Analysis of Dust Cloud Combustion using High-Speed Infrared Imaging

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1 Introduction

Dust cloud combustion is unfortunately at risk in many working environments, jeopardizing several workers. The heat and shock waves resulting from the flame propagation into the dust cloud are harmful and lead to major endangerment or casualties. More precisely, dust cloud (small particles) explosions are even more malicious since they often result from ordinary materials such as coal, flour or pollen. In addition, many metal powdered (such as aluminum oxide and magnesium) can form dangerous dust cloud when they are in suspensions in air. The understanding of this particular type of combustion is critical for the preventive care of sites and workers afflicted to such conditions. In order to study the thermodynamic processes involved in combustion (flame propagation), scientists need to understand the main characteristics of the ignition and its phenomenology. The efficiency of combustion is usually characterized by the quantity of energy that is released, by the velocity at which the thermally expanding gases are released and by the spatial and temporal evolution of the generated heat. These general concepts also apply in the case of a dust cloud combustion process. However, the characterization of flame propagation into a dust cloud is more complex since it implicates a series of small ignitions in a three-dimensional dynamics flow. Ideally, the ignition point needs to be spread evenly and uniformly throughout the dust cloud to maximize the efficiency of the combustion. Understanding the behavior of the secondary ignition points as well as their ranging effect helps understanding the global dust cloud combustion process. This paper presents the results of a dynamic flow analysis of metal particles combustion in a dust cloud. The ignition points, the flow rate as well as the propagation direction of the flow have been characterized using fast infrared imagery.

2 Experimental

Dust Cloud Infrared Imaging

In order to simulate a dust cloud combustion process, metal particles such as magnesium or aluminum oxides are placed into small conical containers. Typical metal particle size is only a few microns in diameter. Pressurized gas is then blown under each container to spread out the dust cloud. Finally, to initiate the

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process, a hot thermal source is launched inside the dust cloud, creating an ignition point. The investigated scene consists in a mixture of different metal particles that are spread into the air in order to create a dust cloud of roughly 10×10 m. In this study, the fast infrared camera was installed in a safe environment at a distance of 33 m from the explosion location. The Telops FAST-IR 2K infrared camera is looking at the scene perpendicularly, measuring the target surface temperature. The FAST-IR 2K camera is a midwave infrared (MWIR, 3.0 µm to 5.5 µm), 320×256 pixels focal plane array infrared camera. It features a maximum frame rate of 2000 frames per second at full frame size. All the measurements performed in this experiment were done in full frame mode at a frame rate of 1300 frames per second. The field of view (FOV) is about 11.0×8.8 m.

Optical Flow Model

An optical flow analysis method was used to estimate the directional velocities of the dust cloud explosion and to study its ignition behavior. Both the velocities direction and amplitude are estimated. The resulting quantities form a vector field that informs very well on the evolution of the explosion throughout space and time. The analyzed combustion sequence typically featured irregular motions that call for a flow estimation method that does not rely on some predetermined shape features or direction of motion. A scene-based radiance gradient method was chosen, as it is well adapted to such highly dynamic and energetic sequences. According to the first law of thermodynamics, the energy entering and exiting a system must be constant. Thus, the chosen optical flow model assumes local conservation of intensity (radiance) between successive frames. Referring to a given pixel in the scene, the following constraint condition is then imposed on the image intensities $f(x, y, t)$:

$$f\left(x + v_x\Delta t, y + v_y\Delta t, t + \Delta t\right) = f(x, y, t) \tag{1}$$

where v_x and v_y are the velocity components in the x (horizontal) and y (vertical) axes respectively, and Δt is the elapsed time between successive frames. If one develops the right hand side of Equation 1 into its Taylor series expansion and neglects the higher order terms, the following relation is obtained:

$$f\left(x + v_x\Delta t, y + v_y\Delta t, t + \Delta t\right) \approx f(x, y, t) + \frac{\partial f}{\partial x} v_x\Delta t + \frac{\partial f}{\partial y} v_y\Delta t + \frac{\partial f}{\partial t}\Delta t \tag{2}$$

It follows from the constraint equation (1) that:

$$\frac{\partial f}{\partial x} v_x + \frac{\partial f}{\partial y} v_y = -\frac{\partial f}{\partial t} = \vec{\nabla} f \cdot \vec{v}) \tag{3}$$

Consequently, the gradient constraint Equation 3 must be solved for the velocities v_x and v_y. The system corresponding to Equation 3 being underdetermined, a common way of solving it is by using the Lucas-Kanade algorithm [1, 2]. This method assumes a locally constant velocity vector to solve Equation 3 in a least-squares sense. The velocity vector $\vec{v} = v_x\vec{\iota}_x + v_y\vec{\iota}_y$ at position (x, y) is estimated by forming a 2×2 system of equations using neighbourhood pixels p around the pixel of interest. The system to be solved is as follows:

$$\begin{bmatrix} \sum_{i\in p} w_i f_{xx}(i) & \sum_{i\in p} w_i f_{xy}(i) \\ \sum_{i\in p} w_i f_{yx}(i) & \sum_{i\in p} w_i f_{yy}(i) \end{bmatrix} \begin{bmatrix} \mathrm{v_x} \\ \mathrm{v_y} \end{bmatrix} = -\begin{bmatrix} \sum_{i\in p} w_i f_{tx}(i) \\ \sum_{i\in p} w_i f_{ty}(i) \end{bmatrix} \tag{4}$$

where $f_{uv} = \frac{\partial f}{\partial u} \cdot \frac{\partial f}{\partial v}$ and w_i is a weighting window. The linear system of Equation 4 is then solved for every pixel across the entire image. Before any flow estimation can be made, the sequence has to be spatially low-pass filtered in order to reduce spurious velocity estimates due to noisy pixels. Doing such filtering increasing the reliability of the measurements and reduces the false alarm rate. Furthermore, in order to compute meaningful velocity estimates over the image sequence, a segmentation step based on the energy contents is first performed. The segmentation selects a set of pixels to analyze on a frame-by-frame basis and by using mainly the following two criteria: at first, find pixels showing energy content larger than a threshold over a few images. This criterion uses a signal to noise (SNR) ratio constraint. A SNR > 5 is required in this experiment to get useful scientific grade results. At second, pixels having a temperature value above a threshold are included in the mask. The image derivatives are computed using a separable convolution filter. A low-pass FIR filter and a derivative approximation FIR filter are used, as described in [3]. For example, for computing $\frac{\partial f}{\partial x}$, the derivative filter is applied in the x direction and the low-pass filter is applied in the orthogonal directions. This filter approach is more robust toward noise than using a simple backward difference filter, which tends to amplify noise. The overall effect of the paired filters is to match the filter delays across dimensions. The velocity estimates are computed using Equation 4. The weighting window is simply a 5×5 Gaussian kernel centered on the current pixel. Finally, a spatial median filter is used on the individual velocity components to filter out the remaining spurious velocities. For display purposes, a compression function is applied to the vectors. The ignition points are calculated by evaluating the divergence of the velocity vectors field. The divergence is a technique used to evaluate the local minimum and maximum of a vector field. Thus, when the divergence of the velocity field is > 0, it means we are in presence of a source. In opposition, when the divergence is < 0 we are in presence of a sink (see Figure 1).

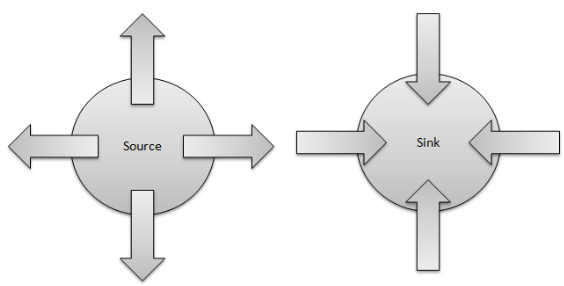

Figure 1. Source and sink definition

3 Discussion and Results

The results reveal an unprecedented capability of measuring key dust cloud combustion characteristics. Figure 2 introduces the step-by-step radiance signature evolution of the dust cloud combustion (flame propagation). The time difference between consecutive frames is 700 microseconds. While the top left image illustrates the primary ignition point, the following five images reveal interesting details on the turbulent flow created by the secondary ignition points. The detailed analysis of the last three images allows evaluating the metal particle ignition propagation and ranging effect. To better illustrate the secondary ignition points, a radiance difference between consecutive images and its Fourier transform is calculated. Several individual ignition points (secondary) can be detected from the local peaks (between 30 ms and 50 ms). For instance, at about 38 ms following the beginning of the sequence, and roughly every 2 ms (430 to 450 Hz frequency), peaks appear, indicating a significant difference in total radiance. These local peaks result from secondary ignition points propagating into the dust cloud. This result indicates unprecedented capabilities to detect fast events such as secondary ignition points.

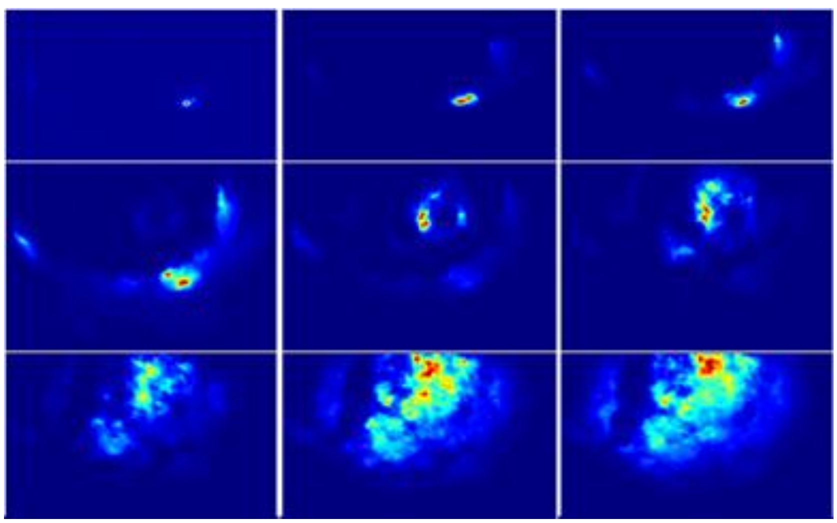

Figure 2. Metal-particule dust cloud exlosion sequence.

From the previous analysis, we can build a metal particles dust cloud flame propagation behaviour and summarize it as described in Figure 3. A given particle (white) explodes and creates a defined active sphere around which most of the particles included in its active radius are exploding (yellow). The particles exploding in this radius are defined as secondary ignition points. The radius of the sphere is defined as the range of an ignition point. This phenomenon is propagating throughout the dust cloud as secondary ignition points (yellow) generate second level secondary ignition points (red). The frequency at which the secondary ignitions happen indicates the time required for the high-energy expanding gas to reach the neighboring metal particles. Thus, it is a good indication of the dust cloud metal particle concentration and the minimum energy required to create an ignition point. Now that the preliminary high-level analysis has revealed the dust cloud general ignition process, a more detailed analysis using the model elaborated previously is being used to quantify the phenomena.

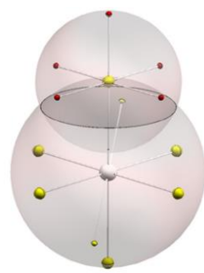

Figure 3. Dust cloud explosion process (schematic).

Figure 4 shows an example of the three partial derivatives applied on the dust cloud explosion sequence. One can clearly see the burst of the explosion at the center of the temporal derivative image. The corresponding locations in the spatial gradient images show a ring-like structure that translates into highly turbulent area with sources of flowing energy.

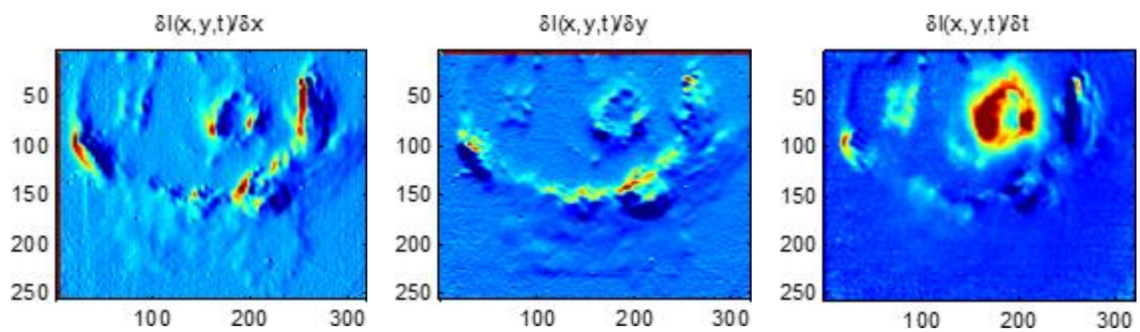

Figure 4. Partial derivative results.

Figure 5a shows the associated radiance image and calculated velocity vector field. When we zoom on the ring-like active location, we clearly see the velocity vectors field directions (red arrows direction). The magnitude of the red vectors corresponds to the high energy expanding gas velocity. For reference purpose, the point marked with a data tip indicates the calculated flow velocity near several source points. As presented previously, it is easy to notice source and sink regions within the velocity vector field. For instance, the main interest is in evaluating the velocity near the source point. After analyzing the velocity profile of more than 20 sources, it reveals the maximum average (peak) velocity is about 300 m/s at the center of the sources. The velocity profile can be defined as a fourth order polynomial function. The average measured source velocity profile is presented in Figure 5b.

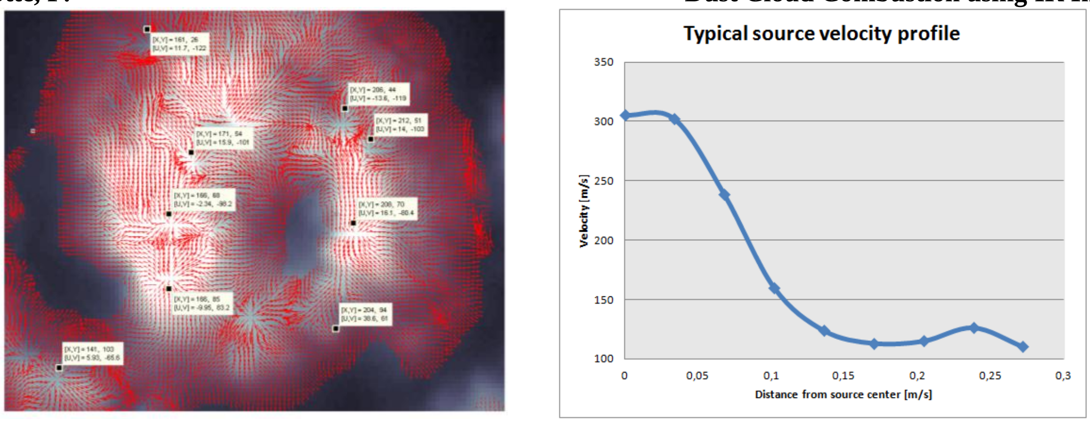

Figure 5. Vector field estimated from optical flow (a). Sources average velocity profile and ranging (b).

This velocity profile is almost constant throughout a given source circumference and is radially oriented. Using the previously found secondary ignition generation rates (roughly every 2 ms) we can find an average single ignition point active radius (range) to be around 0.3 m. By the detailed analysis of the vector flow sources in the vector field and their evolution through time, a model of ignition and chain reaction has also been derived. The center of the sources (local maxima) are easily detected using the velocity field divergence equations. Figure 6 shows the infrared images and the associated vector field. Using the divergence calculation, only the local maxima are displayed. The brighter the white points are, the more instances the ignition points have. One can sees on the vectors field the main ignitions points. By analyzing the small sequences presented in Figure 6 in more details, it is possible to identify the secondary ignition points generated by a main ignition point.

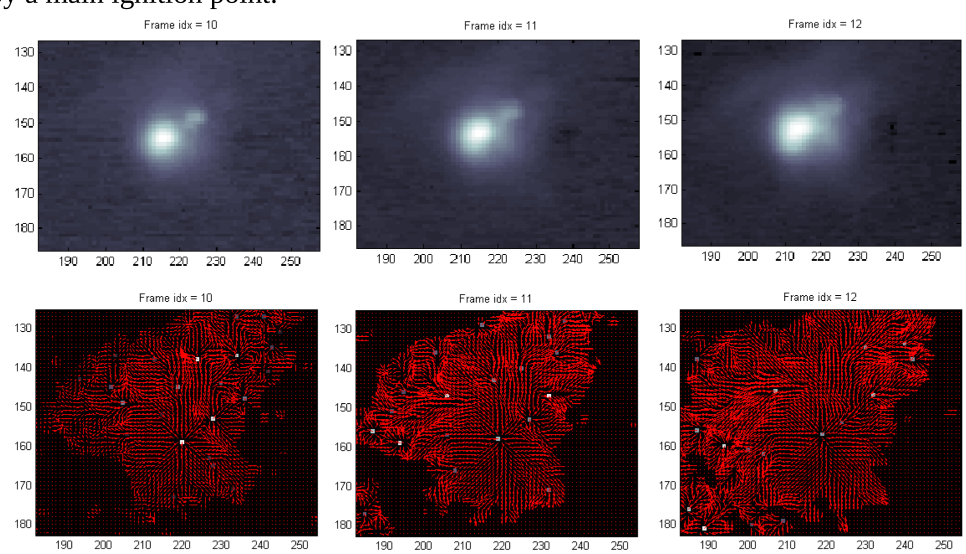

Figure 6. Top: Fast infrared images. Bottom: Source location and associated velocity vector field.

This model also allows tracking ignition points in time. The average ignition point active time is < 3 ms. Following that period the ignition point reaches back equilibrium with the average dust cloud flow. Another interesting way to characterize ignition of a metal-particles dust cloud explosion is to evaluate the amount of energy generated by one single ignition point. In order to perform such analysis, the total numbers of ignition points detected in the camera field-of-view were calculated as a function of time. Dividing the total camera measured radiance by the total number of ignition points detected indicates the amount of energy released by one single ignition point. Figure 10 presents the results.

4 Conclusion

There are several key benefits to characterizing flame propagation into a dust cloud using high-speed infrared imagery. It allows a direct measurement of the total energy released and the active radius of the global explosion process. Such data and derived information helps scientists understanding the thermodynamics of the combustion process as well as the ignition and heat propagation inside the active area. Moreover, fast infrared imagery allowed understanding and validating ignition process in high-speed dynamic applications such as dust cloud combustion. Secondary ignitions active radius, energy released and ranging effect have been successfully quantified.

References

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