was divided. Points 1 and 2 were directly linked only from distance of 0.4 µm but the distance between points 1 and 2 was only 20 mm. When the block was 60 mm large, the distance between blocks must be at least 0.7 µm to directly connect the edges.

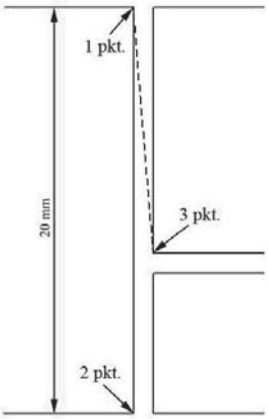


Fig. 7. Extended slice of model showing the error in connection two points

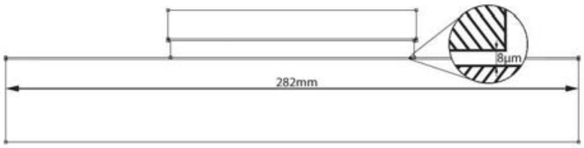


Fig. 8. Maximum distance between the sides of the one block (282 mm) and distance between blocks of material

The maximum distance between the edges of the blocks is 282 mm and only for a distance between blocks of 0.8 µm edges were directly connected (Fig. 8).

4. When the addition of indirect points is needed, program creates different grid than without them (Fig. 9):

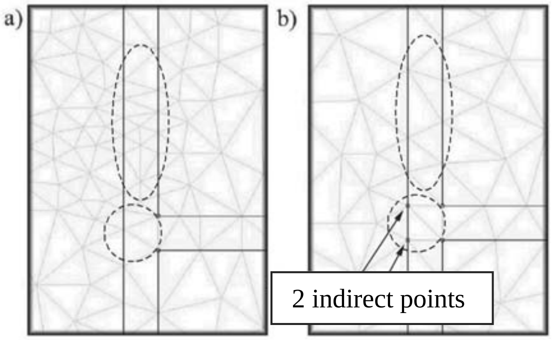


Fig. 9. Observed differences in the model grid, a) model without indirect points, b) model with addition of indirect points

Intermediate points will increase the number of nodes in the grid of about 10% but it had no influence on the final result. However, it is worthily to mention of the observed differences.

5. Materials and boundary conditions of the model

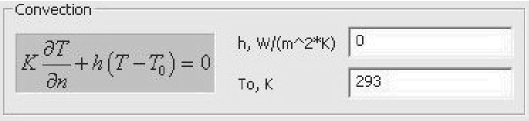
FEMM has possibility to define and use any material. But it also has its limitation:

a) there has to be defined the thermal conductivity – fixed or depending on temperature,
b) and Volumetric Heat Capacity.

Those are properties which has to be defined in first place.

Program offers large library of materials. In model was used six materials taken directly from library:

- Air – which convection set up to h=0 and temperature T=293 K, it was temperature of measurements (Fig. 10).



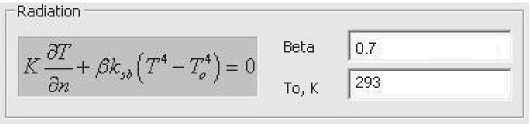
$$K\frac{\partial T}{\partial n}+h\left(T-T_0\right)=0$$

h, W/(m^2*K): 0
To, K: 293

Fig. 10. Boundary condition defined for the Air

Because of measurements were in vacuum, air convection set up to h=0.

- Cellulose, loose – heater insulation (Fig. 11):
  where:
  β – emissivity coefficient [4, 5],
  k_{sb} –Boltzmann constant.



$$K\frac{\partial T}{\partial n}+\beta k_{sb}\left(T^4-T_o^4\right)=0$$

Beta: 0.7
To, K: 293

Fig. 11. Boundary condition (radiation) defined for the heater insulation

- Rubber, hard – the part of the heater (as a lubricant), 1 mm silicone (Fig. 12):

$$K\frac{\partial T}{\partial n}+\beta k_{sb}\left(T^4-T_o^4\right)=0$$

Beta: 0.9
To, K: 293

Fig 12. Boundary conditions for silicone

- Copper, pure – the heater. It is used as a conductor (0.1 mm of thickness) – Fig. 13:

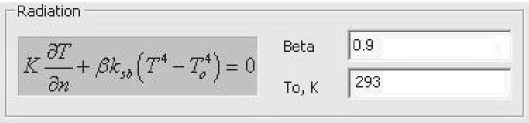
Name: copper
○ Fixed Temperature, K: 0
● Total Heat Flow, W: 2

Fig. 13. Conductor values details

Heater can be defined as:

- points of a defined power value,
- a boundary condition of defined value,
- a conductor.

- Window – glass sample used for examination (Fig. 14):

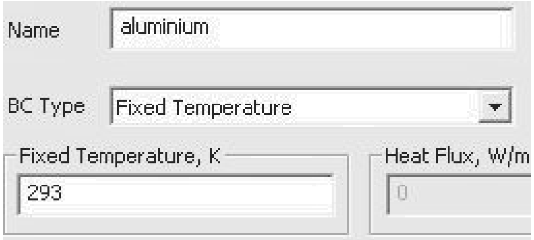


$$K\frac{\partial T}{\partial n}+\beta k_{sb}\left(T^4-T_o^4\right)=0$$

Beta: 0.9
To, K: 293

Fig. 14. Boundary conditions for sample

- Aluminium, pure – cooler had a fixed value of temperature (Fig. 15):



Name: aluminium
BC Type: Fixed Temperature
Fixed Temperature, K: 293
Heat Flux, W/m: 0

Fig. 15. Boundary condition of cooler

Above have been presented the individual materials used in the modelling of the measurement system and the complete model is shown in the Figure 16:

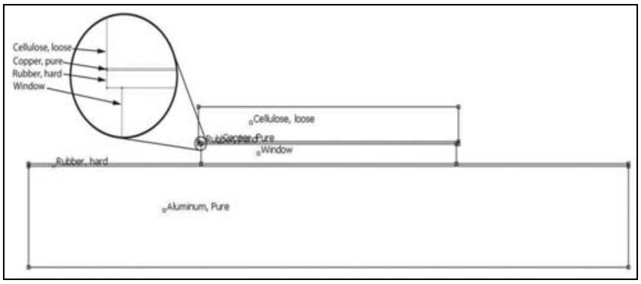


Fig. 16. Complete model

6. Presentation of results

The results obtained during the simulation, can be presented in different ways:

- Vector image of the heat flow (Fig. 17):

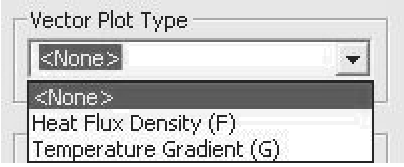


Fig. 17. Vector plot type menu

- Graphics (in colour scale). This picture has been presented as the final result (Fig. 23). Menu selection is presented below (Fig. 18):

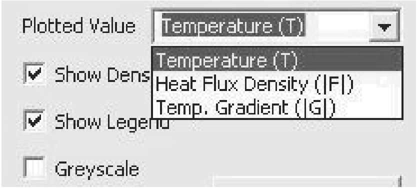


Fig. 18. Menu for colored plot scale

- Boundary lines between the fields of temperature (Figs. 19 and 20):

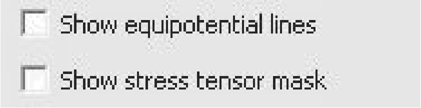


Fig. 19. Border line selection menu

You can connect two points in model. The Program will designate an integral or draw plot according to the created curve (Figs. 21, 22). The plot can be also saved to a text file.

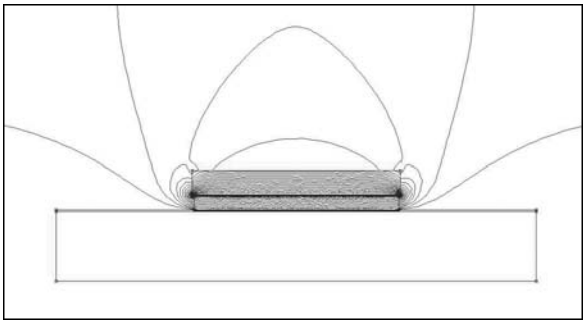


Fig. 20. Border line presentation

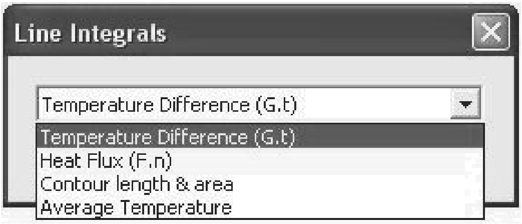


Fig. 21. Menu for integrals

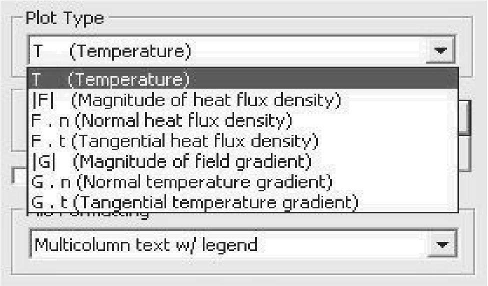


Fig. 22. Menu for type of plot to display

7. The results and analysis of the virtual examination

The Figure 23 shows the graphical results. It should be noted that the FEMM reads temperature in any visible place on the model.

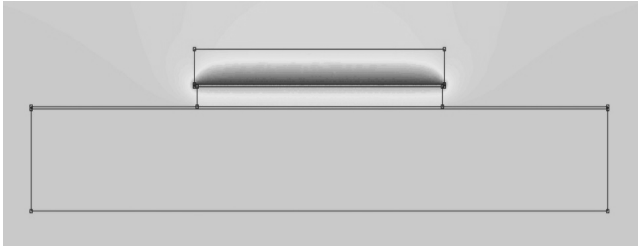


Fig. 23. Image of simulation result

In order to compare the model to measuring station, a thermal image [7] has been made. The photo has been made after 600 s, which result a steady-state condition. It also was made without a vacuum and the power heater was 1 W.

As you can see in the picture (Fig. 22) variations of temperature in the measuring points are of 0.5°C. It was the measured with the power of a 1 W. For this power of simulation is given a small error (Fig. 24).

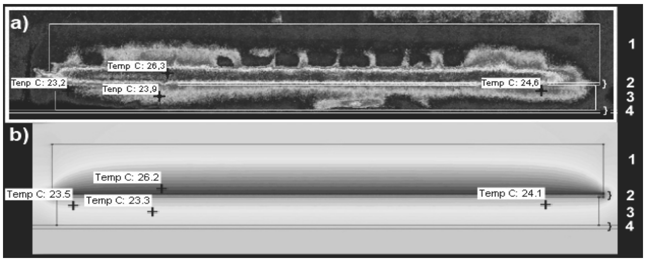


Fig. 24. Comparative picture of: (a) IR camera, (b) the results of the simulations: 1 – insulation of heater, 2 – heater with silicon, 3 – sample, 4 – cooler with a layer of silicone

The test to compare thermal conductivity of simulation and measuring station was carried out by the power of 2 W. The experiment carried out the actual received thermal conductivity of a glass samples – located between 0.69 W/mK to 0.79 W/mK. These thermal conductivities values of the individual samples were put to computer simulation. Then the temperature read from a thermocouples has been compared with the temperatures resulted from the simulation. The results are shown in the Figure 25.

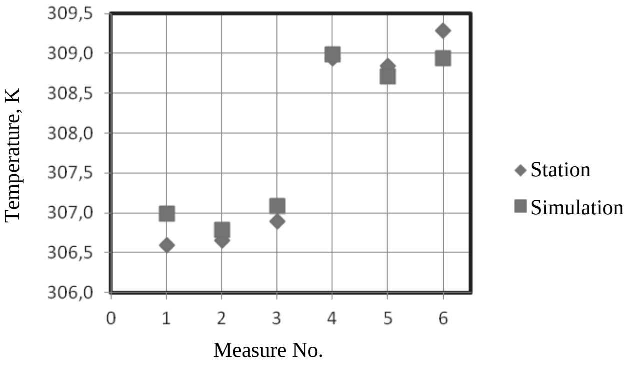


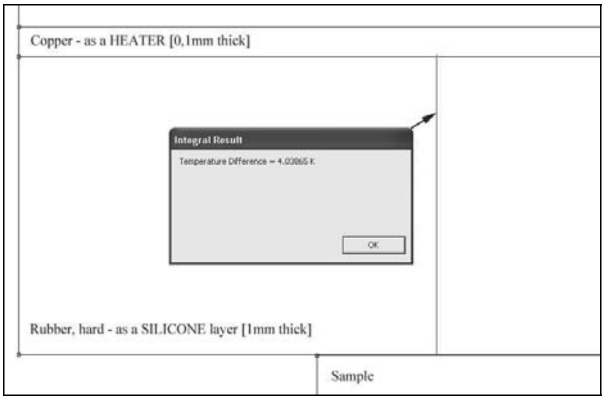
Fig. 25. Results comparison: 1, 2, 3) sample thickness 4 mm; 4, 5, 6) sample thickness 8 mm

As it can be seen from a table that the differences between simulation and station are of the order of 0.4°. The exact results has been shown in Table 1.

The temperature from measuring station was read out from the thermocouples placed in a layer of silicon (Fig. 15) which had a thickness of 1 mm. In turn, the temperature from the simulation is the average temperature of the heater (0.1 mm thickness). The decrease of temperature in a layer of silicone used during simulation has been measured and result is shown in Figures 26 and 27.

Table 1.
Temperatures obtained from a station and simulation

Measure No.	Temperature K/°C	
	Station	Simulation
1	306.6/33.4	307.0/33.8
2	306.7/33.5	306.8/33.6
3	306.9/33.7	307.1/33.9
4	308.9/35.7	309.0/35.8
5	308.8/35.6	308.7/35.5
6	309.3/36.1	308.9/35.7



Temperature Difference = 4.03865 K

Fig. 26. Integral line in silicone layer and result of temperature drop

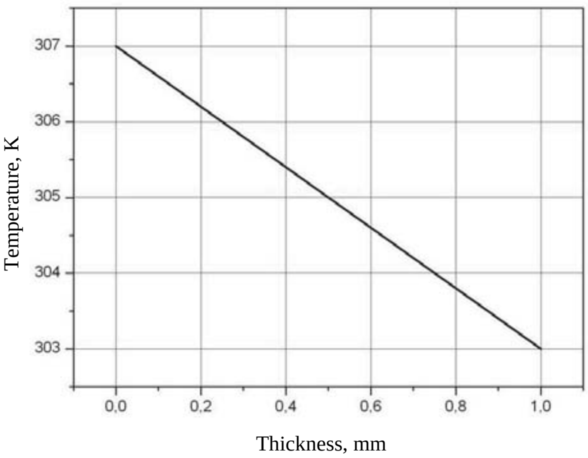


Fig. 27. The temperature drop in silicon layer

Temperature drops in a silicon layer has been shown to realize the differences of temperature depending on the point of reading. Therefore, differences in temperature (Table 1) are due to:

a) thermocouples have a specified diameter,
b) the site of the thermocouples relative to the sample and heater is difficult to determine because of the technology.

Differences between temperatures obtained during simulation and real measurements are no more than 0.4° (Table 1). Therefore, the differences are on level of. 5% which is satisfactory.

Simulations in the FEMM are carried out in a steady – state and steady – state during the real measurements is obtained after the 600 s. (Fig. 28) [3]. After 600 s there was no temperature rise on sample surface.

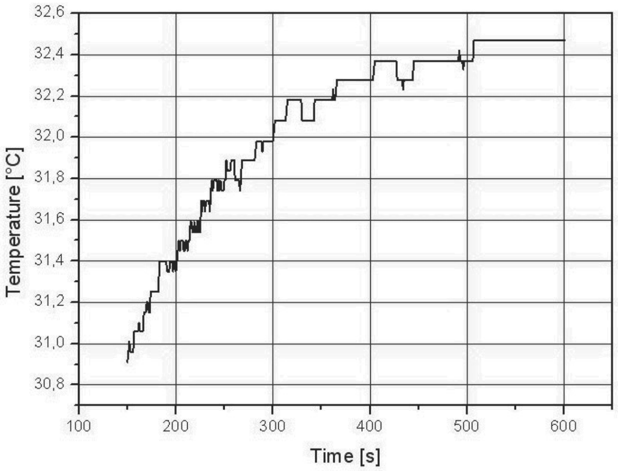


Fig. 28. Time of temperature stabilize

In the FEMM and the real examination the temperature of heater were not defined but only its power. From this it follows that the time to stabilize temperature of the heater (real measurement), and therefore the time of measurement was well chosen, as it is confirmed by the readings of temperatures (Table 1).

8. Summary and conclusions

In this paper has been shown program to Finite Element Method simulation called FEMM. Whole process from drafting, defining material, creating mesh of elements to result and its presentation has been shown. FEMM is a versatile tool for engineering to carry out the simulation of magnetic, electrostatic, the heat flow and electricity. Advantages of the program are:

- possibility to declare your own materials,
- you can quickly test and adjust,
- enables you to establish different conditions of the experiment,
- the simplicity of drawing model,
- different ways of visualizing the results,
- the program does not need a computer with high processing power.

Disadvantages of the program are:

- too small distance between elements preclude the calculation,
- it does not connect the desired points (when the distances are too small),
- if a simulation is very complex (as that presented above: small spaces between blocks), it take very long time so calculate the results (during this examination one simulation took up to 60 minutes),
- a long time to wait for a graphical presentation of the complex calculations,
- output files occupy a large disk space,
- the program does not use the full power of your computer.

From comparison real and virtual experiment, it can be concluded:

- the results obtained from the simulations do not deviate greatly from the real measured results (Fig. 24),
- when you build a model the limitations should be consider (mentioned in earlier posts),
- in simulation the boundary conditions must be precisely specified,
- FEMM proved a suitable program to verify the correctness of the measuring station.

It has been proven that the temperature drop is large in a thin layer (Fig. 26, 27). This situation shows that temperature readout depends greatly from placing the thermocouples in measured material.

To sum up combining together FEMM and real test provides capabilities such as:

- validation of the test bench,
- gives the possibility to design different variants of experiment and check if it’s worthily to create such experiment,
- creation of any model in quick time,
- checks the sensibly of the experiment without incurring costs (program is Free of charge), etc.

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