Journal of Loss Prevention in the Process Industries 49 (2017) 896–904

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Thermal radiation in dust flame propagation

Proust Christophe [a, b, *], Ben Moussa Rim [b], Guessasma Mohamed [c], Saleh Khashayar [b], Fortin Jérôme [c]

[a] Institut de l'environnement industriel et des risques, PARC ALATA, BP2, Verneuil en Halatte, 60550, France
[b] Sorbonne Universities, Technological University technologique of Compiègne, Escom, Centre Pierre Guillaumat, TIMR, bat E-D, Compiègne, 60200, France
[c] Université de Picardie Jules Verne, Laboratoire des Technologies Innovantes, LTI-EA 3899, Saint Quentin, 02000 France

A R T I C L E I N F O

Article history:
Received 7 December 2016
Received in revised form
4 January 2017
Accepted 5 January 2017
Available online 5 January 2017

Keywords:
Dust explosions
Flame propagation
Thermal radiation

A B S T R A C T

The role of thermal radiation in premixed flame propagation has been a matter for 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 (HSL, 2009) 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 (*Proust and al., 2013*). In this paper, new experimental measurements of thermal radiation in dust flames (methane air, methane air seeded with inert particles, aluminum dust air flames) are presented together with a physical interpretation.

1. Introduction

Dust explosions remain quite frequent in industrially developed countries despite significant progresses made during the last few decades not only about the understanding of the underlying explosion development processes (see for instance Eckhoff, 2003; Proust, 2006) but also in the mitigation techniques (Snoeys et al., 2011). A recent survey in France confirms that dust explosions concern all industrial fields because about 75% of the dusts manipulated are sufficiently combustible to explode (Janès and Chaineaux, 2010).

To a large extent, those progresses were possible because a rather close connection was made between the flame propagation mechanisms in premixed gases and in dust flames so that a large body of knowledge could be more or less directly transferred from the first field to the second one.

In particular, it was demonstrated that for a large number of dusts, the heat is being transferred into the reactants by thermal conduction and the particles vaporise/pyrolyse so that at least part of the combustion proceeds in gaseous phase.

Is it true however, if the particles do not vaporize or do produce large amounts of solids so that heat transfer by radiation might appear and play some role ? How would it modify the flame propagation process? In case a strong influence would be found, would the actual body of knowledge about dust explosion mitigation still apply ? And in which industrial field could it be a potential problem?

In the following, a short literature survey is proposed to help answering the first and the last question and new preliminary experimental data are presented to try and address part of the remaining questions.

2. Is it really a problem?

The question of the incidence of the thermal radiation on the flame propagation processes has been raised since decades (Cao et al., 2014; Cassel et al., 1949; Kudryavtsev et al., 1982; Deshaies and Joulin, 1985; Escot-Bocanegra, 2007; Bidabadi et al., 2013) and no satisfactory answer could be given until now, partly because of the difficulties to measure the influence, but also because of the difficulty to choose an adequate model to represent the thermal radiation transfer in a suspension of particles (Ben Moussa et al., 2017). In most cases, assumptions need to be made for the heat transfer equations to be tractable: black body-no scattering, 1 D approximation.

* Corresponding author. Institut de l'environnement industriel et des risques, PARC ALATA, BP2, Verneuil en Halatte, 60550, France.
E-mail address: christophe.proust@ineris.fr (P. Christophe).

http://dx.doi.org/10.1016/j.jlp.2017.01.002
0950-4230/

In the existing library of models that from Cassel can be used to illustrate the potential influence (Proust et al., 2013) of the various heat transfer modes. Cassel extented the « Le Châtelier » approach by incorporating the heat transferred by radiation (Fig. 1), solving the thermal balance in the burning zone (between T_{inf} and T_{ad}) and assuming heat transferred by radiation follows the Beer-Lambert's law (Q_{ext} stands for the extinction coefficient of the radiation and is about 2 when the size of the particle is large as compared to the wavelength of the incident light according to van den Van de Hulst, (1981)). He obtained an analytical formulae given from which the laminar burning velocity S_{lad} can be calculated:

$$S_{lad} = \frac{\lambda_g \cdot \left(T_{ad} - T_{\inf}\right) \Big/ \eta_0 + Q_{ext} \cdot \eta_0 \cdot \sigma_p \cdot F \cdot \sigma_0 \cdot \left(T_{ad}^4 - T_0^4\right) \Big/ \rho_p \cdot d_p}{\left(\rho_g \cdot C_{pg} + \sigma_p \cdot C_p\right) \cdot \left(T_{ad} - T_{\inf}\right)} \quad \text{with} \quad \eta_0 = S_{lad} \cdot \tau_c \tag{1}$$

The view factor defines the geometry of the flame front. If the latter is flat F = 1, if it is convex towards the reactants, F < 1 and if it is concave ("tulip" flame) F > 1.

A numerical application is possible considering for instance aluminium dust air flames since the burning characteristics of individual particles have been investigated for long (Bazyn et al., 2007; Mohan et al., 2009; Goroshin et al., 2007; Escot-Bocanegra, 2007; Huang et al., 2007, 2009). The input parameters required to run Cassel's model, T_{inf}, T_{ad} and τ_c, are given on Fig. 2.

It is now possible to calculate the laminar burning velocity of Al dust-air clouds in situations where heat transfer by thermal radiation is negligible (which is likely to be the case for small experimental device, large particles, convex flame, …). The agreement with experimental data seems then reasonable (Fig. 3).

Using information from Figs. 3 and 2, it comes out that the flame thickness η_0 (in fact the burning zone thickness) is not that different from 1 mm whatever the particle size. With this information, the conductive and radiative fluxes can be compared in equation [1] by dividing the former by the latter to obtain a sort of Boltzmann number (F was set to 1):

$$B_z = \frac{d_p}{\eta_0^2} \cdot \frac{\rho_p}{\sigma_p} \cdot \frac{\lambda_g \cdot \left(T_{ad} - T_{\inf}\right)}{Q_{ext} \cdot \sigma_0 \cdot \left(T_{ad}^4 - T_0^4\right)} \tag{2}$$

For micron sized particles, T_{inf} is about 1700 K, T_{ad} is about 3500 K in the stiochiometric conditions σ_p = 0.25 kg/m^3 (λ_g = 0.1 W/mK at T_{inf}, σ_0 = 5.67.10^{-8}W/m^{2}K^4, Q_{ext} = 2, ρ_p = 2700 kg/m^3) so that it can be estimated using [2] that the amount of heat transferred by radiation is theoretically comparable to that transferred by heat conduction for particles of about 10 µm.

For smaller particles, heat transfer by radiation could theoretically be dominating but what would happen then ? Assume that the flame, initially strongly convex (F = 0) is abruptly disturbed (by a pressure wave for instance) and become concave so that F goes from 0 to 2. It can be calculated using equation [1] that S_{lad} should increase in a larger extent the smaller the particles (Fig. 4). In the example give, S_{lad} is increase by a factor 4. Since at the same time the total flame area would have been increased by the same disturbance, large flame acceleration could result, much stronger than for conduction dominated flames. Note that rather similar findings were obtained recently (Liberman et al., 2015) for the specific situation of inert particles seeding a flammable gaseous

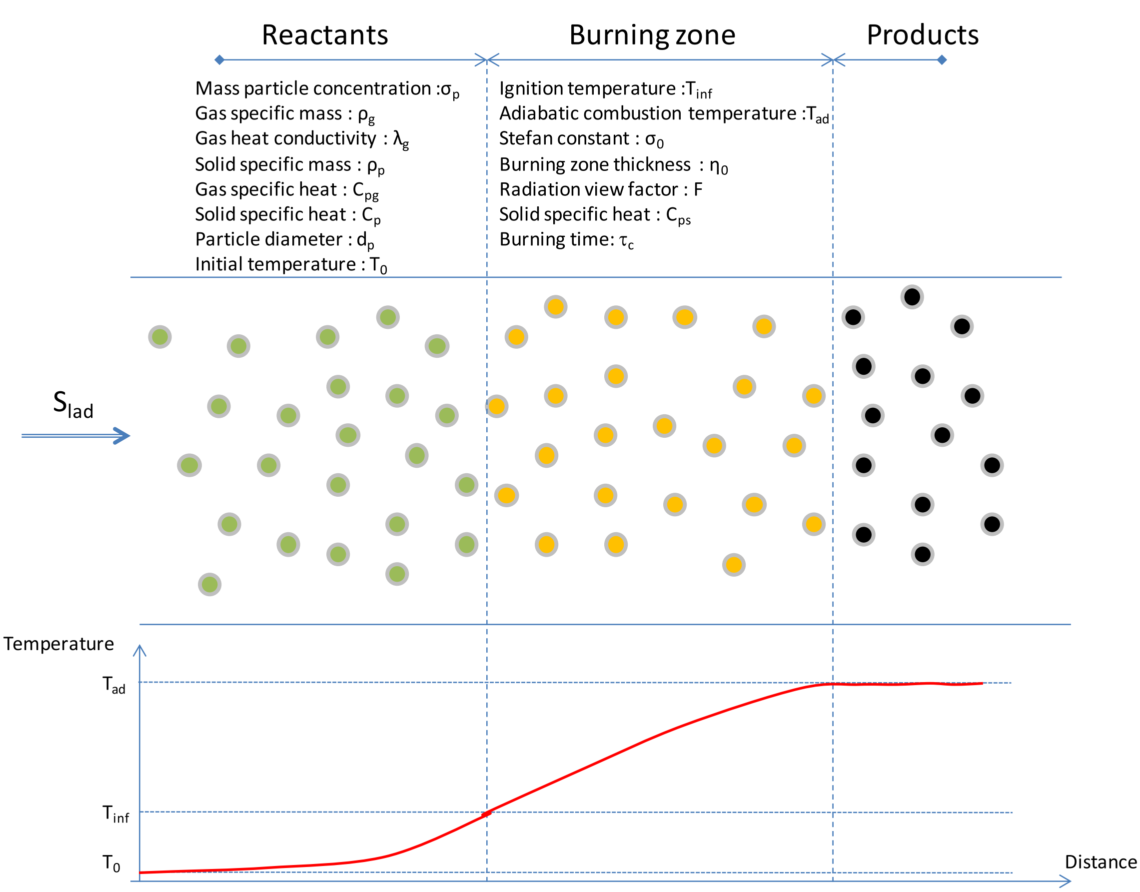

Fig. 1. Cassel's problem and definitions.