Study of Turbulent Combustion of Hydrogen-Air-Steam-Water Fog Mixtures Prepared by Sudden Expansion Technique

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Abstract

Explosion chamber of special type was designed to combine two different tests, namely condensation of saturated vapor in the expansion wave and hydrogen combustion experiment. It was found that the process of turbulent combustion of hydrogen-air mixtures is sensitive to the presence of fog system. The mitigation effect of fog microdroplets on (16-27%)H_2-air-steam flames was revealed.

Introduction

Present paper concerns experimental study of turbulent flame propagation in heterogeneous hydrogen-air-steam-water fog mixtures. The principles of investigation are given in a previous work [1], where it was proposed to simulate an accidental event involving sudden release of high temperature H_2-air-steam mixtures by means of expansion shock tube technique. As a result of sudden expansion the explosible H_2-air-steam-water fog mixture could be produced. It should be noted that the parameters of the generated fog (i.e. mean size of droplets, volume concentration of condensed phase, etc.) are rather different from the parameters of natural conventional fog. These differences are due to specific mechanism of fog formation known as homogeneous nucleation [2,3].

Extended analysis of probable accidental situation involves the consideration of explosion processes. Thus, the investigation of flame propagation in H_2-air-steam-water fog mixture is of great interest from both fundamental and practical points of view. The experiments [1] were performed using an expansion shock tube of laboratory scale (40×40 mm^2 in cross-section). To simulate larger scale conditions in the present study we applied the 6.5 l explosion chamber. Special efforts were undertaken to control the process of fog formation as well as to reveal peculiarities of interaction between hydrogen flames and fog particles. The experimental results allowed to evaluate the effect of fog additive on downward flame propagation limits.

Experimental Procedure

The experiments have been carried out using vertically placed explosion chamber (EC) of 120 mm in diameter and 0.6 m in length. The setup includes proper gas supply and heating systems. A scheme of the experimental setup is given in Fig.1. To provide fast expansion of test mixture the bottom part of the explosion chamber was equipped with the hermetically mounted bursting membrane separating the EC from the surrounding atmosphere. Initially H_2-air mixtures have been diluted by the saturated water vapor of various partial pressures p_v. After the bursting of membrane at pressure p_0 the high-temperature H_2-air-saturated vapor mixture starts to expand. The expansion induces fog formation process that ends when pressure inside the explosion chamber achieves the ambient value (1 bar). This takes about 4 ms after the instance of membrane burst. To reduce turbulence disturbances, the generated hydrogen-air-steam-water fog mixture was left to stand for about 40 ms before the exploding wire was powered. The transient pressure was measured by piezoelectric gauges. The detection of turbulent combustion event was provided by photodiodes PD1-PD3 (Fig.1). Specially designed double-wavelength photodiode PD1 operates as a part of light extinctiometer, i.e. in combination with monochromatic emitters (light diode and laser diode of 0.96 μm and 1.56 μm wavelength respectively). The extinction measurement enables to control the processes of both formation of foggy mixture and interaction between flame front and fog particles. To exclude the influence of flame radiation on the extinction records the signals of the emitters were subjected to fast frequency modulation. Hydrogen-air mixtures of 16, 20 and 27%

H_2 vol. were used in the combustion test. The range of initial pressures was varied from p_0 = 7 bar to p_0 = 14 bar. The steam content could be changed in the range $p_v / p_0 = 0 – 0.4$.

Results and Discussion

Figure 2a presents typical records of pressure and extinction in full cycle of the combustion test. As seen, the pressure fall is accompanied by the fast decrease of the amplitude of modulation signals. This fact convincingly indicates the formation of fog. The ignition is initiated since about 45 ms after the beginning of the expansion. Afterwards the flame appears in the view field of the extinctiometer (at the distance of 115 mm from the top endflange). The increase of the modulation signals points to the fact that fog microdroplets are evaporated in the combustion zone. When considering the extended time scale of the expansion zone (Fig.2b), one can note that the attenuation significantly depends on the wavelength. The modulation signal corresponding to the longer wavelength λ = 1.56 μm decreases more slowly than that corresponding to the shorter wavelength λ = 0.96 μm. Similar behavior is exhibited at the stage of the evaporation of fog particles inside the combustion zone (Fig.2c). Remarkable difference between the two wavelengths in terms of extinction provides the basis on which double-wavelength extinction technique [3] can be applied to the evaluation of dynamics of foggy system at all stages of the process under investigation. Figure 2d shows the temporal change of the volume fraction φ of fog particles.

The experiments show that the developed light extinction technique is suitable for evaluation of fog parameters. Thus, measured value φ together with the initial parameter p_v/p_0 can be used for calculations of the equilibrium steam content at all stages of the process under investigation [2,3]. It was found that at sufficiently high fog particles volume fractions and steam concentrations the H_2-air-steam-water fog mixture becomes non-flammable. From the practical point of view the problem of the influence of water fog on low flammability limit of H_2-air-steam-water fog mixture is of great importance. The present data can be compared with the results [4] where flammability limits of hydrogen-air-steam (without fog particles) mixtures were determined. Obviously, the present study concerns downward flame propagation. Figure 3 presents the results of both successful and unsuccessful initiation of combustion in hydrogen-air-steam-water fog mixtures. The data points in Fig.3 are labeled with the proper values of fog particles volume fraction ($\varphi\ 10^5$) at the moment of ignition. The comparison with the data [4] on downward flame propagation reveals the significant shift of the low combustibility limits to the region of lower water vapor concentrations in the presence of fog microdroplets. Thus, the combustion experiments performed at different values of initial pressure and hydrogen concentration indicate convincingly that the fog system (with fog particles volume fraction of order (1.5 - 2) 10^{-5} facilitates significantly the mitigation of hydrogen-air turbulent flames.

Concluding remarks

The present study demonstrates that the combination of explosion test with sudden expansion technique of preparing of fog system is a convenient tool for study of combustion of hydrogen-air-steam-water fog mixtures. The conditions of fog formation can be controlled by the change of initial parameters such as partial pressure of water vapor and total pressure at the beginning of the expansion process. The described experimental procedure seems to be suitable for adequate simulation of accidental event involving sudden hydrogen release in nuclear power plant.

References

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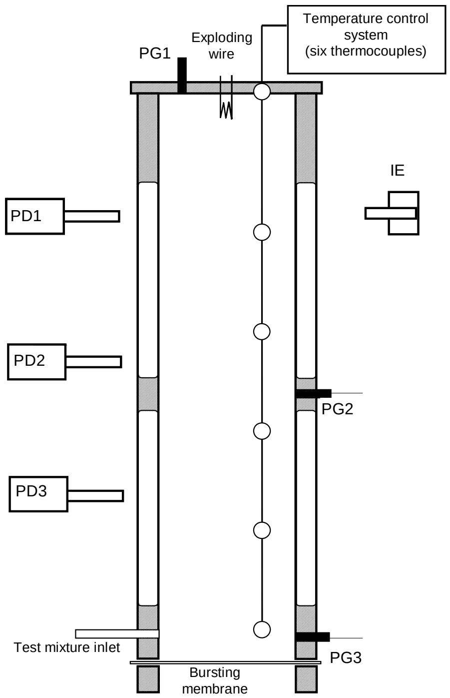

Fig. 1 General scheme of the experimental setup.
PG1-PG3 pressure gauges
PD1-PD3 photodiodes with preamplifiers
IE infrared emitters

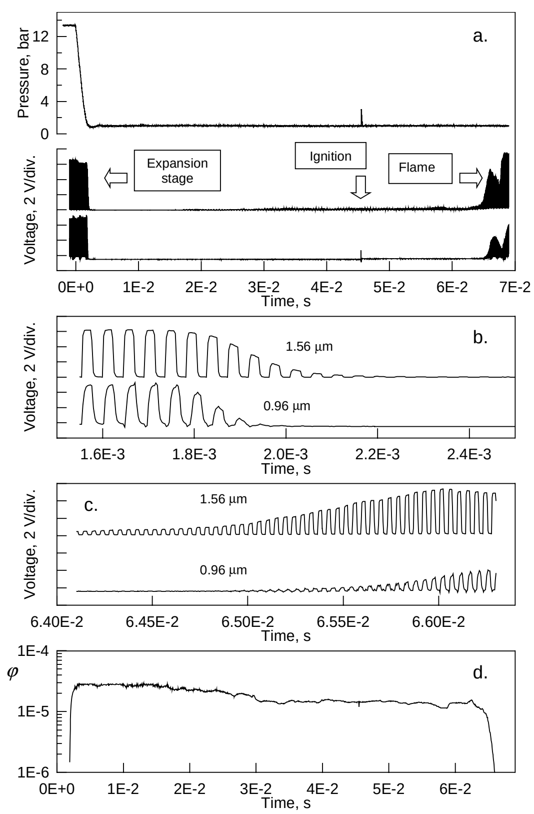

Fig. 2 Combustion test. 27%H_2 in air
p_0 = 13.4 bar, p_v/p_0 = 0.3.
a. Records of pressure and extinction in full cycle of the test
b. Scaled up expansion stage
c. Scaled up stage of flame-fog interaction
d. Temporal change of fog particles volume fraction.

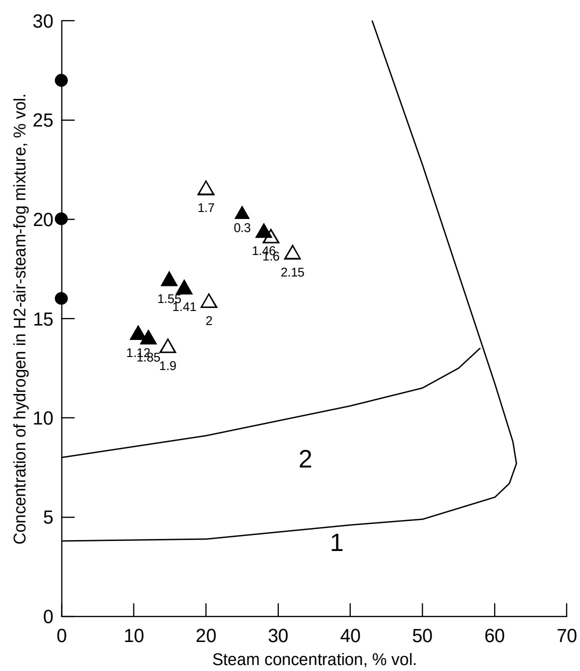

Fig. 3 Flammability limits of hydrogen-air-steam-water fog mixtures. 1 - data [4] for upward flame propagation (without fog), 2 - data [4] for downward flame propagation (without fog).
black - successful ignition in foggy mixtures; open – no ignition