ON SPECIFIC ASPECTS OF SPRAY-FLAME DYNAMICS

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Abstract
Recent experiments in Wilson chambers have shown that spray flames are much more sensitive to wrinkles or corrugations than the single-phase flame propagating in a gaseous mixture of the same equivalence ratio. This leads to spray-flame propagation faster than that of single-phase flame [1-3]. These observations, often carried out in microgravity [2], have motivated our recent numerical works on the spray-flame dynamics [4-6]. In the numerical approach, the spray is schematized by alkane droplets, located at the nodes of a centered 2D-lattice and surrounded by a gaseous mixture composed of alkane and air.

The compositional parameters of these studies are φ_G, the equivalence ratio of the gaseous surrounding mixture, φ_L, the liquid loading and φ_T, the overall spray equivalence ratio ($\varphi_T = \varphi_G + \varphi_L$). The geometrical parameters are s, the lattice spacing, L_X [resp. L_Y], the size of the computational domain parallel to propagation [resp. transverse to propagation]. All geometrical parameters are reduced by δ_L^*, the flame thickness of the stoichiometric single-phase flame.

The numerical results indicate that droplets can play an important role with respect to Darrieus-Landau instability (DL instability). On the one hand, the presence of droplets brings a perturbation, the level of which is enough to trigger the DL instability. On the other hand, when the DL instability is developed in the non-linear domain, the droplets induce additional wrinkles at smaller scales, which increase the effective surface and promote the spray-flame velocity.

Introduction

Among the earliest experiments on spray-flames, the flame propagation in rich sprays has been observed as being quite different from the single-phase premixed flames. More precisely, on the rich side $U_S(\varphi_T)$, the spray-flame speed is found larger than $U_L(\varphi_T)$, the single-phase flame of the same overall equivalence ratio.

An explanation for this velocity increase has been proposed by Hayashi and Kumagai [7,8] : the spray-flame speed is simply $U_L(\varphi_G)$, the velocity of the premixed 1-phase flame with the equivalence ratio of the gaseous surrounding mixture. In other words, droplets do not participate to propagation. Another possible cause for spray-flame speed enhancement, clearly observed in the experiments particularly at high pressure [1-3], is that spray-flames are subjected to front instabilities, whereas 1-phase flames remain planar in the same conditions.

From the numerical point of view, it is known that the computational domain needs to be transversally large enough to observe the development of the Darrieus-Landau (DL) instability. Another requirement for observing the DL instability is a level of the front initial perturbations high enough to trigger the instability. The first part of our results concerns a transversally small computational domain, where the front remains planar, while the second part is devoted to larger L_Y, for which the flame front becomes unstable with respect to DL instability.

The model

General 2-D conservation laws are solved in a computational domain corresponding to Fig.1, where droplets are located at the lattice nodes. The simplest chemical scheme for non-homogeneous combustion has been used [5] : a global irreversible one-step reaction governed by an Arrhenius law with heat of reaction depending on the local equivalence ratio. Non-dimensioning is performed with the use of the theoretical data related to the stoichiometric (gaseous) premixed flame, namely, T_b^*, the adiabatic flame temperature, δ_L^*, the flame thickness, and U_L^*, the laminar flame velocity. In what follows, the x-coordinate corresponds to the direction of propagation of a folded flame front. To define the mean position of this front, we perform an averaging in the transverse (y) direction of the temperature field to get $<T>_y(x)$. By definition, x_F, the front position, is given by $<T>_y(x_F) = 0.5$.

Results in transversally small computational domain

When $L_Y \le 14$, and whatever the initial perturbations of the flame front, the single-phase flame is found to remain flat, indicating that the transverse threshold of the DL instability is not reached. Our studies that concern sprays with rich overall equivalence ratios observe the propagation regime described by Hayashi and Kumagai [7,8]. The existence of this regime is however confirmed by our numerical approach only when the droplet radii R_d are large enough [5,6], i.e. when the fuel under liquid phase does not contribute to combustion spreading. For smaller radii R_d, the droplets vaporization enriches the surrounding gaseous phase that can become greater than φ_G, leading to a spray-flame velocity than depends on droplet radius in a rather complex manner [5]. To delimitate the existence domain of the Hayashi-Kumagai regime, we propose a criterion based on the spray Peclet number, which corresponds to the ratio of two characteristic times, namely the ratio of the vaporization time to the propagation time from a droplet to another

$$Pe_S = (\rho_L/\rho_b)(2R_d^2/s)\times U_L(\varphi_G)/D_{th}^*$$

where ρ_L, ρ_b^* and $D_{th,b}^*$ are respectively the liquid density, the burnt gases density and thermal diffusivity in the burnt gases. Hence, the criterion for observing the Hayashi-Kumagai regime simply reads

$$Pe_S \gg 1$$

Results in transversally large computational domain

When $L_Y > 14$, the computational box is large enough to allow the front to develop wrinkles, if initial perturbations are introduced. For the sake of an easy interpretation of the numerical results, we keep the Peclet number large enough to maintain the spray-flame in the Hayashi-Kumagai (HK) regime. We decide to choose the initial spray parameters in such manner that $Pe_S \approx 4$. More precisely, the composition of the spray is fixed to $\varphi_T = 1.6$ (with $\varphi_G = 1.1$ and $\varphi_L = 0.5$). The parameters that are supposed to change are s (and concomitantly R_d) and L_y (with L_Y= 24, 48, 72). Typical spray example is given in Fig.1, where ignition is performed at right hand side of the computation domain and propagation occurs from the right to the left.

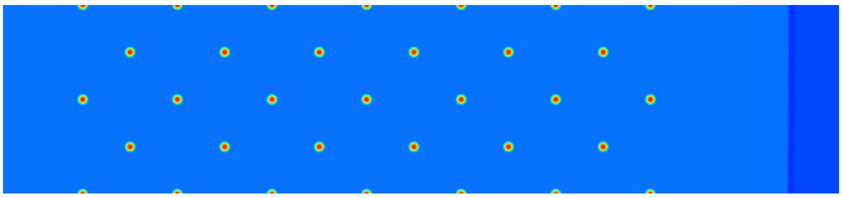

Figure 1. Initial fuel mass fraction: dark blue zone (on the right hand edge) indicates gases already burnt; flame then spreads to the left, hence first in a single-phase pre-mixture, then in the spray zone $\left(L_X = 233 ; L_Y = 48 ; s = 24 ; R_d = 1.08 \right)$

As mentioned above, the computational domain of Fig.1 is now transversally large enough to sustain DL instability. As ignition is carried out in the single-phase pre-mixture, DL instability classically develops as a cusped front. Then, the cusped pattern meets the successive rows of droplets. To illustrate the interaction between the DL affected premixed flame with the spray droplets, we have plotted three successive snapshots of the fuel mass fraction field and reaction rate field. As in our model the droplets can move, they are carried along, and stretched, by the flow (to the right) due to vaporization and gas expansion.

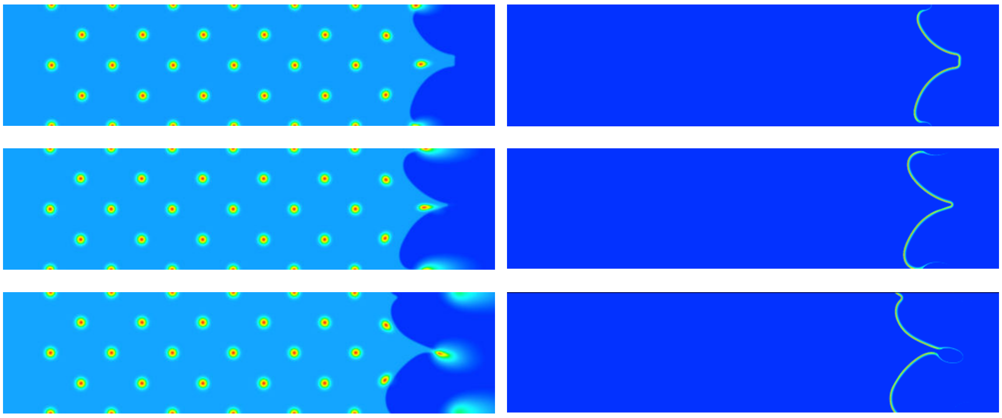

Figure 2. (a) Field of fuel mass fraction (b) Field of reaction rate $\left(L_Y = 48\ ;\ s = 24\ ;\ \varphi_G = 1.1\ ;\ \varphi_L = 0.5\right)$ at instants (t_1=38; t_1=41.8 ; t_1=45.6)

Fig.2 indicates that the droplets are transported by the flow back to the burnt gases much before their complete vaporization and mixing. This confirms that we are faced with the Hayashi-Kumagai (HK) regime of spray-flames. We note the classical cusped pattern of the flame front with a large length scale that corresponds to $L_Y = 48$. The main cusped pattern of the reaction rate is marked by additional wrinkles of smaller length scales due to droplets.

To illustrate the further development of the DL instability, we have gathered about 30 successive snapshots of the reaction rate field in Fig.3.a. Two successive snapshots are separated by the time interval $\Delta t = 4.75$. For the sake of comparison with the averaged front position x_F -which as been defined above- we have plotted $x_F(t)$ in Fig.3.b. When comparing Fig.3.a and Fig.3.b, this slope allows us to assess the mean front velocity that corresponds to every reaction rate profile.

At time t=28, in Fig.3.b we observe a change in the slope of the position curve. This indicates that the DL affected flame meets the spray. In other words, in the range $0 \leq t \leq 28$ we observe the development of the (classical) Darrieus-Landau instability in a single-phase pre-mixture. At the end of this time laps, the speed-up of the flame has enhanced the flame speed from $U_L(\varphi_G = 1.1) = 0.99$ to $U_{DL}(\mathrm{L}_Y = 48) = 1.26$, the single-phase flame speed affected by DL instability.

After time t=28, the cusped form of the front becomes more corrugated because the flame meets the droplets and we are faced with a spray-flame in the HK regime. A spray-flame speed-up again occurs as shown by Fig.3.b. When the spray-flame leaves the last row of droplets, the spray-flame speed is $U_S(L_Y = 48) = 1.43$.

(a)

(b)

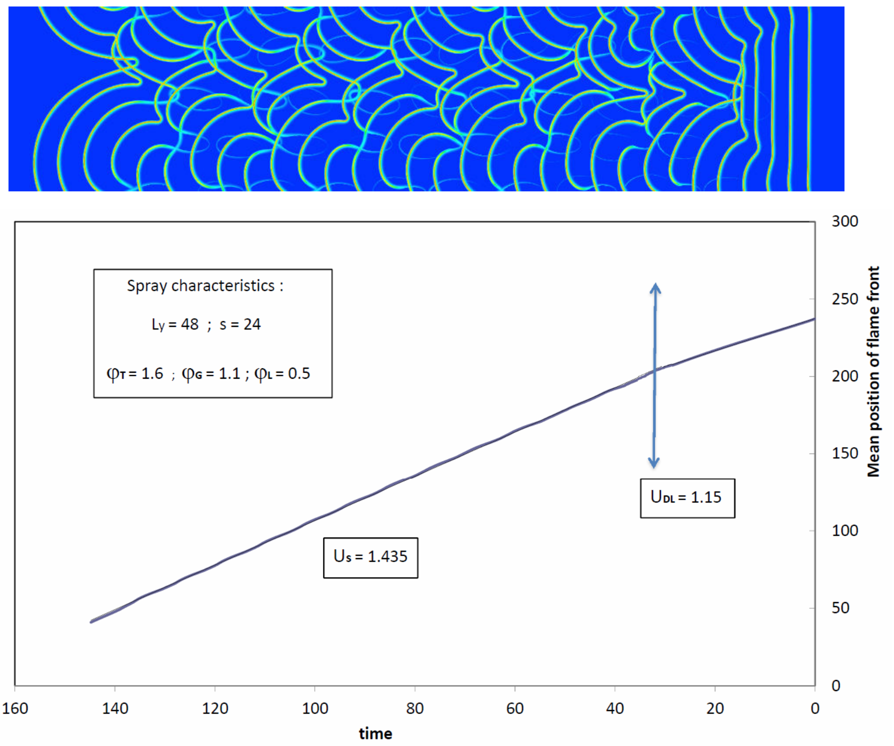

Figure 3: Spray-flame affected by Darrieus-Landau instability $\left(L_Y = 48\ ;\ s = 24\right)$
(a) Superimposition of successive snapshots of the reaction rate field
(b) Mean x-position of the combustion front vs. (time) : spray-flame speed is given by the slope of the curve.

Conclusion

To sum up this numerical study, in Table 1 we have gathered the spray-flame speed for various pairs $\left(L_Y\ , \mathrm{s}\right)$. The first column corresponds to a case stable vs. DL instability. The second and third columns, which roughly report the same results, allow us to downgrade the role played by the number of droplets. On the other hand, the last three columns underline the role of the box size transverse to propagation. First, the DL instability of the premixed single-phase flame gives a flame speed-up that increases with L_Y. Second, the DL instability of the spray-flame -in the HK regime- provokes an even stronger speed-up that also increases with L_Y. The difference between both accelerations is undoubtedly due to the role of the droplets that bring additional wrinkles to the DL-affected flame front.

Table 1. Spray-flame speed U_s for various values of L_Y and s

L_Y / s	12 / 12 (stable)	24 / 12	24 / 24	48 / 24	72 / 24
U_{DL}	$U_L(\varphi_G = 1.1) = 0.99$	1.15	1.15	1.26	1.37
R_d	0.525	0.54	1.08	1.08	1.08
$Pe_s\left[U_L(\varphi_G)\right]$	1.84	1.84	3.89	3.89	3.89
U_s	0.95	1.21	1.24	1.43	1.53

Funding

This study was granted by the Research Program " Micropesanteur Fondamentale et Appliquée "- GDR 2799 - CNRS/CNES under the contract CNES/140569.

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doi: 10.4405/39proci2016.V1