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PRELIMINARY THERMAL AND ACOUSTIC DESIGN OF SHELTERS FOR HIGH-VOLTAGE ELECTRICAL EQUIPMENT THROUGH NUMERICAL MODELLING

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ABSTRACT

The constant development of the electric power grid addresses the needs deriving from the growing use of renewable sources and the dispatching flexibility required by mobility electrification. New infrastructures to control the grid parameters and configuration are also being installed in the urban environment, generally enclosed to prevent unauthorised access. Such a solution has positive implications since these shelters must, on the one hand, attenuate the potential noise emitted by the equipment inside and, on the other hand, guarantee enough air changes to avoid overheating of the devices that can compromise the performance and security of high-voltage elements. Hence, cooling and sound insulation must be properly integrated during the design phase of the shelter. This paper presents a feasible, dual and synergetic strategy of acoustic and thermal simulation applicable to the design of a new high-voltage control system. The proposed solution aims to allow adequate heat dissipation from the high-voltage equipment as well as provide smart noise control measures.

Keywords: *Noise control, High voltage devices, Convective Heat Transfer.*

1. INTRODUCTION

There is a growing need for the production of electricity with time. For various reasons (industrial, heating and personal purposes), it is necessary to provide and transport electricity smartly and flexibly. Thus, the transport of electrical energy has paramount importance and research, be it industrial or academic, has picked up pace.

Distribution of inadequate power is a matter of concern, be it to industrial, commercial [1], [2] or household [3] consumers. It is essential to address the issue of a judicious distribution of power between commercial and industrial centres in an urban environment, based on real-time power demands. A device was needed which would redirect power to both of the above classes of consumers depending on their needs. This device, Compact Sorter on Pole (CSP) has been developed by Terna Rete Italia S.p.A., and still needs to address concerns of heat dissipation and noise production before it is deployed on the field.

For safety reasons, CSP is placed inside a shelter confined by solid walls and this shelter is placed under an electrical trellis [4]. The device emits heat and the walls pose a potential problem not allowing the heat to be properly dissipated, which can lead to malfunction of the device. One solution to deal with overheating is to realise openings in the walls to allow cooling through fresh air intake from the outdoor environment. However, this poses the problem of an improved propagation of noise produced by the device which, in urban environments, can create an issue from the noise pollution point of view [5].

This study deals with the dual and opposing problem of heat dissipation needs and noise propagation abatement. Challenges include choosing the material and thermal

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properties of the walls, their thickness, and the locations and dimensions of the openings. Numerical thermal and acoustic simulations have been carried out. The thermal simulations were made using COMSOL 6.1 with pre-defined airflows, heat powers of the devices and external temperature. The results of the thermal simulations have been used to run acoustic simulations in SoundPLAN 8.2. This series of numerical experiments, a detailed extension of the work [6] earlier done, aim to provide the thermal and acoustic objectives which can be realistically satisfied and provide insights before suggesting feasible solutions.

Section 2 will help in revisiting the theoretical background required before the numerical modelling, summarised in Section 3. Section 4 discusses the results of the thermal simulations in COMSOL 6.1 whereas Section 5 shows the results of acoustic simulations. Section 6 discusses the results. Finally, Section 7 contains the concluding remarks and the work which can be further done to improve and optimise the final solution during the installation phase of CSP.

2. THEORY

2.1 Thermal aspects

First, revisiting the theory required for the numerical modelling performed in this study is advisable. Since the simulations are thermal and acoustic, going through a few fundamental concepts and equations would help in understanding the steps performed later. To be more general, the total heat flow in this study is due to convection and conduction, and the steady-state equation describing it is,

$$\rho C_p(u \cdot \nabla T) - \kappa \nabla^2 T = q'' \tag{1}$$

where ρ is the density of air, C_p is its specific heat capacity at constant pressure, u is the velocity of air, T is its temperature, κ is the thermal conductivity and q'' is the volumetric specific heat flow.

Among the three modes of heat transfer, the primary one in this simulation is convection. As seen later in the results section, the temperatures achieved are not high enough for considering radiation between surfaces. Conduction does not occur from solid to fluid due to the latter being in motion. Also, the solid CSP surfaces inside the domain produce heat due to the electrical processes occurring in them, and conduction from one component to another does happen.

From preliminary calculations, natural convection is not a feasible way for cooling the devices in the shelter. Being this study pilot, it was assumed that the air enters the domain with a fixed speed, implying forced convection of heat transfer at play. The purpose of the moving air is to transfer heat away from the components, and hence the equation governing this phenomenon is,

$$W = hA(T - T_0) \tag{2}$$

where h is the heat transfer coefficient in forced convection, W is the heat transferred per unit of time, A is the area of the solid surface on which convection takes place, T is the temperature of the solid surface and T_0 is the local temperature of the air flowing around the "hot" surfaces.

2.2 Acoustic aspects

The electrical components inside the box consist of three switches that produce noise. One of the primary reasons behind the installation of the shelter around the electrical components is safety. Moreover, for aesthetic reasons, a second set of external panels will be used to mitigate the visual impact of the installation. As seen later in this study, a fan is also used to obtain forced convection. This fan acts as an additional noise source.

The switches in the compound have a certain sound power level (L_w), which is given as an input variable in this study. The sound pressure level (L_p) due to the direct sound field and reflected sound field inside the box is given as [7],

$$L_p = L_w + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{R^*}\right) \tag{3}$$

where r is the distance from the sound source to the point of interest, Q is the directivity index, a dimensionless number and is equal to unity here since the source is suspended in air, and R^* is the room constant:

$$R^* = \frac{A}{1-\alpha} \tag{4}$$

Where A is the sound absorption area inside the enclosure and α is the average sound absorption coefficient of the surfaces limiting the volume.

The total sound pressure level at a point is obtained by the superposition of sound pressure levels from all the sources as well as the reflected waves from the walls.

The internal walls absorb a part of the acoustical energy impinging on it and reflect the rest back. A part of this absorbed energy is transmitted through the wall. The net reduction in sound energy through the wall is, under standard conditions, a characteristic of the material and geometric properties of the wall, known as the sound reduction index (R).

$$R = 10log_{10}(\frac{W_i}{W_t}) \tag{5}$$

where W_i is the incident sound power on the wall and W_t is the transmitted sound power through that wall.
It is thus necessary for the walls and aesthetic panels to have proper sound reduction indices. However, this is usually led by heavier, thicker, and more expensive walls and a trade-off is required coming to the selection of the material and geometric properties of walls.

3. MODELLING

3.1 Real-life scenario

Before studying the modelling of the system in the software, it is important to study real-life conditions. These would act as requirements for the numerical modelling to be satisfied. The requirements presented in real-life consist of a box, a cube, having 8m long sides. The electrical components will be placed inside, with electric cables originating from some electrical components. The description of these elements is outside the scope of this study. To facilitate heat transfer, inlets, and outlets are cut on opposite sides of the box. Due to the outgoing air being hotter than the incoming air, the outlet is located higher than the inlet. The position of the electrical components and that of the inlet and outlet as well as their dimensions are not prescribed, hence granting more flexibility to this study.
The shelter is placed outdoors and hence factors such as wind speed, humidity, solar radiation, temperature fluctuations, etc should be considered in this study. Another factor to consider is an aesthetic panel, which is to be placed outside the box considered in this study. This element consists of a set of four panels used to mitigate the visual impact of the installation. The aesthetic panels will not be considered since their main effect in the thermal simulations is shielding the shelter from solar radiation and wind. Since this contribution is already neglected and the simulations simply rely on the temperature of the air at the inlet, this simplification is not considered to be influencing the design of the shelter during this preliminary phase. However, since the acoustic simulations must consider elements that act as noise barriers or sound sources, the aesthetic panels and the ventilator will be considered in SoundPLAN.

3.2 Numerical modelling

3.2.1 Thermal aspects

In order to properly take into account, the heat dissipation from the surface of the electric components, it was necessary to draw their external shape in SolidWorks. This 3D model was then exported to COMSOL, where the inner air volume of the shelter was modelled. It is important to point out that no solid domain is present in COMSOL, but only the fluid inside the box is modelled. To do so, the electrical components were subtracted from the air domain. The relevant heat powers were assigned to the surfaces so produced. The heat dissipation effect of the solid walls delimiting the shelter will be added in future simulations.
The air inlet is rectangular with dimensions 6.5 m x 6.5 m and its centre is located 2.25 m above the ground. The outlet is rectangular, with dimensions 7 m x 0.5 m and it is placed 7.25 m above the ground. The dimensions were chosen to assure a minimum number of air changes inside the shelter of 27 changes/hour with an air speed of 1.2 m/s. The electrical components are positioned at a minimum height of 0.6 m from the bottom surface. A picture of the geometry implemented in COMSOL is shown in Figure 1.

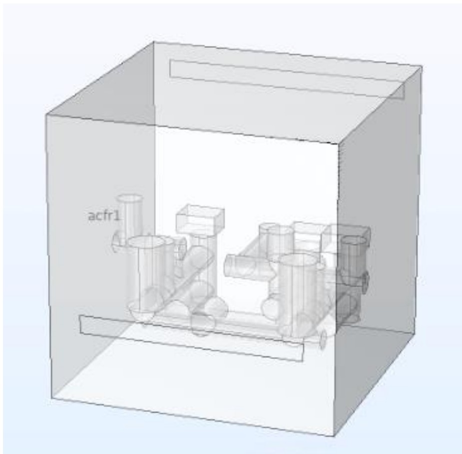

Figure 1. Three-dimensional model of the geometry implemented in COMSOL.

A total of two *Physics* were considered suitable for this study, "Turbulent Flow, Realizable $\kappa - \epsilon$(spf)" and "Heat Transfer in Solids and Fluids (ht)". A turbulent flow physics is chosen as the flow inside the box becomes easily turbulent. The Reynolds number[8] at the opening of the inlet is,

$$\mathrm{Re} = \frac{1.2 \times 4 \times \frac{0.5 \times 6.5}{2 \times (0.5 + 6.5)} \times 1.246}{1.778 \times 10^{-5}} \approx 78000 \tag{6}$$

where U_0 =1.2 m/s is the inlet air speed, 0.5 m is the height of the inlet and 6.5 m is the length of the inlet. The air temperature at the inlet is set to 10° C.
A $\kappa - \epsilon$ SST model was chosen as the flow behaviour away from the walls is to be investigated with the greatest accuracy

and precision [9]. To simulate the presence of walls, a no-slip condition is imposed on the surfaces of the shelter.
At the outlet, a static gauge pressure of 0 Pa is assigned, with no backflow. All the surfaces, except the inlet and the outlet, are assumed to be adiabatic. The electrical components' heat powers are modelled to be uniformly distributed across the specific components. The total heat power emitted by all the components is 3279 W.
A *Multiphysics Coupling* with *Non-isothermal Flow* is also applied to the model. The Boussinesq approximation [10] is made to simplify the computational cost and emphasise the role that buoyancy plays in heat transfer.
The mesh used for the fluid domain has elements with dimensions varying between 0.16 m and 0.536 m , whereas the element size used for the inlet and outlet ranges from 0.0016 m to 0.16 m. All the other wall surfaces and the surfaces of the cavity of the electrical components have elements ranging in size from 0.032 m to 0.296 m. The smallest dimension of a sub-component has been found to be 40 mm. Hence, boundary layers have a specialised mesh setting, with a first layer minimum thickness of 5 mm, to accommodate at least eight elements, and consisting of at least five layers.

3.2.2 Acoustics aspects

The acoustic simulations can afford to accommodate all the elements used in the real case. A test scenario was considered for the deployment of the CSP system. The CSP system is placed at Concesio, in the outskirts of Brescia, Italy, as shown in Fig. 2.

Figure 2: Map of the neighbourhood considered for the acoustic modelling. The blue square in the middle is the CSP shelter.

The electrical components are installed with aesthetic panels [11] surrounding the shelter at a distance of 0.5 m outside it. An axial fan is installed between the aesthetic panel and the box, at a height of 0.5 m, inlet side.
The ground floor of the shelter is modelled as concrete, whereas the four facades and the roof as 40 mm thick mineral wool mats, with a density of 20 kg/m^3, sandwiched between two perforated 1 mm thick steel sheets. The roof will be designed with particular care [12] to avoid noise leakages through its structure and the cable openings. Fig. 3 shows the sound absorption spectra of these elements. The aesthetic panels are modelled as simple panels acting as noise walls, but with no sound absorption properties.

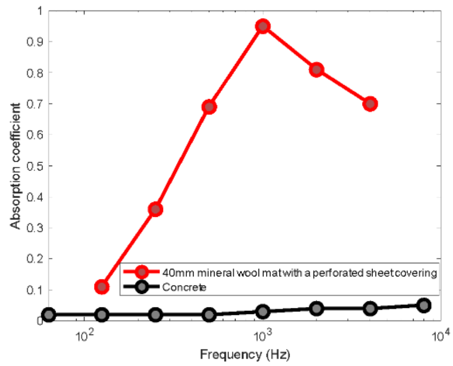

Figure 3: Absorption coefficient of 40 mm thick mineral wool mat, with density 20 kg/m^3 with 18% perforated sheet covering (red) and concrete(black).

In Fig. 4, the sound reduction index of the panels used to simulate the main walls of the shelter is displayed. Fig. 5 shows the sound power levels used for the fan and the switches.

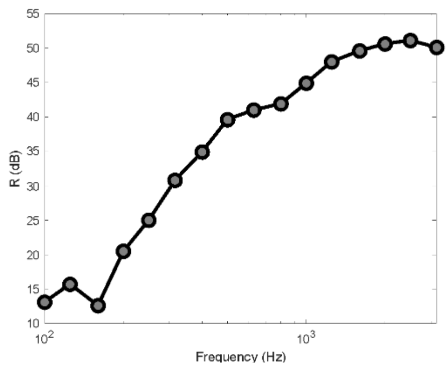

Figure 4: Sound reduction index of 75 mm mineral wool sandwiched between 1 mm steel plates.

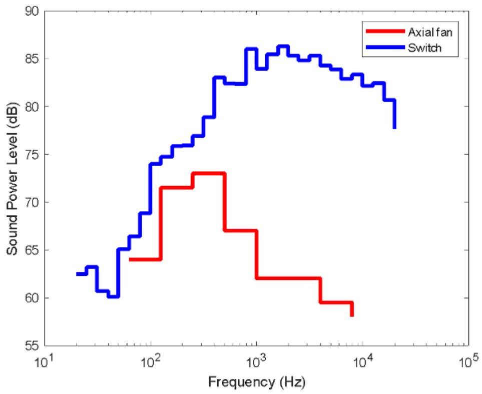

Figure 5: Sound power levels of a switch (blue) and the axial fan (red).

4. THERMAL RESULTS

The thermal simulations are performed in COMSOL. Upon completion, parameters such as airspeed, streamlines, maximum temperature, and the distribution of surface temperature over the electrical components are processed and observed. Fig. 6 shows the streamlines, Fig. 7 shows isothermal surfaces in the shelter whereas Fig. 8 shows the distribution of temperature over the electrical components.

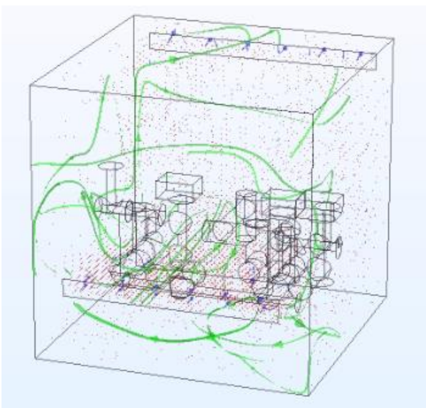

Figure 6: Main volume flow and streamlines inside the shelter.

The maximum permissible temperature of air inside the shelter is 50°C. It can be seen from Fig.7 that the isotherms inside the shelter belong to less than30°C. The temperature of the outlet is nearly the same as the temperature of the inlet. From Fig.6 it can be seen that most streamlines inside the shelter stay at nearly the same height as that of the inlet until it approaches the wall that contains the outlet, at which it turns upwards.

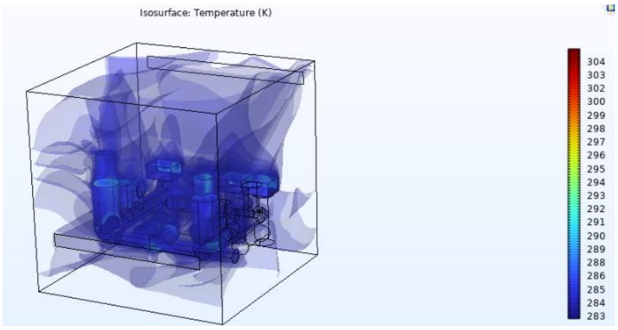

Figure 7: Isothermal surfaces inside the shelter.

The maximum permissible temperature of air inside the shelter is 50°C. It can be seen from Fig.7 that the isotherms inside the shelter belong to less than 30°C. The temperature of the outlet is nearly the same as the temperature of the inlet. From Fig.6 it can be seen that most streamlines inside the shelter stay at nearly the same height as that of the inlet until it approaches the wall that contains the outlet, at which it turns upwards.

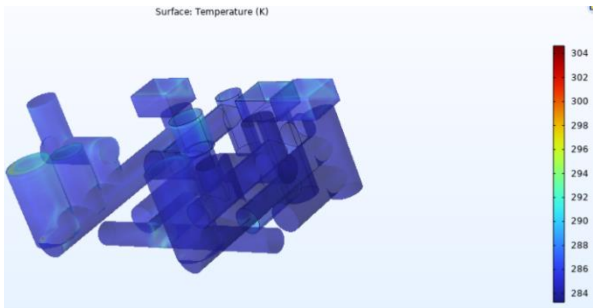

Figure 8: Temperature distribution over the electrical components.

5. ACOUSTIC RESULTS

The acoustic simulations are computed in SoundPLAN. This set of simulations consists of calculating the noise map inside the shelter first (Fig. 9). This noise map is obtained at a height of 2.25 m above the ground, at the same height as that of the inlet opening. The grid space is 0.25 m. SoundPLAN module “in-out” can automatically compute the amount of noise spread by the panels of the shelter and by the openings. The inlet opening can be equivalently modelled as a source with an overall L_W=87.6 dB, while the outlet can be equivalently a model with an overall L_W=90.5 dB.

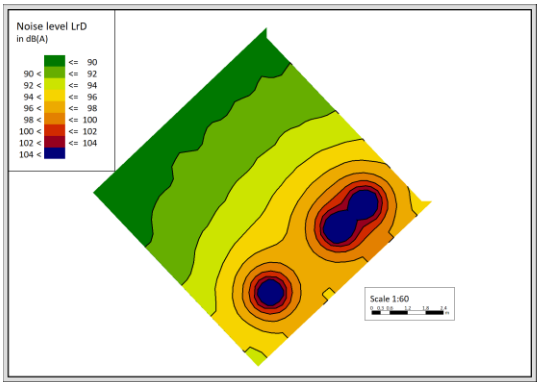

Figure 9: Noise map inside the shelter at a height of 2.25 m from the ground.

The next step is to compute the noise map for the domain outside the shelter considering the sound reduction index of the walls and the presence of the aesthetic panels. The effect of the aesthetic panels is considered only accounting for the diffraction of the upper edge. This noise map is shown in Fig. 10. The grid space is 10 m and is obtained at 2 m above the ground.

It can be seen in Fig.10 that although sound is to propagate following the semi-hemispherical model of propagation in a semi-free field, the presence of various obstacles, mainly in the form of buildings and roads, disturb the sound field. A thicker boundary in the vicinity of the shelter is marked, which denotes the locations where the sound pressure level is 36 dB(A).

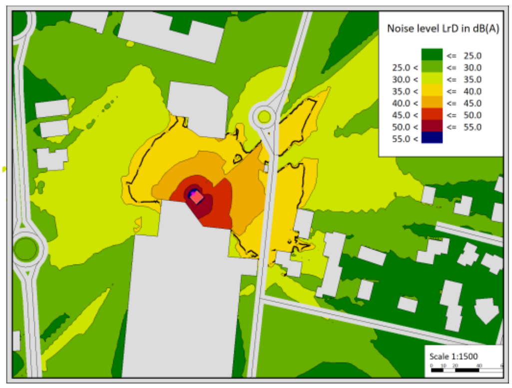

Figure 10: Noise map of the area surrounding the shelter at 2 m above the ground.

6. DISCUSSION

6.1 Thermal aspects

All the inlet height had been chosen such that air supplied by the fan impinges on the hottest electrical sub-components, as the highest temperature achieved inside the shelter is 31 °C, at the component located in front of the inlet. The maximum temperature thus reached is within the safety limits for the functioning of the components.

It can be deduced that high temperatures are reached in locations where the geometrical smoothness is disrupted, i.e. in places with surface boundaries, either within the sub-components or at the boundaries of two sub-components. Hence, bolstering the thermal properties of the materials at the boundaries and ensuring an increased flow of heat at the boundaries can be potential paths for thermal treatment.

6.2 Acoustic aspects

Looking at the sound pressure level inside the shelter (Fig. 9) it reaches a maximum value of 107.4 dB(A). However, at the inlet the L_p decreases to 88.0 dB(A). Overall, the south-eastern wall transmits more noise than the north-western wall out of the aesthetic panels, mainly due to two reasons: a) the sources inside the shelter are located closer to the south-western wall is higher, and b) the axial fan located outside the shelter has a sound power level less than more than 10 dB than the equivalent sound power level at the inlet opening. This also leads to the observation that the choice of the axial fan can be made ignoring its noise rating as long as its sound power level (L_W) is less than 3 dB lower than the equivalent L_W of the inlet.

The noise map outside the aesthetic panel looks dominated by the reflection of the wall to the south of the aesthetic panels. The sound pressure level outside the aesthetic panels is the highest in the immediate vicinity of the panels on the outlet's face (62.1 dB(A) at 1 m from the aesthetic panel). The L_p drops below 36 dB(A) 20 m east from the shelter, 13 m north from the shelter and 11 m west of the shelter. A value of 36 dB(A) can be considered a low sound pressure level, that is close to the background noise level in most contexts.

7. CONCLUSIONS

The maximum temperature achieved is within the safety limits of the electrical components for the given volume flow of air and ambient temperature. However, a well-planned optimisation is required to minimise the temperature inside the shelter for lower volume flow and higher ambient temperatures. This can include the optimisation of the location of the inlet and outlet and a trade-off between

lowering the volume flow of air and optimising the forced convection of heat.
To arrive at the optimised scenario, further additions to modelling are required. These include considering walls that allow conduction and radiation, inserting the aesthetic panels outside the shelter for the thermal simulations and modelling solar radiation.
The noise maps look acceptable when considering distances at least 15 m from the aesthetic panels. Luckily, no buildings can be built at distances lower than 25 m from the installation. However, it must also be kept in mind that the acoustic simulations done in this study are for the switches operational 100% of the time, day and night. This is unlikely to happen in the real case as the purpose of the switches in the electrical components is to activate in case any change in the distribution of the current flow is required.
Yet, further control of noise is possible with passive or path treatment, particularly by improving the sound reduction index of the shelter or increasing the sound absorption characteristics of the aesthetic panels. An effective way can be to design the walls such that the sound reduction index is high at the frequencies where the outlet opening, in particular, gives its highest contribution.

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