Estimation of the turbulent Schmidt number in a model gas turbine combustor

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Abstract. This article presents the estimation of turbulent Schmidt number in a model gas turbine combustor. Different gases are used as the model fuel while maintaining the mass flow rate. The simplest closure models for Reynolds stress and turbulent flux are considered. The anisotropy of turbulent viscosity is demonstrated.

1. Introduction

The organization of flow swirling contributes to the flame stabilization and an increase in the efficiency of the burners [1]. Moreover, low emissions of the harmful substances are achieved using lean premixed combustion [2]. The main problem is the complexity of the processes occurring in the combustion chambers prevents from creation of optimal burners at the design stage. Thus, the experimental study of scalar transport and mixing is needed to validate numerical models which simplify the process of designing combustion chambers.

Particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF) methods are applied simultaneously to study the mixing process. This combination enables the measurements of velocity and concentration fields. The authors of [3] stated that large vortex structures and a precessing vortex core intensify the mixing process. Moreover, they noted that the precessing vortex core makes a significant contribution to flame stabilization. Work [4] reported on the investigation of mixing fuel with air for isothermal flow conditions in a gas-turbine premixer at atmospheric pressure by PLIF in water and PIV methods. In addition, the authors of [5] presented the estimation of the turbulent Schmidt number in a stirred tank from PIV and PLIF measurements. However, there is still a lack of experimental data on scalar transport and mixing in gas-turbine combustors.

The main goal of this investigation is to estimate the turbulent Schmidt number in a model gas turbine combustor for isothermal flow using simultaneous PIV and PLIF measurements. The focus is placed on simple closure models for Reynolds averaged momentum and scalar transport equations.

2. Experimental setup

The experiments were performed for a combustion chamber with optical access. The flow at atmospheric pressure without combustion was studied. The scheme of experimental setup is shown in figure 1. The inset shows the nozzle geometry. It consists of a radial vane swirler and a center-body. The main air was supplied through the radial vane swirler. The outer diameter of the radial vane swirler was 37 mm. A model fuel was injected through the central jet. The central jet diameter was 5.8 mm.

The flow was seeded with acetone vapor and TiO₂ particles to perform PLIF and PIV measurements. The flow rates were controlled by mass flow meters Bronkhorst High-Tech. The main air flow rate was
799 l/min. Methane, neon and air were used as model fuels in this work. Experiments were carried out at the constant mass flow rate of the fuel that was 0.65 g/s. The Reynolds number, based on the main air bulk velocity $U_0 = 12.8$ m/s, was $3 \times 10^4$.

**Figure 1.** The scheme of experimental setup.

The PLIF system contained a tunable pulsed dye laser Sirah Precision Scan, pumped by a pulsed Nd:YAG laser QuantaRay, and sCMOS camera LaVision, 5 Mpix, 16 bit, connected to a UV-sensitive image intensifier LaVision IRO, S20 photocathode. The acetone fluorescence was excited at the wavelength of 283 nm. The image intensifier was equipped with a set of optical filters which included Edmund Optics Multi-Notch filter and LaVision band-pass filter with 90% transmittance in the range of 415–455 nm. A part of the laser beam was reflected into a cuvette with Rhodamine 6G solution to account for the laser sheet nonuniformity. The fluorescence inside the cuvette was captured by a CCD camera ImperX Bobcat IGV-B4820, 16 Mpix, 12 bit.

The stereoscopic PIV system included double-pulsed Nd:YAG laser Quantel EverGreen 200, 532 nm and two CCD cameras ImperX Bobcat IGV-B2020, 4 Mpix, 8 bit. The cameras were equipped with the narrow-band optical filters that transmit the light at a wavelength of 532 nm. The laser beam was converted into a laser sheet using spherical and cylindrical lenses.

The PLIF data processing included several steps: a spatial sensitivity correction, a spatial calibration, a background signal removal, a laser sheet nonuniformity correction and an absorption correction. First, the spatial sensitivity of the camera detector was corrected using the white sheet of paper that was lit uniformly. Second, the calibration target was used for spatial calibration that included perspective transform and matching the PIV data grid. The background signal was captured when the laser illuminated the investigated plane without supplying air and fuel. The laser sheet nonuniformity was taken into account using the fluorescence signal from the cuvette. Moreover, the absorption of the laser sheet intensity by the acetone molecules was compensated according to the Beer–Lambert law for instantaneous snapshots by the algorithm similar to [6].

The PIV data were processed using an iterative cross-correlation algorithm. A final integration area size was $32 \times 32$ pixels. The overlap rate was 50%. A pair of two-component 2D velocity fields and a pair of calibration functions were used for the reconstruction of three-component 2D velocity field [7]. In-house “ActualFlow” software, developed at the Institute of Thermophysics SB RAS, was used to process the PIV data.
3. Results and discussion

Mean concentration and velocity fields were symmetrized according to the equation (1) and then reflected over the y axis to show the distributions in (x, y) coordinates.

\[
f(r) = \begin{cases} 
  \frac{f(x) + f(-x)}{2}, & \text{if } f(x) \text{ is symmetric} \\
  \frac{f(x) - f(-x)}{2}, & \text{if } f(x) \text{ is antisymmetric}
\end{cases}
\]

(1)

Figure 3 shows the mean velocity and concentration fields for three regimes. The recirculation zone is present. Due to the fact that mass flow rate is kept constant, the centerline velocity decreases with increasing density. This results in decreasing the value of \( y/D \) for the point where \( U_y = 0 \).

**Figure 2.** Mean concentration and velocity fields: a) methane; b) neon; c) air.

Figures 3 and 4 show the distributions of Reynolds shear stress and radial turbulent flux. The other components of Reynolds stress tensor and turbulent flux have been calculated but not shown here.

**Figure 3.** The distributions of Reynolds shear stress \( <u'u'_y> \): a) methane; b) neon; c) air.

**Figure 4.** The distributions of radial turbulent flux \( <u'\varepsilon'> \): a) methane; b) neon; c) air.
One of the closure models for Reynolds averaged momentum and scalar transport equations is the simplest gradient model for Reynolds stresses and turbulent fluxes. The components of turbulent viscosity are evaluated from the equations (2-4) [8].

\[
\begin{align*}
V_{r,12} &= -\frac{\langle u_i u_j \rangle}{\partial U_j / \partial r} \\
V_{r,13} &= -\frac{\langle u_i u_\psi \rangle}{\partial U_\psi / \partial y} \\
V_{r,23} &= -\frac{\langle u_i u_\phi \rangle}{r (\partial (U_\phi / r) / \partial r)}
\end{align*}
\]

Here \( \langle u_i u_j \rangle \) are the Reynolds shear stresses, \( U_j \) is the mean axial velocity component, and \( U_\psi \) is the mean angular velocity component.

According to the figure 5, the components of turbulent viscosity are not the same. This fact indicates the anisotropy of turbulent viscosity in swirling flows. Moreover, it may be assumed that using a single scalar value for the turbulent viscosity is not a good approximation. The use of turbulent viscosity tensor may be useful for improving the predictions of numerical models.

Figure 5. The turbulent viscosity components: methane (upper row); neon (middle row); air (lower row).
The turbulent diffusivity coefficient is calculated using the equation (5).

\[ D_{t,r} = -\frac{\langle u_r c' \rangle}{\partial C / \partial r} \]  

(5)

Here \( \langle u_r c' \rangle \) is the radial turbulent flux, \( C \) is the mean concentration.

Figure 6 demonstrates the turbulent diffusivity coefficient, calculated according to the gradient diffusion hypothesis. The axial component of the turbulent diffusivity coefficient is not calculated because the derivative of the concentration in axial direction contains the lines which could not be completely removed when correcting the laser sheet nonuniformity.

Finally, turbulent Schmidt number is estimated as (6).

\[ Sc_t = \frac{\nu_{t,12}}{D_{t,r}} \]  

(6)

The turbulent Schmidt number, calculated on the basis of the experimental data, is shown in figure 7. The values of Schmidt number are in the range from 0.4 to 1.2. These values are in a good agreement with the value widely used for numerical calculations.

**Conclusions**

In this paper, the PLIF and PIV measurements have been performed simultaneously to investigate the turbulent mixing in a model gas-turbine combustor. Three regimes with different gases used as the model fuel have been considered. The mean concentration and velocity fields have been obtained. The radial turbulent flux and the Reynolds stress tensor components have been calculated. The components of turbulent viscosity have been determined and analyzed. It has been concluded that the approximation with single scalar value of turbulent viscosity may be inaccurate. The turbulent diffusivity coefficient has been evaluated on the basis of gradient diffusion hypothesis. Turbulent Schmidt number has been estimated. The values of turbulent Schmidt number used for RANS simulations are in the range of the values obtained from the experimental data.
The results of this paper may be used to validate numerical models.

Acknowledgements
This research was supported by the Russian Science Foundation (grant No. 19-79-10225). The equipment is provided under state contract with IT SB RAS.

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