Thermal Radiation Contribution to Metal Dust Explosions

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1 Introduction

Dust explosions remain a safety and scientific challenge. There has been a gradual evolution in the prevention and mitigation of dust explosions over the past twenty years [1, 2]. This evolution results partly from a better understanding of the phenomena involved; namely the properties and characteristics of dust explosions [3], the propagation of the flame through dust clouds [4], the ignition and the combustion time of particles [5, 6, 7] and the incidence of the size and concentration of particles [8]. Today, the modeling of this type of explosions is generally derived from the modeling of gas explosion because of the similarities between the flame propagation processes in both media at least for some categories of dusts. Flour, starches and sulfur powder certainly belong to this panel because it was shown that the particles are gasified ahead of the combustion zone and that heat conduction through the front leads to this transformation [4]. The situation might be different if the particles do not evaporate and/or if the major part of the combustion process is heterogeneous.
This may occur with fine metal particles as aluminum. In particular, the combustion process might be heterogeneous and results in the presence of solid residues at very high temperature [9] potentially transferring most of the thermal energy to the reactants (aluminum particles) by thermal radiation [10]. Only very few experimental observations and theoretical considerations are available but seem to confirm that thermal radiation exchange is significant in the thermal balance of the flame [11] and that it could lead to a dramatic acceleration of the flame [12]. The aim of this work is to investigate further this phenomenology.

2 Theoretical Approach (numerics)

The coupling between thermal radiation, thermal conduction and particle combustion is extremely complicated and challenges the analytical approach if no reasonable simplifications can be made. In the absence of sufficient convincing experimental results, it is difficult to sort out the potential assumptions. And without some reasonable theoretical grounds, it is difficult to orientate the experimental work. It was decided to investigate the theoretical aspects in the most flexible and open manner. The numerical resources of the Discrete Element Method [13] were used for this purpose under the frame of MULTICOR software developed by LTI [14].

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It was attempted to simulate the radiative transfer between particles in suspension by reproducing a simple total absorption model (without reemission) of the flux impacting each particle. It's schematically the Beer-Lambert attenuation low used by Essenhigh [15] and by many authors after him. The details of this one-dimensional attenuation law (under the assumptions considered) are given in the works of Essenhigh [15].

Every ignited particle is considered a point source that radiates with a power, Q_{Ri}, equivalent to the power of the entire flame:

$$Q_{Ri} = \varepsilon_i \sigma_s S_i T_f^4$$

where ε_i is the emissivity of the particle Ω_i, σ_s is the Stefan-Boltzmann constant, S_i is the surface of the particle Ω_i and T_f is the flame temperature (≈ 3000 °k).

Based on this model, the radiative heat flux density, Q_{ij}, received by the target particle varies inversely to the square of the distance separating the source and the target as follows:

$$Q_{ij} = \frac{Q_{Ri}}{4\pi . d_{ij}^2}$$

where d_{ij} is the distance separating the particle source Ω_i and the receiving particle Ω_j as illustrated on Fig. 1.

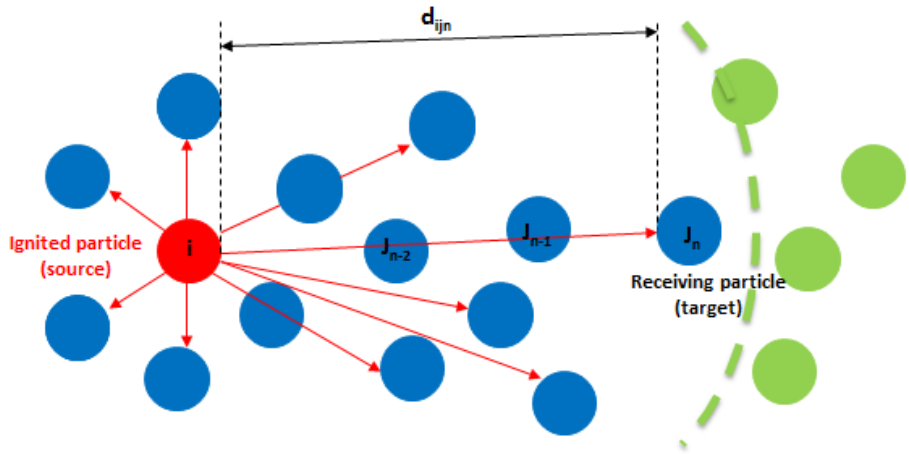


Figure 1. Radiative exchange between particles in suspension

We take into consideration, in addition to the remoteness of particles from each other, the attenuation of the radiation absorbed by the screening effect of the particles between transmitter and receiver. The heat flux density received by the target may be then expressed as follows:

$$Q_{ijn} = \frac{Q_{Ri} - \sum_{j=1}^{n-1} S_j Q_{ij}}{4\pi . d_{ijn}^2} = \frac{Q_{Ri}}{4\pi . d_{ijn}^2} . \left[1 - \left[\sum_{k=1}^{n-1} \frac{S_k}{4\pi . (kD)^2} . \left(1 - \sum_{l=1}^{n-2} \frac{S_l}{4\pi (lD)^2} \right) \right] \right]$$

where D is the mean distance between two particles.

The proposed results are obtained after programming this model with the DEM code MULTICOR [14]. Dust particles are considered as discrete elements. Fig. 2 details the 2D simulation of a uniform dust cloud of 121 spherical particles (d_p = 10 μm) distant of 100 μm from each other. The dust concentration is equal to 600 g/m^3. Air conductivity is considered equal to zero so that the only heat exchange mode taken into account is radiation. Particles located at the plane (x = y = 0) are initially

considered as heat sources at the flame temperature (≈ 3000 °K). We suppose that as soon as the aluminum melting temperature (≈ 933 °K) is reached, particles ignite and their temperatures rise instantly to the flame temperature. As shown in Fig 2, the temperatures of particles rise significantly only due to the absorption of radiative flux coming from the neighboring particles. The decrease of the received radiative flux by particles with distance is shown in Fig.3.

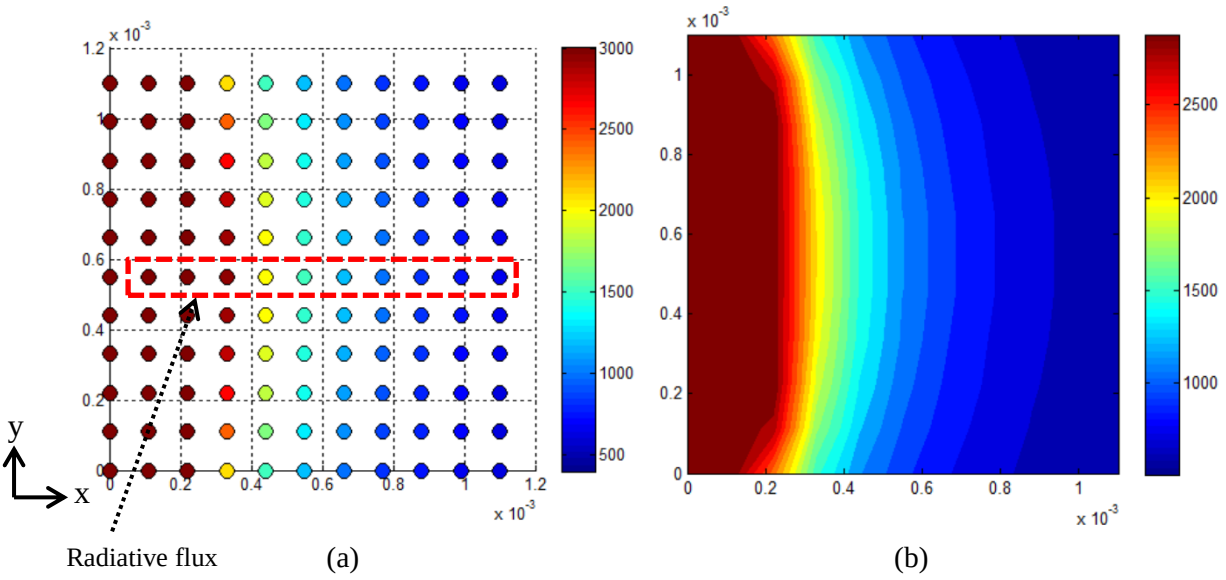


Figure 2. (a) Dust temperature and (b) temperature contours at t = 0.5 s

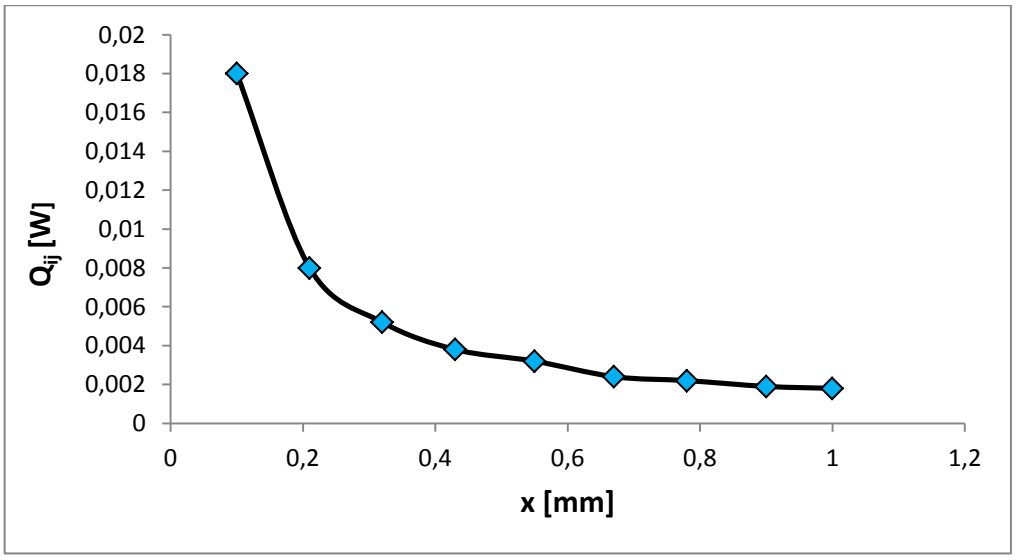


Figure 3. Radiative flux received by particles at different positions at the central axe of the domain

3 Experimental Work

In addition to the numerical approach, an experimental work is being conducted. From a simple analysis [12], and waiting for more quantitative results, the interesting range of particle diameters is 1-10 μm. The following particles were selected (table 1).

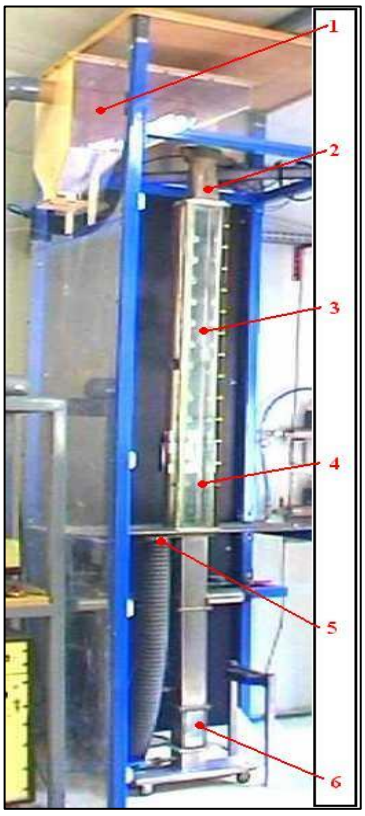
In these size ranges, the interparticle cohesive forces are very strong and agglomerates are formed. The various techniques of disaggregation were studied knowing that the suspension should be laminar in

respect of the simulation conditions. The study confirmed that the fluidized technique of a bed of particles with elutriation is the most promising.

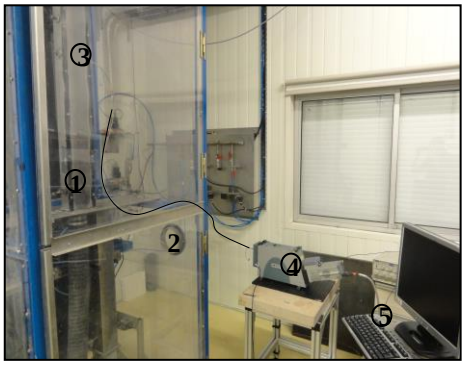
Table 1: Provided data about the nature of aluminum powders

	UTL0165	ULT0365	ULTE0565	ULTE01065
D_10 (μm)	-	> 1.0	> 2.5	> 5.0
D_50 (μm)	1.5 – 2.0	2.5 – 3.5	4.5 – 5.5	9 – 11.0
D_90 (μm)	< 4.0	< 8.0	< 9.0	< 18.0
Shape	Spherical			
% min Al	99.8			
% max Fe	0.1			
%max Si	0.1			

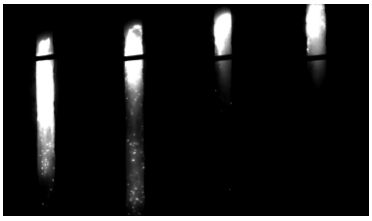
The experimental system is shown on Fig. 4. It basically consists in a fluidized bed device (6) feeding the flame propagation tube (3) by the bottom while the top end is open and communicates with a separator (1) via a valve (2). The ignition device is located at 15 *cm* from the base of the tube (4). The dust-air mixture is fed into the tube during a few tens of seconds. After this sequence, within a few seconds, the air flow is stopped, the top valve is closed and the fluidized bed device is removed and replaced by a flexible tube communicating with the exterior and the igniter is triggered. The flame propagates freely from the bottom to the top giving access to the burning velocity. A typical example is shown on Fig. 4. A number of "thermal" measuring techniques were tested and the optical measurement of the monochromatic heat flux seems to be the best solution (again an example of spectrum is shown on Fig. 4).

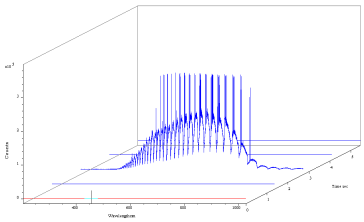


Experimental system



Instrumentation: 1- Radiation measurement, 2- Optical fiber, 3- Flame propagation tube, 4- Spectrometer, 5- Data acquisition system





(a) *(b)*

(a) Sequence of flame propagation (aluminum-air), (b) Example of the emission spectrum

Figure 4. Flame propagation tube and instrumentation

4 Conclusion and perspectives

The modeling of radiative heat exchange trough the flame front is particularly complex because in order to be complete, it must integrate light scattering by particles (reflection, transmission, diffraction), absorption and emission. The coefficients of absorption and emission are dependent on both the wavelength and particle size. A local analysis of the radiation transfer process is still needed to calculate these coefficients but also to determine the incorporation of the diffusion through the flame front.

Experimentally, succeeding in dispersing fine aluminum particles will enable the measuring of the burning rate, the particle temperature and the heat radiation in respect of the simulation conditions. We will try to create the theoretically predicted conditions for instabilities induced by radiation.

Acknowledgements

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