Analysis of field of temperature of power electronic systems in COMSOL MULTIPHYSICS environment

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Annotation: The paper deals with analysis of temperature field in power electronic devices using COMSOL MULTIPHYSICS software. It includes relevant problem of designing, specifically a power semiconductor converter. Till now, there has been one-dimensional interpretation of analysis considering heat transfer by conduction. Presented method results directly from differential equations of system heat balance, whereby heat transfer by conduction, flow and radiation is considered. The results can be animated in 3D view which enables analyzing the space-division switching network in power electronic device.

INTRODUCTION

The relevant problem with designing power electronic systems consists in designing a cooling system. A typical representative is a power electronic systems semiconductor converter, which in principle represents the device that serves for control and transformation of the energy flow. From its physical principle results the final value of efficiency and therefore also existing power loss that causes rise of the system temperature.

In general, architectural elements of a power converter are semiconductor components the correct function of which is guaranteed only at a certain temperature interval at which the upper limit is of great importance. For elements based on silicon technology, it is the range between 150 – 180 ˚C . Upcoming SiC technology based elements are expected to increase this range once or twice. It stands to reason that besides the design of the cooling system, which serves for maintaining the maximum temperature of the semiconductor material, it is necessary to have knowledge of temperature decomposition in the whole device in order to protect other construction elements, such as wiring network, capacitors, induction elements and so on.

Present methods of design are based on simplified interpretation of heat transfer conduction. Its accuracy is relatively low, therefore a designer uses an oversized cooling system. The problem is that convection is replaced by conduction and the radiation is neglected. This is acceptable only at low temperature of the cooler by using forced ventilation. If the temperature is higher, the radiation will come through to a greater extent. On one hand this will cause heat removal from the cooler, but on the other hand it will cause warming of other construction elements.

Therefore, at present, methods of exact analysis of temperature field by means of appropriate software products like COMSOL MULTIPHYSICS are being looked for.

MAIN WAYS OF HEAT TRANSFER

The temperature is a state variable determining atom internal kinetic energy of material. Inside substance, the thermal energy is transferred from the place with higher temperature to the place with lower temperature.

Heat transfer is performed in three ways by:

Conduction - this applies to all states of material with various consistency, especially solid materials

Convection - this type of heat transfer applies to mainly in fluids and gases.

Radiation - it is performed by electromagnetic radiation. It is independent on material environment and is possible to be used also in vacuum. This type is applicable mostly at higher temperatures.

Heat transfer by conduction

If one side of solid is warmer than the other side, then heat (heat flow) goes through the body from the warmer side to the cooler one . The side with area of S [m^2] thickness of d [m] temperature difference of

$$\Delta T = T_2 - T_1 \quad \text{[K]} \qquad (1)$$

then , the heat flow I_{cond} [W] goes through:

$$I_{cond} = S.\frac{\lambda}{d}.(\Delta T) \quad \text{[W; m}^2\text{, W/m.K, m ,K]} \qquad (2)$$

In some cases this heat flow is described as transferred power P [W], where λ [W/m.K] is individual heat conductivity of the material.

Mostly, the reciprocal value of individual heat conductivity called individual heat resistance is being used for expressing the heat in practice

$$R_T = \frac{d}{\lambda.S} = \rho_T.\frac{d}{S} \quad \text{[K.W}^{-1}\text{; m, W/m.K, m}^2\text{]} \qquad (3)$$

, where $\rho_T = \frac{1}{\lambda}$ [K.m.W^{-1}] is specific heat resistance.

Amount of heat Q_{cond}, which goes through area of body is given as product of heat flow I_{cond} and time *t.*

$$Q_{cond} = I_{cond}.t \quad \text{[J; W,s]} \tag{4}$$

Indexes of heat conductivity of some materials that were used during simulation of temperature field of power semiconductor cooler have values [1]:

$\lambda_{Al} = 201$,

$\lambda_{Cu} = 384$,

$\lambda_{Si} = 0{,}83$,

$\lambda_{air} = 0{,}015$.

Heat transfer by convection

Heat transfer by convection applies mostly at passage of heat from a solid material to gaseous or fluid environment that surrounds the solid material. The free fluid flow or gas flow is called convection. Forced convection of the fluid flow is supported by a pumping device, or in the case of the gas flow supported by a ventilation fan. We recognize two types of convection:

- straight-line flow, in which individual parts of the cooling medium are not shuffled because they are moving in parallel. The straight-line flow occurs at lower speeds of the flowing fluid and encapsulated areas of the flow-off material.

- turbulent flow occurs at higher speeds of the flowing medium. This type of flowing causes mutual shuffle of particles of the cooling medium, whereby there is mutual handover between molecules of the cooling medium. Because there is permanent shuffle of the cooling medium, the intensity of the cooling effect is increased.

Heat flow I_{conv} (exhaust heat power *P*) between body of cooling medium is directly proportional to area of body *S* [m^2] and index of heat transfer *k* [W/m^2.K]

$$I_{conv} = k.S.\Delta T \quad \text{[W; W/m}^2\text{ K, m}^2\text{,K]} \tag{5}$$

Indexes of heat transfer of air, water and oil i.e. mostly used cooling mediums at unaltered convection are reaching [1] the following values:

k_{air} = 2-10 [W/m^2.K],
k_{water} = 200- 600 [W/m^2.K],
k_{oil} = 200- 300[W/m^2.K].

Heat transfer by radiation

Every material that has higher temperature than absolute zero becomes the source of thermal radiation. Heat transfer by radiation is realized through vibration. Energy of this vibration after impact on a body is transferred to heat. Three cases could occur after impact of thermal radiation.

- thermal radiation will be partially released through the body. Heat permeability of body α depends on wave-length of thermal radiation and on material, from which the body is made.

- thermal radiation will be partially reflected by the body.

- amount of the reflected thermal radiation depends on the material from which the body was made, on body surface structure and also on wave-length of thermal radiation . It is marked σ .

- thermal radiation will be absorbed by the body. Absorption of the body is dependent on body surface colour. Index of absorption is δ. Absorption of the total black body is equal to 1. The following equation is valid for the whole amount of captured energy

$$\delta + \sigma + \alpha = 1 \tag{6}$$

The heat flow I_υ exiting from the body is proportional to body area *S* [m^2], fourth square of temperature difference and to index of radiating capacity.

$$I_\vartheta = \chi.c.S.\left(T_2^4 - T_1^4\right) \quad \text{[W, W.m}^{-2}\text{ K}^{-4}\text{, m}^2\text{, K]} \tag{7}$$

, where T_1 [K] is ambient temperature, T_2 is temperature of body radiating heat,
χ = 5,67.10^{-8} [W.m^{-2}.K^{-4}] is Stefan – Boltzman constant,
c is radiating capacity index.
At equivalent temperature, light and smooth surfaces radiate less than those with dark and rough surface. Index of radiating capacity of glazed copper has value of c_{Cu} = 0,07, glazed aluminium has c_{Al} = 0,05 and anodized aluminium c_{a_Al} = 0,15 – 0,87.

COOLING OF SEMICONDUCTOR ELEMENTS

Power loss of electronic devices

The main part of power loss in power electronic device is generated during the current flow either in stabilized (conduction) mode or during commutation. There are two ways of heat generation , the first is transfer of charge carriers through a potential barrier (PN junction) or more precisely on resistance of outgoing passage region. At bipolar devices both of the mentioned mechanisms are applied, whereas the second mentioned way is typical for unipolar mechanisms. It is necessary to remove the heat from the device to the ambient surroundings because otherwise the electrical abilities of devices would change tremendously and this might cause the irreversible damage of the device.

The power device, which is not able to transfer heat through the package, requires the use of the cooler that capes allowable temperature of semiconductor material. In case of power transistor structures, the power loss formula is given by equation

$$P = \frac{1}{T_p}\int_0^t u.idt \qquad [\mathrm{W, V, A}] \qquad (8)$$

, where $u(t)$, $i(t)$ are instant values of relevant electrical parameters (voltage at transistor's clips and circuit current) and T_p is its period. Their integrated composition represents so-called instant power, which is very important indicator of device thermal loading in relevant operation modes.

Organization of cooling system

As mentioned above, maintenance of maximum temperature of semiconductor material under selected boundary is necessary for achieving functionality of the device. For this reason, when designing the power electronic system, great attention is paid to mechanism that caps heat conduction from inside of semiconductor structure.

Nowadays, several such systems working at various physical principles are used. The simplest of them is based on heat conduction using a massive cooler, which is connected to the base of the semiconductor device. Heat transfer from the device to a cooler is performed by conduction and its dissipation to surroundings (air) by convection. The efficiency of this most frequently used cooling system can be increased with higher convection of air which can be achieved by using fans blowing air on the cooling areas.

Adjustment of the transistor cooling system within TO220 package, which is isolated from the cooler by insulating pad, is shown in fig.1. When designing it, it is necessary to start with simplified electro-thermal analogy, which considers conduction as the only way of heat transfer from semiconductor material into environment. The mentioned assumption has two disadvantages. The first one is the simplification of 3D system into one-dimensional system taking into consideration only the dominant part of the heat flow. The second one is replacement of convection with conduction when considering heat transfer from the cooler to the environment.

The lower side of fig.1 shows equivalent thermal model of cooling system, where $R_{\upsilon jc}$ is thermal resistance between semiconductor system and package, $R_{\upsilon cr}$ is thermal resistance between package and cooler, and $R_{\upsilon ra}$ is thermal resistance between cooler and environment. As mentioned above, the last parameter represents simplified interpretation

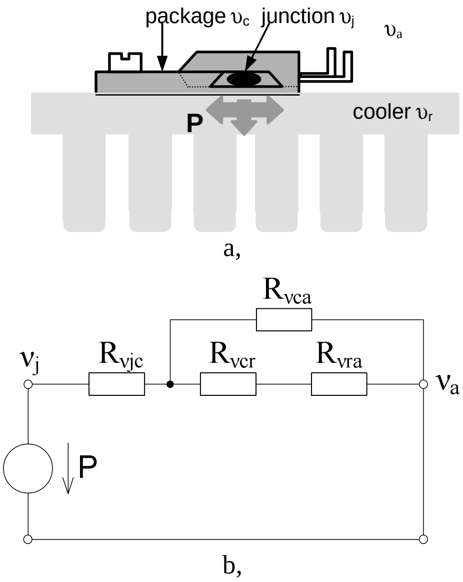

Fig.1: *Cooling system of power transistor (a) and its equivalent thermal model (b)*

of physical mechanism of heat transfer, which in reality is performed by convection. Therefore, the mentioned thermal resistance is non-linear, and its value depends on the temperature difference of cooler υ_r and environment υ_a. The figure also shows specified temperatures of semiconductor system υ_j and package υ_c.

Some values of thermal resistances are stated by manufacturer in their datasheets. Other values of thermal resistances, which are necessary for design, could be found in manufacturer's datasheets of coolers.

Main advantage of the cooling system design that is based on one-dimensional model is its simplicity and reliability. The disadvantage is its difficult usage in designing more complicated multidevice systems with two or more coolers. In this case it is necessary to use 3D design because it can represent even remaining mechanisms of heat transfer. One of these systems is COMSOL MULTIPHYSICS software.

DESCRITPTION OF COMSOL MULTIPHYSICS – SIMULATING PROGRAM

COMSOL Multiphysics is powerful interactive program which presents modeling environment that solves a lot of scientific and engineering problems described by partial differential equations (PDE). With this software not only single-physics applications but also multiphysics studies can be modeled. COMSOL Multiphysics environment contains basic physical models based on fundamental PDE. Each model allows settings of physical properties and quantities like material characteristics, load, power sources, convection sources, etc. Thanks to the versatile basic models we can reduce the developing time for specific examined physical effects. COMSOL Multiphysics processes the

modified PDE without programmer's detailed knowledge of mathematic and numeric analysis.
Mathematical application modes of COMSOL modules perform various types of analysis like stationary and time-dependent analysis, linear and non-linear analysis, etc.
PDEs describe the laws of science. COMSOL transforms the equations into a form suitable for numerical analysis and solve it using the finite-element method. The COMSOL environment is suitable for various application fields like acoustics, biology, diffusion, electromagnetism, fluid mechanics, heat transfer, optics, structural mechanics, etc.

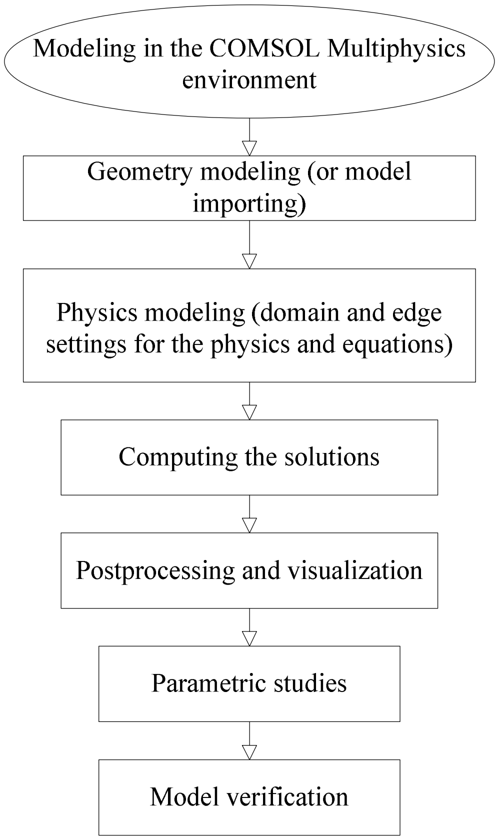

Fig.2: Sequence of the COMSOL multiphysics modeling.

If we start building a new simulation, we can modify the model we have created or use a model from examples in library of models. We choose an application mode and space dimension settings like subdomain settings, boundary settings, and point settings.
Geometric objects are assembled from basic geometrical shapes. It means abscissa and point in 1D space, rectangle, circle, point, abscissa, arch and Bézier curve in 2D space, and block, cone, cylinder, ellipsoid and sphere in 3D space. The COMSOL user environment contains suite of CAD tools for geometry modeling in 1D, 2D and 3D space. Composite space objects are created from basic space objects by Boolean operations.
Internal boundaries arise by combination of the basic objects. We can keep or cancel the boundaries according to various or common physical properties of internal spaces – subdomains.
After creating the geometry model we define physical parameters of domains and domain edges. Subsequently the COMSOL Multiphysics creates the finite element mesh for the model geometry automatically. We can control mesh generation process to customize the mesh by parameters of the mesh driver.
In model solution, the software offers stationary or time-dependent PDE solutions. The COMSOL Multiphysics can solve the linear systems in straight or iterative way.
The post-processing phase makes visualization of optional model phenomena. The analysis results are displayed in shape of surface or isosurface model, cross-section model, slice model, isoline model. The COMSOL visualization offers contour plot, animations, integration on an interval and on a subdomain, etc.
Very useful attribute of COMSOL is possibility to cooperate with MATLAB.

SIMULATION OF THERMAL FIELD OF POWER ELECTRONIC SYSTEM

In the field of heat transfer design using COMSOL MULTIPHYSICS it is possible to choose following application methods:
- heat transfer by conduction.
- heat transfer by conduction and convection.
- heat transfer by radiation.
- heat transfer using all mentioned ways including forced fan cooling.

Heat transfer modeling in COMSOL MULTIPHYSICS environment

To illustrate the analysis and simulating of heat transfer, we present COMSOL Multiphysics modeling of power semiconductor elements heatsinks. Modeled configuration consists of aluminium gilled heatsink and two heat sources – power MOSFET IRFZ44 and power diode MBR1560. Both of them are encased in TO 220 package. Dimensions of extruded heatsink section are 120 mm x 37 mm x 60 mm. The cooling configuration dissipates heat from power elements of step-up DC/DC converter. Their common power dissipation is 29.1 W as result of electrical model simulation in P-Space. Geometrical model was designed in COMSOL MULTIPHYSICS (fig.3). Simulated configuration in fig. 4 consists 10536 dots and 42751 tetrahedral elements. Solver settings of the COMSOL has next properties:
- Direct UMFPACK method
- Transient analysis type 1440 second with 5 second of step setting
- Stability of solution have been set to automatic

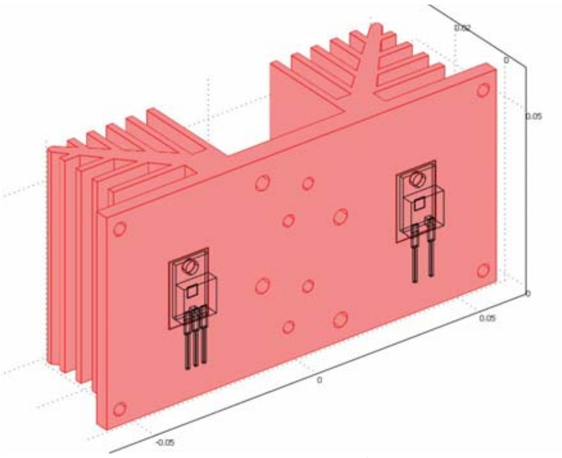

Fig.3: 3D geometrical model of cooler with power semiconductor devices (transistor and diode)

During simulation, maximum temperature of chip was considered to be 150 ºC. Initial value of temperature of cooler has been set to ϑ_a = 26 ºC.

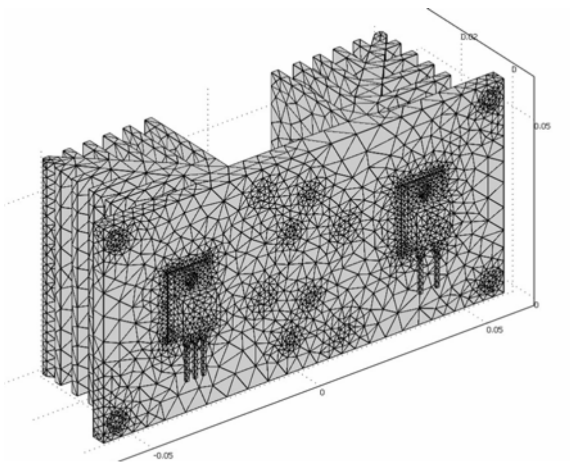

Fig. 4: Model of generated mesh

Results and graphical interpretation of heat transfer

Results of simulation are shown in figures 5 to 10. They are generated as thermal fields in diagram form where temperature is marked in various places of cooler (defined layers) during entered time of simulation 1440 seconds (24 min), whereby temperature is defined by various colour variations (fig. 6). Calculations were entered every 60 seconds. Fig. 7 shows that steady state became after 15 minutes. Results of mentioned simulation experiments were experimentally verified using thermo vision camera (fig.8). Pictures shows that temperatures of cooler obtained by simulation and by measurement are practically the same.
Other simulations, which are allowing heat transfer by conduction, convection and radiation, were supplemented with allowance of forced fan cooling.

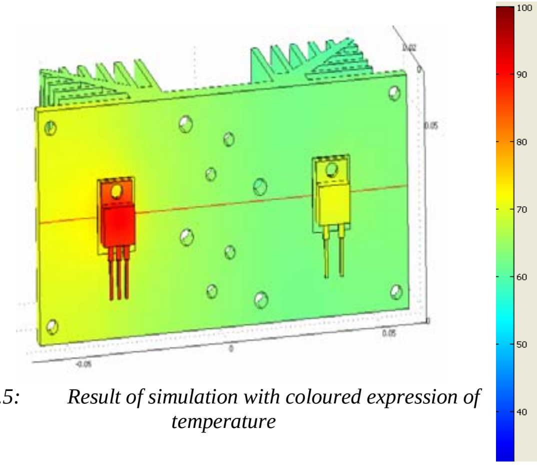

Fig.5: Result of simulation with coloured expression of temperature

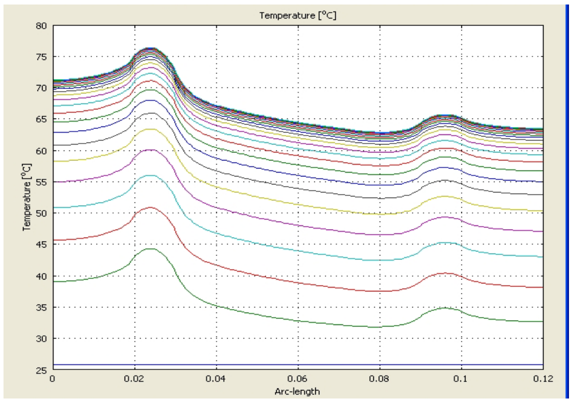

Fig.6: Result of simulation showing temperature of cooler's cut (cut line expressed in fig. 5.) Time difference is 1 min

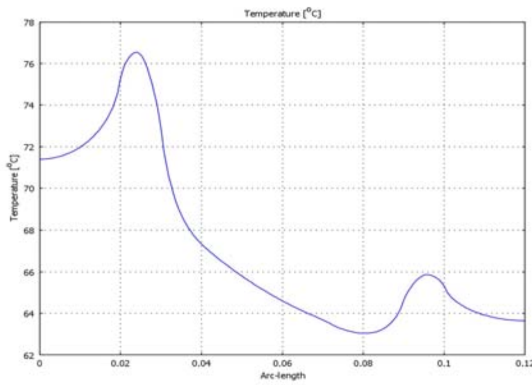

Fig.7: Temperature of cooler (cut line expressed in fig. 5.) after 15 minutes

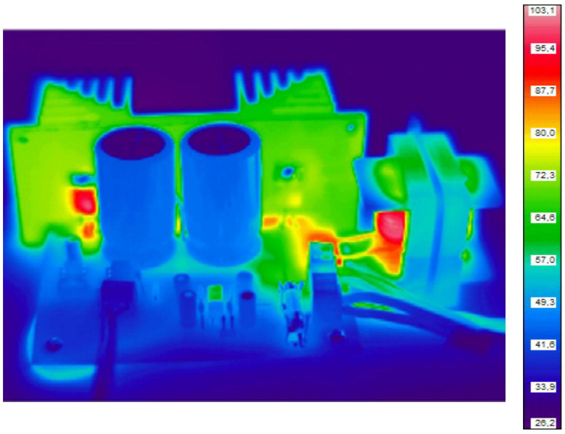

Fig.8: Thermo-vision overview of measured temperature in single parts of cooler

CONCLUSION

The simulation system COMSOL MULTIPHYSICS represents a powerful tool for analysis of complicated actions described by particular differential equations. Its utilization in analysis of heat field of power electronic systems allows to obtain accurate information of temperature distribution. Thereby it is easy to expose areas with the most thermal overload of simulated object before appliance of cooling system. This enables us to make necessary corrections to avoid damage and failure of the whole designed system.

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