# Dust cloud and flame size analysis in premixed powders of organic dusts and flame suppressant based on laser illumination and color space separation

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ABSTRACT

Dust deflagration is a severe safety hazard in various industries that rely on handling and transport of fine powders. In case of an ignition the flame propagation is difficult to predict by modelling approaches using Computational Fluid Dynamics (CFD). Hence, experimental investigations are crucial to better understand the involved physical and chemical effects. High-speed cameras can provide better insight to this highly transient and turbulent behavior but usually suffer from a dynamic range problem. It is almost impossible to capture the dust cloud at low luminosities and the bright flame with a single camera during one experiment. Laser illumination can help to overcome these limitations. In the present study we use a continuous wave Laser to investigate the influence of flame suppressants on the flame size evolution of organic dusts (maize starch). The results provide a better insight on the necessary amount of suppressant powders for flame quenching.

## 1. Introduction

Flame suppressant powders are widely used in active explosion protection (Eckhoff, 2003). In real life applications suppressant powders are injected into closed systems as soon as an ignition is detected (via pressure increase, optical detectors or other means). A thorough understanding of the dust flame suppression mechanism is key in the search for the best flame suppression solutions in industrial plants. The interaction of the suppressant powder, the dust cloud and the propagating flame is complex and not fully understood, since, on a microscopic level, the relative impact of physical and chemical effects to flame suppression are difficult to separate experimentally. The powder properties not only influence the dispersion pattern and injection distances of the suppressant but also the amount of powder needed for reliable explosion suppression. On the one hand a suppressant powder can act as a heat absorber and withdraw energy from the flame, on the other hand chemical interaction between the dust, the suppressant and the flame will change the local

concentration of e.g. $O_2$ and $CO_2$ in the combustion zone. It is therefore of great importance to have sound experimental data for numerical model validation. For experiments on dust explosions two standardized setups are widely used: (i) the Hartman tube device to test the minimum ignition energy (MIE) (Dorsett, 1960) and (ii) the 20 liter SIWEK apparatus to test the maximum pressure gradient (VDI2263, 1990). Both types of test rigs have some disadvantages with respect to optical accessibility and inherently have a strong wall influence. The setup used in the present study has larger dimensions and allows a free propagation of the dust cloud and the flame with much lower wall effects. To eliminate the effects of the suppressant injection system (dispersion of suppressant powder, inertia effects) from our experiments, we use premixed powders of flammable dusts and suppressant powders to obtain good repeatability of experimental results under well defined boundary conditions for the comparison with CFD results.

## 2. Experimental setup

The experimental apparatus represents a modified setup of a Hartman tube device where the dispersion of the dust is separated from the ignition and observation chamber (Fig. 1). The dust sample is aerated in the dispersion box by a pressurized air pulse and moved to the observation chamber with additional flush air through a connecting pipe with inner diameter of 100 mm. At the end of the inlet pipe two electrodes ignite the dust cloud with an electric arc. The test rig has been introduced and described in more detail in previous publications (Puttinger et al., 2023; Spijker et al., 2022).

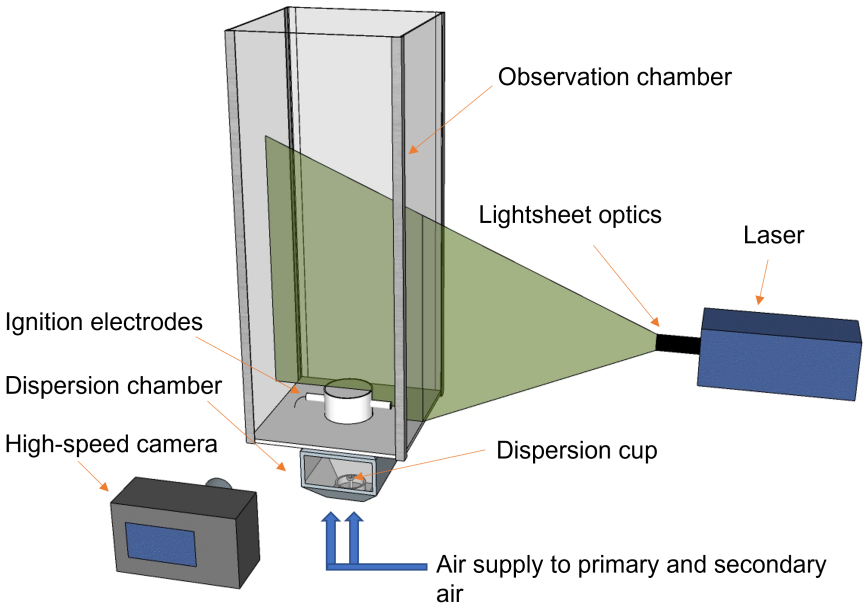



**Figure 1.** Sketch of the experimental setup (Fig. adapted from Puttinger et al. (2023)).

The limited dynamic range does not allow to record both, the dust cloud and the flame, at sufficient quality with the same camera during one experiment. A common approach to solve this problem is to use two cameras with different settings for aperture and exposure time and make use of additional lens filters if needed. The use of a laser to illuminate the dust cloud can reduce the dynamic range problem significantly. Due to the high light intensity of the laser, it is possible to visualize the dust cloud and the flame during the same experiment with only one single camera. We use a 2.5 W continuous wave laser with 532 nm wavelength, allowing a clear distinction between the dust cloud and the flame in the green and red color spectrum. Hence, it also makes sense to use a color high-speed camera (in our case a Chronos 2.1 camera from Krontech, Canada) for such a setup. The camera was set to 1920 x 1080 pixels resolution at a frame rate of 1 kHz for the recordings.

The powders used for the present test series are mixtures of 4 g of maize starch with increasing amount of two different suppressants from 0.1 to 1 g. To ensure good repeatability the starch has been pre-dried in a vacuum chamber at 80 °C and 200 mbar and the mixtures have been sealed in small probe tubes and rotated in a mixing device with 5 rpm for 24 hours. For each mass ratio of dust and suppressant five identical samples have been prepared and each experiment has been repeated five times to allow an averaging of the results, test the spreading of the individual experiment and identify outliers.

## 3. Image processing

Although the laser illuminated dust cloud and the flame do have a good visual separation for the observer, image processing in the RGB color space is not robust enough for fully automated post-processing of a large set of high-speed videos (in our case we have 75 datasets). The major reason for this is that the growing flame produces increasing light reflections at the surrounding walls. This leads to transient background brightness especially in the red color channel. It is therefore beneficial to transform the image into the YCrCb color space and do the image processing there. The luminosity channel Y provides a good approximation for the dust cloud. To extract the flame properly we subtract the inverse chrominance channel Cr from Y. The use of Y-inv(Cr) is more robust to cover the changing brightness of the flame during deflagration compared to using the original red color channel or any of the chrominance channels alone. Based on this color channel separation into dust cloud and flame zones a binary mask is calculated for both to calculate the corresponding areas and bounding boxes. This binarization is obtained from a k-means clustering of the grey level histograms, since this approach allows to extract a more precise identification of the dust cloud and the flame than using a constant threshold or a dual-class binarization like with Otsu's method (Otsu, 1979). A more detailed description of the entire image processing algorithm can be found in Puttinger et al. (2023).

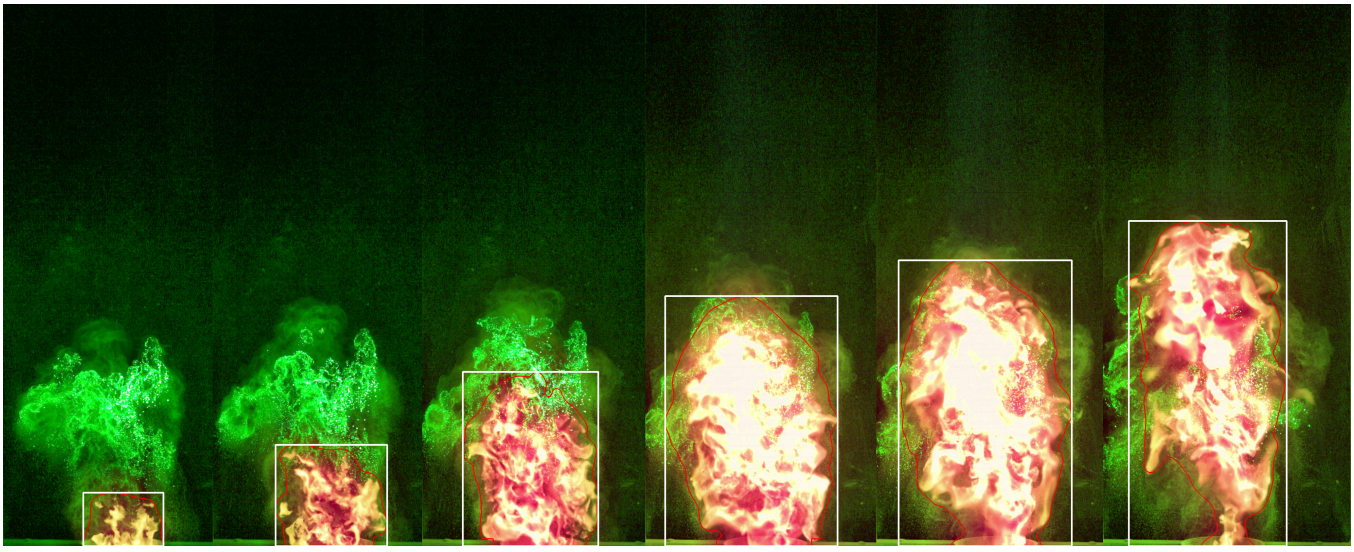


**Figure 2.** Example of an image series from an experiment with suppressant A at 12.5 w.t.% mass (0.5g).

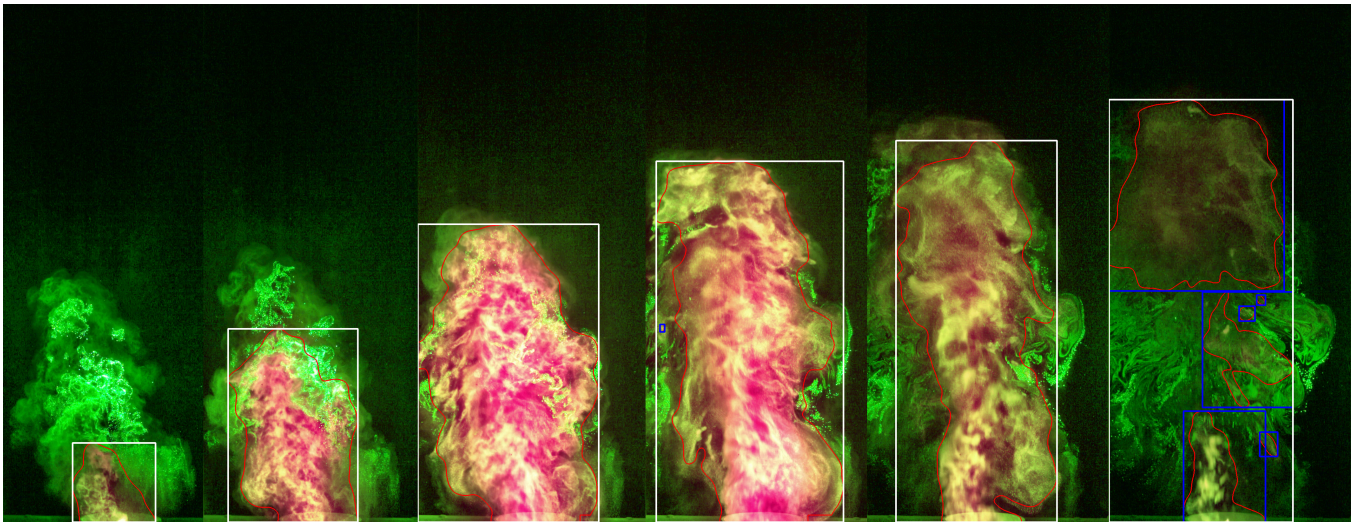


**Figure 3.** Example of an image series from an experiment with suppressant B at 12.5 w.t.% mass (0.5g).

Figures 2 and 3 provide a visual example from the test series with suppressant A and B. Both videos were taken at 12.5 w.t.% mass of suppressant. Note that the original RGB images have been enhanced with the contrast limited adaptive histogram equalization method (CLAHE, Pizer et al. (1987)) for better separation of the dust cloud and the flame. Hence, the images do not represent the original color coding of the RGB channels. The red lines mark the identified flame zone. The white rectangles indicate the bounding boxes. In case the flame decays to multiple patches several blue boxes mark these separated areas. Finally characteristic data can be obtained like the cloud and flame size, flame edge length (indicating the fragmentation of the flame front) as well as vertical and horizontal propagation velocities (derived from the bounding boxes).

## 4. Results and discussion

Applying the image processing procedure described in section 3 allows a detailed quantitative analysis of the ensemble averaged video data. Figure 4 shows the evolution of the dust cloud and the flame as ensemble averaged data. The data is normalized to the total area of the images. The mixtures of starch and suppressant B show a little wider cloud size distribution compared to the mixtures with suppressant A, but the growth of the dust cloud remains similar for all test series. This could be caused by the different particle size distributions and higher density of suppressant B. However, we could not observe apparent segregation effects during dispersion of the pre-mixed powders.

In the depicted graphs for the flame size we clearly see that also small increments of suppressant powder show a significant difference in the overall flame size over time. The proposed methodology using premixed powders of starch and suppressants is therefore a suitable approach to provide meaningful validation data for CFD model develoment and testing.

When comparing the results of the two types of suppressants in detail we can observe that type A has a flame quenching effect even for small amounts and also the increments in mass have a clear incremental effect on flame quenching with the exception of the rather indifferent behavior for 0.2 and 0.3g. Suppressant B does not show significant flame quenching for masses below 10 w.t.% and full flame suppression is achieved at a higher suppressant mass than in case of suppressant A.

These trends are condensed in Fig. 5 showing the maximum dust cloud and flame sizes vs. relative mass of suppressant. While the area of the dust cloud remains in the same range for all w.t.% of suppressant of the experiments, the maximum flame size declines rapidly above 7.5 w.t.% of the suppressant, with a more vigorous flame quenching for suppressant A.

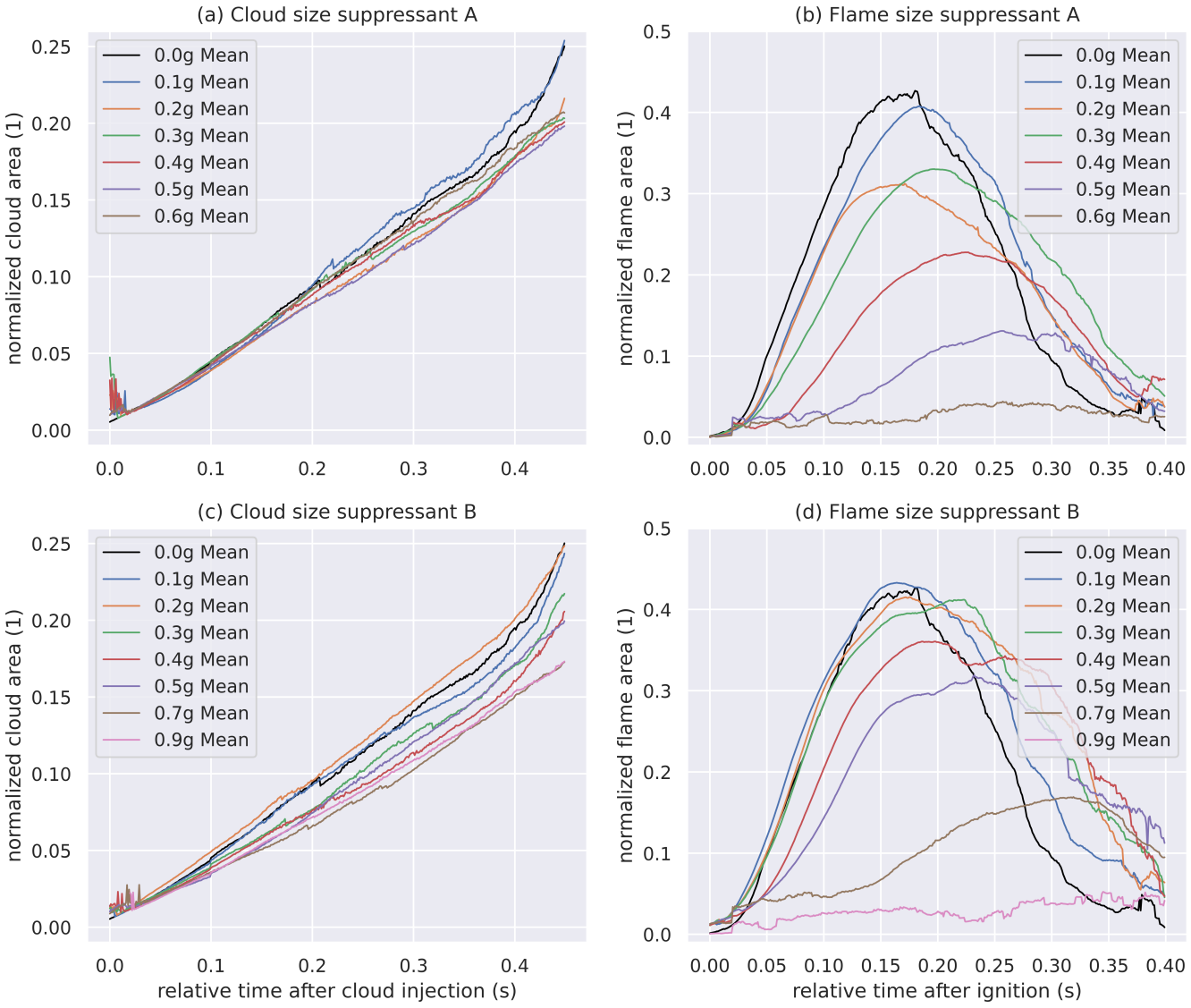



**Figure 4.** Comparison of ensemble averaged cloud and flame size for premixed powders with suppressant A and B.

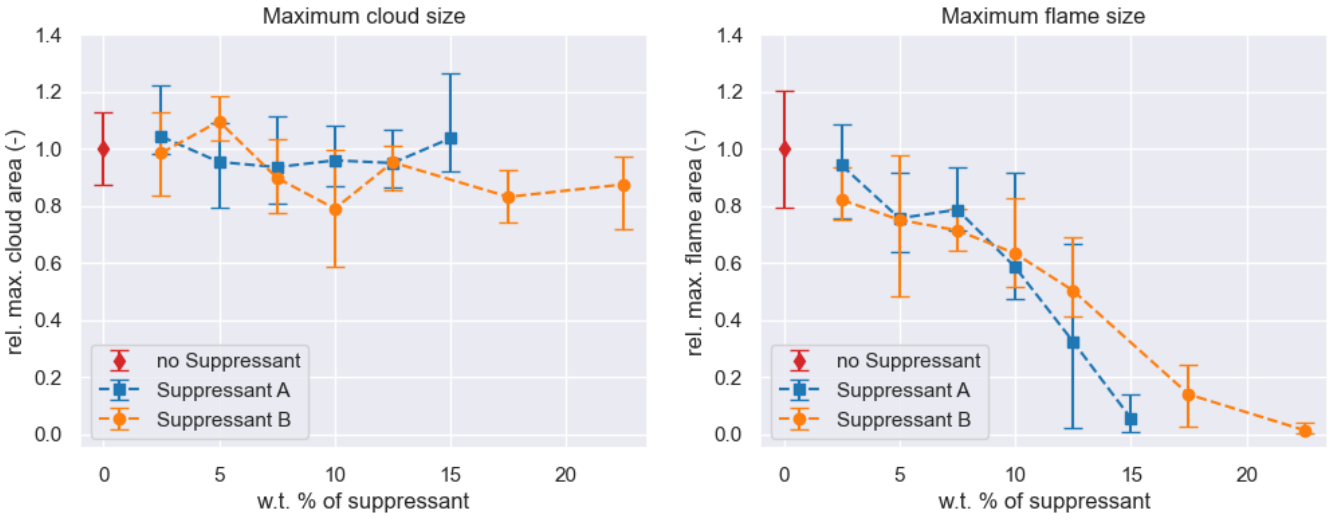



**Figure 5.** Maximum size of the dust cloud (a) and the flame size (b) for suppressant A and B. The error bars indicate the minimum and maximum values for the ensemble averaged sets of experiments listed in Table 1.

## 5. Conclusions

The test rig design proposed in this study allows optical investigation of dust deflagration experiments high repeatability. Laser illumination improves the simultaneous measurement of the dust cloud and the flame in one single experiment and allows the use of one color high-speed camera for the video recordings. The subsequent image processing procedure then delivers data about the transient behavior of the dust cloud and the flame.

The presented results elaborate the influence of small increments of two different suppressants on the evolution of a dust flame of 4 g of maize starch. The mixtures of starch and flame suppressant have been carefully prepared by pre-drying the starch and mixing the probes in a rotary device. Hence, a very good repeatability of the experiments could be achieved and several identical experiments could be used for ensemble averaging of the results.

The data for suppressant A shows a noticeable quenching effect even for small amounts of suppressant with a sharp decline of flame size for >7.5 w.t.% of suppressant. In contrast, suppressant B does not have a quenching effect below 10 w.t.%. Above this level it shows a similar decline in flame size but needs larger w.t.% of suppressant mass until full quenching of the flame is reached. The results provide a good basis for the development and validation of detailed particulate CFD models currently under active development by the group which will then be able to simulate deflagration events also in other scenarios. Upcoming research activities will include multi-camera setups to potentially extract spatially resolved data of particle concentration in the dust cloud from tomographic reconstruction. We believe that such data would provide a deeper insight on the mechanisms of flame propagation, and thus, provide valuable information for the improvement

of numerical models for dust explosions.

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