Numerical coupling strategies for the “separated-to-dispersed” transition within the liquid phase of cryogenic rocket engines

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ABSTRACT

The present paper comes within the scope of the numerical simulation of cryogenic rocket engines under transient operating conditions. That is when the pressure in the combustion chamber is still under Oxygen super-critical conditions, leading to a two-phase Liquid Oxygen (LOx) – Gaseous Hydrogen (GH2) flow. As both propellants exit the shear coaxial injector, the strong velocity difference between the two jets entails the creation of hydrodynamic instabilities. These then grow and eventually provoke the peeling of the main liquid jet , which is referred to as “primary atomization”. Large random-shaped liquid structures are thereby ejected towards the gas flow (see figure 1), subsequently undergoing “secondary break-up” when inertia forces exceed the liquid surface tension. This results in a spray of tiny spherical LOx droplets, which are dispersed by the turbulent gas flow, and finally vaporized to feed the combustion with GH2.

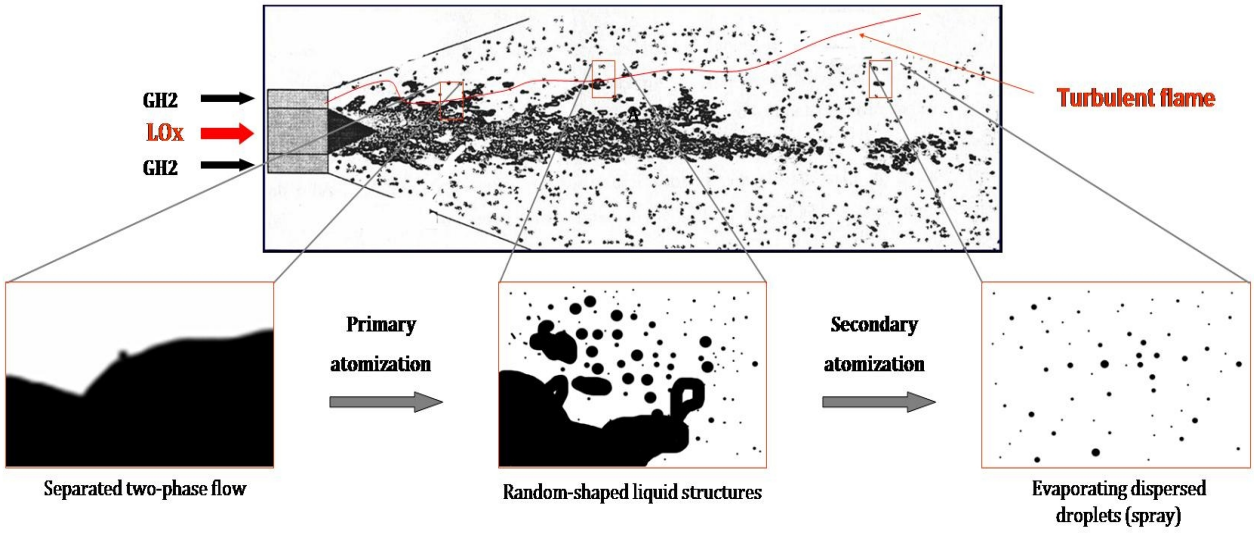

Figure 1: Physical phenomena within the combustion chamber of liquid rocket engines

The ONERA's Mascotte test bench is an experimental device for cryogenic combustion research. This

is representative of one sole rocket engine injector, while they are hundreds in a real engine such as the Vulcain 2 engine of the Ariane 5 launcher. Because of the large experimental data basis available, the Mascotte configuration is a good support for the development of numerical strategies devoted to the simulation of the two-phase flow within cryogenic rocket engines. Our overall objective is therefore to eventually achieve the most accurate and comprehensive numerical simulation of the Mascotte configuration.

However, this kind of simulation is a very challenging process. Not to mention the numerical issues related to the sharp gradients encountered in compressible reactive multiphase configurations, the major issue is actually related here to the wide range of scales to be resolved in the successive atomization steps, up to the smaller spherical droplets of the spray. Indeed, it is important to accurately describe the dynamics of formation, transport and evaporation of the smaller relevant structures of the flow, i.e. the LOx droplets. As a matter of fact, this is what directly impact on the flame behavior, then consequently on the pressure levels in the combustion chamber, and finally on the overall thrust provided by the engine.

Various models are available to describe the atomization mechanisms of a liquid jet in a surrounding coaxial gaseous flow. Those range from interface tracking methods (Level Set, Volume of Fluid) to diffuse interface methods, with potentially different levels of physical modeling. The problem is that if we want to simulate a whole combustion chamber, even in a simplified single-injector configuration as the Mascotte configuration, the mesh which would be refined enough to capture the droplets with any of these methods is still absolutely out of reach. That is why the spray is usually described with dedicated statistical models based upon either lagrangian or eulerian formalism [1], [2]. Unfortunately, the mathematical nature of these models is very different from the above-mentioned ones used to describe the “separated” zones. As a result, there is no straightforward coupling between both kinds of models, which makes it impossible to simulate the whole chain of atomization mechanisms in a continuous way. That is why our strategy in simulations has so far consisted in just describing the spray with assumed initial conditions of velocity and size dispersion, therefore not resulting from the simulation of the chain of atomization mechanisms, but only issued from the few experimental data available in the close-to-injector zone.

So we have to develop coupling strategies in order to describe the spray with the statistical models used so far, but with the initial conditions for the spray being now provided by the simulation of the successive atomization mechanisms. For that purpose, we opt for diffuse interface methods to characterize the dense zone, in spite of their lower accuracy compared to interface tracking methods. This is mainly because the former are more robust and flexible than the latter in the field of energetics, with high density ratios, compressible phases... Furthermore diffuse interface methods are compatible with unstructured meshes. Concerning the spray, the eulerian formalism seems to us a more natural candidate for coupling than the lagrangian one.

Within the framework of diffuse interface methods, different models are available. The 7-equation Baer-Nunziato model [3] is the one with the highest level of physical description. Indeed, in a given cell each phase is described with its own pressure, velocity and temperature (which seems an important feature as soon as both atomization and combustion are involved). On top of that, this model has good mathematical properties, such as hyperbolicity. Nevertheless, simpler models can be obtained by successive relaxation of the pressure, velocity and temperature variables in the 7-equation model, leading for instance to the simplest 4-equation model (two components, but with only one averaged pressure, velocity and temperature in a given control volume).

In this paper, we therefore present the first numerical strategies developed to achieve the coupling of diffuse interface methods for the “separated phases” zones, with an eulerian statistical model for the “dispersed liquid” zones. These developments are implemented in the multiphysics ONERA's

CEDRE platform for energetics, which is a finite volume code handling general unstructured meshes.

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