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Studies on accidental gas and dust explosions

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ABSTRACT

Fires and explosions are the disasters caused by uncontrolled combustion phenomena. The flame propagation during gas and dust explosions is much faster than the flame spread during fire. Therefore, the serious damages by accidental explosions often expand widely in a very short time. In this paper, the gas and dust explosions are described from a viewpoint of flame propagation phenomena. The understanding of flame propagation phenomena is indispensable to perform the consequent analysis of accidental explosions. Basic matters and recent research results on the flame propagation during gas and dust explosions are explained.

1. Introduction

Accidental explosions have happened occasionally at the places where combustible gas or dust were used. Once an explosion happens, damages would spread to wide areas in a very short moment. Therefore, the consequences of the accidents often become very serious. The explosions also happen during fire accident, when the combustible gas is generated and retained without ignition for some period of time [1,2]. Back draft and flash fire are examples of such phenomena. To understand fire phenomena appropriately, the knowledge of explosion phenomena is also important [3].

The prevention and mitigation of accidental explosions are important issues to handle combustible gas and dust safely. Therefore, many studies on gas explosions and dust explosions have been performed. These studies are based on combustion science, safety technology, risk assessment, and so on.

In this paper, I would like to explain the differences between explosion and fire, and then, explain some of the results of our recent researches on gas and dust explosions.

2. Differences between explosion and fire

The term "explosion" means rapid expansion or formation of gases. If it happens in an open space, it generates a pressure wave, which is called blast wave. If it happens in a closed space, the pressure in the space is increasing. Usually the closed space will be broken by the increased pressure to also generate blast wave propagating outward. At the explosion, the expansion is induced by several causes, such as combustion of combustible gas and dust, rapid reaction of explosives, sudden rapture of high pressure vessels, and so on. In this paper, gas explosion and dust explosion are focused, which are induced by combustion reaction same as the fire. Considering that the explosion and fire are also induced by combustion reaction, what is the difference between explosion and fire? It can be summarized as follows.

Explosion. The combustion reaction occurs in premixed medium. The explosion is expanding by "flame propagation" through the premixed medium. The flame propagation phenomenon is mainly governed by the combustion reaction rate, and the propagation speed is relatively fast.

Fire. The combustion reaction mainly occurs in non-premixed medium. The fire is expanding mainly by "flame spreading" along the boundary between combustible material and air. The flame spreading is mainly governed by the heat transfer rate, and the spreading speed is relatively slow. After the spreading, stationary burning occurs on the combustible material, where burning rate is controlled also by the heat transfer rate. In some cases, the premixed medium is formed and the flame propagation occurs in a short moment during the fire. For example, back draft or flash fire.

In the case of explosion, the flame propagates through premixed medium. The premixed medium is combustible gas/air mixture in gas explosions. The propagating flame through the combustible premixed gas mixture is called "premixed flame". This propagating flame is premixed type, therefore, the combustion reaction zone is moving toward unburned premixed medium with consuming the premixed mixture. This movement is "flame propagation", and the propagating speed is mainly governed by rate of combustion reaction. The propagating speed is much faster than the flame spreading speed over non-premixed medium. In dust explosions, the premixed medium is combustible dust suspended in air. In this case, the combustible dust is not mixed with air in molecular level and the flame is not premixed type. However, the flame is propagating through the medium rapidly and the phenomenon, called dust explosion, is similar as the gas explosion.

In the case of fire, the combustion reaction occurs in a variety of situations. Mainly the combustion reaction occurs at non-premixed medium. Usually, the combustible materials (solid or liquid) are heated to generate combustible gases. A non-premixed flame is formed at the

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boundary between combustible gas and air. Burning rate at this non-premixed flame is determined by the generation rate of the combustible gas. Therefore, it is governed by heat transfer rate to the combustible materials (solid or liquid). Although, the flame cannot propagate in the non-premixed medium, the burning area is expanding along the combustible materials. This expansion is induced by the spreading of the leading edge part of the flame. The flame is spreading towards the unburned part of the material, where the combustible gas just starts to be generated by heat input from the flame. This movement of the edge part of flame is called "flame spreading". The speed of flame spreading is governed by heat transfer to the unburned part of the material, therefore, it is much slower than the flame propagation through premixed medium.

In summary, flame propagation in premixed medium occurs in explosion, in which combustion reaction is rate governing factor. In fire, mainly the combustion in non-premixed medium occurs, in which heat transfer to combustible material is rate governing factor. Additionally, premixed type combustion can also occur during fire.

To examine the phenomena of explosion and fire in detail, the heat release rates of explosion (flame propagation) and fire (flame spreading and stationary pool burning) are compared. The gas explosion of vapor and the fire of liquid pool are compared using the same material, octane. The concentration of vapor and air mixture is assumed stoichiometric and the circular pool diameter is assumed 0.6 m so that the initial liquid depth becomes about 5 mm. The ambient temperature is assumed just below the flash point of octane (13 °C). The time history of the heat release rates under the following conditions are evaluated.

Explosion. At the initial stage, 1 kg of octane vapor (gas) and air are well mixed to form the mixture of stoichiometric concentration. The mixture is spherical and its diameter is about 3.0 m. It is ignited at the center and a flame propagates outward spherically. The burning velocity is assumed to be 0.4 m/s and constant. The volumetric expansion ratio is assumed to be 7. The process is schematically indicated in Fig. 1a.

Fire. Liquid octane, whose mass is also 1 kg, is located in a circular pan of 0.6 m in diameter. It is ignited at the center and a flame is spreading outward at the spread rate of 0.03 m/s. After the flame spread over whole surface of the pan, steady pool burning occurs and the regression rate is 1 mm/min. The process is schematically indicated in Fig. 1b.The time history of estimated heat release rate $\dot{Q}$ is shown in Fig. 2. In the case of explosion, $\dot{Q}$ is very quickly increasing and reaches more than 100,000 kW at the moment 0.8 s after the ignition. It takes only 1 s to burn out all the fuel. In the case of fire, $\dot{Q}$ is increasing slowly and becomes steady burning with constant $\dot{Q}$ of 180 kW. It takes about 300 s to burn out all the fuel of the same mass as the explosion. These burning characteristics are important to understand the explosion and fire. In the case of explosion, combustion heat is released in very short time. Therefore, the heat release rate becomes about several hundred times larger and the instantaneous damages tends to be more serious. Also the volumetric expansion in very short time generates blast wave (pressure wave), which causes the damages to be propagated to wide areas. Additionally in the case of explosion, evacuation and fire fighting are usually belated efforts. Prevention is essentially important for explosion safety.

Considering the various fire situations, explosions could often happen during fires [1]. If the combustible gas is generated and flame does not exist nearby, the combustible gas is not burned and mixed with air to form some extent of premixed combustible mixture. The mixture is ignited by flame afterward, then an explosion will happen. Such explosions during fire are known as back draft and flash fire.

3. Risk management of accidental explosions

Before explaining the studies on explosions, risk assessment of explosion is considered. In order to keep the safety, recently risk management of industrial process is performed by using risk evaluation. It is one of the reasonable safety management methods to evaluate and minimize the risk. Usually, the risk is expressed as the combination of probability of accident and consequence (damage) by the accident. A typical scenario of a gas explosion is shown in Fig. 3. The scenario of a dust explosion is similar.

In the case of gas explosion, the probability is governed by the ignitability of the combustible gas, and the consequence (damage) is governed by the degree of explosion violence. In order to minimize the risk of accidental gas explosion, appropriate risk estimation is needed. Therefore, the appropriate evaluations of the ignitability and explosion violence are essential [4–8]. The well known parameters for the ignitability and explosion violence of combustible gas are as follows;

- Ignitability: Minimum ignition energy (MIE), Lower flammable limit (LFL), and so on.
- Explosion violence: Maximum rate of pressure rise (K_G), Maximum explosion pressure (P_{max}), and so on.

In order to assess the risk of accidental gas explosion, appropriate consequence analysis is needed and essential. The main consequences of the gas explosions are breaking of buildings, scattering of materials and blast wave. The breaking and scattering are caused by pressure increase in the space of gas explosion. Therefore, it is essential to understand the explosion phenomena. The recent studies on gas and dust explosion phenomena are explained in the following sections.

4. Gas explosion

The flame propagation and blast wave generation are investigated by unconfined gas explosion experiments. The unconfined explosion is free propagation in open space and suitable for understanding basic behavior of gas explosion. The large scale experiments present interesting and useful results.

4.1. Intensity of the blast wave from gas explosions

In unconfined gas explosions, pressure at the space does not increase so much. Generated blast wave becomes a main hazard. Large scale experiments were performed to investigate the behavior of blast wave [5,6,9,10]. An experimental apparatus is shown in Fig. 4. Combustible gas/air mixture was filled in a tent of thin plastic sheet. An ignition occurred in the tent. The explosion behavior in this apparatus can be identified as an explosion in unconfined space, as the plastic sheet is very thin. A typical measured overpressure of blast wave is shown in Fig. 5. The experiments were performed in a tent of 9.4 m^3, and the combustible gas is 30.2% of hydrogen/air mixture.

If a flame is laminar, the pressure of blast wave can be evaluated by the theory of acoustics as follows [11];

$$p(t) = 2\frac{\rho}{l}\varepsilon^2(\varepsilon - 1)\,S^3\,t \tag{1}$$

where p is the overpressure at the position l m from the explosion point, t the time, ρ the density, ε the volumetric expansion ratio, S the burning velocity. If a laminar flame is propagating, S will be constant. "Laminar model" in Fig. 5 is the overpressure calculated by Eq. (1) in the condition of laminar flame propagation. It is found that the measured overpressure is much larger than the calculated overpressure by the laminar model. The reason of this discrepancy is the effect of flame front turbulence. There is no initial turbulence in the gas mixture, therefore, the flame front turbulence is generated spontaneously. The possible generating mechanisms of the turbulence will be flame front instability, such as "diffusional-thermal instability" and "hydrodynamic instability". In the 30.2% hydrogen/air mixture, hydrodynamic instability might be the main mechanism. In this case, flame