Passive Cooling of Power Electronics: Heat in the Box

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Abstract: Results presented are a contribution to the successful design of a 5kW-DC-AC-converter for applications in forklifts. The device is located in a more or less closed environment and entirely operated with passive cooling. Due to concurrent engineering approach and harsh environmental conditions correct prediction of absolute temperature values by simulation was crucial. Heat sinks have been modeled properly and a lumped-element thermal network has been extracted for co-simulation with the electronic network. In order to characterize the closed environment, heat flow in boxes filled with air has been analyzed by solving coupled heat and mass flow equations with minor simplifications. Some essential results have been achieved concerning heat transport patterns, turbulences, and missing stationary solutions. A sample problem called "heat in the box" has been defined.

Keywords: heat transport, free convection, closed environment, passive cooling, power electronics.

1. Introduction

Low energy consumption turns out to be one of the decisive elements in future environmental protection. As many motors are electrical, the energy efficiency of the conversion from DC to AC is a key technology. The goal of the project "Energy-Efficient Converters" in the context of the "Center of Competence in Power Electronics Schleswig-Holstein" [1] has been the construction of a leading-edge 5kW-DC-AC-Converter for applications in service vehicles, were energy is stored in regular 24V lead acid batteries. Several novelties have been tackled in the project, e.g. power-MOS-devices, assembly and packaging technologies, power modules, and circuit topologies. As all parts of the system had to been designed in parallel, simulation was the method of choice to synchronize the concurrent engineering process. One team working on electromagnetic problems and one on thermal-mechanical problems acted as advisers for appropriate decisions within the project. Semiconductor experts did their own simulations for process- and device-engineering.

Thermal problems in complex technical systems are often very demanding from the simulation point of view, as conduction, radiation and convection occur as transport mechanisms, everything is time-dependent, and the boundaries of the system are not well defined. The DC-AC-converter designed in this project will be situated in the engine compartment of a forklift. Neighboring are motors and batteries, the engine cover is located close above the electronic system. Though the compartment is open at the bottom, air flow is uncertain due to rotating parts and variations of equipment. Therefore, putting the converter in a closed box was the most responsible way of modeling. The use of fans for cooling was not possible, as they had turned out to be the weakest link in the system-chain. There was no cooling loop with fluids available at all. The only way of getting rid of the power losses was free convection.

Maximum outside temperature conditions range from 40 up to 70 ^{o}C. The power transistors were expected to operate at about 120 ^{o}C, while the control unit was limited to 80 ^{o}C to save the life of the capacitors. It is obvious that simulations had to be very accurate, as requirements were really tough. A simple comparison between different designs was not sufficient, as even the best solution could have ended in overheating when looking at the absolute temperature values.

We had to anticipate what questions designers would ask us during the process in order to be able to serve as advisers. Looking at more than 100 different parts of equipment that can be found under the engine cover, it was obvious that complete simulations would neither be efficient nor possible. We instead decided to prepare a bundle of tools like simplified 2D- and 3D-Comsol simulation setups, analytical estimations, lumped-element-models based on simulation results, validated material properties, verified surface models for free convection and radiation, and rules of thumb for convection in covered and closed volumes. Hard- and Software were prepared and parameters were refined for quick response. Spare time between the discussions with the designers has been spent for further improvement and adjustment.

The determination of the thermal resistances of heat sinks in more or less closed boxes led us to definition of the "heat in the box" problem. It lasted about one year to overcome the general problem of non-convergence and to gain evidence that results might somehow be correct. After one additional year of playing around with the results we thought the approach not be useful in the context of the project, as response time was much too long, and instead developed some more rules of thumb for engineering purposes. However, we do believe that the results may be useful when thinking of basic research on turbulent flows in closed rooms and identify some general principles.

2. Engineering Approach

The complexity of the system led us to a dual-track approach: (a) modeling of the converter taking heat conduction into account while fitting the h-coefficients of the simplified models for heat transfer through surfaces mainly at the heat sinks and (b) figuring out more details of heat sinks in this closed environment. While the diffusion equation plus some heuristics for the boundaries are sufficient to solve problems one the first track, a full approach taking coupled heat-transfer- and Navier-Stokes-equations into account was needed for the second track.

We started by improving the reliability of heat sink models through measurements (Fig. 1). Due to high outside temperatures the data sheets supplied were not sufficient.

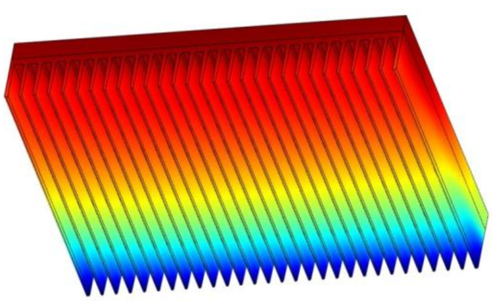

Figure 1. Demonstration of refined heat sink model with constant flow density applied at the backside.

A picture of the complete system illustrates the importance of the heat sinks in this context: More than 60% of the volume of the converter is dedicated to passive cooling (Fig. 2). A detailed description of the module can be found in [2].

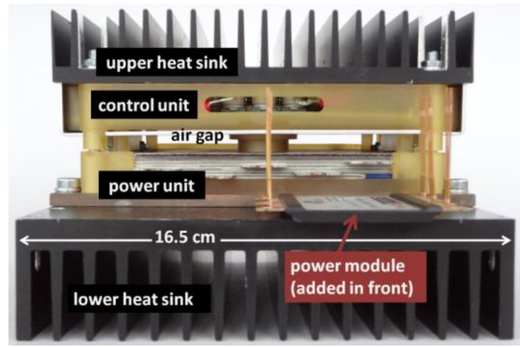

Figure 2. Photograph of the DC-AC-converter showing the construction details.

Once available, heat sink models were combined with a slightly reduced geometry of the electrical heat sources (Fig. 3). In order to be able to go much more into detail, simplified boundary conditions closer to the power modules were derived from this complete model and applied to a heat-conduction problem of higher resolution (Fig. 4).

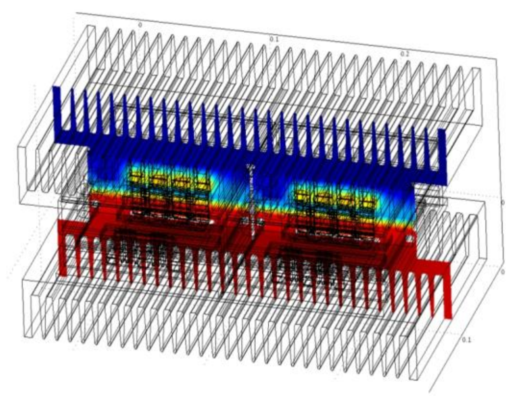

Figure 3. Simulation model of the converter.

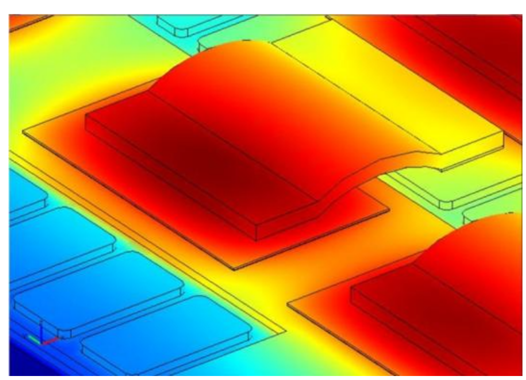

Figure 4. Detailed model near bonding band (image section about 1 cm x 0.7 cm).

There were two reasons why a detailed analysis was necessary: (1) A proper prognosis of temperatures in the semiconductors was needed for electrical design. (2) Heat-induced mechanical stress at the bonds connecting the transistors to a printed circuit board is a prime source of system degradation and lifetime reduction. Temperature data gained at the contact points have therefore been used for lifetime prognosis within the project.

As a support for the lumped-element simulation of the electrical network a similar thermal model has been derived and supplied with parameters (Fig. 5).

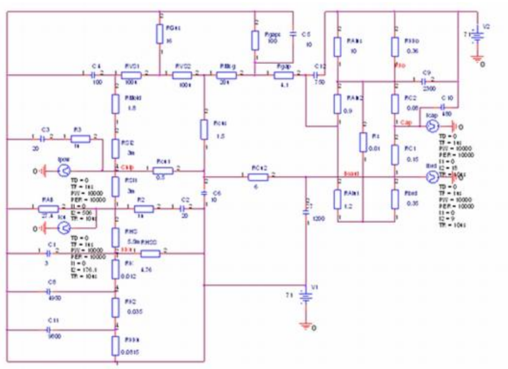

Figure 5. Thermal lumped-element model for co-simulation with electrical network (power unit left, control unit right).

It is evident that resolution and accuracy requirements led us to a high number of variables in the range of millions. Simulations where done on a high-end PC with Comsol Multiphysics 3.5a under Linux to overcome the former limitations of other operating systems. Each drawing of a new iteration of the design took us about two weeks before ready for operation.

3. Design Results

A lot of minor results have been achieved during the design, but we will only discuss the major decisive ones in this paper.

One major result was understanding heat flow directions inside the module: As the power unit is driven to peak temperatures close to or even beyond 120 ^{o}C, the surrounding material may exhibit temperatures well beyond 80 ^{o}C, which is the maximum acceptable temperature for the capacitors of the control unit. Therefore, power losses inside the control unit could not be transferred downwards through the power unit towards the lower heat sink. A second heat sink on top was inevitable, unfortunately increasing costs and volume. Finally, it was necessary to get rid of up to 600 W of power losses with peak currents of 200 A. Furthermore, a strong thermal insulation between power and control unit was needed to reduce the heat transfer upwards. Finally we decided to introduce an air gap as one of the most efficient insulators and even allowing a convection-driven air flow through the gap if the module is oriented properly.

The converter was finally put to life in its natural environment: driving around with the forklift. A leading edge total conversion efficiency of 96% including all surrounding effects could be reached. Measurement of the real temperatures turned out to be very difficult, but we finally were successful with good results (Fig. 6). Power chip temperatures have been measured on-chip.

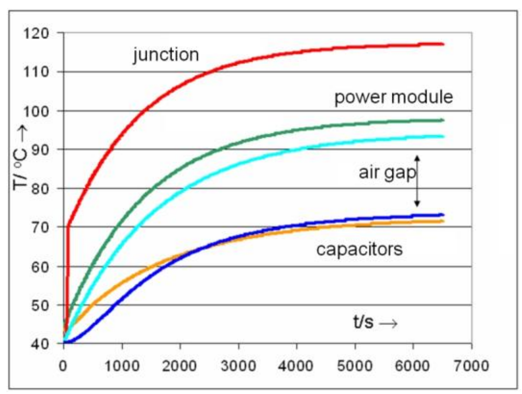

Figure 6. Measured temperatures within the converter (extrapolated from 23 ^{o}C to 40 ^{o}C)

4. Research Topic and Results

Heat sinks in electronic engineering are mainly characterized in an open environment and data sheets are supplied for this ideal case. However, in most relevant situations the electronic equipment will be located in a box for protection reasons. Unless modules will be fixed to the walls of the box directly or there are air inlets or fans, the heat sink will have to exchange the heat with the environment through a closed volume filled with some gas, typically air. We have not been successful in finding a published model for the deterioration of the thermal resistance of heat sinks under these circumstances. Later we found out that for typical power modules of about 10cm in diameter a box of about 100cm in diameter would be needed to make the heat sink behave nearly like in open space.

In order to calculate the real behavior of heat sinks we started with two parallel wings made of aluminum and placed it in a small copper box filled with air (Fig. 7). Outside temperature was fixed to the same value all around the box.

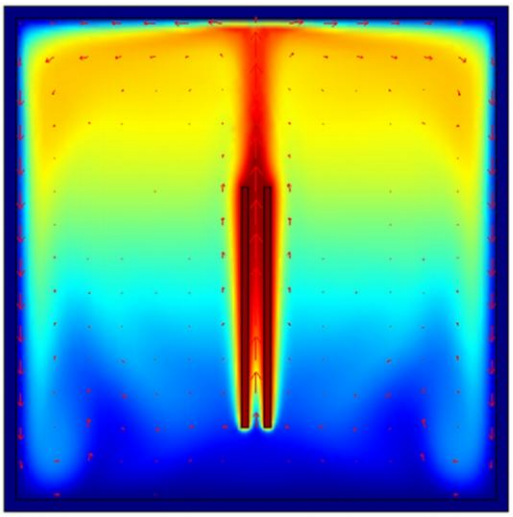

Figure 7. Problem for the first step towards solution (temperature distribution shown in surface plot, arrows show air velocity).

Most inspiring for solving the problem was the light bulb example [3] combining weakly compressible Navier-Stokes-equation (p, u, v) and general heat transfer (T). Dynamical viscosity has been set constant. To improve convergence, in some cases additional minor simplifications have been made, e.g. thermal conductivity of the air as a constant value. However, to come to a solution at all, we had to learn that there is no stationary point in the behavior due to superimposed turbulences, so time-dependent solving was mandatory. Furthermore, the resolution of the mesh has to be comparably fine (Fig. 8).

We are still not able to guarantee convergence for any case at any time, as turbulences may really be heavy and sometimes no underlying circular flow can be detected in the seemingly chaotic movements. We first checked the worth of 2D-simulations compared to 3D (Fig. 9) and then started studying the 2D-case in more detail.

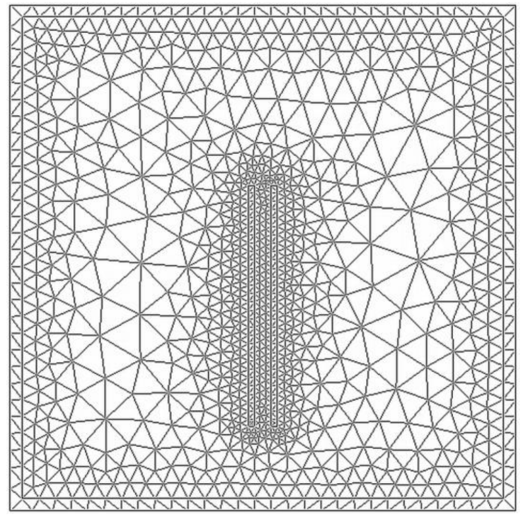

Figure 8. Mesh used to solve the sample problem of Fig. 7.

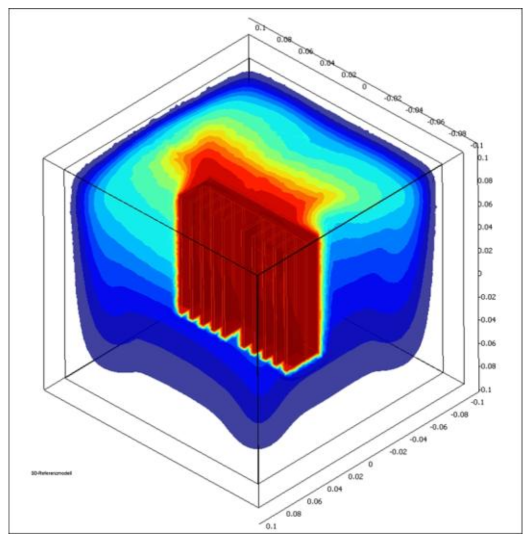

Figure 9. 3D reference model in order to justify 2D-simulations.

As far as we know, the existence and unambiguity of the solution cannot be proven. Therefore, we tried to gain some evidence that pictures dropping out of the simulations were no ghosts. The positive arguments are (a) reproducibility on different grids, (b) continuity with respect to minor variations of parameters or geometry, (c) symmetry, (d) resemblance with some general physical considerations, and (e) recurrence of similar solution patterns. As an example for (e) we can present two solution patterns, we called "the cold drop" and "the double W".

The “cold drop” occurs when warm light-weight air moves to the top of the box and there encounters cold air of higher gravity. The cold air then shifts downwards in small portions like a drop, generating a trail of two eddies left and right rotating in opposite directions. This heart-shaped pattern (Fig. 10) emerges under different circumstances and in different cases.

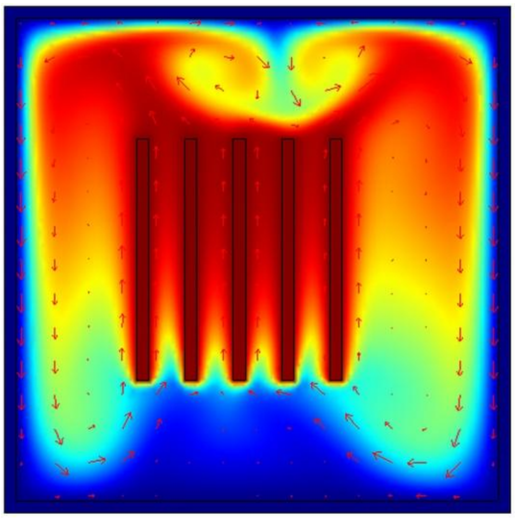

Figure 10. The so called “cold drop” pattern (temperature distribution shown in surface plot, arrows show air velocity).

The “double W” turned out to be typical for the closed loop of air flow at the bottom of the box, where a small heat sink sucks in cold air (Fig. 11). So far, we have not been successful in describing this very stable phenomenon in an analytical way.

Though there is no mathematical proof, we now believe the solutions to be meaningful and worthwhile some consequent basic research activities. When playing around, we encountered very interesting properties of the solutions like seemingly calm behavior misleading us to end the simulation but then finally ending up in wild turbulences. As an inspiration to interested readers we put some videos on our homepage [4].

From the engineering point of view a central challenge is to find the peak temperature near the heat source that will limit the maximum acceptable power loss. As the gradient of the temperature between the inner and the outer side of the box drives the heat exchange, there has to be a stationary point for the maximum temperature (maybe with some fluctuations due to turbulences): If the inner temperature is sufficiently high, one can get rid of any amount of heat generated inside.

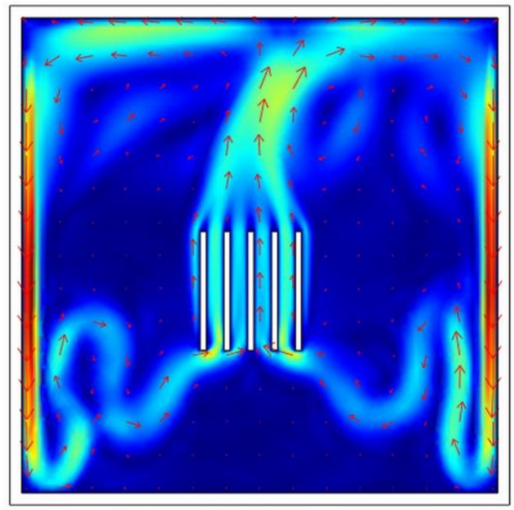

Figure 11. The so called “double W” pattern (air velocity shown in surface and arrows plot).

We developed some estimations of the maximum temperature; however, the models turned out to be more or less useless upper bounds. The main problem is the temperature drop within the “flame” on top of the heat source, we have not yet understood.

5. Defining the Heat in the Box Problem

To overcome the overwhelming diversity of solutions we propose to start further analysis with a simple “heat in the box” problem (Fig. 12). The idea is, to stay close to practical problems but to avoid too much complexity arising from geometric variations.

We propose a quadratic box made of copper with a fixed outside temperature near to 300 K. Inside this box we put a small circular copper heat source to generate a smooth air flow. A streamlined body like a falling drop with a smaller c_w might be better, but we observed only minor deviations, and the circular shape can easily be generated everywhere without further information. We propose the box to be filled with regular air.

The most arbitrary parameters to be fixed are the absolute dimensions of the walls and the heat source. From the mathematical point of view vanishing sizes would be best, but this would cause meshing problems and would somehow be artificial. We propose to keep oriented at the practical problem, where the walls made of copper sheet would be about 1mm thick and heat sources as simplified would hardly be smaller than 1cm in diameter.

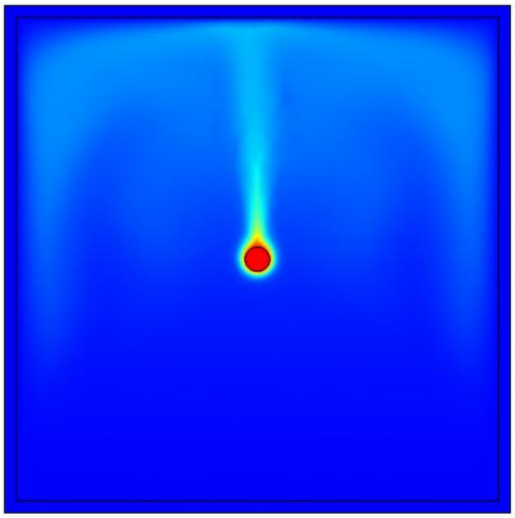

Figure 12. A sample problem of some "heat in the box" at an early point after switching heat on (temperature distribution shown in surface plot).

The size of the box and the location of the heat source as well as the amount of heat delivered or detracted should be kept arbitrary as central research topics.

Showing the solutions to our customers, they suggested many practical applications of this sample problem in electronics, building and lighting technology.

7. Conclusions

Comsol Multiphysics has been successfully integrated into the concurrent design process and delivered very valuable results. Again, it turned out that there is no plug-and-play solution in an engineering context, but the process had to be supported by measurements, analytical and lumped element models, and reasonable simplifications in geometry and parameters.

We believe that the solution of the proposed sample problem and the assorting of the patterns occurring will become very useful in a number of technical problems.

8. References

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2. Mühlfeld, O. and Fuchs, F.W., Development of an Optimized Power Section for a 5 kW Low Voltage Traction Inverter, *EPE ECCE 2011*, **Aug 30th – Sept 1th**, Birmingham, 2011, www.tf.uni-kiel.de/etit/LEA/dl-open/veroeff_2011/Muehlfeld_epe_2011.pdf

3. Comsol model library > Heat Transfer Module > Electronics and Power Systems

4. www.fh-westkueste.de/startseite/fachbereich-technik/fe-t-transfer/klsh.html

9. Acknowledgements

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