Influence of turbulence on the propagation of C7H8/air flames at atmospheric pressure and temperature

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1 Introduction

The reduction of pollutant emissions and energy diversification become a world challenge which require the development of new combustion processes and new combustibles. Combustion constitutes a major source of atmospheric pollutants emissions, like carbon monoxide and dioxide, unburned fuel and nitrogen oxide. Hence, in the field of people and goods transport, engine conception is dictated by the efficiency, the reduction of consumption and emissions, while keeping or increase the power. In such engines, the combustion process is driven by the turbulent flow inside the combustion chamber. The understanding of the complex interactions between the reaction rate of a combustible and the flow is hence of first order. To realize this work, several research group have developed fan-stirred spherical combustion vessels. It consists of a closed bomb where combustible mixtures are introduced for selected thermodynamical conditions (P & T) which allows to study spherically expanding flames from an ignition point located at the center with different optical diagnostics: Schlieren [1,2], shadowgraphy [3] or Mie scattering [4,5]. In such research device, the reliability of investigation relies on the well-known turbulence statistics, comparable in scale to the one of real engines.

At ICARE laboratory, a fan-stirred spherical combustion vessel has been designed and used for the characterization of H2/air flame at atmospheric pressure and temperature for studies relevant to nuclear safety [1,2]. It presents an internal diameter of 563 mm to allow the study of large flame without any perturbation due to the confinement [6]. In the configuration used for hydrogen studies (Config 1), the integral length scale was around 52 mm. The aim of this work is to characterize a new configuration of turbulence generation (Config 2) where the position and the size of the fan have been modified into this large spherical vessel. First a complete study of PIV measurements is presented to determine the turbulence statistic. Secondly, preliminary results of C7H8/air flames at atmospheric pressure and temperature are presented and prospects are announced.

2 Experimental setup

The experimental setup consists of a spherical bomb with an inner diameter of 563mm (total internal volume of 93L). A view of this system is given in Figure 1. It can be used for both laminar and turbulent experiments. It allows a maximum pressure of 200 bars with an initial temperature ranging from ambient to 573K. The temperature is controlled via 2 thermocouple (± 2 K). Fresh gases are introduced successively into the vessel previously vacuumed. The residual partial pressure within the chamber before filling gases is less than 10 Pa. The partial pressure of each gas is controlled with a high precision capacitance pressure transducer with an accuracy of ± 0.1 Torr. Combustion is ignited with two tungsten electrodes place in the horizontal plane. This spark ignition is used to synchronized all acquisition devices. The temporal evolution of the pressure trace inside the vessel is registered by 2 fast piezoelectric pressure transducer (Kistler 6001 and 601A). The flame propagation can be observed with 4 quartz windows of 200 mm optical diameter mounted diametrically opposed two by two. The flame is recorded using a Schlieren imaging system. A continuous lamp (300 W Xe Lot-Oriel) is used to illuminate the flame, a high-speed camera Phantom v1611, with an acquisition rate of 25 kHz at the fixed frame size of 768x768 pixels², records the Schlieren images. Finally, the flame contour is extracted form an algorithm of binarization. After each test, the bomb is flushed with fresh air to evacuate burned gases before vacuum pimping. A complete description of this device and processing can be found in [1,2].

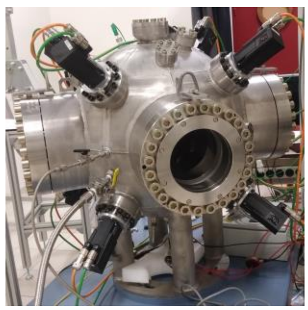


Figure 1. View of the experimental vessel

In order to generate a turbulent flow inside the vessel, 8 fans (moved by 8 electric engines) are placed at the vertices of a cube inscribed in the internal sphere to generate a homogeneous and isotropic turbulence, see figure 1. The flow generation is directed toward the center of the vessel by 80 mm in diameter fans composed of 4 blades. These fans are deported of 85 mm from the vessel wall. As a consequence, the distance between two opposite fans is equal to 393 mm. This distance is reduced compared to the previous experimental set, Config 1, presented in [1,2]. A lower integral length scale is thus expected. The characterization of the turbulent flow has been processed for this new configuration, Config 2, in the same way as in [2], and presented in the next section.

3 Turbulence characterization

3.1 PIV system

In order to characterize the flow field inside the vessel when the fans are in rotation, several experiments have been performed using a high-resolution PIV system. It is composed by an Nd:YAG laser (Quantel evergreen 200) delivering 2 pulse of 200 mJ at 532 nm. The laser sheet thickness is the lowest at the center of the vessel (0.5 mm). The gas inside the vessel is seeded with olive oil since no combustion reaction is involved. The droplets, generated with a Ventury atomizer, are typically of micrometric size. Finally, a high-resolution TSI PowerView Plus 16MP camera is used, with a detector of 4912x3280 pixels² and a recording resolution of 12 bit. Associated with a 50 mm macroscopic Zeiss lens, it allows to observe a field of view of 270x180 mm² with the typical magnification ratio of 50 µm/pixel. For each fan rotation speed, 800 couples of images have been recorded to ensure the statistical validity during data processing. The time interval between two pulses is adjusted accordingly to the flow velocity in order to ensure a droplet displacement average around 3 pixels. All PIV measurements have been conducted for 2 cross plans (XY and ZY plans) and results compared each other in order to ensure the symmetry of the velocity fields in 3D.

3.2 Turbulence statistics

Figure 2 presents for different fan rotation speeds the distribution of the mean and RMS velocities for the two components, *U* and *V*, of the velocity vectors. Equations and processing are taken from [2].

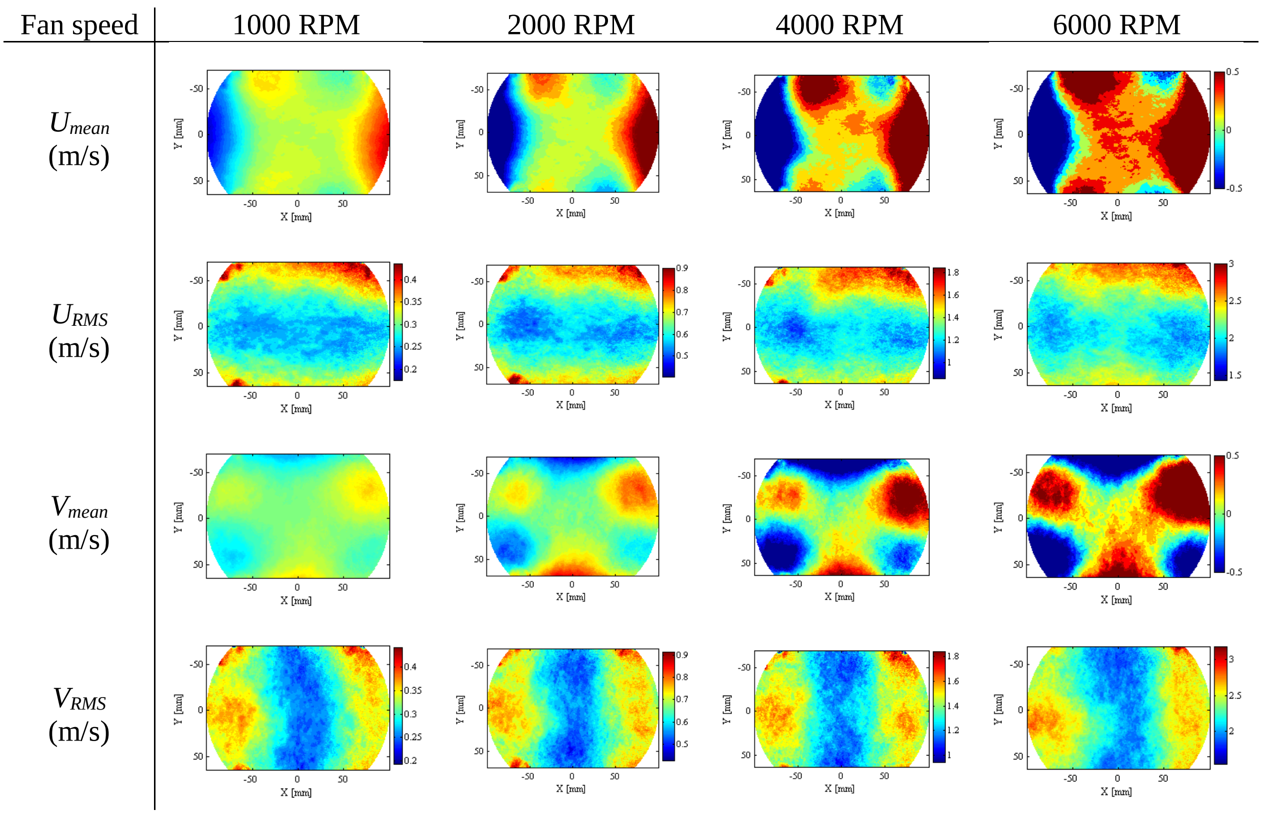


Figure 2. Mean and RMS speed of the two components, *U* and *V*, as a function of the fan rotation speed.

These 2D fields of component *U* and *V* of mean and RMS velocities are used to define qualitatively a central region of diameter around 90 mm where the turbulence can be considered homogeneous since the mean velocity is much lower than the RMS velocity. This observation is confirmed on Figure 3 where the homogeneity of the two component is represented. Furthermore, Figure 3 reports also the isotropy for the studied conditions. From the results of these two figures, it is possible to present the turbulence within the vessel as homogeneous and isotropic (HIT) on a sphere of diameter around 90 mm.
Otherwise, it can be noticed that, as for results of Config 1 presented in [2], the linear increase evolution of the turbulence intensity with the fan rotation speed has been found for Config 2.

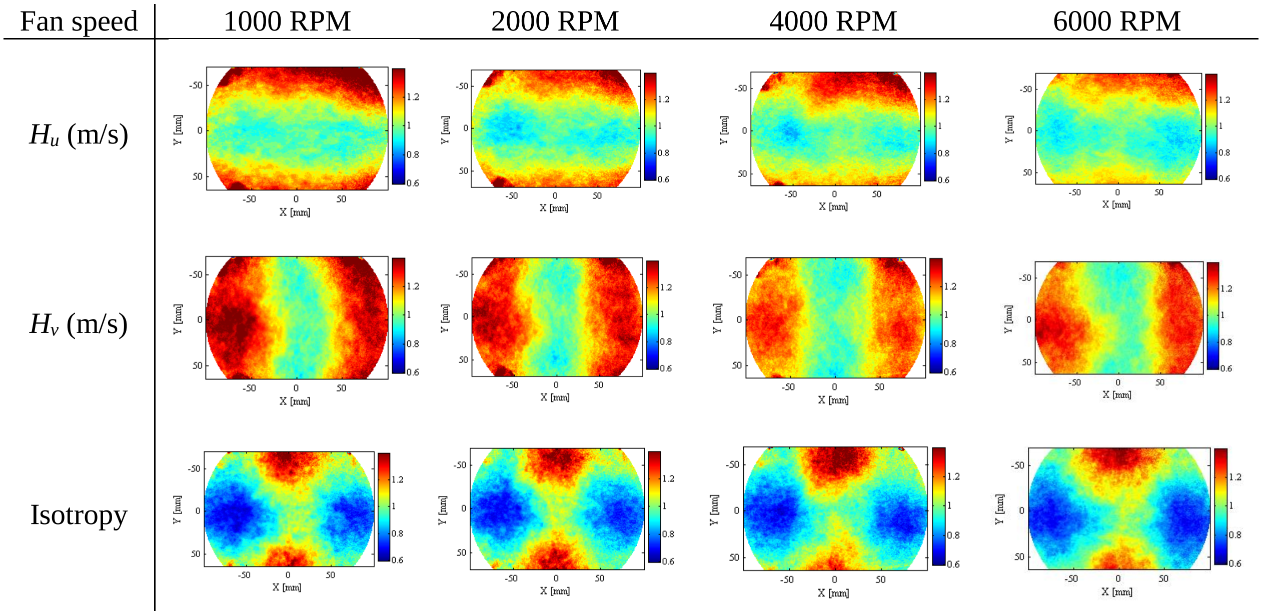


Figure 3. Homogeneity maps of the two components, *U* and *V*, as a function of the fan rotation speed.

To summarize on the set of measures characterizing the turbulent flow, table 1 synthetized the principal results and presents a comparison with similar experimental setup from literature.

Table 1: Overview of perfectly spherical vessels for turbulent flame propagation studies in literature

Reference	Bradley et al. [4,5]	Galmiche et al. [3]	Present device (Config 1)	Present device (Config 2)
Internal diameter	Ø 380 mm	Ø 200 mm	Ø 563 mm	Ø 563 mm
# Optical acces	6	4	4	4
Acces diameter	150 mm	70 mm	200 mm	200 mm
Number of fans	4	6	8	8
Fan blade	-	4	4	4
Fan diameter	-	40 mm	130 mm	80 mm
Offset of the wall	-	-	25 mm	85 mm
Maximal fan speed [rpm]	10,000	15,000	5000	9,000
Maximal turbulent intensity	12 m/s	2.8 m/s	3.7 m/s	3.3 m/s
Longitudinal integral length scale	20 mm	3.4 mm	52 mm	31 mm
Characterization technique	LDV	LDV (u’),PIV (L)	PIV	PIV

5 Results and Discussions

Flame propagation shape is represented in Figure 4 for the two specific equivalent ratios: Φ=0.85 and Φ=1.0 at atmospheric pressure and temperature as a function of the turbulence intensity for a fixed equivalent flame radius of 40 mm.

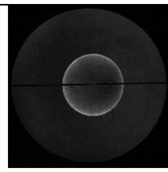
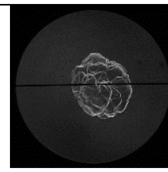
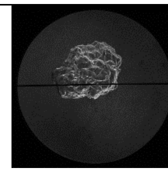
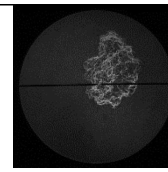
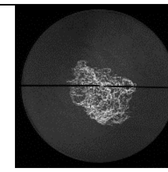
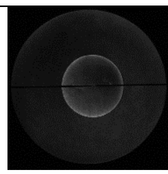
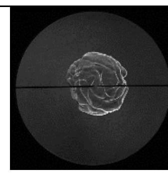
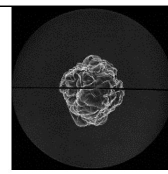
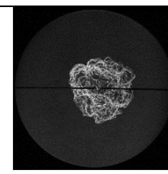
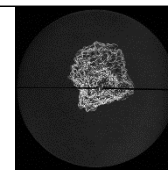
Fan speed	0 RPM	1000 RPM	2000 RPM	4000 RPM	6000 RPM
u' (m/s)	0	0.35	0.7	1.5	2.1
Φ = 0.85					
Φ = 1.0					

Figure 4. Schlieren images of C7H8/air flames for several fan rotation speeds at fixed $R_{flame,eq}$ = *40 mm.*

From images of turbulent flames, it is possible to define an equivalent flame radius defined as the radius of the circle corresponding to the projected surface of the flame. The evolution of the corresponding turbulent propagation flame speed normalized by the laminar unstretched propagation speed in the same thermodynamic conditions is presented as function of the equivalent flame radius in Figure 5.

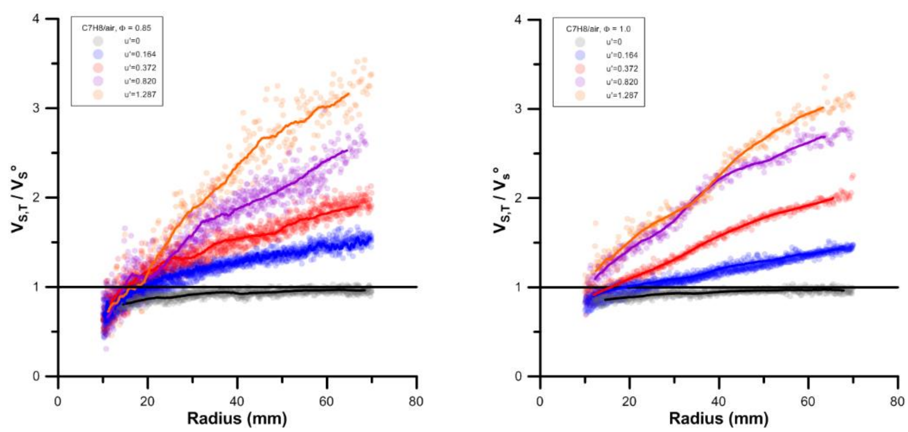


Figure 5. Evolution of the normalized propagation speed as a function of the flame radius.

For this two characteristic equivalence ratio, the ratio $V_{S,T}/V_S°$ increases notably with the turbulence intensity *u'*. Since for these thermodynamic conditions, the laminar flame front stays perfectly smooth on all the field of view, flame winkles can be affected only by turbulence effects and allow direct estimation of the turbulence effect on flame propagation.

Nevertheless, Figure 4 shows also that for high turbulence intensity compared to the laminar flame propagation speed, the ignition kernel and the propagation can be convected on the field of view. Hence the symmetry of turbulent flow can be affected and alter results. To reduce this convection phenomenon, it will be necessary to reduce again the integral length scale. Further investigations and modifications have to been done.

6 Concluding remarks

The presented modification of an existing device has demonstrated the ability to reduce the integral length scale on a large spherical bomb with a fixed diameter of 563 mm. This modification has been possible by using fans with a reduced diameter associated with an offset distance from the wall. Preliminary results on C7H8/air flames have demonstrated the ability of this device to realize study on heavy fuel with a turbulent combustion regime.

Nevertheless, the integral length scale appears to be always too large in the case of lean flames (Φ=0.85) with high turbulence intensity. Further modification should be made.

References

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