AIR COOLING ENHANCEMENT OF A HIGH-PRECISION HIGH-VOLTAGE RESISTOR

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ABSTRACT

A high-precision high-voltage resistor must be cooled to ensure an adequate operation. The resistor consists of an arrangement of 3x10 resistances that dissipates 4W, disposed in a flat plate collocated at the center of a metallic electric shield. The resistor-shield system is placed in a metallic cylinder containing a fan at one end, to force air flow through the uniformly-perforated shield, in order to refrigerate the resistances. With this system, temperatures reached at the resistances were above the requirements. The aim of this work is to improve the ventilation system, in order to obtain the required values of temperature at the resistances, to ensure that its resistance remains virtually unaltered. Due to electric field restrictions, only the modification of the number (not increasing) and location of the holes was considered. Numerical 3D simulations using CFD&HT techniques were performed to test possible holes configurations. Moreover, experiments were performed for some hole configurations with the purpose of measuring the air flux and validating the model. The best configuration consisted of fewer holes than in the original design, placed in such a way that the flow at the interior of the capsule impacts directly on the resistances. Although the reduction of the number of holes causes a reduction in the total air flow, simulations show that the air velocity near the resistances is higher, resulting in higher cooling and temperatures being in an acceptable range.

INTRODUCTION

In the framework of a project that aims to develop a reference system that can measure voltage, current and power up to 100 kHz and 1000 V [1; 2], by the National Metrology Institutes of Brazil (INMETRO), Argentina (INTI) and Uruguay (UTE), high-precision high-voltage resistors are being designed and constructed by UTE. The resistor consists of an arrangement of 3x10 resistances that dissipates 4W, disposed in a flat plate. Due to the high sensitivity of the resistor towards the electric fields, the arrangement is collocated at the center of two symmetric cone-shaped electrostatic-shields (see Fig. 1). The shape of the shield was designed to get null radial electric field at the whole surface of the resistor [3]. The resistor-shield system is contained in a metallic cylinder. The refrigeration of the resistances is constrained by the encapsulation, causing a significant enhancement of the resistor temperature, which generates variations of the resistance of 60 $\mu\Omega/\Omega$ [3], which is over the maximum tolerance.

Figure 1: Electrostatic shield made by two metallic cones.

Originally, a ventilation system was designed in order to avoid high temperature at the resistances. A fan was collocated at one end of the metallic cylinder to force air flow towards the copper shield, which was uniformly perforated to allow the flow pass inside the capsule and refrigerate the resistances. The holes can be observed in Fig. 1. However, the temperatures reached at the resistances were still above the requirements and a non homogeneous temperature distribution was observed along the arrangement. Variations of the resistance of 35 $\mu\Omega/\Omega$ were measured [3].

The aim of this work is to improve the cooling system in order to obtain the required values of temperature at the resistances to ensure that its resistance remains virtually unaltered. The electric field impose some geometrical restrictions; i.e. physical elements cannot be installed inside the capsule, the shape of the capsule must be unchanged and the number and diameter of the holes cannot be incremented. Therefore, the only modification considered in the present work is the number (not increasing) and location of the holes. In order to evaluate the fluid-thermal performance of the system a preliminary study based on numerical 3D simulations using CFD&HT techniques were performed, assuming steady state and laminar flow. Different configurations were tested, the best of which consisted in one with a smaller number of holes, placed in such a way that the local velocity near the resistors was incremented. To fully analyze the proposed geometry, further simulations considering the turbulent nature of the flow, using large-eddy models (LES) were solved. Since the air flux inside the capsule strongly depends on the number of holes, an experimental setup was designed to measure the flux. This information was used as an input of these last simulations.

The following sections describe the preliminary study to find a possible new configuration, a detailed analysis of the proposed solution and concluding remarks.

PRELIMINARY STUDY

In order to perform a first approach to the problem, numerical simulations for different hole configurations were performed using COMSOL [4]. COMSOL is a general-purpose simulation software for modeling multiphysics processes. The Navier-Stokes and energy equations are discretized using the finite-element method. For this problem the flow can be considered incompressible, and despite the real flow is turbulent, in this preliminary study the flow is considered laminar and steady-state. Therefore, only qualitative conclusions are drawn from this first approach.

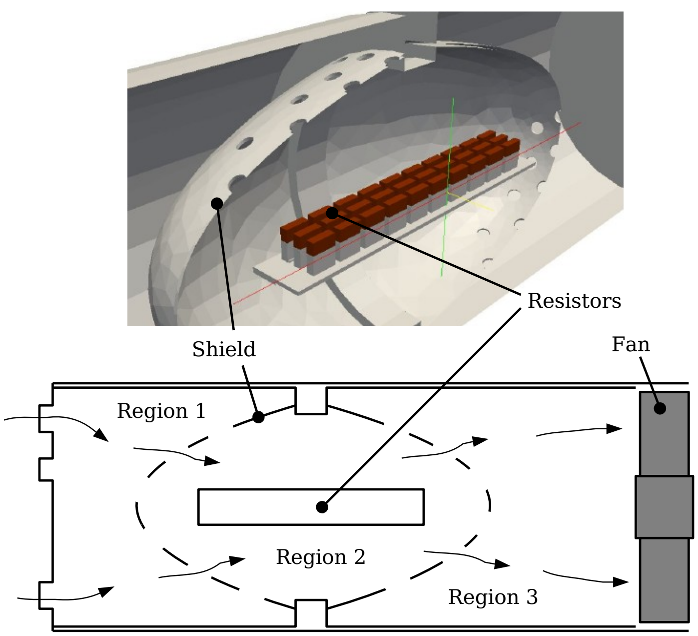

Figure 2: Three-dimensional and two-dimensional views of the model domain.

The domain is presented in Fig. 2. It consists in the volume inside the metallic cylinder. In one end of the cylinder an induced draft fan is located and a set of holes conforms the air inlet in the other end. Because of the presence of the metallic shield, three zones can be differenciated, numerated from 1 to 3 in Fig. 2. The resistors are located in region 2. A perfect seal between zones 1 and 3 is considered, wich means that the total flow passes from region 1 to 2 through the holes of the first half of the shield, and then from region 2 to 3 through the holes of the second half of the shield. The flux is calculated using the fan-curve and the pressure lost computed in the simulation. Non-slip boundary condition is imposed in the solid surfaces (cylinder, shield and resistors) for the velocity. Adiabatic walls are considered in the solid walls, except for the resistors, where a fixed and uniform heat flux is set in such a way that a total of 4W is dissipated.

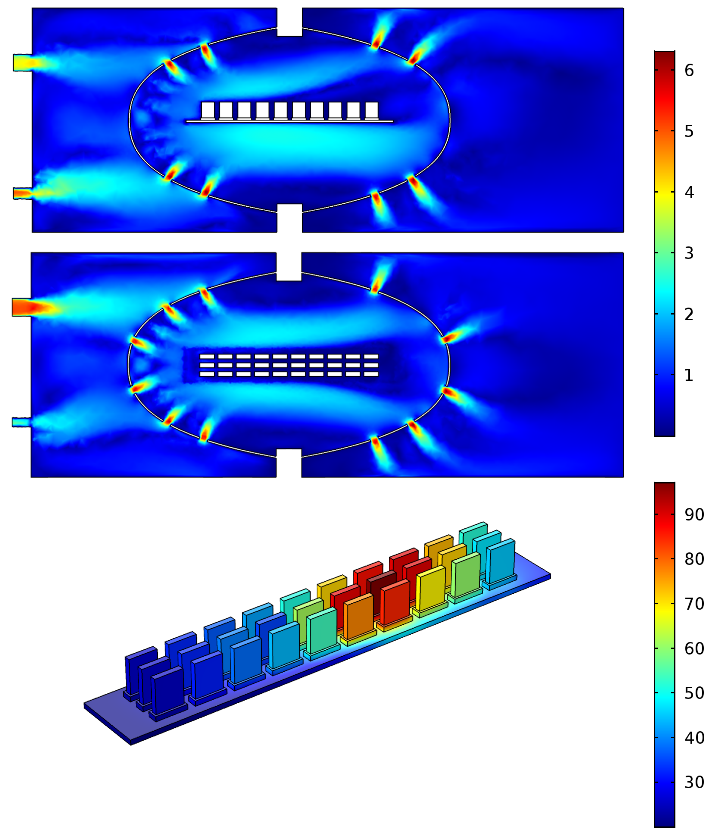

Figure 3: Air velocity fields and temperature distribution of the resistors for the original configuration (A). Numerical results using COMSOL.

First, the original design was simulated, hereafter called configuration A. It consists of 48 holes in each cone, distributed uniformly in the spherical regions of the cones (see Fig. 1). As was expected, the temperature of the resistors were above the requirements, with a non-uniform distribution reaching higher temperatures at the resistors placed near the end (see Fig. 3). Due to the disposition of the holes, only a small fraction of the flow pass through the resistors, limiting the cooling effect (see Fig. 3).

A new configuration eliminating half of the holes is then analyzed. In this new configuration, called configuration B, only the holes at the top of the first cone and the holes at the bottom of the second cone are keeped. The idea of configuration B is to force the air to pass through the resistors, considering that these are at the upper half of the interior of the shield. In configuration B, the flow is better directed through the resistors, as can be observed

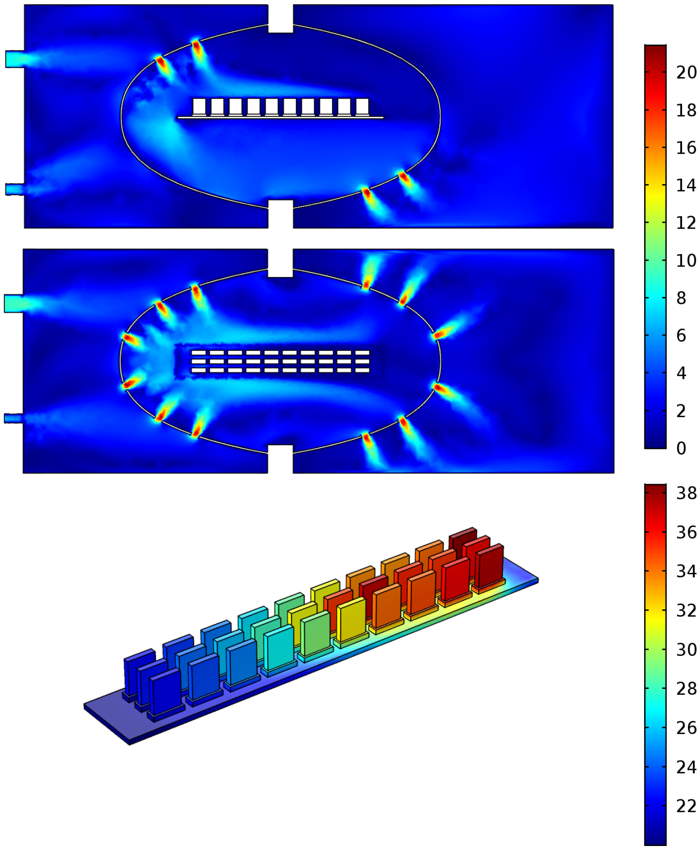

Figure 4: Air velocity fields and temperature distribution of the resistors for configuration (B). Numerical results using COMSOL.

in Fig. 4. Even with a reduction of the total air flow, the temperatures reached are lower in configuration B than in configuration A. However, the temperature distribution is still non-uniform as can be seen in Fig. 4.

After that, more than five configurations of holes were tested. The evolution from of those configurations is schematichally represented in Figs. 5 to 7.

It was observed that placing the holes of the first cone only in the band that is parallel to the resistor arrangement (red rectangle in Fig. 6), the system acts like a set of jets over the first rows. Moreover, the reduction of the number of holes of the second shield at its location in a band placed at the bottom (blue rectanlge in Fig. 6) concentrates the air flow around the resistors.

Further tests show that increasing the number of holes on spherical zone of the second cone force that air flows through the final rows of the resistor arrangement (blue in Fig. 7). It was also verified that a few holes at the top of the first cone close to its end (extension of the red rectanlge in Fig. 7) contribute to the cooling of the final rows of the resistors.

A scheme of the final configuration, called configuration C, is presented in Fig. 8. It has 13 holes in the first cone and 12 in the second, distributed according to the previous analysis. This new configuration has again a lower total air flow, since the reduction

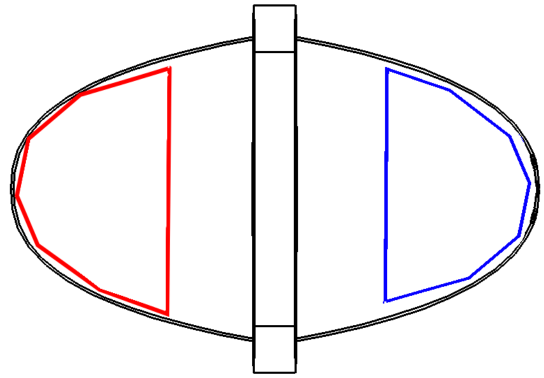

Figure 5: Top view of the regions where holes were distributed of configuration (B). Red indicates only at the top-half of the shield and blue indicates only at the bottom-half.

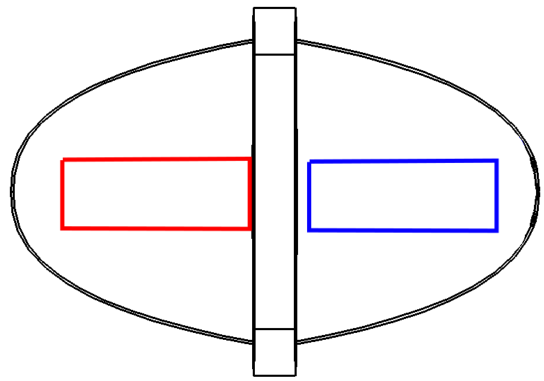

Figure 6: Top view of the regions where holes were distributed for an intermediate configuration. Red indicates only at the top-half of the shield and blue indicates only at the bottom-half.

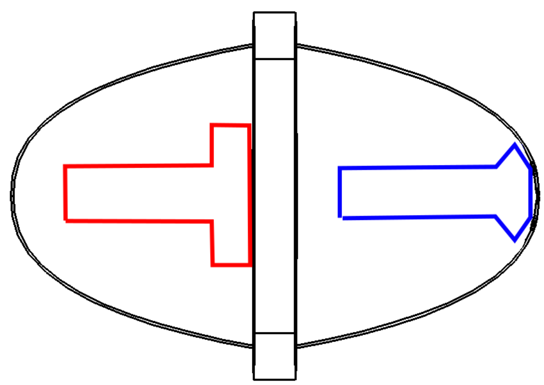

Figure 7: Top view of the regions where holes were distributed for the final configuration (C). Red indicates only at the top-half of the shield and blue indicates only at the bottom-half.

of number of holes increases the pressure loss. However, according to this preliminary study, higher local velocity is expected around the resistors as can be seen in Fig. 9. A more effective cooling is then obtained (see Fig. 9).

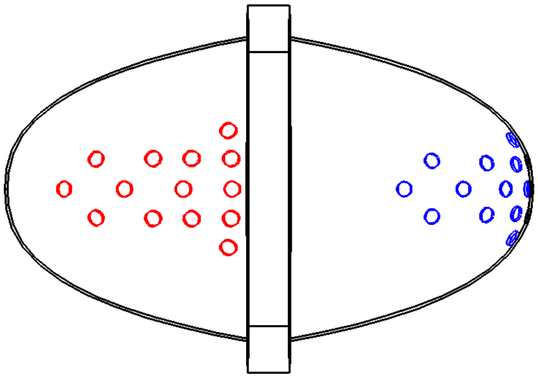

Figure 8: Distribution of holes in configuration (C). Red indicates only at the top-half of the shield and blue indicates only at the bottom-half.

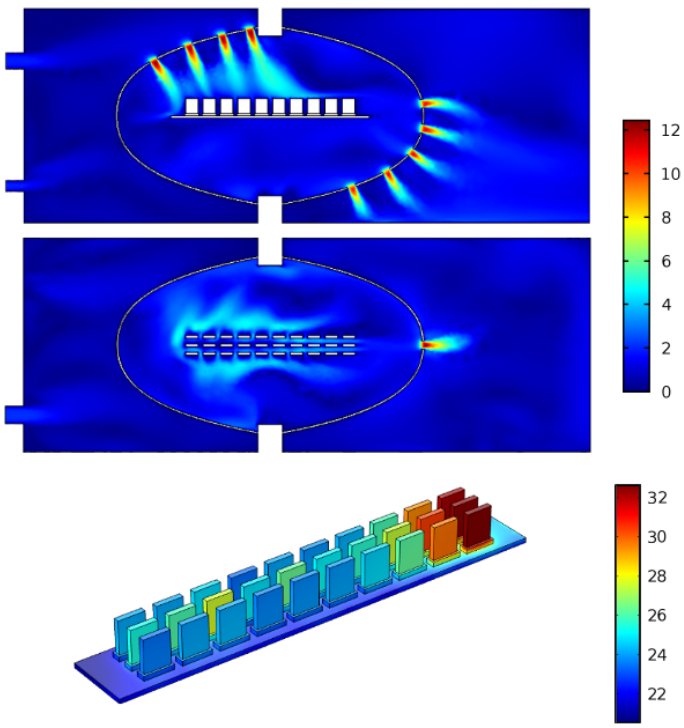

Figure 9: Air velocity field (top) and temperature distribution (bottom) of the resistors for configuration (C). Numerical results using COMSOL.

DETAILED ANALYSIS

In order to quantify the improvement of configuration C, more precise simulations considering the transient and turbulent effect were performed. To do so the CFD&HT software TermoFluids [5] was used. Configurations A and B were solved to validate the methodology, since experimental measurements of the resistors' temperatures were available from UTE. To reduce the sources of error an experiment was set up to measure the air flux for different number of holes, matching the number of holes of configurations A, B and C. The measured flux was used as an input in the simulations.

Experimental setup

In order to obtain the flow supplied by the fan and the head loss imposed by the device, the following experimental setup was designed. At the outlet section of the metallic cylinder an acrylic tube with a length of 10 diameters was inserted. At the end of this tube eight velocity measurements were made, distributed along the same horizontal diameter at a 25 mm, 30 mm, 39 mm and 47 mm distance from the center of the section. At the fan inlet the air pressure was registered. All the variables were measured with a TSI VelociCalc 9565 multi-function anemometer.

Three operational configurations were made varying the number of holes in each shield. The obtained values are summarized in Table 1.

	Number of holes	Total flux [m^3/h]	Δp [Pa]
A	48x48	27.8	108
B	24x24	18.8	117
C	13x12	15.5	127

Table 1: Measured air flux and head loss.

Numerical Method

TermoFluids code describes the turbulent flow by means of Large eddy simulations (LES) using symmetry-preserving discretizations. The spatial-filtered and discretized Navier-Stokes and energy equations can be written as,

$$Mu = 0 \tag{1}$$

$$\Omega \frac{\partial u}{\partial t} = -C(u)u + \nu D u + \rho^{-1} G p + \mathcal{M}\mathcal{T} \tag{2}$$

$$\Omega \frac{\partial T}{\partial t} = -C(u)T + \frac{\lambda}{\rho c_P} DT \tag{3}$$

where M, $C(u)$, D and G are the divergence, convective, diffusive and gradient discrete operators respectively, Ω is a diagonal matrix with the sizes of control volumes, p represents the filtered pressure, u is the filtered velocity, ρ, ν, λ, c_P are the density, the kinematic viscosity, the thermal conductivity and the specific heat of the fluid. $\mathcal{M}$ represents the divergence operator of a tensor and $\mathcal{T}$ is the SGS stress tensor. The LES model used in the present work is the WALE model within a variational multiscale framework [6] (VMS-WALE). The spatial discretization preserves the symmetry properties of the continuous differential operator, ensures stability and conservation of the global kinetic energy on any grid [7]. The fractional-step method is employed to perform the time evolution of the equations. The convective and diffusive terms are explicitly treated with an Adams-Bashforth scheme.

The same domain as in the preliminary study is simulated (see Fig. 2). The meshes are unstructured, composed by tetrahedra and conformal to the geometry. A different mesh is used for each configuration due to the variations of the number and placement of the holes. The total number of control volumes are 4.4, 3.8 and 3.1 millions for configurations A, B and C respectively. The mesh is finer close to the holes and in the resistors' vicinity. The smallest cells have a size of 0.45 mm. A slice of the mesh used in configuration C is shown in Fig. 10.

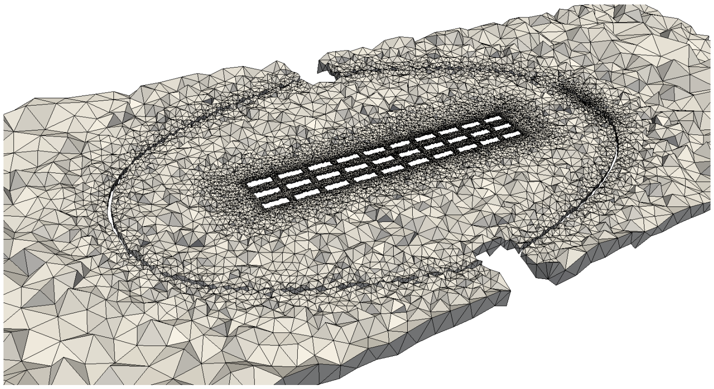

Figure 10: Slice of the mesh of configuartion C.

In the same manner as in the preliminary study, non-slip boundary condition is imposed in the solid surfaces (cylinder, shield and resistors) for the velocity. Adiabatic walls are considered in the solid walls except for the resistors, where a fixed and uniform heat flux is set in such a way that a total of 4W is dissipated. The boundary condition for the velocity at the inlet is defined by a uniform value corresponding to the flux presented in Table 1. The temperature at the inlet is the ambient temperature $T_a = 23$ °C. At the outlet, a pressure-based condition is prescribed for the velocity.

Results

Configurations A and B were simulated to validate the methodology. Experimental measurements of these two configurations were made during the poyect by UTE. It was observed that the flow inside the shields beahaves in a qualitatively similar way to the solutions of the preliminary study.

After the statistical steady state is reached the temperature of each row of resistors is averaged over time. This values are compared to the experimental measurements in Figs. 11 and 12. Good agreement can be observed.

The proposed new geometry, configuration C, is then simulated. As was the design idea, higher local velocities are obtained in the vicinity of the resistors. The first six rows are directly impacted by the air jets coming from the holes of the first shield. These jets have a maximum velocity of 37 m/s at their beginning, and close to the resistors the velocity is around 22 m/s. These details can be observed in Fig. 13.

Moreover, the air flow through the two channels formed between the columns of resistors is favored by the holes located in the spherical zone of the second shield. In this manner, velocities

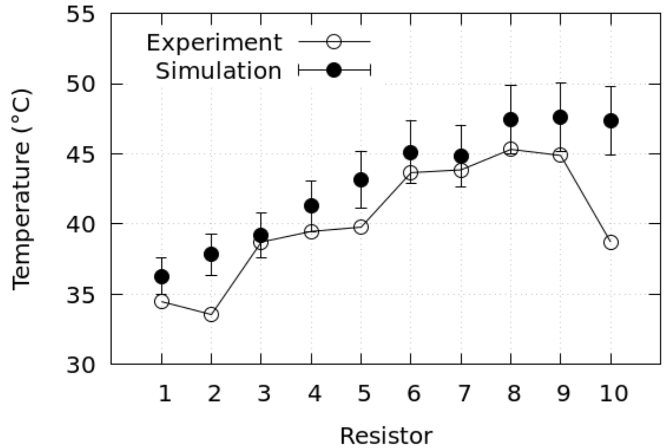

Figure 11: Temperature distribution of the resistors for the original configuration (A). Numerical results computed using TermoFluids [5] and experimental results provided by UTE.

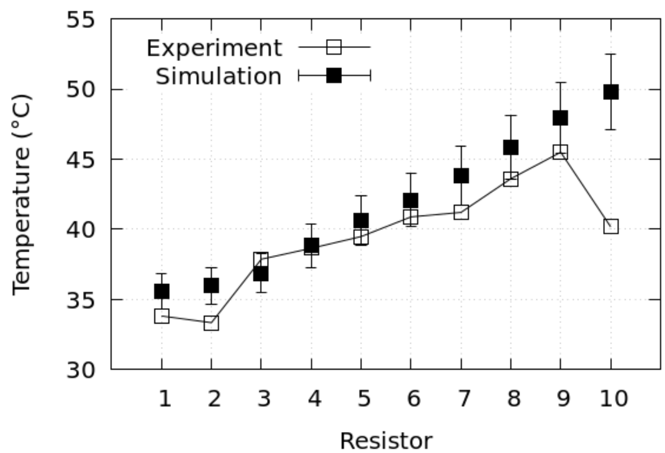

Figure 12: Temperature distribution of the resistors for configuration B. Numerical results computed using TermoFluids [5] and experimental results provided by UTE.

around 19 m/s are obtained in this zone for the last four rows of resistors, as is shown in Fig. 13.

The resistors' temperature values obtained for configuration C are compared with the previous configurations in Fig. 14. Lower temperatures are obtained for every row. The reduction of the number of holes generates an increment of the local velocity of the jets impinging at the first rows, which enhance the local heat transfer there. The new holes placed at the end of the first shield creates new jets, provoking a more effective cooling effect of the fourth and fifth rows. The last rows present the most noticeable temperature reduction, because of the high local velocities generated between resistors. The minimum resistor temperature is reached at the sixth row, probably due to the combined effect of the incoming jets and the high local velocity between resistors.

Finnally, the proposed geometry was tested by UTE. Experimental results show that the resistance variation in the 1024-V

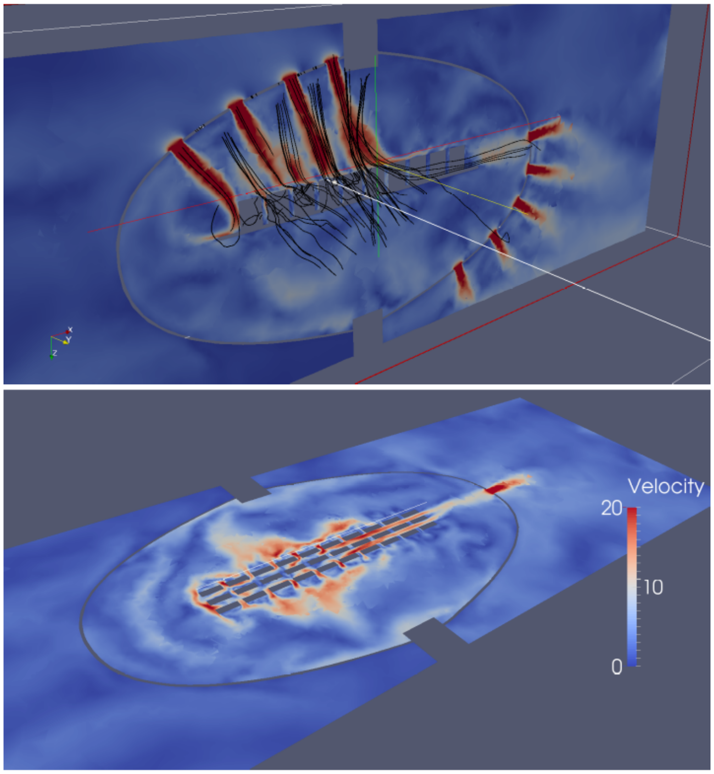

Figure 13: Instantaneous velocity field.

divider applying 1000V was reduced from more than 35 $\mu\Omega/\Omega$ using configuration A, to 19 $\mu\Omega/\Omega$ using configuration C, satisfying the requirements.

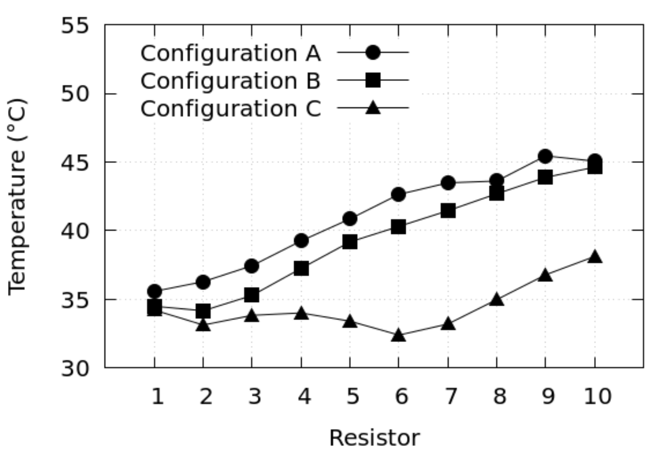

Figure 14: Temperature distribution of the resistors for configuration B. Numerical results computed using TermoFluids [5] and experimental results provided by UTE.

CONCLUSION

The aim of this work was to improve the cooling system of a high-precision high-voltage resistor in order to minimize variations of it resistance. The resistors are collocated at the center of two symmetric cone-shaped electrostatic-shields. Air is forced to flow through a set of holes placed at the shields to refrigerate the resistors. In the present work different configurations of holes were tested using CFD&HT techniques, the best of which consisted of one with a smaller number of holes with a particular distribution. It was verified that a reduction of the number of holes produces a reduction of the total air flow. However, higher local velocities were observed near the resistors, resulting in higher cooling and temperatures being in an acceptable range. Compared with the original configuration of holes, simulations proved that for the proposed geometry a more uniform temperature distribution is reached. Last experiments showed a reduction of 45 % of the resistance variation.

ACKNOWLEDGEMENTS

The authors acknowledge the collaboration of Sergio Teliz for the construction of resistances, and Carlos Faverio and Leonardo Trigo for the tests, all of them from UTE. The authors also wish to thank TermoFluids S.L. for the permision to use the TermoFluids software.

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