Understanding the role of thermal radiation in dust flame propagation

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Abstract

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 proposed explanation of the Buncefield explosion (*HSL, 2009*) was tiny particles were raised by the blast and promoted flame acceleration through enhanced heat exchanges by thermal radiation through the flame front. In dust explosion protection, the flame is implicitly supposed to propagate like a in a gaseous mixtures but if it happens that 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.

The present research team (Ben Moussa et al., 2013, 2017; Proust et al., 2017a, 2017b) and another one (Julien et al., 2015) have been working on this subject for some time. The scientific problem was settled and a significant experimental effort was done. It was shown that thermal radiation could accelerates flames possibly to a considerable extent but without any firm confirmation.

In the present paper a numerical modelling of this problem is proposed to help understanding the physics of the flames seeded with particles and especially aluminum dust flames. The code uses the discrete element method and was developed from scratch over the last years. Some information to understand how the code work is provided into the paper and the results are compared to the experiments. From this comparison it can be concluded that thermal radiation is readily capable of strongly accelerating dust flames depending on the experimental conditions. Large scale experiments are now needed which however could be complicated to perform.

Keywords: *aluminium dust explosion, thermal radiation, dust flame propagation*

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 proposed explanation of the Buncefield explosion (*HSL, 2009*) was tiny particles were raised by the blast and promoted flame acceleration through enhanced heat exchanges by thermal radiation through the flame front. In dust explosion protection, the flame is implicitly supposed to propagate like a in a gaseous mixtures but if it happens that 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.

Ben Moussa et al. (2015, 2017) and Liberman et al. (2015) claim that heat radiation enhanced flame propagation is possible especially for high temperature burning metal particles (like aluminium) : hot burnt particles in the products produce backwards heat radiation towards the cold reactants, preheat them and promotes burning . Liberman claims that very large flame acceleration may be possible.

Unfortunately, an analytical appraisal is possible only under very strong assumptions like infinitely fast combustion and/or Beer-Lambert model for radiative transfers (Ben Moussa et al., 2017; Deshaies et al., 1985; Liberman, 2015; Bidabadi et al., 2013). As shown elsewhere (Proust et al., 2017), the later assumption is not valid so that a representative theoretical analysis remains difficult.

In addition, experimental evidence is clearly still lacking. Recently Proust et al. (2017a, 2017b) showed new results aiming at illustrating the potential flame propagation promoting effect of thermal radiation and at providing measurements strategies to highlight the underlying complicated physics.

In this communication, after recalling some recent experimental data on the subject, the authors investigate the phenomenology using an accurate modelling tool based on the discrete element method. The model compares very well with experimental results. It is shown that heat radiation can greatly promote flame propagation under certain conditions.

2. Some experimental evidence

Experiments were done using the flame propagation tube (fig. 1) already used in several studies (for instance in Proust, 2006). The experimental chamber is a vertical tube (length 1.5 m and diameter 10 cm), filled with the dust cloud from the bottom using a fluidized bed device. 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 freely propagating upwards 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 by measuring the volume of the gas.

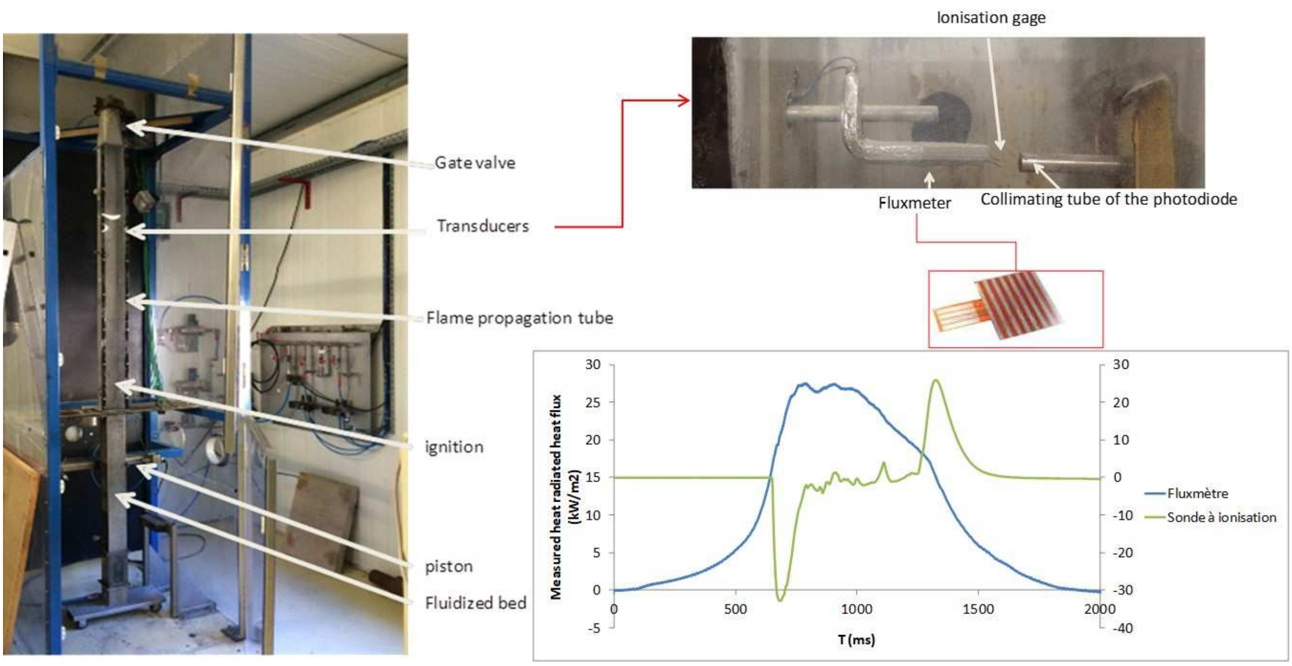


Fig. 1. *Experimental setup and heat flux-ionisation gage signal for a stoichiometric CH_4-air flame*

High speed video was used to obtain an accurate measurement of the flame speed and of the flame area. From this, the laminar burning velocity was obtained using the well-known "tube method" (Andrews and Bradley, 1972). Besides, a fast response fluxmeter was used (Captec technology :0.1 to 12 µm, 0.1 s response time, "looking" in the direction of the flame) coupled with an ionization gage. A typical example of the signals is shown on Fig.1 (bottom right) for a stoichiometric methane air flame (without particles). The heat flux is nearly 30 kW/m^2 (only 2-3% of the total heat release rate).

Experiments were performed using methane-air mixtures with and without particles in suspension (SiC, VMD=30 µm and SMD=15 µm). Tests were also done with aluminium dust air mixtures (VMD=20 µm and SMD=10 µm).

SiC has a rather large absorption/emission coefficient (0.7). For small particle concentrations (below 150 g/m^3), the laminar burning velocity increases so as the radiated heat flux (Fig. 2) suggesting a link between both parameters. For larger particle concentrations, the laminar burning velocity drops.

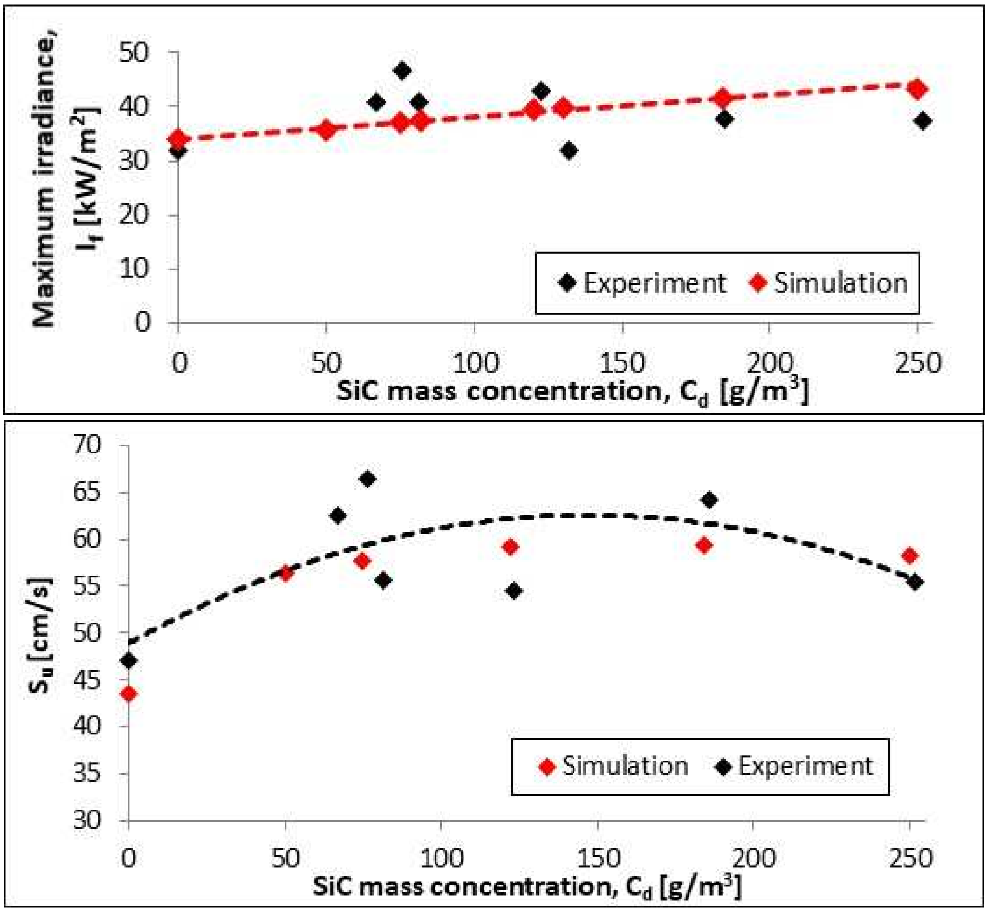
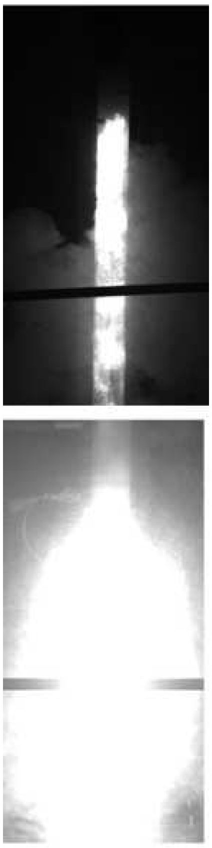


***Fig. 2:** methane air flame (stoichiometry) seeded with SiC particles*

Alumina and aluminium are poor emitters (emissivity 0.1 to 0.2) 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 for methane air flames) would more than compensate the lower emissivity.

Tests were performed with aluminium dust air mixture at varying dust concentrations (Fig. 3). When the concentration of dust is low (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. But above a certain concentration threshold (above 500 g/m^3), 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. The experimental device was significantly impaired preventing further testing.



80 g/m^3

>500 g/m^3

Concentration	Speed (m/s)	Su (m/s)
80	0.5	0.15
350	0.7	turbulent
>500	10 to 60 m/s	accelerating

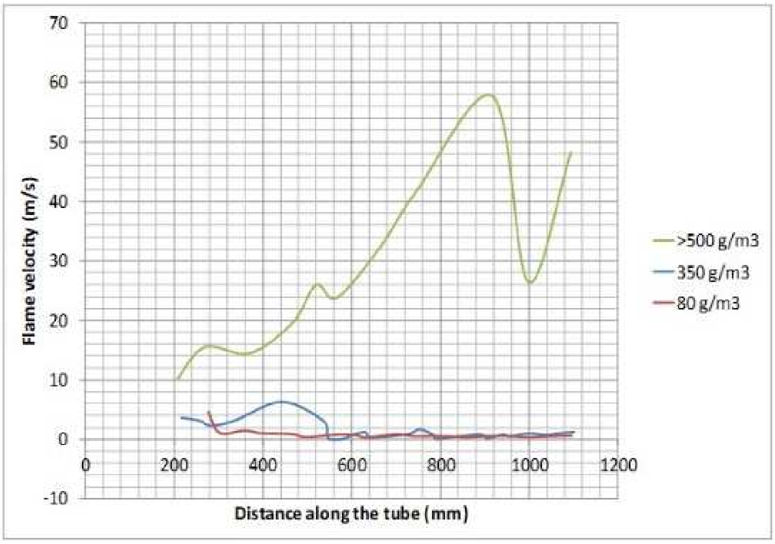


Fig. 3 : self-acceleration of flames propagating in an aluminium dust-air cloud

3. Numerical tool (RADIAN)

The present experimental data suggest that heat radiation transfer through the flame may promote flame propagation possibly with a strong acceleration, as suggested by Liberman (2015), but a strong phenomenological approach is needed.

But many complex and non-linear phenomena intervene (combustion, heat transfer by conduction between phases, heat transfer by thermal radiation between particles, …) so that a complete analytical approach remains difficult without simplifying assumptions.

To preserve the predictive capability of the mode,l integrating most of the non-linear phenomena listed above, a Discrete Element Method (Cundall and Strack, 1983) was implemented. With this technique, the detailed mechanical interactions between the particles ("discrete elements") and between the particles and the boundaries can be described in detail. Originally, this modelling technique was developed to better represent granular flows (Munjiza and Cleary, 2009) and mechanical contacts (Nguyen et al., 2008a). Heat transfer was introduced as a natural expansion of the DEM principles (Nguyen et al., 2008b). More recently a coupling between CFD (Computational Fluid Dynamics) and DEM was established (Zhong et al., 2016) to better describe fluidized beds.

In the present situation, an accurate representation of the physics is looked for, at the expenses of the industrial representativity if needed. The interactions between the phases need to be finely described. The following assumptions (Ben Moussa, 2017) were made:

- The particles are spherical, homogeneous and monodisperse;
- The gaseous reactants are transparent to heat radiation (but not the products);
- The gaseous reaction is described using a one-step global reaction (Coffee et al., 1983);
- The combustion of the aluminium particles is described using an experimental "d^2 law " (Ben Moussa et al., 2007);
- No velocity sliding between the phases.

Otherwise it was shown that, for particle sizes and concentrations under consideration (below 100 µm and below 10 kg/m^3), multiple scattering of the thermal radiation could be ignored, that the temperature inside the particles is homogeneous and that a Nüsselt number of 2 was a very good approximation to calculate gas-particle heat transfer. Since the particles are far from each other (10 diameters), each particle appears as a "point source" to its neighbouring particles. The point source model was thus implemented in which the Mie theory (van de Hulst, 1981) was incorporated to calculate the absorption, emission and scattering coefficients of the thermal radiation (which depend on the angle of the incident light) providing the most accurate and general description. The obscuration effect by the particles located between a source and a target is incorporated.

A tricky point is the simulation of the thermal radiation emission by the burned gases containing radiative species like water and carbon dioxide. From the work of people like Hottel and Sarofim (1967), it is possible to calculate the emissivity of a given volume of gas at a uniform temperature. In the present context, the burnt gases were discretized in small spheres in contact with each other. By trial and error, it was found that the maximum radiated heat flux was constant when the "gaseous" particles are smaller than 50 µm.

Four equations are solved simultaneously :

- The 3D transient equation of heat transfer in the gaseous phase with the one step combustion source term of Coffee, with the convective exchange with the particles and with the thermal radiation sink of the gaseous emitting species (CO2, H2O);
- The heat balance equation for each particle accounting for the net heat radiation flux (emission/absorption) with the solid and gaseous particles, for convective heat exchange with the gas phase and for combustion ("d^2 law ");
- The radiation exchange between solid particles using the DEM methodology (the "connectivity matrix") and the point source approximation;
- The radiation exchange between "gaseous" particles using the DEM methodology and the point source approximation.

An explicit finite difference scheme is applied on a regular mesh using a small enough Fourier number to ensure the convergence (1/6). The particles are randomly distributed through the mesh. The cell size is chosen so that the various scales of the flame propagation can be represented. It was shown that the results converge with a cell size on the order of 10^{-6} m and a time step of 10^{-7} s. In practise, not more than one particle could be present in a cell.

A representation of the “gaseous particles” of the burnt gases, of the dust particles and of the mesh is shown on Fig. 4. To fully compute a propagation in the experimental conditions above requires a week on a powerful workstation. The details of the mathematics and the step by step validation procedure are out of the scope of the present paper.

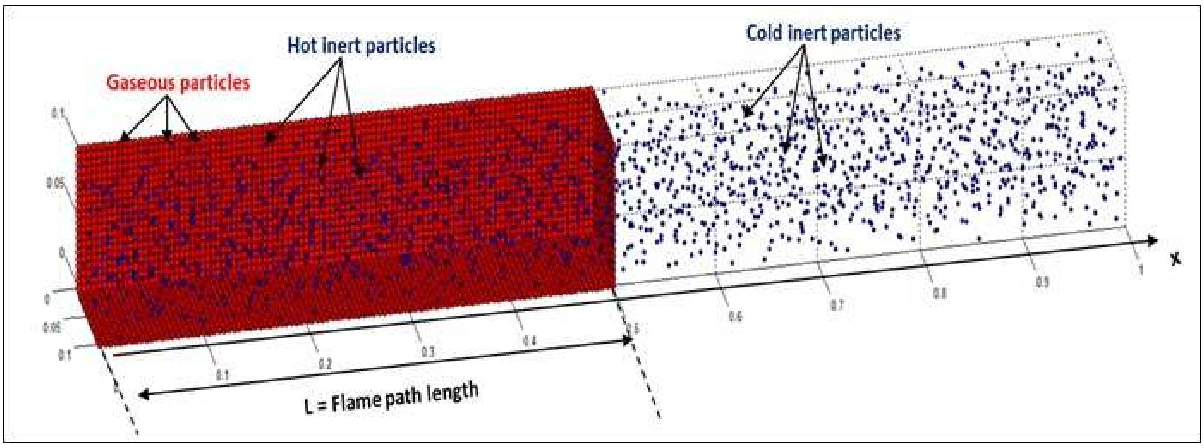


Fig. 4 : *example of the discretization/repartition of dust particles to compute a flame propagating in a methane-air mixture seeded with inert SiC particles.*

4. Results

Preliminary results were obtained for methane air flames (without dust – Fig. 5) and for aluminium dust air flames (Fig. 6) and are compared to data from the literature. For aluminium dust air flames, since experimental results were obtained using very small-scale apparatuses (much smaller that the absorption length), thermal radiation exchanges were neglected to speed up the simulations. A good agreement is found comforting the usage of the tool.

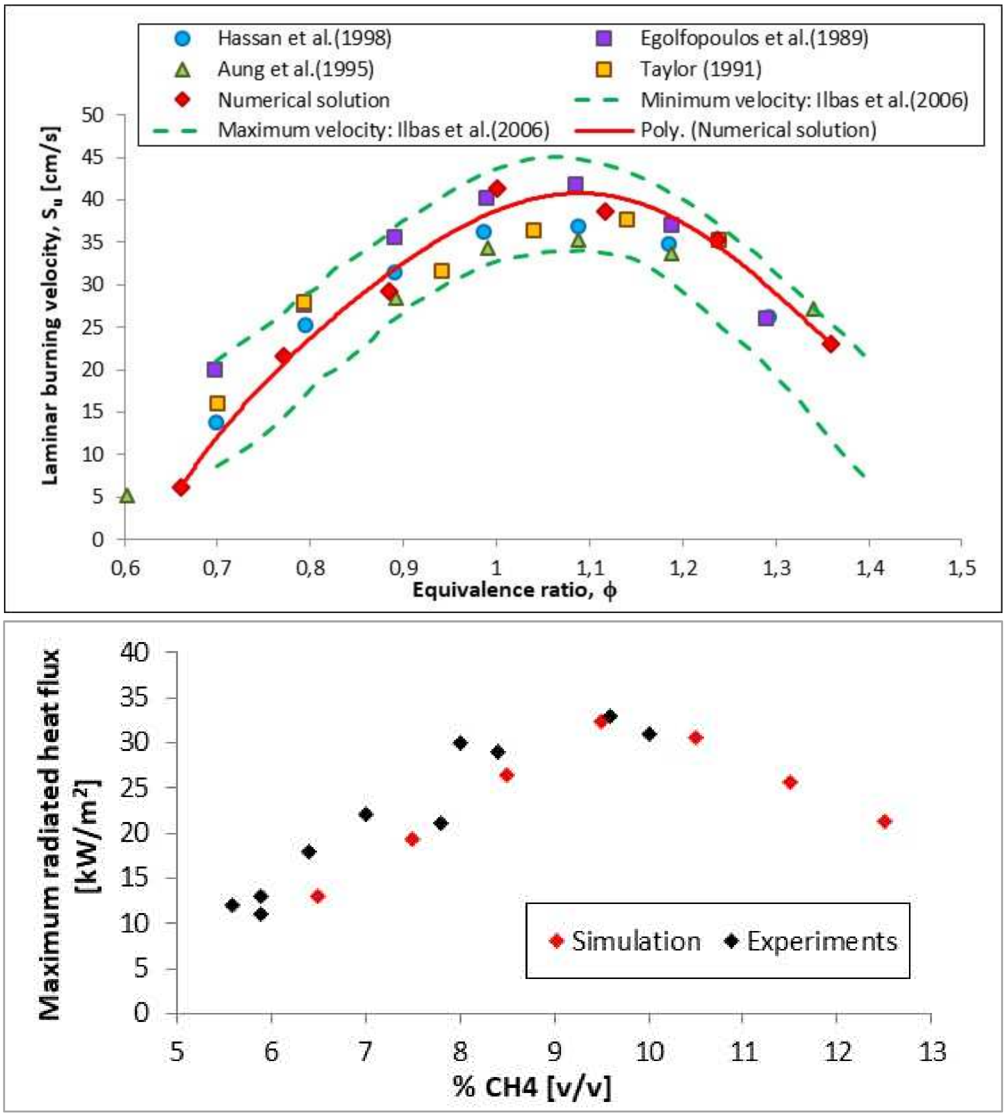


***Fig. 5** : Laminar burning velocity in methane air mixtures and maximum heat radiated flux*

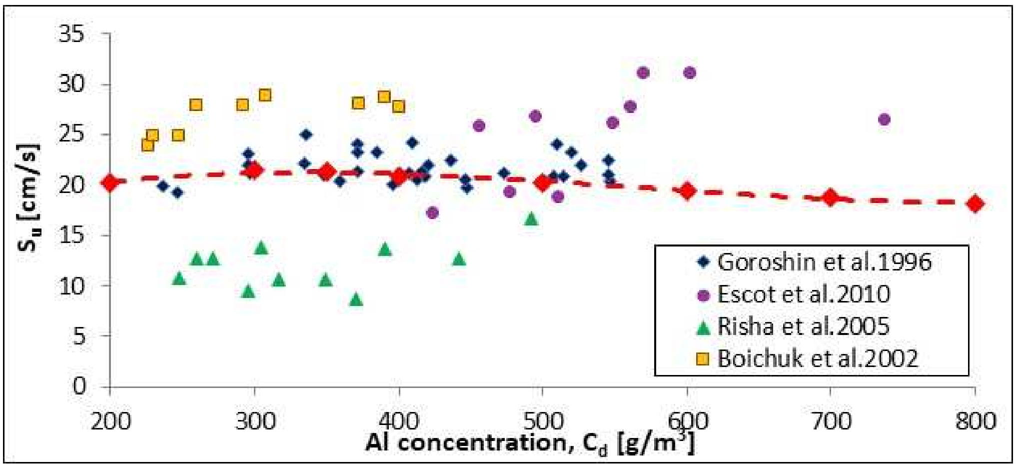


***Fig. 6** : Laminar burning velocity in aluminium dust air mixtures (very small scale)*

The simulations were also done to compare with the experimental data presented in section 2. The evolution of the thermal radiated flux in front of the burning zone is shown on Fig. 7 for a stoichiometric methane-air seeded with SiC particles. The agreement with the experiments is excellent. It may look surprising that the diffusion of the thermal radiation ahead of the flame front hardly depends on the mass particle concentration. This is due to the fact that the geometrical attenuation of the heat flux (proportional to the square of the distance to the emitter in the point source approximation) is much larger than the obscuration by the particles located between the emitter and the receiver. This explains why the Beer-Lambert's law cannot apply (at least for industrial configurations).

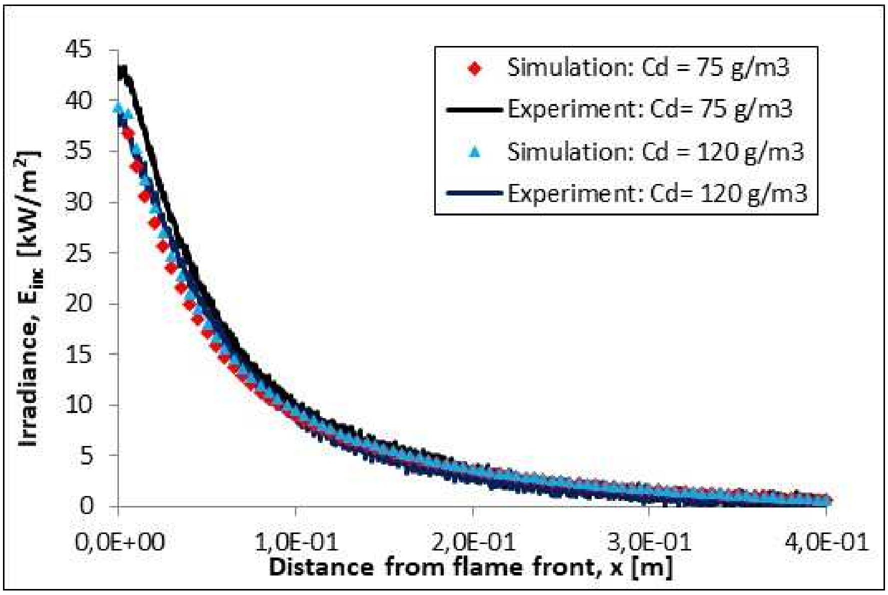


***Fig. 7** : Thermally radiated flux ahead of the burning zone of a stoichiometric methane air flame seeded with SiC particles.*

On Fig. 2 of section 2, the simulated maximum heat fluxes and laminar burning velocities are plotted together with the experimental results showing also a good agreement. The interpretation suggested by the simulations is the following. The thermally radiated flux is absorbed by the particles ahead of the flame which induces a heat up of the reactants amounting of few tens of degrees. This should favour the gaseous reaction of combustion and should accelerate the flame as shown by Joulin (1987). But simultaneously, heat is extracted by the particles from the burnt side of the flame and radiated away which is a loss for the flame and will reduce the burning velocity. So, there should be a maximum in the burning velocity curve as function of the mass particle concentration.

Similar simulations were performed for aluminium dust air flames.

First, a marked increase in irradiance with the particle mass concentration is observed (Fig. 8). This is due to the significant increase in the combustion temperature between the flammability limit conditions (2000°K at 70 g/m^3) and the stoichiometric conditions (3500°K at 300 g/m^3). The combustion temperature stays close to 3500°K up to a mass particle concentration of 500 g/m^3 (Ben Moussa et al., 2017). Experiments did not provide much information about the radiated heat flux (because of very harsh conditions) but about 20 kW/m^2 was measured at about 150 g/m^3 which is not in disagreement with the simulations.

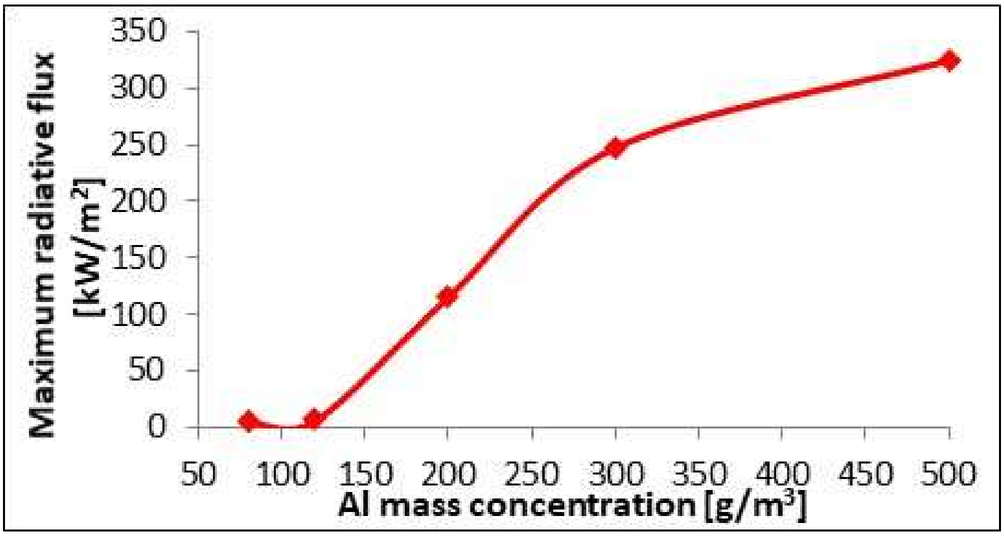


Fig. 8 : *Simulated maximum irradiance versus Al mass concentration*

The simulations also show that for mass particle concentrations smaller than 450 g/m^3, the burning velocity is constant (Fig. 9). Above, the burning velocity increases dramatically. At 700 g/m^3, the burning velocity raises by 1.5 m/s over a distance of 0.08m. All of this is in reasonable agreement with the experiments.

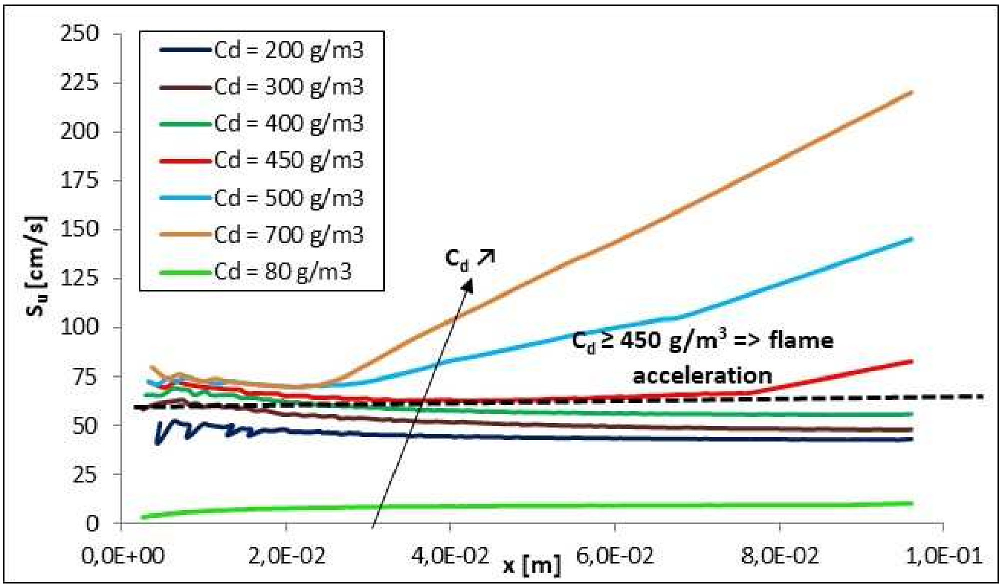
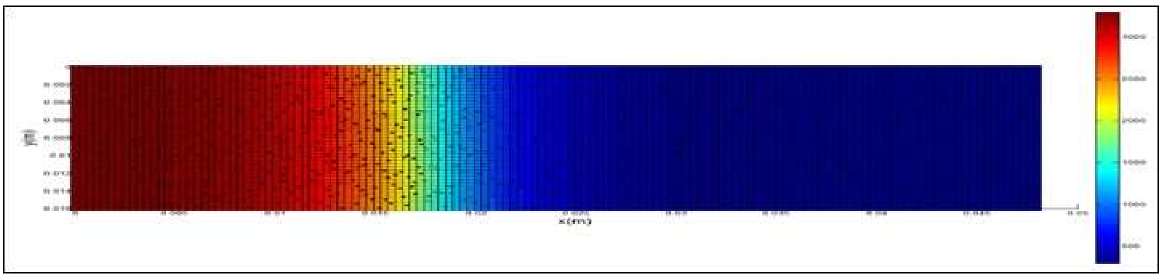


Fig. 9 : *Burning velocity VS distance across the combustion tube for different Al mass concentrations*

Further information about the structure of the flame front can be found in Fig. 10 for non- accelerating flames and in Fig. 11 for accelerating flames.



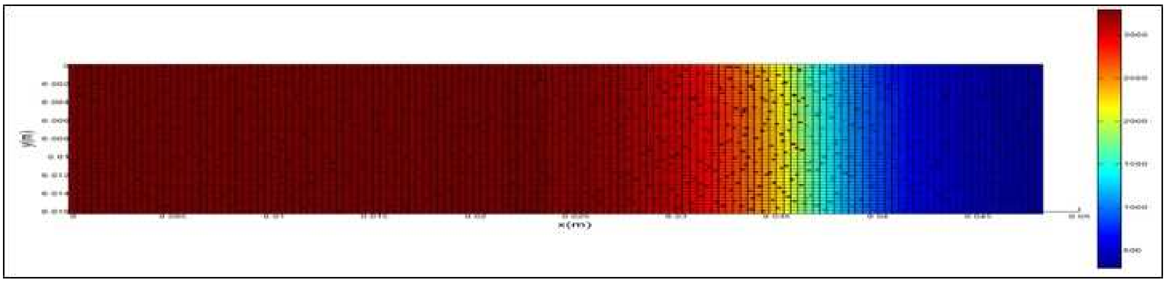


Fig. 10: Zoom on temperature field at two different instants, Al dust-air flame, C_d = 80 g/m³

In the first case (of non-accelerating flames), the structure of the front does not change and a representative flame thickness is some mm (3 mm between isotherms 1500°K and 2500°K for instance). This is a typical heat conduction/reaction flame front.

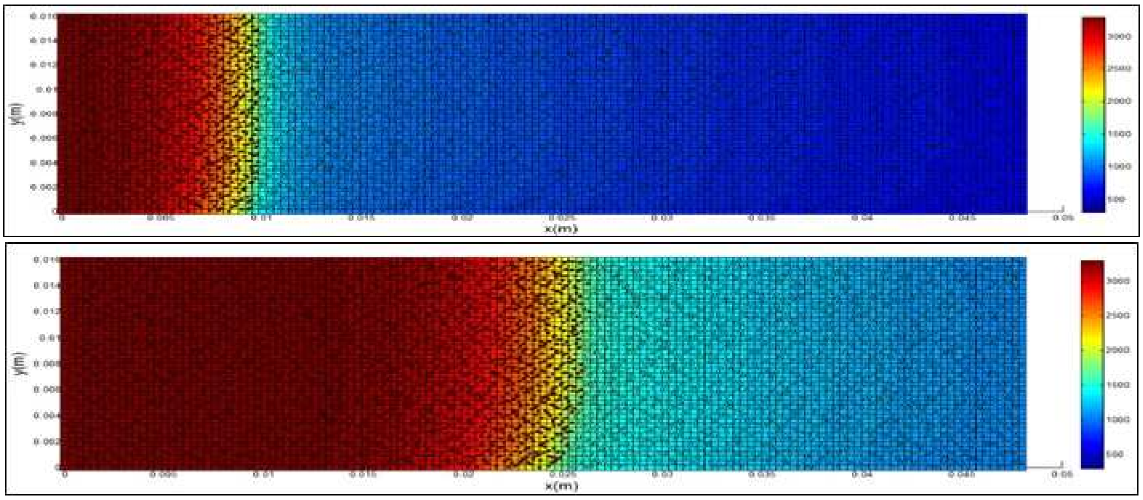


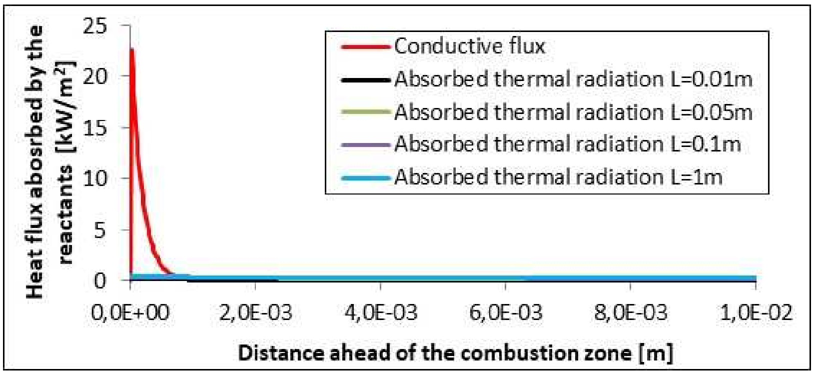
Fig. 11: Zoom on temperature field, Al dust-air flame, C_d = 500 g/m³

In the second case (of an accelerating flame), the flame thermal thickness evolves rapidly during the propagation : 3mm at the beginning of the propagation between the isotherms 1500 K-2500 K and 10 mm after 20 cm of flame propagation.

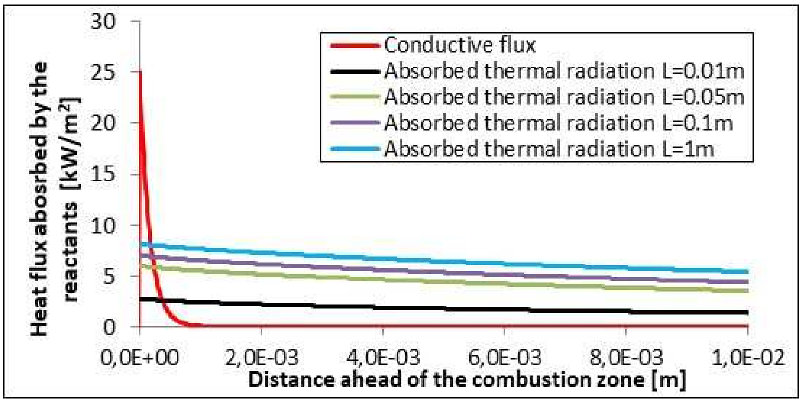
For our purpose of clarifying the role of the thermal radiation transfer in the aluminum dust flame propagation process, it might be sufficient to compare the amounts of heat absorbed by the reactants (up to the ignition temperature) by thermal conduction and by thermal radiation. The former heat transfer mechanism is always at work even in non-radiating flames.

To estimate the thermal conduction heat flux at the ignition point (1750°K in the present situation, Ben Moussa et al., 2007), the temperature maps obtained with RADIAN in situations where the irradiance is negligible were used. The temperature gradient at the ignition point is on the order of 250 000 K/m. Multiplying it by the local thermal conductivity of the gas mixture (0.1 W/m.K) provides the thermal conduction heat flux at the ignition surface : 25 kW/m². This should normally be the maximum heat conduction flux through the flame.

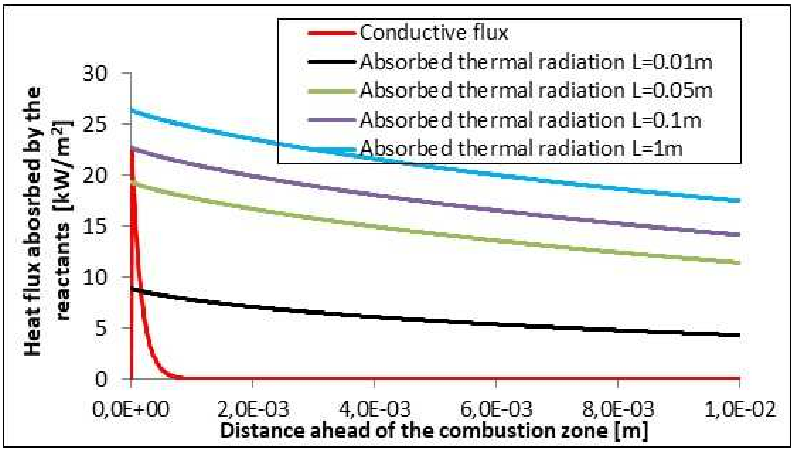
The thermally radiated heat flux ahead of the combustion zone can also be extracted from the simulations. The results are given in Fig. 12 were the origin of the abscissae is the ignition point.



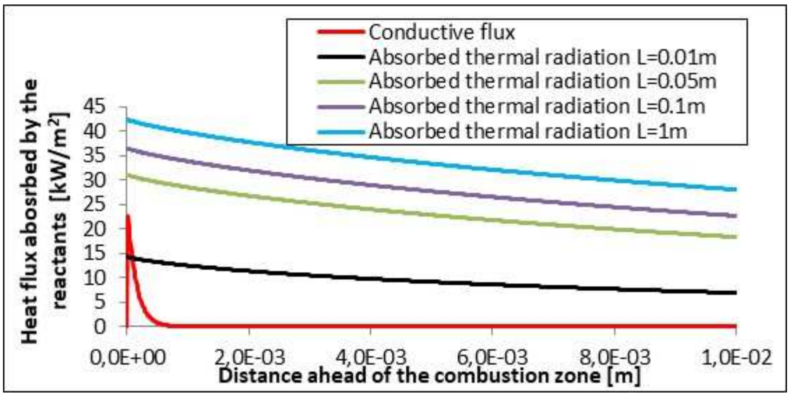
(a) C_d = 80 g/m^3



(b) C_d = 200 g/m^3



(c) C_d = 300 g/m^3



(d) C_d = 400 g/m^3

Fig. 12: *Comparison of the heat conductive flux and thermal radiation flux absorbed by the reactants (aluminum dust-air cloud) ahead of the ignition surface for several mass particle concentrations (L is the "flame path length" or equivalently the length of the burnt products column)*

It appears immediately that for concentrations below 200 g/m^3, the reactants are mainly heated up to the ignition point by the conductive thermal transfer. The burning regime then resembles to the standard "Le Chatelier" concept. For large enough concentrations, above 400 g/m^3, the thermal radiation flux absorbed by the reactant is well above that due to the heat conduction in all the relevant temperature domain (from ambient temperature to the ignition point). Note that this is true only when the burnt products column is large enough, typically larger than 1 to 5cm. When this occurs, since the heat flux is now larger, the laminar burning velocity must increase to keep the balance of energy through the flame:

Because of this, and because the amount of thermal energy transferred by radiation to the reactants increases with the length of the burnt product column, the flame speed is expected to increase in proportion to the propagated distance. For 400 g/m^3 dust concentration, the radiated heat flux exceeds that of the thermal conduction some cms after the start of the propagation triggering the acceleration. This observation seems in line with the simulations but also with the experimental results.

Although not included in the present paper, a very significant influence of the particle size is expected.

5. Conclusions

In the present work, a new simulation code based one the discrete element method is presented to interpret experiments perform to highlight the potential influence of thermal radiation on dust-gas flame propagation.

Although bounded by some simplifying assumption, the code (RADIAN) is close to a direct numerical tool.

Methane-air flames seeded with inert SiC particles and aluminium dust-air mixtures were studied. The simulation seems to reproduce very well the experimental results. In particular, thermal radiation may add up to the flame propagation, in the first situation, or may completely dominate in the second one.

The present, still too limited, simulations do not answer the question of the maximum burning velocity and do not give information about the behaviour of the flame towards disturbances. Additional work is needed. Nonetheless, the present information may be enough to propose in the future a semi-analytical model enabling a phenomenological analysis of flames dominated by thermal radiation.

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