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Experimental study of combustion behavior during continuous hydrogen injection with an operating igniter

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HIGHLIGHTS

- Combustion during continuous hydrogen release.
- Periodical slow burning with a low release rate or weak turbulence.
- Fast global burning with stratified hydrogen or strong turbulence.
- Initiation of standing flame.

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ABSTRACT

Deliberate hydrogen ignition systems have been widely installed in many water cooled nuclear power plants to mitigate hydrogen risk in a loss-of-coolant accident. Experimental studies were performed at a large scale facility to simulate a post-accident containment scenario, where hydrogen is released into a volume (not closed) with an energized igniter. The test chamber had a volume of 60 m^3. The test parameters included hydrogen injection mass flow rate, injection elevation, igniter elevation, and level of turbulence in the chamber. Several dynamic combustion behaviors were observed. Under certain conditions, slow burning occurred periodically or locally without significant pressurization, and the hydrogen concentration could be maintained near the lean hydrogen flammability limit or a steady hydrogen distribution profile could be formed with a maximum hydrogen concentration less than 9 vol.%. Under other conditions, a global fast burn or a burn moving along the hydrogen dispersion pathway was observed and was followed by an immediate initiation of a standing flame. The study provided a better understanding of the dynamic combustion behavior induced by a deliberate igniter during a continuous hydrogen release. The data can be used for validation of combustion models used for hydrogen safety analysis.

1. Introduction

In response to the Fukushima Daiichi nuclear accident, countries with nuclear installations have taken significant steps to improve the safety of their plants with various degrees of practical implementation, in particular for hydrogen management. Installation of hydrogen mitigation measures has become a high priority if they were not implemented before. In water-cooled nuclear power plants, large amounts of hydrogen can be generated from various mechanisms, including oxidation of metallic components of the reactor core (e.g., Zr-steam reaction) and molten core concrete interaction. The hydrogen can be subsequently released through breaks in the primary heat-transport system into the containment atmosphere. It has been well recognized that hydrogen combustion in containment presents a challenge to containment integrity as evidenced in the Fukushima accident. Breaches in containment will result in higher source term releases. To prevent or limit hydrogen explosion consequences, various hydrogen mitigation measures have been implemented in the reactor or containment buildings (Implementation, 1996). One of the methods to mitigate the effects of hydrogen combustion is deliberate ignition at low hydrogen concentrations by igniters in the containment. The deliberate ignition concept was explored after the Three Mile Island event, leading to installation of glow plug igniters (active systems) in the containments. Numerous experimental programs have been conducted to determine the effectiveness of deliberate ignition system by Carmel (1989), focusing on many aspects of hydrogen combustion characteristic, such as flammability limits, combustion pressure and completeness, flame speeds, effect of water sprays on igniter performance, and effect of steam condensation on igniter

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effectiveness. The majority of these studies examined the behavior of pre-mixed combustion or diffusion flames, including Lowry et al. (1982), Thompson et al. (1985), Shepherd (1985), Tamanini (1983) and Tamm et al. (1985). Some dynamic combustion tests were performed with a glow plug igniter energized during a continuous hydrogen or hydrogen steam injection into a 3.8 m^3 sphere by Liparulo et al. (1981). As revealed by Carmel (1989), the ignition behavior observed most frequently in the continuous injection tests was slow ignition and diffusion flame burning as opposed to fast ignition (deflagration) which occurred in the premixed tests.

The concept of using igniters in the containments is to initiate combustion at low hydrogen concentrations (i.e., near the low flammability limit, 4 vol.% H_2 in air) rather than allowing the hydrogen to accumulate to more threatening levels. The consequence of igniting such weak mixtures should generally pose a minimal challenge to containment integrity and equipment survivability. During an accident, the igniters generally remain on for some time after they are activated. Depending on the hydrogen release rate and location, the igniter location, and the level of turbulence, combustion may occur during the transient of gas mixing in either quiescent or turbulent atmosphere with well-mixed or stratified mixtures. In such a dynamic atmosphere, the combustion outcome could be a combination of various modes, such as local or global, slow or fast burning, or standing flame. The early studies (Carmel, 1989; Lowry et al., 1982; Thompson et al., 1985; Shepherd, 1985; Tamanini, 1983; Tamm et al., 1985; Liparulo et al., 1981) were mostly focused on examining the combustion characteristics of single combustion mode (i.e., premixed-mixed combustion and diffusion flame). The dynamic combustion behavior of continuous hydrogen injection with an operating igniter has not been examined in a large scale facility.

The current study was motivated to further examine the dynamics of the combustion behavior during continuous hydrogen injection. A series of tests were performed in the Large Scale Vented Combustion Test Facility (LSVCTF) at Canadian Nuclear Laboratories' (CNL's, formerly Atomic Energy of Canada Limited) Whiteshell Laboratories. The test results provided a better understanding of the possible combustion modes induced by the deliberate ignition system with a continuous hydrogen injection. It should be noted that these experiments are not representative of real nuclear power plant geometries or conditions; rather they provide experimental data for code validation to support plant safety analysis.

This paper presents a selected number of test results to demonstrate the possible combustion characteristics during continuous hydrogen release with an operating igniter. It is intended to provide some insights for hydrogen mitigation strategies in containments.

2. Experimental setup

2.1. Facility

The LSVCTF is a 10-m long, 4-m wide, and 3-m high rectangular chamber with an internal volume of 120 m^3. Two removable structural steel internal walls (~0.5 m thick) can be used to divide the test chamber into three rooms. All the tests of this study were performed in the front half chamber by blanking off the rear chamber with the central wall (Fig. 1a). The combustion chamber 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. The end walls (front and back) are covered with rectangular steel plates bolted to the end-wall structure. For combustion tests, some of the steel panels are removed from the end walls to allow gas release from the vent to reduce the

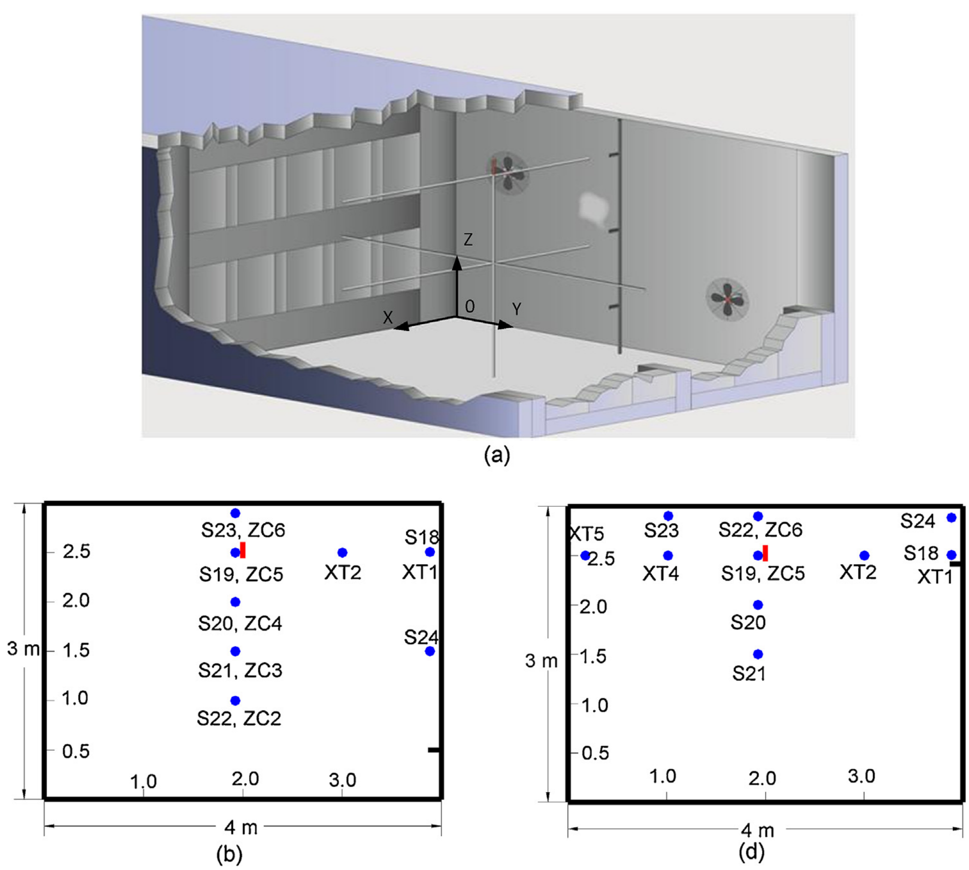

Fig. 1. Schematic of the LSVCTF: (a) configuration of the front chamber, (b) location of gas samples & thermocouples for cases 1, 2, 4 & 5, and (c) case 3.