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Free underexpanded jets in a quiescent medium: A review

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ABSTRACT

When dealing with high-pressure releases, be it needed by some operating conditions or due to an emergency protocol or even to the occurrence of an accident, one has to consider the relevant risks associated to this leakage. Indeed, in addition to the mechanical and blast effects, the dispersion of the released fluid is of primary importance if it is hazardous, as an example for toxic gases or flammable ones (where explosions or fires may be expected).

In fact, despite the numerous studies dealing with underexpanded jets, many aspects of their structure are not clearly described, particularly when one seeks for quantitative predictions. By performing an exhaustive overview of the main experimental papers dealing with underexpanded jets, the present paper aims at clarifying the characteristics which are well known, from those where there is clearly a lack of confidence. Indeed, and curiously enough, such a work has never been done and no review is available on such a topic.

Two particular regions have drawn most of the attention so far: the nearfield zone, where the shocks/rarefaction pattern that governs the structure of the jet is encountered, and the farfield zone, where the flow is fully developed and often approximated by an equivalent flow.

Finally, some clues are given on the numerical methods that may be used if one wants to study such jets numerically, together with an emphasis on the specific thermodynamical difficulties associated to this kind of extreme conditions.

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1. Introduction

Historically, the underexpanded jets have long been studied, particularly by some of the most famous scientists [1–8]. They are involved in practical engineering and challenging situations, such as exhaust and plumes of aircrafts and rockets (where the thermal signature, jet noise and screech or flow behavior were studied), and mixing issues in supersonic combustors or parallel injection, and accidental leakage of pressurized fluid, etc. In each of these situations, the main features concerning the risk prediction and control are linked to the overall structure of the jet, that is to say the pressure (or temperature, or velocity) levels attained in its surrounding, and to the knowledge of the concentration evolution, which permits a comparison with some physical criterion (such as the permissible exposure limits or the inflammability limits). Generally, one distinguishes between the free jets and the impacting ones, and the exhausted fluid may be released either in a quiet medium or in a moving one (i.e. a coflow jet or a jet in crossflow). Besides, the jet may be either axi-symmetric or present an asymmetry. The present review will concentrate on the former configuration.

Nowadays, thanks to all the associated papers, the overall structure of underexpanded jets is very well known. Yet, in spite of the large amount of studies that has been published, many characteristic features or quantitative aspects are still ill-known or even ignored by those numerous publications, e.g. the curvature of the Mach disk, the characteristic lengths of the jet in the supersonic case or with various jet/ambient fluids, the position where entrainment arises, the turbulent transition in the mixing layer, the interactions between hydrodynamic instabilities and the shock waves pattern, the fine and complete structure of turbulent vortices, the method to correctly approximate the flow in the farfield region, etc. Moreover, there sometimes exists a large scattering between the different measurements, which are even sometimes occasionally in contradiction.

In order to have a fair view of the reliable results among all the available studies, the goal of this paper is thus to propose an exhaustive analysis of the open literature on axi-symmetric free underexpanded jets by comparing the qualitative and also quantitative predictions proposed therein. Thereby, the aim is to know exactly in which characteristics and associated correlations we may have confidence in. Let us mention here that we are mainly considering experimental studies.

The paper is organized as follows: in Section 2, a brief summary is given on the physical appearance of axi-symmetric under-expanded jets, and their global structure is presented in Section 3. Then, a deeper description of the potential zone (nearfield region) and of the fully developed one (farfield zone) is given in Sections 4 and 5. Finally, an overview of the numerical models and methods that may be used to further improve our knowledge of the underexpanded jets is proposed in Section 6. The possible issues raised by the thermodynamical behavior of the fluid are addressed in Section 7.

2. Forewords

An underexpanded jet may occur whenever a fluid is released from a device at a pressure greater than the ambient pressure. It is known from a long time that such a behavior arises with convergent and convergent–divergent nozzles (holes being a particular case of these ones), as recalled in [9–11].

For a convergent nozzle, two main situations may be encountered, depending on the initial pressure of the fluid or, more precisely, on the ratio between the total pressure of the fluid and that of the ambient atmosphere. Thus, two different regimes with different evolutions of the pressure inside the device are encountered, as depicted in Fig. 1. The associated evolutions of the