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Investigation of heat transfer in the petal detector structure

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Abstract. This paper describes the CFD numerical simulation of heat transfer in the petal complex structure. Petal consists of core structure and detectors designed to improve the detection capabilities of the ATLAS detector and take advantage of operating at the High Luminosity LHC (HL-LHC). New generation silicon detectors in the petal require more efficient cooling of the front-end electronics and the silicon sensors themselves. To minimize reverse annealing of the silicon sensors the operating temperatures need to be reduced. In this case the evaporative CO2 cooling medium is used as it is ideal for this purpose. This work describes the flow simulation setup and results for the current prototype and heat transfer behavior for different operating states.

1 Introduction

The ATLAS detector is one of the seven particle detector experiments constructed at the Large Hadron Collider (LHC) in a particle accelerator at CERN in Switzerland. Currently, the development is focused in the Phase-II Upgrades of the ATLAS Detector and this development is coordinated by the DESY ATLAS group.

The DESY group is involved in a wide area of activities ranging from simulation studies, sensor assembly and testing, the overall system design (both mechanical and electrical) to the readout electronics. In our case, we will deal with petal component. The petal is the detector designed to improve the detection capabilities of the ATLAS detector and take advantage of operating at the High Luminosity LHC (HL-LHC). The increased luminosity and the accumulated radiation damage will render the current Inner Tracker no longer suitable for long term operations. It is one of the many reasons for replacing a current detector by new generation of silicon detectors. The new generation silicon detectors in the petal require more efficient cooling of the front-end electronics and the silicon sensors themselves. Other important requirements of the new generation cooling systems for the petal are the reduced mass and maintenance free operation.

In this case the evaporative CO2 cooling system is used as it is ideal for this purpose. It is known that two phase cooling is more efficient than single phase cooling. For high cooling and good evaporative capability the smaller diameters of tubes are used. The diameter of tubes is about 2 mm.

Our workplace New Technologies - Research Centre participates in the petal development in collaboration with DESY group. Our work is to focus to heat transfer numerical simulations. These numerical simulations describe the heat transfer and flow behavior in the the current prototype and also the behavior for different operating states. In this article we will focus on verifying the accuracy of the calculation model, the correct identification of material and first results describing the cooling capacity of petal component.

2 The Petal

The Figure 1 shows the assembly of all petal pieces in the detector. Turbo-fan end-cap support structure consists of seven disks with 32 petals each and a total of 50 000 readout chips.

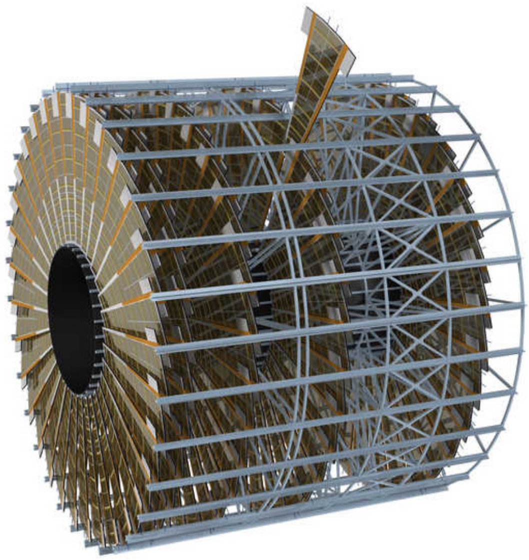

Figure 1. Turbo-fan end-cap support structure. (source: http://wiki.nikhef.nl/atlas/Upgrade)

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The end-cap petals follow very closely the design of the barrel staves. However, the design of the petal is more complex in comparison to the barrel. The petal itself hosts 9 sensor modules per side and it is staffed from both sides (18 modules per petal in total). These modules are not identical within each petal: there are in total 6 different types of sensors, and 8 different types of hybrids. The petal can be divided in 6 different regions, or rings, depending on the type of sensor each ring hosts. This division is shown in Figure 2.

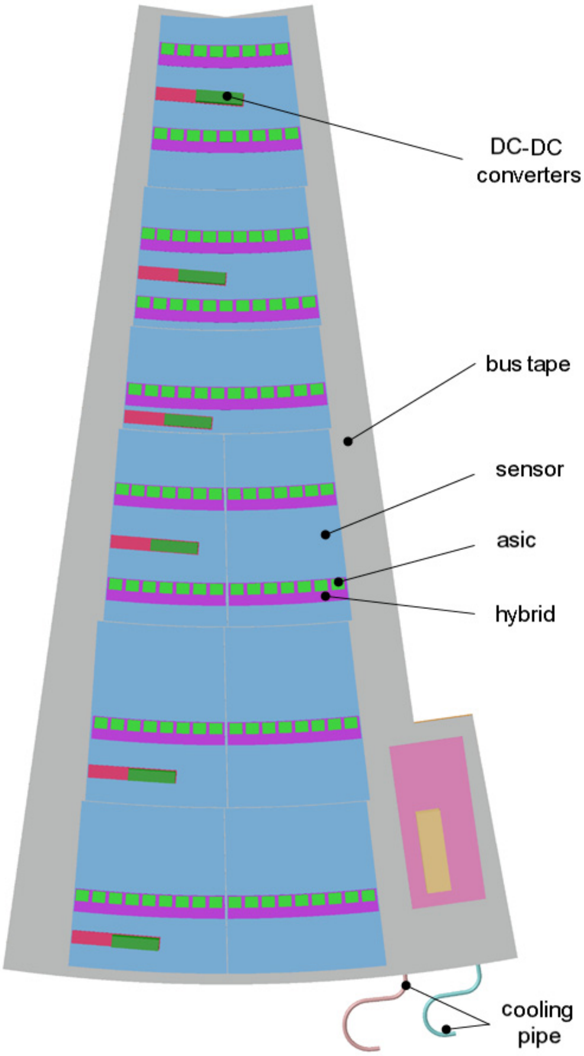

Figure 2. Description of the Petal

The Petal consist of the inner and outside parts. The base core box of petal is made from carbon fibre. Inner parts contain tubes for coolant medium. In our case the coolant medium is liquid CO_2, which is ideal for this purpose. The currently preferred material of tubes is titanium. In this work thin-walled tubes are used with the wall thickness of about 0.1 mm. The tube diameter is 2 mm. In future work, the investigation of other materials (for example stainless steel, carbon fibre, glass and more) is planned. The cut through the petal core structure is presented at Figure 3.

The space around the tubes is filled with high thermal conductive foam and the honeycomb. The honeycomb is currently replaced by air as its function is to isolate the rest of the inner part of petal. Inner part has a thickness of about 5 mm.

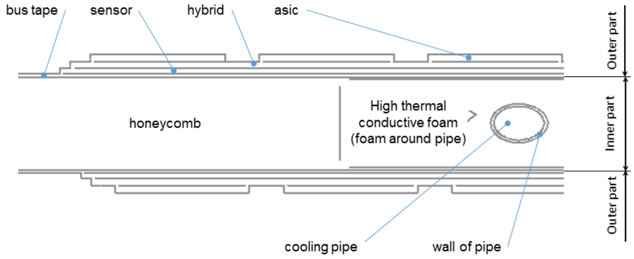

Figure 3. Inner and outer part of petal

The petal outer parts are made of silicon detectors of different sizes and in different layers. The thickness of silicon detectors is around 200 microns, which is a very small thickness. Some layers are described at Figure 2 and Figure 3. Each silicon layer is joined by glue to petal core or another layer. The presence of the glue appears to be a major obstacle for the precise definition of material properties to be used in the numerical model.

This dividing of model to the inner and outer parts is advantageous, because it allows to quickly respond to changing geometry of petal core inner part, for instance for changing the cooling tube shape.

3 Computational mesh

The petal structure geometry is exported from IGES files. The model needs be to simplified and modified for easier and correct meshing. For instance, the bus cables connecting the silicon detectors to asic modules has to be neglected. Also, it was necessary to join and merge inner and outer parts as describing in Figure 3. The Figure 4 shows the diversity of the mesh density on the inner and outer parts.

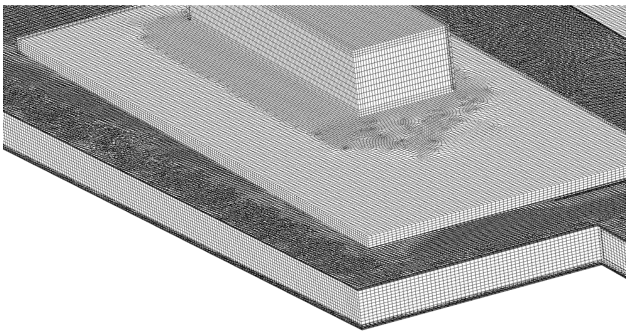

Figure 4. The surface mesh on the inner and outer parts.

The CFD preprocessing software was used to modify the model geometry and to prepare the computational mesh. Volumetric mesh was obtained by application of the “cooper” mesh scheme (similar to “sweep”) in that software. The vertical number of elements is not distributed uniformly. The volumetric mesh contains approximately 31.35 million of 3D mainly hexagonal cells. The inner part has approximately 13.03 million cells and outer parts has approximately 18.32 million cells.

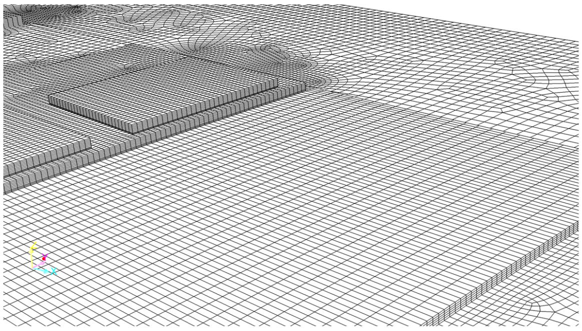

Figure 5. The surface mesh on silicon detectors.

The size of mesh is very big, because the simulations are focused mainly on the heat transfer to the surroundings. In this case, heat transfer simulations are very sensitive to the cell size and other characteristics such as skewness, expansion factor and more.

The volumetric mesh of tubes contains approximately 2.26 million of 3D cells and it is set as the fluid for flow of the cooling medium. The rest of cells is set as solid with different material properties to handle the simulation of heat transfer. The mesh detail is shown in Figure 6.

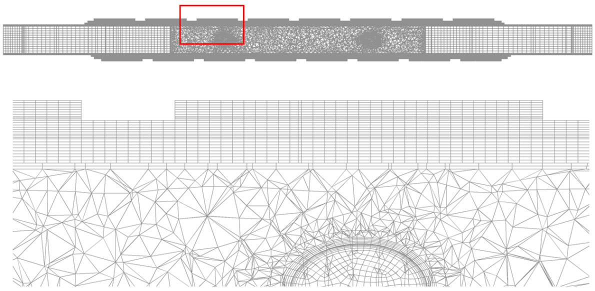

Figure 6. Detailed to boundary layer mesh of the tube.

4 Definition material and cooling fluid

The material definitions and material properties are the key issue for obtaining the correct results from numerical simulations. In our case, the material properties were supplied by DESY Atlas group from appropriate measurements, for instance for silicon detectors or for interlayer, where the material called polyimide is used. The honeycomb core structure inner part is replaced by air, because the material acts as insulation there. In numerical simulations, the adhesive layer between silicone detectors is not considered. This simplification may have a noticeable effect on the results.

Another important issue is the definition of cooling fluid. In fact, the used coolant is in two-phase mixture. In our case, the numerical simulation treats this mixture as a liquid and the evaporation effect of the liquid is not considered. But the material properties of liquid are set according to values for the material representing CO2 mixture. This mixture consists of liquid and vapor phases for which values were estimated.

5 Numerical simulation

The boundary conditions for numerical simulation are described in Figure 7. The blue tube (on right in Figure 7) has the boundary condition defined to the mass-flow-inlet. The mass flow rate has been set variably to values 1 g/s and 5 g/s. The red tube on left is set to pressure-outlet. The initial state before the start of calculation has been set for solid and fluid zones to 248 K (-25°C).

The numerical simulation and postprocessing was performed in the commercial software package ANSYS FLUENT v.15.0. The flow model included the turbulence model “Standard k-epsilon” in the second order of accuracy. The numerical simulation was performed in the stationary mode in the second order of accuracy in 6000 iterations.

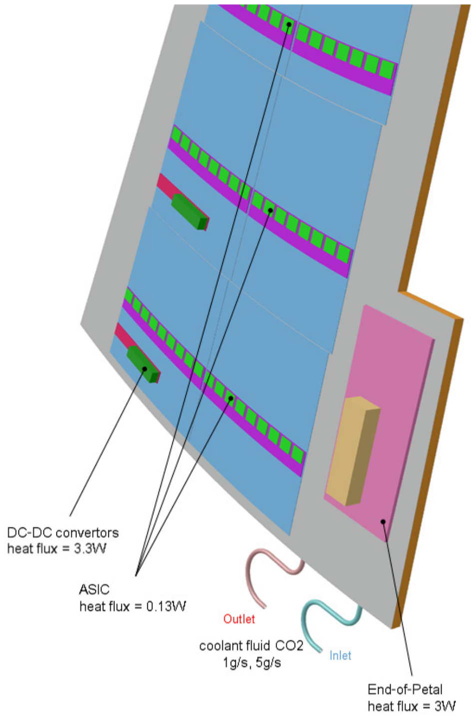

Figure 7. Boundary conditions and heat sources.

The heat sources (see Figure 7) has been set at appropriate components: in the DC-DC convertors to 3.3 W, in the ASIC to 0.13 W (for each silicon detector) and in the End-of-Petal component to 3 W. The total heat source through all components and for both sides is approximately 49 W. Heat transfer coefficient to surrounding medium is set to 15 W/m^{2}K and the ambient temperature is set to 248 K (-25°C).

6 Results

The simulation results are presented for 2 operating states for mass flow rates at 1 g/s and 5 g/s with the same initial conditions. Figure 8 shows the surface temperature distribution for coolant flow 5 g/s. Some temperature values are pinned for both flow rates. From the results it can be seen the largest heat source are the components of the DC-DC convertors, and they significantly affect the temperature of the whole petal structure. The bottom DC-DC convertor has higher temperature than the other DC-DC convertors. The temperature augmentation is there because the cooling pipe is not present in the core structure under this DC-DC convertor. This situation is same for both petal sides.

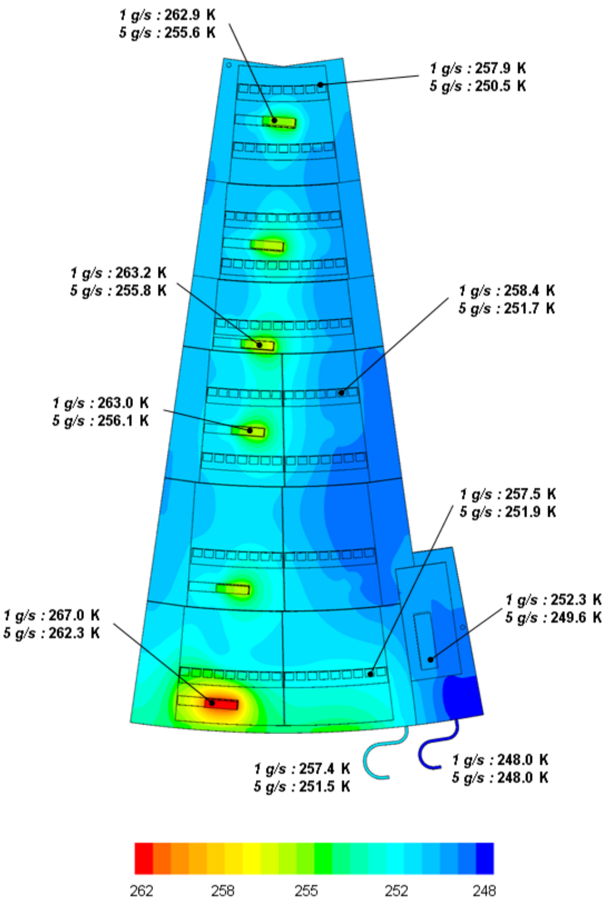

Figure 8. Surface-temperature distribution for 5 g/s.

Figure 9 shows the temperature situation in the cooling tube also for both operating conditions. The influence of the size of the flow rate and velocity in the pipe there is significant to temperature augmentation in the upper part of the device for a flow rate of 5 g/s. For the flow rate of 1 g/s the corresponding coolant velocity in the tube is approximately 0.26 m/s and Reynolds number is 1022. For the flow rate 5 g/s, it is almost 1.32 m/s and Reynolds number is 5190.

These calculations are characterized by Prandtl number 9.9. This number is only dependent on the material properties of the fluid.

The increased coolant velocity in the tube significantly affects the heat transfer mainly in the upper part of the petal. The surface temperature difference between the two variants has the value of 6 °C.

7 Conclusion

The aim of these simulations is to describe the heat transfer and flow behavior in the petal structure. The numerical model for CFD simulations and the definition of basic boundary conditions was set up. The results showed in the previous chapter are consistent with the expected results.

In future work, we will focus on improvement of material properties for solids and also to focus on more detailed description of the coolant mixture together with the evaporating process. In the next steps, we will also deal with the optimization of the cooling duct and the location of silicon detectors in the petal.

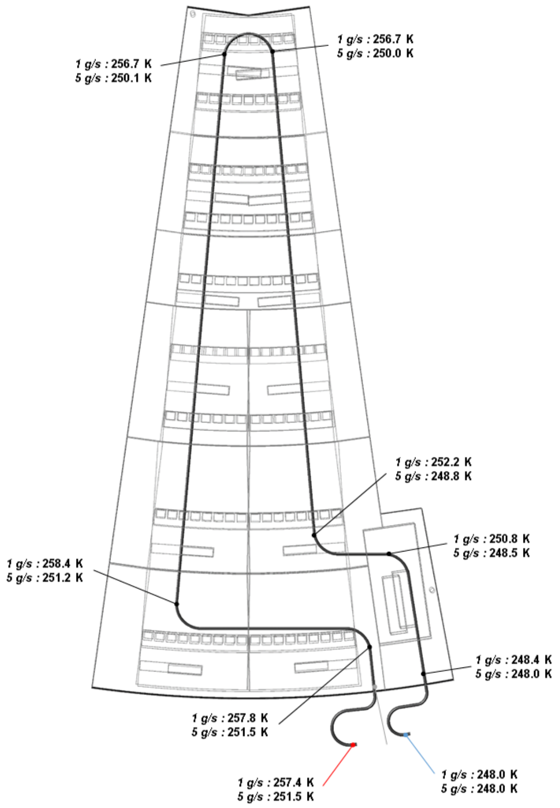

Figure 9. Temperature situation in cooling duct

Acknowledgment

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