MASSIVELY PARALLEL FINITE ELEMENT COMPUTING FOR AEROTHERMAL APPLICATIONS

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Summary. The present work focuses on the methods and algorithms that underlie the high-fidelity analysis of Aerothermal problems. Solving such problems involves the coupling of unsteady Navier-Stokes equations and the heat transfer equation on complex geometries. The multiscale nature of the problem, the complexity of the geometry and the unsteadiness of the flow lead to a large-scale problem requiring a large amount of parallel resources. We propose in this work a parallel adaptive finite element scheme that adapts the mesh dynamically with respect to the multiscale variation of the solution. The finite element solution is used to drive the mesh adaptation in a fully parallel way. The proposed framework is used here to run a 3D complex jet impingement cooling system. The computation was executed over more than thousand cores for two weeks.

1 INTRODUCTION

Jet impingement cooling is one of the most frequently used techniques for turbine blade cooling. As a preamble of this complex industrial context, we can note that an important number of investigations of a single turbulent isothermal round jet impinging normally on a hot plate [1,2] have been made during the past few years. In particular, numerical studies have put in lights the important amount of computational resources needed to simulate with high precision this complex aerothermal problem.
The present work focuses on the numerical methods that can solve accurately aerothermal problems on massively parallel computers. Solving such problems involves the coupling of unsteady turbulent Navier-Stokes equations and the Convection-diffusion-reaction heat transfer equation on complex computational domains.
This work is based on our in-house parallel adaptive finite element library, the CimLib [5, 6], which is designed for large eddy simulation (LES) and variational multiscale (VMS) of turbulence in complex domains. Many important thermal transport questions are accessible only through detailed simulations that span the full range of scales set by the geometry and the high Reynolds numbers encountered within a reactor or an airplane engine. Such simulations will require extreme-scale computing resources and highly accurate numerical discretizations to capture the scale interactions that govern the aerothermal behavior of the target problem.

The multi-scale nature of these simulations requires very large anisotropic meshes to capture the small scales. The classical use in the literature is to build a static large mesh at the beginning of the simulation which is not an efficient way to handle the transient problem. Our approach is different from former one and focuses on the design of energy-aware algorithms which are dynamic and adaptive to the multi-scale solutions. We have developed a parallel anisotropic mesh adaptation algorithm that divide the number of degrees of freedom by 100 with respect to the isotropic one while the precision still unchanged [3]. Combining this mesh adaptation technique with unsteady Navier-Stokes solvers remains a challenge in the literature. Moreover, designing an efficient parallel adaptive mesh and solver tools is still also a tough HPC challenge. In this work, we try to meet these challenges and bring some answers in the context of impingement cooling simulations. The next section introduces the case study and discusses and analyzes the results obtained on more than thousand cores simulations.

2 RESULTS AND DISCUSSIONS

As mentioned in the previous section, the present work aims at characterizing numerically the flow field and heat transfer for a schematic but realistic vane cooling scheme (see Figure 1.). The turbine vane is composed by 15 holes on the intrados (lower part), 15 holes on the extrados (upper part) and 9 holes on the semi-cylinder part. In the literature, detailed experimental database of the investigated configuration can be found for both velocity and heat transfer measurements in [4].

From the fluid geometry, we generate unstructured isotropic tetrahedral 3D meshes. In order to test our parallel numerical tools, we propose in this work an incremental space discretization. In fact, 3 meshes M1, M2 and M3 counting respectively 500 000, 7 000 000 and 25 000 000 elements are generated. These meshes are presented in Figure 1. In this figure, we observe that, in order to obtain a homogeneous distribution of the cells inside the geometry, at least 25 million elements are necessary.

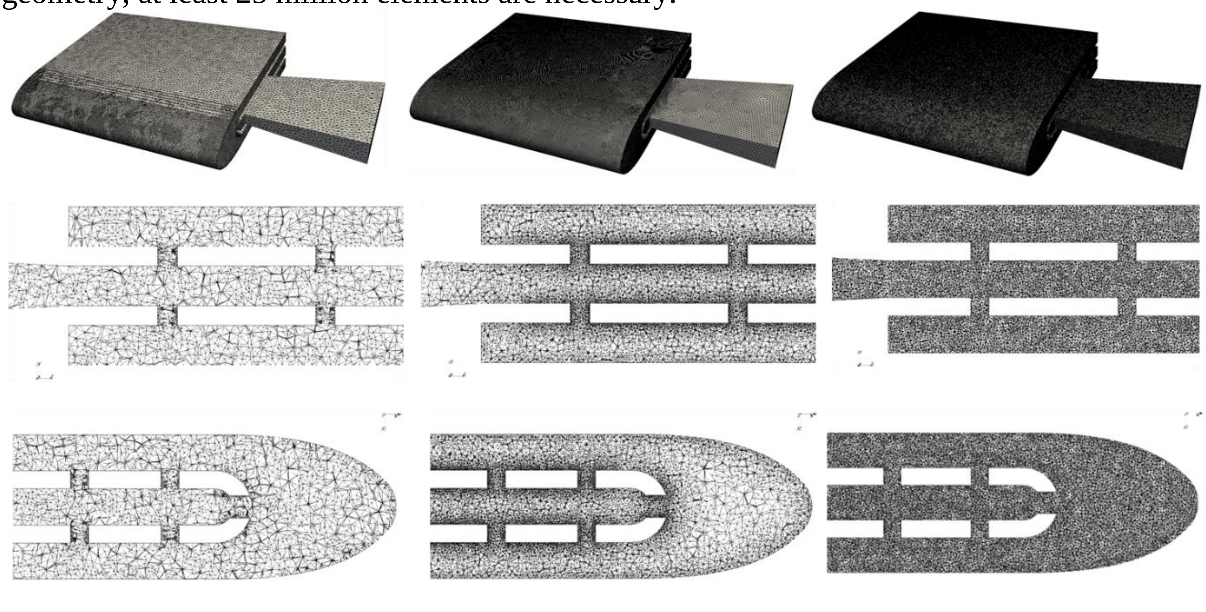


Figure 1: Unstructured isotropic tetrahedral 3D meshes counting (from left to right): M1: 500 000, M2: 7 000 000 and M3: 25 000 000 elements; (top) Global view; (middle) Slice view in plane YZ at x=-45 mm; (bottom) Slice view in plane XY at z=-0 mm.

The three computations corresponding to the three meshes previously described are launched on the GENCI Occigen II supercomputer [7]. We adapt the requested resources to the size of the meshes. After numerical experiments, it was decided to allocated one CPU for around 25 000 elements of the mesh. The allocated resources for each mesh are given in Table 1. The data concerning the computational time of each of the three computations are presented in Table 2.

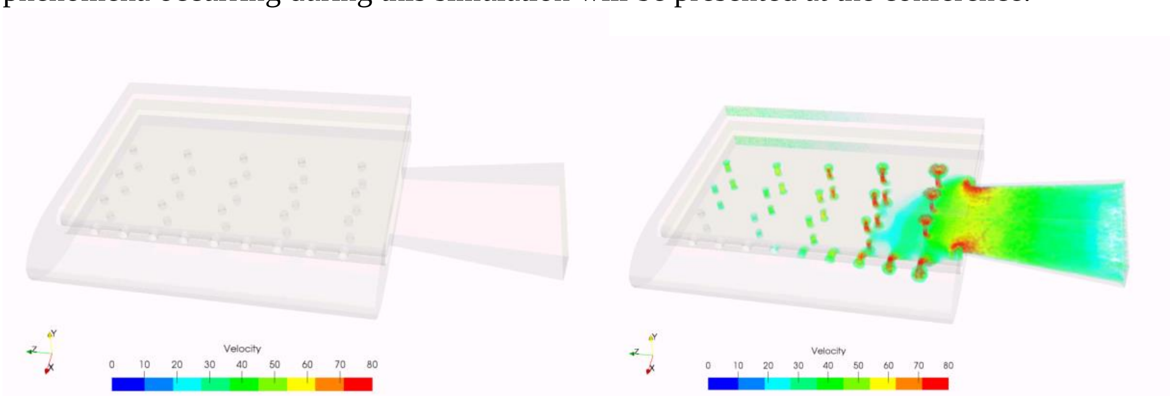
Mesh name	Nb elements	Nb cores/nodes	Nb nodes	Nb cores
M1	500 000	20	1	20
M2	7 000 000	24	12	288
M3	25 000 000	24	42	1008

Table 1: Allocated resources for each case on the GENCI Occigen II supercomputer

Mesh name	100 increments	1000 increments	Total
M1	1 h 02 min	0 days 14 h 49 min	2 days 12 h 00 min
M2	1 h 55 min	1 days 04 h 33 min	4 days 05 h 28 min
M3	4 h 11 min	2 days 01 h 19 min	11 days 11 h 31 min

Table 2: Computational times on the GENCI Occigen II supercomputer

The current work on the turbine vane cooling has brought interesting results. These results are presented in Figure 2 for the velocity field. As one can see, the flow behavior inside the geometry is extremely complex due to (i) the complex geometry, (ii) the flow unsteadiness and (iii) the turbulence. Additional quantitative results to understand all the physical phenomena occurring during this simulation will be presented at the conference.



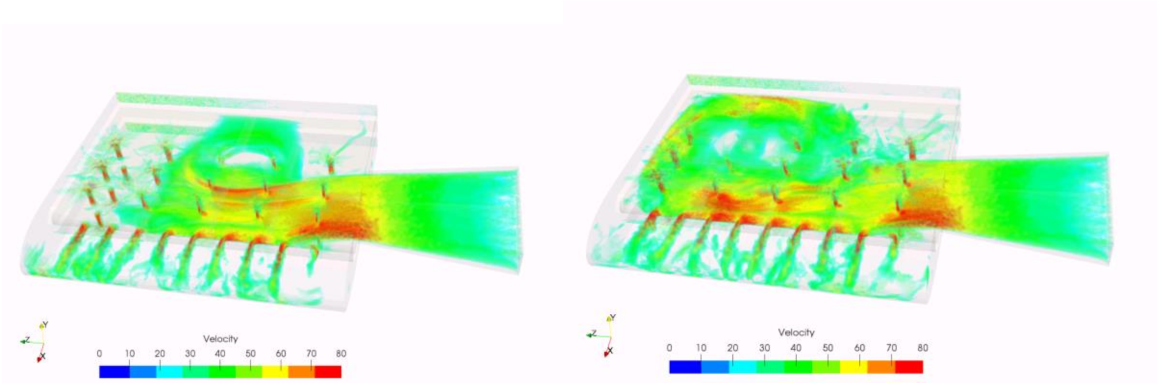


Figure 2: Transitory regime of the turbine vane cooling

3.5 Conclusions

Solving unsteady aerothermal problems on complex geometries is a typical test case of massively parallel simulations. A single computation of the turbine vane cooling on 25M element mesh requires 1008 cores working during 11 days which represents around 300 000 CPU hours. A parallel adaptive simulation is a serious alternative to reduce this time by several orders of magnitude. For this reason, we proposed in this work a parallel and adaptive finite element framework to deal with large-scale cooling systems. More adaptive simulations will be presented during the conference.

3.5 Acknowledgements

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