Chinese Journal of Aeronautics, (2017), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

# Numerical simulations of turbulent flows in aeroramp injector/gas-pilot flame scramjet

**Bing Chen** [a,*], **Xu Xu** [a], **Baoxi Wei** [a,b], **Yan Zhang** [a]

[a] *School of Astronautics, Beihang University, Beijing 100083, China*
[b] *Science and Technology on Scramjet Laboratory, Beijing Power Machinery Institute, Beijing 100074, China*

Received 8 April 2016; revised 24 January 2017; accepted 16 March 2017

**KEYWORDS**

Combustion mode;
Laminar flamelet model;
Menter's SST $k$-$\omega$ model;
Scramjet;
Turbulent combustion

**Abstract** To uncover the internal flow characteristics in an ethylene-fueled aeroramp injector/gas-pilot (ARI/G-P) flame scramjet, a Reynolds-averaged Navier-Stokes (RANS) solver is constructed under a hybrid polyhedral cell finite volume frame. The shear stress transport (SST) $k$-$\omega$ model is used to predict the turbulence, while the Overmann's compressibility corrected laminar flamelet model is adopted to simulate the turbulent combustion. Nonreactive computations for Case 1 (G-P jet on), Case 2 (ARI jets on), and Case 3 (both ARI and G-P jets on) were conducted to analyze the mixing mechanism, while reactive Cases 4–7 at equivalent ratios of 0.380, 0.278, 0.199 and 0.167 respectively were calculated to investigate the flame structure and combustion modes. The numerical results are compared well to those of the experiments. It is shown that the G-P jet plays significant role in both the fuel/air mixing and flame holding processes; the combustion for the four reactive cases takes place intensively in the regions downstream of the ARI/G-P unit; Cases 4 and 5 are under subsonic combustion mode, whereas Cases 6 and 7 are mode transition critical and supersonic combustion cases, respectively; the mode transition equivalent ratio is approximately 0.20.



## 1. Introduction

Supersonic combustion ramjet (i.e. scramjet) has long been recognized as one of the most suitable systems for the hypersonic propulsion. Of the special consideration in the development of a scramjet are the efficient mixing and combustion processes, given our limited experience with sustained hypersonic propulsion. Hydrocarbon-fueled scramjet has received considerable attention in recent years due to the high volumetric energy density, low cost, and relative simplicity of operation over hydrogen-fueled one. However, on account of the longer residence time required for mixing and completion of chemical reactions for hydrocarbon fuels, there are still several challenges in the development of a high-performance scramjet. Air and fuel must mix at a molecular level before combustion, so turbulent mixing and combustion are at the heart of scramjet operation. Recently, numerical tools are playing a more and more important role in the predictions of this kind of combus-

* Corresponding author.
E-mail address: MarkChien@buaa.edu.cn (B. Chen).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2017.06.010

tion flows.[1–5] One of the main focuses in these research activities for modeling the turbulent combustion has been the complex interaction between turbulence and chemical reaction. Due to a very short fuel residence time in the combustor, the flame stabilization mechanisms are usually governed by autoignition. Thus, detailed chemical kinetics is usually required to accurately model the ignition and extinction phenomena.[3–5]

In this case, the traditional species transported finite-rate kinetics method becomes useless for several reasons. First, when a detailed chemical kinetics mechanism is adopted, there will be a large amount of species involved in the species transport equations, which will evoke a vast amount of computational work even beyond the state-of-the-art computer hardware capabilities. Second, to get the chemical source terms in the species transport equations, the Arrhenius law is often used with the turbulence-chemistry interaction ignored, which may cause severe errors. To account for this interaction, some researchers used the eddy dissipation concept (EDC) model[6], linear eddy mixing (LEM) model[7], transported probability density function (PDF) model[8], etc. Third, the coupled Reynolds-averaged Navier-Stokes (RANS) equations and species transport equations are very stiff and difficult to solve accurately due to the strong nonlinearity of the source terms as well as the wide range of time scales associated with both chemistry and turbulence.

One alternative approach to calculate the vast number of species involved hydrocarbon/air turbulent combustion flow is the laminar flamelet model, and there has been extensive research regarding this aspect.[1–5,9–15] This model successfully separates the chemical time scale and turbulence time scale, allowing the chemistry to be solved independently before the combustion flow computation. The chemistry results can be stored in a tabulated form as a function of a limited number of indexing scalars. During the real-time combustion simulation, just these scalars are needed to be determined in addition to the RANS calculation, while the species transport equations are not needed to be solved anymore. Because the number of the indexing scalars is independent of chemical mechanism, the computational effort is not proportional to the species number. This is very attractive in the detailed chemical kinetics involved combustion flow calculation.

The laminar flamelet model was originally established for the low Mach number turbulent combustion flow, and has been successfully applied to the simulation of turbulent diffusion flames in the subsonic flow. In the supersonic turbulent combustion flow, due to complex flow patterns such as shock waves, contact discontinuities and flame fronts, the model's applicability is questioned by many experts. The key doubtful point is whether the thickness of the flamelet is really smaller than that of the Kolmogorov vortices or not. But according to the investigations conducted by Bray et al.[16], Waidmann et al.[17], and Williams[18], the combustion in a typical scramjet was approximately in the flamelet regime. More recently, Fan et al.[19] conducted a careful theoretical and quantitative comparison of these scales in a scramjet combustor and argued that: (A) the flamelet model assumption is valid for the premixed combustion in the recirculation zones and/or the shear layers for all flight Mach numbers; (B) the assumption is also accurate for the non-premixed combustion for most of the flight Mach numbers except for very high Mach number under which the slow reaction mode dominates the combustion. Moreover, several authors have reported successful computations for scramjet turbulent combustions with this model in recent years.[1–5,14,15,17,19] All these studies confirmed that the laminar flamelet model could model the supersonic turbulent combustion flows very well.

The aim of this paper is to develop a parallel finite volume RANS/flamelet computational fluid dynamics (CFD) code for supersonic turbulent combustion flow and validate the code against the experimental measurements on an ethylene ($C_2H_4$)-fueled aeroramp injector/gas-pilot (denoted as ARI/G-P) flame dual-mode scramjet combustor developed early this decade at Beihang University (BUAA).[20–22] Wei et al.[20,21] and Zhang et al.[22] experimentally studied the operation properties and mode transition influencing factors. It is worth doing careful three-dimensional (3D) CFD simulation to further clarify the flow structure, fuel/air mixing mechanism, and turbulent flame structure, especially to uncover the flow details in the vicinity of the ARI/G-P injection unit and the intensive combustion region. Therefore, the other more important objective of the present study is to numerically investigate the internal flow characteristics in the ARI/G-P combustor.

In the RANS/flamelet simulation, the ethylene/air chemical model[23] at the University of California at San Diego (UCSD) was used to generate the flamelet table with the FlameMaster[24] code. The ratio of chemical reaction characteristic time scale to turbulence characteristic time scale was evaluated. Numerical results were analyzed with the main emphasis focusing on the mixing mechanism, flame structure, and combustion mode judgment.

The present paper is organized in the following. Descriptions on the flamelet combustion model, flow governing equations, and numerical algorithm are given in tion 2. In Section 3, the ARI/G-P scramjet combustor configuration and the computation setups (such as computational grids, modeling of G-P jet, chemical reaction model, and boundary conditions) are presented. In Section 4, the numerical results of three nonreactive cases, i.e. Case 1 (only G-P jet on), Case 2 (only ARI jets on at equivalent ratio of $\varphi = 0.380$), and Case 3 (both ARI and G-P jets on at $\varphi = 0.380$), are given to analyze the mixing mechanism and the role of the G-P jet. In Section 5, the numerical results of four reactive cases (Cases 4–7) at $\varphi = 0.380$, 0.278, 0.199 and 0.167 respectively are presented in detail. Finally, some conclusions are drawn in Section 6.

## 2. Computational methodology

### 2.1. Laminar flamelet model

The main assumptions of the laminar flamelet model are as follows[1–5,9–15]:

(1) The turbulent flame can be regarded as a statistical ensemble of steady laminar diffusion flame structures (named as flamelets) embedded in the turbulent flow field.
(2) Each flamelet can be approximated as a 1D structure (Fig. 1) with respect to the mixture fraction according to the laminar diffusion flamelet concept presented by Peters et al.[9–11]
(3) All chemical time scales are short compared to the smallest turbulent time scale, and the combustion is in equilibrium relative to the turbulence; the thickness scale