Available online at www.sciencedirect.com
ScienceDirect
C. R. Mecanique 337 (2009) 362–372
COMPTES RENDUS MECANIQUE

Combustion for aerospace propulsion

Stabilization of non-premixed flames in supersonic reactive flows

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Available online 21 July 2009

Abstract

A Lagrangian framework is set out to describe turbulent non-premixed combustion in high speed coflowing jet flows. The final aim is to provide a robust computational methodology to simulate, in various conditions, the underexpanded GH2/GO2 torch jet that is used to initiate combustion in an expander cycle engine. The proposed approach relies on an early modelling proposal of Borghi and his coworkers. The model is well suited to describe finite rate chemistry effects and its recent extension to high speed flows allows one to take the influence of viscous dissipation phenomena into account. Indeed, since the chemical source terms are highly temperature sensitive, the influence of viscous phenomena on the thermal runaway is likely to be all the more pronounced since the Mach number values are high. The validation of the extended model has been recently performed through the numerical simulation of two distinct well-documented experimental databases. Only a brief summary of this preliminary validation step is provided here. The main purpose of the present work is to proceed with the numerical simulation of geometries that bring together the essential peculiarities of the underexpanded GH2/GO2 torch. The behavior of the corresponding supersonic coflowing jet flames for various conditions is discussed in the light of computational results. ***To cite this article: J.-F. Izard, A. Mura, C. R. Mecanique 337 (2009).***

Résumé

Stabilisation des flammes non prémélangées dans les écoulements supersoniques réactifs. Une approche Lagrangienne est introduite pour décrire les flammes turbulentes non prémélangées dans des jets co-courants supersoniques. L'objectif final est de disposer d'un modèle numérique robuste pour la simulation de la torche sous-détendue GH2/GO2 utilisée comme système d'allumage dans un moteur fusée. L'approche retenue repose sur les travaux de Borghi et de ses collaborateurs. Elle permet de décrire les effets de chimie finie et sa récente extension aux écoulements à grandes vitesses permet de prendre en compte l'influence des phénomènes liés à la dissipation visqueuse. En effet, les termes sources chimiques étant fortement sensibles à la température, l'influence des phénomènes visqueux sur l'emballement thermique devient d'autant plus importante que le nombre de Mach est grand. La validation du modèle étendu a été récemment effectuée en considérant deux cas expérimentaux de référence. Cette étape préliminaire de validation est brièvement résumée mais le but essentiel de la présente étude est de procéder maintenant à la simulation numérique de configurations regroupant les particularités de la torche sous-détendue GH2/GO2. Le comportement des flammes jet supersoniques correspondant aux différentes conditions est discuté à la lumière des résultats des simulations numériques. ***Pour citer cet article : J.-F. Izard, A. Mura, C. R. Mecanique 337 (2009).***

Keywords: Combustion; Lagrangian modelling; Supersonic combustion; Viscous effects; Underexpanded jets

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1631-0721/$ – see front matter
doi:10.1016/j.crme.2009.06.006

Mots-clés : Combustion ; Modèle Lagrangien ; Combustion supersonique ; Effets visqueux ; Jets sous-détendus

1. Introduction

In rocket engine applications, ignition phenomena, as well as eventual re-ignition in space, are of primary concern. However, their experimental investigation in rocket engine conditions still remains difficult and often incomplete; accordingly, reliable and robust numerical tools are still needed to perform design and parameter studies of such reactive flow configurations. In the specific case of a GH2/GO2 torch igniter, the peculiar flow configuration gives birth to a Mach disk featuring triple point conditions, the stability of which being still an open question even in non-reactive situations. The turbulent non-premixed flame that is expected to stabilize within the mixing layers, where favorable conditions are reached, needs to be studied in detail and the phenomena that drive the associated stabilization process must be taken into account in the final modelling proposal. Lagrangian strategies have been previously retained for their robustness and affordable computational costs to describe turbulent mixing and combustion either in supersonic coflowing jets [1] or in a laboratory scramjet geometry [2]. However, these previous studies did not address the modelling of the ignition phenomena associated with the conversion of kinetic energy into thermal energy via the viscous dissipation heating, a mechanism that is likely to affect the early developments of the chemical processes in high Mach number reactive flows. Even if the corresponding phenomena do not bring special additional difficulties to the simulation of laminar reactive flows, the situation is different from the turbulent combustion modelling point of view and some efforts have been already done to take them into account under the fast chemistry assumption. For instance, a revisited flamelet model has been put forward for non-premixed combustion in supersonic reactive flows by Sabel'nikov et al. [3]. Nevertheless, this issue remains challenging for situations where finite rate chemistry effects come into play. A possible way to include such an influence for high velocity reactive flows is described below within the MIL framework of turbulent non-premixed combustion. The reliability of this proposal has been recently assessed for gaseous conditions through the numerical simulation of two well-documented experimental databases and it is carried out herein with the investigation of the central GH2/GO2 igniter.

The present manuscript is organized as follows: the essential characteristics of the model are briefly recalled in the next section. It is followed by a synthetic description of the retained numerical methodology. Results of numerical simulations are then reported for: (i) supersonic reactive coflowing jets at atmospheric pressure; and (ii) highly under-expanded supersonic coflowing jets. Finally, the article ends with a brief section where conclusions are drawn from the numerical simulations and future works are presented.

2. The Lagrangian intermittent model

The MIL (Modèle Intermittent Lagrangien) representation of turbulent non-premixed combustion essentially describes the competition that takes place between micro-mixing phenomena and finite rate chemistry effects. The main features of this model, introduced in the early works of Borghi and Gonzalez [4], are briefly recalled below.

2.1. Joint scalar PDF estimation

The MIL model is a Lagrangian model in the composition space which is based on the knowledge of two scalar variables, namely the mixture fraction ξ and the mass fraction of a reactive species Y which indicates the progress of the chemical reaction. The oxygen mass fraction has been retained as Y in the present study. The MIL model relies on the sudden chemistry assumption [4], thus permitting a strong but clearly stated functional dependence between the two scalars to be introduced: $Y = Y^{\mathrm{MIL}}(\xi)$. As a result, the estimation of the joint scalar Probability Density Function (PDF) $\widetilde{P}(Y, \xi; \boldsymbol{x}, t)$ can be simply expressed from the knowledge of the marginal mixture fraction PDF $\widetilde{P}(\xi; \boldsymbol{x}, t)$. If the latter is represented thanks to the usual Beta function PDF, the joint scalar PDF can be written $\widetilde{P}(Y, \xi; \boldsymbol{x}, t) = \beta(\tilde{\xi}, \widetilde{\xi''^2}) P(Y \mid \xi; \boldsymbol{x}, t)$ where the conditional PDF is closed by considering the MIL trajectory: $P(Y \mid \xi; \boldsymbol{x}, t) = \delta(Y - Y^{\mathrm{MIL}}(\xi))$.

The presumed Beta shape is fully determined provided that both mean $\tilde{\xi}$ and variance $\widetilde{\xi''^2}$ of the mixture fraction are known. These quantities are calculated through the numerical resolution of the following set of transport equations: