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The Role of Burning Velocity in the Validity of Hybrid Mixtures

Matouš Helegda[a], Jan Skřínský[b,*], Tomáš Jastrzembski[a], Ján Vereš[b], Jakub Čespiva[b], Tadeáš Ochodek[b]

[a] Faculty of Safety Engineering, VSB - Technical University of Ostrava, Lumírova 630/13, 700 30 Ostrava - Výškovice, Czech Republic
[b] Eergy Research Centre, CEET, VSB - Technical University of Ostrava, 17. listopadu 2172/15, 708 00 Ostrava-Poruba, Czech Republic
jan.skrinsky@vsb.cz

A small quantity of flammable gas mixed with dust can cause a large explosion with severe consequences. In this study, hybrid mixtures explosion tests were performed in constant volume 0.02 m^3 and 1 m^3 spherical vessels. Fifty pressure-time curves were recorded. The effects of ignition source and test vessel volume on burning velocity were investigated for Lycopodium Clavatum-methane-air hybrid mixtures. The most important results from evaluated experiments are the values of burning rates to understand better the fundamental flame propagation process in hybrid mixtures and the impact of volume and ignition source on combustion regimes.

1. Introduction

The burning velocity is known to be altered by turbulence. It depends on the coupling interaction between the explosion pressure, rate of pressure rises, the volume of the vessel, and the ignition source. When discussing hybrid mixtures, the focus is on an admixture of flammable gas in concentrations below the lower explosive limit of the gas itself. If this limit for the gas is exceeded, one soon has a situation where the worst-case scenario for a primary explosion would be a pure gas explosion. (Amyotte and Eckhoff, 2010) Saeed et al. (2016) investigated the influence of particle size on the burning velocity of pulverized biomass based on the ISO 1 m^3 dust explosion vessel. Stahmer and Gerhold (2016) searched for the relationship between the explosion indices of dispersed dust and particle surface area and the heat of combustion and found that the prime effect on burning velocity was the mean particle size. Janovský et al. (2019) determined the coal dust, lycopodium, and niacin hybrid mixtures with methane and hydrogen in 1m^3 and 20 l chambers. Cloney et al. (2020) presented the role of particle diameter in laminar combustion regimes for hybrid mixtures of coal dust and methane gas. They concluded that the burning velocity was calculated for a wide range of dust concentrations and initial gas equivalence ratios for 10 µm and 33 µm particles. More recently, Spitzer et al. (2021) published a comparative study on standardized ignition sources used for explosion testing and the influence of pre-ignition pressure rise on safety characteristics of dust and hybrid mixtures. Published p_{max} and K_G/K_{st} values depending on volume and ignition source for Lycopodium Clavatum-methane-air mixtures are summarized in Table 1.

Table 1: Lycopodium Clavatum-methane-air hybrid mixtures

bar	K_G/Kst bar·m/s	Volume m^3	Ignition
7.9	295	0.02	10 kJ
6.3	96	0.02	Electrical spark
8.0	179	1.00	10 kJ
7.7	88	1.00	Electrical spark

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The present paper compares the burning velocity of a lycopodium-methane-air hybrid mixture based on the explosion parameters obtained in 20 l and ISO 1 m^3 explosion chambers using the two 5-kJ chemical igniters and a permanent spark.

2. Experiment

The experiments have been performed in a 0.02 m^3 constant volume stainless steel double wall vessel of spherical shape (CA 1M^3, OZM Research, s.r.o) and a 1 m^3 electro-heated spherical vessel (CA 20L, OZM Research, s.r.o) adopted for the hybrid mixture experiments. The laboratory-size vessels used in the presented study are geometrically similar, different sizes, and with point ignition. The dynamic explosion pressures have been recorded by pair of piezoelectric pressure sensors (Kistler, model 701A) and with a transducer sensor charge amplifier (Kistler, model 5041E1) combined with Programmable logic controllers (model 1215 in 1.00 m^3 and 5073A211 in 0.02 m^3, Siemens). Both experimental setups are schematically introduced in Figures 1-2.

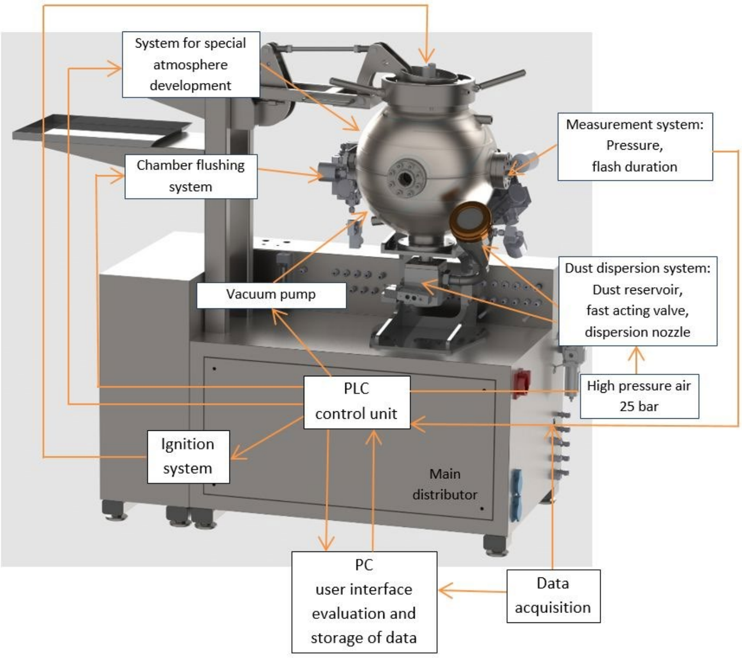

Figure 1: The standard 20L-sphere

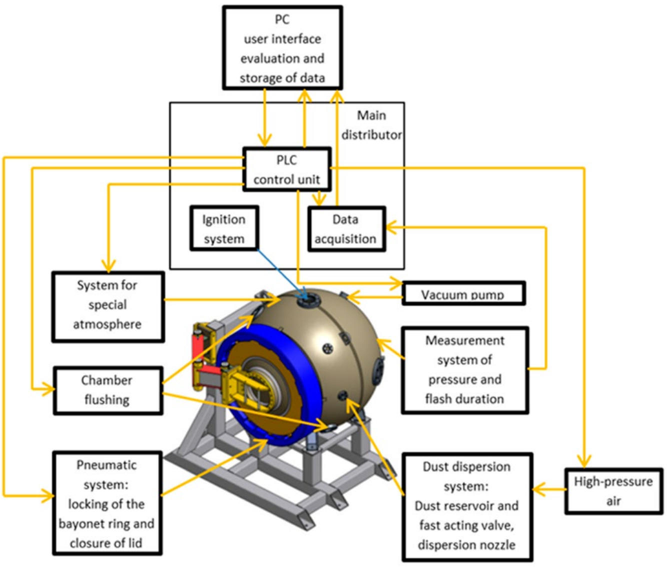

Figure 2: The ISO 1 m^3 standard

2.1 Procedure

The methodology is applied to investigate the explosion severity characteristics is based upon the combination of three standard procedures and one recently published: the European Standards EN 14034-1+A1 (2011), EN 14034-2+A1 (2011), EN 15967 (2011), and operating procedure for Round Robin (BAM, 2021). The latter one allows the explosion of the dust-air mixture parameters measurement to adapt for hybrid mixtures studies. The illustrative results of Pre-Tests – the leakage rate and the post-injection pressure drop – for standard 20L-sphere are shown in Figures 3-4.

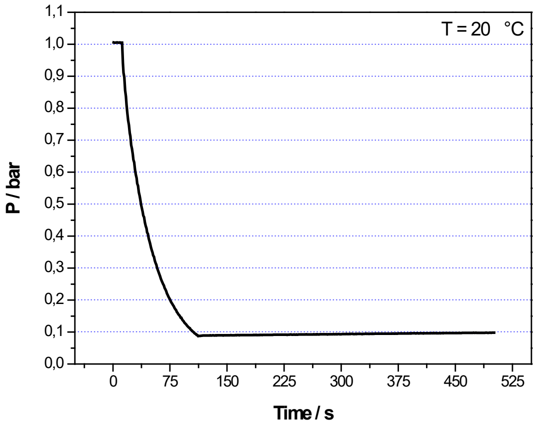

Figure 3: Leakage rate (lower than 1 mbar / min.)

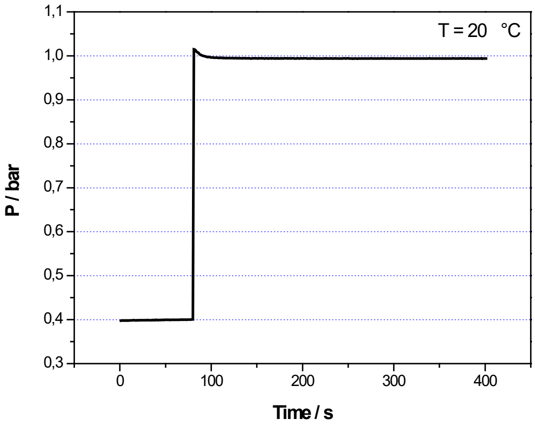

Figure 4: Post-injection pressure drop

In this research, the purity of the CH_4 used for the experiment was 99.9% (Siad, Czech Republic). Lycopodium Clavatum samples were obtained in the dust (OZM Research, s.r.o, Czech Republic).

2.2 Analysis

The accurate dust particle size distribution was determined as a mean from three independent measurements. The laser particle size analyzer, a type 1090 CILAS, is used to characterize the particle size distribution of the Lycopodium Clavatum sample. Moisture content was measured using a Mettler Toledo type 256 moisture analyzer. The results of the dust sample analysis are listed in Table 2-3.

Table 2: Particle size distribution

Parameter	Value µm	Value µm	Value µm	Mean value µm
Diameter at 10%	10.0	11.2	10.0	10.4
Diameter at 50%	32.6	33.7	32.6	32.9
Diameter at 90%	46.1	45.4	46.1	45.8
Mean diameter	32.3	35.1	32.3	33.2

Table 3: Moisture content

Parameter	Value Vol. %	Value Vol. %	Value Vol. %	Mean value Vol. %
Moisture	2.2	2.7	2.6	2.5

3. Calculation

To determine the burning velocity of the hybrid mixture, the thin-flame model was used. The model assumes that during explosion phenomena, the content of the vessel consists of a spherical inner region of the completely burnt mixture, enclosed by an outer part of the completely unburnt mixture. Both areas are supposed to be separated by an infinitely thin spherical flame front. The flame front is then a surface where a discontinuous transition takes place from unbumt to burnt mixture and propagates radially from the ignition point towards the vessel wall. The role of propagating flame thickness is accessed via the maximum rate of pressure rise – the volume of the vessel-dependent characteristic. Since it depends on the size of the vessel, it is normalized by the deflagration index according to Equation 1.

The deflagration index was defined as:

$$K_G = \left.\frac{\mathrm{d}P}{\mathrm{d}t}\right|_{\max} \sqrt[3]{V} \tag{1}$$

The ordinary differential equation for the burning velocity, S_u, at pressure P_0 is given by:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \frac{3(P_e - P_0)}{R_{\mathrm{vessel}}}\left[1 - \left(\frac{P_0}{P}\right)^{\frac{1}{\gamma}} \frac{P_e - P}{P_e - P_0}\right]^{2/3} \left(\frac{P}{P_0}\right)^{\frac{1}{\gamma}} S_u \tag{2}$$

4. Results and discussion

4.1 Explosion parameters

The main input parameters for Equations 2 are the maximum explosion pressure and the maximum rate of pressure rise. In the first step, the maximum explosion pressure of steady-state methane-air and Lycopodium Clavatum air mixtures were measured in a wide range of equivalent ratios. To obtain appropriately averaged results, each test was repeated 3 times for 0.02 m^3 and 2 times for 1 m^3, and the average is plotted in the pressure-time curve. The measured data for studied materials are depicted in Figures 5-12.

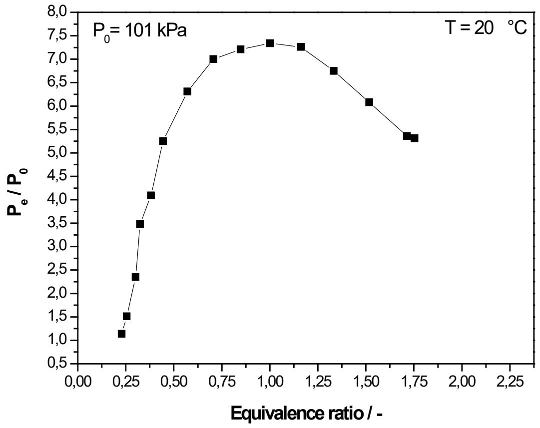

Figure 5: P_e/P_0 for CH_4 in 0.02 m^3 (spark)

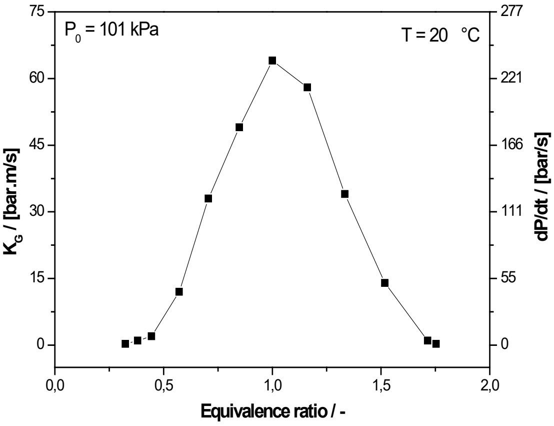

Figure 6: K_G for CH_4 in 0.02 m^3 (spark)

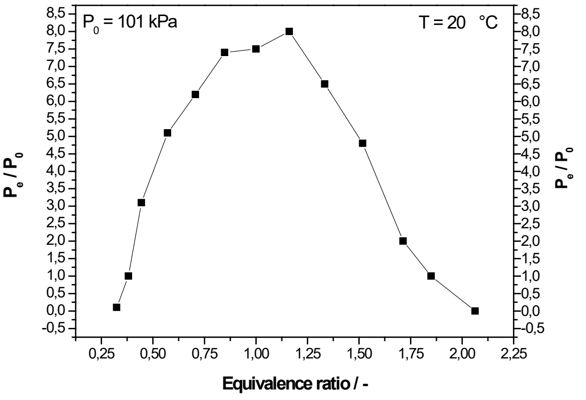

Figure 7: P_e/P_0 for Lycopodium in 0.02 m^3 (igniter)

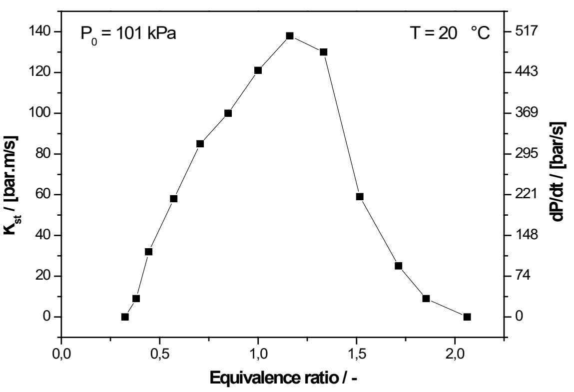

Figure 8: K_{st} for Lycopodium in 0.02 m^3 (igniter)

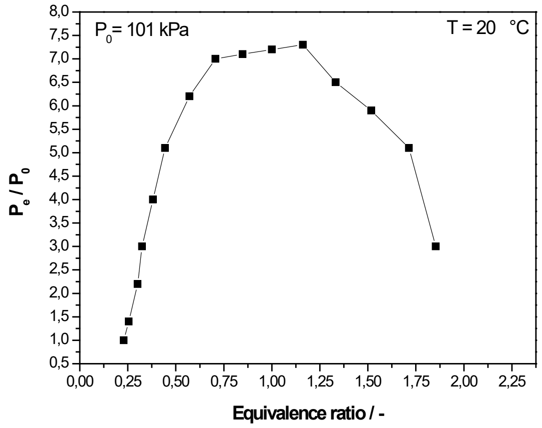

Figure 9: P_e/P_0 for CH_4 in 1 m^3 (spark)

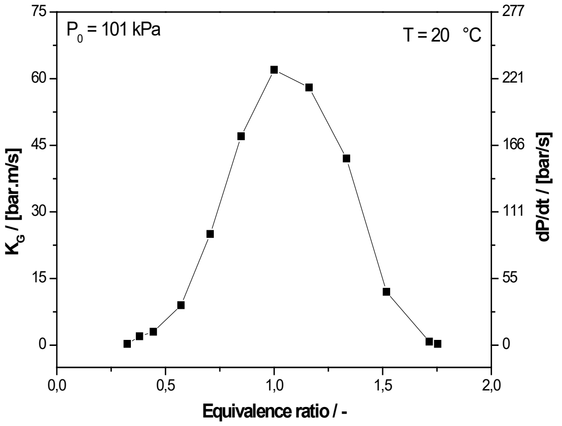

Figure 10: K_G for CH_4 in 1 m^3 (spark)

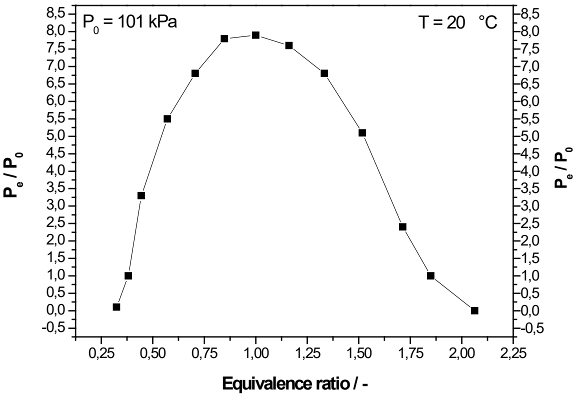

Figure 11: P_e/P_0 for Lycopodium in 1 m^3 (igniter)

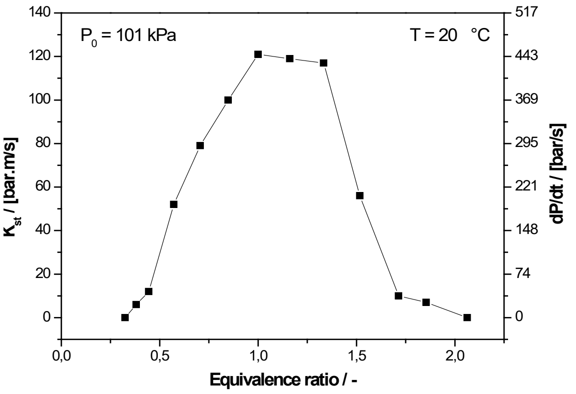

Figure 12: K_{st} for Lycopodium in 1 m^3 (igniter)

4.2 Burning velocities

The results of the detailed derivation of burning velocities are in Table 4. Examination of Table 4 shows certain aspects of volume and ignition effects. A rough correlation with the explosion parameters is also apparent. The obtained results are crucial because the maximum rate of pressure rise does not occur when the explosion pressure attaints its maximum value. As a result, the maximal parameters yield not maximal burning velocities values. Such behavior is, although not completely, seen by comparing Figures 5-12 and Table 4.

Table 4: Burning velocities in m/s

Concentration	2 x 5 kJ		Electrical spark	
g/m^3	1 m^3	0.02 m^3	1 m^3	0.02 m^3
CH_4 concentration: 0 vol. %				
125	0.34	0.45	0.37	0.32
250	0.45	0.53	0.47	0.44
500	0.54	0.51	0.52	0.46
CH_4 concentration: 4 vol. %				
125	0.44	0.48	0.55	0.30
250	0.57	0.64	0.60	0.54
500	0.61	0.89	0.56	0.68
CH_4 concentration: 8 vol. %				
125	0.72	0.96	0.76	1.34
250	0.75	1.65	0.79	2.81
500	0.70	1.82	0.72	1.90

5. Conclusions

Burning velocity is coupling two dust explosion parameters being important for assessing the venting requirements and suppression equipment. The cube-root law for dust and gases becomes invalid when the burning velocity is significant. At the same time, the same law states that the burning velocity should be the same in both volumes. By studying the explosion behavior from the presented results, we can see the scale-up relation between the burning velocity and the volume in practice. The second important issue dealt with in this work is the behavior of burning velocity when using different types of ignition sources – chemical and physical.

The main conclusions:

1) Accurate determination of maximum explosion pressure and deflagration index at atmospheric temperatures and pressure for equivalence ratios φ = 0.25 - 2.50.
2) The burning velocity and the burning zone do not reach maximum values where the explosion pressure and rate of explosion pressure rise.
3) The values of burning velocity varied slightly up to 0.1 m/s when only dust is present, and the cube-root law has not been affected.
4) Increasing the concentration of the flammable gas and creating a hybrid mixture has affected the burning velocity with a difference higher than 0.1 m/s for 0.02 m^3 vessel volume. I am starting from a CH_4 concentration of 4 vol. %, the burning velocity in 0.02 m^3 is 0.61 m/s, and the burning velocity in 1 m^3 is 0.89 m/s. In higher CH_4 concentrations is, this behavior is even more pronounced.
5) The type of ignition does not so influence the burning velocities in 1 m^3. But when compared to the maximal values for 0.02 $m^{3,}$ the difference is many times larger.

Nomenclature

φ – fuel-air equivalence ratio, -
K_G – deflagration index, bar.m/s
P – pressure, N/m^2
P_0 – initial pressure, N/m^2
P_e – explosion pressure, N/m^2
R_{vessel} – vessel radius, m
t – time, s
T – temperature, K
V – vessel volume, m^3

Acknowledgments

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References

BAM, Operating Procedure for a Round Robin Test on Hybrid Dust/Gas-Mixtures “HYBRID 1”, 2021.

Amyotte P. R., Eckhoff R. K. Dust explosion causation, prevention and mitigation: An overview, 2010, Journal of Chemical Health & Safety, 15-28.

Cloney C. T., Ripley R. C., Pegg M. J., Amyotte P. R. Role of particle diameter in laminar combustion regimes for hybrid mixtures of coal dust and methane gas, 2020, Powder Technology, 399-408.

EN 15967, Determination of Maximum Explosion Pressure and the Maximum Rate of Pressure Rise of Gases and Vapours, 2011.

EN 14034-1+A1, Determination of explosion characteristics of dust clouds - part 1: determination of the maximum explosion pressure of dust clouds, 2011.

EN 14034-2+A1, Determination of explosion characteristics of dust clouds - Part 2: determination of the maximum rate of explosion pressure rise of dust clouds, 2011.

Janovský, B., Skřínský J., Cupák J., Vereš J. Coal dust, Lycopodium and niacin used in hybrid mixtures with methane and hydrogen in 1m^3 and 20 l chambers, 2019, Journal of Loss Prevention in the Process Industries, 103945.

Saeed M. A., Slatter D. M., Andrews G. E., Phylaktou H. N., Gibbs B. M. The Burning Velocity of Pulverised Biomass: the Influence of Particle Size, 2016, Chemical Engineering Transactions, 53, 31-36.

Spitzer S., Askar E., Krietsch A., Schröder V. Comparative study on standardized ignition sources used for explosion testing, 2021, Journal of Loss Prevention in the Process Industries, 104516.

Spitzer S., Askar E., Benke E., Janovsky B., Krause U., Krietsch A. Influence of pre-ignition pressure rise on safety characteristics of dust and hybrid mixtures, 2021, Fuel, 122495.