Potential accelerating effect of thermal radiation in dust flame propagation : some experimental evidence

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1 Introduction

The role of thermal radiation in premixed flame propagation has been a matter of debate for decades. And it is not only a challenging scientific point, it has significant practical implications. For instance, a route to explain the Buncefield explosion ([4]) was the implication of tiny particles raised by the blast and promoting flame acceleration through enhanced heat exchanges by thermal radiation in the flame front. In dust explosion protection, the flame is implicitly supposed to propagate like a in a gaseous mixtures but if thermal radiation is dominant for some dusts, many aspects concerning the way to mitigate the explosions for those particular dusts would need to be revised ([7]).

A review of the various aspect linked to this question was proposed recently ([2]) suggesting in particular that aluminium dust flames could be subject to heat radiation dominated flame propagation regimes. A very similar point was made for the specific case of premixed gases seeded with particles ([5]). But to date, experimental evidence is severely lacking.

It is intended to provide in this communication, preliminary experimental evidence of the potential promoting role of thermal radiation is dust flame propagation.

2 Experimental setup

2.1 Infrastructure

Experiments were done using the flame propagation tube (figure 1) already used in a number of studies (for instance [6] The experimental chamber is a vertical tube (length 1.5 m and diameter 10 cm), filled with the dust cloud by the bottom thanks to a fluidized bed device. The suspension is rising slowly upwards until complete filling (duration 30 seconds). This way, the suspension may be very homogeneous. The cloud is ignited (spark) at the bottom after having stopped the flow, shut the upper part of the tube with a gate valve and removed the suspension generator. The flame is then propagating upwards freely without being thrusted by the expansion of the burnt products which are vented out through the open end. The dust concentration is controlled by weighting the dust suspension generator before and after the tests, and measuring the volume of the gas flow.

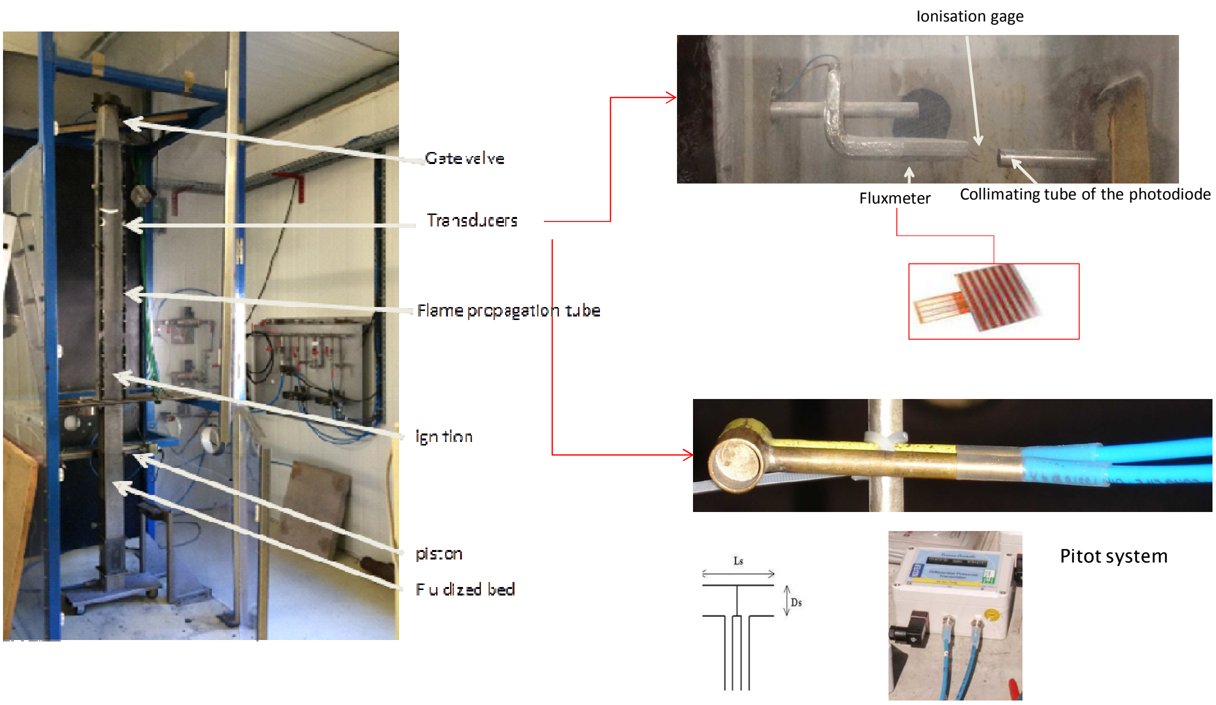

Figure 1. Experimental setup

2.2 Measurements

High speed video is used to obtain an accurate measurement of the flame speed. Besides a set of transducers is used and installed at about 1 m from the bottom end of the tube (figure 1 right) :

- A fast response fluxmeter. This device (Captec technology) is a thin polymer sheet on each side of which a collection of thermocouples are inserted. On side of the sheet is glued on a cold wall acting as a reference. The voltage between both sides of the sheet is proportional to the heat received thermal flux. In this particular version of the device, optically shielded and bare strips alternate is such a way that only the radiative flux is measured. The response time is lower than 0.1 s. The wavelength absorption range is 0.1 to 12 µm i.e. over nearly all the absorption spectra of CO_2 and H_2O. The absorptivity is 0.5. Note the fluxmeter is “looking” in the direction of the flame while the photodiode is transversal to the direction of the propagation.

- A pitot sensor pointing towards the flame front and able to measure the flow velocity ahead of the flame. This technique coupled with the flame velocity measurement (video) was used to obtain the burning velocity in situations where the "tube method" was not applicable as explained hereafter.

2.3 Burning velocity

As shown by Andrews and Bradley ([1]), a number of methods exist to try and measure the laminar burning velocity of premixed flames. In tubes open at the ignition and closed at the other end, the mixture ahead of the flame is supposed to be at rest so that the burning velocity can be deduced applying the mass conservation on a control volume limited by a cross section upstream, the flame area downstream and the joining portion of the tube (Figure 2). This technique is in practice accurate only if the flame area is easy to determine which is not often the case is rather large tube. In this case, an alternative consists in measuring at the same point of the flame, preferably on the top, the flow velocity and the flame velocity. The difference between both would give the burning velocity provided the angle of the flame relative to the direction of the propagation is known. A comparison between both methods is shown on figure 3 in the case of premixed methane-air mixtures. A good agreement is found.

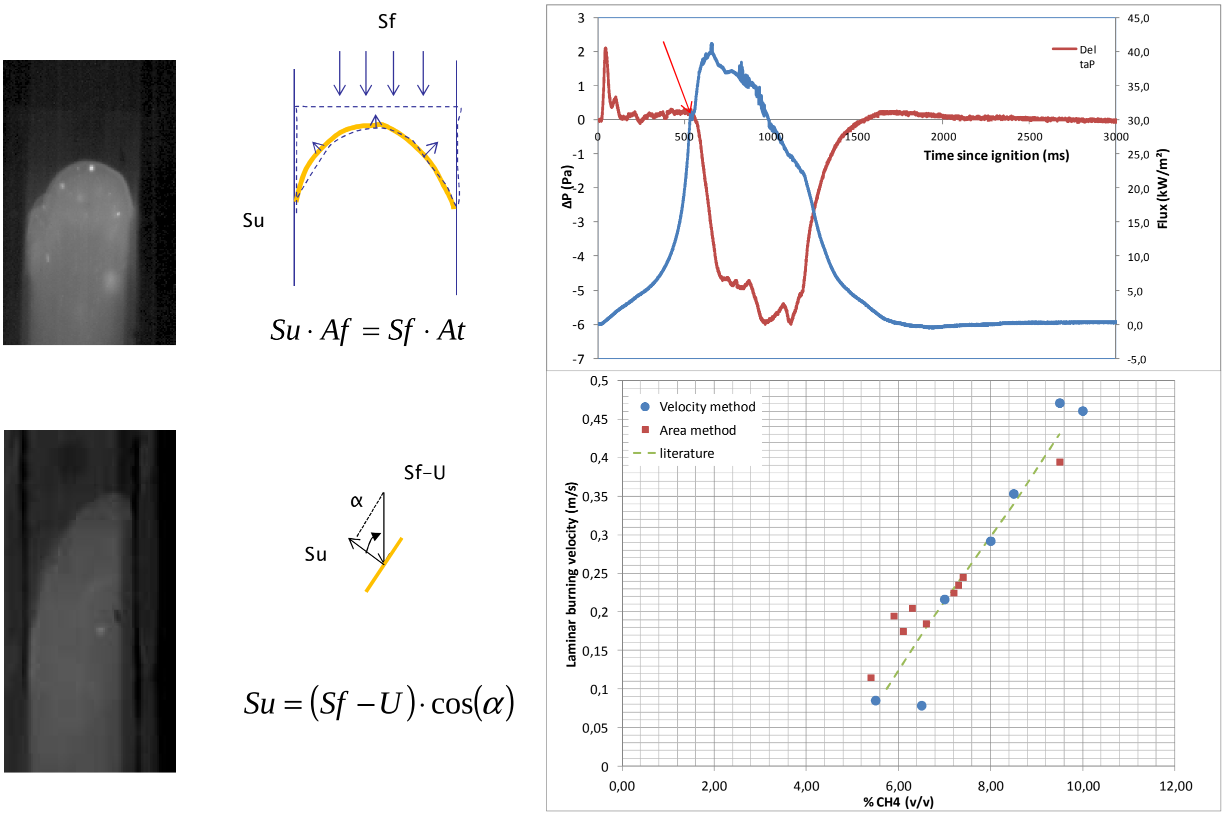

Figure 2 : laminar burning velocity methods

2.4 Combustible mixtures

A large number of experiments were performed using methane-air mixtures with and without particles in suspension (Alumina and SiC). Some tests were done with aluminium dust air mixtures. The characteristics of the dusts are given in table 1.

Table 1: main characteristics of the dusts.

Nature	Specific mass (kg/m^3)	Mass median diameter (µm)	Sauter mean diameter (µm)
Aluminium oxide	3950	80	40
Silicium carbide	3210	30	15
Aluminium	2700	20	10

3 Results

Heat fluxes measurements were presented earlier ([8]). The measured values are recalled here in view of comparison with the flame dynamics. The reference situation is that of methane air mixtures and the results are presented graphically on figure 3. Clearly, the amount of energy lost by radiation is not large but may play some role in the near limit situation since it is believed that flame may extinguish as soon as the amount of energy lost by the flame amounts about 10%.

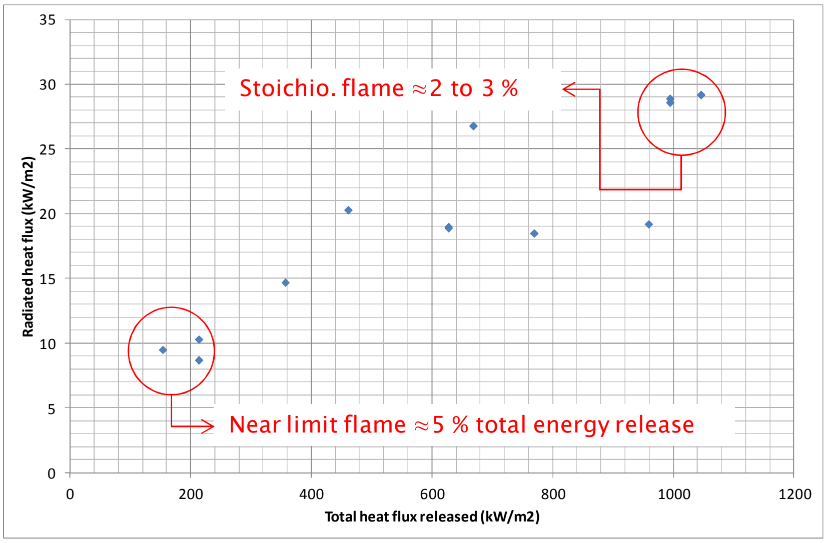

Figure 3. radiated heat flux as function the total heat flux released (methane air flame)[1]

When alumina particles are added, a continuous reduction of the burning (and flame) velocity is observed. But at the same time, the radiated heat flux diminishes which might simply imply that the flame temperature diminishes. The reduction of the temperature should be linked with the absorption of heat by the particles (conductive exchanges). Extinction is observed when the radiated heat flux amounts that of the limit CH_4-air flame. Surprisingly, alumina particles do not seem to increase the radiated heat flux. A closer look to the optical properties of this material, reveals that, in the spectral range of methane-air flame (a few microns), the absorption/emission coefficient is as low as 0.1 to 0.2 which may explain this unexpected result.

[1] The total flux is calculated on the basis of the experimental values of S_{lad} and theroretical T_{ad} (Tseng and al., 1993) using expression $\Phi_{tot} = \rho_g \cdot S_{lad} \cdot (T_{ad} - T_0)$

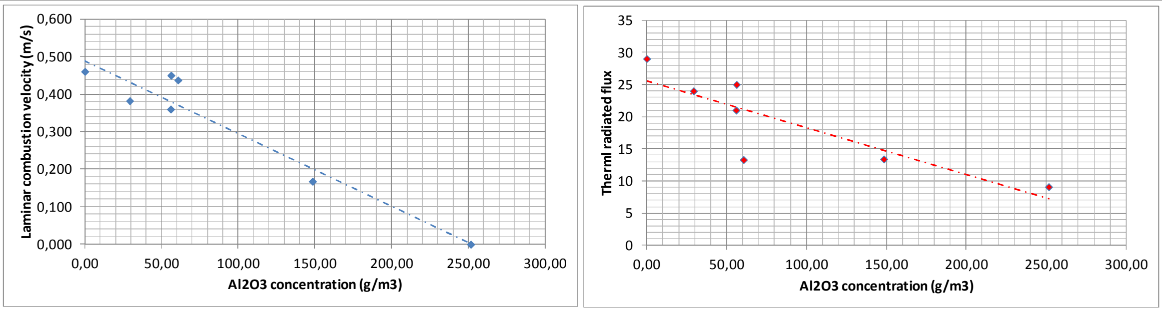

Figure 4. methane air flame (stoichiometry) seed with alumina particles

SiC particles have a much higher absorption/emission coefficient (0.7) and a different behaviour is observed (figure 5). And a different result is obtained. It seems that for small particle concentrations (below 150 g/m3) the laminar burning velocity increases so as the radiated heat flux showing a link between both parameters. For higher particle concentrations, the amount of heat absorbed (by conduction) by the solid increases which leads to a reduction of the flame temperature, burning velocity and flux.

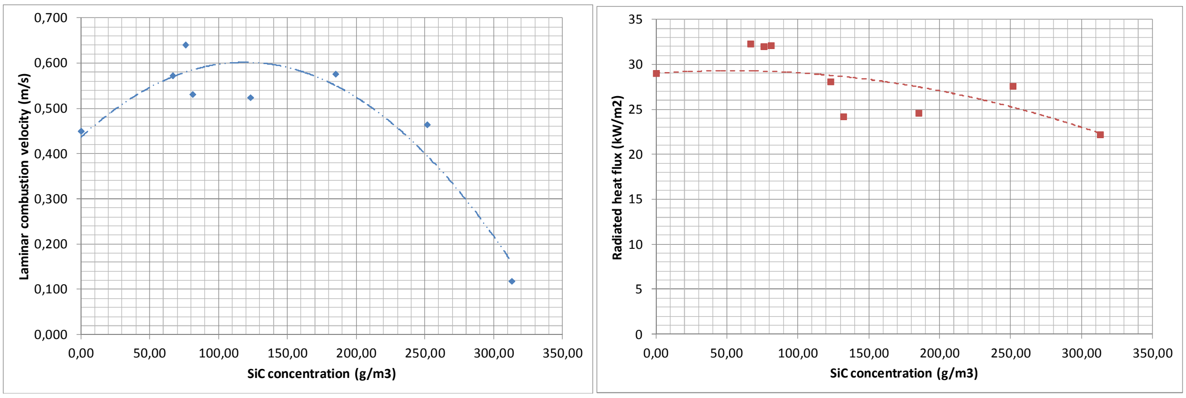

Figure 5. methane air flame (stoichiometry) seed with SiC particles

There seems to be a possibility for a promoting effect of the radiated heat flux even with rather low additional flux, since a 10 to 20% increase of the laminar burning velocity seems to be associated to a 10% increase of the radiated heat flux. It is however possible that the radiated heat flux could be underestimated because of the deposits of powder on the sensor.

Note that the temperature of the methane-air flame is rather low and much more effect would be expected with a large burning temperature like in aluminium dust air flames. Alumina and aluminium are poor emitters as compared with SiC but it can be expected that the much larger combustion temperature in the flame (3300°C as compared to 1900°C) would more than compensate for the lower emissivity. Tests were performed with increasing dust concentration (figure 6). Remember that the tube is open at the ignition end (bottom). Clearly when the concentration of dust is rather low, perhaps below 500 g/m^3, the flame speed reaches a constant value, 0.4 m/s at 80 g/m^3, 0.7 m/s at 350 g/m^3, suggesting a burning velocity on the order of 0.3 m/s (in line with available data). But above a certain concentration threshold, a tremendous flame acceleration is observed : the flame speed increases from a few m/s in the ignition zone up to 50 m/s after one meter of propagation. Although the present authors already witnessed abnormally violent explosions in this same configuration, with aluminium dust, it is the first time they managed to record the phenomenon.

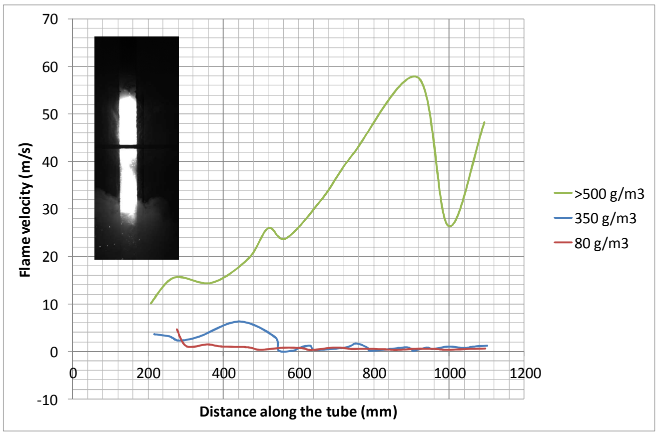

Figure 6 : self acceleration of flames propagating in a aluminium dust-air cloud

4 Conclusion and perspectives

In this paper, some evidence of the promoting role of thermal radiation on the flame propagation process in dust cloud is provided. It seems to confirm some theoretical predictions ([5]). One potential consequence of the interaction of thermal radiation in the propagation process would be fast flame self acceleration ([2]). The present data seem also to confirm this view. Furthermore, the manifestation of the self acceleration seems to depend on the amount of dust in the cloud. As far as aluminium particles are concerned, not less than 500 g/m^3 which is well above the stiochiometric conditions. This trend was suggested earlier in theoretical studies ([3]). However, this work needs to be pursued first to confirm this self acceleration process and second to investigate further the condition of appearance (size of the device, dust concentration, particle size effect,…). In parallel a theoretical study is in progress to try and explain these findings.

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