NUMERICAL STUDY OF TWO-PHASE FLOWS FOR PERFORMANCES IN SOLID ROCKET PROPULSION

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Abstract

Solid rocket propulsion has been widely used for decades for its ability to produce high values of thrust for instance in European launcher Ariane 5, and soon Ariane 6, in the first phase of flight at take-off, and for its high reliability, handling and easy storage in military applications. The basic principle of solid propulsion is the combustion of a solid propellant in a highly pressured chamber that generates a mass of gases accelerated in a convergent-divergent nozzle until a maximum exhaust velocity, which produces thrust by a reaction principle. Solid propellants containing metal powders (such as aluminium) have been developed to improve performances by increasing the flame temperature in the chamber as well as the global density of the flow. However, the presence of a spray of liquid alumina droplets in the mixture of gases after combustion generates performance losses. Because of their high inertia, particles are not accelerated as fast as the gas flow and modify properties of the surrounding gas. Besides, during combustion phase, an increasing mass of alumina impinges the internal structure and remains stuck inside the propulsion system, lowering the actual mass flow rate that is accelerated to generate thrust. Experiments led at ArianeGroup have shown that this effect gets increases with particle sizes in the two-phase flow. The multi-physic platform CEDRE developed since 2001 by the French research centre for aerospace (ONERA) is able to provide CFD simulations of gases for solid propulsion applications, but also to model liquid sprays of alumina and in particular the evolutions in particle sizes due to fragmentation and coalescence. Two solvers have been developed in that purpose: Lagrangian solver SPARTE, currently used at ArianeGroup for most of two-phase flow simulations, and Eulerian solver SPIREE, whose potential has to be evaluated in terms of accuracy and numerical cost with regards to the performances offered by SPARTE. To achieve that objective, a bibliographic review was performed about physical hypotheses that describe two-phase flows in solid rocket propulsion, physical and mathematical description of sprays implemented in SPARTE and SPIREE, with a particular highlight of the Eulerian solver SPIREE that was issued more recently. The Eulerian solver SPIREE is more difficult to implement, and it still lacks simple descriptions in the literature, which can partially explain why it is not as used as the Lagrangian solver SPARTE to describe two-phase flows. A post-processing method was
developed and implemented for SPARTE and SPIREE on the basis of classical granulometry analysis methods, with a common mathematical basis. In particular, expressions of mean diameters and standard deviations of the particle size distributions were derived mathematically in similar ways for the Lagrangian and the Eulerian description, and post-processing scripts were implemented. Eventually, simulation tests were performed to evaluate and compare the potential of both solvers to model evolution of size in sprays. Tests were performed first for fragmentation which is easier to analyse than coalescence. A simplified geometry inspired from existing propulsion device was designed to generate particle fragmentation. The fragmentation module was first tested with SPARTE for monodisperse injections (i.e. for sprays with uniform size of particles at injection). The convergence of this solver was verified and optimal settings were found for a compromise between precision and cost. Then, the influence of injected diameters on two phase flow properties will be tested and measured in SPARTE, in particular the velocity and temperature differences at nozzle throat between gas and particles, as well as the pressure drop between theoretical equivalent gas and actual combustion gas mixture carrying particles. Mass losses due to walls impingements were also evaluated. Finally, SPARTE computational times were measured. The fragmentation module was then tested with SPIREE. A first convergence test was performed and injections setting were determined to approach a monodisperse injection with the Eulerian method. A second serie of convergence tests was run and settings for the discretization of the particles size distribution were determined to comply with a requirement of compromising between accuracy and cost of the simulation. Optimal settings for fragmentation cases in SPIREE were found and the influence of injected diameters on the flow properties and on the alumina loss was simulated in SPIREE for the fragmentation case. SPIREE appears to be a very promising alternative two-phase solver to SPARTE, for its ability to model the losses of alumina mass flow rate due to wall impingements, granulometry characteristics as well as shifts of some physical variables (called A and B) that are expected to be responsible for performance losses in solid rocket propulsion. Numerical costs with SPIREE were found to be the same order of magnitude as with SPARTE, and could even be lowered with further studies on optimal discretization schemes in the Eulerian Multi-Fluid models. These results offer great perspectives for the use of SPIREE solvers in the Aerodynamics department. Further investigations will have to be carried out in the department to compare the performances of SPARTE and SPIREE for coalescence, and to be able to model realistic cases of injections with Eulerian solver SPIREE.
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