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Explosibility of hydrogen–graphite dust hybrid mixtures

A. Denkevits*

Forschungszentrum Karlsruhe, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

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Abstract

To evaluate the hazard of combined hydrogen/dust explosions under severe accident conditions in International Thermonuclear Experimental Reactor (ITER), standard method of 20-L-sphere was used to measure the explosion indices of 4-μm fine graphite dust in lean hydrogen/air mixtures. The mixtures were ignited by a weak electric spark. The tested fuel concentrations were 8–18 vol% H_2 and 25–250 g/m^3 dust. If the hydrogen content is higher than 10 vol%, the dust constituent can be induced to explode by the hydrogen explosion initiated by a weak electric spark. Depending on the fuel component concentrations, the explosions proceed in either one or two stages. In two-stage explosions occurring at low hydrogen and dust concentrations, the mixture ignition initiates first a fast hydrogen explosion followed by a slower phase of the dust explosion. With increasing dust concentration, the dust explodes faster and can overlap the hydrogen-explosion stage. At higher hydrogen concentrations, the hybrid mixtures explode in one stage, with hydrogen and dust reacting at the same time scale. Maximum overpressures of hybrid explosions are higher than those observed with hydrogen alone; maximum rates of pressure rise are lower in two-phase explosions and, generally, higher in one-stage explosions, than those characteristic of the corresponding H_2/air mixtures.

Keywords: ITER safety; Hybrid mixtures; Hydrogen explosion; Graphite dust explosibility; Two-phase explosion; 20-L sphere

1. Introduction

The work addresses the explosion hazard considered in the design of the next-step fusion machine 'International Thermonuclear Experimental Reactor' (ITER). A large amount of fine dusts produced as a result of plasma-wall interaction during ITER operation is expected to accumulate in its vacuum vessel (VV). The dusts under concern are beryllium, tungsten, and graphite dusts of sub-micron particle size; the expected dust masses amount to several hundred kilograms. In case of severe accident involving air ingress into VV, the dusts could be mobilized forming explosible cloud. Explosion of the cloud can generate pressure loads dangerous for the VV integrity (ITER Generic Site Safety Report, GSSR, 2001).

Explosibility of fine graphite and tungsten dusts was measured by Denkevits and Dorofeev (2006). It was found out that 4-μm graphite and 1-μm tungsten dusts can explode generating about 6 bar overpressure. The necessary ignition energy ranges from 1 to 2 kJ. Such an ignition source cannot be excluded considering a typical ITER accident scenario. However, another ignition source seems more realistic there. Lost-of-coolant- or lost-of-vacuum-accident scenarios involve appreciable amount of hydrogen coming out of cryo-panels of ITER vacuum pumps or as a result of beryllium–water reaction (GSSR, 2001). Hydrogen can be easily ignited by a low-energy source like a weak electric spark, and the energy delivered in the course of the hydrogen combustion might be enough to ignite the dusts.

The aim of the present work is to investigate the possibility of ITER-relevant dust to be triggered to explode by low-energy ignition sources. The explosion indices of 4-μm graphite dust ignited by a weak electric spark in hydrogen-containing atmospheres are measured using a standard 20-L-sphere method.

Most of the studies on hybrid explosions have been concentrated on the measurements of the flammability limits (Amyotte, Mintz, Pegg, & Sun, 1993; Cashdollar, 1996; Hertzberg & Cashdollar, 1987; Landman, 1995). In

*Tel.: +49 7247 82 8140; fax: +49 7247 82 4777.
E-mail address: andrey.denkevits@iket.fzk.de

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these studies, the hybrid mixtures were ignited mainly by strong chemical igniters which were capable to ignite the dusts without presence of the gaseous fuel constituent. The gases were easier to ignite, so both fuels seemed to start burning together. In the presented work, the dust/hydrogen/air mixtures have been ignited by a weak electric spark. The hydrogen concentrations in the tests were high enough to be ignited by the spark in any test, while the dust alone could not. So the main attention is focused on the ignitability of the dust constituent and its influence on the hybrid explosion severity.

2. Experimental

The tests have been performed in a 20-L apparatus (Siwek, 1985). It consists of a 20-L spherical combustion chamber and a 0.6-L dust container connected with the combustion chamber via a fast valve. Tested dust cloud is formed inside the sphere by dispersion of a dust sample, which is first placed into the dust container and then injected into the sphere with a portion of compressed air via the connecting valve.

The dust/air cloud is ignited at the sphere center by electric spark. The spark is generated by a high-frequency transformer with high voltage ratio. It provides a train of unipolar half-sine voltage pulses of 5–7 kV amplitude, 3 kHz frequency, and 20 ms train-pulse duration. The spark electrodes are made of 1-mm diameter stainless-steel wire and sharpened to a point; the inter-electrode gap is 2 mm.

The pressure evolution during the explosion is measured with two Kistler 701A pressure transducers (70 kHz natural frequency, 0.1% uncertainty). The transducer outputs are digitized at 5 kHz sampling rate and recorded by a data acquisition system based on a 12-bit ADC controller installed in IBM PC.

The tests are performed as standard ones in compliance with German standards (VDI-Richtlinien, 1990). The dust storage container, charged with a dust sample, is pressurized with compressed air to 21 bar; the pressure in the combustion chamber before the dust injection is 400 mbar, so that the resulting pressure after the injection is 1 bar. At the test start, the dust outlet valve is triggered to open and 90 ms later is closed; the spark ignition is activated after 100 ms from the test start. The time delay between the start of pressure rise in the sphere and the moment of ignition is 60 ms.

The hydrogen–air mixtures are prepared inside the sphere prior to test by partial pressure method. The sphere is evacuated to lower than 5×10^{-2} mbar, then some amount of hydrogen is let inside (80–180 mbar in the tests), and after that ambient air is added to final 400 mbar. During dust dispersion, the air from the dust container mixes with the hydrogen–air in the chamber to produce the final test mixture at 1-bar pressure. The pressure inside the sphere during gas mixture preparation is controlled with JUMO dTRANS p01 pressure transducer (0.5% accuracy). The pressure values are given here as absolute pressures.

The content of the combustion products is measured by a quadrupole mass spectrometer. The following masses are traced: H_2, H_2O, N_2/CO, O_2, and CO_2. The mass spectrometer was calibrated to measure species concentrations in the medium mass range; the values of O_2 or CO_2 concentrations reported below in absolute volumetric percent are accurate within 1.5 vol% abs. Measurements of the hydrogen concentration in the combustion products required a special calibration of the device, which was not possible to do. However, the mass spectrometer could detect hydrogen, and one can conclude qualitatively from the test-to-test variations of the H_2 peak height in the mass spectra how the real concentration changes.

The H_2O peaks are always lower than 0.5%, i.e., the steam resulting from hydrogen combustion condenses inside the sphere. So all the other reported product 'concentrations' refer to the mixture with the steam condensed. All the gaseous concentrations are given below in volumetric percent.

The graphite dust used in the tests is of 4-μm particle size; its more detailed description was given by Denkevits and Dorofeev (2006). The dust concentrations in the sphere are calculated as the mass of the sample charged into container divided by the sphere volume.

3. Results

Hydrogen concentration in the performed tests is varied from 4% to 18%. Pure hydrogen/air mixtures without dust can be reliably ignited under the described conditions starting from 8% H_2. (It differs from lower ignitable concentrations observed by Cashdollar, Zlochower, Green, Thomas, and Hertzberg (2000) in 120-L chamber, maybe due to higher turbulent level in the Siwek chamber.) The mass spectra show no hydrogen in the combustion products; the measured maximum explosion pressures are practically equal to the corresponding P_{aicc} values. So hydrogen is assumed to burn out completely in these tests.

Maximum overpressures and rates of pressure rise of 8% H_2/graphite dust hybrid mixture explosions are presented in Fig. 1; diamonds there represent the hybrid mixtures, solid lines show the values obtained in the 'pure H_2' test. The pressure–time curves and $dP/dt(t)$ curves for 100 and 200 g/m^3 dust concentrations are plotted in Fig. 2(a) and (b), respectively, together with the curves recorded in the 'pure H_2' test. After 40 ms from the test triggering, the pressure starts to rise due to income of the injecting air, reaches 1 bar after about 60 ms, and then, after ignition at this moment, rises further due to mixture combustion.

In these tests only hydrogen constituent explodes; the dust is not involved in the combustion process. The combustion product mass spectra contain only O_2 and N_2 peaks and neither CO_2 nor H_2 peaks. The dust acts like a heat sink reducing the resulting maximum overpressures and slowing down the hydrogen explosion.

With 10% of hydrogen, a similar explosion regime is observed for the mixtures of 25 and 50 g/m^3 dust density