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Temporal evolution of flame stretch due to turbulence and the hydrodynamic instability

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Abstract

The temporal evolution of the strain rate on a turbulent premixed flame was measured experimentally using cinema-stereoscopic particle image velocimetry. Turbulence strains a flame due to velocity gradients associated both directly with the turbulence and those caused by the hydrodynamic instability, which are initiated by the turbulence. The development of flame wrinkles caused by both of these mechanisms was observed. Wrinkles generated by the turbulence formed around vortical structures, which passed through the flame and were attenuated. After the turbulent structures had passed, the hydrodynamic instability flow pattern developed and caused additional strain. The hydrodynamic instability also caused the growth of small flame front perturbations into large wrinkles. In the moderately turbulent flame investigated, it was found that the evolution of the strain rate caused by turbulence–flame interactions followed a common pattern involving three temporal regimes. In the first, the turbulence exerted extensive (positive) strain on the flame, creating a wrinkle that had negative curvature (concave towards the reactants). This was followed by a transition period, leading into the third regime in which the flow pattern and strain rate were dominated by the hydrodynamic instability mechanism. It was also found that the magnitudes of the strain rate in the first and third regimes were similar. Hence, the hydrodynamic instability mechanism caused significant strain on a flame and should be included in turbulent combustion models.

Keywords: Turbulent premixed flames; Flame stretch; Flame–vortex interaction; Hydrodynamic instability; Cinema stereoscopic PIV

1. Introduction

The use of turbulent premixed flames to reduce NO_x from combustion devices such as gas turbine engines has become a popular method of meeting increasingly stringent emissions requirements. However, the accurate simulation of such flames is still a challenge and improved models are required to design the efficient, clean, and robust engines of the future. In this mode of combustion, reactions typically occur in thin corrugated sheets that are similar in structure to dynamically stretched laminar flames. The area of these sheets or 'flamelets' largely determines the rate at which fuel is consumed, heat is liberated, and the turbulent flame propagates. Hence, an accurate model for the manner in which turbulence generates flame surface area is required.

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Turbulence can strain a flame surface due to: (1) velocity gradients related directly to the turbulence and (2) velocity gradients caused by the hydrodynamic instability, which are initiated by the turbulence. During the turbulence–flame interaction, turbulent structures exert strain on the flame surface, creating wrinkles. The wrinkled flame in turn causes channeling of the flow into negatively curved regions (concave towards the reactants) and away from positively curved regions (convex towards the reactants). This channeling causes additional strain and is the mechanism behind the hydrodynamic instability [1–3]. In weakly turbulent flames, measurements and simulations have shown the second mechanism to be significant in setting the scale of flame cells, controlling the turbulent burning velocity, and causing flame-generated vorticity [4–6]. Yuan et al. [5] showed that the turbulent burning velocity in such cases fluctuated in a periodic manner. As the turbulence intensity was increased, these fluctuations became more random; turbulence initiated the majority of flame surface area generation. However, even in such cases, the mechanism responsible for the hydrodynamic instability is always present. Analytic work by Bychkov [7] has shown the significance of the hydrodynamic instability and turbulence working in concert for strongly corrugated flames. Furthermore, experimental measurements have shown that the velocities induced by the hydrodynamic instability mechanism in moderately turbulent flames can be several times the laminar burning velocity [8]. That is, as stronger turbulence creates larger corrugations in a flame surface, the hydrodynamic channeling of flow also increases. Hence, straining of the flame caused by this channeling may be significant over a considerable range of conditions.

In general, turbulent combustion simulations require sub-models for the strain rate in order to determine the amount of flame surface area present [9–12]. Such sub-models are generally derived from Direct Numerical Simulations of two-dimensional laminar flame-vortex interactions [9,11,13]. However, such models are intrinsically simplified due to the *a priori* assumed toroidal vortex geometry and the reduced complexity of two-dimensional turbulence. Furthermore, with the exception of work by Paul and Bray [14], there has been little effort to include the additional strain rate imposed by the hydrodynamic instability.

Hence, a better understanding of the mechanisms responsible for the generation of flame surface area in a turbulent flame is required. To this end, this work addresses the following questions: (1) what is the expected strain rate caused by turbulence compared to that induced by the hydrodynamic instability, (2) does the hydrodynamic instability induce significant strain rate compared to the turbulence in a moderately turbulent flame, (3) what is the temporal evolution of the overall strain rate, and (4) when is each mechanism dominant? These questions are addressed using temporally resolved measurements of turbulence–flame and hydrodynamic processes in a fully turbulent premixed flame. The measurements were obtained using a recently developed cinema-stereoscopic PIV (CS-PIV) diagnostic [8].

2. Diagnostics and experiment

In order to investigate the processes straining a turbulent flame, detailed measurements of the temporally evolving turbulent flow field and flame front position were required. These measurements were obtained using the cinema-stereoscopic particle image velocimetry (CS-PIV) [8] system shown in Fig. 1. The diagnostics employ a dual forward scatter angular stereoscopic configuration. For the current experiment, the CS-PIV was operated at 1111 Hz, producing three-component vector fields every 0.9 ms. The field of view was 12.8×18.2 mm and the 16 pixel interrogation box used corresponded to 280 μm. With a 50% interrogation box overlap, this provided vectors every 140 μm. The flow was seeded with sub-micron TiO_2 that survived passage through the flame front. Adjusting seed levels in real time allowed accurate vectors to be computed in both the reactants and products simultaneously. The number of spurious vectors was less than 1.5% in both states.

The position of the flame front was determined by observing the dilation of the gas. This manifested itself as a significant drop in PIV particle image density. A two step predictor–corrector scheme was used to identify the contour of maximum particle density gradient. Using simultaneous CH-PLIF/Mie scattering diagnostics, this contour was shown to agree well with the true location of maximum gas density gradient and the center of the density gradient region [8].

The flame studied was stabilized on a 2D slot Bunsen burner. In order to minimize both thermo-diffusive and preferential-diffusive effects on the flame speed, a methane-air mixture at an equivalence ratio (ϕ) of 0.70 was selected. The Lewis number of the deficient reactant in this mixture is approximately unity. While there is significant scatter in measured Markstein numbers [15], the $\phi = 0.70$ case falls within the commonly reported range of $Ma \approx 0$ for methane-air flames, indicating that preferential diffusion effects are small. Hence, the propagation speed of the flame was expected to remain relatively constant, irrespective of the local stretch rate.

The experimental geometry consisted of the three slot burners shown in Fig. 1. The center burner, which anchored the Bunsen flame of interest,