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Influence of a heat-absorbing surface on the propagation of a hemispherical flame

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ABSTRACT

Gaseous explosions lead to severe damage. Elimination or mitigation of damage is a key problem in industrial safety. This paper presents an experimental study of hydrogen–air flame front dynamics and flame suppression by means of a surface coating. The experimental stand is a metal frame that confines the cylindrical envelope to a diameter of 1.5 m and 2.4 m in height of high-density 100 μm thick polyethylene. Experimental data on the hemispherical flame propagation in hydrogen–air mixtures with a hydrogen content of 15% were obtained at the initiation of combustion with an energy of 5 J. The flame propagates at atmospheric pressure over a solid aluminium wall or a layer of steel wool. To measure the flame propagation speed, an infrared InfraTec ImageIR 8320 camera with spectral range 2–5.7 μm was used. The flame acceleration dynamics were compared at flame radii up to 0.4 m. It was found that in a mixture with a hydrogen content of 15% the flame over the layer of steel wool propagates 2.5 times more slowly than that over the surface of an aluminium wall. The steel wool was investigated by scanning electron microscope using an energy dispersive analysis system before and after the passing of the flame front. The structure and chemical composition of the metal wool was studied. Calculation of heat absorption in the steel wool layer shows that the heat losses due to the absorption are the main phenomenon causing the flame front speed reduction, which was observed in the experiments. Additionally, the speed of the flame was affected by the absorption of oxygen and the release of heat during the oxidation of the steel wool, as well as by the roughness of the layer of steel wool.

1. Introduction

Large gaseous explosions can occur in power and processing industries, such as oil or gas petrochemical industries, and thermal and nuclear power plants. The most likely scenarios for the development of a gas explosion begin with a weak initiation by a spark or a heated surface. Under certain conditions, the flame propagates with acceleration, generating compression waves in front of it. With the acceleration of the flame, the intensity of the compression waves also increases (Di Benedetto and Di Sarli, 2016; Nishimura et al., 2013; Otsuka et al., 2007). The damaging effects of gas explosions are caused by the high temperature and strong compression waves (van der Voort et al., 2007). Flame propagation is one of the key phenomena in safety issues. The character of the flame propagation is influenced by many factors: the type of ignition (Clavin, 2017), the composition of the flammable mixture (Clavin, 2017; Gostintsev et al., 1988; Tsai et al., 2017; Yang et al., 2016), the characteristics of the surface (Hayashi and Yamashita, 2014; Huo et al., 2014; Wu and Ihme, 2015) and the coating on the surfaces (Davison et al., 2004; Johansen and Ciccarelli, 2008; Nie et al., 2016; Cui et al., 2017; Wang et al., 2017; Zalosh, 2003; Zhang et al., 2016). Understanding the causes of flame acceleration is necessary to create effective means of preventing and mitigating the factors involved in gaseous explosions.

Experimental, theoretical and numerical studies of premixed unconfined or semi-confined flame propagation in large volumes are presented in (Akkerman et al., 2011; Bradley et al., 2001; Clavin, 2017; Gostintsev et al., 1988; Karlin and Sivashinsky, 2006; Kim et al., 2013; Liberman et al., 2004; Molkov et al., 2007). Asymptotic analyses for spherical flame kernels (steady solutions) and slow flame expansions in mixtures near and beyond flammability limits which correspond to a molecular diffusion coefficient of the limiting species greater than the thermal diffusivity (Lewis number less than unity) are presented in Clavin (2017). The author reports different regimes of flame propagation: unsteady expanding flames, with a radius growing approximately at the square root of time; self-extinguishing flames; and accelerating cellular flames.

In (Bradley et al., 2001; Gostintsev et al., 1988; Kim et al., 2013; Liberman et al., 2004; Molkov et al., 2007), the acceleration of a flame

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in various gas mixtures in spherical or hemispherical geometry is described by the equation:

$$R = R_0 + A(t - t_0)^{1.5} \quad (1)$$

Such regimes are observed at Peclet numbers of several hundreds. In each specific case, the value of the critical Peclet number is determined by the parameters of the flammable mixture. Karlin and Sivashinsky (2006) and Kim et al. (2013) present the time dependence of the flame front radius as described by power equations of the form:

$$R = R_0 + B(t - t_0)^{\alpha}, \quad (2)$$

where $1 < \alpha < 1.5$.

Apart the acceleration, interaction with the walls can cause a decrease in the flame velocity and complete extinguishing (Hayashi and Yamashita, 2014; Huo et al., 2014; Wu and Ihme, 2015). Wu and Ihme (2015) considering the loss of heat in the walls that limits the combustion region. Heat losses reduce the flame velocity and are of special importance in the design of microcombustors. In (Davison et al., 2004; Hayashi and Yamashita, 2014; Huo et al., 2014; Nie et al., 2016; Xie et al., 2017), the propagation of a flame along a wall leads to a deceleration or complete extinguishing of the flame. The papers take into account both the thermal effect of the wall and the chemical reactions of the chain termination. Several papers (Cui et al., 2017; Johansen and Ciccarelli, 2008; Xie et al., 2017; Zalosh, 2003; Zhang et al., 2016) are devoted to the use of various coatings to prevent flame propagation, the effects of gas explosion mitigation and the suppression of smoke formation.

This paper presents an experimental study of hemispherical flame propagation in a hydrogen–air mixture. The flame propagates over a solid aluminium wall or a layer of steel wool. The velocities of the flame propagation are compared at flame radii up to 0.4 m.

2. Experimental details

The experimental stand is a metal frame that confines the cylindrical envelope to a diameter of 1.5 m and 2.4 m in height (1) of high-density polyethylene (HDPE) 100 μm thick (see Fig. 1). The top of the cylinder was closed with a thin (100 μm) rubber shell. The bottom of the construction was closed with an aluminium plate. In the experiments with steel wool it was covered with a 50 mm layer of steel wool (3). The construction was placed inside an explosion chamber, VBK-2, which is part of the Moscow Regional Explosive Centre for Collective Use. The envelope was filled with a hydrogen–air mixture with a hydrogen content of 15% at normal atmospheric pressure at a temperature of T ≈ 293 K. The filling was carried out as follows. In the shell, initially filled with air, the necessary amount of hydrogen (0.686 m^3) was added. The gas in the shell was mixed with a stirring fan 200 mm in diameter, providing a flow velocity of 5 m/s. After 1 h of mixing, the fan was stopped. The error of the mixture composition was 0.3%. The flame was ignited 0.5 h after the stirring fan was stopped. Ignition was performed with the explosion of a thin nichrome wire 0.1 mm in diameter, 10 mm in length, placed between two steel electrodes 4 mm in diameter at the bottom of the cylinder. The energy released on the wire was 5 J. In all experiments, the distance from ignition point to the surface remained unchanged and amounted to 100 mm. To measure the flame propagation speed, an infrared InfraTec ImageIR 8320 camera with a spectral range of 2–5.7 μm was used. The water formed during the oxidation of hydrogen emits radiation with a characteristic maximum at a wavelength of 2.8 μm. Thus, the object captured by the IR camera is the flame front.

3. Experimental results

The sequence of frames demonstrating the flame propagation is shown in Fig. 2. The images presented in Fig. 2 demonstrate a globally hemispherical flame front with perturbations at all time moments observed. The pictures show that at the propagation of the flame in mixtures with hydrogen content of 15% the envelope does not rupture during the flame propagation. The experimental flame propagation radii time dependences can be determined from the experimental image sequences. The flame front radius was measured in a vertical direction upward and in the horizontal direction both to the left and to the right of the ignition point. The repeatability of the experiments can be estimated from the results of processing three experiments, shown in Fig. 3. At a flame front radius of 0.2 m and higher, the standard deviations from the mean values of the radius for three experiments are less than 3%. For the sideways flame propagation the standard deviations from the mean values are less than 5%. Experimentally obtained mean time dependences of the flame front position for the cases with and without steel wool are presented in Fig. 4. Fig. 5 shows the dependences of the flame velocity in two directions above the steel wool layer and a solid wall in different directions. Due to the short measurement base, the error is significant. Further conclusions about the flame velocity are made on the basis of smooth approximations of the flame propagation trajectories.

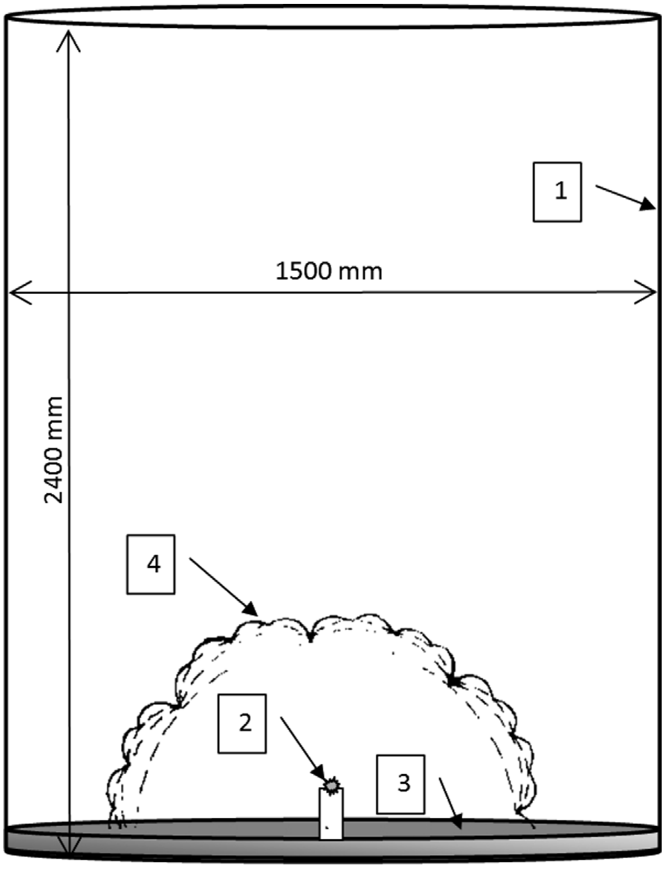

Fig. 1. Experimental setup. (1) HDPE envelope; (2) ignition wire; (3) steel wool layer (aluminium plate); and (4) flame front.

Initially, the flame propagates hemispherically. In this case, the horizontal propagation of the flame was accompanied by interaction with the boundary layer on the bottom plate. In Fig. 4 one can see that at the initial stage the flame along the wall propagates faster than that perpendicular to the wall, i.e., vertically upwards. At a time of 60 ms, the flame radii upward and sideways become equal and are about 450 mm. Further, the flame in the upward direction is rapidly accelerated, and in the sideways direction it slows down. To explain the reason for this difference, one should remember that the volume of combustion products exceeds the volume of the initial fuel mixture. Therefore, the expanding hemispherical front of the flame induces a flow of combustible mixture directed from the point of initiation. With