Turbulent Characteristics in a Taylor-Couette Flow

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Abstract
For future work on the turbulent premixed flame propagation in high intensity turbulent flow, we measured the turbulence characteristics in the Taylor-Couette flow apparatus between two counter rotating concentric cylinders. The turbulence characteristics such as the integral, the Taylor’s micro, and the Kolmogorov scales, intensities and power spectral density functions are obtained from the velocity fluctuations of the radial and circumferential components in the annulus measured by hotwire anemometry.

The intensity of the velocity fluctuation of the circumferential component linearly increased as Reynolds number Re increased. At the highest Reynolds number (Re = 7,200) in the present work, the intensity is more than two times as large as the lean laminar flame velocity for a methane-air mixture (0.12 m/s), which corresponds to the regime of corrugated flamelets. Our results suggest that the Taylor-Couette flow apparatus is useful to study the premixed-flame propagation in high intensity turbulent flow.

Key words
Taylor-Couette Flow, Turbulence Structure, Turbulence generation

1. Introduction
Earlier studies of flame propagation in turbulent flow have used fan-stirred chambers [1], stagnation-point burners [2,3], turbulent-jet burners [4], V-flame burners [5-7] and so on. Since using these flow configurations under uniform and steady conditions is difficult, a quantitatively good agreement of the experimental results with the theoretical results based on the assumptions of the homogeneity and the steadiness of turbulent properties cannot be obtained. For example, in stagnation-point, turbulent-jet, and V-flame burners, the turbulence properties are nonuniform along the flame-brush area due to the existing unsteady condition at the flame propagation front. In fan-stirred chambers, the turbulence properties are also nonuniform due to increasing temperature and pressure in the closed-volume chamber as the reaction advances. On the other hand, in a Taylor-Couette flow apparatus that consists of two rotating concentric cylinders, the mean and turbulence properties are independent of time and uniform upstream of the flame zone, and nearly homogeneous over half of the brush area. In addition, the intensity of turbulence may be controlled independently by the mean axial velocity and the mean flame propagation. The present study measures the turbulent characteristics of premixed flame propagation in the Taylor-Couette flow apparatus that consists of two rotating concentric cylinders to quantify the regime for the turbulent premixed combustion formed in the Taylor-Couette flow apparatus by investigating turbulence intensity, the autocorrelation function, the integral scale, power spectral density, the Taylor’s micro length scale and the Kolmogorov scale.

2. Experiment
Fig.1 shows a schematic of the Taylor-Couette flow apparatus, which consists of two rotating concentric cylinders with the top open to the atmosphere and the bottom closed. The inner cylinder is made of brass with 160 mm O.D. and the outer cylinder is made of Pyrex glass with 180 mm I.D. The annulus gap between the two concentric cylinders is 10 mm. Air enters through approximately 900 small holes at the bottom of the inner cylinder, and exits via the open top of the apparatus. The mixture is ignited at the top, and then an annular flame propagates downward, consuming the reactant. The cylinders are allowed to rotate independently in every direction using two motors of 0.75 kW at 1,800 rpm. The Taylor-Couette flow is formed in the annulus between the two independently rotating concentric cylinders, and different flow regimes are made by adjusting the relative cylinder rotation rate. In the present study we rotated only the inner cylinder. The Reynolds number Re is defined at cylinder speeds of 1,800, 3,600, 5,400, and 7,200 by Eq. (1):

$$Re = \frac{U_d D}{v}$$

Fig. 1 Taylor-Couette apparatus for turbulent flame propagation studies
$\text{Re}_L = \frac{(\Omega_0 r_0) d}{v}$  \hspace{1cm} (1)

where $\Omega_0$ is the angular rotation rate of the inner cylinder, $r_0$ is the radius of the inner cylinder, $d$ is the annulus width, and $v$ is the kinetic viscosity of the mixture. The axial flow is maintained at a constant velocity of 5 cm/s. The velocity fluctuations of the radial and circumferential components in the annulus are measured by hotwire anemometry recording 500,000 data with a sampling speed of 400 kHz.

3. Result and Discussion

Fig. 2 shows the intensity of the velocity fluctuations in the radial and circumferential components plotted versus the cylinder Reynolds number $\text{Re}_L$. The intensity of the circumferential component of the velocity fluctuation linearly increases as $\text{Re}_L$ increases, and the radial component is approximately constant and independent of $\text{Re}_L$. At the highest Reynolds number of 7,200, the intensity of the circumferential velocity fluctuation is more than two times as large as the laminar burning velocity for unstretched methane-air lean-burning laminar flame $S_L$ (0.10 m/s, equivalence ratio $\phi=0.60$).

Fig. 3 shows the variation of the autocorrelation functions $\langle u(t)u(t+\tau) \rangle$ in both the radial and circumferential components versus time $\tau$ at different the cylinder Reynolds numbers $\text{Re}_L$. The autocorrelation function $R(\tau)$ is defined in Eq. (2):

$$R(\tau) = \frac{1}{\langle u^2 \rangle} \lim_{T \to \infty} \frac{1}{T-\tau} \int_0^{T-\tau} u(t) u(t+\tau) dt ,$$  \hspace{1cm} (2)

where $\langle u(t) \rangle$ is the velocity fluctuation at time $t$, $u'$ is the turbulence intensity, and $T$ is the measurement time. As indicated by the arrow in Fig. 3, the autocorrelation curves show a steeper exponential decay as $\text{Re}_L$ increases. The slope of the curve for the radial component is longer than that for the circumferential component.

The integral time scale $L_t$ is estimated using the autocorrelation function, and defined in Eq. (3):

$$L_t = \int_0^\infty R(\tau) d\tau .$$  \hspace{1cm} (3)

Fig. 4 shows the integral time scales $L_t$ in the radial and circumferential components plotted versus the cylinder Reynolds numbers $\text{Re}_L$. The integral time scale of both components decreases as $\text{Re}_L$ increases.

The integral length scale $L_x$ is estimated using a statistical approximation of the Taylor’s hypothesis by Eq. (4):

$$L_x = \overline{U} L_t ,$$  \hspace{1cm} (4)

where $\overline{U}$ is the mean velocity. Fig. 5 shows the integral length scale $L_x$ in the radial and circumferential components plotted versus the cylinder Reynolds numbers $\text{Re}_L$. The integral length scale of the radial component is approximately constant. On the other hand, the integral length scale of the circumferential component decreases in the range $\text{Re}_L = 1,800$ to $3,600$, but it is nearly constant in the range where $\text{Re}_L$ is higher than $3,600$.

Fig. 6 shows an example of the power spectral density of the velocity fluctuation calculated from the present data of $\text{Re}_L = 5,400$.

The power spectral density of velocity fluctuation $P(f)$ is defined by Eq. (5):

$$u'^2 = \int_0^\infty P(f) df ,$$  \hspace{1cm} (5)
where \( f \) is the frequency. The power spectral density of velocity fluctuation \( P(f) \) is derived from Fourier analysis for the velocity fluctuations.

The Taylor’s micro scale \( \lambda_\mu \) is estimated using the power spectral density of the velocity fluctuation by Eq. (6):

\[
\frac{1}{\lambda_\mu^2} = \left( \frac{2 \pi}{U} \right)^2 \int_0^\infty f^2 P(f) df.
\] (6)

Fig. 7 shows the Taylor’s micro time scale \( \lambda_t \) in the radial and circumferential components plotted versus the cylinder Reynolds number \( Re_\Omega \). The Taylor’s micro time scale in which component is approximately constant. In the same way as in the integral scale, the Taylor’s micro length scales \( \lambda_x \) are estimated using a statistical approximation of the Taylor’s hypothesis by Eq. (7):

\[
\lambda_x = \bar{u} \lambda_t.
\] (7)

In Fig. 8, the Taylor’s micro length scales \( \lambda_x \) in the radial and circumferential components are plotted versus the cylinder Reynolds numbers \( Re_\Omega \). The Taylor’s micro length scale in the radial component is approximately constant. On the other hands, the Taylor’s micro length scale in the circumferential component linearly increased as \( Re_\Omega \) increased.

The Kolmogorov scale \( \eta \) is estimated using the Taylor’s micro length scale by Eq. (8),

\[
\eta = 15 \frac{1}{\lambda_x} \left( \frac{u'}{S_L \delta} \right)^{\frac{1}{3}},
\] (8)

where \( \delta \) is the laminar premixed flame thickness. The rate at which the kinetic energy is dissipated equals to the rate at which cascades from the large to the small eddies and the Kolmogorov scale represents the smallest scale of eddies. The flame structure is changed regardless whether the Kolmogorov scale is larger than the laminar premixed flame thickness. Fig. 9 shows the Kolmogorov scale \( \eta \) in the radial and circumferential components plotted versus...
the cylinder Reynolds number ReΩ.

The Kolmogorov scales in each component increase as ReΩ increases.

The turbulent premixed flame is influenced by such factors as the turbulence intensity and the length scale, the chemical properties of the reactant mixture and the strength of the flame-turbulence interaction. Various behaviors are indicated in the regime diagram for the turbulent premixed combustion. Fig. 10 shows Peters’ diagram [8] with the results of our present study by the dots within a circle. The experimental conditions are the regime of the corrugated flamelets. We only rotated the inner cylinder. If both the inner and outer cylinders are rotated, the experimental conditions may shift towards the regime of the thin reaction zones.

4. Summary and Conclusion

We measured the turbulence characteristics in the Taylor-Couette flow between two counter rotating concentric cylinders. The results suggest that this apparatus will be useful in future studies on turbulent premixed flame propagation in high intensity turbulent flow.

The intensity of the circumferential velocity fluctuation linearly increases as the Reynolds number ReΩ increases. At the highest Reynolds number, the intensity of the circumferential component of the velocity fluctuation is more than two times as large as the lean laminar flame velocity for the methane-air mixture, which corresponds to the regime of corrugated flamelets.

Nomenclature

- D Taylor Couette annulus width, m
- f frequency, Hz
- φ equivalence ratio, dimensionless
- η Kolmogorov scale, m
- Lt integral time scale, s
- Ll integral length scale, m
- λt Taylor’s micro time scale, s
- λx Taylor’s micro length scale, m
- ν kinetic viscosity, m²/s
- r0 inner cylinder radius, m
- ReΩ Reynolds number, dimensionless
- R(τ) autocorrelation function, dimensionless
- P(f) power spectral density function of velocity fluctuation, m²/s
- Sl laminar burning velocity, m/s
- U mean velocity, m/s
- u’ turbulence intensity, m/s
- u(t) velocity fluctuation at time t, m/s
- T measurement time, s
- t time, s
- τ time, s

References