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# Brief review on passive and active methods for explosion and detonation suppression in tubes and galleries

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A B S T R A C T

Gaseous and dust (including hybrid) explosions often occur in mines, grain elevators, and industrial plants, and always lead to severe damage. Strategies for suppressing or mitigating explosions are developed based on an understanding of their physical mechanism. This study briefly summarized previous studies on explosions, detonations, and the deflagration-to-detonation transition (DDT), and then discussed potential passive/active or hybrid methods for suppressing explosions and detonation in tubes and galleries. Suppression can be achieved using methods that are focused on eliminating or mitigating factors that can either promote the reactive process or break down the DDT process. These methods involve lowering temperature and pressure, diluting the mixture concentration, and venting the closed system. The method of tuning wall materials (using aerogel) is also validated for the effectiveness of detonation suppression. By using various sensors to detect propagating flames or pressure increases in tubes or galleries, active systems can disperse a suppressing agent to extinguish combustion in a timely manner. It is commonly regarded that the active systems are superior to passive methods that operate without additional control units in some ways, but there are always limitations on the application due to reasons such as the cost of equipment, regular maintenance as well as reliability of the complicated integrated-systems. Practice applications show that there is no method of explosion prevention is absolutely safe. In reality, people must consider various factors in the development of an explosion/detonation suppression system to reduce the risk to an acceptable level.


## 1. Introduction

Statistics show that explosions occur frequently in industry and lead to considerable losses of life and property. Industrialized Western European countries have paid considerably for damage caused by explosions. For example, at least one explosion incident was recorded for each working day in the 1970s, on average (Bartknecht, 1981). Preventing industrial explosions and enhancing process safety have always been important methods for abating damage, even in modern industrial society (Theimer, 1973).

Explosions can be classified into three different types: dust, gaseous, and hybrid (containing gas and dust combustible components). Dust explosions usually occur in coal mines, grain elevators, and industrial plants (Amyotte, 2013; H.L, 1926; Lebecki et al., 1995; Theimer, 1973). Very large gaseous explosions can occur in processing industries, such as oil or gas petrochemical industries. Hybrid mixture explosions mostly occur in coal mines where explosive coal dust and methane can exist simultaneously. However, they may also occur in the chemical and petroleum industries where liquid droplets and fuel vapors ("mist") can be generated. Hybrid mixtures are typically less frequently generated than gas or dust mixtures because of the requirement for more complex multi-physical and chemical processes. According to Kauffman's dust explosion "Pentagon" (Amyotte, 2014), five factors must exist in order for an explosion to occur. These factors include a sufficient concentration of oxygen, combustible dust, dispersion of dust, confinement, and an ignition source. For example, a coal dust explosion may occur when the uncontrolled exothermic combustion of airborne, ultra-fine coal particles are incidentally ignited by a hot surface, spark, open flame, or chemical source. As a result of this so-called "primary explosion," a large amount of dust is lifted by a blast wave. This creates an explosive mixture with air and leads

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to a much stronger "secondary explosion." With regard to combustible gases, typically an uncontrolled release of gas (e.g., methane in a mine) can lead to the creation of an explosive mixture. If such a mixture is ignited, it would lead to a violent explosion. In some cases, both combustible gas and dust mixed with air can create dangerous explosive mixtures that can generate very violent explosions. In general, explosions are very likely to occur if fuel and air are within explosibility (combustibility) limits. A resulting explosion can generate pressure more than eight times the initial pressure of the combustible mixture, and reach temperatures up to 2000 K. During an explosion, the flame propagation velocity varies widely. In the initial stage of a laminar flame, its propagation velocity is on the order of centimeters or meters per second. However, the propagation velocity of turbulent flames can be much faster, with an order of magnitude of more than 100 m/s. If an explosion occurs in a long tube or in a coal mine gallery, flames can continuously accelerate and transition into detonation.

If the transition into detonation occurs, then the detonation front propagates with velocity on the order of kilometers per second. In typical detonations, the pressure can be 13–16 times higher than the initial one, but the pressure can rise much higher if reflected from the end wall. In addition, the highest pressure occurs during the transition process, where a so-called "explosion in an explosion" occurs (Urtiew and Oppenheim, 1966). The pressure generated in detonation has significant destructive potential. Because the detonation flame front propagates at a supersonic speed relative to the fresh mixture, researchers have been trying to study how to attenuate the explosion and detonation intensity, in order to lower their destructive potential (Frolov and Gel'fand, 1991; Plessis, 2015; Zhang et al., 2011; Zou, 2001).

To prevent dust explosions from occurring, it is necessary to eliminate one of the elements from Kauffman's Pentagon. For example, fuel can be eliminated to prevent the accumulation of dust in mines. We can try to eliminate ignition sources as well, but the elimination of air or confinement is very difficult or impossible. Therefore, the last line of defense against an explosion is to apply passive or active explosion suppression methods during the initial stage. To stop explosions, a suppressing agent should be evenly sprayed on the propagating flame to extinguish combustion. Explosions may also be prevented by eliminating accidental fires or sparks, thereby reducing the reactive medium concentration, and by cooling hot elements (Plessis, 2015; Zou, 2001).

To effectively suppress explosions, dispersing the suppressant agent at the proper time is vital. If the suppressant agent is dispersed as the flame front reaches the barrier, the flame will be extinguished; if it is dispersed too prematurely or too late, the flame may not be suppressed effectively (Zou, 2001). This type of system involves dispersion without a detector, and is considered to be a passive method of explosion suppression in tubes and galleries. However, active suppression systems are considered to be the best methods for explosion suppression. In such systems, a special sensor is used to detect oncoming flames (shock), and then the suppressant agent is dispersed at the right moment. This effectively quenches the explosion.

In order to employ suitable methods to suppress explosions and detonations, their physical mechanisms and the factors that influence them should be discussed. Therefore, this paper will briefly compare deflagrative and detonative explosions, and summarize the recent research processes of deflagration-to-detonation transition. In addition, the different methods used to address explosion prevention, mitigation, and suppression in different combustion modes will be reviewed. Potential passive and active methods are compared, including both conventional and new (developed in recent years) methods.

## 2. Explosion, DDT, and detonation

As previously mentioned, certain conditions must be met in order for an explosion to occur. For example, a specific dust (gas) concentration in air, or ignition source are two conditions needed. Fig. 1 shows the variation of ignition energy on the dust concentration and the resulting pressure generated by the explosion. This image illustrates that explosions can only occur within the flammability (explosibility) range of the fuel (dust) concentration. Most often, the highest explosion pressure occurs within similar concentration to the concentration for which ignition energy is the lowest. It is evident that explosions most easily occur when fuel concentrations that are capable of producing a maximum explosive pressure are available. These types of explosions are the most difficult to suppress. However, the closer an explosion is to its mixture explosibility limit, the easier it is to prevent or suppress. By diluting a mixture with inert dust, gas, or suppressant, we can modify the explosibility range or simply create a non-explosive mixture. In summary, the main idea behind explosion suppression is to dilute the concentration of the explosives, usually by using a suppressant agent or an inert gas.

Unlike deflagrative explosion, detonation can be very destructive in mines and under industrial conditions. In coal mines or other industries, the mechanism of detonation production is complex (Ciccarelli and Dorofeev, 2008; Gelfand et al., 2012; Han et al., 2017; Kersten and Förster, 2004; Sichel et al., 1995; Wolański, 1993; Zeldovich, 1950). Explosions almost universally begin with the ignition of a flame from either an electrical spark, or the auto-ignition of a mixture, or from contact with a very hot surface (Ciccarelli and Dorofeev, 2008). If such a flame is not weakened immediately, the flame will transfer from a low-speed laminar flame to high-speed deflagration under certain conditions. If the flame is accelerated continually, detonation will occur in the tubes or galleries. For a typical fuel-air detonation, the propagation velocity of the detonation wave is in the range of 1500–3000 m/s. The maximum pressure in a detonation front increases to 13–16 times the initial pressure, and the maximum pressure during the reflection of detonation from the wall is approximately two times the pressure in front of the detonation.

The first detailed explanation of the mechanism of transition from deflagration into detonation (DDT) was reported by Urtiew and Oppenheim (1966). They studied DDT in a hydrogen-oxygen mixture using high-speed Schlieren photography. They found that

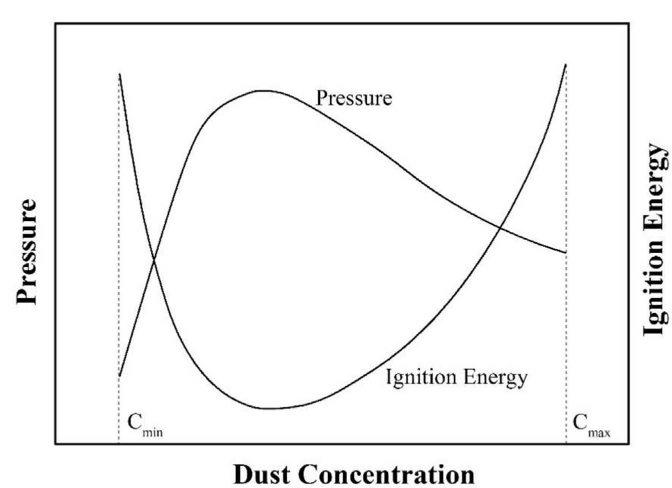


**Fig. 1.** Diagrammatic sketch of the dependence of ignition energy and explosion pressure on dust concentration.