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Research Paper

# Estimation of turbulence characteristics from PIV in a high-pressure fan-stirred constant volume combustion chamber

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## HIGHLIGHTS

- Multi sections of laser sheet were adopted to reconstruct the three-dimensional homogeneous region.
- Morphology of the homogeneous region proved to be a flat and deformed cylinder.
- High ambient pressure led to smaller critical eddy scales of viscosity dissipation emergence observably.

## ARTICLE INFO

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## ABSTRACT

In this paper, a systematic experimental study was conducted to clarify characteristics of turbulence field generated by two opposite fans in a cubic constant volume combustion bomb (CVCB). The effect of the fan speed (1000–2900 rpm) and ambient pressure (0.1–3.0 MPa) on root-mean-square fluctuations, probability density functions, integral length scales and energy spectra was investigated. To overcome the limitation of the 2D-PIV, three sheet velocity fields were measured to reconstruct the three-dimensional boundary of the homogeneous region. Experimental results showed that a nearly homogeneous turbulence field in a flat region around the center of the CVCB was generated while a slight departure from isotropy was unavoidable in the current configuration. The turbulence intensity was independent of the ambient pressure, but positively proportional to the fan speed. Absence of both fan speed and ambient pressure's effect was observed for the integral length scales. Analysis of the turbulent energy spectra implied that the increase of fan speed and ambient pressure resulted in a smaller critical eddy scale where the viscosity dissipation effect started emerging.



## 1. Introduction

It is essential to understand the complex interactions between fluid dynamics, thermodynamics and chemical processes in engines combustion processes. In order to clarify those influence factors separately, devices such as Bunsen burner [1–3] and constant volume chamber [4–9] have been widely used to investigate turbulent flame. Comparatively, Bunsen burner, creating turbulence through gas coflow, provides steady flames but restricted to ordinary pressure, while the constant volume chamber, either jet-stirred or fan-stirred, enables high pressure and provides a nearly homogeneous and isotropic turbulence (HIT) [10–14].

Considering the repeatability and accuracy of turbulent combustion experiments, turbulence characterization of the test chamber needs to be demarcated. Bradley et al. [6] pointed out that, relevant turbulence parameters including root-mean-square (RMS) turbulent velocity and the turbulent integral length scale, should be measured for turbulent burning experiments. Actually, measurement of these parameters had been done by several research groups with various geometric experimental instruments. Weiss et al. [5] reported the turbulent intensity and integral length scale measured in a cubic explosion vessel at normal temperature and pressure, by means of Laser Doppler velocimetry (LDV). Moreover, Sick et al. [15] concentrated on the integral scale of a fan-stirred combustion bomb with a near-spherical chamber. Sick's work indicated that the integral scale remained constant at the bomb center with Reynolds number greater than 100. Birouk et al. [16] drew similar results from their research. Furthermore, they found that HIT was generated within a 20 mm radius spherical region located in the center of the chamber.

*Abbreviations:* TDC, top dead center; HIT, homogeneous and isotropic turbulence; LDV, Laser Doppler velocimetry; PIV, particle imaging velocimetry; RMS, root mean square; CVCB, constant volume combustion bomb; rpm, revolutions per minute; DFT, discrete Fourier transform; PDF, probability density function.

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**Nomenclature**

| | |
|---|---|
| $i$-direction | direction ($i = 1, 2, 3$ represents X, Y, Z coordinates respectively) |
| $P$ | ambient pressure [MPa] |
| $D$ | fan diameter [mm] |
| $f$ | rotational fan speed in Hertz [Hz] |
| $\omega$ | rotational fan speed in revolutions per minute [rpm] |
| $U_i$ | instantaneous velocity components in the $i$-direction [m/s] |
| $\overline{U}_i$ | mean velocity components in the $i$-direction [m/s] |
| $u_i$ | instantaneous fluctuating velocities in the $i$-direction [m/s] |
| $u_{iN}$ | standardized fluctuating velocities in the $i$-direction [–] |
| $u'_i$ | root-mean-square (RMS) velocity fluctuations in the $i$-direction [m/s] |
| $u'$ | ensemble mean RMS velocity fluctuations [m/s] |
| $\sigma$ | the standard deviation |
| $K$ | kurtosis factors of the velocity probability distribution functions [–] |
| $S$ | flatness factors of the velocity probability distribution functions [–] |
| $\zeta$ | spatial lag [mm] |
| $R_{ii}^k$ | autocorrelation coefficient of the $u_i$ in the $k$-direction [–] |
| $L_{11}$ | longitudinal integral length scale [mm] |
| $L_{33}$ | lateral integral length scale [mm] |
| $\kappa_1$ | wavenumber in the horizontal direction [rad mm$^{-1}$] |
| $F_i$ | the FFT of fluctuations in the $i$-direction |
| $F_i^*$ | the complex conjugate of $F_i$ |
| $E_{ii}^k$ | energy spectral density of $u_i$ in the $k$-direction [m$^3$/s$^2$ rad] |
| $\nu$ | kinetic viscosity [m$^2$/s] |
| $Re$ | Reynolds number [–] |
| $\lambda$ | Taylor microscale [mm] |

Equipped with apparatuses such as LDV, standard particle imaging velocimetry (PIV) and time-resolved particle imaging velocimetry, Galmiche et al. [10] conducted a comprehensive work on turbulent properties in a spherical combustion vessel. Their research revealed the effect of fan rotational speed, gas pressure (0.1–1.0 MPa) and temperature (300–473 K) on turbulent characteristics in the center of the vessel. Hwang and Eaton [11] used eight synthetic jet actuators, installed on the corners of a cubic chamber to create relatively homogeneous turbulence. Results showed that HIT was achieved, with RMS velocities as large as 0.87 m/s. Ravi et al. [13] investigated statistics of turbulence generated by three impellers inside a Plexiglas model of a cylindrical flame speed vessel, concentrating on the effect of different impeller geometric features. It was found that, homogeneity ratios were unaffected by changes of the impeller geometry, and the prototype with the higher number of blades caused the flow to become away from isotropy. Therefore, quantitative analysis of these flow fields, especially upon the turbulence homogeneity and isotropy inside these constant combustion vessels, have long been the prevailing issue.

In this work, experiments were carried out in a fan-stirred cubic combustion chamber. Similar to the experimental setups of Hayakawa et al. [17], two fans were mounted at the top and bottom of the vessel, rotating at the same speed but the opposite direction, driving ambient gases toward the center of the chamber. Different from previous studies [10,11,13,15–19], in this experiment, the target scope of PIV measurement were extended to test sections which located away from the chamber center, to obtain more information of the boundary flow field. Moreover, influence of pressure was concerned as well. Ambient pressure was intensively investigated up to 1.5 MPa and 3.0 MPa, which was equivalent to the non-turbo and turbo-charged diesel engine's cylinder gas density at top dead center (TDC) of the compressing stroke.

The purpose of this paper is to study the fan-stirred constant volume chamber device's turbulent characteristics by means of particle imaging velocimetry (PIV) measuring method. Parameters, including RMS velocity fluctuations, various length scales and energy spectra are concerned and analyzed.

## 2. Experiment apparatus and conditions

Experiments were conducted in a cubic constant volume combustion bomb (CVCB) [20–22] with optical access, while flow field velocity measurement was realized by means of the particle image velocimetry system. Composition of the test system will be introduced in this section.

### 2.1. Composition of CVCB

As shown in Fig. 1, the CVCB is the chief device of the test system, which has a cubic inner length of 136 mm, with six main ports for optical access or fans installation [20,21]. In this test, three main ports were used for PIV optical access with quartz windows which had a max optical diameter of 130 mm and a thickness of 50 mm. To be specific, two of them, in the X direction, were installed in line with the laser light beam, to provide optical access for laser sheet; another one, in the Y direction, was used as a CCD window, allowing full visualization of the central and surrounding region of the chamber. Two identical four-blade fans which had a diameter of 100 mm, located on the top and bottom main ports of the chamber in the Z direction, rotating at same speeds ranging from 1000 to 2900 revolutions per minute (rpm) but in opposite directions, directing flow toward the center of the chamber. Fans were driven through magnetic coupling by electric motors, ensuring the maximum sealing load of 16 MPa to provide a high pressure condition.

### 2.2. Particle image velocimetry system

A two-dimensional PIV system produced by TSI is employed, consisting of a dual-head laser device and a high-resolution CCD camera. The dual-head Nd: YAG laser is located in the X direction, providing laser rays of 200 mJ/pulse at 532 nm wavelength with maximum frequency of 15 Hz, used to illuminate the tracer particles in the XZ plane. To ensure particle displacements between two continuous frames are within a quarter of the interrogation windows length, the time separation between two consecutive laser pulses is adjusted from 15 to 100 μs in experiments, according to the fan speed. The high-resolution CCD camera (TSI Power View Plus), with 2048 $*$ 2048 pixels and minimum frame span time of 190 ns, was fixed in the Y direction and equipped with a Micro-Nikon f/4D 200 mm lens to give a magnification ratio of 22.76 μm/pixel. In addition, an optical band-pass filter (532 ± 5 nm) was installed in front of the camera lens in order to ensure that only the scattered laser light was transmissible to form PIV images on the CCD sensor of the camera. Besides, a TSI synchronizer system (model 610036), with a time resolution of 0.25 ns, was used to synchronize the laser pulses with image acquisition.

Hydrophobic $Al_2O_3$ particles with an average size of 2 μm were used as solid tracer particles in this experiment. It had been confirmed [23] that 2 μm solid particles, such as $TiO_2$ and $Al_2O_3$, showed appropriate following performance and optical