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Secondary Flow Behaviour in Various Rounded-Edge Bifurcation T-Junctions and Its Relation to Head Loss†

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Visualization of secondary flow behavior were carried out for the laminar flow ($\mathrm{Re} = 81$) in a sharp-edged and rounded-edged $90°$ T-junction with an inlet flow perpendicular to both inline outlet flows orientation with a bifurcation ratio of 0.5. Particles were added to the fluid. The fluid was salt solution for density similarity with the particles, leading to eliminate the bouyance effect. Static pressures were measured at the inlet and one of the outlet channels by a U-manometer. The result shows that the rounded edge affected the recirculation secondary flow area and position leading to the reduction of the head loss. The image of the secondary flow demonstrates that a T-junction with the rounded edge with a rounded-edge radius ratio of 0.5 had a broader bifurcation area and a smaller secondary flow occupation area in the outlet channel, as compared to the sharp edge. The decreasing head loss ratio was $51\ \%$. At rounded-edge radius ratio of 0 up to 1.5 part of secondary flow was located in the bifurcation area and the outlet area, whereas at rounded-edge radius ratio of 2 and of 2.5 it was located completely within the bifurcation area. Changing rounded-edge radius ratio from 1.5 to 2 reduced the head loss ratio up to $49.72\ \%$.

* * *

Nomenclature

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R	radius of pipe [mm];
H	height [mm];
W	width [mm];
$\mathrm{AR} = H/W$	aspect ratio [-];
ρ	density [$\mathrm{kg/m^3}$];
ν	dynamic viscosity [$\mathrm{m^2/s}$];
P	pressure head [$\mathrm{mm_{fluid}}$];
Q	flow rate [ml/s];
$R_{\mathrm{ER}} = r/H$	rounded edge ratio [-];
H_L	head loss [mm];
K_L	coefficient of losses [-];
D_h	hydraulic diameter [m];
V_{average}	fluid flow average [m/s].

Introduction

T-junctions are fittings that commonly used for industrial systems and water distribution networks, either as flow separators or flow mergers. Flow disturbance created by fittings and accessories cause head loss, which is directly proportional to the extra energy dissipation [2]. The flow in a 90-degree T-junction experiences huge disturbance which creates separation and recirculation causing a huge loss of energy. Therefore, an efort for improvement should be done to reduce the energy cost.

Flow separation is strongly influenced by Re, the surface roughness and the shape of flow surface. It is difficult to predict where the point of flow separation will occur, except for sharp corners. When a fluid separates from the body at a separation point, a separated region will be formed, where the secondary flow (recirculating flow) and backflow occur, starting from the separation point up to the reattachment point. The larger the separated region, the larger the head losses [1]. Giving a radius in the turn of 90° T-junctions can reduce head losses, but the behaviour of the separation flow depends on the flow rate ratio, the outlet to the inlet diameter ratio and the flow regime [9]. The changing area and position of secondary flow have not been fully understood and documented, which was the motivation to conduct the present research.

The available information about fluid flow behaviour in 90° T-junctions is very limited and the available comparison sources are less than expected. This fluid flow is very complex, three-dimensional and not accessible to any simplified theoretical analysis. The secondary flow and head loss behaviour, whose value can change very significantly, depend on the orientation of the flow and the value of the bifurcation ratio, namely the output flow rate divided by the input flow rate (β). In the simulation with an flow input channel perpendicular to both the inline output channels and similar to the channel area, there are at least two secondary flows. When $\beta = 0.5$, both the secondary flows are symmetric and similar in dimension and shape, located at the early part of the output channel, where separation points are exactly on both the edges and the reattachment point depends on Reynolds number, Re [5]. This flow orientation with $\beta = 0.5$ produces the smallest head losses among the others [5, 11]. In $\beta = 0.9$ there are three and four secondary flows in $\mathrm{Re} = 1000$ and 2000 [11]. In the flow orientation, there are also six symmetric recirculation flows for the area ratio 3 with $\beta = 0.5$ and $\mathrm{Re} \geq 600$ [10].

Rounded corners lead to higher turbulence which result in a shorter, thinner and weaker recirculation flow region. A rounded corner ($r = 3$ mm) in a circular channel T-junction ($R = 30$ mm) significantly reduces head losses [3]. When the input flow orientation is in line with the output channel and perpendicular to other output channels, a rounded corner with $r/R = 0.1$ decreases the energy losses up to $20\ \%$. The increased turbulence diffuses momentum more efficiently thus reducing the length or the recirculation area by $25\ \%$ [9]. At present, the flow behaviour and the amount of decreasing head losses occurring to a T-junction with larger rounded corner $(r/R > 0.1)$ is still not much known yet.

A secondary flow visualization in T-junction is rarely presented. The experiment conducted by Mathioulakis et al. [8] shows the visualization of two secondary flows in a T-junction with the orientation of input flow in a straight channel and the output flows in straight and branch channels with $\beta = 50\ \%$, $\mathrm{Re} = 1200$. Currently, there is no reference available on twin secondary flow visualization with input and channel orientation perpendicular to both output channels.

This present study aims to experimentally investigate the behaviour of the secondary flow in sharp-edged and rounded-edged T-junctions. The flow orientation is the input flow perpendicular to both the output channels and with a bifurcation ratio $\beta = 0.5$ that has the smallest head loss. The laminar flow behaviour in sharp-edged and rounded-edged 90° T-junctions is investigated in detail.

1. Methods

1.1. Experiment apparatus. The main experiment apparatuses were an upper fluid tank, a T-junction, valves, a measuring cup, a bottom fluid reservoir, and a pump, which were arranged as in Fig. 1. The experiment was conducted with the fluid height difference between the surface level of the upper fluid tank and the surface level at the centre of the T-junction of $3500\ \mathrm{mm}$. The height difference of the centre of T-junction and the surface level of lower tank fluid surface was $250\ \mathrm{mm}$. Both height differences were always maintained constant. The fluid circulation was produced by flowing fluid from the lower tank to the upper tank by using a $200\ Wt$ water-pump with a maximum water discharge of $6800\ \mathrm{l/hr}$ and the maximum head was $5.5\ \mathrm{m}$.

The fluid entered T-junction from the bottom of vertical channel and flows out from two output channels on the sides. Both the output flows were in line but with an opposite direction and perpendicular to the inlet flow. The length of the input channel was $190\ \mathrm{mm}$ and that of each output channel was $220\ \mathrm{mm}$ (Fig. 2). The input channel was set to be quite long to ensure the flow to be uniformed and to be fully developed in the bifurcation area. The length of this input channel met the entry length requirement suggested by Goldstein and Kreid [6], which was $0.09\mathrm{Re}$ for a square-shaped-section channel. Two air rejectors were installed in the end (outer part) of the output channel to remove the air trapped in the channel in the starting process. A regulated valve was installed after both outlet channels to control the flow rate entering the T-junction. Other balancing valves were installed after each air ejector to balance the outlet flow rate to maintain the bifurcation ratio $\beta = 0.5$.

The experiment apparatuses were six T-junction channels with different bend radii: 0, 10, 20, 30, 40 and $50\ \mathrm{mm}$ respectively given codes as R00 (sharp bend), R10, R20, R30, R40 and R50 (Fig. 3). The aspect ratio, AR of the straight outlets and inlets channels was 10, defined as the ratio of height $(H = 20\ \mathrm{mm})$ to width $(W = 2\ \mathrm{mm})$, and the cross sectional area $(H \times W)$ was $20\ \mathrm{mm} \times 2\ \mathrm{mm}$. This AR value met the requirement to make two dimensional flows (the minimum AR value was 7), as suggested by Dean [4] and Launder et al. [7]. The straight inlet channel and straight outlet channels were connected by a bifurcation channel. This channel was transparent so that the light source illuminated all parts of the channels for the flow visualization.

1.2. Visualization technique. The working fluid was water added with specially-treated particles to allow the observation of the flow pattern in the channel. To make the visualization

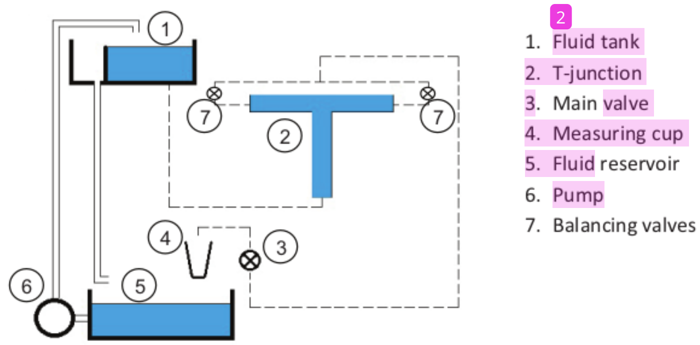

Fig. 1. The scheme of the devices arrangement.

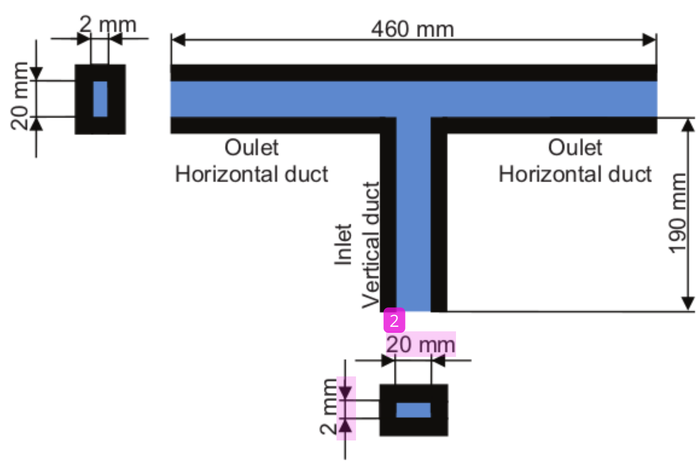

Fig. 2. Main dimension of T-junction.

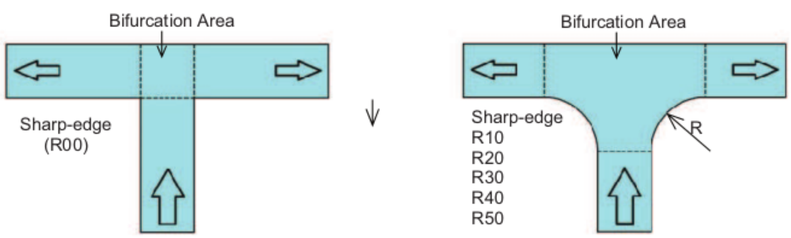

Fig. 3. T-Junction channel shapes, bifurcation area and flow directions.

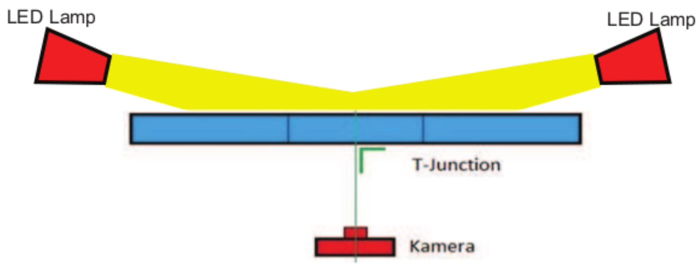

Fig. 4. Camera and T-junction position (plan view).

possible, the water density was made similar to the particle density by salt solution to eliminate the buoyancy effect. The addition of salt solution increases the density of water to $1235\ \mathrm{kg/m^3}$. The particles for the flow visualization were hair glitter cosmetic accessories, with a density of $1270\ \mathrm{kg/m^3}$. The particles were between 100 and 200 meshes in size. The fluid density was estimated by measuring the volume and weight of the fluid. The hair glitter cosmetic accessory density measurement was conducted by measuring the weight and volume of the glitter. Fluid viscosity (μ) measurement was conducted by using the drop ball viscometer method. The length of the vertical path of viscometer was $900\ \mathrm{mm}$. The ball used for the measurement was a $3\ \mathrm{mm}$ diameter steel ball. The falling time was measured with a digital stopwatch and a digital high speed camera (FUJI Series FINEPIX F600 EXR with a maximum speed of 320 frames per second).

The lighting allowed convenient observation of the fluid flow and excellent flow pattern images. The experiment used two lighting sources. Both lighting sources were set in the end of the outlet, $23\ \mathrm{cm}$ from the centre line, in the opposite side of the camera (Fig. 4). The light sources were two daylight type beam led-lamps with a power of $1\ \mathrm{Wt}$ $(3.2\ \mathrm{V}, 0.31\ \mathrm{A})$ each. The electric power supply for the led-lamp units was $220\ \mathrm{V}$.

The image of the flow pattern in the T-junction was recorded with a NIKON D3200 series camera, applying various speed shutters (1/25, 1/30 and 1/40). The camera was set in ASA 3200 with brightness of +0.7 with an automatic aperture. The flow images were captured at a distance of $30\ \mathrm{cm}$ from the T-junction with a position focused on the bifurcation area as shown in Fig. 4 The movie of flow pattern was also recorded with another FUJI, FINEPIX F600 EXR series camera.

1.3. Pressure drop measurement. The pressure drop was measured by two pressure taps with a hole diameter of $2\ \mathrm{mm}$. The pressure taps were connected to a U-manometer; P_i was the pressure measured in the input section and P_o was pressure measured in the output section. P_i and P_o were measured $70\ \mathrm{mm}$ away from the horizontal axis of the output channel and $220\ \mathrm{mm}$ from the centre axis of the inlet duct. These locations were more than sufficient to the minimum entry length requirement. The flow rate measurement was conducted by measuring the fluid volume coming out from both outlets at a certain time interval.

2. Results and Discussion

2.1. Head losses (H_L) and coefficient of losses (K_L). The relation between the flow rate Q and the head loss hL in the sharp-edged and rounded-edged T-junctions are shown in Fig. 5 and Table 1. The radius of a rounded edge is expressed by non-dimensional parameter R_{ER} (rounded-edge radius ratio). The R_{ER} is the radius of the rounded-edge T-junction divided by the height of

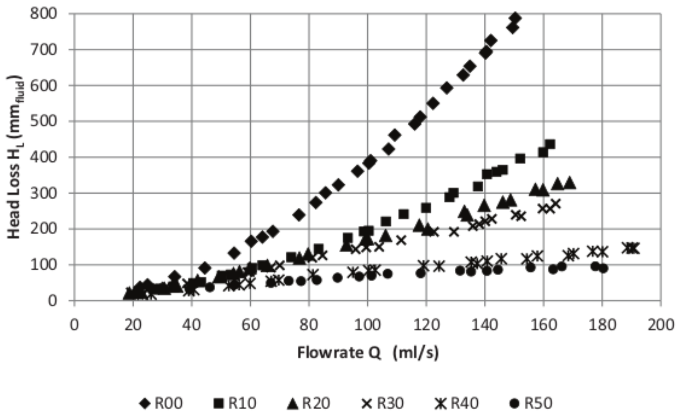

Fig. 5. Head loss Δh versus flow rate Q.

Table 1.
Head loss equations

R_{ER}	Equation	R^2
0.0	$H_L = 0.027Q^2 + 1.005Q$	0.999
0.5	$H_L = 0.011Q^2 + 0.787Q$	0.999
1.0	$H_L = 0.003Q^2 + 1.176Q$	0.997
1.5	$H_L = 0.001Q^2 + 1.239Q$	0.998
2.0	$H_L = -0.000Q^2 + 0.838Q$	0.995
2.5	$H_L = -0.002Q^2 + 0.894Q$	0.992

the channel (20 mm). The head loss increases following the quadratic equation of flow-rates at all rounded edge radii as presented in Table 1. As shown in Fig. 5, an increased rounded-edge radius reduces the head loss. The head loss of $R_{\mathrm{ER}} = 0$ to 1.5 increases with a positive coefficient of Q^2 whereas that at $R_{\mathrm{ER}} = 2$ to 2.5 it increases with a negative coefficient of Q^2. This shows that when the rounded-edge radius is larger, the positive coefficient of the square component becomes smaller and tends to turn into negative above $R_{\mathrm{ER}} = 1.5$.

Naturally, in any fluid flow, the head losses are the combination of minor losses caused by the flow disturbance and major losses due to friction. The experiment results suggest that minor losses have more dominant influence than the major losses. The equations in Table 1 show that the first components (quadratic components) of the right-hand terms of the head loss equations give a more significant curvilinear change than the second components. In other words, consecutively the first and second components are the representatives of minor losses and major losses.

The head loss decreases significantly from $R_{\mathrm{ER}} = 0$ to 0.5 and 1.5 to 2 (Fig. 5). The equation in Table 1 shows that the coefficient of the first components of the right-hand terms of head loss equation decreases almost one third from $R_{\mathrm{ER}} = 0$ to 0.5, from 0.5 to 1, or from 1 to 1.5. This indicates that the significant decrease in head loss from $R_{\mathrm{ER}} = 0$ to 0.5 is caused by the fact that the decrease in minor losses induces the reduction of the major losses represented by the coefficient of

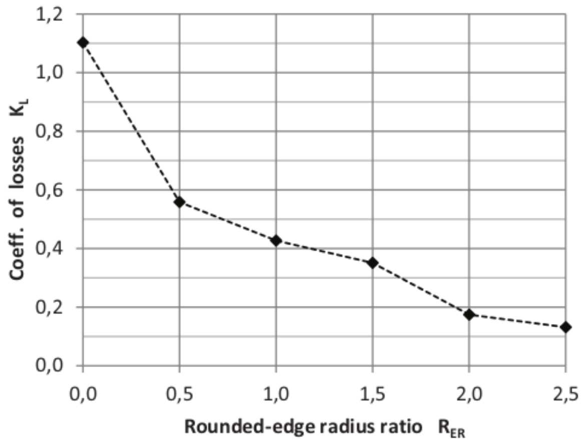

Fig. 6. The relationship between Coeff. of losses and the R_{ER}.

the second term. A similar phenomenon occurs in the reduction of the head losses from $R_{\mathrm{ER}} = 1.5$ to 2 in which the coefficient of the first component changes to negative. This means that the minor disturbance becomes gain of energy for the flow which also induces the reduction of major losses represented in the coefficient of the second term.

Fig. 6 shows the coefficient of losses (K_L) at various rounded-edge radii for the flow-rate around 140 milliliter/second. In this flow-rate, the Reynolds number ($\mathrm{Re} = V_{\mathrm{average}} D_h/\nu$) is around 81. Fluid density (ρ) is $1235\ \mathrm{kg/m^3}$. The average flow velocity (V_{average}) is obtained from the inlet flow-rate divided by the cross-sectional inlet channel area, which is $20\ \mathrm{mm} \times 2\ \mathrm{mm}$. The hydraulic diameter for rectangular channel is estimated as $D_h = 2HW/(H + W)$, the kinematic viscosity of the fluid (ν) is $0.142007\ \mathrm{m^2/s}$. Considering the Re, then the inlet flow is a laminar flow regime. K_L is estimated as $K_L = 2H_L g/V^2_{\mathrm{average}}$. The gravitational acceleration $g = 9.81\ \mathrm{m/s^2}$. The equation shows that H_L is directly proportional to K_L. Fig. 6 shows that the largest decrease in the head loss occurs from $R_{\mathrm{ER}} = 0$ to 0.5 and then from $R_{\mathrm{ER}} = 1.5$ to 2. This is because of the reduction in the first coefficient from $R_{\mathrm{ER}} = 1.5$ to 2 shown in Table 1 is higher than one third.

The influence of a rounded-edge radius ratio towards a sharp bend ($R_{\mathrm{ER}} = 0$) is observed more clearly using the K_L ratio, which is obtained from the K_L to K_L in $R_{\mathrm{ER}} = 0$ (K_L is R00) ratio as shown in Fig. 7.

The lowest K_L ratio is 12 $\%$ in $R_{\mathrm{ER}} = 2.5$ (Fig. 7). The reduced K_L ratio is significant in two radius changes at $R_{\mathrm{ER}} = 0$ to 0.5 and 1.5 to 2 because the reduced value is only about half of it. Compared to a sharp bend ($R_{\mathrm{ER}} = 0$), $R_{\mathrm{ER}} = 0.5$ leads to more reduction of the K_L ratio, which also means that it reduces the H_L ratio as much as $50.65\ \%$. Compared to $R_{\mathrm{ER}} = 3$, R_{ER} 4.0 reduces the K_L ratio as much as $49.72\ \%$.

Fig. 8 shows the contribution of the change of the K_L ratio. The contribution of the change is obtained from the K_L ratio difference. Based on the figure, it is clearly seen that compared to $R_{\mathrm{ER}} = 0$ and 1.5, the rounded-edge $R_{\mathrm{ER}} = 0.5$ and 2 resulted in more significant pressure drop effects (49.35 and $50.28\ \%$). Both of them give contribution effects twice as much and more than

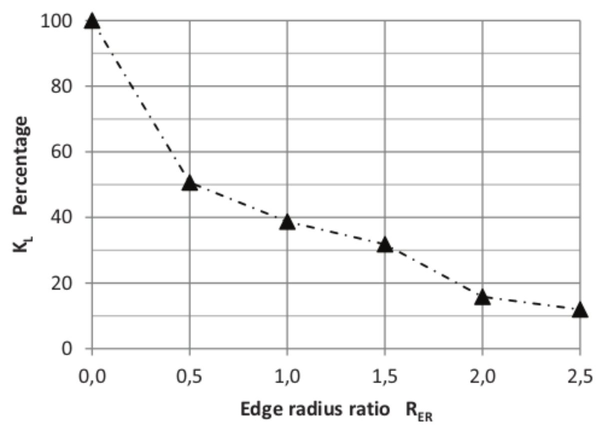

Fig. 7. The loss change percentage versus the R_{ER}.

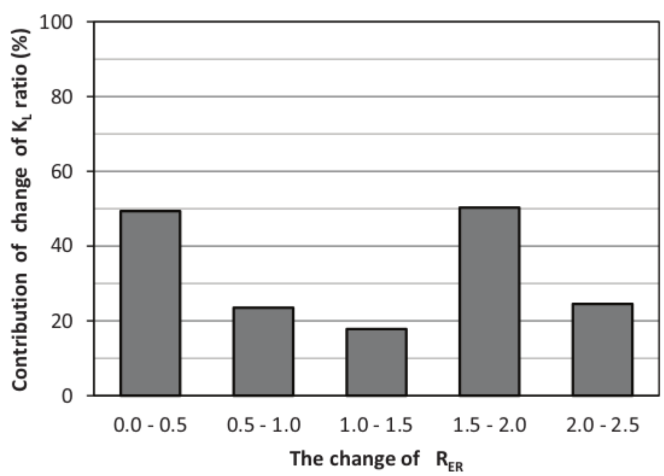

Fig. 8. Contribution of the K_L change and the R_{ER} change.

the others.

2.2. Secondary flow: T-junction flow pattern. The flow pattern was observed by setting the flow rate at around $140\ \mathrm{ml/s}$ in accordance with the Re of around 81. The observation was focused on the recirculation flow or secondary flow which started from the separation point until the reattachment point.

Fig. 9 shows the symmetric recirculation flows. The secondary flow which always appears in any T-junction geometry shows that there is always flow disturbance which causes losses in the

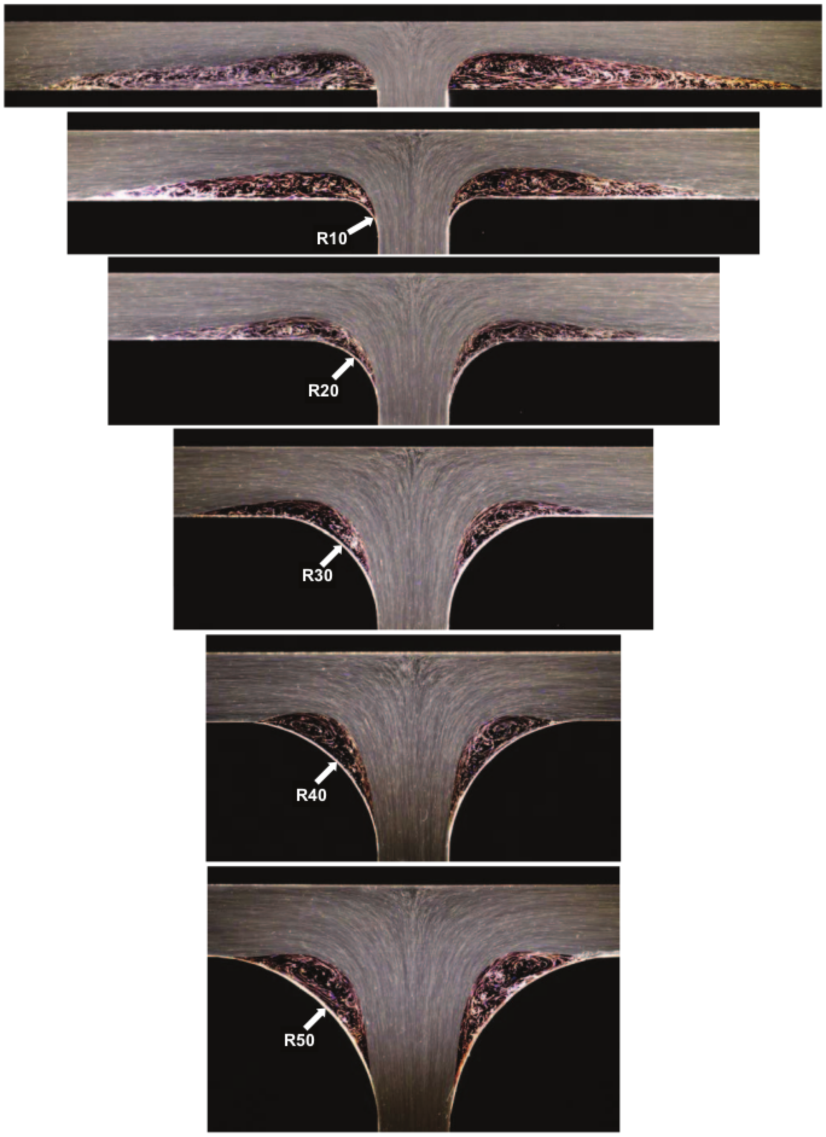

Fig. 9. Fluid flow pattern in various rounded-edge radius.

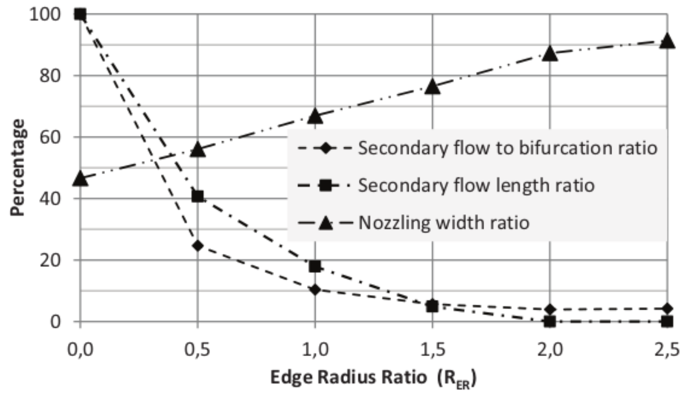

Fig. 10. Non-Dimensional Parameter and R_{ER}.

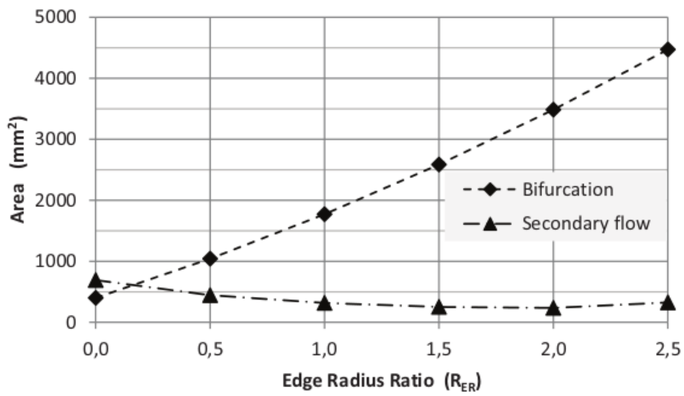

Fig. 11. The relation of area and R_{ER}.

T-junction bifurcating area [1] and it cannot be avoided. The secondary flow produces a nuzzling effect. At $R_{\mathrm{ER}} = 0$, the secondary flow occupies almost half of the outlet channel and it creates a nozzle effect. This effect strongly disturbs the flow so that the head loss is large. As a rounded-edge radius increases, the secondary flow tends to decrease and shifts to the bifurcation region. Its occupation on the outlet channel is reduced so that its disturbance to the flow decreases. Therefore, the head loss is reduced. At $R_{\mathrm{ER}} = 2$ it is completely located in the bifurcation region; and as shown in Fig. 6 and Fig. 7, the coefficient of head loss drops from $R_{\mathrm{ER}} = 1.5$ to 2.

Fig. 10 shows the reduction of the secondary flow area, which means that flow cross section area at the nozzle throat (nozzle area) and the length of secondary flow are reduced. The secondary flow area drops from $R_{\mathrm{ER}} = 0$ to 0.5 and the throat of the nozzle area increases. This shows that the disturbance produced by the secondary flow decreases significantly and the local velocity in the throat of the nozzle decreases due to the increase in the nuzzling width ratio. The decrease of the local velocity weakens the recirculation that reduces the minor losses, as represented by the decrease of the first coefficient as much as about one third as in Table 1. On the other hand, the reduced length of the secondary flow elongates the attachment that increases wall friction. However, the significant reduction of the local velocity decreases dynamic pressure. The balance of these two factors results in the decrease of the major head loss as represented by the decrease of the second coefficient from 1.05 to 0.9787 in Table 1. The sum of these loss reductions results in the drop in the head loss as shown in Figs. 6 and 7.

As shown in Fig. 11, the bifurcation area greatly increases while the secondary flow area decreases gradually along with the increasing rounded-edge radii. The secondary flow area is much smaller than the area of bifurcation. This suggests that the effect of the secondary flow occupation in the bifurcation region on the head loss is insignificantly small. As the secondary flow is completely located in the bifurcation region at $R_{\mathrm{ER}} = 2$ and 2.5 (Fig. 9), its disturbance on the flow in the outlet channel is completely eliminated. In this situation the secondary flow transforms the minor loss to become gain of energy so that the first coefficient in Table 1changes from positive into negative. On the other hand, without a secondary flow occupation in the outlet section, the fluid is fully attached to the wall so that the major head loss is higher. However, the larger main-flow cross sectional area in the throat of the nozzle without a secondary flow occupation largely reduces the local velocity and it greatly decreases the dynamic pressure. Therefore, the balance of these two parameters leads to the decrease of minor head loss as represented by the decrease of the first coefficient of the equation in Table 1. As a result, the head loss drops from $R_{\mathrm{ER}} = 1.5$ to 2 as shown in Figs. 6 and 7.

Conclusions

The experiment successfully observed the laminar flow behaviour in a T-junction with a vertical inlet channel and both horizontal outlet channels with a bifurcation ratio, $\beta = 0.5$. The change of the secondary flow behaviour due to the change of various rounded-edge radii and also its effect to flow disturbance in the T-junction channel were clearly observed. The results shows the effect of a rounded-edge to the secondary flow and its relation to head losses.

Changing the rounded-edge radius in a T-junction leads to the change of the area and position of secondary flow, which is occupied the outlet channel. As a result, the head losses are reduced.

As the secondary flow shifts fully to the bifurcation area, the disturbance on the flow in the outlet channel is completely eliminated. In other words, reducing the occupation area of the secondary flow at the outlet channel and shifting the secondary flow to bifurcation area have a strong effect to the reduction of head losses.

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Secondary Flow Behaviour in Various Rounded-Edge Bifurcation T-Junctions and Its Relation to Head Loss

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