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EXPERIMENTAL DETERMINATION OF THE MAXIMUM FLAME TEMPERATURES AND OF THE LAMINAR BURNING VELOCITIES FOR SOME COMBUSTIBLE DUST-AIR MIXTURES

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Abstract

In this paper are presented some results of measurements of the laminar burning velocities, Sl, and of the maximum flame temperatures, Tfmax, for starch dust-air mixtures, lycopodium-air mixtures and sulfur flour-air mixtures (mean particle diameter between 25 and 45 µm).

The "tube method" and a "direct method" have been used in order to determine laminar burning velocities. Values of some tens of cm/s have been obtained. The agreement between both methods is satisfactory indicating that the "tube method" seems adequate for measuring laminar burning velocities of two phase mixtures. With this information the previously observed (Veyssière and Proust, 1990) dependency of Sl with respect to the geometry of the experimental setup is discussed.

Thin (25 µm and 50 µm) thermocouples have been used to measure maximum flame temperatures. Calculation of the theorical values of this parameter have also been performed and a significant discrepancy between theoretical and experimental values appears. The physical meaning of this discrepancy is addressed.

Standard explosion parameters (KST, Pmax,...) have also been determined with a "20 litre-sphere" for the mixtures investigated. The existence of links between these parameters and the burning properties of the mixtures like the laminar burning velocities and the maximum flame temperatures is discussed briefly.

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1-Introduction

In view of the possible consequences of a dust explosion, it is acknowledged that there is a need for assessing the reliability of the tools used to assess the explosion hazard and of the protection methods. Surely for this, a better understanding of the mechanisms of dust explosion development is compulsary. In particular a better knowledge of the different flame propagation regimes is necessary. In this area, some progresses have been performed in the recent years (Proust and Veyssière, 1988; Rzal et al., 1991; Kauffman et al., 1987; Wolanski et al., 1990; Mazukiewicz et al., 1990; Pu et al., 1988) concerning laminar, cellular, turbulent and detonation propagation regimes. The laminar flame propagation regime seems particularly interesting since, provided the experimental conditions are convenient, some important characteristics of the flame (laminar burning velocity, maximum flame temperature) should depend only on the mixture and seem good candidates for the definition of explosion parameters which depend only on the nature of the mixture. Moreover, refering to the information available (Proust and Veyssière, 1988) concerning the similarities and differences between gas and dust explosions, it might appear that the other flame propagation regimes (except detonation) could be linked to the laminar one. From this point of view, the knowledge of the characteristic parameters of laminar flames in dust-air suspensions is particularly interesting. In the following are presented and discussed experimental methods and results of the measurement of the laminar burning velocities, Sl, and maximum flame temperatures, Tfmax, for some combustible dust-air mixtures.

1-Experimental details

Among the various techniques available (Taï et al., 1988; Bradley et al., 1988; Proust and Veyssière, 1988; Smoot and Horton, 1977; Marshall et al., 1964; Mazurkiewicz and Jarosinski, 1990), it appears that using a "flame propagation tube" (Proust and Veyssière, 1988) seems to be well fitted with respect to the determination of Sl and of several other flame characteristics. We thus selected this latter technique.

1.1-Description of the experimental setup

The apparatus designed is similar to that described by Proust and Veyssière (Proust and Veyssière, 1988) although slightly different.

The experimental chamber (figure 1) is a vertical glass tube, with a square cross section 10 cm × 10 cm, with a length of 1.5 m. The suspension is produced at the bottom of the tube by the elutriation of a fluidised bed of particles. A gate valve is settled at the upper end of the tube. An ignition source (hot wire) is located near the bottom end. During the propagation of the flame, the tube is open at the bottom end and closed at the top (for further details see: Proust and Veyssière, 1988).

The propagation of the flame was filmed with a video camera (50 frames/s, variable exposure time) coupled with a U-Matic recorder. Most records were performed with only the natural light of the flame but in some instances a tomographic technique was used so as to visualize the movement of the particles ahead of the flame front (see Proust and Veyssière, 1988 for further details). In order to measure Tfmax, thin Chromel-Alumel thermocouples were used. In most cases 50/100 µm bead diameter thermocouples were used but in some circumstances finer gages also (25 µm bead diameter). The time constant of the thermocouples are respectively of the order of 10 ms and 100 ms for the 25 µm and 50 µm thermocouples.

1.2-Some characteristics of the mixtures

Preliminary tests have been performed with premixed methane-air gaseous mixture.

Three kinds of combustible particle-air mixtures were tested. The particles were: starch dust, lycopodium, sulfur flower. Some characteristics of the particles and of the suspensions are presented in table 1. The (mass) average particle diameter is in the range of a few tens of micrometers.

2-Maximum flame temperatures

2.1-Results

The results obtained with the 50 µm thermocouples are presented in figure 2, 3, 4 respectively for starch dust-air mixtures, sulfur flower-air mixtures and lycopodium-air mixtures. The junction of the thermocouples were installed on the axis of the tube.

Calculations of the theoretical maximum flame temperatures were also performed, assuming no heat losses, taking into account the production of a great range of species as well as dissociation at high temperatures. The results are presented on the same figures as the experimental values.

The scattering of the results might be partly due to the experimental error on the composition of the mixture but other phenomena might also be important such as the thermal inertia of the sensor and the perturbations induced in the flame front by the holder of the thermocouple.

If mean curves are plotted through the experimental points and compared to the theoretical curves, it appears that the measured values are globally lower than the theoretical ones. For instance, for nearly stoechiometric conditions, the difference is of the order of 750 °C for starch dust-air suspension and 500 °C for the other mixtures.

In order to analyse this temperature difference, the influence of the transducer need to be considered.

2.2-Influence of the tranducer

The influence of the thermal inertia has to be considered.

Temperature measurements of laminar flames propagating in starch dust-air mixtures have been performed with finer thermocouples (bead diameter= 25µm) installed on the axis of the tube. The results are presented on figure 5 together with the measurements made with the 50 µm thermocouples and the theoretical values of Tfmax. Mean curves are also plotted.

It appears that the temperature determined with the 25 µm thermocouples are about 250/300 °C larger than those obtained with 50 µm thermocouples indicating a significant influence of the thermal inertia of the tranducer at least for the case of flames propagating in starch dust-air mixtures. Although, the time constant of the 25 µm thermocouples is about ten times smaller, a significant difference still remain between theoretical maximum flame temperatures and the experimental data: for a nearly stoechiometric mixture the experimental data are about 500 °C lower than theoretical values.

Similar results were found previously (Proust, 1988; Proust and Veyssière, 1988) and, since the time constant for the finer thermocouples (25 µm) is a priori very small, it was suggested that the temperature difference between theoretical and experimental values of Tfmax could originate from heat losses of the flame by radiation.

2.3-Heat losses of the flame by radiation

This investigation has been limited to flames propagating in starch dust-air suspensions.

The light emitted by the flame front in the direction of the walls and not absorbed or reflected (toward the flame) by the particles of the suspension is lost. The characteristic length for the attenuation of the intensity of the light by the suspension is of the order of a few cm (Proust, 1988) so that the amount of energy lost by flame radiation is likely to depend on the geometry of the experimental setup as suggested by Veyssière and Proust (Veyssière and Proust, 1990).

On figure 6 are plotted the measured values of Tfmax obtained previously (Proust and Veyssière, 1988) in similar conditions (similar thermocouples, same mixtures) except that the experimental setup is two times larger than the present one. Corresponding data from the present work are also shown on this graph. It can be shown that the measured value of Tfmax are similar in both setups indicating that heat losses by flame radiation do not seem to have a great influence. But further work is needed to confirm this.

3-Laminar burning velocities

Several methods can be used to determine the laminar burning velocity (Lewis and Von Elbe, 1987; Andrews and Bradley, 1972) but with the experimental setup used in the present work , two of them are particularly suited: the "direct" method and the "tube" method (Proust, 1988; Proust and Veyssière, 1988; Veyssière et Proust, 1990).

3.1-"Tube" method

With the experimental conditions considered, Sl can be derived from the flame speed and shape according to the following expression:

$$Sl = S \cdot Ap / Af \qquad [1]$$

where S is the flame speed, Af the flame front area and Ap the projected flame area on a plane perpendicular to the direction of flame propagation. Provided the flame geometry is simple enough, the determination of Sl by this method is simple and only requires a video equipment.

This method has been used for the determination of the laminar burning velocities of premixed gaseous flames propagating in the experimental setup of figure 1. Homogeneous methane-air mixtures were used since reliable data are available for these mixtures (Andrews and Bradley, 1972). Obtained values of Sl are displayed in figure 7 with a curve representing the best available data in the litterature. It appears that the present results are very close to the published values indicating that the "tube" method is applicable in the present experimental conditions.

Therefore, this method has been extensively applied to determine the laminar burning velocities for the dust-air mixtures described previously (cf § 1.2). A photograph of the flame front for one kind of dust is shown in figure 8. The values of the laminar burning velocities versus the nature of the dust and the concentration of particles in the suspension are presented in figures 9, 10 and 11. The results are scattered. One cause of this dispersion is the difficulty for estimating with precision the flame front area. For stoechiometric conditions, the laminar burning velocities are given in table 1. These values are of the same order of magnitude than for some gaseous mixtures such as CH_4-air. The largest values have been obtained for lycopodium-air suspensions (47 cm/s). For sulfur flower-air and starch dust-air mixtures, Sl is of the order of 20 cm/s.

3.2-"Direct" method

For the "tube" method to give reliable results some requirements have to be fulfilled. For instance the laminar burning velocity has to be constant over the flame front. The "direct" method allows the determination of the local burning velocity. In this latter method Sl is directly derived from its definition:

$$Sl = \vec{S} \cdot \vec{n} - \vec{U} \cdot \vec{n} \qquad [2]$$

where $\vec{n}$ is the unit vector normal to the flame front at the point under consideration and $\vec{U}$ the flow velocity (vector).

The experimental determination of Sl with this method is difficult since $\vec{S}$ and $\vec{U}$ have to be sufficiently accurate and $\vec{U}$ has to be determine very close to the flame front. For this, the tomographic technique was used (for further details see: Proust and Veyssière, 1988). The particle velocity is derived from the luminous traces left by the particles on the video pictures (figure 12). The flame speed is derived from the flame movement on several successive frames . The applicability of this method seems limited to lean mixtures for which the movement of a single particle can be isolated. Furthermore, the precision on $\vec{U}$ is not very good (perhaps ±25%).

Some experimental determinations of Sl with this method have been performed with the mixtures considered in this paper and are presented in figures 9, 10 and 11. Given the accuracy of the "direct" method, the results are in good agreement with those obtained with the "tube" method, indicating that the latter seems reliable with the experimental conditions used.

3.3-Influence of the tube diameter

The laminar burning velocities of flames propagating in starch dust-air suspensions have been obtained (Proust and Veyssière, 1998) with experimental conditions very similar to those described previously (cf § 1.1) except that the experimental setup was two times larger (tube diameter 0.2 m). These results are presented in figure 9.

It appears that the results obtained in the present work are approximately 20 % smaller indicating *a significant influence of the geometry of the experimental setup* (Veyssière and Proust, 1990). The origin was firstly attributed to heat losses of the flame by radiation. However, as shown before (cf § 2), the maximum flame temperatures are very similar in both setups indicating that *heat losses (by radiation), all other phenomena excluded, are not likely to justify such a variation.*

However, ahead of the flame front is generated a flowfield which can be seen on the pictures obtained with the tomographic technique. It can be shown (Proust, 1988; Lewis and Von Elbe, 1987) that the existence of this flow is closely linked to the flame front geometry through expression [2]. This flow might be partly induced by the gravity forces acting on burnt products, pushing the flame upward (elongating it) and "forcing" the suspension to flow around the flame front but other phenomena such as flow velocity profile in the burnt products (Guenoche and Jouy, 1952; Marskstein, 1964; Lewis and Von Elbe, 1987) might also be considered.

Aerodynamically, the flame tip might be regarded as a stagnation point. Near the walls, the flow is submitted to friction and a boundary layer appears. In these regions, velocity gradients are produced and the flame is "stretched" (Lewis and Von Elbe, 1987). Since Sl is dependent on the magnitude of this stretch (Matalon, 1983), it appears that flame stretch might be taken into consideration in order to understand the influence of the geometry of the experimental setup on Sl possibly in connection with other factors as for instance heat losses of the flame (Libby and Williams, 1983).

4- Standard explosivity parameters

Standard explosivity parameters for starch dust, lycopodium and sulfur flower in suspension in air have been determined with the classical "20 litre sphere". The maximum explosion overpresure Pmax and the well-known KST coefficient obtained are presented in table 2.

Pmax represents the total (thermal) energy released during the combustion and can thus be compared to Tfmax. In table 2 have been reported the theoretical values of Tfmax for the stoechiometric mixtures considered (taking the experimental data instead of theoretical values does not change the following development). It can be observed that the lowest value of Pmax is obtained for sulfur flower-air mixtures which also exhibit the lowest value of Tfmax.

KST should be linked to the rate of energy release. It seems that KST could be related to Sb = Sl . Tfmax / To where To is the initial temperature of the mixture. Sb represents the volumetric production rate of burnt products by unit flame area. In a closed vessel, it can be easily shown that this rate is related to the rate of pressure rise. Sb has been calculated for the mixtures under study (table 2). Considering KST values, it appears that the rate of energy release of starch dust in air is lower than for sulfur flower-air suspensions. Comparison between Sb values indicate that within the experimental accuracy, the combustion should give the same rate of pressure rise. This indicate that the rate of pressure rise in the standard apparatus depends on additional factors (such as initial turbulence) and that KST might not be directly linked with the flame properties. In these circumstances, a classification of the dusts established on the basis of flame propagation and combustion properties might be different from another based on KST values. Consequently, it might be preferable to consider KST as a scaling parameter for explosions developping in a "similar" way as in the 20 litre sphere. Some care is required when it is intended to use this parameters for explosions occuring in very different conditions like in pipes.

5- Conclusions

In this paper are presented some results of measurements of the laminar burning velocities, Sl, and of the maximum flame temperatures, Tfmax, for starch dust-air mixtures, lycopodium-air mixtures and sulfur flower-air mixtures (mean particle diameter between 25 and 45 µm).

The classical "tube method" has been used in order to determine laminar burning velocities. Values of some tens of cm/s have been obtained. In order to assess he validity of this method, it has first been used for premixed gaseous mixtures (CH_4-air) in the experimental setup described. The results are compared with the best available data for these mixtures and the agreement is satisfactory. In addition, some direct measurements of Sl for the studied particle-air mixtures have been performed by using a tomographic technique allowing the simultaneous determination of the flame speed and mixture velocity ahead of the flame front. The results are compared with those obtained with the tube method and the agreement is again satisfactory indicating that this method seems adequate for measuring laminar burning velocities of two phase mixtures.

Thin (25 µm and 50 µm) thermocouples have been used to measure maximum flame temperatures. Calculation of the theorical values of this parameter have also been performed and a significant discrepancy between theoretical and experimental values appears. This discrepancy is partly due to the thermal inertia of the transducers.

Standard explosion parameters (KST, Pmax,…) have also been determined with a "20 litre-sphere" for the same mixtures. The physical meaning of these parameters is briefly discussed in relation with laminar burning velocities and maximum flame temperatures. From the few data available, it appears that Pmax varies in the same way as Tfmax indicating that Pmax seem to represent conveniently the total amount of energy released during the explosion. It also appears that KST is not directly linked to the combustion and flame propagation charactistics of dust-air mixtures and it is suggested that classifications of dust according to KST values might be different from those derived from the burning properties.

Many aspects of dust flame propagation need to be further analysed. In particular, the magnitude of heat losses by radiation has to be determined since several mechanisms involved in flame propagation depend on the degree of adiabaticity of the flame (ex: flame stretch). For this, accurate flame temperature measurements would be useful but many technical difficulties have to be overcome.

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