Thermal Model Development for LabPET II Scanner Adapter Board Detector Module

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Abstract— The aim of this paper is to develop a thermal model for the LabPET II, a positron emission tomography scanner dedicated to small animal imaging. This scanner is based on adapter board detector module (ABDM) which contains two customs ASICs dissipating ~0.6 W each. This development is based on two digital techniques: the computational fluid dynamics (CFD) and the heat transfer analysis (HTA). The CFD technique takes into account the strength of the specific heat flow mechanism around the ABDM to perform the heat transfer analysis using its physical properties. The temperature distribution on the chip surface of each ASIC is used for predicting the heat flow to be evacuated out of an ABDM. We reused this ABDM model and created a simplified 2D model of the scanner containing 8 ABDM along with their associated FPGA. Three analyses have been conducted: No convection, internal natural convection and internal forced convection on the system model in COMSOL. The forced convection seems to be a good candidate to stabilize the temperature in a LabPET II scanner.

Keywords: Avalanche PhotoDiode **(**APD), Positron Emission Tomography, natural convection, forced convection.

1. Introduction

The LabPET II is a new positron emission tomography (PET) scanner dedicated to small animal imaging being developed at the University de Sherbrooke with the goal of achieving sub-millimeter spatial resolution [1,2]. The LabPET II is based on a 128-channel module called adaptor board detector module (ABDM), which includes four 4 × 8 avalanche photodiodes (APD) monolithic arrays individually coupled to four 4 × 8 scintillator crystal arrays [1]. This configuration allows to build up scanners with ~ 37000 channels compared to ~ 4600 channels in previous LabPET 1 version [3] for the same scanner diameter and axial length (16 cm x 12 cm). Two 64-channel custom ASICs designed to handle up to 3000 PET events/s per channel extract relevant event information such as pixel address along with the energy and the timestamp. Extracting the two latter information requires an amount of power estimated at 0.6 W. As a scanner can contains up to 290 ABDM, ~300 W are dissipated in a very confined volume.

Since the APD gain and noise are dependent of temperature [5], they must be carefully thermally stabilized to maximize the scanner performance. The scanner power dissipation as well as ambient temperature variations inherent to building cooling are among factors influencing the overall performance. In order to evaluate the factors that will mostly affect the scanner performance regarding thermal considerations, computational fluid Dynamics (CFD) and heat transfer analysis (HTA) simulations have been conducted. The paper is organized as follows: section 2 presents the HTA dedicated to the ABDM, section 3 is dedicated to the simulation and finally section 4 contains the results and discussions.

2. Heat transfer analysis of an ABDM

2.1 Description of the LabPET II scanner

The ABDM gives to the LabPET II the ability to tailor the scanner in diameter and length to the animal to be scanned. Currently, rabbit, rat and mouse scanners are under development. The rabbit scanner is the larger and contains 36 strip boards spread in a star-like fashion on which are connected 12 ABDM (fig. 1).

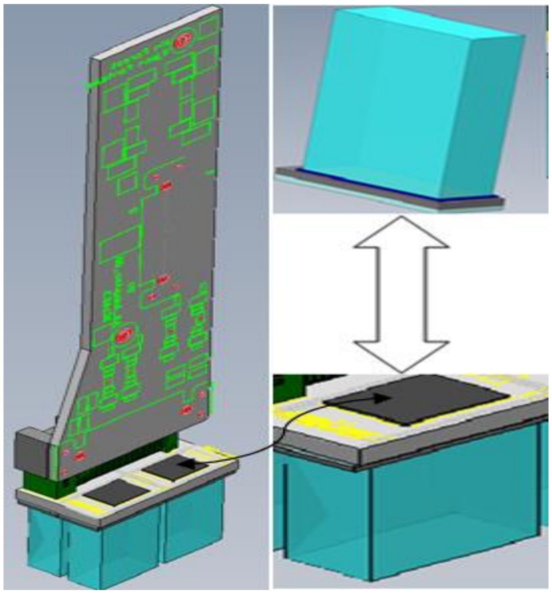

Fig. 1: The ABDM (left) with two ASICs under the APD and crystal arrays (right).

2.2 Thermal analysis for ABDM

For VLSI (Very Large Scale Integration) ASIC design, thermal analysis is an important aspect for safe operation. A heated materials layer expands and generates stress which can damage the device, especially if an overheated material is close to corrosion and oxidation area. When a circuit overheats, both mechanical and electrical properties can be lost. The thermal analysis is normally made as a preliminary study to a stress assessment where the temperature is analyzed by a structural finite element model. In this paper, the thermal analysis is required to achieve a thorough understanding thermal behavior of the different parts of the ABDM. The thermal analysis with the finite element model will include the following parts:

- analysis of the thermal radiation to surfaces,
- analysis of the convection around the ABDM model,
- conduction analysis within the ASIC,
- steady state thermal analysis.

Since a structure is a continuous domain, a finite element method must be used which involves performing a geometric discretization. The structure is divided into sub-areas of simple geometric shapes called finite element. In other words, it reduces the problem of the continuous medium by a plurality of discrete problems with a finite number of unknown parameters that are determined by application of energy criteria. The COMSOL specific simulation software was used for ABDM model discretization and for fluid-heat flow analysis.

2.3 Thermal boundary conditions

One of the major problems that arise when one wants to make a thermal study for the ABDM is to determine the boundary conditions. Thus, for this purpose a coefficient of natural and forced convection equivalent has been selected to avoid specifying the temperature below module, which introduces a thermal short circuit. However, this problem can be overcame by meshing the entire structure. This requires the use of a system model that can reach tens of millions of finite elements making complex analysis even impossible. So the finite elements method used must impose more or less simplifying assumptions on the material properties and boundary conditions. The finite element method is based on the discretization in space and time. The main advantage of this method is its great generality; it can handle complex geometries, taking in account the boundary conditions and the properties of temperature dependent materials [6].

3. Simulation results of ABDM

3.1 Presentation of a simplified ABDM with COMSOLtool

In this part we put a temperature of 25 °C all around the structure representing a room constant temperature. Boundary conditions must be defined beforehand in order to solve the thermal diffusion equations in transient. For shake of simplicity, the ABDM has been simplified to a simple APD array together with its crystal array and an ASIC below (Fig 2). The crystal was replaced by an analog material with same temperature characteristics. The APD array is embedded in a ceramic (Al2O3) carrier. A PCB named daughter board support both ceramic carrier and the ASIC. The APD array, represented by a silicon layer, is relatively thin and required more than 872,332 finite elements having the same amount degrees of freedom (DOF) for the model construction. Then to perform a transient simulation, a power amplitude modulation function TIMEAMP in time was built. The power was divided evenly throughout the volume of the ASIC. This power was applied for 15 seconds to visualize the evolution and distribution of heat around the ASIC. The Dirichlet boundary conditions (DBC) at 25 °C (298.15 °K) were applied around the daughter board.

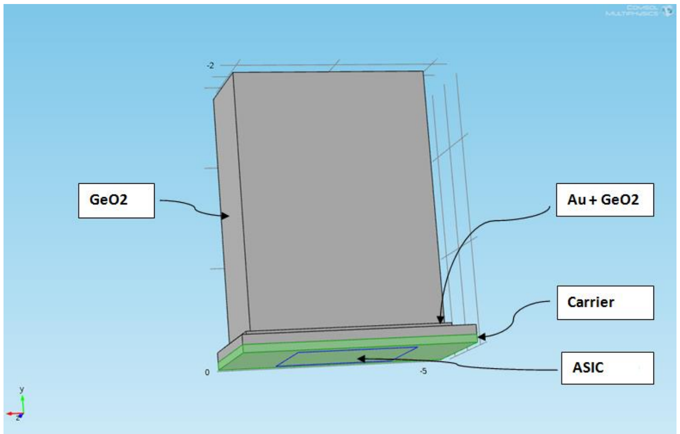

Fig 2 : The PDA and its ASIC under COMSOL tool.

3.2 Simulation of the full APD with COMSOL tool

Figure 3 below shows the simulation results of a heat source having a dimension of 4.68 × 5.97 mm^2 in COMSOL.

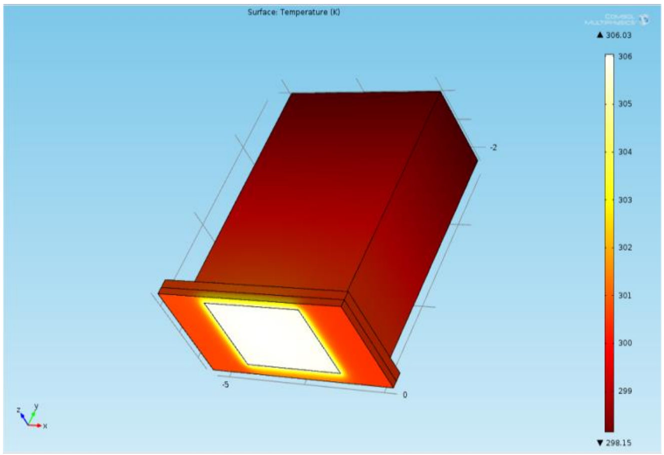

Fig. 3 : The temperature distribution for a 4.68 × 5.97 mm^2 heat source in the simplified ABDM.

The use of COMSOL tool gives us an idea about the thermal diffusion around the ASIC. We have shown that the complete thermal response of APD with its ASIC also depends on the physical properties of materials. The simulation results will help us to understand the thermal evolution throughout the ABDM. As seen in fig. 4, the temperature evolution in one node taken at the center of the ASIC's structure is plotted.

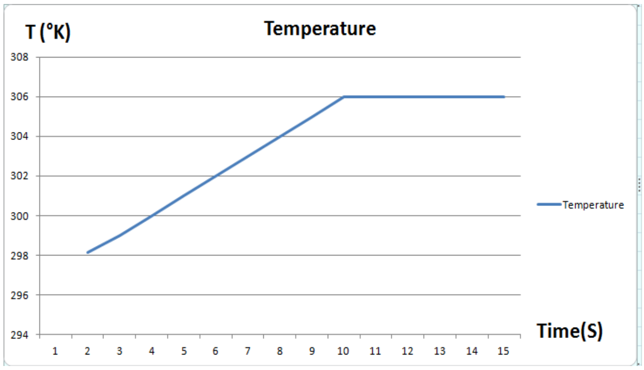

Fig. 4: Thermal evolution at one node taken at the center of the ASIC's structure in function of time.

This simulation gives a good idea about the thermal evolution in the structure of the heat source which presents a thermal equilibrium after 10 s at 306 °K.

3.3 ABDM module with COMSOL tool

A PET scanner contains an array of ABDM spread in a star-like fashion to create a cylinder where the animal will be scanned. We use COMSOL preprocessor to build a simple model of the scanner in 2D. This model will allow us to perform thermal simulations to see the evolution of the temperature throughout the LabPET II scanner. We designed our own simplified mechanical model because it is impossible to import a complete model from any CAD (Computer Aided Design) tools. For sake of simplicity, the model contains 8 ABDM equally distributed at 45 degrees (fig 5) and each ABDM is coupled to a 21 W source coming from ancillary electronics (FPGA in this case) required to read data from ASICs. This model allows us to visualize the temperature in different corners of the scanner. Then to make a transient simulation we followed the steps to build the mechanical structure, mesh and boundary conditions. The DBC-type conditions (Dirichlet Boundary condition) to 25 °C (298.15 °K) were applied around the ABDM following fig. 5.

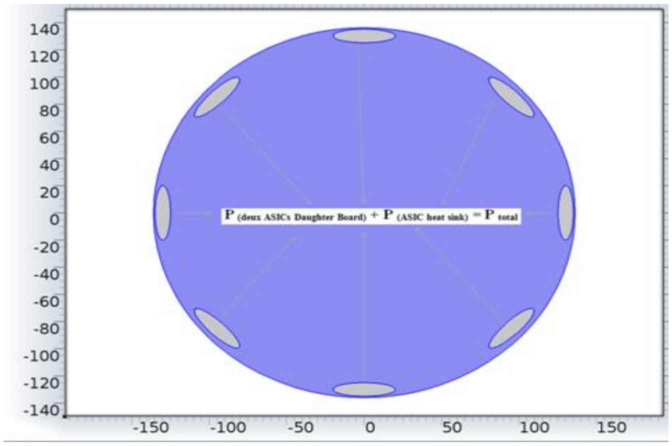

Fig. 5: Eight ABDM distributed in the scanner are modeled in COMSOL.

The second law of thermodynamics states that heat always flows spontaneously from a warmer to a cooler area. Both active and passive devices are considered as heat sources if they are warmer than the mean temperature of their immediate environment. In the case of practical VLSI circuits, there are two types of analysis envisaged by circulating air: natural convection and forced convection. In applications where power dissipation is low, the natural convection analysis has a lower computational burden and is sufficient. However, because of the high level of the power dissipated in both ASIC and the FPGA, forced convection analysis is the most effective way to stabilize this amount of heat around a desired temperature. Table 1 below shows the different convection coefficients associated to different types of analysis [8].

Table 1: Different convection coefficients associated to different types of analysis [8].

Cooling Type	Heat Transfer Coefficient ^{c} (W/m^2 K)	Comments
Radiation	<kW/m^2	Black body radiation at 120° C with environment at room temperature
Air, free convection	3-12	Typically about 5
Air, forced convection	10-100	Typically about 50
Liquid, forced convection	200-2000	Fluorocarbons
Liquid, forced convection	2000-7000	Water and Water/glycol mixtures
Boiling	2000-6000	Fluorocarbons
Boiling	50000	Water

For LabPET II electronics, it is obviously out of question to use the last four types of cooling analysis since they are based on a liquid refrigerant for practical assembly issues. Theoretically the typical air free heat transfer coefficient (HTC) of 5 W/m^2 is insufficient to properly discharge the accumulated energy. However, the forced convection with a typical HTC of 50 W/m^2 can respond appropriately.

3.4 The presentation of first simulation of the ABDM in COMSOL tool

In this section, we will present the first simulation results from 8 heat sources spread in a circular fashioned way in COMSOL. Figure 7 shows the thermal behavior of our model in COMSOL using natural convection.

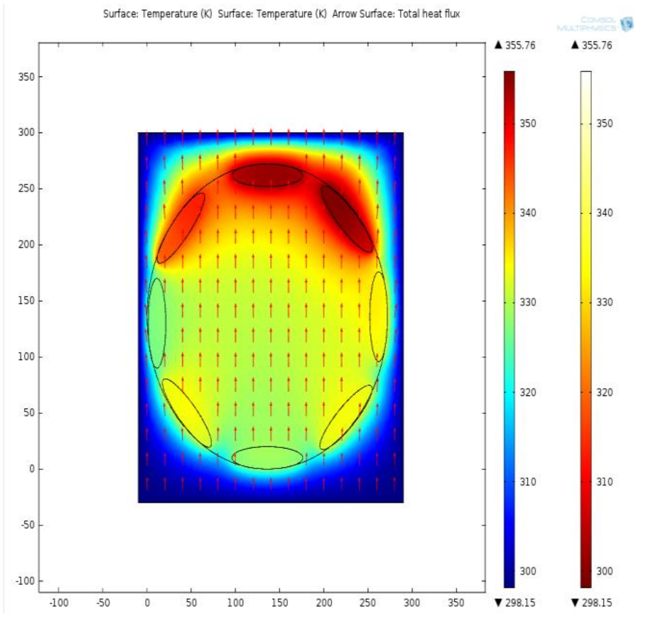

Fig. 6: Evolution of the first thermal simulation of the eight ABDM in COMSOL.

The first simulation of the ABDM along with its FPGA in COMSOL gives a good idea on the behavior and the thermal diffusion of heat sources in a LabPET II scanner, and also shows that the temperature increase significantly to 365.76 °K at the top of the scanner.

3.5 Simulation of the ABDM using natural convection

In this section we present the simulation results of eight ABDM models with their associated FPGA represented in a circular way in COMSOL using the natural convection. Figure 8 shows thermal evolution of our model in COMSOL.

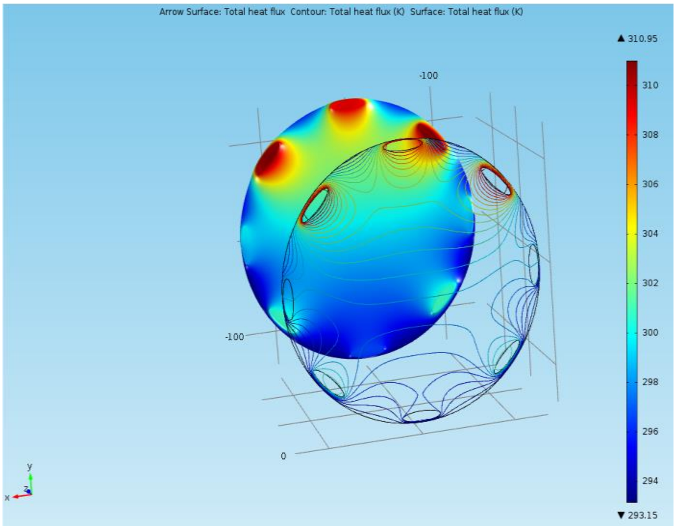

Fig 7: Thermal evolution of the model in COMSOL by natural convection.

The simulation in COMSOL of the ABDM distributed in the scanner gives us an important idea about the thermal evolution, as this figure shows the increase in temperature to 310 °K it is just for eight ABDM. So we must address a very important question. What will be the value of the scanner temperature with 290 ABDM? The figure 7 clearly shows how the evolution of the temperature of each ABDM and how thermal energy is accumulated in a LabPET II scanner.

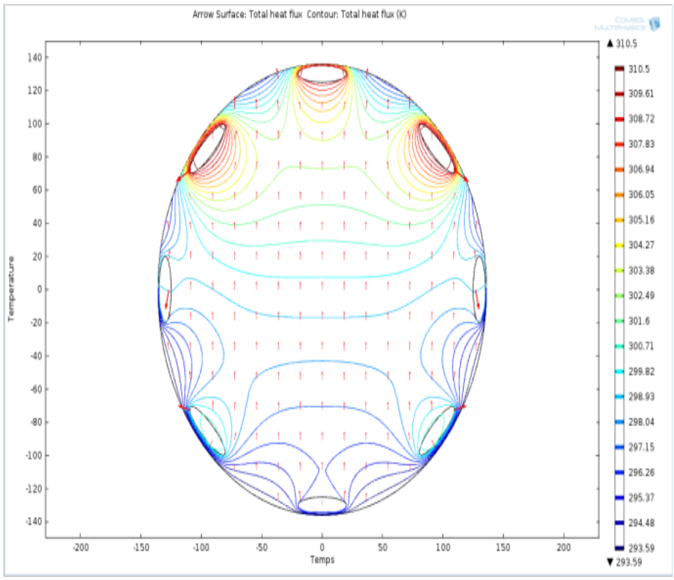

Fig. 8: The heat flow direction and thermal energy accumulation prediction in COMSOL.

3.6 Simulation of the ABDM using forced convection

In this part we present the results of the simulation of 8 ABDM in a circular fashioned way in COMSOL using the forced convection technique. Figure 7 and 9 shows thermal evolution of our model in COMSOL.

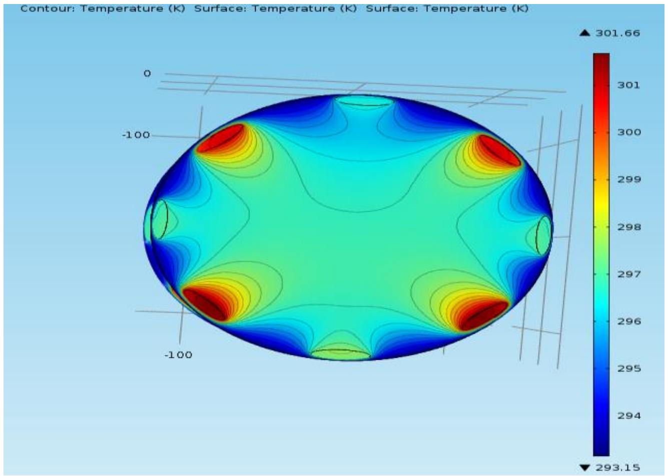

Fig. 9: The thermal evolution of the model by forced convection in COMSOL.

The simulation of the ABDM with their associated FGPA in COMSOL shows the difference between these two types of thermal analysis for a LabPET II scanner. Figure 9 shows that the temperature decreases of 10 °K for the eight ABDM model compare to fig. 7. For this simplified model forced convection thermal analysis demonstrate a good candidate to discharge the energy stored in a LabPET II scanner.

3.7 ABDM thermal result evolution of the LabPET II scanner with COMSOL

In this section we present the evolution of temperature for three types of thermal analysis at an imaginary vertical line from the center of the eight ABDM models passing through different nodes (ASIC, Ceramic and crystal). Figure 10 shows a graph simulation for:

1) No convection only with ambient temperature (25°C)
2) Internal natural convection ($5W/m^2$) with ambient temperature (25°C)
3) Internal forced convection ($50\ W/\ m^2$) with ambient temperature (25°C)

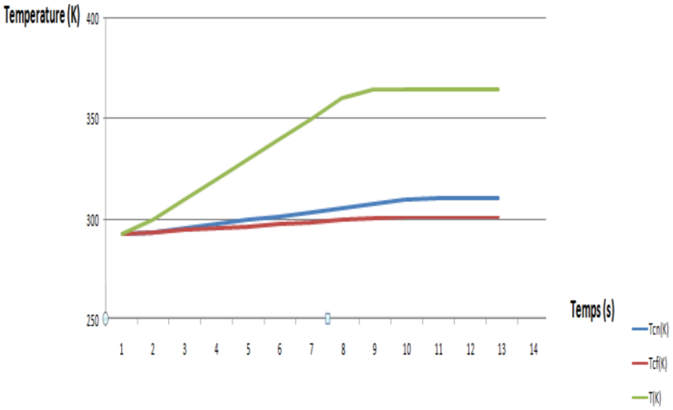

Fig. 10: The graph simulations of eight ABDM for the three type of analysis.

Furthermore, figure 10 presents the difference between the three simulations. It can be concluded that the forced convection is the best way to reduce the temperature in a logical and realistic way for our LabPET II scanner.

4. Results and discussion

In this paper, we developed a simple 2D model for a quick analysis of heat flow for a LabPET II scanner. We also presented the COMSOL simulations for both transient thermal analyses for the eight ABDM. This step is important because the cost of thermal management system strongly depends on the effectiveness of the design. On the other hand, the active self-heating device and passive LabPET II scanner affect the overall scanner performance. We use the COMSOL simulation with a simple model of the scanner to grasp a clear idea about the thermal diffusion around each ABDM. We have shown that the thermal response depends on the type of thermal cooling type used in the boundary conditions. In the case of our project two types of air thermal cooling are possible: natural convection and forced convection. However, due to the high level of the power dissipated in the scanner, the forced convection cooling is the most effective way to remove this quantity of heat from the housing of the LabPET II scanner.

5. Conclusions

In this article, we developed a transient thermal model in COMSOL for ABDM included in LabPET II scanners. This study was conducted by COMSOL finite element tools to get an estimation of the heat flow around the ASICs. In this analysis, the temperature of the APD is computed for typical packages and the power level by using boundary conditions in order to evaluate the thermal stability of our system model. This is an important capability because the cost and thermal management of electronic systems depend heavily on the effectiveness of the design circuits and because of self-heating devices that may affect the scanner performance. It is known that modern computer techniques such as finite element simulations are useful tools for design engineers and help avoid unexpected pitfalls. These simulations allow accurate prediction of temperature distribution in a VLSI package and help to minimize the thermomechanical stresses occurring in different parts of the ASIC. Designers are then able to optimize the system geometry and material of a VLSI package before electronics prototypes are constructed. This greatly reduces development time and increases product quality. This paper presented practical results to determine the thermal stability of the ABDM and helped to ensure the stability of the entire scanner. We also realize and presented COMSOL simulations for both thermal analysis by natural and forced convection for eight ABDM and conclude that forced air is a good candidate to stabilize the temperature inside a LabPET II scanner.

6. References

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