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Spectral element applications in complex nuclear reactor geometries: Tet-to-hex meshing

Haomin Yuan[a,*], Mustafa A. Yildiz[c], Elia Merzari[a], Yiqi Yu[a], Aleksandr Obabko[b], Gerrit Botha[c], Giacomo Busco[c], Yassin A. Hassan[c], Duy Thien Nguyen[c]

[a] Nuclear Science and Engineering Division, Argonne National Laboratory, United States of America
[b] Mathematics and Computer Science Division, Argonne National Laboratory, United States of America
[c] Nuclear Engineering Department, Texas A&M University, United States of America

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ABSTRACT

The spectral element code Nek5000 is an open-source, higher-order computational fluid dynamics code developed at Argonne National Laboratory. It is designed to solve incompressible Navier-Stokes equations, but it also has a low-Mach-number approximation feature available. Large eddy simulation is approached by explicit filtering of the velocity field (and other fields) to mimic the effect of dissipation due to the unresolved scale. The computational domain is decomposed into second-order hexahedral elements that conform to the boundaries. However, generating a high-quality pure-hexahedral mesh can be challenging for some problems. For simple geometries, traditional blocking methods can be used to decompose the domain into smaller blocks to generate a so-called structural mesh. A structural mesh can maintain good orthogonality but can have a highly skewed mesh to conform to the geometry, as well as unnecessary refinement in the far field. Moreover, for geometries with relative complexity, blocking the geometry becomes impossible. To address these issues, we adopted a tet-to-hex strategy to generate a pure hexahedral mesh for Nek5000. First, we generate a pure tetrahedral mesh for the geometry; then we divide one tetrahedral element into four hexahedral elements. A pure tetrahedral mesh could be easily generated for complex geometries by using many current meshing codes. In this paper, we use the commercial codes ANSYS meshing and ANSYS ICEM to generate the pure tetrahedral mesh and then convert it to a pure hexahedral mesh. Boundary layers are extruded in ANSYSICEM to maintain near-wall resolution.

1. Introduction

In the recent decade, computational fluid dynamics (CFD) has emerged as an important tool for nuclear engineering professionals, and it has become widespread as an analysis tool for design applications (Smith, 2002; Conner et al., 2010; Baglietto and Ninokata, 2006). Reynolds-averaged Navier-Stokes (RANS) methodologies in particular have been applied to systems of increasing size and complexity. Such methods, however, suffer from significant uncertainties due to the use of turbulence modeling; and they can present significant errors if inappropriate turbulence modeling is applied. Wall-resolved large eddy simulation (LES) and direct numerical simulation (DNS) data can be instrumental in helping reduce that uncertainty by providing a way to select the appropriate turbulence model (Merzari, 2011, 2016; Merzari et al., 2012). Unfortunately, wall-resolved LES and DNS data using higher-order method are exceedingly rare because high-order methods have not been generally developed to deal with the complex geometries encountered in nuclear engineering. However, some researches using Finite Element Method (Fang, 2018; Fang, 2019) and Finite Volume Method have been performed to reach wall-resolved LES and DNS level resolution.

In this article we discuss ongoing efforts to expand the use of the high-order methods for simulation of turbulent flows in complex geometries of direct application to nuclear engineering. We focus on Nek5000, an open source code in development at Argonne National Laboratory. Nek5000 is based on the spectral-element method (Maday et al., 1990), which is a high-order weighted residual technique that combines the geometric flexibility of finite elements with the rapid convergence and tensor-product efficiencies of global spectral methods. Globally, the spectral-element method is based on a decomposition of the domain into smaller domains (elements), which are assumed to be curvilinear hexahedral elements that conform to the domain boundaries (Merzari, 2011, 2016; Deville et al., 2002). Locally, functions within each element are expanded as Nth-order polynomials cast in tensor-

* Corresponding author.
E-mail address: hyuan@anl.gov (H. Yuan).

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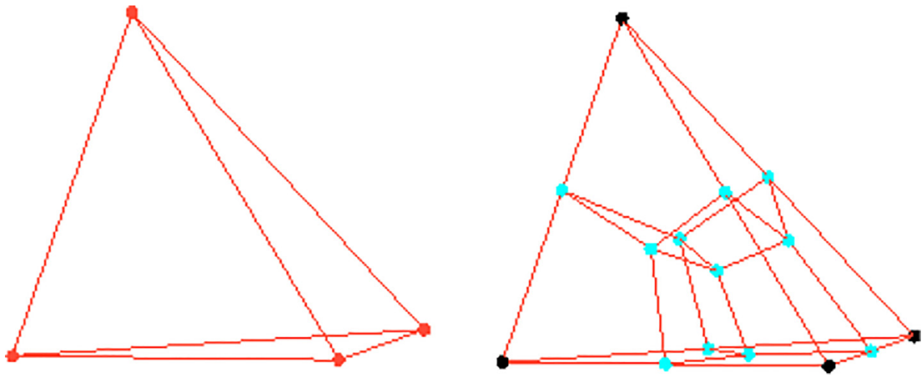

Fig. 1. One tetrahedral element (left) converted to four hexahedral elements (right) (ANSYS Inc, 2013).

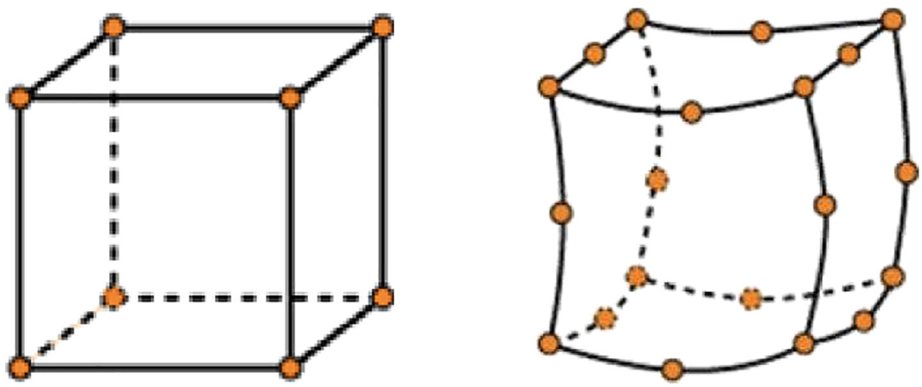

Fig. 2. Hex8 element (left) and Hex20 element with curvature (right).

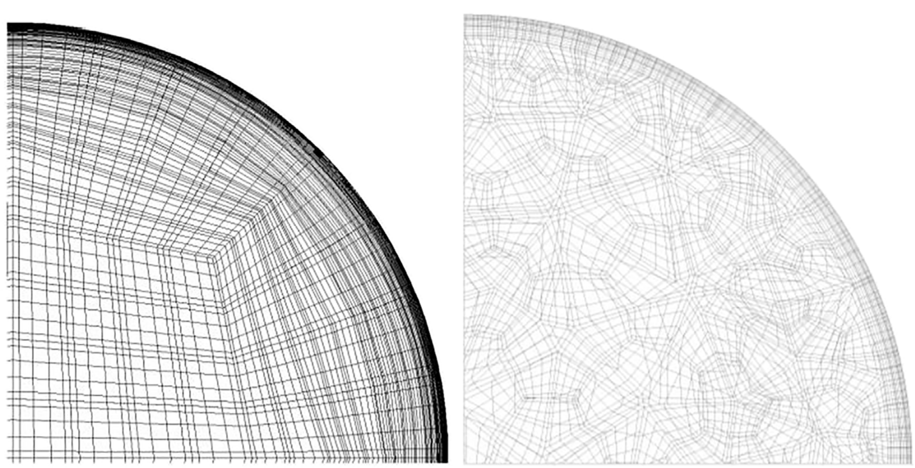

Fig. 3. Pipe cross-section mesh from structural mesh (left) and tet-to-hex mesh (right).

product form. The method has shown remarkable advantages in simulating turbulent flows in nuclear engineering (Merzari, 2011, 2016; Maday et al., 1990; Deville et al., 2002; Merzari, et al., 2017; Yuan et al., 2017).

Because Nek5000 decomposes the computational domain into hexahedral elements, a pure hexahedral mesh is needed. Traditionally, a block-method is used to generate such a mesh: the domain is subdivided into smaller blocks. The union of the blocks corresponds to the domain. Each block is then divided into conformal hexahedral elements. This method can be used for geometries with some complexity. If the geometry complexity reaches a certain degree, however, using the block method becomes time consuming and sometimes impossible. The benefit of using a structural mesh is that good orthogonality is maintained. Again, however, when the geometry reaches a certain degree of complexity, a block-structured mesh will need a highly skewed mesh in order to remain conformal. Moreover, the block-structured mesh will have unnecessary refinement in the far-field region. For the example cases we present in this paper—a fuel assembly with a spacer grid, a cross-helical steam generator, and a random pebble bed—creating a high-quality pure-hexahedral mesh with the blocking method is overly time consuming and perhaps impossible. To address these issues, we devise here a tet-to-hex meshing method. The tet-to-hex meshing method can utilize the high flexibility of a pure tetrahedral mesh to conform to the geometry, but it can still maintain the higher-order accuracy of Nek5000. Moreover, in complex geometries, it can do so at a computational cost and accuracy comparable to the block-structured mesh when available. We report on several simulations that have been performed with the method demonstrating its power and flexibility. We