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Experimental investigation of the propagation of deflagration flames in a horizontal underground channel containing obstacles

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ABSTRACT

The deflagration of premixed methane–air gas (concentration of 9.5%) was experimentally investigated in a closed channel (0.2 m × 0.2 m × 6.5 m) containing different obstacles. Rectangular, trapezoidal, and spherical obstacles were employed. Various tests on the deflagration flames were carried out (using schlieren imaging and pressure and flame sensors) and the diverse characteristics of the deflagration flames were analyzed. In this work, we concentrate on the change in shape of the flames as they pass the obstacles, the instantaneous overpressure formed in the local areas in front and behind the obstacles, and the change in velocity of the deflagration flame. The results suggest that extremely complex changes occur when the deflagration flames pass the differently-shaped obstacles in the closed channel. The shape of the obstacle and the structural form of the confined space between the boundaries of the obstacle and channel walls both exert a significant effect on the mechanical characteristics of the deflagration flames as they develop. Obstacles in the channel enhance the propagation of the deflagration flame to unburned areas away from the local area where the flame forefront had been. The flatness of the flame front is therefore broken. A certain amount of flame stagnation appears to occur which results in a larger crosswise span of the flame front. The obstacle's angles and effective barrier area presented to the incoming flow of the deflagration flame have an effect on the propagation of the flame and instantaneous overpressure of the deflagration flame in the local areas just in front and behind the obstacle. Moreover, the correlation between the obstacle angle and mainstream direction of the deflagration flame as it passes the obstacle also has an effect. Of the three obstacles investigated, the trapezoidal obstacle exhibits the weakest ability to strengthen the inertial force of the deflagration flame. Compared to the others, the spherical obstacle most significantly enhances the inertial force of the deflagration flame as it passes through the obstacle's neighborhood.

1. Introduction

There are various electromechanical devices and ventilation equipment to be found in coal mine tunnels, e.g. tramcars, fans, and wind tubes. Therefore, once a gas deflagration accident occurs in a tunnel, it is inevitable that these objects will appear as obstacles to the deflagration flame as it propagates down the tunnel. Therefore, they may have a significant influence on the way the gas deflagration flame develops in the tunnel.

Some work has already been carried out on the deflagration characteristics of premixed gases in pipelines containing obstacles. Moen et al. (1980) investigated the effect of obstacles on the propagation of freely expanding cylindrical flames. Their research suggests that the factors controlling the flame acceleration mechanism are the large-scale flow field distortions produced by the obstacles. In particular, the flame speed was found to critically depend on the size of the obstacle relative to the flow field as a whole. Nie et al. (2016) used an image processing method to calculate flame velocity based on some correlation coefficients of the images. Their results indicate that the velocity and structure of a flame are both unstable when it propagates in a pipeline. They also found that the flame does not always propagate with a constant acceleration. Instead, it undergoes an alternating cycle of mutual acceleration and deceleration.

Boeck et al. (2017) investigated the acceleration of flames in a stoichiometric mixture of H_2/O_2 at 12 and 25 kPa in an obstacle-laden channel of square cross-section. These studies used planar laser-induced fluorescence imaging of the hydroxyl radicals produced combined with high-speed schlieren imaging. Lv et al. (2016) investigated the combined effect of obstacle position and equivalence ratio on the overpressure of premixed hydrogen–air explosions in a vertical duct with a

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cross-section of 100 × 100 mm^2 and height of 500 mm. They concluded that the overpressure of the explosions is closely related to the flame's structure. Moreover, the maximum peak overpressure depends mainly on the maximum surface area of the flame within the duct.

Li et al. (2015) conducted explosion experiments using methane/air and hydrogen/air mixtures and different gas volumes in an 8.9 m long closed tube with obstacles placed inside. Yu et al. (2016) experimentally investigated the effects of three obstacles (triangular, square, and circular) on the characteristics of gas explosions in a chamber that was 0.5 m tall and 15 cm × 15 cm in cross-section. Luo et al. (2016) carried out a numerical study of explosive waves propagating from a cylinder of one size to other cylinders of different size.

Oh et al. (2001) carried out experiments to study the characteristics of gas explosions in enclosed/vented gas-explosion vessels with obstacles built-in. They concluded that instead of being accelerated, the flame propagating inside the explosion vessel was decelerated by plate obstacles fixed at the bottom of the vessel. Also, explosions in enclosed vessels are not as affected by built-in obstacles as those in vented vessels. Li et al. (2018) examined the characteristics of gasoline–air explosions in a semi-confined organic glass pipe (10 cm square in cross-section and 1 m long) and investigated the effect of the obstacle to ignition-point distance, blockage ratio (BR) of the obstacle, and separation between obstacles.

Li et al. (2017) performed large eddy simulations coupled with a TFC sub-grid combustion model in a semi-confined pipe with a length: diameter ratio (L/D) of 10 and volume of 10 L and considered the presence of four hollow–square obstacles (area blockage ratio of 49.8%) with circular hollow cross-section to investigate their effect on the explosion of premixed gasoline–air mixtures. Cross and Ciccarelli (2015) carried out experiments using hydrogen–air and ethylene–air mixtures at atmospheric pressure. A 6.1 m long, 0.1 m diameter tube was used with different obstacle configurations and ignition types. The deflagration to detonation transitions (DDTs) and detonation propagation limits were measured and analyzed.

Wang et al. (2016) analyzed the effect of concentration and obstacles on methane–air mixture DDTs in a long circular duct of 40 m in length and inner diameter of 35 cm. Yang et al. (2011) experimentally investigated the effect of meshy obstacles on methane gas explosions in a 2.1 m long tube using a high-speed schlieren technique. Images of the flame crossing the obstacle were obtained and the flame propagation velocity and temperature measured.

Wen et al. (2013a, 2013b) investigated how a premixed methane–air deflagration flame interacts with obstacles along its path in a vented chamber with internal dimensions of 150 mm × 150 mm × 500 mm. Three obstacle configurations with different cross-wise positions and porous-media quenching behavior of gas deflagration in the presence of obstacles were studied. Wen et al. (2015) investigated the flame and overpressure characteristics of methane–air explosions with different obstacle configurations in an experimental chamber with internal dimensions of 150 mm × 150 mm × 500 mm. In this experiment, a 150 mm × 75 mm × 10 mm plate was used as an obstacle. Consideration was given to the number of obstacles, distance of the obstacle from the ignition source, and the obstacle's stream- and cross-wise positions. Wen et al. (2017) also investigated the effect of different obstacle angles on the characteristics of a methane–air deflagrating flame.

Johansen and Ciccarelli (2009) demonstrated the effect of BR on the initial phase of the flame acceleration process in an obstructed channel of square cross-section. Flame acceleration was promoted using an array of top- and bottom-surface mounted obstacles equally distributed (by a distance equal to the channel height) along the entire length of the channel. Na'inna et al. (2013,2014,2015) performed explosion tests in an elongated and vented cylindrical vessel (162 mm internal diameter with an overall L/D ratio of 27.7). The effect of obstacle BR on the obstacle spacing during the gas explosions was investigated. Park et al. (2008) performed experiments to investigate the interactions of flames with several obstacles in chambers with different L/D ratios.

Kindracki et al. (2007) investigated the effect of ignition position and obstacles on explosion development in premixed methane–air mixtures using a tube of length 1325 mm and diameter 128.5 mm. Ding et al. (2011) investigated the effect of structure, BR, spatial layout, and distance from ignition point of obstacles on flame speed and overpressure (using a 144 cm long tube with 10 cm square cross-section). In these experiments, the obstacle was placed onto the bottom of the tube so that the deflagration flame could not pass under it. Dong et al. (2012) investigated methane–air explosions in a horizontal pipe closed at both ends with and without obstacles and deposited coal dust.

Zhou et al. (2012) carried out hybrid methane–coal dust explosions in closed tubes with different types of obstacles inside. Valiev et al. (2010) presented a theoretical treatment and carried out numerical simulations to model flame acceleration in channels containing obstacles. Di Sarli et al. (2009) used validated large eddy simulations to model the propagation of an unsteady premixed flame to investigate vented gas explosions in the presence of obstacles.

In a single-sided vented channel, deflagration flames can propagate relatively freely in the vented direction. In contrast, deflagration flames involving premixed gases in a closed channel exhibit significantly different development processes. In a channel closed at both ends, the spatial pressure in the unburned area (ahead of the deflagration flame front) increases because the development of the deflagration flame is hindered by the closed end of the channel. Therefore, the entire development of the deflagration flame occurs in a space where the ambient pressure constantly rises. This will exert an effect on the propagation of the deflagration flame front in the channel. If there are obstacles in the tunnel, the effect on the spatial development and propagation of the deflagration flame will be even more complex.

Most of the current research on the influence of obstacles on a deflagration flame assumed that the obstacles are fixed onto the bottom of the tunnel. Therefore, the deflagration flame can only pass the obstacle via the two sides and gap above the obstacle. However, few studies investigated the detailed characteristics of deflagration flames passing through the obstacles that surrounding spaces are available.

Considering this, in this work, the deflagration flames from premixed gases propagating in a long, closed channel with a square cross-section and containing obstacles of different shapes (rectangular, trapezoidal, and spherical) were investigated experimentally. We analyzed the characteristics extensively and look for disparities in the incoming flow of the deflagration flame as it passes the area housing the obstacle. Identical deflagration environments and conditions were used throughout, and the three types of obstacles were fixed in the same position in the channel at the same (nonzero) height relative to the bottom of the channel.

2. Experimental devices

The experiments were carried out in a long, closed channel (Fig. 1) composed of several steel sections connected using sealing flanges. The total length L of the experimental channel is 6.5 m and its square cross-section corresponds to 0.2 m × 0.2 m. The ignition point lies in the center of one end of the channel. An ignition energy of 10 J was set using a multifunctional intelligent controller. The experimental system also includes a circular pipeline system to allow circulation and uniform mixing of the gases used and removal of combustion products using an explosion-proof vacuum pump. Before carrying out an experiment, the required amounts of the flammable gases were fully cycled inside the apparatus to uniformly distribute them throughout the whole channel.

At a position close to the other end of the channel (4.11 m from the ignition end), a window was established in the side wall of the channel which is 0.28 m long and 0.2 m tall. This was used to make experimental observations. In our experiments, images of the deflagration flames as they crossed this part of the channel were recorded using video recording equipment. The whole process was recorded using a