Drag Reduction of T-junction Pipe Flow by Small Obstacles

Toshitake ANDO**, Toshihiko SHAKOUCHI**, Kensuke NISHIBATA** and Koichi TSUJIMOTO**

** Graduate School of Engineering, Mie University
Kurimamachiya-cho 1577, Tsu-shi, Mie 514–8507, Japan
E-mail: ando@mach.mie-u.ac.jp

Abstract
Flows in the T-junction of a counter-flow pipe are run counter to each other and they usually flow out vertically together. A flow separated from the junction corner forms separated vortex regions and they reduce the effective cross-sectional areas of the pipe, and this increases flow resistance, i.e., drag (pressure loss). The corner of the junction is generally rounded to prevent the flow from separating and to reduce drag. This method can reduce drag by 30% with a rounded radius of 0.1D (D: pipe inner diameter), but some process is needed to remove the corners. We propose a simple method of reducing drag in the flows of T-junction pipes by mounting two small weir-shaped obstacles on the upstream of the walls of the two pipes beside the junction corners. This method is a simple way of reducing drag without having to use a removal process. The pressure distribution along the pipes was measured and the drag in a T-junction pipe was derived. The flow pattern was visualized with a tracer method and this was evaluated to confirm the separation of flow from the corners. As a result, we clarified that drag in a T-junction could be reduced by a maximum of about 30% by mounting small obstacles at heights of 0.30D and 0.47D from the upstream of the corners.

Key words: T-junction Pipe, Flow Separation, Flow Control, Drag Reduction

1. Introduction

T-junction pipes [Fig. 1(a)], which are frequently used in many industrial facilities cause problems such as flow resistance or non-uniform mixing of two fluids. Asano et al. investigated the mixing of two fluids that had different temperatures in a vertical T-junction(1). Hibara et al. investigated flow patterns in a T-junction that consisted of a rectangular main pipe and a small circular branch pipe(2), and they then controlled the mixing of two fluids by using a turbulent promoter(3). Nakayama et al. clarified the flow and thermal characteristics of flows

Fig. 1 Flow model of T-junction
(a) Without small obstacles
(b) With small obstacles

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in a counter-flow T-junction that consisted of rectangular pipes of the same size\(^{(4)}\).

The guide vane or mesh is generally mounted or the corners of a junction are rounded to reduce the flow resistance (drag) in these kinds of flows. To reduce flow resistance in ducts or pipes with making abrupt changes to cross-sectional areas, simple obstacles have been mounted on their inner walls in some studies. Mochizuki et al. reduced the flow resistance in the 90\(^{\circ}\) bend of a circular pipe by mounting a half trip on the pipe wall\(^{(5)}\). The authors clarified that the flow resistance in abrupt contractions of circular pipes and pipe inlets could be reduced by mounting small obstacles near the corner to suppress the vortex region\(^{(6)}\)–\(^{(9)}\).

We investigated the flow characteristics and the pressure distribution of a counter-flow T-junction pipe that had circular cross sections of the same size, and we reduced flow resistance by mounting small weir-shaped obstacles [Fig. 1(b)] on the pipe wall. We expected that the flow resistance in the T-junction would be reduced, because we expected the separated flow could be made to flow along the wall of pipe 3 and the vortex regions on this wall would decrease. The authors examined various positions and heights of small obstacles to find combinations of these that would minimize flow resistance. In addition, we visualized flow patterns to clarify what effect small obstacles had on flow patterns.

2. Nomenclature

\[ \begin{align*}
C_p & : \text{pressure coefficient } (=2p/(\rho U_1^2)) \\
D & : \text{pipe diameter } (= 30\text{mm}) \\
H & : \text{height of small obstacles } [\text{Fig. 1 (b)}] \\
i & : \text{pipe number } (i = 1, 2, 3) \\
L & : \text{position of small obstacle } [\text{Fig. 1 (b)}] \\
p & : \text{pressure} \\
p_0 & : \text{reference pressure} \\
Q_i & : \text{flow rate in pipe } i \\
Re & : \text{Reynolds number } (= DU_i/\nu) \\
U_i & : \text{mean velocity in pipe } i \\
W & : \text{width of small obstacle } [\text{Fig. 1 (b)}] \\
x & : \text{position along the center line of pipe } 3 \ [\text{Fig. 1 (a)}] \\
y & : \text{position along the center line of pipe } 1 \text{ and } 2 \ [\text{Fig. 1 (a)}] \ \\
\alpha & : \text{flow rate ratio } (= Q_1/Q_3 = 1 - Q_2/Q_3) \\
\zeta & : \text{pressure loss factor of T-junction } (= \alpha \zeta_{13} + (1 - \alpha) \zeta_{23}) \\
\zeta_{13} & : \text{pressure loss factor between pipe } 1 \text{ and } 3 \\
\zeta_{23} & : \text{pressure loss factor between pipe } 2 \text{ and } 3 \\
\lambda_i & : \text{friction factor of pipe } i \\
\nu & : \text{kinematic viscosity} \\
\rho & : \text{density}
\end{align*} \]

3. Experimental Set Up and Procedure

3.1. Experimental set up

3.1.1. Outline Figure 2 has a schematic of the experimental set up. The water in the reservoir (1) was pressurized by the pump (2), divided into two flows, controlled by the valve (3), measured with the flow meter (4), and introduced into the test section (5). The test section (5) was made of transparent acrylic resin, consisting of three straight pipes that had circular cross sections with a diameter of \( D = 30\text{mm} \) and it was placed horizontally. Pipes 1 and 2 had a length of \( 53D \) and they had a flow straightener at their inlets. Water that flowed out from pipe 3 flowed back to the reservoir (1) after the junction. The surplus water was back to the reservoir (1) after passing through not the test section (5) but bypass (10). Many pressure holes that were 0.6 mm in diameter were at the mid-height of the test section enabling the pressure distribution along the pipes to be measured. The pressure taps were set along the segment of \((x, y) = (-0.5D, y)\) for pipe 1 and 2 and the segment of \((x, y) = (x, -0.5D)\) for pipe 3. The pressure was measured as the difference in pressure at \( y/D = -27.93 \) (without small obstacles) with a reversed U-shape manometer (6). Fluorescent dye (water solution of fluorescence sodium) (7) and a laser light sheet from laser oscillator (8) and its optics (9) were used to visualize the flow.

3.1.2. Details of test section Figure 3 gives details on the T-junction with a small obstacle. The T-junction was formed by boring two orthogonal oriented holes in a thick flange of acrylic resin. A flange with a built-in obstacle whose thickness was \( W = 3\text{mm} \) and a spacer flange made of aluminum were placed between the T-junction and flange of the pipe. Flanges
with built-in obstacles and the number or thickness of spacer flanges was changed to alter obstacle height $H$ and place $L$. The obstacles were placed symmetrically in this study. The T-junction without small obstacles was made of three acrylic resin circular pipes.

3.1.3. Test section for visualizing flow  
Obstacles in the built-in flanges in the T-junction described in the previous section obstructed light and prevented inner flows from being observed. Many pressure taps in the T-junction without small obstacles at the mid-height of the pipe also obstructed light in the flows. For these reasons, other T-junctions were manufactured to enable the flow to be visualized. The T-junctions for visualization were formed by boring two orthogonal oriented holes in the thick plate of the acrylic resin. These holes were bored so that the $x$-$y$ plane was orthogonal to the thickness of the plate. As the outer pipe walls were flat, there was little distortion in the images of the visualized flow patterns for the shape of the T-junction as previously described. T-junctions of this type were made both with and without small obstacles. The latter junction had small obstacles of $(L/D, H/D) = (0.47, 0.30)$, which minimized flow resistance for $\alpha = 0.5$. Fluorescent dye was infused into the test section from taps at the position of $|y| = 30$[mm]. The flow pattern on the plane at center height ($x$-$y$ plane)
visualized with a laser light sheet was recorded with a digital video camera.

3.2. Experimental conditions and definition of pressure loss factor

3.2.1. Reynolds number and flow rate ratio

The Reynolds number was defined as follows:

\[ Re = \frac{DU_3}{\nu} \]

where \( U_3 \) is the mean velocity in pipe 3 and \( \nu \) is the kinematic viscosity of the water. The Reynolds number is basically \( Re = 1.0 \times 10^5 \) except \( 3.0 \times 10^3 \) for the visualization of the flow.

The flow rate in pipe 3, \( Q_3 \), equals the sum of the ones in pipes 1 and 2, \( Q_1 + Q_2 \), and flow rate ratios \( \alpha_1, \alpha_2 \) are defined as follows:

\[ \alpha = \alpha_1 = \frac{Q_1}{Q_3} = 1 - \frac{Q_2}{Q_3} = 1 - \alpha_2 \]

Flow rate ratio \( \alpha \) was changed between 0.5 and 1.

3.2.2. Definition of pressure loss factor

The pressure distribution in the T-junction of a counter-flow pipe is outlined in Fig. 4. The horizontal axis means the position, \( x/D \), \( y/D \) (see Fig. 1) and the vertical axis means the pressure coefficient, \( C_p = 2(p - p_0)/(\rho U_3^2) \) (\( p_0 \): reference pressure. \( y_1, y_2, \) and \( x_3 \): positions in pipes 1, 2 and 3. \( U_3 \): mean velocity in pipe 3. \( \rho \): density)

The non-dimensional form of the equation for energy conservation between pipes \( i \) (\( i = 1, 2 \)) and 3 is as follows:

\[ \alpha^2 + C_{pi} = 1 + C_{p3} + \lambda_i \frac{y_i}{D} + \lambda_3 \frac{x_3}{D} + \zeta_3, \]

where \( C_{pi} \) is the pressure coefficient in pipe \( i \), \( \lambda_i \) is the friction factor of pipe \( i \), and \( \zeta_3 \) is the pressure loss factor between pipes \( i \) (\( i = 1, 2 \)) and 3. The non-dimensional pressure and the following equations, indicate the non-dimensional gradients of linear pressure distribution in pipes 1–3 are:

\[ C_{pi} = \lambda_i \frac{y_i^2}{D} + C_{p0} \quad (i = 1, 2) \]

\[ C_{p3} = -\lambda_3 \frac{x_3}{D} + C_{p30}, \]

where \( C_{p0} \) (\( i = 1–3 \)) is the intercept of the linear pressure distribution in pipe \( i \) on the vertical axis (Fig. 4). Friction factor \( \lambda \) can be calculated by using Brasius’ equation; hence, the pressure gradients in pipes 1–3 can be calculated by:

\[ \frac{dC_{pi}}{d(y_i)} = \text{sgn}(y_i) \lambda_i \alpha_i^2 \]
\[ dC_{p3} = -A_3 = -0.3164Re^{-\frac{4}{3}} \]  

The pressure gradients obtained in the experiment are then compared with those obtained with these equations. Equations (4) and (5) are substituted into Eq. (3) to obtain:

\[ \zeta_{13} = \Delta C_{p13} - (1 - \alpha^2) \]  

\[ \zeta_{23} = \Delta C_{p23} - (2\alpha - \alpha^2), \]  

where \( \Delta C_{p3} = C_{p0} - C_{p30} \) (i = 1, 2; see Fig. 4).

From the sum of products of \( Q_i \rho U_3^2 / 2 \) and Eq. (3) for \( i = 1 \) and 2, the relationship between the power loss of T-junction \( Q_3\zeta\rho U_3^2 / 2 \) and \( \zeta_i \) (i = 1, 2) is derived, and then \( \zeta \) is described as:

\[ \zeta = \alpha\zeta_{13} + (1 - \alpha)\zeta_{23} \]  

The purpose of this study was to reduce this value, \( \zeta \).

3.2.3. Measurement of pressure distribution

The relative pressure to reference pressure \( p_0 \) was measured by using a reversed U-shaped manometer. The pressure distribution downstream of the T-junction was basically measured in the region of \( x/D < 30 \), whose pressure gradient was larger than the value of Brasius’ equation Eq. (7) by a constant percentage of about 15%. However, as the pressure loss factors were calculated by using this region, the authors assumed that the relative magnitude of pressure-loss factors had not changed. The pressure loss factor, \( \zeta \), for particular conditions was calculated by using a pressure distribution, which was also measured for the region of \( x/D < 50 \). The pressure loss factor calculated by using the former region (\( x/D < 30 \)) is expressed with prime sign “′”.

4. Results and Discussion

4.1. Equal flow rate

4.1.1. Pressure distribution and loss

The diamonds ♦ in Fig. 5 plot the pressure distributions for an equal flow rate ratio (\( \alpha = 0.5 \)) and that without small obstacles. The pressure distribution in the region in front of the junction was symmetric about the vertical axis. In addition, the pressure decreased linearly with decreasing \(|y/D|\) in the region of \(|y/D| > 2\). Near the junction (\(|y/D| < 2\)), the pressure took a large value because of the collision of the two flows approaching the junction, and then pressure took a maximal value of \( C_{p} = -0.02 \) at \( y/D = 0 \). After junction \( x/D > 7 \), the pressure gradients became almost constant and took \(-0.0205\) in the region of \( 8 < x/D < 28 \) and \(-0.0177\) in \( 33 < x/D < 53 \). The latter value agrees with Brasius’ equation (6). The pressure loss factor of the junction is \( \zeta = 0.63 \) and this value agrees with the general value for this kind of flow(40).

\[ \zeta = 0.3164\text{sgn}(y_i)\alpha_i^{\frac{7}{3}}Re^{-\frac{4}{3}} \quad (i = 1, 2) \]  

\[ \frac{dC_{p3}}{d\left(\frac{x}{D}\right)} = -A_3 = -0.3164Re^{-\frac{4}{3}} \]  

Fig. 5  Pressure distribution (\( \alpha = 0.5, L/D = 0.47 \))
4.1.2. Visualized flow pattern Figure 6 shows the visualized flow that separated from the corner of the junction. Reynolds number Re is $3.0 \times 10^3$ here. The flow from pipes 1 and 2 to pipe 3 oscillated, and the image was roughly selected at the moment there was an average flow pattern. The flows separated from the corners of the T-junction flowed to the center line of pipe 3 and formed significant vortex regions on the wall of pipe 3. Thus, the effective cross-sectional area of the flow decreased, and the flow resistance of the T-junction increased.

4.1.3. Effects of small obstacles

(a) Pressure distribution Figure 5 plots the effect of obstacle height $H/D$ on pressure distribution for the obstacle position of $L/D = 0.47$. However, small obstacles did not affect the linear pressure distribution in pipes 1 or 2, but small obstacles reduced the pressure near the junction ($|y/D| < 2$). The pressure in pipe 3 increased with increasing $H/D$ in the region of $H/D \leq 0.30$ and decreased with increasing $H/D$ in the region of $H/D > 0.30$. The gradient of the linear pressure distribution in pipe 3 did not change.

(b) Flow resistance, drag Figure 7 plots the effect of obstacle position $L$ and height $H$ on pressure loss factor $\zeta'$, which was calculated from the pressure distribution. There is a minimal value of $\zeta'$ for each condition of $L/D$. Pressure loss factor $\zeta'$ takes a minimal value for $(L/D, H/D) = (0.47, 0.30)$ for the equal flow rate ($\alpha = 0.5$). By additionally measuring the pressure distribution in the region of $x/D < 50$, we clarified that pressure loss factor $\zeta$ was 0.44.
and the reduction rate of flow resistance \((\zeta_0 - \zeta)/\zeta_0\) was about 30%.

(c) Flow pattern  The visualized flow pattern for \(\alpha = 0.5\) and \((L/D, H/D) = (0.47, 0.30)\), which minimize the flow resistance for \(\alpha = 0.5\) and \(Re = 1.0 \times 10^5\) is shown in Fig. 6(b). We found that separated flows from the corner of small obstacles flowed in a direction that was closer to the wall of pipe 3 than for the case without small obstacles. We thought that qualitatively same phenomena arose as the case of \(Re = 1.0 \times 10^5\) and the effective cross-sectional area of the inlet of pipe 3 was increased by mounting small obstacles, and then the flow resistance of the junction was reduced.

4.2. Effects of flow rate ratio, \(\alpha\)

Section 4.1 clarified the components of the position and height of small obstacles that minimized flow resistance at equal flow rates. This section explains the range of flow rate ratios, \(\alpha\), for which flow resistance can be reduced by small obstacles under this condition \((L/D, H/D) = (0.47, 0.30)\).

4.2.1. Pressure distribution  Figure 8 plots the effect of flow rate ratio \(\alpha\) on pressure distribution. The flow rates in pipes 1 \((Q_1)\) and 2 \((Q_2)\) approach those in pipe 3 \(Q_3\) and zero with increasing \(\alpha\), respectively. Thus, the gradient of linear pressure distribution in pipe 1 approaches that of pipe 3 with increasing \(\alpha\). However, the one in pipe 2 approaches zero, and pressure coefficient \(C_p\) increases up to 0.14 with increasing \(\alpha\). In pipe 3, the gradient of the linear pressure distribution has not changed because of constant flow rate \(Q_3\), but the pressure has decreased with increasing \(\alpha\).

Fig. 8  Effect of \(\alpha\) on pressure distribution

(a) Without small obstacles  (b) With small obstacle \((H/D=0.30, L/D=0.47)\)

Fig. 9  Visualized flow pattern \((Re = 3.0 \times 10^3, \alpha = 0.8)\)
There was a region of low pressure in pipe 3 near the junction \((x/D < 5)\), especially for \(\alpha = 1\). There seemed to be a large vortex region that caused large flow resistance on the side of pipe 1 on the wall of pipe 3.

### 4.2.2. Flow pattern

When flow rate ratio \(\alpha\) increased, separated flow from the corner on the side of pipe 1 flowed nearer the opposite wall and formed a larger vortex region on the wall of pipe 3 on the side of pipe 1. Separated flow, on the other hand, from the corner on the side of pipe 2 flowed along the wall of pipe 3. Figure 9(a) shows the visualized flow pattern for \(\alpha = 0.8\) as an example of the high flow rate ratio.

### 4.2.3. Effects of small obstacles

**(a) Pressure distribution**

Figures 10 and 11 plot the pressure distribution for flow rate ratios of \(\alpha = 0.8\) for the former and 1 for the latter. In these figures, the open circles and diamonds \(\circ\) and \(\Diamond\) plot the results with obstacles of \((L/D, H/D) = (0.47, 0.30)\) and those without small obstacles, respectively. The pressure distribution in pipe 1 was not affected by small obstacles except near the junction whose pressure was reduced by mounting a small obstacle. However, the pressure distribution in pipe 2 decreased by mounting small obstacles of \(H/D = 3.0\), especially for \(\alpha = 1.0\), that did not make the flow resistance of the T-junction much smaller [Eq. (10)]. The pressure in pipe 3 decreased by mounting a small obstacle for \(\alpha = 1\).

**(b) Flow resistance**

Figure 12 plots the effect of flow rate ratio \(\alpha\) on pressure loss factor \(\zeta''\). Regardless of the presence or non-presence of small obstacles, \(\zeta''\) increased with increasing flow rate ratio \(\alpha\). In the region of \(\alpha \leq 0.8\), \(\zeta''\) was reduced by mounting small obstacles.
obstacles, but the difference decreased with increasing $\alpha$. In the region of $\alpha > 0.9$, $\zeta$ was increased by mounting small obstacles. Additional measurements of pressure distribution in the region of $33 < x/D < 53$ were carried out under these conditions with small obstacles to estimate pressure loss factors $\zeta$ and their reduction rate $(\zeta_0 - \zeta)/\zeta_0$. The open circles ◦ in Fig. 13 plot the results. The reduction rate took a maximum of 30% at $\alpha = 0.5$, decreased with increasing $\alpha$, and took a negative value for $\alpha = 1.0$. The region of $\alpha$ in which small obstacles of $(L/D, H/D) = (0.47, 0.30)$ could reduce the flow resistance of the T-junction was about $0.5 \leq \alpha < 0.9$.

(c) Flow pattern 
Figure 9(b) shows the visualized flow pattern for the flow rate ratio, $\alpha = 0.8$, with small obstacles of $(L/D, H/D) = (0.47, 0.30)$. When the small obstacles were mounted, turbulence in the inlet of pipe 3 was increased, but separated flow from the corner of the obstacle in pipe 1 flowed near the wall in pipe 3 on the opposite side. We thought that small obstacles under these condition could not reduce flow resistance, because the obstacle did not decrease the vortex region.

4.3. High flow rate ratio

The authors investigated another condition for obstacles in which the flow rate ratio ($\alpha \geq 0.8$) could not reduce the flow resistance of the T-junction due to small obstacles of $(L/D, H/D) = (0.47, 0.30)$.

4.3.1. Pressure distribution 
Figures 10 and 11 plot the pressure distributions for flow rate ratios $\alpha = 0.8$ and 1. The positions of small obstacle $L/D$ are both 0.47. However the...
pressure in the whole region in pipe 2 decreased with increasing $H/D$ in both cases, this did not affect significantly the flow resistance of T-junction. The pressure in pipe 3 took a maximal value for $H/D=0.25$ (□ in Fig. 10) and 0.20 (○ in Fig. 10) for flow rate ratios of $\alpha=0.8$ and 1, respectively.

4.3.2. Flow resistance

Figures 14 and 15 plot the pressure loss factor $\zeta'$ for $\alpha=0.8$ and 1. The conditions that minimized $\zeta'$ were $(L/D,H/D)=(0.47,0.25)$ for $\alpha=0.8$ and $(0.47,0.20)$ for 1. However, obstacle height $H/D$ that minimized $\zeta'$ became smaller, and obstacle position $L/D$ that minimized $\zeta'$ did not change when flow rate ratio $\alpha$ was increased.

Additional measurements of pressure distributions in the region of $x/D<50$ were carried out under these conditions with small obstacles to estimate pressure loss factors $\zeta$ and their reduction rate $(\zeta_0-\zeta)/\zeta_0$. The closed triangles and squares ▲ and ■ in Fig. 13 plot the results. We clarified that the flow resistances could be reduced by a maximum of 13% and 10% for flow rate ratios of $\alpha=0.8$ and 1.0, which could not be achieved without small obstacles.

5. Conclusion

We clarified that drag in a T-junction pipe could be reduced by mounting small weir-shaped obstacles on pipe walls upstream of the corner. The four major results are discussed below.

(1) Small obstacles that minimized flow resistance had a height of $H/D=0.3$ and were placed at $L/D=0.47$ for the equal flow rate ratio ($\alpha=0.5$). The obstacles under these conditions reduced flow resistance by about 30% because the separated flows from the obstacles
flowed along the wall in pipe 3.

(2) The pressure loss factor, $\zeta$, increased with increasing flow rate ratio, $\alpha$. When $\alpha$ was increased, the separation vortex region on the wall in pipe 3 on the side of pipe 1 whose flow rate $Q$ was larger increased and the other one decreased. The latter vortex region was almost suppressed for the high flow rate ratio.

(3) For $(L/D, H/D) = (0.47, 0.30)$, the reduction rate in flow resistance was decreased with increasing $\alpha$. For the high flow rate ratio, the flow resistance was not reduced by mounting small obstacles under these conditions. Flow resistance increased by about 12%, especially for $\alpha = 1$.

(4) The conditions that created minimal flow resistance for $\alpha = 0.8$ were $(L/D, H/D) = (0.47, 0.25)$ and 1 for $(0.47, 0.20)$, and obstacle position $L/D$ was not changed. In the latter, the reduction rate of flow resistance was about 10%.

References


