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Effect of igniter type and number of igniters on vented deflagrations for near lean flammability limit hydrogen-air mixtures in a large scale rectangular volume

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ABSTRACT

This paper examines the effect of igniter type (glow plug vs. spark igniter) and number of igniters on the dynamics of vented combustion under both initially quiescent and fan-induced turbulent conditions. These experiments are a subset of many series of tests performed in a 120 m^3 large scale vented combustion test facility at the Canadian Nuclear Laboratories using near lean flammability hydrogen-air mixtures (8–12% H_2). One of the objectives of these studies was to have a better understanding of the effectiveness of deliberate ignition for mitigation of hydrogen during a postulated accident and to provide data for code validation. The test results of the current study show that the two types of ignition sources have no significant influence on the maximum combustion overpressure except that the initial burning rate is slightly faster using the spark igniter. Under either the quiescent or turbulent conditions, the maximum combustion overpressure always increases with an increase in the number of igniters, but under the current experimental conditions, the turbulent combustion overpressure with one igniter is always higher than quiescent combustion with multiple igniters.

Introduction

During certain loss of coolant accidents in water-cooled nuclear power plants, hydrogen can be generated from various mechanisms, including oxidation of metallic components of the reactor core and molten core concrete interaction. The hydrogen can be released into the containment atmosphere and the subsequent hydrogen explosion could cause severe damage of the containment structures, as evidenced in the Fukushima accident, resulting in the release of radioactive materials to the environment. To prevent or limit hydrogen explosion consequences, various hydrogen mitigation measures have been implemented in the reactor or containment buildings [1]. The deliberate ignition concept was explored after the Three Mile Island event, leading to installation of tens to hundreds of glow plug or spark igniters in containments. The igniter technology was established as a method of preventing damaging burns by ensuring ignition near the limits of flammability. Numerous experimental studies were

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conducted in the 1980s to determine the effectiveness of deliberate ignition, such as Carmel [2], Lowry et al. [3] and Tamm et al. [4]. All these studies focused on hydrogen combustion characteristics in closed volumes.

The nuclear containment buildings consist of many interconnected compartments. Combustion-generated overpressures in a post-accident containment building can be relieved by venting to adjacent compartments through relief panels or existing openings. Extensive studies on vented hydrogen combustion behavior were performed at the Canadian Nuclear Laboratories (CNL; formerly Atomic Energy of Canada Limited - AECL) using a 6 m^3 spherical facility by Kumar et al. [5,6] and a 120 m^3 rectangular Large Scale Vented Combustion Test Facility (LSVCTF) by Kumar [7,8] and Liang [9,10]. The main purpose was to understand the fundamental mechanisms that control the overpressures resulting from vented combustion. The experimental data have been used to develop and validate models to analyze scenarios involving mitigation by deliberate ignition in post-accident nuclear reactor containments.

Venting is also a common industrial practice to reduce the consequences of confined explosions in equipment and buildings. Implementation of a venting technique has also motivated extensive studies on vented combustion dynamics and predictive methods, such as Bradley and Mitcheson [11,12], Cooper et al. [13], Bauwens and Dorofeev [14], Molkov et al. [15], and Molkov and Bragin [16]. It has been demonstrated in these studies that the maximum overpressure achieved during a vented deflagration can be dominated by one of a number of specific transients, which correspond to different phenomena and processes, such as vent rupture, flame jet ignition, and flame acoustic coupling. There are numerous parameters that can affect these transients.

The study presented in this paper is a subset of series of vented combustion tests performed in CNL's LSVCTF. The experiments were performed with either one glow plug or spark igniter, or multiple spark igniters (2, 4 or 6) using lean hydrogen-air mixtures under initially quiescent or turbulent conditions. The general combustion properties of hydrogen mixtures and flammability limits due to buoyancy have been well summarized by Lee and Berman [17] and won't be repeated in this paper. The main objective of this paper is to examine the effect of igniter type and multiple ignition sites on the vented combustion dynamics and to provide data for code validation. The measured peak overpressures will be compared against the semi-empirical correlations proposed by Bradley-Mitcheson [11,12] and Molkov et al. [15].

Experimental details

Facility

The LSVCTF is a 10-m long, 4-m wide and 3-m high rectangular enclosure with a total internal volume of 120 m^3. A schematic of the facility configured with three chambers is shown in Fig. 1. It is constructed of 1.25-cm thick steel plates welded to a rigid framework of steel I-beams. The entire structure is anchored to a 1-m thick concrete pad. Two roller mounted movable end walls are provided to open the vessel for internal modifications. Both the front and rear end walls

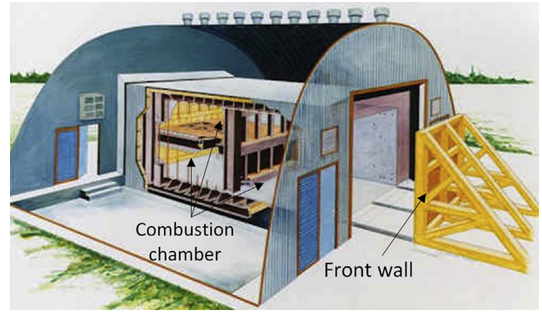

Fig. 1 – Schematic of LSVCTF configured with three chambers (120 m^3).

are covered with rectangular steel plates bolted to the end wall structure. The combustion chamber, including the end walls, is electrically trace heated and heavily insulated. The entire combustion chamber is enclosed in an insulated metal Quonset. The side walls, floor and ceiling inside the chamber consist of smooth and flat steel panels. Internal walls made of structural steel beams can be inserted into the facility to divide the entire chamber into multiple volumes.

The facility was configured as a single 120 m^3 chamber for the current study. All the internal subdivisions were removed except instrumentation racks shown in Fig. 2. The vent was located in the front wall and the vent area was varied by removing appropriate number of panels in the central row. Prior to a test, the vent opening was covered with aluminium foil to prevent loss of pre-combustion gases. To facilitate vent rupture at lower pressure (<1 kPa), small tears were made in the centre of the foil.

Eight hydraulic fans (four on each side wall) were diagonally installed in the chamber to mix the gases uniformly during gas addition. They were also used to generate initial turbulence for the turbulent combustion tests.

The number of igniters was varied from 1, 2, 4 to 6 and their locations are shown in Fig. 2. One glow plug or spark igniter was located in the center of the chamber at the location A, two spark igniters at B and C, 4 spark igniters at D, E F and G, and 6 spark igniters at B, C, D E, F and G. The glow plug igniter is a hermetically sealed 120 V TAYCO glow plug igniter assembly. It rises to a maximum surface temperature of 800–900 °C in ~20 s. The heating section of the glow plug is a resistive heater comprised of a spiral wire (wire diameter of 0.5 cm, spiral diameter 2.54 cm and height of 10 cm). The spark is produced by a 3A4 Champion FHE-246-4 aircraft igniter and Unison Industries ignition exciter. It sparks every 2 s for ~20 s. The integral energy delivered by the spark is on the order of 1 J, which is sufficient for the ignition of the mixtures studied.

U-shape instrumentation channel racks (2-in wide) were installed along three-axes across the volume in three vertical planes to attach the igniters and thermocouples (Fig. 2).

Measurements

The initial gas composition was analyzed by a process mass spectrometer and sampled at ~30 s intervals. The mass spectrometer was calibrated using primary calibration gases