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Overview of hydrogen combustion experiments performed in a large scale vented vessel at Canadian Nuclear Laboratories

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ABSTRACT

Hydrogen combustion inside a post-accident containment environment may pose a threat to the integrity of the containment structure and equipment. In CANDU reactors, combustion-generated overpressures in an accident will be relieved by venting to adjacent from one compartment volumes through relief panels or existing openings. To have a better understanding of the fundamental mechanisms that control the overpressures resulting from a vented hydrogen deflagration, a 120 m^3 large scale vented combustion test facility was constructed at Canadian Nuclear Laboratories. A number of experiments have been completed in this facility to investigate hydrogen combustion behavior simulated in a post-accident reactor containment environment. A selected number of experimental results are presented in this paper to demonstrate several parameter effects on vented combustion dynamics by varying the number of chambers (single, two or three interconnected), volume and vent size, initial turbulence (quiescent vs. turbulent), initial temperature and steam concentration, mixture uniformity (well mixed vs. highly stratified), vent locations, and number of igniters. These results have provided useful insights for hydrogen management for the Canadian nuclear industry and CANDU utilities participating in the CANDU Owners Group research program. Most experimental data have been used for validation of combustion models and development of user guidelines.

1. Introduction

In water-cooled nuclear power plants, hydrogen can be generated from various mechanisms during an accident, including oxidation of metallic components of the reactor core with steam and molten core concrete interaction. It has been well recognized that hydrogen combustion in a post-accident containment presents a challenge to containment integrity, which could alter the fission-product release source term from the containment, as evidenced in the Fukushima accident. Since the 1980s, Canadian Nuclear Laboratories (CNL, formerly Atomic Energy of Canada Limited) has established a comprehensive program to improve understanding of hydrogen behavior in simulated post-accident reactor containment environment. The early program was motivated to establish theoretical and experimental foundations for determining the containment atmosphere response to various postulated reactor accidents, and to establish a database for code development/validation. Over the past three decades, the Canadian nuclear industry has developed a good understanding of the key phenomena regarding hydrogen behavior. Analytical tools have also been developed to assess the potential risks of hydrogen.

The reactor containment buildings consist of many interconnected compartments. Combustion-generated overpressures in a post-accident containment building can be relieved by venting from one compartment to another through relief panels or existing openings. As a result, CNL has completed a number of studies to understand combustion characteristics in vented vessels and the dominating mechanisms that influence vented combustion behavior (Kumar et al., 1987, 1989; Kumar, 2006, 2009; Chan, 2005; Liang, 2017a,b). Combustion pressure in a vented volume is influenced by the rate of heat release due to combustion and the rate of mass loss due to venting. While the latter depends on the vent size and the pressure difference across the vent opening, the former depends on a number of processes that may be affected by the scale of the experimental set up. The overall burning rate depends on the burning velocity at the reaction front and the total flame surface area. CNL's early studies performed in a 6 m^3 spherical Containment Test Facility (CTF) by Kumar et al. (1987, 1989) provided a good understanding of the dynamic behavior of vented deflagrations; however, questions were raised regarding the scale of the vessel and shape of the enclosure as well as relevance of phenomena to post-accident containment buildings because flame front instabilities require time to develop and are often observable in larger scale systems. Thus, a 120 m^3 rectangular (more representative of reactor buildings) Large

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Scale Vented Combustion Test Facility (LSVCTF) was constructed to examine the scale and acoustic effects (Kumar, 2006, 2009; Chan, 2005; Liang, 2017a), as well as vented combustion dynamic in inter-connected volumes (Liang, 2017b). Kanzleiter and Fischer (1994) showed that combustion in an interconnected multi-compartment geometry can produce drastic flame acceleration and local pressure build-ups due to flame jet ignition and flame interaction between compartments, resulting in much higher overpressures than from a single volume.

Knowledge gaps in combustion characteristics for non-uniform mixtures are being raised by the international nuclear community as early investigations dealt with uniform mixtures. In reality, stratified regions of hydrogen concentration may exist prior to complete mixing or in regions where steam is condensing. If considerable hydrogen stratification exists, pockets of high hydrogen concentrations may affect combustion behavior. Rudy et al. (2013) showed that fast deflagration or detonation could occur in a partially unconfined flat layer with stratified mixtures in presence of obstructions.

This paper provides an overview of the vented hydrogen combustion studies performed in the LSVCTF. A selected number of experimental results are presented to demonstrate the effect of initial hydrogen concentration, turbulence, gas temperature and steam content, vent size and location, volume size, number of igniters, stratification and vessel shape on pressure dynamics of vented hydrogen deflagrations.

2. Experimental facility

The LSVCTF (Fig. 1a) is a 120 m^3 (10-m long, 4-m wide and 3-m high) rectangular structural-steel test chamber enclosed in an insulated Quonset. The test chamber is constructed of 1.25 cm-thick steel plates welded to a rigid steel I-beam framework. The entire structure is anchored to a 1-m-thick concrete pad. Two movable end-walls slide out in the event a significant overpressure is achieved. The end walls are covered with rectangular steel plates bolted to the end-wall structure. Removing the appropriate number of panels can change the vent area to the outside. Internal walls, made of structural steel beams, can be inserted into the facility to divide the entire chamber into two or three volumes (Fig. 1b & c). They can be used as a single volume (Fig. 1d) or interconnected volumes. One side of the Quonset houses a mass spectrometer for gas analysis and the hydraulic fan system, while the other side houses process piping. The facility is instrumented and temperature-controlled for operation at ambient temperatures up to 100 °C. The design pressure is 300 kPa(g), with a dynamic load factor of 2.

The LSVCTF was designed and built to systematically quantify the effects of key parameters affecting pressure development of vented deflagration under conditions relevant to deliberate ignition (as may be the case for some nuclear reactors). Some of the key features that were included in the design of the facility consist of accurate control of initial thermodynamic conditions, instrumentation capability to validate three-dimensional combustion codes and variable geometric configuration (with geometries similar to actual nuclear containment rooms).

Eight hydraulic fans are installed in a diagonal pattern on the sidewalls to mix the gases uniformly during gas addition or generate turbulence during a test. At 1000 RPM, the maximum air speed is ~9 m/s at the fan outlets and ~4 m/s in the centre of the room. The volume-averaged turbulent intensity is on the order of 1 m/s.

The total volume of LSVCTF was chosen to be 20 times larger than that of the 6 m^3 sphere because the volume of reactor buildings is typically on the order of 3,000–6,000 m^3. This would help to justify whether the combustion behavior observed in the 6 and 120 m^3 vessels can be extrapolated to reactor-size volumes. In addition, the maximum vent-to-volume ratio (vent area/[vessel volume]$^{2/3}$) is limited to 0.05 for the sphere, but a ratio up to 1 is achievable in LSVCTF, which is of interest for nuclear applications.

The LSVCTF has been used to perform a wide variety of hydrogen safety related experiments, including quiescent and turbulent vented combustion experiments (Kumar, 2006, 2009), effects of scale and acoustic coupling (Chan, 2005; Liang, 2017a), effect of interconnected volumes (Liang, 2017b), and effectiveness of deliberate igniter (Liang et al., 2016).

3. Experimental results

Selected test results are discussed in this section to demonstrate the effects of initial hydrogen concentration, turbulence, temperature, steam concentration, vent and volume sizes of a single chamber, interconnected-chambers, number of ignition sources, vent location, mixture stratification and vessel shape on pressure development. The experiments were performed in four configurations of LSVCTF chambers: two in a single chamber with a volume of 57 or 120 m^3, and the other in two or three interconnected chambers. The vessel geometry characteristics for these four configurations are shown in Table 1. The maximum length-to-height ratio is 1.6 for the half chamber, and 3.3 for the full chamber. For each single chamber, the tests with a vent-to-volume ratio ($A_v/V^{2/3}$) close to 0.023 or 0.0452 are compared. For the two and three interconnected chambers tests, the front vent (i.e., the most outer vent open to the atmosphere) was chosen to be the same as the full chamber (i.e., 1.1 m^2) and the internal vents are listed in Table 1. The vent locations are shaded areas as shown in Fig. 1b, c and d.

Unless otherwise specified, the tests were performed at an ambient temperature (18–25 °C) and atmospheric pressure (96–100 kPa) with dry hydrogen-air mixtures. Mixing fans were turned on during hydrogen addition to ensure a uniform mixture for well-mixed tests, but off for stratified tests (Section 3.9). They were turned off before the ignition for quiescent tests, but remained on for turbulent tests. Ignition was triggered by a glow plug igniter (with the exception of the tests described in Section 3.7 which used spark igniters) and the igniter was located in the center of each single volume, or the inner most chamber of the two (rear chamber) and three-chambers (rear top). The vent in the front end wall was located in the center, but slightly off center in the inner walls for two or three chamber tests. Prior to the gas addition, the vent openings were covered with aluminum foil to prevent premature loss of gases, but they could break easily (i.e., < 5 kPa) during the combustion. To facilitate vent foil rupture at lower pressure (< 1 kPa), small tears were made in the center of the foil for all the tests.

The measurements included initial gas concentrations, dynamic pressure, temperatures from fast-response thermocouples to capture flame arrival, and infrared images during the combustion. The uncertainty of the hydrogen concentration measurement was within ± 0.2% (absolute). The pressure transducers were periodically calibrated with an overall uncertainty of ± 0.5 kPa. The infrared camera had a frame rate of 48 frames per second. It was calibrated for a temperature range of 300–1,200 °C, but able to discriminate temperature difference below 300 °C with a resolution of 1 °C.

The tests conditions presented in Sections 3.1–3.9 are listed in Table 2. Note the time zero of the pressure transients were shifted to coincide with a dynamic pressure increase of 0.05 kPa. Most pressure traces included high oscillations after the vent foil rupture, so the traces were smoothed using a 50 Hz low pass filter and included in the plots to help determine peak values.

3.1. Effect of initial hydrogen concentration

Pressure transients of 8–10%[1] H_2 tests performed in the half chamber (57 m^3) of LSVCTF with a 0.55 m^2 vent under initially quiescent conditions are shown in Fig. 2. The pressure transients exhibited three major peaks for the 9 and 10% H_2 tests, but only one major peak for the 8% H_2 test. As discovered by Cooper et al. (1986), the 1st peak

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[1] All the gas concentrations are expressed on % volume basis.