Study of the thermally-induced shell deformation of high amperage Hall-Héroult cells

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ABSTRACT

It has been previously demonstrated [1] that there is no obvious thermal balance related issue limiting the size of a Hall-Héroult cell. Yet, it is well known that a forced-air sidewall cooling system is part of the AP50 cell design [2].

In the present study, the authors analyze the impact of thermal loading on the mechanical deformation of high amperage cell potshells. The effect of adding cooling fins or a forced-air sidewall cooling system is then assessed.

INTRODUCTION

It seems that the 20th century trend towards the regular introduction of new cell designs of higher and higher amperage has considerably slowed down in recent years.

The AP30 cell design, the last major step in this evolution, is now more than 15 years old. The aluminum industry, in order to maintain the momentum of the last century, should already be using the AP50 or a similar technology for its current greenfield smelter projects.

It is true that new high amperage cell designs in the 250 to 350 kA range are now emerging in China and Russia for example, challenging the 15 years dominance of the AP30 as the obvious technology for greenfields. However, the 500 kA mark still seems to be out of the question in the near future.

One might argue that just as the Moore Law will eventually hit the quantum mechanics physical barrier in the computer industry, a similar barrier has already stopped the aluminum industry in its effort to continuously produce higher amperage cell designs.

If it is the case, it has been clearly demonstrated in [1] that if there is a limit, that limit is not related to the cell heat balance aspect of the cell design.

With its width to length aspect ratio, a 300 kA potshell dissipates less that 20% extra heat in its end walls as compared to its sidewalls. This in turn represents not much more that 10% of the global heat dissipated by the cell. A simple reduction of 10% of the cell current density, for example from 0.73 A/cm^2 to 0.65 A/cm^2, would be sufficient to allow the operation of an infinitely long cell with the exact same lining design while preserving a perfect thermal balance.

On the MHD cell stability aspect, as the cell gets longer and the return line influence increases, minimizing the longitudinal gradient of the Bz component of the magnetic field is certainly becoming more challenging. Yet the magnetic compensation techniques (asymmetric busbar, compensation loop, further extension of the return line location, etc) are not loosing their efficiency as the cell amperage increases. Some very well established MHD experts argue that there is a MHD barrier to the continuous increase of the cell amperage, other are not so sure.

Even if the jury is still out on the possible existence of an MHD related cell amperage limit, there is no indication that we are currently near that limit as it was not that difficult to find a stable cell busbar configuration in order to produce a demonstration 500 kA cell design [3].

MECHANICAL ASPECT OF THE CELL DESIGN

The thermo-mechanical response of the cell results from complex interactions between the refractory lining and the steel shell. The lining expands thermally, but some materials – prebaked carbon and ramming paste for instance – may also experience irreversible deformations like chemical swelling and contraction, plastic deformation, creep, etc. [4,5]. The shell also expands thermally, and it may also deform plastically. The confinement provided by the shell must be able to keep the lining in compression while avoiding cracking of the cathode blocks.

The mechanical aspect of designing a high amperage cell with a length to width aspect ratio of 4 or more is not well covered in the literature. When a potshell reaches a given length, its vertical deformation due to the presence of thermal gradient in the sidewalls starts to affect the cell operation. The difference of level between the middle of the shell floor and its corners leads to a metal pad of varying depth. This in turns may have a notable effect on the local temperature distribution in the lining, contributing to the “cold corner” effect.

This problem of vertical potshell deformation in high amperage cells is significant enough to induce some smelters to take active measures in order to reduce its impact. Two of such measures are the usage of cooling fins and that of forced-air sidewall cooling system. Contrary to the “popular belief”, those two measures are not affecting the cell heat balance, since cooling the sidewall temperature simply induces the cell to grow more ledge in order to maintain its steady-state superheat and hence global heat loss. However, these measures not only reduce thermal gradients in the shell wall but also reduce the temperature in this area. This helps the steel retain its strength [6] and reduces creep in the shell wall.

In the present study, the efficiency of the cooling fins and the forced-air sidewall cooling system to reduce the vertical deformation of the potshell in operation has been analyzed for 300 and 500 kA cell designs.

FINITE ELEMENT MODELING APPROACH

As mentioned previously, the prediction of the mechanical response of an operating cell is a challenging task. As a first approximation and for comparison purposes, a simple “Empty-Shell” modeling approach was used [7].

A quarter shell was modeled using four-nodes quadrilateral Finite Strain shell elements (*SHELL181*) in the commercial code ANSYS. The corresponding symmetry boundary conditions were imposed, while one point was supported in the vertical direction on the second closest cradle to the end wall. A constant downward pressure was applied on the shell floor to represent the combined weight of the lining and the liquids. A constant outward pressure was applied to the shell wall opposite to the cathode block to represent the effect of the lining expansion. The cradles were considered welded to the shell.

The temperature distribution obtained from the full cell coupled thermo-electric model was applied as a body load to the shell and cradles [8].

A temperature-dependent isotropic hardening von Mises plasticity law with non-linear hardening was used (the *MISO* option in ANSYS). The stress-strain curves at different temperatures were obtained from [9]. Time-dependent phenomena such as creep were neglected.

The non-linear finite element problem was solved in 100 load steps. Each step required typically 4 Newton-Raphson iterations. The linearized system was solved using an iterative preconditioned conjugate gradient solver (the ANSYS *pcg*).

Six cases were modeled:

Amperage (kA)	Enhanced Cooling Measure
300	None
300	Fins
300	Forced-air
500	None
500	Fins
500	Forced-air

IMPACT OF MESH REFINEMENT

It is well known that the element size has a strong impact on the accuracy of a finite element solution. The adequate size is however physics-dependent. In a mechanical simulation using a non-linear constitutive law, for example plasticity, the response is strongly dependent on the strain level, which is obtained from the displacement gradient. Finer meshes are therefore required compared to a thermal simulation.

Figure 1 compares the vertical displacement on the long axis of the shell floor for the initial mesh (Figure 2a) and for a refined mesh (Figure 2b) of the 300 kA cell without cooling enhancement measures. It is quite obvious that the initial mesh was inadequate for the mechanical analysis, as the maximum displacement is almost twice as large for the coarser mesh.

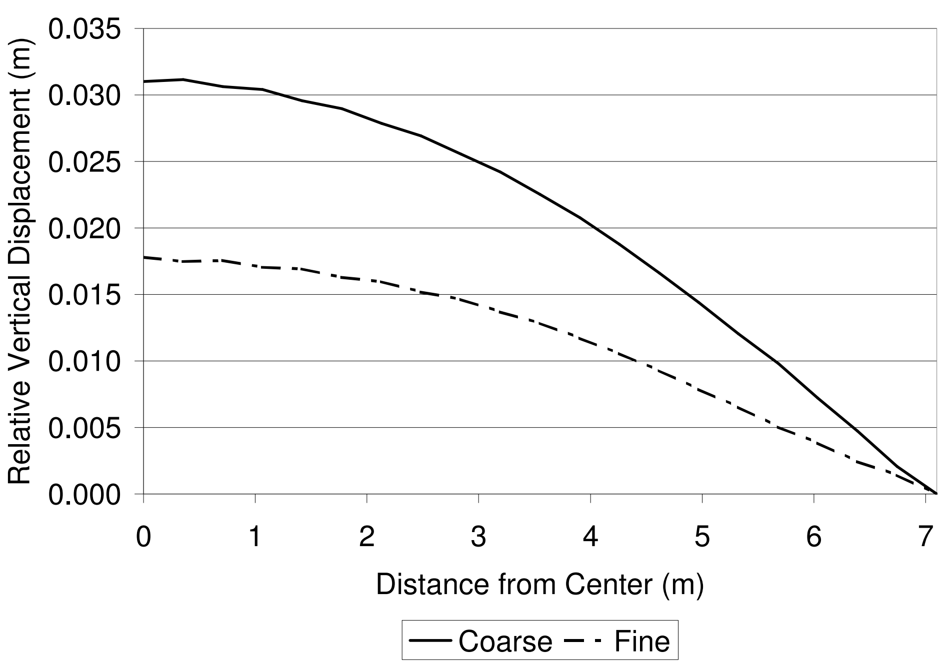

Figure 1 – Vertical displacement on the 300 kA cell shell floor on the long axis

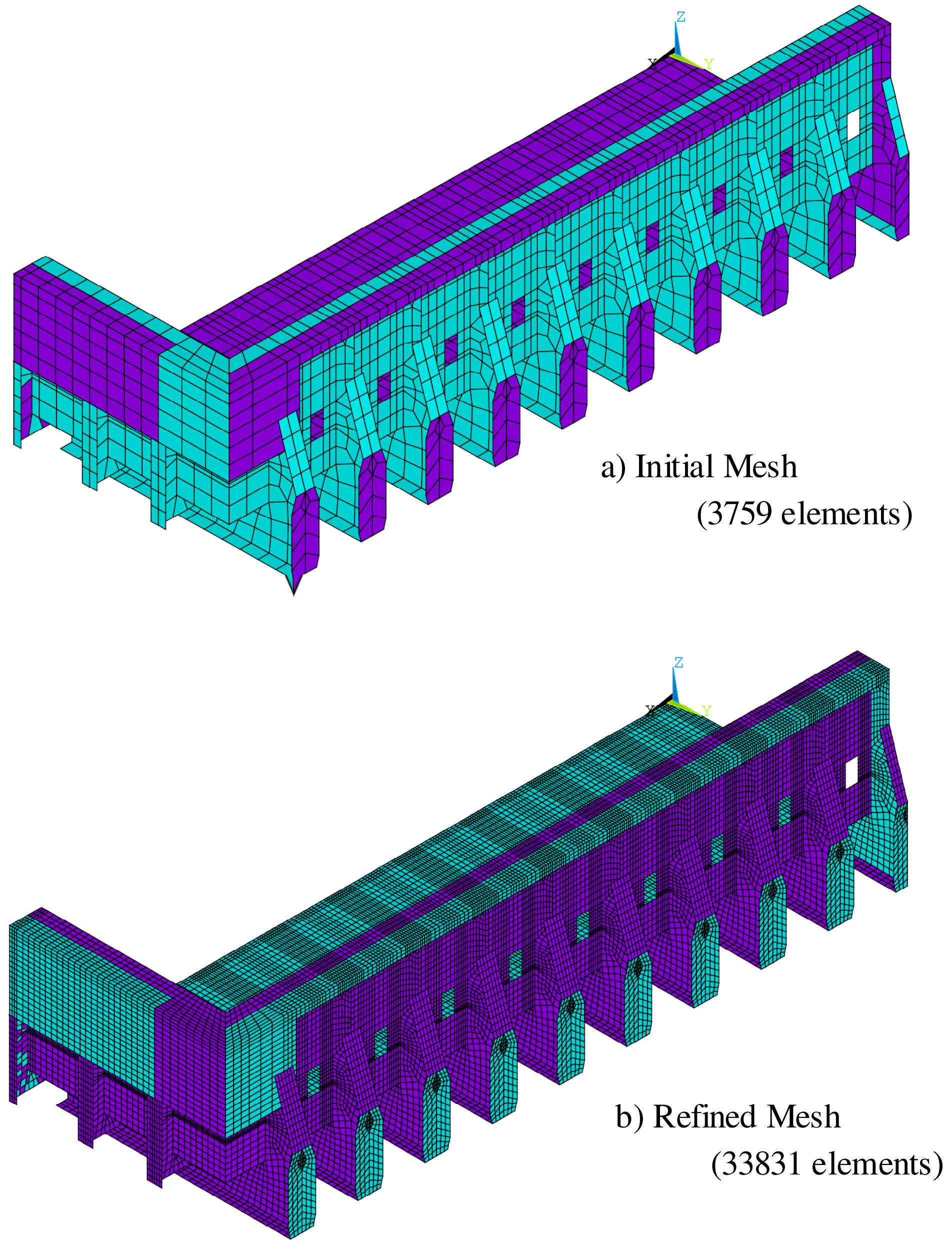

Figure 2 –Initial and refined meshes for the 300 kA base case

Figure 3 shows the typical sidewall von Mises stress distribution and corresponding equivalent plastic strain. A significant portion of the lower sidewall is plastically deformed. The coarser mesh cannot adequately capture the plastic deformation of the sidewall, which leads to an overestimation of the stiffness of the structure.

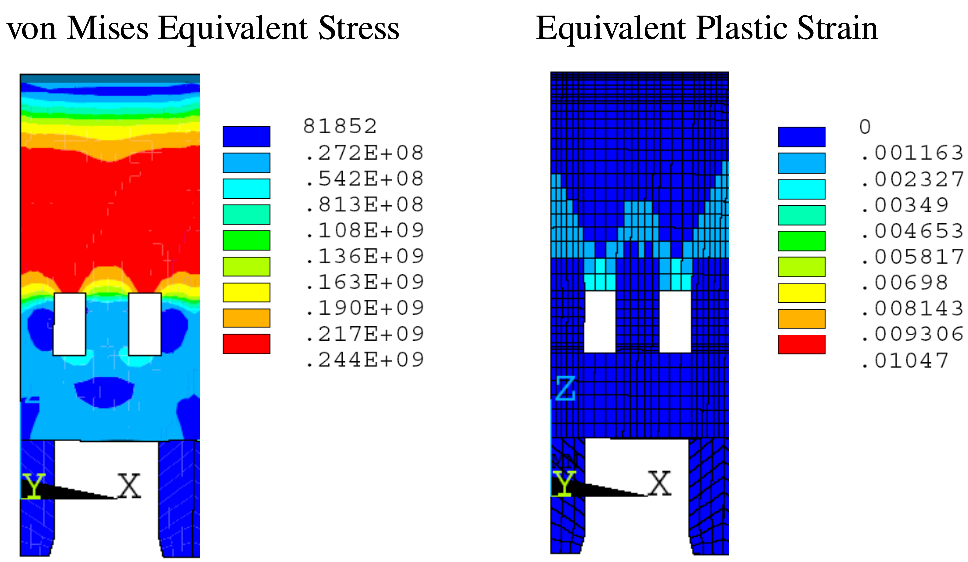

Figure 3 – Typical sidewall von Mises stress and equivalent plastic strain for the 300 kA base case

The non-reinforced top portion of the cradle is also quite flexible in this design and bends in plane due to the sidewall thermal dilatation, as shown in Figure 4. The ANSYS manual [10] recommends at least four elements in the direction of bending for these members. This effect was therefore not adequately captured with the initial coarse mesh, once again overestimating the stiffness of the structure. A refined mesh was therefore used for all the subsequent analyses.

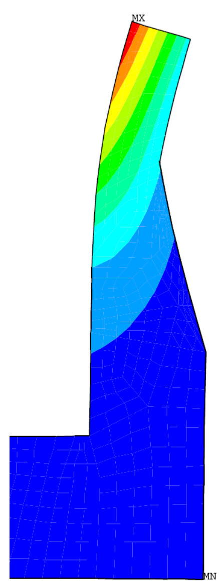

Figure 4 – Amplified typical deformed shape of a cradle, showing in plane bending

300 kA CELL RESULTS

The obtained temperature distributions are shown in Figure 5a) for the 300 kA base case, Figure 5b) for the cell with fins, and Figure 5c) for the cell with forced-air cooling. The fin configuration used in Figure 5b) reduces the temperature gradient in the shell upper sidewall, but slightly increases it just above the collector bars. This surprising side effect will have an impact on the mechanical displacement as will be seen later. The forced-air cooling in Figure 5c) is so effective that the maximum shell temperature is now on the floor.

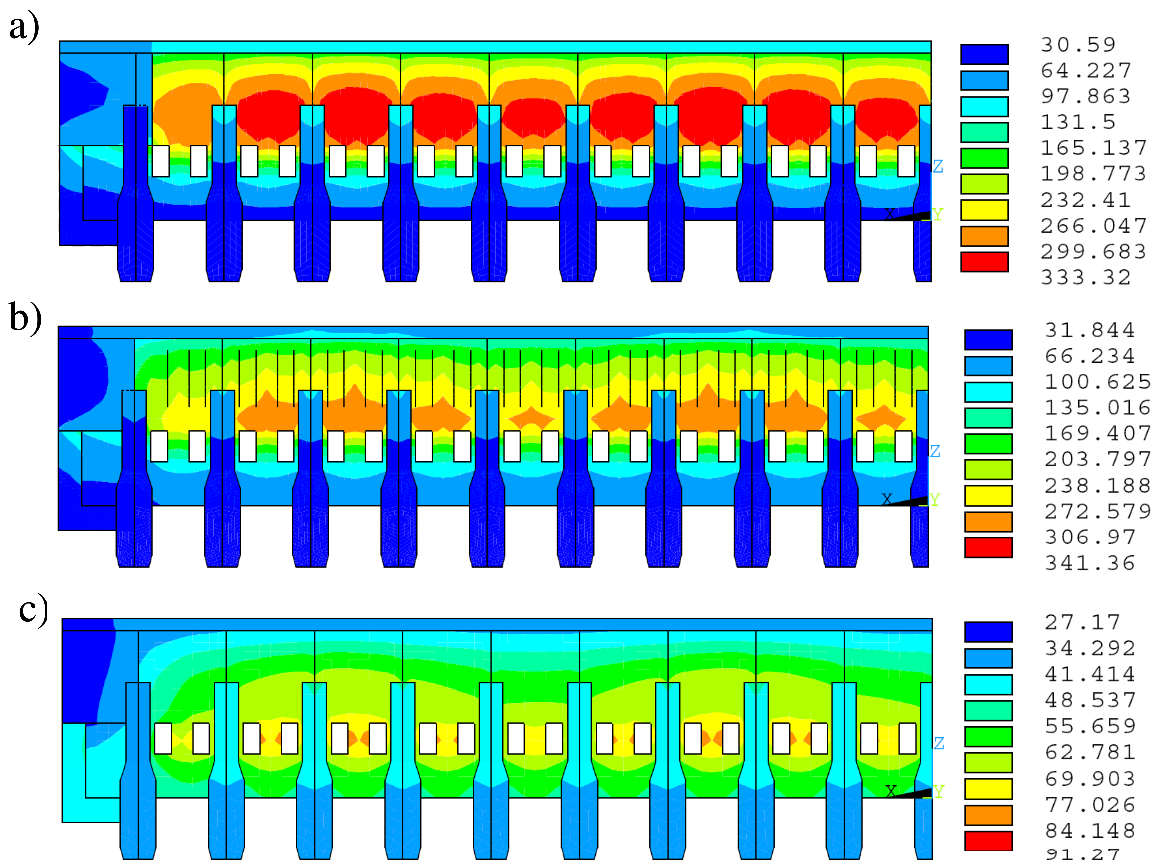

Figure 5 – Temperature distribution for the studied 300 kA cell configurations

The vertical displacement on the long axis of the shell floor is compared for all three cases in Figure 6.

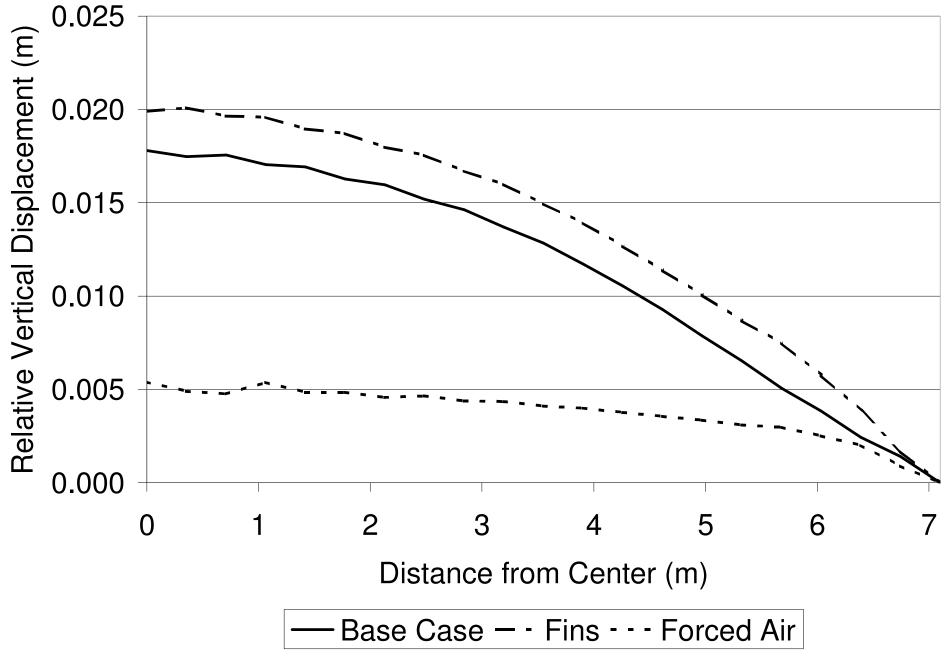

Figure 6 – Comparison of the relative vertical displacement on the long axis of the 300 kA cell

Surprisingly, the fins increase the vertical relative displacement. As mentioned previously, the temperature of the lower shell sidewall is slightly higher, partially compensating for its reduction in the upper sidewall. However, the increase in stiffness provided by the fins – acting as reinforcement – is the most important factor. The reduction in plastic deformation is also significant, as seen in Figure 7 (also refer to Figure 3 to compare with the base case). The most effective measure is therefore using forced-air cooling.

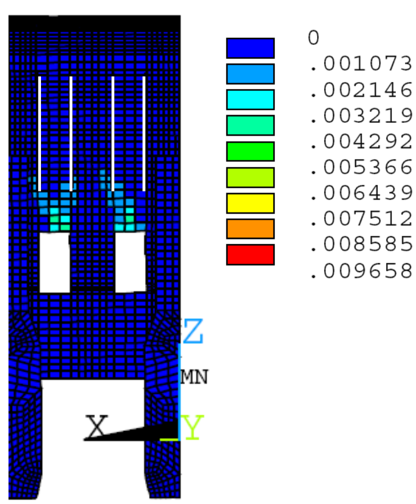

Figure 7 - Equivalent plastic strain for the 300 kA cell with fins

500 kA CELL RESULTS

The obtained temperature distributions are shown in Figure 8a) for the 500 kA base case, Figure 8b) for the cell with fins, and Figure 8c) for the cell with forced-air cooling. The fin configuration used in Figure 8b) reduces the temperature gradient in the shell upper sidewall and its maximum temperature. Like in the 300 kA case, the forced-air cooling (Figure 8c) is so effective that the maximum shell temperature is now on the floor. This time however, the difference between the shell floor and the sidewall temperatures is larger than in the 300 kA case (Figure 5).

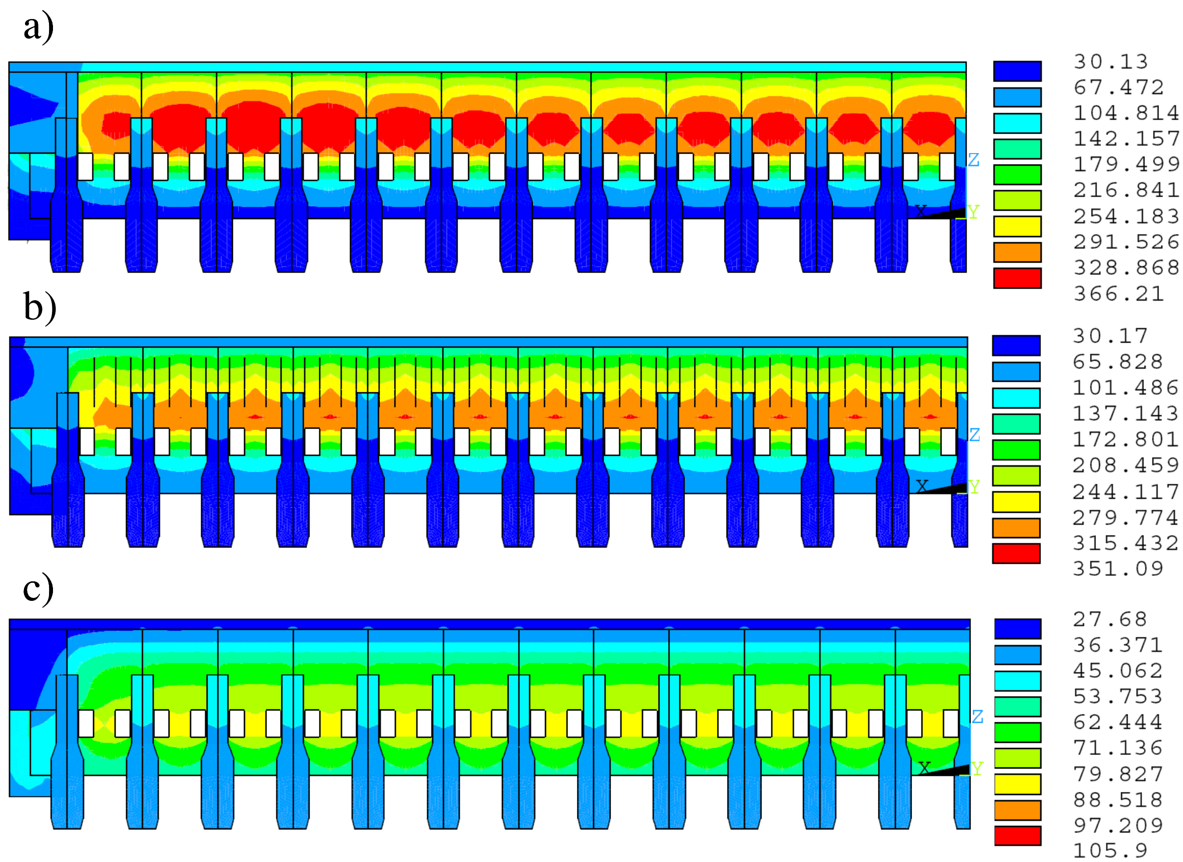

Figure 8 - Temperature distribution for the studied 500 kA cell configurations

The vertical displacement on the long axis of the shell floor is compared for all three cases in Figure 9.

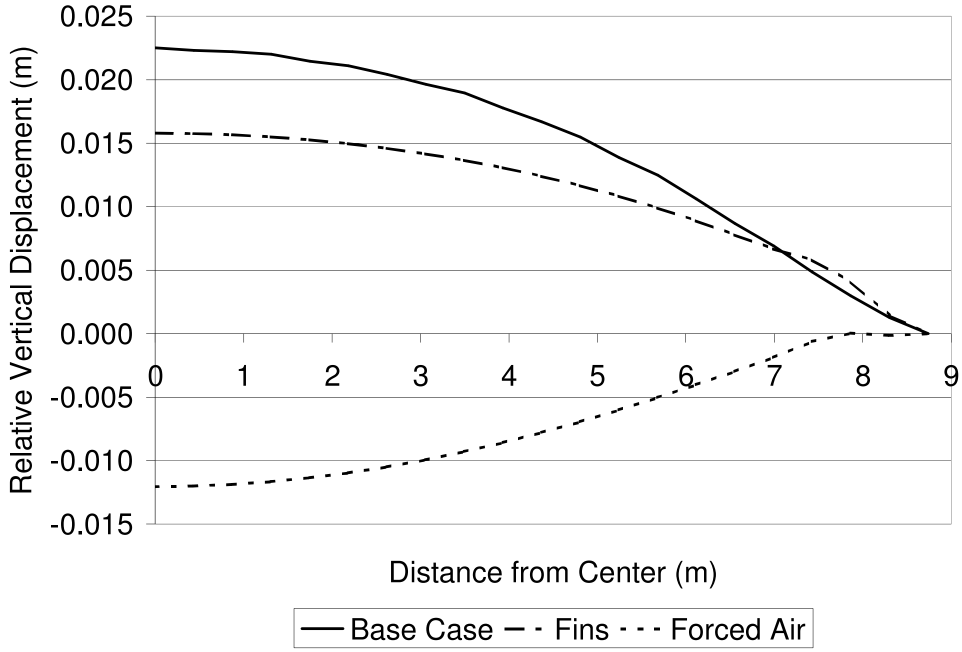

Figure 9 – Comparison of the relative vertical displacement on the long axis of the 500 kA cell

For this cell configuration, the effect of the temperature gradient and maximum temperature reduction provided by the fins (Figure 8b) is almost completely overshadowed by the increased wall stiffness. Once again, the forced-air cooling is the most effective measure. In fact, it is too effective, resulting in a net displacement of the same order of magnitude, but downward. The larger temperature difference between the shell floor and sidewall is a likely explanation, given that the bending of the sidewall is now about their intersection, as seen by the stress distribution shown in Figure 10. The cradles are very stiff at this location, limiting the in plane bending.

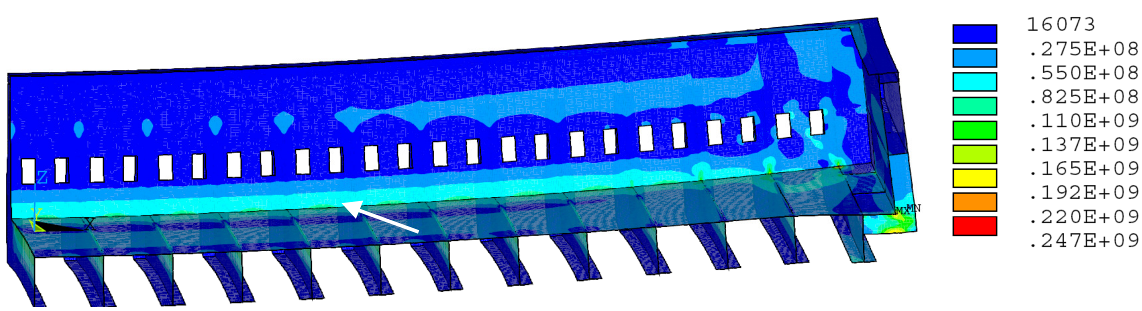

Figure 10 – von Mises equivalent stress distribution on forced-air cooled 500 kA cell

DISCUSSION

It was hinted previously that stiffer sidewalls increase the relative upward displacement due to thermal gradients. Therefore, although cooling fins lower the sidewall temperature and reduce the gradients, they were not effective for the studied shell design.

Furthermore, it is well known that the cradles of the AP30/AP35 are fully reinforced, so their sidewalls will be significantly stiffer than the studied design. The in plane bending showed in Figure 4 will be drastically reduced. It is likely that the magnitude of the relative upward displacement for these cells will be much larger than what has been computed for the 300 kA base case (see Figure 6).

Forced-air cooling was found to be the most effective measure to reduce the relative upward displacement. For instance, it was reduced from 17 to 5 mm for the 300 kA cell (Figure 6). In fact, for the cell at 500 kA (Figure 9), the sidewalls were too cold with respect to the shell floor, leading to a downward relative displacement.

CONCLUSIONS

Simple “Empty-Shell” finite element models were used to assess the impact of two different shell sidewall cooling enhancement measures – fins and forced-air – on the relative upward displacement of the shell floor.

It was shown that a good mesh for thermo-electrical simulations may not be adequate for a mechanical analysis, more so if non-linearities are present. The quality of the global solution depends on the ability to capture local phenomena such as in plane bending and plasticity.

It was hinted that stiffer sidewalls lead to larger relative upward displacements. This is one of the reasons why cooling fins were not very successful in this aspect. Forced-air cooling reduced the relative displacement to almost nil for the 300 kA cell and even caused a downward relative displacement for the 500 kA cell. A proper amount of cooling must therefore be performed to avoid having the shell floor warmer than the sidewalls.

Since it is likely that the magnitude of the relative upward displacement is larger in the AP50 than in the studied design, it is plausible that the forced-air cooling system is primarily used to solve this problem. After all, easier solutions are available to control the ledge thickness of the cell.

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