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DESIGN STUDY OF COOLING FOR FORWARD-TYPE DETECTORS UNDER INCREASED LUMINOSITY EXPECTED AT THE FUTURE LHC OPERATING CONDITIONS

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Abstract: *The team members of the Faculty of Mechanical Engineering of the Czech Technical University in Prague have been working together on projects at CERN for more than 22 years. Some work is related to cooling systems for the inner detector of the ATLAS experiment and to forward types of detectors. Such as TOTEM experiment, today incorporated under CMS as PPS2 and AFP ATLAS. Based on our prototypes, two cooling systems in the LHC tunnel have been implemented so far, namely a compressor cooling circuit with C3F8 refrigerant for TOTEM and the second system for the AFP project using AIRCOOLER-Split type units It was designed by us and worked for the last 5 years without failure and free of maintenance for needs of AFP forward detectors. We are starting work on systems for forward-type detectors to withstand increased luminosity conditions in the LHC tunnel to be expected after 2027. A substantial part of our paper is related to this ongoing research work and to the possibilities of variable 3D metal printed heat exchangers. These could be used for cooling forward detectors and their electronics under demanding operating conditions and limits given by their dimensions soon.*

Keywords: **Particle detectors, CERN LHC experiments, cooling systems, forward type detectors, 3D metal type heat exchangers.**

1. Introduction

Our research group has been working for more than 25 years on developing and applying cooling systems for detector technology in the field of elementary particle physics research. These activities include carrying out studies of the thermophysical properties of fluids, designing, constructing, and testing various types of cooling equipment, optimizing the heat transfer for high-tech electronics, and developing adequate DAQ systems, including sensors that can be used for these special applications.

Our paper will present examples of vortex-tube cooling applications around the two largest detectors of the LHC (**L**arge **H**ydron **C**ollider - project (see Fig. 1) at CERN, i.e. the ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) and CMS (**C**ompact **M**uon **S**olenoid) detectors. In both projects, we are a part of a broad international cooperation network.

Many traditional elements known from classical refrigeration technology cannot be simply applied due to the minimal available space for installation inside the detector, and due to issues with radiation, the strong magnetic field, and dialectical and cleanliness requirements. Due to environmental restrictions, fluoroinerts will no longer be used for future types of inner detectors and cooling systems, and many next systems will use CO_2 as a refrigerant for the future runs. We will limit our presentation here only to activities related to the forward type detectors located both around main detectors ATLAS and CMS. In these installations, the range of cooling power is usually between 500 W and 1.5 kW. We will mainly concentrate to problems of cooling systems AIRCOOLER Split type unit using an air as the coolant (Vacek et al., 2016; Seabra et al., 2017 and Vacek and Doubek, 2021).

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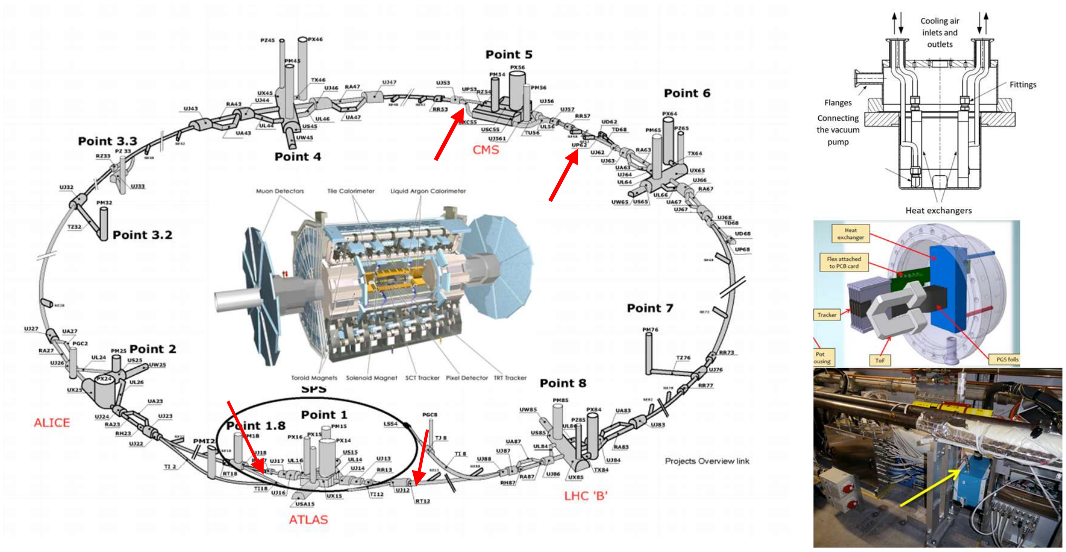

The simplified schematic of Roman Pots

Si detector connected to the heat exchanger.

Air cooler Box in the LHC tunnel placed next to RP

Fig. 1: The large hadron collider project map (adopted from https://cds.cern.ch). Red darts indicate approximate locations of forward type detectors.

Limiting elements are small and efficient heat exchangers that must be placed as close as possible to the silicon detectors and their electronics. All these sub-components are located inside the highly vacuumed space of the detector body referred to as the Roman Pot.

2.1. Heat exchanger development

There were developed several types of heat exchangers over the last 15 years starting from the fully machining units up to the multi-component variations and we must cope with the "ever-shrinking" space that was available for its placement. However, this is in direct contradiction to the gradual increase in cooling performance. The problem was solved using foam metal inserts. Our latest installation of AIRCOOLER-Splits units with the use of metal heat exchangers (Al or Cu) plus foam inserts. Such exchangers fulfill requests for cooling AFP detectors and has been in maintenance-free operation for the past 5 years without a single defect.

A brief overview of the development of exchangers and their improved functionality is shown in Fig. 2.

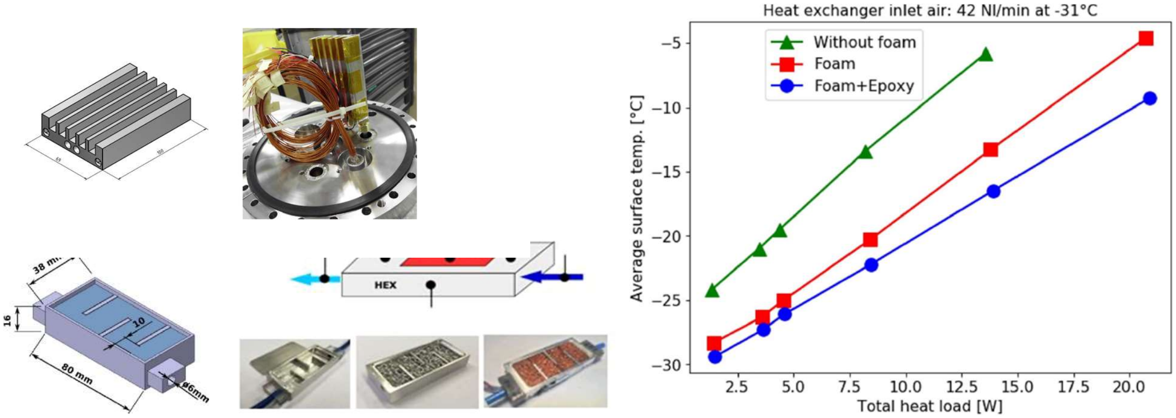

Fig. 2: The summary of the development of exchangers and improvement their functionality.

$$Q = h.A.\left(T_w - T_f\right) \tag{1}$$

From Eq. (1), it is obvious that the transferred heat depends on the heat transfer coefficient h [W/(m^2·K)], the heat transfer contact surface A [m^2] and the temperature difference $(T_w - T_f)$ [K]. So it is necessary increase the heat transfer coefficient, the surface area or the temperature difference. In order to keep the cold plate surface temperature T_w within the requirements for the AIRCOOLER outlet air temperature T_f has to be maximally lowered for a large transferred heat flux. The heat transfer coefficient is small for gas flows (in comparison with liquids or two-phase flows), depending mainly on the air flow velocity, which is itself limited by the working pressure achievable at the AIRCOOLER output unit. Since the available air pressures are also imposed by the safety regulations for compressed air installations (usually 7–9 bars). It can be concluded that the surface area is the most important parameter to be optimized in order to achieve the desired performance in our applications. An enhanced inner surface of the cold plate exchangers was therefore investigated in several studies and configurations. Fig. 3 shows typical values recorded during the test, where the value of dissipated energy reaches 20 W.

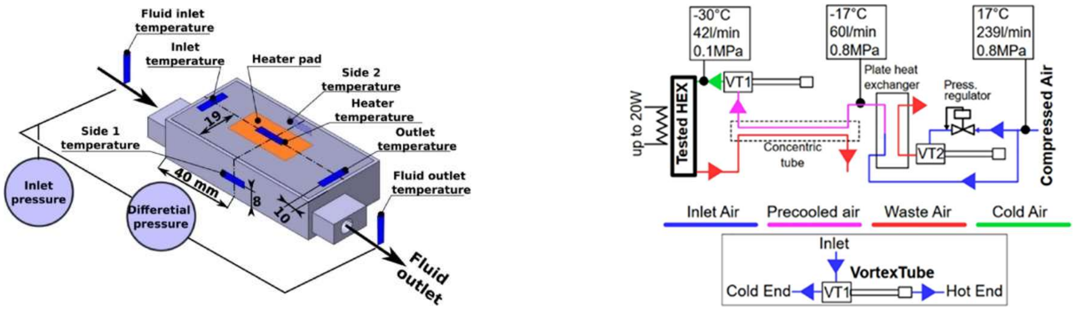

Fig. 3: The parameters during one of the many tests are illustrated in here.

2.2. 3D printed metal heat exchangers development

In the last few years, 3D printing experienced an enormous rise, since technology improves and processes are refined, metal 3D printing has grown increasingly popular and accessible. But even as price points for 3D printers come down and new applications for additive manufacturing are discovered, problems and challenges remain that still prevent many companies from utilizing this innovative technology to its full potential (Andronov, 2021). The R&D project of forward detectors for operating conditions with significantly increased luminosity after 2027 begins at CERN this year. That's why we decided to focus more on 3D printing of metallic materials. This will allow for easy adaptation to frequently changing specifications. This technology brings several advantages, among which flexibility in terms of shape and dimensions dominates. Such changes of the specifications will undoubtedly occur within development cycle. Considering our experience with many types of exchangers for these demanding applications, we were particularly concerned on studies of commonly known problems with metal 3D printing. The most important ones for us were the porosity of the products obtained and its impact on required tightness and the necessary cleaning of micro particles after 3D printing (Vafadar, 2021).

2.3. 3D printed heat exchangers tests

To print functional heat exchanger its design needs to be adjusted. For this purpose, original model was scanned with the CT (computed tomography) and data were transferred to surface model format STL. Surface model worked as reference geometry for new heat exchanger design. Some geometrical changes were made in the design to improve cooling properties or to secure flawless printing result. The main changes were following inner radiuses were added to lower tension in corners, partitions to increase cooling channel length, holes for threaded pneumatic connectors were added.

A model was used to get printing data for LPBF machine GE Concept Laser M2 in Materials MAGICS. Aluminum alloy AlSi10Mg was selected among available range of materials to ensure good heat transfer properties. Next step was a post processing of printed part. Printed heat exchanger was then cleaned, outer surfaces were machined, and preprinted inlet and outlet holes were drilled and tapped. Printed heat exchangers are going to be installed inside the Roman Pots with the high level of vacuum. No leaks are acceptable. Because of expected use of heat exchangers in particles detector surrounding, leak tests were carried out. Test setup was prepared for this purpose as shown in Fig. 4.

The first five 3D printed samples of the exchangers showed varying degrees of leaks. The load pressure test was slowly decreasing despite the series of setup modifications. We have observed small leaks in the screw connections, but the main leakage was probably formed during machining due to high deformations and insufficient machining thickness allowance. Then machining allowances were increased for the second set of heat exchangers. The heat exchanger ver. 2 was printed with the same post processing techniques and heat exchanger inlets and outlets were sealed with silicon high temperature gasket and tested. The standard operational pressure of cooling air on the site will be up to 2 bars.

Fig. 4: Overview of heat exchanger prototypes with inner structures details and leak test setup.

Following experiment, even with higher pressure of 7 bars, was finally successful with no noticeable pressure loss in three days. Then testing under extreme conditions of 10 bars was carried out to verified reliability of printed part. Even under high pressure no leakage occurred for nearly one month. Density of the structure was chosen according to previous test with copper foam porosity to 30 %. Inner structures of the tested heat exchangers diamond like shapes we prepared with two diameters of 5 and 13 mm. It may show us its impact on cooling performance. We plan to investigate the operating parameters of the 3D printed exchangers to compare with the most efficient and used original exchangers nowadays. We will study and compare mainly differences in temperature profiles, pressure losses and flow, i.e. consumption of cooling medium-air. For this purpose, third version of heat exchanger with complex diamond shape structure was designed.

2. Conclusions

In our article, we mainly dealt with the issue of cooling the forward-type elementary particle detectors used at the CERN LHC accelerator. Special attention was paid to the optimization of the small heat exchangers used for cooling both the detectors themselves and their electronics. R&D projects are starting this year aimed at the operation of the LHC accelerator after 2027, when a significant increase in its luminosity is expected. We chose the path of developing the necessary metal heat exchangers by 3D printing. At the end of last year 2023 and the beginning of this year, we produced the first prototypes of such exchangers and carried out successful tests for their required tightness and their necessary cleaning from micro particles after 3D printing. A test set up is being prepared, including the DAQ system and the necessary sensors for conducting measurements on the Roman Pots mock-up with a new type of heat exchangers. By the end of the year, experiments aimed at proving the suitability of using exchangers produced by 3D printing will be carried out in comparison to heat exchangers with foam metal inserts used so far. We will focus on comparing relevant temperature profiles, pressure losses and consumption of cooling medium-air of all types of heat exchangers.

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References

Andronov, V., Šimon, J., Pelikán, L., Beránek, L. and Novák, P. (2021) Analysis of strength properties of 3D printed lightweight structures made of AlSi10Mg material: A Review of Common Processes, *IOP Conference Series: Materials Science and Engineering*.

Seabra, L., Banaś, E., Caforio, D. et al. (2017) The AFP detector control system. In: *Proc. 16th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS)*.

Vacek, V. and Doubek, M. (2016) Air-driven cooling device for high tech electronics. In: *Proc. 12th IIR-Gustav Lorentzen Natural Working Fluids Conference (GL 2016)*, Edinburgh, United Kingdom.

Vacek, V. and Doubek, M. (2021) Universal heat exchanger for air and evaporative cooling of electronics, *Thermal Science and Engineering Progress*, Elsevier, vol. 32, pp. 11.

Vafadar, A., Guzzomi, F., Rassau, A. and Hayward, K. (2021) Advances in Metal Additive Manufacturing: A Review of Common Processes, Industrial Applications, and Current Challenges, *Applied Sciences*, vol. 11, iss. 3.