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Experimental study of laminar and turbulent flame speed of a spherical flame in a fan-stirred closed vessel for hydrogen safety application

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ABSTRACT

The aim of this paper is to report new experimental results on the effect of turbulence on the propagation speed of hydrogen/air flames. To do so, a new experimental setup, called the spherical bomb, has been designed and built at CNRS-ICARE laboratory. With this new setup, the effect of a given and well-characterized turbulence intensity on the increase of hydrogen/air flame speed can be investigated. This new facility consists of a spherical vessel equipped (563 mm internal diameter) equipped with 8 motors which are linked to fans inside the bomb. Fan actuation induces the generation of a turbulent flow inside the vessel prior to any ignition. The spherical bomb is equipped with 4 quartz windows (200 mm optical diameter) that allow the use of a Particle Image Velocimetry diagnostic in order to characterize the turbulence level inside the bomb. The flame propagation was recorded using a high speed camera at 19,002 frames per second. These experiments were performed for lean to stoichiometric hydrogen/air mixtures (16–20% of H_2 in air), initially at ambient temperature and pressure, and for a rotation speed from 1000 to 5000 rpm. The PIV measurements showed that a homogeneous and isotropic turbulence is created with a fluctuation speed that can reach 4 m/s at 5000 rpm.

1. Introduction

In case of a severe accident in a nuclear reactor with core meltdown, the interaction of the hot core with the cooling water can generate large amounts of hydrogen (H_2). Hydrogen may be produced by the oxidation of metals present in the corium pool or in the basemat during the molten corium-concrete interaction phase. Since hydrogen/air mixtures are characterized very low ignition energies, the presence of hot surfaces in the vicinity of the flammable mixture may lead to ignition and production of an initially slow flame. During its propagation, the flame can accelerate to a fast flame that can cause high pressure loads threatening the nuclear reactor building. Hence, it is mandatory to understand the acceleration process and to be able to identify the phenomena that are responsible for this strong flame acceleration and from the early beginning of the flame formation. Recent benchmarks (Bentaib et al., 2014; OECD NEA Report, 2011) have shown the importance of the turbulent flame models used in the CFD codes used worldwide in the assessment of the explosion risk in nuclear power plants. In fact, the lessons learnt from these benchmarks show that the computer codes are able to reproduce the maximum pressure generated by combustion. On the other hand, they do not well predict the flame propagation regimes as observed in the experiments and the rate of pressure increase. These exercises highlighted the need to measure the turbulence in the fresh unburnt gas mixture and to characterize the transition from laminar flame to turbulent flame regime. These data are necessary for the improvement and validation of turbulent combustion models. However, in the majority of the available experimental research performed so far, this information is missing. The relation between the turbulent flame speed and the laminar one has been investigated for several decades, but still there is no consensus over the most relevant expression. Many studies have identified a relationship between the turbulent flame speed and different characteristics of the laminar combustion such as the laminar flame speed, S_L, the flame thickness, δ_{lam} and of the turbulence such as the intensity of the turbulence (u'), the integral length scale (L_T). Borghi Borghi, 1985 proposed a classification into four regimes of combustion based on the non-dimensional turbulent Reynolds number (Re_T), Karlovitz number (Ka) and Damköhler number (Da):

1. The wrinkled flame regime, for which the $Re_T > 1$ and $u'/S_L < 1$
2. The corrugated flamelet regime, for which $u'/S_L > 1$ and $Ka < 1$

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3. The thickened flame regime (or thin reaction zone) Ka > 1 and Da > 1
4. The distributed reactions regime when Da < 1.

In the work of Faix-Gantier (2001) estimated that, in case of a nuclear reactor accident, the integral length scale would vary between 0.02 and 2 m and the turbulent intensity would be between 0.03 and 15 m/s. Considering lean H_2/air mixtures, it then follows that the combustion regimes 1–3 are most relevant to nuclear power plants would cover from regions 1–3 as it is shown in Fig. 1.

Several expression of the turbulent flame speed for H_2/air mixtures can be found the literature (Abdel-Gayed and Bradley, 1977; Kumar and Tamm, 1985; Koroll et al., 1993; Heitsch, 1996; Leisenheimer and Leuckel, 1996). The most recent work of Kitagawa and et al. (2008) with various exponent over the ratio u'/S_L. These studies, at the exception of Kitagawa et al. have focused on H_2/air mixtures that have positive Markstein lengths. It is then important to acquire data on mixtures that are more relevant to PWR which are characterized with negative Markstein lengths (Cheikhravat et al., 2012; Bentaib et al., 2014).

The aim of the present paper is to present new experimental results concerning laminar and turbulent flame speed of premixed hydrogen/air mixtures. The experiments are conducted in a closed spherical vessel in which a homogeneous and isotropic turbulence is generated using several fans. The first part of the paper will describe the experimental setup and the diagnostics. The second part of the paper will summarize the measured flame speeds and the temporal evolution of the combustion overpressure according to the fans rotations speeds (and hence turbulent intensity) for several conditions of molar percent of H_2 in the mixture.

2. Experimental setup

The laminar and turbulent combustion experiments have been performed in a spherical vessel with an inner diameter of 563 mm (total volume of 93.43 L). The wall thickness is 42 mm which allows a maximum pressure of 200 bar with an initial temperature ranging from ambient to 300 °C (Fig. 2(a)). It is equipped with 4 quartz windows (200 mm optical diameter) and 8 ports to mount the fans (Fig. 2(b)). Two tungsten electrodes are mounted along a diameter of the sphere, in the horizontal plane. They are linked to a high voltage discharge in order to create the electric spark necessary to ignite the mixture. The electric spark is used to trigger the recording equipment (camera and oscilloscopes) in order to synchronize the temporal flame growth with the evolution of the pressure inside the bomb. Indeed, the temporal behavior of the induced overpressure following the ignition is measured with two fast piezoelectric pressure transducer (Kistler 6001 and 601A models). The pressure transducers are mounted flush with inner wall of the vessel and located on opposite sides along a diameter of the bomb at +42° and −42° from the equatorial plan respectively.

2.1. Flame visualization

The visualization of the flame was obtained using a Z-shape Schlieren apparatus (Fig. 3(a)). A white continuous lamp (300 W Xe Lot-Oriel lamp) is used to illuminate the flame via two lenses and two concave spherical mirrors. A high speed camera (PHANTOM V1210), with an acquisition rate of 19,002 frames per second, records the Schlieren images of the growing flame. The frame size was fixed to 768×768 pixels^2. An example of images acquired with the spherical bomb is given in Fig. 3(b) and (c).

2.2. Experimental methodology

Before each test, the chamber was vacuumed and the residual pressure was lower than 3 Pa. The gases were introduced at the partial pressures required to give the desired mixture composition starting from H_2. The air used was dry laboratory air. Based on the precision of the pressure gauges, the concentrations were determined with an accuracy of 0.2%. Then the fans were activated and the rotation speed set to the desired value. For the laminar experiments, the fans were not activated. Once the steady state is reached, the ignition is obtained using the spark generator and all the recording equipment are triggered on the onset of the electric spark.

The raw images, as shown in Fig. 3, are processed using an in-house code based on Matlab libraries in order to identify the edge of the flame, at each time, and determine the surface enclosed in this boundary. From the surface of the flame, an average radius is calculated based on an equivalent circle matching the experimental area (Fig. 4). From this image processing the increase in the

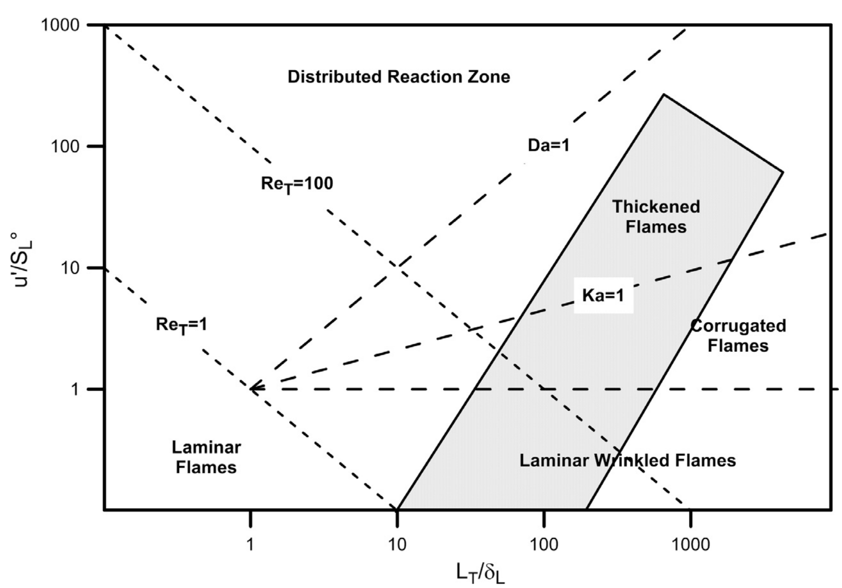

Fig. 1. Borghi diagram with four combustion regimes. The relevant region of nuclear power plant accidents according to Faix-Gantier (2001) is colored in gray.