Small transparent prism for the cross-sectional visualization for a turbulent scalar mixing layer using a water-channel PLIF method

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Abstract. This study introduces a simple method that enables cross-sectional visualization in the measurement of the planar-laser induced fluorescence (PLIF) method. The concentration field of the high Schmidt number scalar mixing layer generated by grid-generated turbulence is measured by a water-channel experiment in this study. The high Schmidt scalar mixing layer is produced by Rhodamine B aqueous solution and water. A small transparent prism, installed on the outside wall of the test section, aids in applying cross-sectional visualization. The small transparent prism is an isosceles triangular shaped prism filled with the working fluid through the test section of the water channel. The setting and details of the small transparent prism are shown in this study. By using the small transparent prism, the concentration field on the plane set into the test section is shown as a result of the cross-sectional visualization. In this result, a scalar structure like a mushroom is visualized around the mixing interface of the scalar mixing layer, as found in a previous experiment.

1. Introduction

Incompressible turbulence [1] is often found in the flow of engineering equipment in the field of fluid engineering. An essential property of incompressible turbulence is the turbulent mixing of heat and mass [2]. In particular, the diffusion of the scalar quantity with a low diffusion coefficient value is produced by turbulent mixing, and a scalar quantity with a low diffusion coefficient is characterized as a high Schmidt numbers scalar. Concentration fluctuations characterized by a scale smaller than the smallest scale of the turbulent flow field are found in the high Schmidt scalar concentration fields. This study considers the importance of clarifying the phenomenon related to the turbulent mixing of high Schmidt scalar quantities.

The turbulent mixing of a high Schmidt number scalar has been approached as a high Schmidt number scalar mixing layer by previous experiments using a water channel [3-6]. The planer-laser-induced fluorescence (PLIF) method [7-11] is used to measure the concentration field of this scalar mixing layer. This scalar mixing layer, produced by grid-generated turbulence, is generated by a homogeneous, quasi-isotropic turbulence-generating grid [12]. Previous studies have measured the concentration field of turbulent plume produced from the wall of the turbulent boundary layer using the PLIF method [8-9]. The measurement error of the PLIF method is caused by various factors such
as quantum yield, laser intensity, and camera gain [3]. Methods for correcting these measurement errors have been used in previous studies using the PLIF method [3-5].

The PLIF method measures/visualizes the concentration field of the measurement targeted field as a two-dimensional plane field [3-5, 7-10]. In previous studies using the PLIF method, the two-dimensional plane field has been determined by the test section’s shape and the position of the set camera that measures the fluorescence of the dye. In previous research, a two-dimensional plane consisting of the main flow and the transverse directions has been set. In comparison, the number of previous studies that has measured/visualized a component in the direction normal to the two-dimensional plane, the spanwise direction has been smaller [12]. This study considers that the measurement of the concentration field, including the spanwise component, is needed to be facilitated.

The purpose of this study is to apply a simple method to visualize the concentration field of the high Schmidt scalar mixed layer, including the component in the spanwise direction. In this study, as in previous studies, the PLIF method is used for visualizing the high-Schmidt number concentration field. An additional experimental device having the shape of an isosceles triangle is used as a small transparent prism. The small transparent prism is made of acrylic plate and filled with a working fluid that flows through the test section. The instantaneous concentration field on the visualization plane, including the component of the spanwise direction set in the test section, is measured using the small transparent prism. The specific shape of the small transparent prism and the detailed application method are examined in this study. Then, the instantaneous concentration field of the high Schmidt number scalar-mixing layer is visualized using the PLIF method and the small transparent prism. The effectiveness of the small transparent prism is examined by using the observed visualization results.

2. Scalar mixing layer and PLIF method

2.1. Turbulent scalar mixing layer

In this study, a water channel installed at Nagoya University was used [3-6]. The working fluid in the water channel experiment was water. The test section of the water channel was 1500 mm in length in the streamwise direction, and the cross-section area of the test section was 10,000 mm² (100 × 100 mm²). The freestream was provided using two head tanks set in the upstream region. In addition, the working fluid passed through screens and the contraction part and flowed into the test section. The flow rate of the flowing fluid was measured using two electromagnetic flowmeters. A turbulence-generating grid was installed at the entrance of the test section. The coordinate system was composed of streamwise, vertical, and spanwise directions, which were indicated as x, y, and z directions, respectively. The origin of the coordinate system was located at the center of the plane on which the turbulence-generating grid was set. Here the freestream flows in the x direction. High Schmidt scalar is mainly turbulently diffused in the y direction. The water channel was the same as in previous studies [3-6]. A small transparent prism, described below, was set outside the test section.

A turbulence-generating grid generates decaying, homogeneous turbulence to provide a high-Schmidt number scalar mixing layer. The turbulence-generating grid installed at the entrance of the test section was the biplane type with a grid consisting of 3 mm round bars, and mesh, 20 mm wide. From the set values of the round bar diameter and the mesh width, the solidity σ was calculated as σ = 0.28. The grid-generated turbulence generated by the turbulence-generating grid decays in the streamwise direction and has a homogeneous quasi-isotropic nature [1]. The nature of decaying homogeneous turbulence used in this study is shown in previous studies [5]. In this study, the Reynolds number of the grid-generated turbulence was approximately 20.

The concentration field of the scalar mixing layer due to the decaying grid-generated turbulence was measured. The scalar mixing layer was given based on a high Schmidt number scalar. To set the scalar mixing layer, the inflow section up to the entrance of the test section was divided into two water channels.
Figure 1. Schematic figures of the small transparent prism. (a) overall view of the small transparent prism. (b) the small transparent prism set on the outside wall of the test section.

An aqueous solution of Rhodamine B, a fluorescent dye, and water passed through these two channels [7]. The present two channels with and without the dye have been set up vertically. Here the present value of the Schmidt number is comparable to that of previous studies [3, 6-8] and is considered to be about 2000. The flow rate values of both fluids were set using two electromagnetic flowmeters. The difference between the values of the flow rate through the water channels was negligibly small. The scalar mixing layer started to develop from the streamwise direction where the turbulence-generating grid was installed and continued to develop in the streamwise direction. The scalar mixing layer in this study was like those in previous studies.

2.2. PLIF measurement

In this experiment, the PLIF technique [7] was used. A continuous laser with the band wavelength set to 532 nm, a single-lens reflex camera (Nikon D700), and lens system (Nikkor 50 mm F/1.2S lens) were used to visualize the concentration field of the scalar mixing layer. A laser plane was constructed using the lens system from the continuous laser. The laser was used to excite the fluorescent dye that provided the concentration fields. The effective thickness of the laser plane was estimated to be about 0.5 mm. The thickness of the laser plane in this study is comparable to that in previous studies. This study also considers that the thickness of the laser plane does not affect the use of the small prism. The single-lens reflex camera measured the two-dimensional field of the laser-induced dye. The laser and the single-lens reflex camera used in the experiment in this study were similar to those used in previous studies to measure the concentration field of a high-Schmidt number scalar mixing layer [3-6].

The mesh Reynolds number \( \text{Re}_M \) characterized the flow of this experiment. The definition of the mesh Reynolds number \( \text{Re}_M \) is as follows: \( \text{Re}_M = \frac{U_o M}{v} \). \( U_o \) and \( M \) are the cross-sectional mean flow velocity calculated from the flow rate and the mesh width of the turbulence-generating grid, respectively, and \( v \) is the kinematic viscosity. The value of the mesh Reynolds number was set to 2500, which is equal to those of previous studies [3-5, 12]. To set the mesh Reynolds number in this experiment, the flow rate characterizing the bulk flow was established based on the obtained value of the kinematic viscosity. In the measurement using the single-lens reflex camera, ISO value was set to 400. The depth of bit in the captured RAW images was set to 14.
3. Results on the Cross-Sectional visualization using the small transparent prism

For the velocity field, there were three components. One of the components was taken as the direction of the freestream as in the previous experiment. The two directions normal to the direction of the freestream were a vertical direction and a spanwise direction. In previous studies, physical quantities were measured in a plane composed of the streamwise and vertical directions. In retrospect, the number of previous studies that measured components that included the spanwise direction, such as the spanwise component of the concentration, was seen to be smaller than those that measured the other two components. This study considered that measuring the spanwise component of the concentration field was more complicated than measuring the other two components. A small transparent prism was installed as a method to measure the spanwise component of the concentration easily. This study expected that using this small transparent prism can make it easier to measure the concentration component in the spanwise direction.

The schematic of the small, acrylic water prism used in this study is shown in Figure 1(a). As shown in the figure, the shape of the small transparent prism is an isosceles triangle. The bottom of the isosceles triangle is made of an acrylic plate. The height of this small transparent prism corresponds to the height of the test section in the water channel. The small transparent prism was filled with the same fluid as the working fluid in this water channel experiment. The acrylic plate constituting the small transparent prism was bonded so that the working fluid does not leak. An additional schematic of the small transparent prism installed on the sidewall surface of the test section is shown in Figure 1(b). As shown in the figure, the small transparent prism was installed such that the long side of the isosceles triangle contacted the outside wall of the test section. This small transparent prism can arbitrarily be installed in the test section. Therefore, by using this small transparent prism, the spanwise component can be measured at any position in the streamwise direction.

In Figure 2, a schematic for measuring a spanwise component using the small transparent prism is shown. As shown in the figure, the section to be measured, plane A, is located in the test section. The center of plane A was set to \( x/M = 20 \) in this experiment. In previous studies that measured the scalar mixed layer [3, 6], the focus on measuring was mainly paid to the position of the mainstream direction around this streamwise position to obtain turbulent statistics. Also, in contrast to the grid-generated turbulence behind the grid, at this position, the velocity fluctuation intensity is considered to be described by a decay law, as shown in previous works. Therefore, this measurement has focused on visualizing scalar structures around the position.
Figure 3. Drawings of the parts of which the small transparent prism is composed. The parts of the sidewalls of the small transparent prism are shown in A - C. In D, the bottom plate of the prism is shown. These parts of the prism are made of acrylic plates.

The small transparent prism was used to measure the instantaneous concentration field on plane A. Observed fluorescence measured by the single-lens reflex camera passed through the small transparent prism, which was the same as the working fluid in the test section. Thus, the difference in fluids in the test section and in the small transparent prism, which may affect the fluorescence measured by the camera, can be negligible. As shown, the axis of the fluorescence captured by the camera is normal to the plane to be observed. Detailed drawings of the small transparent prism are shown in Figure 3. As shown in the figure, the small transparent prism is composed of four parts. These parts are made of acrylic plate. The height of the small transparent prism was set on the outside width of the test section. This small transparent prism was filled with a fluid, which is the same as the working fluid passing through the test section. The shape of the joint parts between the plates is determined so that the working fluid does not leak from the small transparent prism. The thickness of the small prism wall may cause a slight displacement to the centerline of the targeted plane. In this case, the installation position in the streamwise direction may be slightly different between the laser plane and the camera. In this study, the laser plane is set at the position of the streamwise direction to be measured. Therefore, this study considers that the effect of the prism wall thickness can be ignored in this kind of experiment.
Figure 4. Visualization result of the instantaneous concentration two-dimensional field using the small transparent prism. This visualization result of the concentration field on plane A is shown.

A visualization result of the instantaneous concentration field using the small transparent prism is shown in Figure 4(a). The visualization result shown in the figure was obtained at the position of $x/M = 20$ in the streamwise direction. In addition, the width of the figure was equal to one side width of the cross-section in the test section. As shown in the figure, the instantaneous concentration field is clearly visualized by using the small transparent prism. If the small prism in this study is not used, this study has considered that cross-sectional measurements are impossible. In this case, by reflecting off the outer wall of the test section, unrequisite light is measured by the camera. Around the center of the observed instantaneous concentration field, there was a mixing interface of the scalar mixing layer. As shown in the figure, a scalar structure like a mushroom can be found around the mixing interface. A previous experiment has experimentally shown that a scalar structure resembling a mushroom was found around the mixing interface in a high Schmidt-number scalar mixing layer [6]. The visualization result of this study is qualitatively consistent with that of the previous experiment. Therefore, in this study, the visualization result, which agrees with the previous research, was obtained by using the small transparent prism.

4. Conclusions
The purpose of this study is to apply the small transparent prism as a simple method to visualize the spanwise component of the field of a high Schmidt scalar mixing layer. The instantaneous concentration field of the high Schmidt scalar mixing layer is measured using a PLIF method. The high Schmidt scalar mixing layer is developed in the test section of the water channel. In this study, the working fluid is set to water. A turbulence-generating grid is installed at the entrance of the test section to develop the present scalar mixed layer. In order to set the value of the given mesh Reynolds number, the flow rate is set using two electromagnetic flow meters based on the kinematic viscosity. This high Schmidt scalar-mixing layer is provided by using Rhodamine B aqueous solution and water.

The small transparent prism used in this study has the shape of an isosceles triangle. This small transparent prism is filled with the same fluid as the working fluid passing through the water channel. The small transparent prism is installed at any streamwise point with the long side of the isosceles triangle in contact with the outside wall of the test section. A single-lens reflex camera measures the fluorescence caused by the instantaneous concentration field on the measurement section set in the test section through this small transparent prism. By using this small transparent prism, the instantaneous concentration field of the high Schmidt number scalar mixing layer can be clearly visualized. In this visualization result, a scalar structure, which is mushroom-like, is clearly found around the mixing interface of the scalar mixing layer. The existence of the mushroom-like, scalar structure is qualitatively consistent with the visualization results obtained by a previous experiment.

The visualization results that were obtained by using the small transparent prism shown in this study can be transformed into instantaneous concentration fields using a known uniform concentration
field, as shown in previous studies. The necessity of conducting cross-sectional measurement in a water-channel experiment is considered to be significantly high. The small prism proposed in this study is very simple and very inexpensive to enable to conduct a cross-sectional measurement. This study has shown that the cross-sectional measurement can be realized using the present simple and inexpensive method in the measurement of the scalar mixing layer as a significant opportunity. As future work, the instantaneous concentration field can be calculated from the instantaneous concentration field obtained using the present method. In calculating the instantaneous concentration field, the data processing method used in the previous PLIF experiment is used to compensate for the time variations of quantum yield, laser intensity, and camera gain. The present isosceles triangular prism design can be changed accordingly if the plane to be visualized in the fluid flow is inclined at a different angle (other than π/4 set to the largest angle). Also, there is a possibility to visualize also the velocity field by means of particle image velocimetry with this proposed set-up using the present small transparent prism.

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