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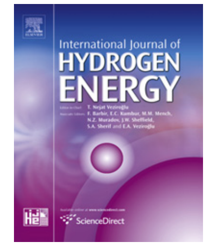

Numerical study of the near-field of highly underexpanded turbulent gas jets

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ABSTRACT

For safety issues related to the storage of gases (e.g. hydrogen) under high pressure, it is necessary to determine how the gas is released in the case of failure. In particular, there exist limited quantitative information on the near-field properties of gas jets, which are important for establishing proper decay laws in the far-field. Simulations of the near-field of highly underexpanded (high pressure) gas jets have been performed using Finite-Volume solver of the CAST3M code and validated using several sources available in the literature. The numerical model solves the 3D Compressible Multi-Component Navier–Stokes equations directly without relying on the compressibility-corrected turbulence models. It provides sufficiently fair mean predictions both in the case of one-component air–air and two-component helium-air releases. Possible initial conditions for the far-field simulations are suggested in terms of distance from the source, as well as the turbulence characteristics and gas-dynamic parameters at this location. In addition, these results are used to evaluate several notional nozzle concepts in order to determine the one physically consistent.

1. Introduction

In aerospace and industrial applications, sonic and supersonic jets are often encountered. In particular, an accidental discharge of a high-pressure gas (e.g. hydrogen) to atmosphere from a small opening in a reservoir can result in under-expanded sonic/supesonic jet (pressure at the exit is much greater than atmospheric). In these cases, knowledge of the temperature and flammable gas concentration are important in order to suggest the appropriate safety standards. However, there exist very limited quantitative information on the near-field properties of gas jets, as a result of great challenges of flow measurements and simulation in the supersonic/subsonic shock-structured regions. Therefore, in literature currently there exist various simplifying approaches.

The group of authors, including Birch et al. [1], [2], Ewan and Moodie [3], Yuceil and Otugen [4], among others, provided several types of scaling laws for velocity, temperature and/or concentration irrespective of the particulars in the initial expansion of the underexpanded jet by using the notional nozzle concept. Birch et al. [1] developed this concept based on the ideal gas law, the equation of conservation of mass between the choked flow through the actual nozzle and a sonic flow through the notional nozzle. In addition, a uniform velocity profile and atmospheric temperature were assumed after the jet expansion region. Yuceil and Otugen [4], among others, attempted to advance the original concept by introducing the momentum and energy equations. This analysis provides the gas properties such as temperature and density at the notional location.

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Despite this progress, the notional nozzle does not necessarily exist in the physical sense and, thus, the aforementioned models are to be further validated and/or refined. In particular, it has been shown (e.g. Chenoweth [5]) that the ideal gas law overestimates the hydrogen/helium mass release by a significant amount for a very high pressure storage. Another problem rises from the assumption that there is no entrainment of the stationary fluid into the shear layer during the expansion. Therefore, an approach alternative to the notional nozzle, was recently suggested by Xu et al. [6]. In this work axisymmetric Navier–Stokes equations with $k-\omega$ model were solved in the near-field of the highly underexpanded hydrogen jet. The results of this computation were analyzed to find a critical distance from the nozzle, where they considered to be suitable for the subsequent simulations of the far-field. However, neither attempt to define a criteria for this distance, nor validation of the computation have been performed.

Previous numerical studies of the unsteady highly underexpanded gas jets were two-dimensional in their nature in order to provide high-fidelity transient computations of the shock waves and flow structures in the near-field (e.g. Ishii et al. [7], Pèneau et al. [8], among others). Pèneau et al. [8] studied both the one-component and two-component (hydrogen-air) releases. However, a total time of these computations was rather limited and thus a quasi steady state has not been reached. In the case of Reynolds-averaged Navier–Stokes equations (RANS) simulations some of the authors (Chauveau et al. [9], Lehnasch [10]) utilized turbulence models with compressibility correction of Sarkar et al. [11], which is limited to isotropic turbulence scenario.

Taking into account the outlined limitation of the previous studies, it was attempted in this paper to solve 3D Compressible Multi-Component Navier–Stokes equations in the near-field of highly underexpanded gas jets with the particular emphasis on experimental validation of the numerical model. The following background section gives a short review of theoretical and experimental studies, as well as lists the major objectives of the present work.

2. Background

2.1. Shock-wave structure

The major parameter utilized in the past to classify free underexpanded jet, discharging to atmosphere is the pressure ratio P_0/P_∞, where P_0 is a stagnation pressure in the tank and P_∞ is an ambient pressure (Ashkenas and Sherman [12]). However, it has been also shown (see Bier and Schmidt [13], Crist et al. [14]), that the shock-wave structure in these jets also depends on a geometry of the nozzle and the nature of gas. As the flow leaves the nozzle the high pressure mismatch causes it to expand and accelerate. Expansion waves originate near the expansion point, propagate and meet the outer boundary of the jet, where they are reflected as compression waves. Coalescence of these waves results in a curved barrel shock surrounding the immediate supersonic region (a schematic describing the process can be found in the studies cited above). For higher values of P_0/P_∞ (>15), which are considered herein, the shock structure is rather complex. The reflection of the incident shock is not regular anymore, and a so-called Mach disk pattern appears a few diameters downstream the orifice. The flow is subsonic just after the Mach disk, while it remains supersonic downstream of the barrel shock. The triple point connects various discontinuities and becomes the origin of a new slip line, which gives rise to a supersonic shear layer. The lengths of the shock cell and subsonic zone are increasing functions of pressure ratio and exit Mach number, while the diameter of the Mach disk depends significantly on γ (Bier and Schmidt [13], Crist et al. [14]).

In view of the latter, and in the context of an accidental discharge of high-pressure hydrogen (or helium), a theoretical analysis based on dimensional groups has been developed in Ref. [15]. It was shown, in particular, that

$$\frac{X_m}{D_e} = \frac{1}{2}\sqrt{\gamma}\sqrt{\frac{P_e}{P_\infty}} \times \left(\frac{\gamma+1}{\gamma-1}\right)^{1/4} \quad (1)$$

$$\frac{D_m}{D_e} = \alpha\frac{X_m}{D_e}\sqrt{1-\frac{\gamma+1}{\gamma}\times\left(\frac{\gamma+1}{\gamma-1}\right)^{-1/2}} \quad (2)$$

where X_m and D_m are location and diameter of the Mach disk, P_e is a static pressure at the exit section, and α is an empirical constant, which accounts for the growth of the mixing layer. The latter can be for instance approximated, at the location of the Mach disk, using experimental measurements of Bier and Schmidt [13] provided for various gases, including hydrogen. It should be also noted, that the Mach disk location, X_m as given by Eqn. (1), is in fact weakly dependent on γ, and is well approximated by a commonly used experimental correlation of Ashkenas and Sherman [12]:

$$\frac{X_m}{D_e} = 0.67 \times \sqrt{\frac{P_0}{P_\infty}}.$$

2.2. Quantitative measurements and validation techniques

Quantitative measurements in the near-field of underexpanded jets are scarce due to the highly complex nature of the flow. Most of the early experimental data in the near-field was obtained using impact techniques. For example, Glotov [16] utilized probes immediately after the Mach disk to determine the length of the subsonic core (L_s). Correlation (3), thus obtained, can be used for $P_e/P_\infty \le 30$.

$$\frac{L_s}{D_m} = 1.96 \times \left(\frac{P_e}{P_\infty}\right)^{-0.16} \quad (3)$$

The essentially non-intrusive methods such as particle image velocimetry (PIV) show some promise for the quantitative characterization of supersonic jets as it has been demonstrated by Chauveau et al. [9] and Yuceil et al. [17]. However, a dramatic particle inertia effect was found to exist just downstream of the Mach disk. For example, recent PIV measurements of a hydrogen jet release of Veser et al. [18] provide velocity data only beyond the shock-structured region (i.e. $> 25D_e$ in the case of $P_0 = 19.2$ -bar).