Experimental Study on Turbulent Flow and Mixing in Counter-Flow Type T-Junction*

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Abstract
An experimental study was conducted on turbulent flow and mixing in a counter-flow type T-junction. We measured the velocity and concentration fields simultaneously by combining PIV and PLIF. Special attention was directed to the concentration fluctuation near the channel wall, which might bring about the high-cycle thermal fatigue in case of mixing of hot and cold flows. The velocity ratio of the counter-channel flow to the main-channel flow was changed from 1.0 to 5.0. The fluorescent dye was mixed in the main-channel flow. The dominant structures of the fluctuating velocity and concentration fields that cause the concentration fluctuation near the channel wall were analyzed by POD. It was found that the concentration fluctuation near the channel wall was caused by the superposition of the spanwise wobbling motion of the mixing interface of two flows and the rotational oscillation of the flows.

Key words: Turbulent Mixing, T-Junction, Thermal Fatigue, PIV, PLIF, POD

1. Introduction

A T-junction in which two fluids with different velocities, temperatures, and/or concentrations are mixed turbulently is encountered in many industrial applications such as piping systems in plants, combustion chambers, and chemical reactors. Among these applications, the piping system in a nuclear power plant has many T-junctions in which two water flows with high and low temperatures meet at various velocity ratios. It is pointed out that a large temperature fluctuation of fluid that is caused by the mixing of hot and cold water hits the pipe wall and induces the high-cycle thermal fatigue of the structure around a T-junction\(^{(1)(2)}\). This phenomenon is called thermal striping and is an important issue for the safety design of the nuclear power plant.

The flow filed in the mixing T-junction has a complex unsteady three-dimensional structure, because the flow impingement, flow separation and reattachment, and longitudinal vortices coexist in it. Thus, the mechanism of thermal striping is also quite complex, and experimental and numerical researches have been carried out to date. In general, the mixing T-junctions are classified into two categories\(^{(1)(2)}\). One is the
cross-flow type channel, and the other is the counter-flow type channel. The investigations on turbulent mixing and thermal striping in a T-junction have been conducted so far mostly in the cross-flow type channels, in which hot and cold flows meet at right angles (3)-(7). On the other hand, with regard to the counter-flow type channels shown schematically in Fig. 1, the research has been mainly conducted for combustors (8)(9), but detailed flow and mixing characteristics and the relationship between the flow structure and the thermal striping are not clarified yet (10)(11).

With these points as background, we have conducted an experimental study on turbulent flow and mixing characteristics in the counter-flow type T-junction. The mixing channel is connected with the main and counter channels at right angles, and all of them have square cross sections. The test fluid is water. Reynolds number of the main-channel flow is kept at 3500, and the velocity ratio ($VR$) of the counter-channel flow to the main one is changed from 1.0 to 5.0. We have measured the velocity field by time-resolved PIV and the concentration field by time-resolved PLIF based on the analogy between the thermal and concentration fields. Simultaneous measurements of the velocity and concentration have been also carried out as appropriate by synchronizing PIV with PLIF. Special attention has been directed to the concentration (temperature) fluctuation near the channel wall that may induce the thermal fatigue around the T-junction. The analyses based on the proper orthogonal decomposition (POD) have been applied to the fluctuating velocity and concentration fields to extract the dominant flow structures that cause the concentration fluctuation near the channel wall.

Nomenclature

$a^{(k)}$: time-dependent coefficient of $k$th mode of POD (Eq. (1) and (2))
$C$: time-averaged concentration
$C_m$: $C$ in the main-channel flow before mixing
$c$: fluctuating component of concentration
$c'_{\text{rms}}$: RMS value of concentration fluctuation
$D$: hydraulic diameter of the test channel (= 60 mm)
$Re$: Reynolds number
$U$, $V$, $W$: time-averaged velocity component
$U_b$: bulk velocity in the mixing channel
$u$, $v$, $w$: fluctuating velocity component
$u'_{\text{rms}}$, $v'_{\text{rms}}$, $w'_{\text{rms}}$: RMS value of velocity fluctuation
$VR$: velocity ratio of counter to main channel flows
$X$, $Y$, $Z$: coordinate system (Fig. 1)
$\Phi^{(k)}$: eigenfunction of $k$th mode of POD (Eq. (1))

2. Experimental Apparatus and Procedure

Figure 1 shows the schematic diagram of the test channel and the camera arrangements. The mixing channel is connected with the main and the counter channels at right angles, and all of them have square cross sections of 60 mm $\times$ 60 mm (hydraulic diameter $D = 60$ mm). After flowing through settling chambers and developing channels, the flow in the main channel and that in the counter channel collide head-on at the T-junction. Since the lengths of the developing channels are $30D$, the flows that enter the T-junction are nearly fully developed. The origin of the coordinate system is at the center of the end wall; mean velocities $U$, $V$, $W$; and fluctuating velocities $u$, $v$, $w$ are defined as components in the $X$-, $Y$-, and $Z$-directions, respectively. The test fluid was isothermal water controlled at 25°C. Reynolds number of the main-channel flow was kept at 3500, and the velocity ratios ($VR$) of the counter-channel flow to the main flow were changed from 1.0 to 5.0. Due to the limitation of space, however, only the results for $VR = 3$ are presented in this paper, which
Figure 1 Experimental setup

represent the mixing phenomena observed for \( VR > 1 \).

We measured the velocity field by the time-resolved PIV with a digital high-speed video camera (Photon: FASTCAM-ultima1024) and a continuous YVO\(_4\) laser (Melles Griot: 85GLS 309). The fluid was seeded by Polyamide resin particles (diameter of the particles is about 50µm, density is 1.02 kg/m\(^3\)). The captured images were processed by the direct cross-correlation code with a three-point-Gaussian interpolation for the peak location determination with sub-pixel accuracy\(^{(12)}\). An own post-processing program was used to calculate the velocity distribution, to eliminate the spurious vectors, and to calculate the statistical flow properties. We also measured the concentration field, instead of the temperature field, by the time-resolved PLIF based on the analogy between the heat and mass transfer. A dilute solution of Rhodamine 6G (0.1mg/l) was used as a fluorescence tracer and it was supplied to the main channel flow (low velocity fluid for \( VR > 1 \)) only. Careful calibrations were conducted prior/posterior to each experiment run to account for the non-uniform distribution of the light intensity in the laser sheet\(^{(13)}\).

In addition to these individual measurements of the velocity and concentration fields, we measured them simultaneously by combining PIV and PLIF to clarify the spatio-temporal structure of the flow that induces the concentration fluctuation near the channel wall. As shown in Fig. 1, in the measurement in the \( Y-Z \) plane (cross-sectional plane of the mixing channel), a half mirror was arranged on the \( X \)-axis. In order to separate the scattering light and the fluorescence, an optical filter (sharp-cut filter) was attached in front of each camera lens. For the statistical analysis, the ensemble averages were computed based on about 4000 instantaneous fields. These data were normalized by the bulk velocity \( U_b \) in the mixing channel and by the mean concentration in main channel before the mixing \( C_{in} \) that corresponded to the initial concentration difference between two fluids.

3. Results and Discussion

3.1 Global characteristics of mean velocity and concentration fields

Before discussing the concentration fluctuation near the channel wall, the global characteristics of the flow and concentration fields in the mixing channel are briefly reviewed here\(^{(11)}\). Figure 2 shows the time-averaged velocity vectors measured in the symmetric plane of the channel (\( Z/D = 0 \)) for \( VR = 3 \). The flow from the counter channel with a larger momentum is separated at the edge of the T-junction, and a large reverse flow region (green region in the figure) is formed in the mixing channel along the wall in the counter-channel side (lower side in the figure). Due to the formation of this separation
bubble, the flow in the main-channel side (upper side) is accelerated near the entrance of the mixing channel, but the spanwise non-uniformity of the mean velocity distribution almost disappears near the end of the measuring section.

Figure 3 shows the contour map of the mean concentration $C/C_m$ obtained in $Z/D = 0$. Near the flow merging region ($0 < X/D < 1$), due to the larger momentum of the counter-channel flow with initially zero concentration, the mixing layer is formed in the main-channel side. In a further downstream region of $X/D = 5 ~ 8$, however, a relatively high concentration region appears in the counter-channel side. This reversal of the high concentration region suggests that the fluid with higher concentration (fluid in the main
channel) is transported to this region by the secondary flow.

Next, we show the distributions of the secondary flow vectors (upper figure) and the mean concentration distributions (lower figure) obtained at four cross sections in the mixing channel ($X/D = 1, 2, 3$ and $5$) in Fig. 4. It was confirmed that these results were symmetric with respect to the $Y$-axis. The impingement of two flows is clearly observed at $X/D = 1$, i.e., entrance of the mixing channel. At $X/D = 2$, a large longitudinal vortex rotating in the counter-clockwise direction is observed in the main-channel side (right-hand side of the figure). It is thought that this vortex is caused by the centrifugal force because the flow entering from the counter channel is bent sharply to the $X$-direction. Such a vortical structure and its generation mechanism are thought to be similar to those observed in a $90^\circ$ bend (14). At $X/D = 3$ and 5, the secondary flow proceeding toward the counter-channel side along the top wall is observed. Thus, it follows that the streamwise scale of the longitudinal vortex mentioned above is quite small (less than $1D$) in the present channel.

The secondary flows exert a direct influence on the mean concentration field. At $X/D = 1$ where the impingement of the main and counter flows occurs, $C/C_m$ is distributed almost uniformly in the $Z$-direction. In further downstream cross sections, the high concentration fluid in the main channel is transported by the secondary flow and the mixing layer develops toward the counter-channel side along the bottom wall of the channel. Thus, the concentration field shows three-dimensional characteristics. $C/C_m$ is almost uniform at $X/D = 5$, and a high concentration region appeared in the counter-channel side in a further downstream region as observed in Fig. 3. Such flow and mixing characteristics of $VR = 3$ are qualitative similar to those observed under all the velocity ratios of $VR > 2$ in this study.

### 3.2 Turbulence intensities

The distributions of intensities of the fluctuating velocity components $u'/U_b$ and $v'/U_b$ measured in $Z/D = 0$ are shown in Figs. 5(a) and 5(b), respectively. The streamwise velocity component $u'$ shows very large values along the shear layer of the reverse flow region that is formed on the channel wall in the counter-channel side. On the other hand, the spanwise component $v'$ has two peaks; one is observed in the above-mentioned shear layer around the separation bubble, and the other appears along the mixing layer observed in Fig. 3. It is estimated that the latter is caused by the wobbling motion of the mixing interface of the main and counter flows. Details are discussed later in this paper.

Figure 6 shows the concentration fluctuation $c'/C_m$. The values of $c'$ attain the maximum in the mixing layer, thus it follows that this high $c'$ region is closely related to the high $v'$ region shown in Fig. 5(b). It is found that $c'$ becomes very large in the vicinity of the sidewall in the main-channel side (upper side in the figure) near the T-junction, and this suggests that the thermal fatigue can occur at this location in case of mixing of hot and cold fluids. In order to examine the detailed distributions of $c'$ in this region, we have measured $c'$ in the plane near the sidewall in the main-channel side, i.e., at $Y/D = 0.45$ (3 mm away from the channel wall) just after the T-junction. Figure 7 shows the result. $c'/C_m$ shows quite large values over the whole region of the measurement, and attains the maximum value ($= 0.43$) at $X/D = 1.5$ on the spanwise centerline ($Z/D = 0$). In the next section, we examine the mechanism of the occurrence of this large concentration fluctuation based on the proper orthogonal decomposition (POD) analysis.

### 3.3 Proper Orthogonal Decomposition (POD)

In this study, the proper orthogonal decomposition (POD) analysis has been applied to the fluctuating velocity and concentration fields to extract dominant structures that bring about large $c'$ near the sidewall of the channel. The outline of the direct POD used in this study is explained here. In PIV (PLIF), instantaneous velocity (concentration) can be measured simultaneously at $M$ positions in space and $N$ points in time (a set of $N$ “snapshots”). Here we define $f(x, t)$ as a fluctuating velocity or concentration in a finite
spatial domain $S$, and $f(x, t)$ can be expanded into a finite series of $M$ orthogonal eigenfunctions $\Phi^{(k)}(x)$ with time-dependent coefficients $a^{(k)}(t)$ as follows.

$$f(x, t) = \sum_{k=1}^{M} a^{(k)}(t)\Phi^{(k)}(x)$$

(1)

$$a^{(k)}(t) = \int f(x, t)\Phi^{(k)}(x)dx$$

(2)

The eigenfunction $\Phi^{(k)}(x)$, which represents the spatial structure of the fluctuating velocity (concentration) field, is obtained as a solution of the following integral equation.

$$\int R(x, x')\Phi^{(k)}(x')dx' = \lambda^{(k)}\Phi^{(k)}(x)$$

(3)

$R(x, x')$ is the two-point spatial correlation matrix defined below, and $\lambda^{(k)}$ is the eigenvalue of the $k$th mode that is ordered in a decreasing order as $\lambda^{(1)} > \lambda^{(2)} > \lambda^{(3)} > \ldots > 0$. The
superscript $k$ denotes the eigenmode ($k = 1, 2, 3, \ldots M$):

$$R(x, x') = \frac{1}{N} \sum_{i=1}^{N} f(x, t_i) f(x', t_i)$$

The total “energy” of $f(x, t)$, denoted as $E$ and defined below, captured in the POD is defined as the sum of all the eigenvalues.

$$E = \int \left( \int f^2 (x, t) dx \right) dt = \sum_{k=1}^{M} \lambda^{(k)}$$

The contribution ratio made by the $k$th mode to the total energy, $E_k$, is given by the following equation.

$$E_k = \frac{\lambda^{(k)}}{\sum_{k=1}^{M} \lambda^{(k)}}$$

Thus, it follows that the structure expressed by the lower mode has larger contribution to the total energy. This means that a dominant structure of the fluctuating velocity or concentration field can be reconstructed by several lower modes extracted by the POD analysis. In the following sections, we show the results of the analyses that are applied to the fluctuating velocity and concentration fields, and make clear the mechanism that causes high concentration fluctuation near the channel sidewall.

### 3.4 POD analyses of fluctuating concentration field

At first, we have applied the POD analysis to the instantaneous fluctuating concentration field ($c$) measured at $Y/D = 0.45$, the RMS contours of which are shown in Fig. 7. Figures 8(a) and 8(b) show the contour maps of the eigenfunctions of POD for the first and the second modes ($\Phi^{(1)}(x)$ and $\Phi^{(2)}(x)$), respectively. The contribution ratios of the first and second modes to the total “energy” of $c$ in the measuring section are about 16% and 10%, respectively. It is found that the first mode shows positive values over the most part of the measuring section, while the second mode shows the antisymmetric distribution with respect to the centerline of the wall $Z/D = 0$. These results can be interpreted as follows. The first mode shows a large scale fluctuation of the concentration that varies from positive to negative (and negative to positive) in time uniformly in space. The second mode means that when the instantaneous fluctuating concentration $c$ is positive in the upper half of the section ($Z/D > 0$), it is negative in the lower half, and vice versa.

![Figure 8 Distributions of eigenfunctions for $c$ near the channel sidewall ($Y/D = 0.45$)](image-url)
This suggests that the high concentration fluid (main-channel flow) comes to the upper and lower parts of the near-wall region alternately in time.

Next, we have made the POD analysis on the fluctuating concentration field measured in the cross section at $X/D = 1.5$, in which $c'/C_m$ attains the maximum in the near-wall plane as shown in Fig. 7. As described later, the fluctuating concentration $c$ analyzed here was measured simultaneously with the cross-planar fluctuating velocity components $v$ and $w$. Figure 9 shows the contour map of $c'/C_m$ and Fig. 10 shows the distributions of the eigenfunctions (the first and second modes). The results are consistent with those shown in Fig. 8. That is, the first mode shows the symmetric distribution with respect to the plane of $Z/D = 0$, while the second mode shows the antisymmetric distribution. In order to elucidate the mechanism that causes these structures of the fluctuating concentration field, we have made the POD analyses on the fluctuating velocity field and the results are discussed in the next section.

3.5 POD analyses of fluctuating velocity field

As described so far, it has been found that the large $c'$ observed near the channel wall is caused by the superposition of two representative structures. In order to elucidate the mechanism that makes these structures of the concentration field, we have analyzed the flow field in the cross section at $X/D = 1.5$ by POD. In this analysis, we used the instantaneous fluctuating velocities $v$ and $w$ measured simultaneously with the concentration $c$ to make clear the relationship between the instantaneous structures of the flow and concentration fields.

At first, the results of RMS of $v$ and $w$, i.e., $v'/U_b$ and $w'/U_b$, are presented in Fig. 11; $v$ is the horizontal component in the figure, and $w$ is the vertical one. $v'$ shows large values near the sidewalls in both the main-channel side (right-hand side in the figure) and the counter-channel side (left-hand side). The former corresponds to the mixing layer of two flows, and the latter reflects the shear layer around the reverse flow region. It is understood that the high $v'$ region in the main-channel side is closely related to the large $c'$ now concerned. The distribution of $w'$ is qualitatively similar to that of $v'$, but the high $w'$ region in the main-channel side moves closer to the channel wall.

Next, we show the results of the POD analyses. At first, we show the distributions of the eigenfunctions of the first mode for $v$ and $w$ ($\Phi_v^{(1)}(x)$ and $\Phi_w^{(1)}(x)$) in Figs. 12(a) and 12(b), respectively. The distribution of $\Phi_v^{(1)}(x)$ is qualitatively similar to that of $\Phi_c^{(1)}(x)$ shown in Fig. 10(a) except that the sign is reversed. This result confirms that the concentration fluctuation near the channel wall is closely related to the mass transfer by the fluctuating velocity component $v$. $\Phi_w^{(1)}(x)$ shows quite different characteristics; it shows an antisymmetric distribution with respect to the $Y$-axis, and a couple of counter-sign regions appears in each half cross section.
Based on these results, we have reconstructed the typical instantaneous velocity vectors and concentration distributions using the time constants with positive and negative values. Figure 13 shows the examples of the reconstructed fields. It should be noted that in these figures the time-averaged components of velocity and concentration are added to the reconstructed fluctuating components to approximate the real instantaneous fields.
From these results, it is understood that the concentration fluctuation near the sidewall of the mixing channel is caused by the wobbling motion of the counter-channel flow in the $y$- (spanwise) direction. When the counter-channel flow with higher velocity and lower concentration moves to the main-channel side (right-hand side in the figure), the main-channel flow with higher concentration is pushed out to the top and bottom corners symmetrically (Fig. 13(a) with negative time-dependent coefficients). The main-channel flow then returns to the region near the $y$-axis when the counter-channel flow moves left (Fig. 13(b) with positive coefficients). These flows cause the concentration fluctuation near the channel wall in the main-channel side, which corresponds to the first mode of $c$ shown in Figs. 8(a) and 10(a).

Next the eigenfunctions of the second mode $\Phi_v^{(2)}(x)$ and $\Phi_w^{(2)}(x)$ are shown in Fig. 14(a) and 14(b), respectively. Similar to the first mode, the eigenfunction for $v$ ($\Phi_v^{(2)}(x)$) shows qualitatively similar distribution to $\Phi_v^{(1)}(x)$ shown in Fig. 10(b) and the sign is reversed. It is remarkable that in $\Phi_w^{(2)}(x)$ the regions with significant values appear not only in the main-channel side but also in the counter-channel side (left-hand side in the figure). As observed in Figs. 2 and 11, large $w'$ in the counter-channel side is caused by the flow separation at the edge of the T-junction. These distributions of $w'$ and $\Phi_w^{(2)}(x)$
suggest that the large velocity fluctuation \( w' \) observed near the wall in the main-channel side in Fig. 11(b) is partially caused in relation to the flow separation in the counter-channel side.

The reconstructed instantaneous velocity vectors and concentration distribution are shown in Fig. 15. These results suggest that the concentration fluctuation in the main-channel side is caused by the rotational oscillation of the main-channel flow. That is, when the counter-channel flow with lower concentration moves to the lower part in the main-channel side, the main-channel flow with higher concentration is pushed out to the upper part, and vice versa. This flow structure causes the vertically antisymmetric distributions of \( \Phi^{(1)}(x) \) and \( \Phi^{(2)}(x) \). In the concentration fluctuation measured at \( X/D = 1.5 \), the contribution ratios of the first and second modes to the total “energy” of \( c \) are about 32% and 15%, respectively, and the distributions of the eigenfunctions are consistent with those obtained near the channel wall (\( Y/D = 0.45 \)). Thus, it follows that the large concentration fluctuation observed near the wall in the main-channel side is mainly caused by the superposition of the spanwise wobbling motion and the rotational oscillation of the flows.

4. Concluding Remarks

An experimental study has been made on turbulent flow and mixing in a counter-flow type T-junction. The main-channel flow (higher concentration and lower velocity) collides with the counter-channel flow (lower concentration and higher velocity) in the T-junction with the velocity ratio of 3. Simultaneous measurements of velocity and concentration fields have been conducted using PIV and PLIF. A special attention has been directed to the concentration (temperature) fluctuation near the channel wall, which may cause the high cycle thermal fatigue in case of the mixing of hot and cold flows.

It has been found that the concentration fluctuation shows quite high values near the sidewall in the main-channel side just after the T-junction. By POD analysis of the fluctuating velocity and concentration fields, the mechanism of this high concentration fluctuation near the channel wall has been investigated. It is mainly caused by the superposition of two representative flow structures. One is the spanwise wobbling motion of the counter-channel flow and resulting vertically symmetric oscillation of the main-channel flow. The other is the rotational oscillation of the main-channel flow that is caused by the vertically asymmetric movement of the counter-channel flow. The former makes a vertically symmetric pattern of the fluctuating concentration field, while the latter makes an antisymmetric pattern. The concentration fluctuation caused by these two flow structures makes up about 50% of total concentration fluctuation near the sidewall of the channel.

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