PIV MEASUREMENTS OF SEPARATING AND REATTACHING FLOWS OVER PERMEABLE WALLS

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ABSTRACT

PIV measurements are performed for turbulent flows in a rib-mounted channel whose bottom wall is made of a porous layer. The effects of the wall and rib permeability are investigated focusing on the separating and reattaching flow region. Three kinds of porous media are employed. They have the same porosity of 0.8 but each has different permeability from the others. Two kinds of square cylinder ribs are used, one of which is an impermeable smooth solid rib and the other is a permeable porous rib which is made of the same porous medium as that for the bottom wall. The obtained mean velocity profiles of the solid rib cases suggest that the reverse flow in the recirculation behind the rib becomes weak as the increase of the bottom wall permeability. The recirculation area is thus shrunk. The main factor is found to be the increase of the bypassing flow rate through the bottom porous wall below the solid rib. Indeed, the local streamwise flux across the clear channel is confirmed to decrease above the rib and then increase behind the rib, according to the increase of the permeability. In the porous rib case, the recirculation and reattachment point are shifted further downstream and the recirculation bubble is slightly expanded. As the increase of the permeability, the recirculation is finally vanished. These are due to the bypassing flow not only through the bottom wall but also through the rib. The decrease of the local streamwise flow rate in front of the rib becomes less compared to that for the solid rib case. This suggests the increase of the bypassing flow through the rib. The bleeding flow from the back of the rib becomes dominant factor on the shift of the recirculation area.

INTRODUCTION

Porous media have many various pores inside and thus the contact area to a gas/liquid is extremely large. Therefore, it is employed to heat exchangers, catalytic converters and the fuel cells, etc., for the enhancement of heat and mass transfer and the chemical reaction rate\textsuperscript{1}. Not only the flows inside the porous media, flows over the porous media can be seen in those engineering devices and natural environment. There are various characteristic parameters for the porous media; the porosity, the permeability and the roughness of surface, thus the transport phenomena inside and over the porous media become complex. Hence, many studies and researches have been carried out over the last decades.

Beavers and Joseph\textsuperscript{2} reported that the friction over the porous walls decreased a little in the laminar flow by the porosity on the porous media. On the other hand, in the case of turbulent flow, the friction increases compared with the same roughness impermeable walls. Kong and Schetz\textsuperscript{3} investigated the increase of the friction by the combined effect of the surface roughness and the porosity. Zippe and Graf\textsuperscript{4} also pointed out the same phenomenon experimentally. In recent years, Breugem et al.\textsuperscript{5} tried to clarify the phenomena by the numerical analysis, and they reported that the wall friction increased as the increase of the porosity and permeability. They also reported the decrease of the streak structure near the walls. However, they applied the volume average model for the porous media, and they treated the permeability as the function of the porosity. Thus they were not able to discuss the effect of the permeability, the porosity and the surface separately. Recently, Suga et al.\textsuperscript{6} focused on the effect of the permeability and studied flow over the porous walls experimentally. In their experiment, foamed porous media which had the same porosity but different permeability were employed. They clarified the relation between the friction and the wall permeability in the turbulent flow at a range of the Reynolds number.

To enhance the heat and mass transfer, it is well known that an obstacle in the channel can disturb the flow drastically and the heat transfer coefficient becomes maximum at the reattachment point. A large number of related studies have been done both experimentally and numerically. However, the separating and reattaching flow with the effect of the porous media has not been clarified yet. A few studies focusing only on the rib permeability are reported; Panigrahi et al.\textsuperscript{7}\textsuperscript{8} studied experimentally the effect of the slit rib which can be regarded as the partially porous rib. Leu et al.\textsuperscript{9} used the accumulated circular cylinder rib. Their study was imposed on the effect of the porosity not on the permeability.

In this study, standing on the effect of the porous wall, the effect of the rib on the flow is studied experimentally by using the PIV system. The effects of the wall and rib permeability and Reynolds number on the recirculation and the reattachment point behind the rib are investigated.

EXPERIMENTAL METHOD

Figure 1 shows the experiment setup used in this study. It contains of a closed channel flow facility and a PIV system (DANTEC dynamics).

Channel Flow Facility

The closed channel facility consists of a rectifier device, a drive section and a test section. In this device, tap water is used as a working fluid. The tap water is stored in a tank and pumped up by one-way whirling-up pump. It passes over the flowmeter and runs into the rectifier device. The flow rate is controlled by a power converter and a valve. The rectifier device is combined with a perforated
plate and a honeycomb structure. The temperature of the water is measured by a digital thermometer mounted in the rectifier device. The flow, which is rectified at the rectifier device, passes the drive section(3m) and the test section(1m), and goes back to the tank. Both the drive and test sections have a rectangular cross section which is 305mm wide(W) and 62mm high. The half height of the cross section is paved by the foamed ceramics, so the region between the top and the porous bottom walls forms the flowing channel, which is about 30mm high (H). The ratio of the length to the height of the drive section is 100 to 1, so the flow develops well enough before the test section. A square cylinder rib, which is of half height (h = H/2) of the height of the flowing channel (H) and is of the same width(W) as that of the channel, is set perpendicular to the flow direction. The rib is carefully positioned on the upstream side not to be affected by the outlet nozzle. Two kinds of square cylinder ribs are used. One is an impermeable rib made of solid acrylic resin and the other is a permeable rib made of the same foamed ceramics as those for the bottom wall.

PIV Measurement

PIV(Particle image velocimetry) is used to measure the velocity distribution of the flow. Double-pulse Nd-Yag laser beam (120mJ/pulse, λ =532nm) illuminates the test section located at the center of the channel, and a CCD camera (2048×2048pixels) takes photos from the side position with the lens(60mmf/2.8D). The thickness of the laser sheet is 1mm, and the frame size of a photo is about 30×30mm². The measured cross section is vertical to the direction of the channel. Figure 2 shows the measurement zones. Because the resolution of the photo is not enough when a photo covers the whole flow region at once, the camera is relocated 8 times, being moved in parallel along the channel. Each photo overlaps 15%, and the camera takes photos of the zones between x = −5h ~ 8h, where the origin of x (x = 0) is set of the back face of the rib.

In the interrogation window of PIV, the dimetric region (32×32pixels) is used and they are overlapped 50% each other in the horizontal and vertical directions. As the result, a set of photos produce 127×127 vectors at each camera point. Available vectors in the wall normal direction(y) are about 110.

Acrylic colloid particles, which are 0.5μm of the mean diameter and 1.19 of the specific gravity, are used as the tracer particles of the PIV. To extract the acrylic colloid particles, the white paint was at first diluted: about 1ml was homogeneously dissolved into 500ml water. More than 12 hours later, the homogeneous white-coloured solution became layered: white precipitation at the bottom of the container and translucent solution in light-milky colour in the upper part. The upper translucent part is then used to seed in the flow for the PIV measurements.

The tracer particles are seeded, and the space density becomes more than 10 on average in the interrogation window. One particle is captured by about 2×2pixels. Time between the pulses of the laser Δt is adjusted to make the maximum displacement of the particle less than 25%(≤8pixels) of the interrogation window. As the result of a sampling analysis, we determine the sampling number of the ensemble averaging as 4800 and the frame rate as 4Hz, so the total sampling time becomes 20min.

Two schemes are used to get rid of error vectors; “Peak average validation” and “Moving average validation”. Peak average validation is the way to use the ratio of the first correlation value P1 and the second correlation value P2, and judge whether the vector is correct or not using Eq. 1. In this experiment, k is 1.3.

\[ E = \frac{P_1}{P_2} < k = 1.3 \] (1)

The Moving average validation is the way to compare the center vector \( U_{i,j} \) and the average value of surrounding vector containing itself \( \overline{U}_{i,j} \) as in Eq. 2. In this experiment, α is set to 0.1.

\[ |U_{i,j} - \overline{U}_{i,j}| > \alpha \max_{i,j} |U_{i,j} - \overline{U}_{i,j}| \] (2)

The error vectors removed are less than 5% of the total vectors available.

Characteristics of Porous Media

Three kinds of foamed ceramics (#20, #13 and #06) are used as the porous media in this experiment, their photographic images are shown in Figure 3. The characteristics of these porous media are measured preliminarily,
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Figure 4: Streamwise mean velocity profile at solid rib and \( \text{Re}_b \approx 3500 \) on different permeable wall (#20, #13 and #06).

Figure 5: Streamlines of rib-mounted channel flow at solid rib and Re\( \text{b} \approx 3500 \). (a)#20 (b)#06.

and are listed in Table 1. These porous media have almost the same porosity \( \varphi \) but their permeability \( K \) is different.

### Table 1: Parameter of porous media.

<table>
<thead>
<tr>
<th></th>
<th>( D_p ) (mm)</th>
<th>( \varphi )</th>
<th>( K ) (mm(^2))</th>
<th>( \sqrt{K/D_p} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>#20</td>
<td>1.7</td>
<td>0.82</td>
<td>0.020</td>
<td>0.083</td>
</tr>
<tr>
<td>#13</td>
<td>2.8</td>
<td>0.81</td>
<td>0.033</td>
<td>0.065</td>
</tr>
<tr>
<td>#06</td>
<td>3.8</td>
<td>0.80</td>
<td>0.087</td>
<td>0.078</td>
</tr>
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</table>

**Experimental Conditions**

The mean velocity profiles and turbulent intensities are measured on the three kinds of porous media (#20, #13 and #06) with the two kinds of rib (solid or porous) at bulk Reynolds numbers \( \text{Re}_b(= U_b H/\nu) \approx 1000, 3500 \) and 10000. The bulk mean velocity \( U_b \) is measured at the position \( x = -5h \). Totally, 18 cases are measured. The bulk mean velocity at the position at \( x = -5h \) is confirmed not to be affected by the rib, comparing the mean velocity and Reynolds shear stress profiles with those of the non-obstructed porous channel case\(^6\). In this study, the effects of bottom wall and rib permeability on the flow are investigated.

**RESULTS AND DISCUSSIONS**

**Effect of Wall Permeability**

First, the effect of the permeability of the bottom wall is investigated. The solid rib cases and the porous rib cases at \( \text{Re}_b \approx 3500 \) are discussed.

**Solid rib case**

Figures 4 and 5 show the streamwise mean velocity profile at the different permeability of the bottom porous media at \( \text{Re}_b \approx 3500 \) and the streamlines of the most different permeability cases (#20 and #06), respectively. The solid line in Figure 4 is the result of the LES analysis in which a solid rib is placed on the solid bottom wall, and the bulk Reynolds number is \( \text{Re}_b = 3350\)\(^{10}\). The surface of the bottom and that of the top solid wall are \( y/H = 0 \) and \( y/H = 1 \), respectively.

First, at the front side of the rib near the bottom wall \((-2h \leq x \leq -h)\), LES case has the stagnant region due to the impermeable solid bottom and rib, thus a recirculation region and a reverse flow exist. On the other hand, the reverse flow is not observed in our experiment. This is due to the porous wall at the bottom and thus
the bypassing flow goes through the bottom porous media. The tendency is enhanced as the increase of the wall permeability since the local streamwise velocity increases a little (too small to be recognized in the figure).

Secondly, the flow fields of the LES and our cases are similar above the rib. The reverse flow is observed. This is because both the top and bottom surfaces are solid, thus the effect of the permeability is less remarkable.

From the back of the rib, if the bottom surface is solid, it is known that the flow which separates at the rib develops entraining the fluid from the downstream which is shown in LES case of Figure 4. However, in the current case, the bottom surface is porous, thus the separating flow develops entraining the bypassing flow which is bled from the bottom porous media as shown in Figures 5(a) and (b). Indeed, the streamwise mean velocity just behind the rib (0 ≤ x ≤ h) near the bottom wall (y ≤ 0.5H) is negative in LES (solid bottom) but that in our experiment becomes positive as shown in Figure 4. Additionally, as shown in Figure 5(b) it is interesting that the recirculation vortex is formed just behind the rib at the higher permeability case. This is because the fluid behind the rib is entrained by the bleeding flow which goes to above the rib. In further downstream, the reverse flow exist at the lower wall permeability case (#20). The reverse flow disappears in the higher wall permeability cases (#13 and #06), due to the increase of the bypassing flow going through the bottom porous media.

**Poros rib case**

Next, the porous rib cases are discussed. Figures 6 and 7 show the streamwise mean velocity profile at the different permeability of the bottom porous media at \( \text{Re}_b \geq 3500 \) and the streamlines of the most different permeability cases (#20 and #06), respectively.

In the porous rib case, the flow can go through not only bottom porous wall but also inside the rib. Thus, the velocity at the front side of the rib \((-2h \leq x \leq -h)\) becomes faster as the increase of the permeability.

Separation and reverse flows are not observed above the rib in the porous rib case shown in Figure 7 due to the bypassing flow inside the porous rib. Furthermore, the velocity above the rib becomes slower as the increase of the permeability, which implies that the increase of the fluid going through bottom wall and the rib.

In addition, the velocity behind the rib also becomes
faster as the permeability increases by the same reason, and it is confirmed that the reverse flow does not occur near the rib. In the lower permeable case (#20), the reverse flow is observed further downstream though it is very weak compared to the LES. However, In the higher permeability case (#13 and #06), the reverse flow and recirculation bubble disappear at downstream of the rib shown in Figure 7(b).

For the porous rib cases, the flow structure is found to be complicated strongly depending on the rib permeability.

**Effect of Reynolds Number**

Next, the effect of the Reynolds number over lowest permeability wall (#20) with the solid rib case is investigated. Three kinds of Reynolds numbers are discussed. One is the laminar inlet flow ahead the rib ($R_e = 1000$), and the others are fully developed turbulent inlet flow ahead the rib ($R_e = 3500$ and 10000). However, all of them become turbulent in the region downstream the rib.

Figure 8 shows the streamwise mean velocity profiles of different Reynolds numbers of the solid and porous cases. First, the solid rib case is discussed. In the front side of the rib, the reverse flow exists near the bottom porous media at the lower Reynolds number case ($R_e = 1000$). On the other hand, the reverse flow disappears in the higher Reynolds number cases ($R_e = 3500$ and 10000).

In the region behind the rib, the reverse flow of the $R_e = 1000$ is relatively stronger than that of $R_e = 3500$ and 10000. The reverse flow stretches to downstream and upper region comparatively. Furthermore, the region of the reverse flow spreads to further downstream than that of $R_e = 3500$ and 10000. From this result, the recirculation bubble of $R_e = 1000$ becomes bigger and stronger relatively. The porous rib case represents the same tendency with the solid rib case.

**The Reattachment Point $x_R$ and The Bypassing Flow Rate**

From the aforementioned results, recirculation bubble is affected by the permeability of the bottom wall and the Reynolds number. Thus, the reattachment point $x_R$ and the bypassing flow rate are discussed in all the cases measured. Table 2 shows the reattachment point $x_R$, the upstream edge of the recirculation vortex $x_F$ and the bypassing flow rate at $x = -h$.

The reattachment point $x_R$ is defined as the point where the streamwise mean velocity nearest the bottom changes from the negative to the positive (the nearest data point to the bottom porous media is $y/H = 0.01$). Furthermore, in the case of the porous rib, the upstream edge of the recirculation vortex $x_F$ is determined where the sign of the streamwise component of the mean velocity vector changes through the mean velocity vector map (from the second quadrant to the first quadrant). The bypassing flow rates going through the bottom porous media are estimated as follows. Local flow rate is calculated by integrating the velocity profiles along $y$ direction. In the same way, the characteristic bulk flow rate on the flat porous wall is obtained at further upstream ($x = -5h$). Finally, flow rate difference from the characteristic flow rate yields the bypassing flow rate. In Table 2, the rep-
representative bypassing flow rate at the rib \((x = -h)\) is listed. On the other hand, in the case of the porous rib, the flow goes through the rib and it is impossible to measure the velocity profile inside the rib, thus the flow rate through the bottom wall is estimated just ahead of the rib \((-1.02h < x < -h)\). Additionally, the bypassing flow rate including through the rib can be also estimated by using the flow rate above the rib \((x = -h)\).

In Table 2, the reattachment point \(x_R\) is not obtained in most of \#13 and \#06 cases. This is due to the absence of the recirculation at high Reynolds number (\(Re_b \approx 3500\) and 10000). The upper edge of the recirculation vortex \(x_F\) appears only in the porous rib case of \#20, but \(x_F\) of \(Re_b \approx 1000\) cannot be determined unfortunately due to the chaotic vector map.

First, the effect of the bottom wall permeability is discussed. The common parameter is the solid rib and the difference is that one has the solid bottom \([10][11]\) and the other has the porous wall of our experiment. The results of \#20 at \(Re_b \approx 3500\) can be compared with the LES data \([10]\). They are both in the turbulent flow ahead the rib. In the table, the presence of the bottom wall permeability apparently affects the reattachment point. \(x_R\) becomes closer to the rib \((x_R = 6.65h - 5.2h)\) by the presence of bypassing flow. Another comparison can be done in the laminar inlet flow ahead the rib, at \(Re_b \approx 1000\) \([13]\). Our data show \(x_R = 6.7h\) in case \#20 and that in reference \([11]\) is roughly \(7.5h\), which supports the shift of the reattachment point closer to the rib and the descent of \(x_F\) is found to be remarkable in the turbulent flow ahead the rib. Due to solid rib, the main flow in the clear channel is blocked and then the vortex appears behind the rib. If the bottom wall has the permeability, the split flow submerges into the wall and bleeds behind the rib. Thus, the extreme of the wall permeability represents the channel flow with square cylinder at the center.

Secondly, the effect of the rib permeability is discussed at the same bottom wall (\#20). Compared at the corresponding Reynolds number \(Re_b\), the reattachment point \(x_R\) at the porous rib increases compared to the solid rib case. This implies the recirculation vortex is shifted further downstream as shown in Figure 5(b). In addition to the porous rib case, the recirculation vortex size becomes small compared to the solid rib case with the increase of \(Re_b\). This can be explained by the bypassing flow not only through the bottom wall but also through the rib. Indeed, the contribution of the bypassing flow rate through the rib and bottom wall is confirmed to increase in Table 2.

Next, the effect of bottom wall permeability is discussed for the solid rib. Compared at \(Re_b \approx 1000\), \#06 data has the smallest, that is, \(x_R\) is the closest to the rib at the highest wall permeability case. In addition, the bypassing flow rate increases as the permeability increases. This increase becomes remarkable according to the increase of the Reynolds number. These confirm the aforementioned tendency of the presence of the bottom wall permeability with a solid rib. However, \(x_R\) of \#20 and \#13 does not change drastically and even has the opposite tendency (6.7h in \#20 and 7.0h in \#13), this reverse trend is probably due to the small experimental error.

For the porous rib, the bypassing flow rate increases as the permeability increases.

For the further discussion of the wall permeability dependence, flow rate through the bottom porous wall is plotted in the streamwise direction. Figure 9 shows the

<table>
<thead>
<tr>
<th>rib</th>
<th>bottom porous media</th>
<th>(Re_b)</th>
<th>reattachment point (x_R)</th>
<th>upper edge of vortex (x_F)</th>
<th>bypassing flow rate through bottom wall</th>
<th>bypassing flow rate including inside rib</th>
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<td>7.0h</td>
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<td></td>
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<td>3350</td>
<td>6.65h</td>
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</table>

Table 2: Reattachment points and bypassing flow rates.
solid rib cases at $\text{Re}_b \approx 3500$. The flow rate at $x = -5h$ is not affected by the rib, and thus is determined as the characteristic flow rate $Q_b$. The bypassing flow rate $Q_p$ can be obtained by $Q_b - Q_c$, where $Q_c$ is the flow rate of the channel region. That value at $x = -h$ corresponds to the data in Table 2.

The flow goes into the bottom porous media ahead the rib as shown in the streamlines in Figure 5(a), where the bypassing flow rates increases as the permeability increases. At the front side of the rib, the submerging rate becomes maximum. The flow rate of the #06 and #13 are almost same at $x < 0.5h$, which seems the saturation of the flow rate through the bottom. As flow passes over the rib, flow rate in the clear channel ($Q_c/Q_b$) slightly recovers. This is due to the presence of the flow entrainment behind the rib from the bottom wall to above the rib, resulting in the vortex above the rib as shown in Figure 5(a).

After passing the rib (behind the rib), flow rate of #20 data quickly recovers around 1.0 and the flow rate in the bottom increases a little, which corresponds to the flow entrainment in the recirculation region. For higher permeability cases, it is interesting that the flow rate in the clear channel increases downstream as the permeability increases. The supplied flow rate from upstream should be at most $Q_c/Q_b = 1.0$, thus this increase suggests that the entrainment not only from the upstream bottom wall but also the downstream bottom wall. However, the PIV used in this experiment can not measure the velocity distributions inside the porous media. For the validation of the entrainment from the downstream bottom wall, a sample turbulent flow simulation ($k - \epsilon$ model) is carried out. Though the solid rib case is apparently better to compare with Figure 9, the porous rib case at #20 and $\text{Re}_b = 3350$ is calculated due to the computational costs and the stability. The streamlines obtained in the computation are shown in Figure 10. The streamlines in the clear channel are in good agreement with the experimental data in Figure 5(b), which represents the validity of the computation. This result has the entrainment from the downstream bottom wall such as $x > 4.2h$. This suggests that the same entrainment is supposed to occur in the solid rib case, which supports the result shown in Figure 9.

CONCLUSIONS

PIV measurements are performed in the separating and reattaching flows with a solid rib or a porous rib over the three kinds of porous media, which have the same porosity but different permeability, and the followings are discussed; the effects of the bottom porous wall permeability and the Reynolds numbers.

1. In the solid rib case, the reverse flow decreases behind the rib, and the reattachment point also becomes closer to the rib. The tendency becomes remarkable in the higher permeability cases. Indeed, in the higher permeability cases, the reverse flow and the reattachment point disappear behind the rib. These are explained by the increase of the bypassing flow rate going through the bottom porous wall shown in Table 2.

2. In the porous rib case, the fluid goes through not only bottom porous wall but also inside the rib. Thus, the separation does not occur above the rib due to the bypassing flow inside the rib. The reverse flow behind the rib also becomes weak, and the reverse flow area shifts to the downstream. Thus, the recirculation vortex and the reattachment points also shift to the downstream. Furthermore, their sizes become smaller than those of solid rib cases.

3. In the lower Reynolds number case ($\text{Re}_b \approx 1000$), the stagnant region exists in front of the rib even though the bottom wall is porous. However, the higher Reynolds number cases ($\text{Re}_b \approx 3500$ and $10000$), the stagnant region disappears. In the downstream of the rib, the reverse flow becomes stronger in the lower Reynolds number case ($\text{Re}_b \approx 1000$) than the higher Reynolds number cases ($\text{Re}_b \approx 3500$ and $10000$). Furthermore, the recirculation bubble in the lower Reynolds number case ($\text{Re}_b \approx 1000$) stretches further downstream and upper region compared to the higher Reynolds number cases ($\text{Re}_b \approx 3500$ and $10000$).
4. In the case of the lower Reynolds number case (Reₐ ≥1000), the reattachment point shifts the downstream than that of higher Reynolds number cases (Reₐ ≥3500 and 10000). However, the reattachment point of the lower Reynolds number case (Reₐ =1000) over the porous wall is shorter than that of over the solid wall. The reattachment point becomes shorter as the increase of the wall permeability at lower Reynolds number case (Reₐ =1000). In the higher Reynolds number cases (Reₐ =3500 and 10000), the reattachment point disappears in the higher bottom permeability cases.

5. The flow rates going through the bottom porous media are estimated and it is clarified that the by-passing flow rate increases as the increase of the permeability of the bottom wall and the Reynolds numbers. Moreover, the flow rate through the bottom porous media of each cross section is estimated and it is clarified that the flow rate in the channel region increases downstream at the higher permeability case compared to the that ahead of the rib. This is explained by the fluid bleeding out from the bottom porous wall coming from both the upstream and downstream regions.

The discussions with measured turbulence quantities will be presented elsewhere in the near future.

**References**


**NOMENCLATURE**

- h: the height of rib (H/2), mm
- D_p: mean pore diameter of porous media, mm
- H: the height of channel, mm
- K: permeability of porous media, mm²
- Q_b: bulk flow rate, m³/s
- Q_c: flow rate in channel region, m³/s
- Q_p: flow rate in porous region, m³/s
- Reₐ: bulk Reynolds number U_bH/ν
- U_b: bulk mean velocity, m/s
- W: the width of channel, mm
- x, y: coordinates, mm
- x_F: upstream edge of recirculating vortex, mm
- x_R: reattachment point, mm
- φ: porosity of porous media
- ν: kinematic viscosity of the fluid, m²/s

**SUBSCRIPTS**

- b: bulk
- c: channel region
- p: porous media

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