Investigating turbulence and turbulent flame propagation in dust clouds

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1 Introduction

Some degree of turbulence is always required to produce and maintain a dust cloud and it is well known that turbulence has an influence on the propagation of the flame. Quite an extensive literature has been devoted to flame propagating in turbulent premixed gaseous media. The main features are known which can be summarized as follows. The turbulence in a flow can be described as a collection of transient eddies originating from the velocity gradients [1]. The larger eddies are disrupted in smaller structures producing a continuous cascade from the largest eddies, scaling as the flow (integral scale of the turbulence), towards the smallest scaling as the viscous scale (Kolmogorov scale). If the thickness of the flame is much smaller than the Kolmogorov scale, the flame front remains locally laminar, and the eddies distort the flame front and enlarge the flame surface, accelerating the flame. This is the “wrinkled” and “corrugated” flame front regimes as identified by Borghi for instance [2]. In practice and especially in industrial dust explosion situations, the Kolmogorov scale is typically on the order of 1 mm (integral scale in cms or tens of cms [3]) while the typical flame thickness is a small fraction of a mm. It seems then quite natural that the turbulent burning velocity should be correlated to the typical scales of the laminar flame (laminar burning velocity-Sl_{ad}, flame thickness-δ_{ad}) on one end and to the characteristic scales of the turbulence (intensity of the turbulence-u’, integral scale-L) on the other end. Many such correlations were proposed having all their field of application but for safety application the present authors used the Gülder one [4]. It was shown earlier by one of the present authors [5] that laminar dust flame propagation regimes exists and that, at least for carbonaceous particles, the mechanisms of flame propagation were very similar to that in premixed gaseous flames. The temptation is to extrapolate the similarities to the turbulent regimes and use the same correlation than for premixed gases. Although doubts were raised from the beginning [6], it was only recently that it was possible to show that this assumption was not valid [3]. In the present work, it is intended to investigate further the various aspects of the problem considering first the possibility for a laminar dust flame to remain locally laminar in a turbulent field. Second the specificities of the turbulence in a dust cloud are discussed on the basic of some experimental observations. Finally, the aspect and behavior of turbulent dust flames are analyzed. This work is a first step of in-depth analysis, using simulation tools and further testing.

2 Laminar dust flames and interaction with the turbulence

For premixed gases, the increase of the flame front area in a turbulent flow is due to the flame stretch mechanism operated by the velocity gradients of the flow. In a turbulent stream, the later scales as K=u'/L. Besides increasing the flame front area, flame stretch has some influence on the local (laminar) burning velocity [7]. If large enough, quenching can even occur but typically when $(\delta_{ad}/Sl_{ad})/(L/u')$ is on the order of 1000 for premixed gaseous flames. Experiments were performed on starch dust-air laminar flames in tubes of different diameters [5, 8, 9] and the laminar burning velocity was determined. The flame is propagating upwards from the bottom in a vertical tube closed at the top and open at the bottom (0.01 m^2 square cross section and 1,5 m high). The flame front is roughly hemispherical (Fig.1) so that the top and the sides of this cap are stretched by the flow of unburned mixture which is deflected sidewise by the flame. Assimilating this flow to that around a bubble raising in a tube, the stretch parameter can be estimated and a plot providing the evolution of Sl_{ad} with K was obtained (Fig. 1).

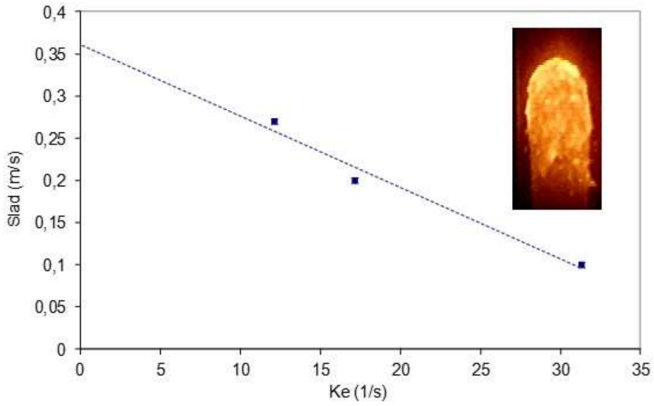
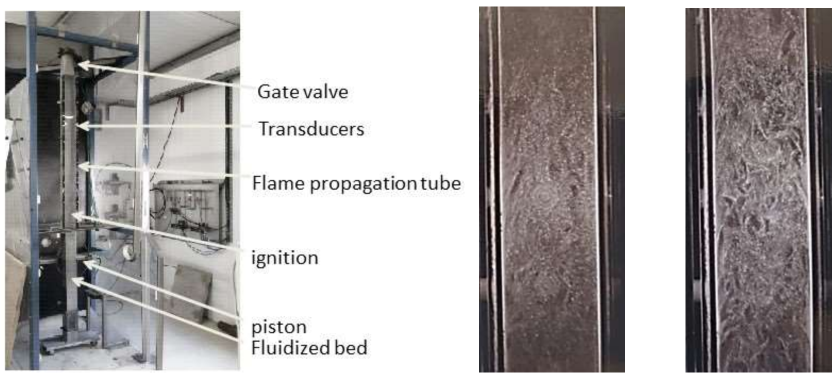


Figure 1: evolution of the laminar burning velocity of flames propagating in starch dust (VMD=20 µm)-air clouds as function of the stretch due to the flow.

As a first remark, if this curve were extrapolated towards higher value of K, stretch would cause extinction when reaching 40. But as shown in [3], typical values for u' and L in the well-known 1 m^3 ISO vessel are respectively 2 m/s and 4 cms. And these conditions are said representative of industrial explosions. Yet, the stretch "potential" of this turbulence is about 50. So, the laminar flame would not exist anymore. But, powerful explosions still occur suggesting an alternative combustion regime. The second remark is about the very low value of K at extinction as compared to premixed gaseous flames (at least one order of magnitude below), even with comparable laminar burning velocities. It is known that the sensitivity of a premixed laminar flame front to stretch does not depends only on the thermal aspects of the flame but also on the diffusion of species. The combustion in laminar dust flames is more complex, with additional diffusion steps around each particle. Could it explain this second remark ?.

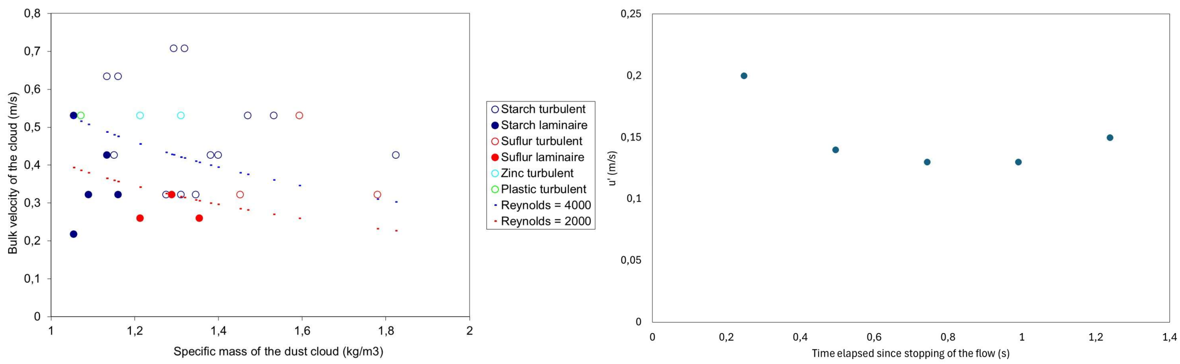
3 Turbulence in dust clouds

Quite a significant literature is devoted to the influence of turbulence on dust explosions but little about the structure of turbulent dust clouds. It should be recognized that turbulence measurement in (real) dust clouds has been made possible only rather recently [3] and the modelling is still very difficult [10], the representation of the interactions between the phases being still very rough. Experimentally, if the estimation of u' and L seems possible, the structure of the turbulent cascade is not yet accessible. Some direct observations obtained with the device presented in Fig.2a may nevertheless be useful. This apparatus was used to obtain the flame shown in Fig.1. The dust cloud is produced by a fluidized bed located below the bottom part of the tube so that the cloud circulates from the bed toward the dust separator above the tube. A honeycomb is inserted above the bed up to the top mouth of the dust cloud generator. Its role is to limit the vertical concentration gradient in the tube and to produce a laminar homogeneous cloud. The tube is transparent, and tomographic video recordings can be made. When the flow velocity through the tube is large enough the aspect of the flow switches from a very homogeneous aspect, that may be called "laminar", to a highly heterogeneous structure, that may be called "turbulent" (Fig.2 b and c). This transition occurs inside the tube at some distance above the honeycomb. It is not generated by some change in the fluidized bed. It was attempted to identify a criterion to distinguish the laminar flow from the turbulent one. The Reynolds number seems a reasonable parameter using the dynamic viscosity of the air, the bulk velocity of the flow and rather than the specific mass of air, the specific density of the cloud is used (thus adding the mass particle concentration). As shown on Fig. 3-a, this criterion seems rather robust because apparently valid for very different dusts.



a b c

Figure 2: experimental device used to produce laminar and turbulent dust flames (a), tomographic record of a nearly (transiting) laminar (starch) dust-air flow (b) and of a fully turbulent flow (c).



a b

Figure 3: a- Laminar/turbulent flow border in the device of Fig.2, b- u' as function of time elapsed after stopping the flow and closing the upper end of the tube (starch dust air 90 g/m^3)

This would suggest that the particles act on the inertial forces of the turbulence but perhaps not on the shear forces. If so, the shear layers of the flow should be like those produced by the air flow alone. Then, perhaps the eddy structures produced in the shear layers should be the same than in an air flow. The effect of the particles may increase the turbulence intensity because of the additional inertia or change the cascade of turbulence. A series of snapshot of the suspension at different time after stopping the flow and closing the upper part of the tube is shown on Fig.4. As said, the repartition of the particles is highly heterogeneous in a turbulent flow. A closer look reveals some "dark" structures of typically cm size, with little or no particles inside, and the border of those structures is brighter than the average suggesting richer zones. As time passes, the smallest structures seem to vanish leaving only the largest. After about 2 sec. the cloud is laminar again.

Knowing the time of exposure, the velocity field can be approached by measuring the length of the traces left by the particles on the photos. The average velocity fluctuations over the snapshot is an estimate of u'. On the example of Fig. 3-b, u' can be as large as 0.2 m/s (the initial bulk velocity of 1 m/s before stopping the flow) even 1 sec. after stopping the flow.

0.5 sec. 1 sec. 1.5 sec. 2 sec. 2.5 sec.

Figure 4: snapshots of a decaying turbulent flow field (in sec. time elapsed after stopping the flow, initial flow U=0.9m/s, starch dust air cloud 130 g/m^3)

As suggested earlier [8], the correlations established a long time ago by Andrews and coworkers can be used to estimate u' and L :

$$u' = 0.168\, U\, Re^{-0.119} \qquad L = \frac{\nu}{u'}\, 0.01345\, U\, Re^{0.902}$$

Where U is the bulk flow velocity, ν the kinetic viscosity and Re the Reynolds number. With U=1 m/s, Re=7 000 in the device of Fig.2 ($\nu=15.10^{-6}$), it comes u'=0.06 m/s and L= 0.01 m. So, it seems the "dark" zones could be eddies of the gaseous phase, deprived from particles because of the centrifugal forces. It seems also that the turbulent intensity is larger. If this were confirmed by future results, could the reason be that the particles extract more energy than the gas phase from the boundary layer because of their inertia? This could support what was said about the laminar/turbulent transition and the associated Reynolds number.

4-Turbulent dust flames

A typical turbulent flame propagating in the device of Fig. 2 is shown on Fig. 5. The cloud was obtained in approximately the same conditions than for Fig. 4. The time elapsed between stopping the flow and when the pictures were taken is about 1-2sec. The flame front is strongly disrupted with large zones without any combustion and some, brighter, suggesting a more intense burning. Those more "intense" burning zones are a few cms large and show some similarities with the eddies in the turbulent cloud.

On Fig. 6 and Fig. 7 are presented the evolutions of the turbulent burning velocity (=the flame velocity in the tube since the flow is stopped and the top of the tube is closed) and of the flame temperature. The flame temperatures were measured using K bar thermocouples (bead diameter 25 µm). Note the flow condition were the same as for Fig. 5.

First, the burning velocity does not show a maximum close to the stoichiometric conditions (220 g/m^3) in turbulent conditions, contrary to the laminar situation. Although it is not very clear, a shallow maximum may appear between 500 and 1000 g/m^3 as usually observed in closed bomb experiments where the cloud is very turbulent. Second, the maximum flame temperature for turbulent flames does hardly vary with the dust concentration, in contrast with what observed for laminar flames with a steep increase up to 1300°C at the stoichiometric conditions (normally followed by a slow decrease but on

Fig. 7, data points at concentrations larger than stoichiometric conditions are lacking. The reader can refer to [5] for a more complete curve).

This would suggest a specific combustion mode in turbulent clouds, quite different from the combustion in a laminar regime, which makes a significant difference as compared to premixed gases in similar turbulent flame propagation mode. On Fig. 5, only part of the cloud seems to burn, perhaps only in the zones where the cloud can support the combustion (because of enough dust concentration? Low enough shear ?) in the present turbulent conditions. And the propagation seems driven by the convection of the burning pockets.

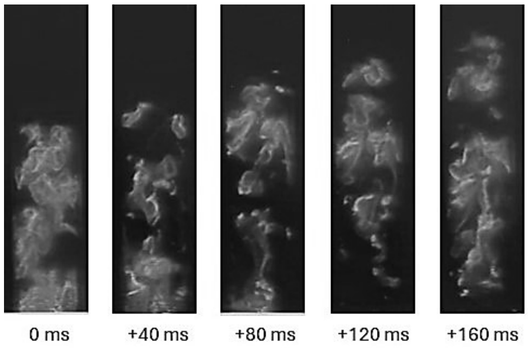


Figure 5 : snapshot of a starch dust-air flame propagating in a turbulent dust cloud (190 g/m^3)

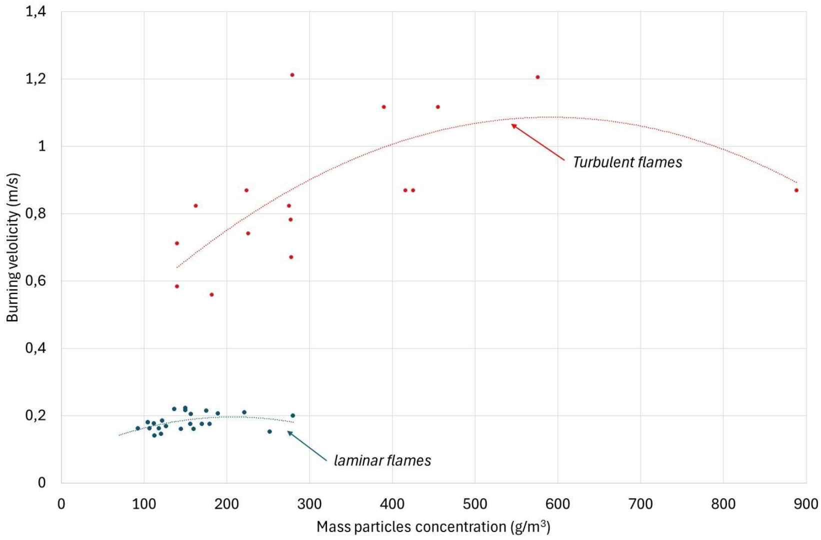


Figure 6 : burning velocity of flames propagating in turbulent starch dust-air clouds as function of the mass particle concentration (time elapsed between stooping air and measurement between 1.5 and 2 sec., initial air flow=1 m/s)

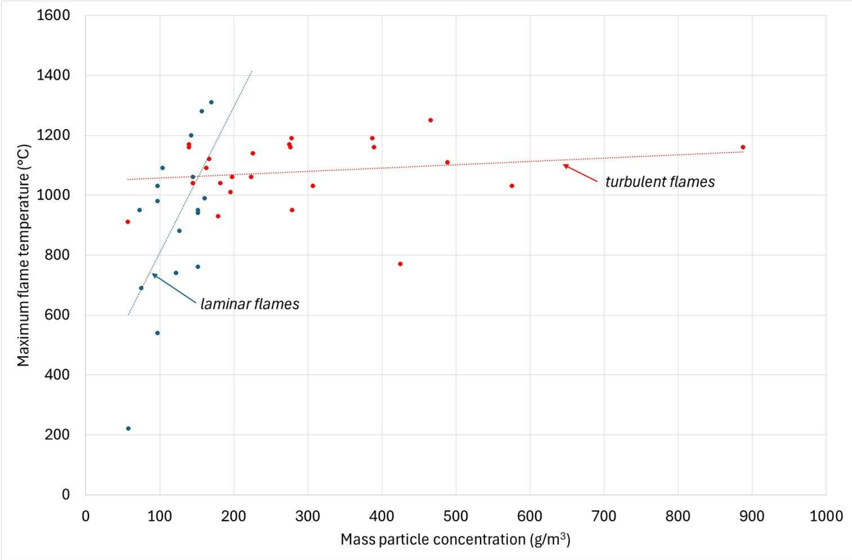


Figure 7 : maximum combustion temperature of flames propagating in turbulent starch dust-air clouds as function of the mass particle concentration

5-Conclusion and outlook

In this article, some experimental results are provided to feed a reflexion about the flame propagation in turbulent dust-air clouds. In accidental gas explosions, the characteristics of the turbulence are such that the turbulent flame is in fact a wrinkled laminar flame. For dust flames, both laminar and turbulent flame regimes have been identified for long. Although the laminar flame propagation mode is quite resembling, as least for agricultural dusts, the turbulent mode seems rather disconnected from the laminar one. Two reasons might explain this. First, it is shown that the laminar flame front seems very sensitive to flame stretch and might only survive in "quiet zones" of any practical turbulence flowfield. Second, the turbulence in the cloud induces very strong concentration gradients depleting the core of the eddies and presumably pushing the particles at the periphery. The flame front looks like a series of burning pockets convected by the turbulence.

These are only very preliminary results and further work is need to clarify the structure of a turbulent dust cloud and to investigate where the combustion could develop. This part of the work is done numerically to a large extent, starting by understanding the burning in an homogeneous cloud.

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