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Propagation speeds for interacting triple flames

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ABSTRACT

Triple (or tribrachial) flames propagate through mixtures faster than the premixed laminar flame speed due to streamline divergence ahead of the flame base that decelerates the flow into the leading edge of the flame. When multiple triple flames are in close proximity, the bulk propagation speed of the structure can be even faster due to additional streamline divergence. Turbulent flames in partially-premixed conditions can encounter these situations, where multiple stoichiometric crossing are in close proximity, leading to multiple interacting triple flames being formed. Propagation speeds of the flame structure with respect the bulk flow for individual triple flames have been well characterized in previous studies, and the local flame speed of interacting triple flames have been reported; however, characterization of the propagation speed for the overall flame structure of interacting triple flame speeds has not been reported. The present work utilizes a laminar five slot burner, which allows both the concentration gradients and stoichiometric separation distance of two interacting triple flames to be varied. The bulk propagation speed of the multiple edge flames has been characterized as a function of the distance between the flame bases (or stoichiometric locations) and the local flame curvatures in order to better understand the conditions which lead to larger streamline divergence and faster propagation speeds. Interaction between multiple edge flames has been found to play an essential role in this propagation speed. Interacting edge flame speeds were modeled by modifying the relationship for single triple flame propagation speed with an added term for the interaction between the two flames to account for the increased effective divergence.

1. Introduction

Propagating edge flames can occur in partially premixed conditions where stratification between fuel and oxidizer causes an equivalence ratio gradient resulting in both lean and rich mixtures ahead of the flame base. These types of flames have been well characterized in the literature [1,2]. First observations of the triple (or tribrachial) flame were made by Philips [3] where three distinct flame branches were identified: a lean premixed, rich premixed, and diffusion flame branch. The propagation speed of the structure was found to exceed the laminar flame speed by as much as five times. Investigations by Kioni et al. [4] found that streamline divergence ahead of the flame base locally reduced the velocity into the leading edge of the flame, allowing the structure to propagate faster through the mixture. Further studies showed that the triple point, where the three flame branches meet, is at a stoichiometric mixture and propagates locally at the stoichiometric laminar flame speed [5]. The triple point was further confirmed experimentally to be at the stoichiometric mixture fraction [6]. The curvature of the premixed branches and flame heat release induces a pressure gradient that causes flow divergence ahead of the premixed flame base, which allows the velocity to locally reduce in the streamwise direction [7]. This aerodynamic effect allows the flame to locally travel at the laminar flame speed in the reduced velocity environment but at a faster overall propagation speed with respect to the bulk flow. Ruetsch et al. [7] showed that the propagation speed of a single triple flame was proportional to the square root of the density ratio between upstream reactants and downstream products in the limit where the equivalence ratio gradient was zero. It was also shown that the propagation speed of the triple flame structure was inversely related to the equivalence ratio gradient ahead of the flame base [8–11].

The equivalence ratio gradient ahead of the flame base was further shown to affect the propagation speed by changing the flame curvature at the leading edge [9–12]. With very low equivalence ratio gradients, the flame is wide and has large streamline divergence. As the equivalence ratio gradient is increased, the flammable mixture width decreases, leading to a smaller flame base, higher local curvature and subsequently smaller streamline divergence, depicted in Fig. 1, where ρ is the radius of curvature. Hirota et al. [13] further characterized this relationship and showed that the fuel concentration gradient was linearly related

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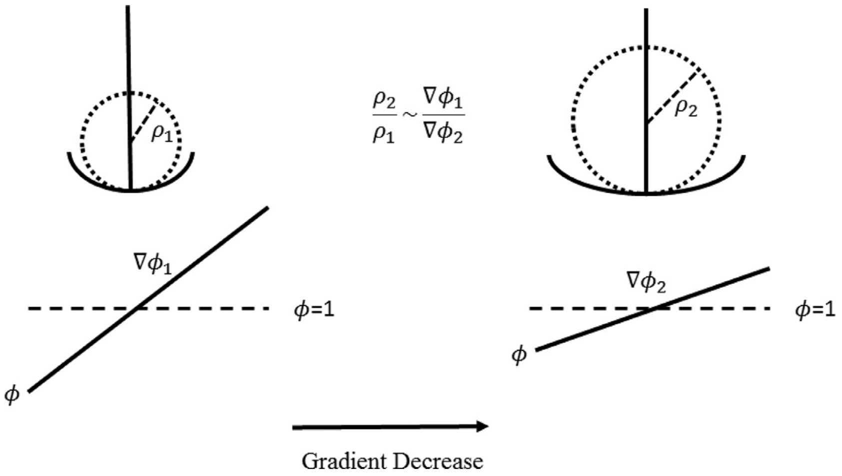

Fig. 1. Individual triple flame curvature response to equivalence ratio gradient.

to the flame curvature ahead of the flame base, similar to [10,11]. Ko and Chung derived the dependence between curvature and the fuel concentration gradient and showed that it was linear [9].

Kim et al. [12] characterized the propagation speed of a single triple flame through the bulk flow for different concentration gradients using a lifted, steady, laminar flame. The largest speed before blowoff, where the flame could no longer propagate through the flow, was taken as the freestream propagation speed of the triple flame with respect to the bulk flow. This approach was used since the effect of flow divergence will persist all the way to the burner exit if the flame structure is stabilized at a fixed lift off height and this can affect the boundary conditions, leading to an inaccurate description of the propagation speed. When the flame just blows off, the flame structure can no longer diverge the streamlines quickly enough to allow stabilization, leading to a well characterized speed. At relatively high equivalence ratio gradients, reduction in the gradient led to linearly higher propagation speeds due to larger diverging streamlines. A critical concentration gradient was shown to exist at very low gradient magnitudes where the propagation speed is maximum, first observed in [14], and it was speculated that this point represents the transition from a triple flame to a laminar premixed flame [12]. Further reduction in the equivalence ratio gradient no longer sustained a triple flame structure as the diffusion tail sufficiently weakened, leading to lower propagation speed. At low equivalence ratio gradients, the propagation speed varied linearly with equivalence ratio gradient [12], but over a larger range the propagation speed varies inversely with equivalence ratio gradient [8,9]. Propagation speeds in highly strained conditions, to the point where the premixed wings of the triple flame structure collapse into a bibrachial or monobrachial structure have also been studied [15–17].

Turbulent partially premixed combustion leads to non-uniformities in species concentrations, allowing multiple stoichiometric crossings in close proximity [18]. Since the stoichiometric crossings are close in length, multiple neighboring edge flames may stabilize. If the crossings are close enough, aerodynamic interactions may occur which change the stabilization of one or both flames. Domingo et al. [19] simulated a complex flowfield which led to numerous triple flames, many of which were in close proximity and interacting. In order to take a step towards understanding flame propagation through a more complex partially-premixed flowfield with the potential for many interacting triple flames, the propagation characteristics of interacting triple flames need to be further studied.

Wason et al. [20] studied steady laminar neighboring and interacting edge flames by constructing a five slot burner to create two stoichiometric crossings. Different flame stabilization modes were observed with interacting triple flames [20], similar to the twin flames from a concentric jet burner in [21]. With high equivalence ratio gradients, the flames were symmetric and acted as two individual triple flames that were not interacting. As the gradient decreased, interaction occurred, which led to a bifurcation where one flame was lifted higher than the other. The structure could be switched between two stable states with either triple flame at the lower liftoff height. The bifurcation was suggested to occur by small perturbations in the incoming diverging streamlines allowing the divergence of one flame base to dominate slightly over the other and the other flame being pushed to a higher lift off location. Once this structure is created, lowering the equivalence ratio gradient led to the inner premixed branches merging and the formation of a single continuous premixed structure with alternating rich and lean sections and multiple trailing diffusion flame branches. Further reduction in equivalence ratio gradient caused the triple flame structure to no longer exist, but instead create a large premixed flame.

In prior work [20], interacting triple flames were also found to stabilize at lower heights compared to a single triple flame with the same equivalence ratio gradient, suggesting larger propagation speeds than for single triple flames. However, these faster propagation speeds were not quantified. The local edge propagation speeds for the interacting triple flames in [21] were measured, but the overall free-stream propagation speed of the two triple flames together was not studied. The increased propagation speed of the interacting triple flame structure was proposed in [20] to be due to a larger streamline divergence ahead of the flame base caused by the effectively wider flame structure of two triple flames. This can be observed in Fig. 2, which shows streamlines of both a single and interacting triple flame under similar equivalence ratio gradients. These streamlines are computed from velocity fields measured in each flame as discussed later in this paper. The leading edges of the two flames have been overlapped to directly compare the differences in the streamlines. Clearly interacting triple flames have increased divergence which is likely the cause of increased propagation speed.

Later work by Kostka et al. [22] performed both Rayleigh scattering imaging for fuel concentration and combined hydroxyl (OH) and formaldehyde (CH_2O) planar laser induced fluorescence (PLIF) to identify whether chemical interactions existed between two interacting triple flames. Relative heat release measurements were made, which showed that no chemical interaction occurred between the interacting flames, concluding that the interaction was only due to aerodynamic effects. It was also shown that both