TRIPLE FLAMES AROUND TWO DROPLETS IN FLOWS WITH FUEL VAPOR

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Abstract

Flame structures around two fuel droplets in high-temperature flows are examined numerically. When the flame is sustained between the two droplets while the flow is pure air, an anchor-shape flame structure, i.e. the triple flame, is observed. Increasing the fuel vapor concentration of the upstream enlarges the flow's reactivity. As a result, two wings of the flame, viz. the fuel-lean and the fuel-rich flames, extend outward from the stoichiometric point. When far-field temperature or ambient equivalence ratio is increased, the flame propagates upstream and then evolves into a double-flame structure. Therefore, the impact of the preceding two environmental factors on the two burning droplets is outlined.

Introduction

Over the past several decades, many studies concerning laminar flames have been carried out and a variety of flame structures have been pointed out. During those of found flame structures, triple flame is particularly worthy of note. This is because that, in this flame, three different combustion modes including fuel-lean, fuel-rich, and stoichiometric burnings can be simultaneously observed. In the earlier study of Philips [1], an experimental investigation by making flame propagate along the interface between a layer of methane and air was conducted. As a result, a triple flame was observed. On the other hand, in the theoretical studies of Peter [2,3] by employing the concept of laminar diffusive flamelet, this flame could also appear in turbulent combustion. Basically, the generation of the triple flame is attributed to the incomplete mixing between fuel and oxidizer. For example, in the theoretical analysis of Buckmaster and Matalon [4], and Dold [5], it indicated that this special flame transpired when a premixed flame propagated into a non-uniform mixture.

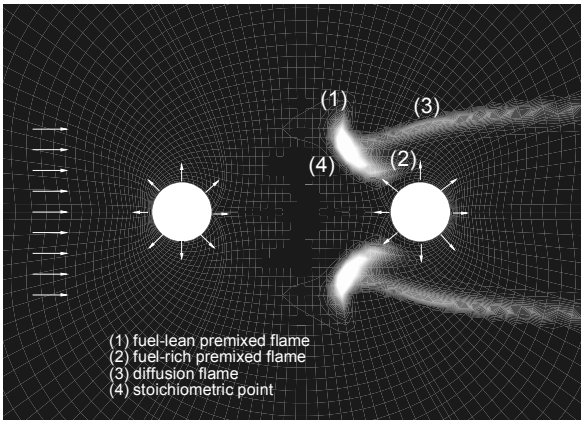


Figure 1: Triple flame structure around two droplets at ϕ=0.

For a two-droplet system, the leading droplet versus the trailing one intrinsically acts as a fuel vapor source [6]. Therefore, a similar condition of non-uniform mixture around the trailing droplet to that of the mentioned studies [4,5] is exhibited. Under such a situation, when gas-phase combustion is excited while the flame is sustained between the two droplets, the triple flame structure is elicited [7]. Figure 1 demonstrates the triple flame structures around two equal-sized fuel droplets. The first branch shown in Fig.1 is fuel-lean combustion whereas the second branch is fuel-rich burning. Both branches build a premixed flame. When the residual fuel and oxidizer penetrate through the premixed flame, they further react with each other and form a diffusion flame, viz. the third branch. Accordingly, a stoichiometric point is identified from where the three branches meet. To proceed farther into an analysis of the triple flame structure for two interactive droplets in spray, two important parameters of ambient equivalence ratio and far-field temperature will be taken into consideration in this study.

Method of Approach

The quasi-steady assumption in the gas-phase is adopted to facilitate solving the problem. Consequently, the governing equations consist of continuity, momentum, energy, and species conservation equations of the gas-phase [6]. The physical geometry shown in Fig.1 is irregular so that a body-fitted technique in association with non-orthogonal curvilinear coordinate is employed [8]. For gas-phase combustion, one-step global finite-rate chemical reaction for the burning of *n*-octane (C_8H_{18}) [9] is adopted. Four different parts of the boundary conditions, including upstream inflow, downstream outflow, axis of symmetry, and gas-liquid interface, are defined individually [6]. The SIMPLER algorithm [10] in association with power-law scheme is employed to solve the gas flow field. The line-by-line TriDiagonal-Matrix Algorithm (TDMA) is applied as the equation solver. With regard to the grid system, a hyperbolic tangent function is primarily used to stretch the grids outward from two droplets' surfaces to the far-field region along the centerline. The entire grid system is then generated by means of the elliptic differential equation technique [11]. Non-uniform staggered grid system of 41×65 is utilized. Rigorous convergence is assured by requiring the relative differences of the vaporization rates for two droplets between two iterations being smaller than 10^{-6}.

Results and Discussion

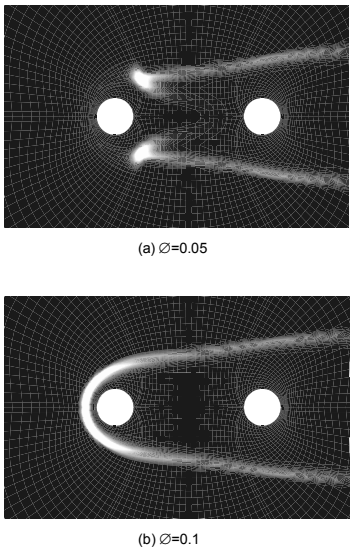


Figure 2: Flame structure around two droplets at T_∞=1000K

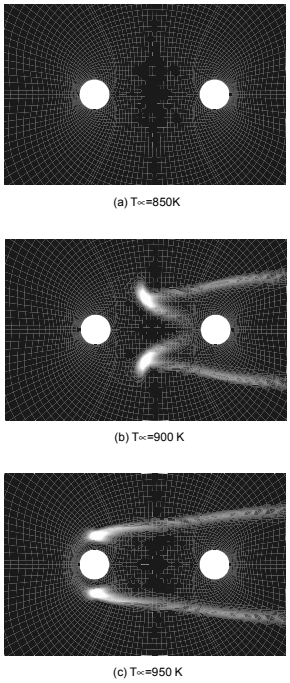


Figure 3: Flame structure around two droplets at ϕ=0.1

Figure 4: Vaporization-rate profiles of two droplets at T_∞=1000K.

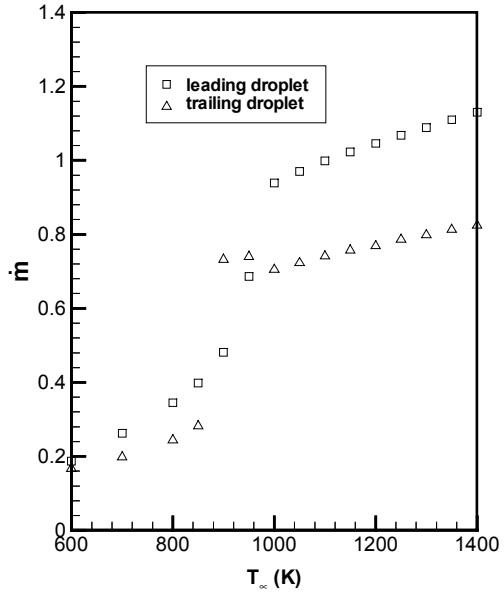
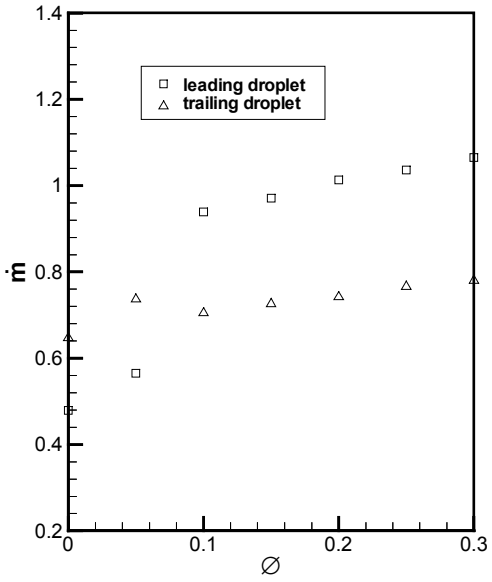


Figure 5: Vaporization-rate profiles of two droplets at ϕ=0.1.



Two 100μm-diameter *n*-octane droplets burning in a hot flow serves as a basis of the present study. The ambient pressure and Reynolds number are unitary atmosphere and 10, respectively. The droplet spacing is fixed to be 6 radii. First of all, the flame structures around the two droplets with ambient equivalence ratios (ϕ) of 0.05 and 0.1 are shown in Fig.2, where the far-field temperature is 1000K. In contrast to Fig.1, Fig.2(a) depicts that when ϕ=0.05 the triple flame propagates toward the leading droplet and is very close to it (Fig.2a). On account of relatively poor mixing, the fuel-lean premixed flame withered. When the ambient equivalence ratio is increased to 0.1, Fig.2(b) shows that

the flame further moves upstream and an envelope rather than the triple flame develops. Accordingly, it is recognized that increasing ambient equivalence ratio is conducive to flame formation.

On the other hand, the influence of the far-field temperature on the flame structure under ϕ=0.1 is sketched in Fig.3. As a whole, increasing the far-field temperature enlarges the flame speed; hence it evolves from a wake flame (Fig.3a) to a transition flame (Fig.3b) and eventually into an envelope flame (Fig.3c). In particular, when the far-field temperature is 950K, Fig.3(c) reveals that the stoichiometric point is located beside the leading droplet while the fuel-lean premixed flame encompasses it. Nevertheless, the strength of the first branch is weakened significantly.

Figure 4 demonstrates the vaporization-rate profiles of the two droplets with respect to ambient equivalence ratio under T_∞=1000K, where the droplets' vaporization rates have been normalized based on the room temperature air density (298K) and unitary velocity (1m/sec). When the ambient equivalence ratio is lower such as ϕ=0 and 0.05, because the flame is stabilized between the droplets (Figs.1 and 2a), the vaporization rate of the leading droplet is lower than that of the trailing one. However, once the flame encloses the two droplets at higher ϕ (e.g. Fig.2b), the vaporization rate of the former is amplified thereby increasing the cooling effect on the latter. As a result, the vaporization rate of the leading droplet is higher than that of the trailing one. In addition, it can be seen that the vaporization rates of both droplets tends to grow with increasing ambient equivalence ratio.

The vaporization-rate profiles of the two droplets versus far-field temperature under ϕ=0.1 are examined in Fig.5. Basically, the global exhibitions of the two droplets are similar to that shown in Fig.4. A monotonically increasing distribution of the leading droplet is always characterized, whereas a local maximum profile on that of the trailing droplet is found. The local maximum exhibited is owing to the appearance of the transition flame, as shown in Fig.3(b).

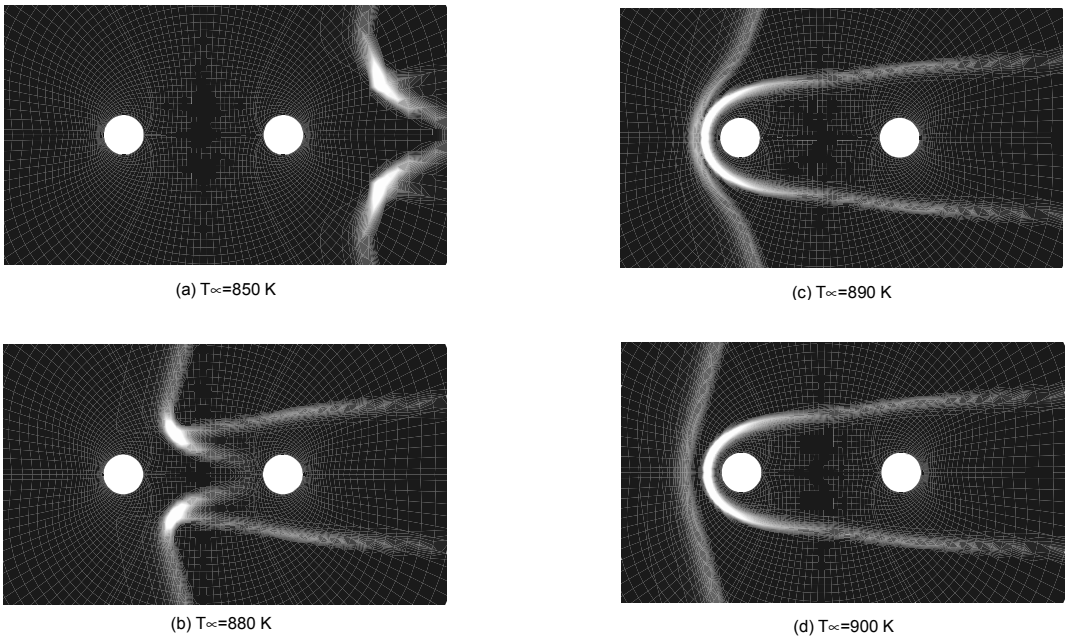


Figure 6: Flame structures around two droplets under various far-field temperatures at ϕ=0.3.

Subsequently, in Fig.6 the emphasis is placed on the flame structures under the condition of a higher ambient equivalence ratio, say, ϕ=0.3. It reveals that, as shown in Fig.6(a), the triple flame exists behind the two droplets at T_∞=850K. Once the far-field temperature increases slightly such as 880K, the triple flame is located between the two droplets (Fig.6b). When the temperature reaches

890K, the flame moves to the anterior part of the leading droplet. As a consequence, the triple flame converts into a double-flame (Fig.6c), which contains a fuel-lean premixed flame accompanied by a diffusion flame. It is worth noting that the premixed flame and the diffusion flame connect with each other. After that, with further increasing the far-field temperature, the premixed flame departs from the diffusion flame (Fig.6d) but the latter is retained in front of the leading droplet all the time. This arises from the fact that the diffusion flame is governed by the leading droplet's vaporization whereas the premixed flame by the upstream fuel vapor. Moreover, in comparison to Fig.1, Figs.6(a) and 6(b) depict that two wings of the triple flame, particularly the fuel-lean premixed flame, extend outward from the stoichiometric point in a significant way. The foregoing results elucidate that the flame structure is affected markedly by the ambient fuel vapor concentration. In other words, the flame structure, especially for the fuel-lean premixed flame, has a deep connection with the reactive environment.

The vaporization-rate profiles of the two droplets at ϕ=0.3 are plotted in Fig.7. It should be emphasized that the characteristic of the vaporization rate of the leading droplet surpassed by the trailing one merely takes place within a narrow temperature interval. It follows that the opportunity for the flame stayed between the two droplets is compressed.

Concluding Remarks

The influences of far-field temperature and ambient equivalence ratio on the vaporization and flame structure of two equal-sized droplets have been analyzed numerically. With increasing the temperature or ambient equivalence ratio, it was found that the flame tended to propagate upstream. As a result, the vaporization rates of the two droplets grew in a significant way. However, when the flame was sustained between the two droplets, viz. the transition flame, a triple flame structure was clearly observed. Under such a situation, a local maximum distribution on the trailing droplet's vaporization was characterized and the trailing droplet might surpass the leading one in vaporization rate. Two wings of the triple flame would extend outward from the stoichiometric point as the ambient equivalence ratio increased. On the other hand, when the ambient equivalence ratio was as high as 0.2 (i.e. $\phi \square 0.2$), as long as the flame encompassed the two droplets, a double-flame structure consisting of a fuel-lean premixed flame and a diffusion flame was exhibited. This implies, in turn, that the upstream reactivity plays a vital role on both vaporization rate and flame structure.

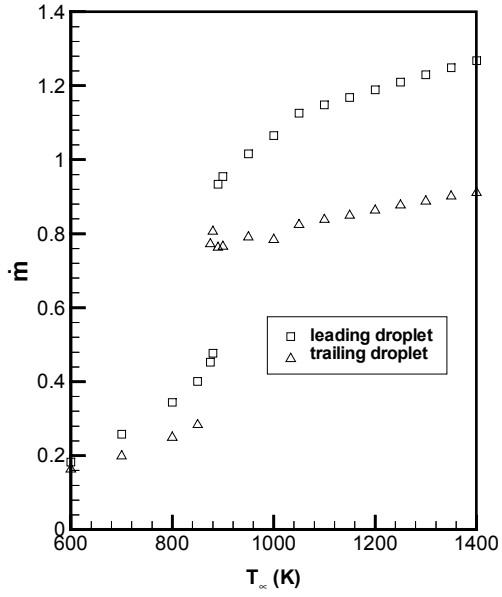


Figure 7: Vaporization-rate profiles of two droplets at ϕ=0.3.

Acknowledgments

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