Flow Visualization

Team #1 Project

Butane Explosion

Team

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The purpose of this project is to investigate the behavior behind a hydrocarbon-air mixture explosion. For this first team project, I wanted to analyze the behavior of a flame combustion and propagation process of an explosion by filming it at high speed. For security matters, combustion experiment guidelines were followed to guarantee the safety of the team. Many attempts were made in order to find a good way to show the physics behind the explosion. Regarding the type of explosions, these ones can be considered either deflagrations or detonations. In a deflagration, the hydrocarbon air mixture burns relatively slow (velocities around 1 m/s). On the other hand, a detonation, also called supersonic combustion, is characterized by a flame shock front that is followed by a combustion wave releasing energy to sustain the shock wave. For hydrocarbon air mixtures, the detonation velocity is normally around 2,000-3,000 m/s [1].

In order to create an explosion, butane gas was ignited by a gasoline flame. To accomplish the latter, a small party balloon was filled with butane gas while a knife with ignited gasoline poured small droplets of this ignited gasoline on top of the balloon (fig. 1). By doing this, the butane-balloon-gasoline boundary layer is prone to break, letting the butane mix with the surrounding air and ignited by the gasoline flames. Even though the behavior of the flames observed is highly complex to understand, a basic comprehensive study is possible to achieve in order to address the combustion process.

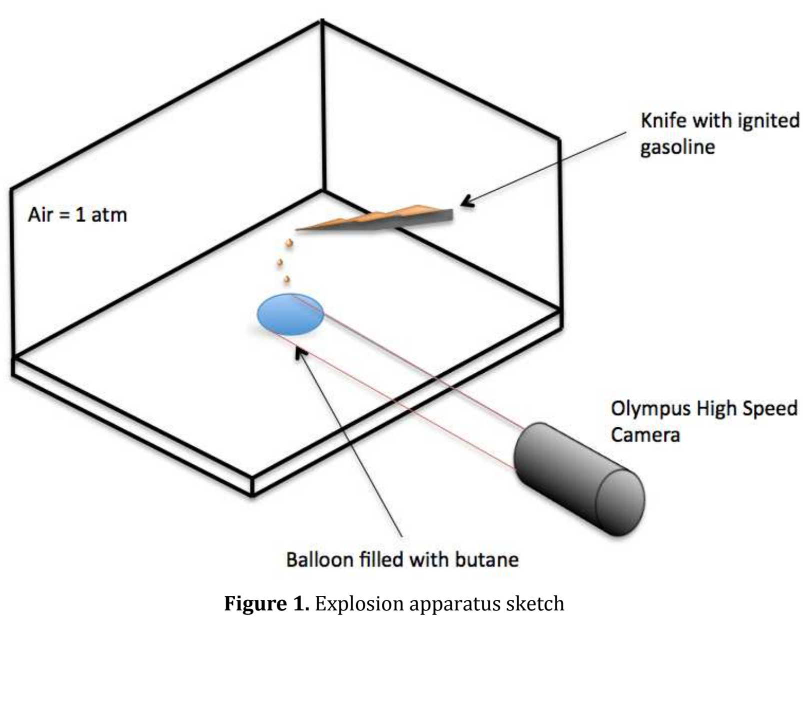

Figure 1. Explosion apparatus sketch

Therefore, to understand the physics behind the flow it is indispensable to understand the chemical reaction between butane and air. Furthermore, it is essential to understand that explosions can occur in confined and unconfined places, which will drive the explosions to behave in different ways. In this experiment, when the butane balloon explodes due to the heating of the boundary layer, a butane vapor cloud is released, making our particular experiment an Unconfined Vapor Cloud Explosion (UVCE). The rapid expansion of the gas together with the heat added by the combustion process is what drives the explosion behavior. If an ideal pure oxygen environment is assumed, the combustion chemical-molecular equation for butane-air reaction is the following:

$$C_4H_{10} + O_2 \rightarrow CO_2 + H_2O + energy$$

where the energy term on the products side is related to the thermal expansion. Moreover, when the equation is balanced, it is noticeable how the expansion process is also driven by an increase in total molecules from the combustion process from 15 molecules in the reactants and 18 in the products.

$$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O + energy$$

In addition, a way to measure the power of the explosion, UVCEs can be modeled using an equivalence correlating the flammable material of TNT with observed UVCEs [1].

$$W = \frac{\eta * m_c * E_c}{E_{TNT}}$$

where W is the equivalent weight of TNT, m_c is the weight of material in the cloud, η is the empirical explosion yield (from 0.01 to 0.1), E_c and E_{TNT} is the heat of combustion of the cloud and TNT, respectively. Also, the power will vary depending on the dispersion rate of the cloud and the flammability limits. For butane, the low and upper flammability limit falls between 1.5 and 8.5 %vol, respectively [2].

However, after analyzing the video, an innumerable amount of vortex rings were seen, created after the butane-air mixture exploded (fig. 2). The rapid expansion and heating generates an immense pressure gradient, creating high flame velocities. Therefore, the resulting vortices are categorized as pulse vortex rings due to an impulse made by the rapid detonation expansion. The high velocities originated at the beginning of the explosion interact with the slow moving fluid that surrounds the explosion, creating circulation (Γ) of the lighter fluid, thus originating a big amount or vortex rings [3]. Although the previous explanation resumes pretty well how vortex rings are formed, more complex physics are involved in vortex ring formation that were not explained.

Figure 2. Vortex rings forming after the explosion

The video was created using an Olympus high-speed camera system, which is capable to record up to 30,000 fps (frames per second). However, the video was taken at 500 fps and played back at 20 fps. The camera was placed at one point without being able to zoom neither in nor out. Also, the exposure and depth of field on the camera system was fixed depending on the fps recorded. The software Adobe Premiere Pro CS5 was used to add an introductory frame as well as the credit

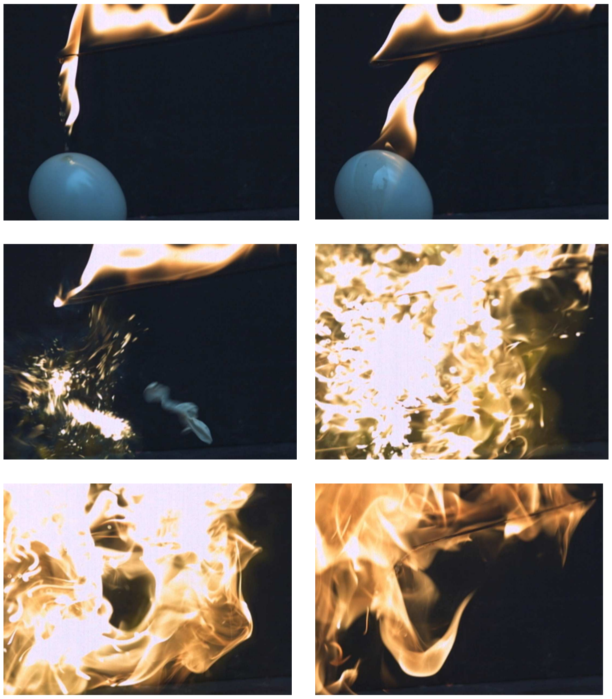

Figure 3. Explosion sequence at different time frames

section. Furthermore, figure 3 shows a sequence of pictures illustrating how the explosion developed at different time steps.

Finally, the series of images or video reveals the untamed nature of explosions in a fascinating way. With the help of the high-speed camera it was possible to capture moments in an explosion that at normal speeds would have been impossible to capture. The physics of the explosion was well captured by showing the drastic expansion and propagation of the flame at high velocities. Furthermore, the formation of vortex rings is a fascinating phenomenon. I am really pleased with the video I took, which opened an immense curiosity for fire physics in general. However, for future research I would like to have more control over the initial and boundary conditions that create an explosion in order to calculate the power, flame velocity propagation, vortex sizes and velocities, among many other variables that influence the behavior of an explosion.

References

[1] Fullwood, R. (2000). *Probabilistic safety assessment in the chemical and nuclear industries.* Woburn: Butterworth-Heinemann.

[2] Martinez, I. (1995). *Combustion kinetics*. Retrieved March 21, 2012 from http://webserver.dmt.upm.es/~isidoro/bk3/c15/Combustion%20kinetics.pdf

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