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Accurate measurements and analysis of the thermal structure of turbulent methane/air premixed flame

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Abstract

This paper provides further experimental and numerical results concerning the premix turbulent combustion of lean methane-air mixture. For V-shaped flame, the experimental data were acquired by two-dimensional Rayleigh scattering technique. The main purpose of this investigation is to obtain quantitative information on the instantaneous thermal structure of the flame front for both laminar and turbulent conditions. Four values for turbulence intensity have been considered. The flame surface density is closely related to the two-dimensional temperature gradient. For turbulent combustion, a general decreasing trend of averaged temperature gradient was observed. However, this tendency is inverted for very high turbulence intensity when the instantaneous temperature gradient presents high fluctuations. The flame front thickness PDF and the curvature PDF decrease with the turbulence intensity. The joint PDF of curvature and the maximum of the progress variable's gradient have the tendency to rotate counterclockwise with the increase of turbulence intensity. Negative curvature brings more energy in preheat zone of flame and enhances combustion; consequently the temperature gradients increase.

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1. Introduction

In spite of their significant role in environmental contamination, fossil fuels still represent, due to their high availability and volumetric energy density, the primary source of global energy production. Lean premixed combustion is one of the most promising concepts for substantial reduction of pollutant emissions because it reduces the burning temperature, therefore leading to a reduction of NOx emission. Development of efficient combustion devices in a rapid and cost-effective manner requires predictive models that should be, as much as possible, universal and robust. Modeling a premixed flame in a turbulent flow environment remains a challenging task due to the non-linear coupling between the time and length scales of turbulence structures and those of the combustion process. Usually, the different turbulence-combustion interaction types are indentified by so-called combustion diagrams [1]. The turbulent combustion model can be identified given the turbulence intensity, the laminar burning velocity, the turbulence integral scale, the laminar flame thickness and the value of the Karlovitz number. From this point of view, the following regimes are usually encountered: flamelets regime and pocket or distributed reaction zones, respectively.

Usually, the turbulent burning rate is estimated in respect to flame surface density. However, the flame surface density is directly related to the temperature gradient. Consequently, to validate or to develop new turbulent combustion models, the accurate measurements of temperature gradients and of the flame structure have to be provided.

The flame surface density may be determined by using statistical processing of experimental measurements of temperature and its gradient [2] or by geometric methods [3]. For Bunsen flames, surface density distributions were reported by Deschamps et al. [4], Lee et al. [5], Chen and Bilger [6] and Bell et al. [7] and for V-flames by Shepherd [3] and Veynante et al. [8,9]. Flat flames were considered by Shepherd and Cheng [10], Shepherd et al. [11]. Lawn and Schefer [12] addressed the low-swirl and diffuser type burners, Renou et al., [13] the freely propagating flame, while Shy et al. [14] the cruciform burner. The profiles of surface density reported by Veynante et al. [9] are tall and narrow at upstream locations. The profiles become shorter and wider at downstream locations because the brush thickness increases due to turbulent diffusion. A similar trend is observed by Bell et al. [7] for the Bunsen burner. More recently, Sweeney et al. [15] presented a comparison of different method that can be used to calculate the surface density.

The paper is organized as follows. First, the experimental arrangement and the operating condition are described. Second, Rayleigh scattering theory and post-processing method are briefly introduced. In the last part, validation of the measurement for laminar flame with numerical results and turbulence influence on the flame front structure are presented.

2. Experimental setup

The experimental setup consists of a vertical wind tunnel (Fig. 1) adapted for laminar and turbulent combustion. Fuel and air are mixed far upstream from the burner nozzle to obtain a perfectly homogeneous mixture. Both fuel and air are filtered by high-efficiency filters (filtering efficiency is more than 99.9% for 0.1 mm particles) to avoid Mie scattering for small particles.

The flow is laminarized with a divergent-convergent channel and a series of screens and honeycombs providing a very low velocity fluctuation of u'=0.06 m/s for an average velocity of 4 m/s. At the exit of the convergent, a V-shaped flame is anchored on a 1 mm diameter heated rod. The rod is mounted on the central axis of the square exit section (80mm x 80mm). To avoid the effect of lateral mixing layers, the analysis zone (18×6.5 mm) is chosen in the near-field, located at 35 mm above the heated rod.

To obtain Rayleigh scattered images, this area is illuminated with a Nd-YAG laser (10Hz, 630mJ/pulse) with a second harmonic generating crystal that produced a Q-switch output in □=532 nm. Experimental scheme is shown in Fig. 2. The laser sheet is obtained by a combination of one spherical and two cylindrical lenses. Scattered light is filtered by Melles Griot CG-KG-3-2x2-2 and Croma ZET 532/10 filters to suppress flame chemiluminescence and to isolate the frequency of 532nm. Images are captured with a Photometrics CoolSNAPHQ2 696×520 resolution CCD camera, characterized by 2x2 binning and 12bit digitizer. A magnification ratio of 38.2 pixel/mm is obtained with a Micro-Nikkor 105 mm f/2.8 lens.

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