Large eddy simulation of dense gas effects in a high-loaded turbine cascade

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Résumé

Over the last thirty years considerable interest has been given to compressible gas flows with complex thermodynamic behavior with respect to perfect gases. The focus of this paper is oriented toward so-called "dense" gases, characterized by complex molecules and working pressures and temperatures near the liquid/vapor critical point. A promising application is represented by Organic Rankine Cycles (ORC), commonly used for energy production from low-temperature heat sources (i.e. below 300 C) such as solar, geothermal or biomass sources. Such cycles involve an expander, very often a turbine, whose isentropic efficiency is highly influential on the overall cycle efficiency; hence the importance of an accurate design of such kind of component. Presently, ORC turbine design largely relies on numerical simulations based on the Reynolds-Averaged Navier-Stokes (RANS) equations and standard commercial CFD codes. These are well validated for perfect gas flows, but not for dense gas flows, due to the absence of detailed and reliable experimental data.
The aim of the present work is to carry out high-fidelity simulations, and more precisely Large-Eddy Simulations (LES) of dense gas turbine flows. The objective is twofold: 1) have a better understanding of physical mechanisms governing flow expansions through turbines using a dense gas; 2) generate a database for the validation of lower-fidelity RANS simulations.

For that purpose, we solve the compressible Navier-Stokes equations supplemented by the Martin and Hou equation of state to account for dense-gas thermodynamics and the dense gas transport property models by Chung et al.The geometrical configuration is the linear turbine cascade LS-89, investigated experimentally by Arts et al. (1990) using a perfect gas (air) as the working fluid. For this configuration, several perfect-gas LES results have been also reported in the literature.Here, we consider a heavy fluorocarbon, known under the commercial name PP11, as the working fluid. This fluid possesses a region of negative values of the fundamental derivative of gas dynamics in its vapor phase, i.e. it is a so-called Bethe-Zeldovich-Thompson (BZT) fluid. As such, it is expected to admit non-classical compressible waves in the BZT thermodynamic region. The governing equations are discretized by using a finite-volume scheme on a H-type structured mesh. The total number of grid points for the blade passage is 30.6 millions. A high-accurate implicit residual smoothing scheme is used for time marching, which allows to use a maximum CFL of 5. Space discretization uses a directional non compact spatial (DNC) scheme of third or fifth order accuracy, supplemented with Jameson-type artificial dissipation. The latter is also used as an implicit model to represent the effect of subgrid scales. The condition simulated here, referred-to as

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MUR129, is characterized by an outlet Reynolds number of one million and a pressure ratio of 1.59, corresponding to an isentropic Mach number at the outlet of 0.84 for a perfect gas. Validations have been conducted for the perfect gas case and the present results compare favorably with reference LES and experiments. For the dense gas, the solution depends on the thermodynamic conditions at turbine inlet. In the present calculation, we choose an inlet pressure equal to 1.35 Pc and inlet temperature equal to 1.01 Tc (where Pc and Tc are respectively the critical pressure and temperature of the PP11), corresponding to a highly non-ideal thermodynamic behavior. At such conditions, a non-classical shock is created at the blade upper surface.

At the conference, we will present an in detail analysis of the LES database and accurate comparisons with the perfect gas and with RANS results for the dense gas.

Mots-Clés: Turbomachinery, dense gas, LES, compressible flow