Introduction

Direct Numerical Simulation (DNS) of turbulent flows is feasible only for low Reynolds numbers \((Re)\) due to the required computational resources, which already become prohibitively large for \(Re \approx 10^4\). For this reason, turbulence modeling is a necessary step for the numerical simulation of flows of engineering interest. In this context, the most widely used approach for the simulation of high-Reynolds number turbulent flows is the one based on the discretization of the Reynolds-Averaged Navier-Stokes equations (RANS). In the RANS approach, time averaging is applied to the Navier-Stokes equations and only the time-averaged flow is simulated. In this way a noticeable simplification of the problem is obtained, computational costs are drastically reduced and become almost independent of the Reynolds number when this is sufficiently large. However, RANS simulations usually have difficulties in providing accurate predictions for flows with massive separations, as for instance for the flow around bluff bodies. Indeed, RANS models are in general too dissipative to properly simulate the three-dimensional and unsteady phenomena occurring in such flows, yielding to significant discrepancies with respect to the experimental results.

An alternative approach is the Large-Eddy simulation (LES), in which a spatial filter is applied to the equations to get rid of the small-scale turbulent fluctuations, which are thus modeled, while the remaining flow scales are directly simulated.

Thus in practical implementations, one is required to solve the filtered Navier-Stokes equations with an additional sub-grid scale (SGS) stress term. The most commonly used SGS models are the Smagorinsky model and its dynamic variants. They compensate for the unresolved turbulent scales through the addition of an "eddy viscosity" into the governing equations.

LES requires less computational effort than direct numerical simulation (DNS) but more effort than RANS.
The main advantage of LES over computationally cheaper RANS approaches is the increased level of detail it can deliver. While RANS methods provide "averaged" results, LES is able to predict instantaneous flow characteristics and resolve turbulent flow structures. In this way, the three-dimensionality and unsteadiness of the flow are naturally taken into account and the LES approach is generally more accurate than the RANS one. LES offers significantly more accurate results over RANS in particular, for flows involving flow separation prediction.

The cost of LES simulations increases as the flow Reynolds number is increased. Indeed, the grid has to be fine enough to resolve a significant part of the turbulent scales, and spatial resolution becomes particularly critical in the near-wall regions. A recent approach to LES based on a Variational Multi-Scale (VMS) framework was introduced by Hughes et al. in Ref. [23]. The VMS-LES differs fundamentally from the traditional LES in a number of ways. In this approach, the Navier-Stokes equations are not filtered, but uses instead a variational projection is made. This is an important difference because as performed in the traditional LES, filtering works well with periodic boundary conditions but mathematical issues range in wall-bounded flows. The variational projection avoids these issues. Furthermore, the VMS-LES method separates the scales a priori, that is before the simulation is started. And most importantly, it models the effect of the unresolved-scales only in the equations representing the smallest resolved-scales, and not in the equations for the large scales. Consequently, in the VMS-LES, energy is extracted from the fine resolved-scales by a subgrid scale (SGS) eddy-viscosity model, but no energy is directly extracted from the large structures in the flow.

The previously described approach has been implemented in a numerical solver (AERO) for the Navier-Stokes equations in the case of compressible flows and perfect Newtonian gases, based on a mixed finite-element/finite-volume scheme formulated for unstructured grids made of tetrahedral elements. Finite elements (P1 type) and finite volumes are used to treat the diffusive and convective fluxes, respectively. Concerning the VMS approach,
the version proposed in Ref.[1] for compressible flows and for the particular numerical method employed in AERO has been used here.

The first objectif of this report is to investigate the influence of SGS eddy viscosity models in the VMS-LES approach, and the effect of low-mach preconditioning and grid resolution. The SGS models used in the simulations are the traditional Smagorinsky model as reference model and two recent and promising models: the Vreman model Ref. [2] and the WALE model Ref. [3]. Contrary to the previous calculations performed with the VMS-LES framework [1], [4] in which wall laws were systematically used, no slip condition are implemented in this work. Simulations of the flow around a circular cylinder at Reynolds number, based on the free-stream velocity and the cylinder diameter, equal to 3900 are carried out. Simulations have ben carried out on two different grid: a coarser one having 290498 nodes and a finer one with 1133825 nodes.

The present report is organized as follows, we review in section 1 some of the standard approaches in turbulence simulation as well as our VMS-LES . Section 2 contains the numerical method implemented in our CFD software. Results of the simulations are presented and discussed in sections 3 and 4.