FLAME PROPAGATION OF DUST AND GAS-AIR MIXTURES IN A TUBE

A. Di Benedetto*, A. Garcia-Agreda*, O. Dufaud, I. Khalili**, R. Sanchirico*, N. Cuervo**, L. Perrin** and P. Russo*****

dibenede@irc.cnr.it

*Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, Napoli, Italy

** Laboratoire Réactions et Génie des Procédés, CNRS, 1 rue Grandville, 54001 Nancy, France

***Dipartimento di Ingegneria Industriale, Università di Salerno, Fisciano (SA), Italy

Abstract

The flame propagation of hybrid (nicotinic acid/methane-air) mixtures has been studied using the open-tube method. During the flame propagation four phases can be distinguished and two phases, the first and the third, have been selected as useful for the evaluation of the burning velocity. The first phase has a spherical shape propagation mode while during the third phase the flame propagation can be considered as pseudo stationary and planar.

In both phases, the role of the pre-ignition turbulence and of the turbulence induced by the flame itself has been addressed. The main issues which arise when estimating the burning velocity of hybrid mixtures have been evaluated and suggestions for future work are addressed. In the first phase the flame propagation is laminar but mixing between methane and nicotinic acid is prevented. In this case, in order to guarantee a homogeneous dispersion of the dust as well as a good mixing with the flammable gas, the injection of the dust/gas mixture should be realized from the reservoir.

In the third phase, the turbulence induced by the flame propagation plays a major role and the determination of the turbulence level is required in order to evaluate the burning velocity.

Introduction

Explosion severity of dust-air and dust/gas-air mixtures strongly depends on the mode of flame propagation. Several studies have been devoted to reveal the mechanisms driving the flame propagation of dust-air mixtures. The widely accepted idea is that the key mechanisms are heat transfer by radiation and/or conduction, heterogeneous reaction, production of volatile components, heat transfer by convection and conduction [1-3]. All these mechanisms have to be considered when quantifying the burning velocity. However, the role of heat transfer by radiation is often negligible [4,5] and for small particle sizes the controlling mechanism is generally the combustion of volatiles [6].

In order to fully characterise the flame propagation and then the explosion behaviour of dust-air mixtures, the knowledge of the flame burning velocity is required. The method for the evaluation of the dust-air mixtures burning velocity is different from that of gas-air mixtures since the dust dispersion has to be accomplished.

In the literature, three methods for measuring the laminar burning velocity of dust-air mixtures have been implemented: burner method [4,7-10], contained explosions method [4,11-13] or tube method [1,2,4,5,14-26].

In this latter, also called the “open tube method”, the propagation of the flame front occurs in a partially open and transparent tube and so the evaluation of the burning velocity is direct and is performed by following the images of the flame front by means of a video camera. The dust dispersion is ensured by injecting a mixture of dust-air into the tube from a pressurized reservoir [16,24]. Krause and Kasch [22] studied the dust flame propagation in a cylindrical fluidized bed.

From all these studies it appears that the most relevant concern is the dust dispersion. Dust dispersion is guaranteed by injecting the dust mixtures into the tube or the closed vessel thus generating pre-ignition turbulence. As a consequence, measurements of the burning velocity are strongly dependent on the turbulent flow conditions. Apart from pre-ignition turbulence, turbulence is generated by the flow induced by the expanding burnt gases which eventually affects the flame propagation.

Considerable effort has then been devoted to the evaluation of the turbulence induced by the dust-air mixture injection into the tube. Schneider and Proust [18] visualized both the propagating flame and the turbulence intensity using a high speed digital video camera and Laser Doppler Anemometry (LDA). Wang et al. [24] measured the RMS of the turbulent velocity fluctuations in the horizontal and vertical directions, generated in the tube after dust injection, as a function of the ignition delay time elapsing between the time of injection and the time of ignition. They were able to measure the dust concentration at different heights along the tube showing that the dust concentration is not uniform along the tube height.

This aspect is more complicated when dealing with the study of the flame propagation of hybrid mixtures (dust/gas-air), where it is important to control not only the concentration of the dust and its dispersion along the tube length, but also the fact that the gas to dust concentrations ratio is uniform everywhere.

In the literature, few works have been devoted to the study of the flame propagation of hybrid mixtures [27-31]. Bradley et al. [27-29] studied the laminar burning velocities of methane-air-graphite mixtures and of fine coal dusts by using a burner. Methane and air were fed in a pre-mixing chamber; then this mixture was divided into two streams, one passing through a fluidized bed to entrain the graphite. They demonstrate that in the coal dust explosion the pyrolysis/devolatilization step is very fast and that the combustion occurs substantially in the gas phase. Moreover, they underlined that the presence of the char does not change the gas phase composition and kinetics.

Liu et al. [30] and Chen et al. [31] studied the flame propagation of methane and coal dust in a vertical combustion chamber to measure the flame speed. A premixed methane-air mixture is injected in the tube to disperse the dust in the chamber. They found that in the presence of methane, even at concentration lower than LFL, the flame speed and the flame front temperature are higher than that of coal dust flame. They observed an initial flame with poor light imputable to the methane flame and only subsequently the coal dust starts participating to combustion. The combustion of coal dust is further complicated by the presence of flammable methane, this prevents a deep understanding of the detailed nature of coal dust/methane-air combustion propagation process. However, the authors did not deal with the issue of dispersion of the gas and the dust as well as how the turbulence influences the flame propagation of the hybrid mixture.

In this paper, tests have been performed with methane-air, nicotinic acid-air and nicotinic acid/methane-air mixtures at various dust concentrations (up to 200 g m^{-3}) and methane contents (up to 8 % v/v). Firstly, the feasibility of the tube method for the measurement of the burning velocity of hybrid mixtures has been evaluated by highlighting the role of the dust dispersion and mixing with the flammable gas. Moreover, the role of turbulence, both pre-ignition turbulence and induced turbulence, on the values of the burning velocities has been discussed. Eventually, some suggestions have been done to improve the tube method when dealing with the measurements of burning velocity of hybrid mixtures.

Experimental apparatus

The flame propagation experiments have been performed in a vertical tube of 1 m height with a square cross section of 0.07 x 0.07 m (V = 4.9 L). The tube has two opposite walls made of glass and two opposite wall made of stainless steel. The top end is open by means of a removable vent (pressure at which vent opens is of about 1.023 bar). At the bottom, the end is closed; in fact, the tube is attached to a metal base equipped with a dispersion cup of hemispherical shape, where the dust is placed. In the hybrid mixture tests, firstly, the methane-air mixture is fed to the tube. Then, in order to generate a homogeneous cloud, the dust is dispersed by an air blast of 7 bars issuing from a mushroom-shaped nozzle linked to a 0.05 L reservoir. The ignition of the dust/gas cloud is obtained by means of a capacitive spark, provided by a modified Hartmann tube (Mike 3 - Kühner AG), between two 2 mm diameter tungsten rods with a spark gap of 6 mm, located near the closed bottom end of the tube at 12.5 cm from the bottom. The delay time is equal to ~ 140 ms. In order to have an initial pressure inside the chamber at the moment of ignition of less than about 1 bar, the tube is connected by means of a vacuum line to a vacuum pump. A pressure transmitter is used to measure the evacuation pressure and to prepare gas mixture in the tube by partial pressure method. Methane and air are premixed in a chamber of about 0.6 L of volume.

A Phantom V91 high speed video-camera is used to record ignition of dust/gas cloud with a frame rate of 2000 fps (period: 500.00 μs). The timing sequences and the ignition system are controlled remotely by means of electronic system adapted from the modified Hartmann tube. A simple scheme of the system is showed in Fig. 1.

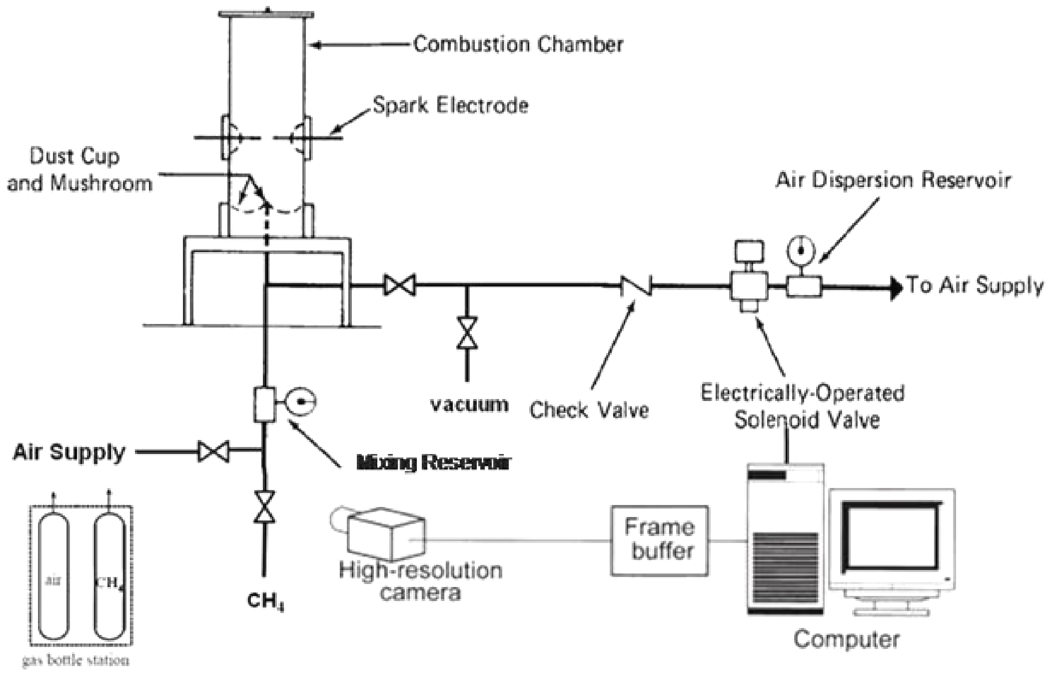


Figure 1. Modified scheme of the flame propagation experiment system [32].

Determination of the laminar burning velocity

The tube method is used in this work to determine the spatial flame velocity. The laminar burning velocity, $S'_{s,l}$, is then calculated according to the method proposed by Andrews and Bradley [14]. At first, the effect of the flame curvature is taken into account:

$$S_{s,l}' = \frac{A'}{A_f} \cdot S_f \tag{1}$$

where S_f is the flame velocity, A' is the projected flame area on a plane perpendicular to the direction of flame propagation and A_f is the surface area of the flame front. The flame velocity S_f is calculated as the prime derivative of the distance between the flame front and the ignition point (∂x/∂t). In this method it is considered uniform over the tube cross section. When the flame is completely developed along the tube, A' should correspond to the entire squared section. But, when the flame does not occupy the entire section of the tube, the dead space near the tube walls should necessarily be taken into account [33]:

$$S_{s,l}' = \frac{\pi \cdot r_f^2}{A_f} \cdot S_f \tag{2}$$

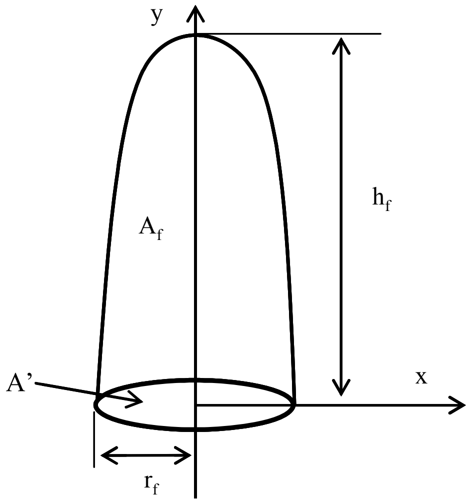


Figure 2. Geometry of the flame

The shape of the flame surface, A_f, may be considered as a paraboloid of revolution with height h_f and radius r_f. The Fig. 2 shows the flame geometry. Therefore, the surface can be calculated by the equation [34]:

$$A_{f,prolate} = 2 \cdot \pi \cdot \left(r_f^2 + \frac{r_f \cdot h_f \cdot a}{e} \right) \tag{3}$$

where $a = arccos\left(\frac{r_f}{h_f}\right)$ and $e = sin(a)$, called eccentricity. This is valid when the spheroid is defined as "prolate". In the case of oblate spheroid, the equation becomes:

$$A_{f,oblate} = 2 \cdot \pi \cdot \left(h_f^2 + \frac{r_f^2}{2 \cdot e} \cdot ln\left(\frac{1+e}{1-e}\right)\right) \tag{4}$$

where $a = arccos\left(\frac{h_f}{r_f}\right)$ and $e = sin(a)$.

During the flame propagation, the top end is open thanks to an exhaust vent whereas the bottom end is closed. In this situation, it is necessary to take into account the effect of the thermal expansion of the burned gases on the laminar burning velocity, $S_{s,l}$, by dividing $S_{s,l}'$ by the thermal expansion coefficient β:

$$S_{s,l} = \frac{S_{s,l}'}{\beta} \tag{5}$$

where β is evaluable thermodynamically by the following relationship:

$$\beta = \frac{\rho_u}{\rho_b} = \frac{T_u}{T_b} \tag{6}$$

where ρ_u and ρ_b are respectively the densities of the reactants and of the combustion products, T_u is the temperature of the reactants, considered equal to the ambient temperature, and T_b is taken as the adiabatic flame temperature. To evaluate the densities of burned compounds, assuming an adiabatic combustion at constant volume, the adiabatic flame temperature is calculated by means of CEA Software and GASEQ. Adiabatic flame temperatures ranging between 1100 and 2800K have been determined as a function of the mixture fuel ratio, leading to values of β ranging from 3.9 to 9.1.

The calculated values of the laminar burning velocities are, in effect, stretched values. The flame speed depends on the laminar burning velocity and also on phenomena generated by the presence of turbulence as front wrinkling and stretching by large eddies. The rate of change of area is then defined as the flame stretching and the velocity of the flame surface normal to itself is the flame speed. On the basis of the flame response to these perturbations, the flame may be stable or unstable. An indicator of the flame stability is the Markstein length, L. It depends on thermodynamic and transport properties of the mixture and can assume positive or negative values depending on Lewis number (Le). Le expresses the ratio of the heat diffusivity to the mass diffusivity.

On the one hand, positive values of L suggest that, on increasing the flame stretch, the burning velocity decreases, hence reducing the local disturbance and wrinkling of the flame front and stabilizing the flame. At the flame front, thermal and mass diffusive flows are encountered. The mass flow is proportional to the mass diffusivity and the heat flow is proportional to the thermal diffusivity. For a wrinkled flame, an increase of fuel concentration or temperature is obtained as a function of the flame local curvature, leading to a competition between mass and thermal transfers. When L is positive, the Lewis number is greater than unity ($Le>1$), i.e. thermal diffusion is greater than mass diffusion. As a consequence, the wrinkles are reduced and the flame is stabilized.

On the other hand, if L is negative, then the burning velocity increases when the flame stretch increases. In these conditions, any disturbance to the flame is enhanced and the flame is intrinsically unstable [35,36]. At these values correspond a Lewis number lower than unity ($Le<1$). In this case, when the molecular diffusivity of reagents is greater than the thermal diffusivity, the rate of heat release is considerable, which leads to the flame instability and even to the flame quenching. In the early stages of flame propagation, a linear relationship between the burning velocity and the stretch rate holds [37]:

$$S_{s,l} = S_{u,l} - L \cdot \alpha \tag{7}$$

where α is the flame stretch rate. $S_{u,l}$ can be calculated as the intercept value at $\alpha = 0$, in the plot of $S_{s,l}$ versus α and the Markstein length, L, is the slope. The flame stretch rate, α, may be defined as:

$$\alpha = \frac{1}{A_f}\frac{dA_f}{dt} \tag{8}$$

Results

In Fig. 3 the distance of the flame as calculated from the images sequence is plotted versus time for pure dust (nicotinic acid 190 g/m^3), pure methane (methane 6 % v/v) and a mixture of them (nicotinic acid 190 g/m^3 – methane 6 % v/v). For each test, the ignition delay has been set at 140 ms.

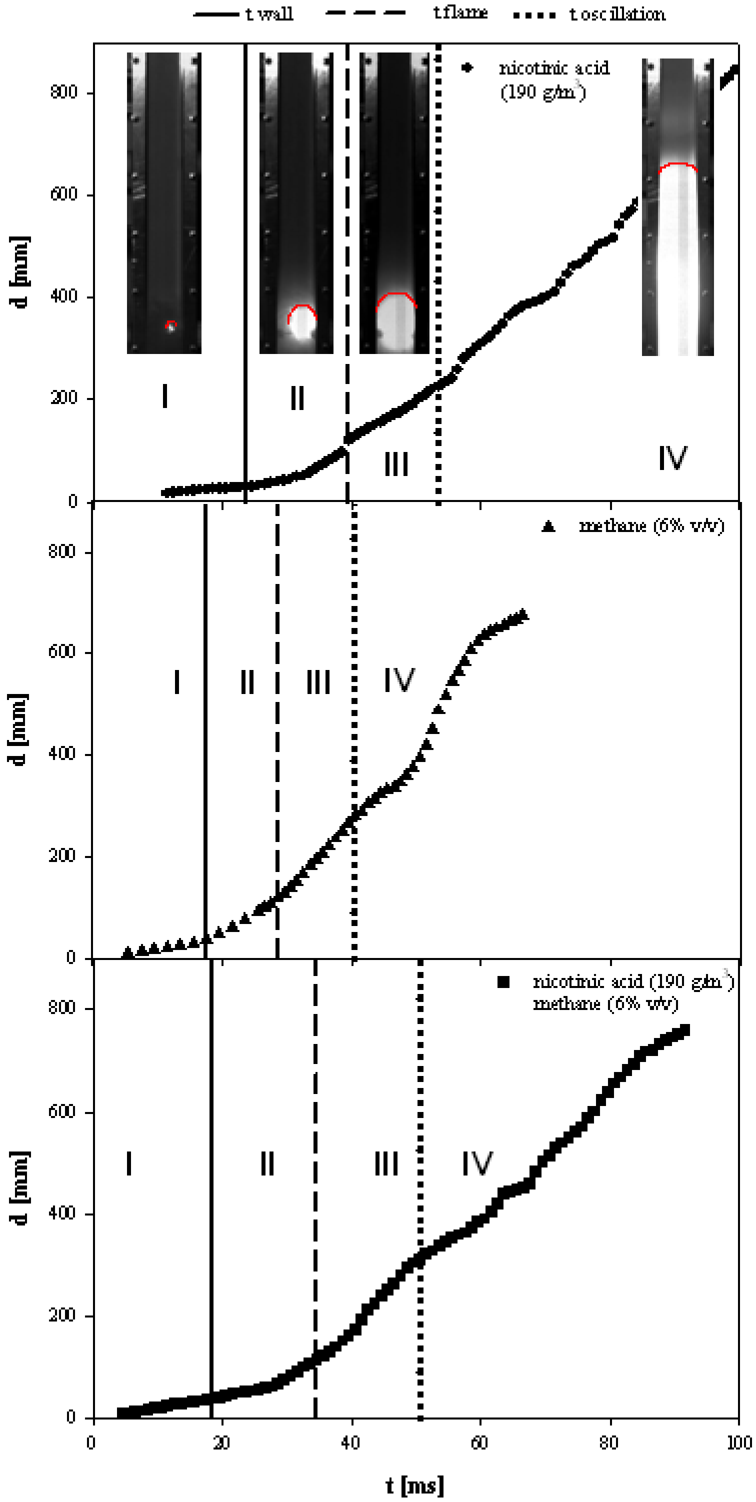


Figure 3. Flame distance versus time

From these plots, four different phases can be distinguished:
Phase I: the flame propagates in a spherical shape;
Phase II: the flame reaches the vessel walls and a progressive temporal variation of the radial profiles of temperature, concentration and velocity occurs;
Phase III: a pseudo-steady state flat flame propagation is attained;
Phase IV: the distance versus time curve exhibits an oscillating behavior due to the oscillations of pressure inside the tube. These oscillations are probably due to the interactions between combustion and venting through the top of the tube; until the valve is completely open and the gas vented through the top entire section.

In Fig. 3 the images of the flame for 190 g/m^3 nicotinic acid pure dust are shown for each phase. In order to evaluate the burning velocity, we used the data of distance of the flame vs. time on phase I and III. Indeed, phase II is strongly affected by progressive evolution of the temperature, concentration and velocity radial and axial profiles. As a result, in this phase, the flame front is not fully established along the horizontal plane and it is still developing. In phases IV the role of pressure fluctuations becomes significant and then the flame propagation cannot be considered as undisturbed anymore.

In Fig. 4 the burning velocity as computed in phase I (top) and III (bottom) for all the runs investigated are shown as determined by using the equations 2, 5 and 7. It is worth noting that the data of the burning velocity of phase I ranges between 0.05 and 0.25 m/s and are slightly affected by the methane content, decreasing by increasing the methane content. This result suggests that the injection of dust-air from the reservoir is pushing the methane-air mixtures already present in the tube downstream the electrodes thus perturbing the mixing between the dust and the flammable gas. Conversely, the value of the burning velocities computed in phase III are much higher and are significantly affected by the presence of methane presenting a maximum at about 2 % of methane content.

In Fig. 4-bottom the burning velocity of methane as computed from the images in phase III is plotted versus the methane content. The literature data of the laminar burning velocity [38-41] are also given. It is worth noting that the literature data are quite lower than the values measured in this work. This result suggests that in our experiments, turbulence is significantly affecting the values of the burning velocity.

To further prove this conclusion, we compared the burning velocity measured for the dust-air mixture alone. In Table 1 the values of the measured burning velocity for the dust alone are given as measured in phase I and phase III. It appears that the values obtained in phase III are higher than the values measured in phase I, suggesting that in phase I and III different levels of turbulence are established.

Table 1. Burning velocity as measured for the pure dust

C_{dust} (g m^{-3})	125		190	
	I phase	III phase	I phase	III phase
$S_{u,l}$ (m s^{-1})	0.132	0.73	0.105	0.29

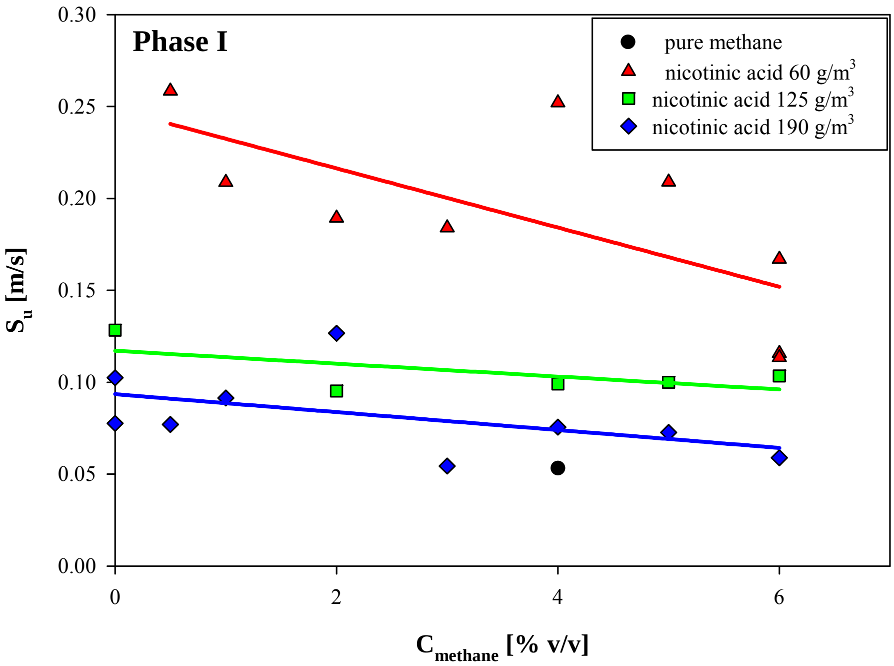
The values reported in the work are unstreched. From our calculations it turns out that the Markstein lengths are very low. More precisely for the dust alone, they are negative (ranging between - 0.03 mm and - 0.5 mm). On adding methane to the dust, the Markstein lengths from negative (- 0.2 mm) become positive (up to 0.08 mm).

The role of turbulence

In order to accomplish the different values of the burning velocity measured in phase I and III, the turbulence distribution in the tube has been analyzed.

After injection of the dust-air mixture from the reservoir, a pre-ignition turbulence establishes along the tube [16-18]. Wang et al. [24] measured the RMS horizontal (u’) and vertical (v’) RMS values as function of time in a vertical tube (0.78 m height), with square section (0.16 x 0.16 m), closed at the bottom and open at the top. They derived a correlation for both u’ and v’, whose values are shown in Fig. 5.

The values of u’ and v’ are very low if compared to the typical values (decaying from 20 m/s to about 0.2 m/s), which were established for the 20 liters spherical bomb [42]. This result is related to the leading role of the overpressure in the reservoir as shown by Schneider [17]. He showed that the initial turbulence intensity changes from 0.25 m/s up to 3.5 m/s when the pressure in the reservoir of the tube increases from 5 bars to 32 bars. In our experiments, the reservoir pressure is equal to 7 bars and then the initial turbulence intensity may be assumed as equal to about 0.5 m/s [17]. This value suggests that the pre-ignition turbulence level of phase I is quite low.



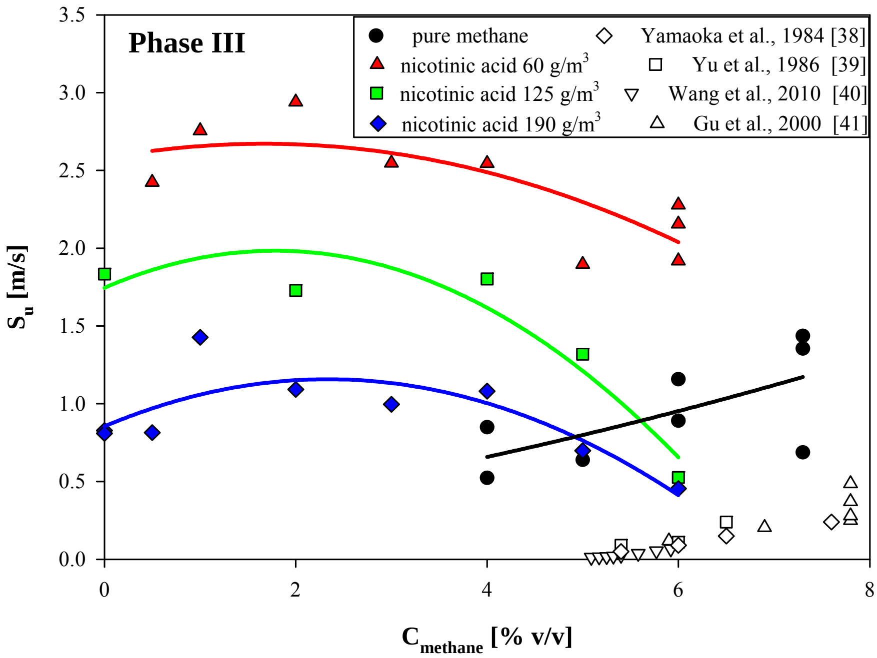


Figure 4. Burning velocity as computed in phase I (top) and phase III (bottom) as function of the methane content.

Skjold [13] in a 20 L cubical vessel found a correlation for the turbulent burning velocity of niacin amide as function of the turbulent intensity, reported as dashed curve in Fig. 5. From these values it can be concluded that the variation of the burning velocity with turbulence intensity in these range of values is very small and then that the burning velocity measured in phase I is close to the laminar value.

During the flame propagation, the turbulence is induced by the flow due to the burnt gas expansion. The turbulence level increases as the flame moves upward. As a result, in phase I the turbulence level induced by the flame itself may be considered as negligible. Conversely, we may assert that in phase III the turbulence intensity is due not only to the pre-ignition turbulence but mainly to the turbulence induced by the flame propagation along the tube. As a consequence the burning velocity measured in this phase is the turbulent burning velocity.

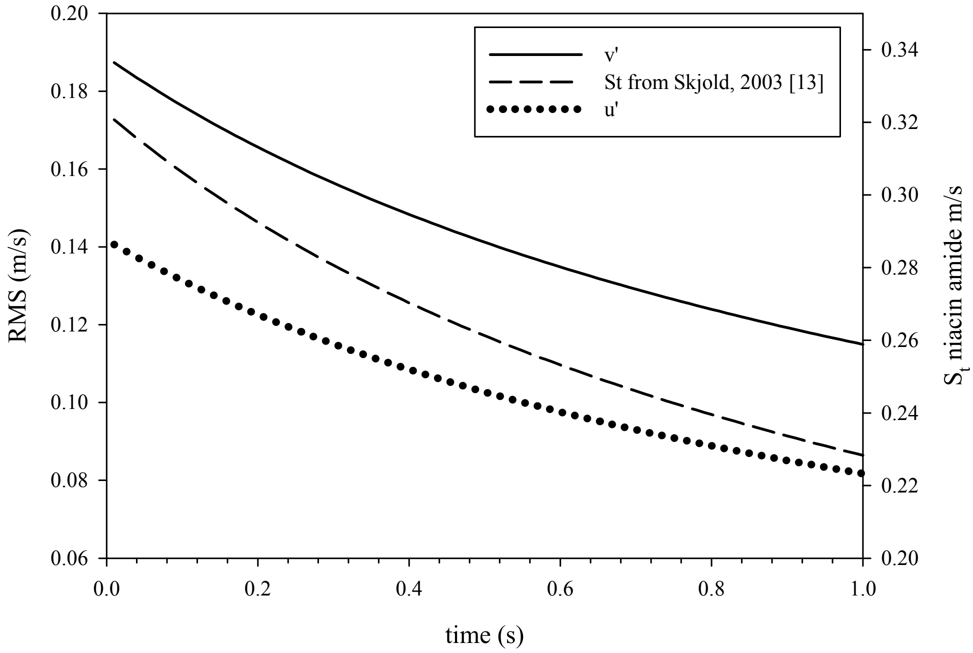


Figure 5. Horizontal (u') and vertical (v') component of RMS velocity as function of time, from Wang et al., 2006 [24] and relevant value of S_t for niacin amide [13].

Optimal experimental conditions for determining the burning velocity of hybrid mixtures

From all the above discussed results, it turns out that the measurements of the burning velocity of hybrid mixtures may be performed in the tube, provided that some modifications are performed.

Phase I: the measured burning velocity is laminar but the mixing between the dust and the flammable gas is not ensured if the dust is injected in the tube where the mixture gas-air is already present. In order to improve such measurements, the dust/flammable gas has to be co-fed trough simultaneous injection from the reservoir, thus ensuring mixing of the fuels.

Phase III: the burning velocity is strongly affected by the turbulence induced by the flame propagation itself. To evaluate the laminar burning velocity the simultaneous measurement of the turbulence level is needed.

Conclusions

The study of the flame propagation along a vertical tube of a hybrid mixture has revealed that the flame propagates in four phases. The evaluation of the burning velocity in the vertical tube is strongly affected by the phase of flame propagation at which it is evaluated. In the initial phase, when the flame propagation is almost spherical and the flame has not touched the tube walls, the effect of the pre-ignition turbulence is almost negligible.

In the third phase, when a flat like stable flame propagation establishes, the burning velocity is affected by the turbulence level induced by the flame propagation.

From these results it turns out that in order to correctly quantify the burning velocity of dust-gas/air mixtures with the tube method, the turbulence intensity induced by the flame propagation has to be measured. The determination of the laminar burning velocity and of Markestein length, which has to be compared with the flame thickness, will give us the opportunity to better understand the specificity and the stability of such hybrid mixtures in order to propose adequate means of prevention and protection.

Nomenclature

A'	projected flame area on a plane perpendicular to the direction of flame propagation
A_f	surface area of the flame front
C	concentration of the dust
e	eccentricity of the spheroid
h_f	height of the flame
L	Markstein Length
r_f	semi-axis, minor axis of the flame
S_f	flame velocity
S_l	laminar burning velocity
$S'_{s,l}$	Burning velocity that takes into accounts the flame curvature
$S_{s,l}$	stretched burning velocity
$S_{u,l}$	unstretched burning velocity
t	time
T_{ad}	adiabatic flame temperature
Tb	temperature of the burned gases
T_u	temperature of the reagents
α	flame stretch rate
β	factor of expansion
ρ	density of a component

Subscripts

l	laminar
u	unburned
b	burned

References

[1] Mazurkiewicz J., Jarosinski J., Wolanski P., "Investigations of burning properties of cornstarch dust–air flame", *Archivum Combustionis* 13(3-4): 189–201 (1993).

[2] Proust, C., Veyssiere, B., "Fundamental Properties of Flames Propagating in Starch Dust-Air Mixtures", *Combust Sci Technol*, 62(4-6): 149-172 (1988).

[3] Russo, P., and Di Benedetto A., "The Effect of Turbulence on the Theoretical Evaluation of Dust Explosions Severity", *Chemical Engineering Transactions*, 11: 983-988 (2007).

[4] Van Der Wel, P., "Ignition and propagation of dust explosions", Delft University Press, Delft, (1993).

[5] Proust, C., "Flame propagation and combustion in some dust-air mixtures", *J Loss Prevent Proc*, 19: 89-100 (2006).

[6] Di Benedetto, A., Russo, P., "Thermo-kinetic modelling of dust explosions", *J Loss Prevent Proc* 20: 303–309 (2007).

[7] Dahoe A. E., K. Hanjalic, B. Scarlett, "Determination of the laminar burning velocity and the Markstein length of powder–air flames", *Powder Technol*, 122(2-3): 222-238 (2002).

[8] Kolbe, M. "Laminar burning velocity measurements of stabilized aluminum dust flames", Masters thesis, Concordia University, (2001).

[9] Milne, T.A., Beachey, J.E., "The microstructure of pulverized coal-air flames – I. Stabilization on small burners and direct sampling techniques", *Combust Sci Technol*, 16: 123-138 (1977).

[10] Cassel, H.M., "Some fundamental aspects of dust flames", Rep. 6551, Bureau of Mines, U.S. Department of the Interior, 1964.

[11] Silvestrini, M., Genova, B., Leon, F.J., "Correlations for flame speed and explosion overpressure of dust clouds inside industrial enclosures", *J Loss Prevent Proc*, 21: 374–392 (2008).

[12] Pu, Y.K., Jia, F., Wang, S.F., Skjold, T., "Determination of the maximum effective burning velocity of dust-air mixtures in constant volume combustion", *J Loss Prevent Proc*, 20: 462-469 (2007).

[13] Skjold, T., "Selected aspects of turbulence and combustion in 20 litre explosion vessels" Cand. Scient. Thesis, University of Bergen, (2003).

[14] Andrews, G.E., Bradley, D., "Determination of burning velocities: A critical review", *Combust Flame*, 18:133-153, (1972).

[15] Proust, C., "Experimental determination of the maximum flame temperatures and of the laminar burning velocities for some combustible dust-air mixtures", *Archivum Combustionis* 13(3-4): 175-188 (1993).

[16] Proust, C., "A few fundamental aspects about ignition and flame propagation in dust clouds", *J Loss Prevent Proc*, 19: 104-120 (2006).

[17] Schneider, H., "Measurement of turbulent burning velocities by means of the open tube method", *J Loss Prevent Proc*, 19: 130-134 (2006).

[18] Schneider, H., Proust, C., "Determination of the turbulent burning velocities of dust air mixtures with the open tube method", *J Loss Prevent Proc*, 20: 470-476 (2007).

[19] Hamberger, P., Schneider, H., Jamois, D., Proust, C., "Correlation of turbulent burning velocity and turbulence intensity for starch dust air mixtures", *Third European Combustion Meeting (ECM2007)*, in Chania, Crete, (2007).

[20] van Wingerden, K., Stavseng, L., "Measurements of the laminar burning velocities in dust-air mixtures", *VDI-Berichte*, 1272:553-564 (1996).

[21] Krause, U., Kasch, T., Gebauer, B., "Velocity and concentration effects on the laminar burning velocity of dust-air mixtures", *Archivum Combustionis* 16(3-4): 159-176 (1996).

[22] Krause, U., Kasch, T., "The influence of flow and turbulence on flame propagation through dust–air mixtures", *J Loss Prevent Proc* 13: 291-298 (2000)

[23] Wang, S., Pu, Y., Jia, F., Gutkowski, A., "Effect of turbulence on flame propagation in cornstarch dust-air mixtures", *J Therm Sci*, 15(2): 186-192 (2005).

[24] Wang, S., Pu, Y., Jia, F., "An experimental study on the flame propagation in cornstarch dust clouds", *Combust Sci Technol*, 178: 1957-1975 (2006).

[25] Han, O.S,, Yashima M., Matsuda T., Matsui H., Miyake A., Ogawa T., “Behavior of flames propagating through lycopodium dust clouds in a vertical duct”, *J Loss Prevent Proc* 13: 449–457 (2000).

[26] Han O.S., Yashima M., Matsuda T., Matsui H., Miyake A., Ogawa T., “A study of flame propagation mechanisms in lycopodium dust clouds based on dust particles’ behaviour”, *J Loss Prevent Proc* 14: 153–160 (2001).

[27] Bradley, D., El-Din Habik, S., Swithenbank, J.R., “Laminar burning velocities of CH4 – air – graphite mixtures and coal dusts”, *Twenty-first Symposium (International) on Combustion/The Combustion Institute*, pp 249 – 256 (1986).

[28] Bradley, D., Dixon-Lewis, G., El-Din Habik, S., “Lean Flammability Limits and Laminar Burning Velocities of CH_4 – Air – Graphite Mixtures and Fine Coal Dusts”, *Combust Flame*, 77: 41-50 (1989).

[29] Bradley, D., Chen, Z., El-Sherif, S., El-Din Habik, S., John, G., Dixon-Lewis, G., “Structure of Laminar Premixed Carbon-Methane-Air Flames and Ultrafine Coal Combustion”, *Combust Flame*, 96: 80-96 (1994).

[30] Liu, Y., Sun, J.H., Chen, D.L., “Flame propagation in hybrid misture of coal dust and methane”, *J Loss Prevent Proc*, 20: 691-697 (2007).

[31] Chen, D.L., Sun, J.H., Wang, Q.S., Liu, Y., “Combustion Behaviors and Flame Structure of Methane/Coal Dust Hybrid in a Vertical Rectangle Chamber”, *Combust Sci Technol*, 180: 1518-1528 (2008).

[32] ASTM E 789-95, *Standard Test Method for Dust Explosions in a 1.2-Litre Closed Cylindrical Vessel*, Annual Book of ASTM Standards 2004. USA: ASTM International, 1995.

[33] Rzal, F., “Etude expérimentale de l'interaction d'un anneau tourbillonnaire avec une flamme laminaire dans un mélange gaz-particules solides”, thèse de doctorat de l'université de Poitiers, n° 509, (1992).

[34] Perry, R., Green, D.W., *Perry's Chemical Engineers' Handbook*, 8^{th} ed., McGraw-Hill, 2007.

[35] Cammarota F., Di Benedetto A., Di Sarli V., Salzano E., Russo G., “Combined effects of initial pressure and turbulence on explosions of hydrogen-enriched methane/air mixtures”, *J Loss Prevent Proc*, 22(5): 607-613 (2009).

[36] Chen Z., Burke M.P., Ju Y., “Effects of compression and stretch on the determination of laminar flame speeds using propagating spherical flames”, *Combust Theor Model*, 13: 343-364 (2009).

[37] Bradley, D., Gaskell P. H., Gu X. J., “Burning Velocities, Markstein Lengths, and Flame Quenching for Spherical Methane-Air Flames: A Computational Study”, *Combust Flame,* 104:176-198 (1996).

[38] Yamaoka, I., Tsuji, H., “Determination of Burning Velocity Using Counter-flow Flames”, *Twentieth Symposium (International) on combustion, The Combustion Institute*, Pittsburgh, pp 1883-1892, (1984).

[39] Yu, G., Law, C.K., Wu, C.K., “Laminar flame speeds of hydrocarbon + air mixtures with hydrogen addition”, *Combust Flame,* 63:339-347 (1986).

[40] Wang S.F., Zhang H., Jarosinski J., Gorczakowski A., Podfilipski J., “Laminar burning velocities and Markstein lengths of premixed methane/air flames near the lean flammability limit in microgravity”, *Combust Flame*, 157(4): 667-675 (2010).

[41] Gu X. J., Haq M. Z., Lawes M., Woolley R., “Laminar burning velocity and Markstein lengths of methane–air mixtures”, *Combust Flame*, 121(1-2): 41-58 (2000).

[42] Dahoe A.E., Cant R.S., Scarlett B., “On the decay of turbulence in the20-Liter explosion sphere”, *Flow Turbul Combust,* 67:159–184 (2001).