Jurnal
Teknologi

Full Paper

CHARACTERISTICS OF FLOW THROUGH RIGID, EMERGENT AND SPARSE VEGETATION

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Article history
Received
30 November 2015
Received in revised form
28 May 2016
Accepted
15 September 2016

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Graphical abstract

Abstract

This paper looks into the flow profiles in terms of longitudinal and transverse velocities, turbulence intensity and turbulent kinetic energy in relation to the vegetation density, flow depth and stem Reynolds number. An experimental study was conducted in a fully vegetated flume, whereby a control volume was selected for detailed velocity measurement using Acoustic Doppler Velocimeter (ADV). This research considered 0.97%, 3.90% and 7.80% vegetation density or solid volume fractions (SVF) which are categorised as sparse in the lab work. Series of experiments were conducted in uniform flow condition with stem Reynolds number, Re_d ranging between 1300 and 3000. Experimental results managed to capture the wake area (velocity deficit; $\bar{u}_{xz}/U < 1$) and fast flow region (velocity enhance; $\bar{u}_{xz}/U > 1$). The boundary between the wake area and fast flow region is reflected by the highest magnitude of the normalised longitudinal turbulence intensity and turbulent kinetic energy. Positive normalised transverse velocity represents the flow diversion away from the vegetation and the negative normalised transverse velocity indicates flux towards the centre of the wake. Both turbulence intensity and turbulent kinetic energy display no observable relation with the flow depth. This is probably because the characteristic length for turbulent flow through vegetation is the stem diameter.

Keywords: Emergent vegetation, mean velocity, transverse velocity, turbulence intensity, turbulent kinetic energy

Abstrak

Kertas ini melihat profil halaju membujur dan halaju melintang, keamatan gelora serta tenaga kinetik gelora dan hubungannya dengan kepadatan tumbuhan, kedalaman aliran dan nombor Reynolds. Kajian makmal dijalankan di dalam flum penuh tumbuhan, di mana halaju dicerap secara terperinci di dalam kawasan kawalan dengan menggunakan pengukur Halaju Akustik Doppler (ADV). Kepadatan tumbuhan ujikaji adalah jarang dengan nilai pecahan isipadu pepejal (SVF) 0.97%, 3.90% dan 7.80%. Ujikaji dijalankan dalam aliran seragam dengan nombor Reynolds, Re_d antara 1300 dan 3000. Hasil ujikaji berjaya mengukur kawasan olakan (halaju menyusut; $\bar{u}_{xz}/U < 1$) dan kawasan aliran laju (halaju bertambah; $\bar{u}_{xz}/U > 1$). Sempadan antara kawasan olakan dan kawasan aliran laju dikenalpasti dengan nilai keamatan gelora dan tenaga kinetik gelora yang tinggi. Halaju melintang positif menunjukkan lencongan aliran menjauhi tumbuhan, manakala halaju melintang negatif menunjukkan aliran ke arah kawasan olakan. Keamatan gelora dan tenaga kinetik gelora tidak menunjukkan hubungan dengan kedalaman air. Ini mungkin disebabkan pencirian panjang bagi aliran gelora melalui tumbuhan adalah diameter batang tumbuhan tersebut.

Kata kunci: Tumbuhan muncul, halaju purata, halaju melintang, keamatan gelora, tenaga kinetik gelora

1.0 INTRODUCTION

The presence of emergent vegetation along the bed influences the hydrodynamic behaviour of open channel (i.e. river). In early years, the scientists and engineers had perceived the vegetation as a blockage of flow that can cause upstream flooding. Therefore there has been much research that looks into the mean velocity distribution in the presence of vegetation to measure the flow resistance and further improves the water conveyance. However in recent years, vegetation is more accepted as one of the important ecological aspects in the river health. As a result more research in turbulent transport process in natural flow condition is deemed important especially as it helps one to understand the mixing and sedimentation process.

It is known that the flow characteristic obstructed by a single object (i.e. single circular cylinder) is not the same with the flow observed in multiple cylinders. For example Douglas *et al.* [1] elaborated the variation of the wake development of a single circular cylinder with stem Reynolds number, Re_d where eddies start to break away alternately from each side of the cylinder at Re_d equal to 90. This phenomenon is known as *Von Karman Vortex Street*. However in her study for vegetation density, *ad* equal to 0.008 to 0.07 (i.e. a = numbers of vegetation per unit area; d = stem diameter) vortex shedding only occurs at *Re* around 150 to 200.

Nepf [3] divided the velocity field in a vegetated (or multiple circular cylinders) area into three regions. The first region is the recirculation zone located at the immediate downstream of the vegetation (cylinder). In this region the average longitudinal velocity is zero. The second is the wake region, where the velocity is positive but it is reduced relatively to the spatially averaged velocity, *U*. The overlapping wakes are the velocity deficit region which is equivalent to the cumulative individual wake deficit. The third region is the gap flow between the vegetation and wakes. The flow in this zone by conservation of mass should be greater than *U*.

To further understand the velocity and turbulence profile, Zavistoski [4] studied the details within the control volume of the vegetation arrays. Three types of vegetation density were categorised based on the degree of the wake interaction. In the low vegetation density there is no wake overlapping, meanwhile in high vegetation density, there is an intense wake interaction where there is very little gap flow (i.e. three or more wakes overlapping) between the vegetation and wakes. Medium vegetation density is between low and high vegetation density with limited wakes overlapping. The velocity was measured using the Laser Doppler Velocimeter (LDV) and there are about a line of 15 to 19 sampling points depending on the vegetation density. Experimental results show that the velocity profiles become nearly uniform with the depth, the bottom boundary layer depresses as the plant density increases, the shear stress increases at the bed and the horizontal and vertical turbulence levels increase with the vegetation density because of the wakes lateral shear increases.

Lui [5] studied in detail the hydrodynamic flow in a control volume within the vegetation arrays. There were four measurement points downstream a cylinder and two measurement points in the fast flow region with no immediate obstruction in the control volume. This experimental study used staggered and aligned rigid cylinders as the simulated vegetation. A systematic analysis, studied the effect of dowel arrangement, density and roughness to longitudinal velocity, vertical velocity and turbulence intensity for emergent and submerged flow conditions. Longitudinal velocity profile displays a consistent pattern with almost constant velocity throughout the flow depth but this is followed by an inflection point near the bed (emergent vegetation) and just below the top of the vegetation (submerged vegetation). These inflection points were associated with a coherent structure dominated by clockwise vortices at the top of vegetation and counter clockwise vortices near the bed. The vertical velocity is mostly negative (going downward) except for the immediate upstream of the vegetation where vertical velocity is positive (going upward). This is explained by the higher momentum fluid moving from the free stream region to the slower fluid behind the dowel. The data analysis also found that turbulence intensities are highest immediately downstream the vegetation which then decrease, as the flow travels downstream and displays the lowest turbulence intensity in the fast flow region.

Buckman [6] studied the partially vegetated channel where the channel width is divided into two, one part is open channel and the other part is vegetation section. The experiment conducted, tested on both emergent and submerged rigid cylinders to look into spatial and temporal distributions of maximum stem forces exerted on individual plants. From the flow analysis, the critical area is between the boundary of the open channel and the vegetation patch. S-curve shape can be observed for the mean stream-wise velocity profile where the velocity gradient is steep at the vegetation boundaries and it is also known as mixing layers. The magnitude of the turbulent kinetic energy (TKE) was found at the peak either near or at the boundary and it decreased as it went deeper into the vegetation array but remained higher in the open channel section.

The aim of this paper is to study the characteristics of flow through emergent and rigid vegetation. A detailed analysis investigates the mean velocity, turbulence intensity and turbulent kinetic energy in relation to the stem Reynolds number, vegetation density and flow depth. These analyses give a systematic approach to further understand the behaviour of the wakes.

2.0 METHODOLOGY

Experimental work was conducted in a 10 m length, 1.2 m width and 0.30 m depth recirculating flume. The flume is attached to a re-circulating reservoir and pipe system and to an operating centrifugal pump to continuously supply water from a reservoir tank to the flume. The longitudinal bed slope was adjusted to a 0.001 gradient. The bed and side wall are constructed from glass with steel frames. A sheet of PVC material with a series of holes attached to the glass bed allowed the simulated vegetation to be slotted into place. Flume holes were located laterally every 60 mm (hole centreline to hole centreline) and a total of 20 holes were constructed in each row across the 1.2 m flume width. The longitudinal distance between each row of holes was 105 mm (hole centreline to hole centreline) and in total there were 88 rows of holes along the full length of the flume.

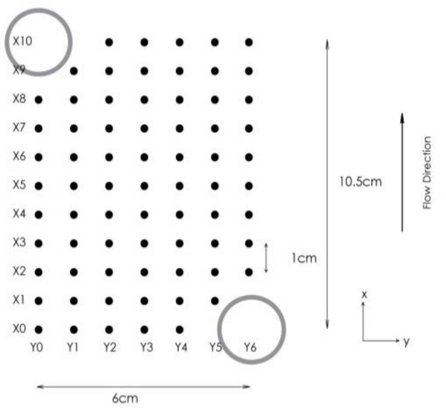
The vegetation used in this study was a rigid wooden cylinder with diameter, *d* equal to 25 mm. The vegetation was arranged either in an aligned or staggered arrangement that covered the whole length of flume to ensure that the flow is fully developed at the measurement area. The vegetation densities were calculated using a solid volume fraction (SVF) in equation (1) for aligned vegetation and equation (2) for staggered vegetation. There were six sets of experiment with four different vegetation densities. The flow was set to uniform flow with stem Reynolds number, Re_d ranging from 1300 to 3000 which is considered as turbulence and Froude number, *Fr* less than 1 categorised as subcritical flow. The details of the experiment can be referred to Table 1 wherein the test name, *S* denotes staggered and *A* represent aligned vegetation arrangement; *L* is low water level and *H* is high water level; δx and δy are the longitudinal and transverse distance of the control volume; *d* is the stem diameter; *Q* is the flow discharge; *h* is the flow depth; *U* is the mean area velocity; Re_d is the stem Reynolds number and F_r is Froude number.

$$SVF(aligned) = \varphi = \frac{\pi d^2}{4\delta_x \delta_y} \times 100\% \quad (1)$$

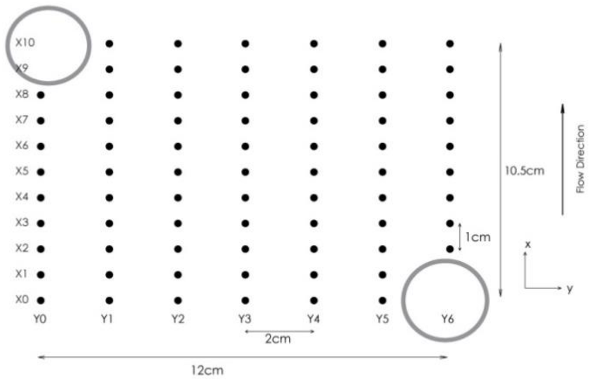
$$SVF(staggered) = \varphi = \frac{\pi d^2}{8\delta_x \delta_y} \times 100\% \quad (2)$$

Table 1 Experimental detail where the vegetation covers the complete length of flume

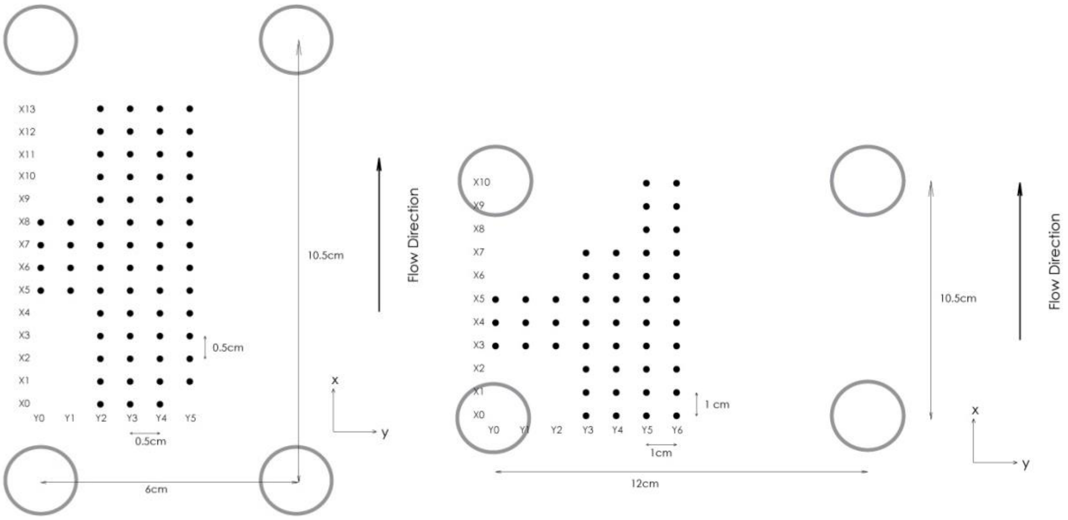
Test Name	SVF Φ (%)	δ_x (m)	δ_y (m)	Q (m³/s)	h (m)	U (m/s)	Re_d	F_r
3.90A	3.896	0.105	0.12	0.015	0.145	0.086	2,150	0.08
7.79A	7.792	0.105	0.06	0.015	0.257	0.049	1,677	0.04
3.90SL	3.896	0.1	0.06	0.015	0.175	0.071	1,775	0.02
3.90SH				0.014	0.220	0.053	1,325	0.04
0.97SL	0.974	0.2	0.12	0.020	0.140	0.119	2,975	0.04
0.97SH				0.033	0.240	0.115	2,875	0.09



(a) Sampling points for 0.97S



(b) Sampling points for 3.90S test



(c) Samplings points for 3.90A test (d) Sampling points for 7.79A test

Figure 1 Black dots represent the sampling points (a) test 0.97S; (b) test 3.90S; (c) test 3.90A; (d) test 7.79A

Velocity was measured using a downward looking 3D Acoustic Doppler Velocimeter (ADV) device known as Vectrino which was manufactured by Nortek AS. The measurement technique is based on the Doppler Effect whereby a short pulse of sound is transmitted by the probe head, and the change in its frequency of the reflected sound pulse is measured by the probe receivers.

A test was conducted to determine the optimum sampling time for velocity measurement that can capture accurately the time-averaged statistics of the velocity and turbulence fields. Results show that the optimum sampling time was one minute for measurement using Vectrino of 200 Hz sampling rate.

The sampling points (black dots) are shown in Figure 1(a) - 1(d) for test 0.97S, 3.90S, 3.90A and 7.79A. The vertical distance between the sampling points is 10 mm for aligned arrangement and 20 mm for staggered arrangement, which in total produces 5 to 19 points depending on the water depth. Detailed information of the velocity measurement can be referred to Table 2.

Table 2 Detailed information of velocity measurement for each vegetation density

Test name	SVF Φ (%)	No of measurement points in x-y plane	No of vertical levels	Vertical increment (mm)
0.97SL	0.974	71	5	20
0.97SH	0.974	71	10	20
3.90SL	3.896	71	7	20
3.90A	3.896	47	8	10
3.90SH	3.896	71	9	20
7.79A	7.792	64	19	10

3.0 RESULTS AND DISCUSSION

The flow within the emergent vegetation is predominantly driven by the pressure gradient compared to the flow in submerged vegetation driven by pressure gradient and turbulent stress [3]. To further understand the flow, several analyses have been conducted including mean velocity, transverse velocity, turbulence Intensity and turbulent kinetic energy. All the velocity data are temporal and space average to eliminate the turbulence and spatial fluctuation due to the flow variation associated with the vegetation structure [3].

3.1 Mean Velocity Distribution

Figure 2(a) presents the transverse profile for normalised longitudinal velocity, $\bar{U}_{xz}/U$ for aligned vegetation arrangement, where $\bar{U}_{xz}$ is time and spatial averaged in x and z directions and U is the cross sectional mean velocity. There is approximately 50% to 60% reduction in velocity, as the vegetation doubles in density from 3.90% to 7.79%. At y/y_{max} equal to 0 and 1 (y_{max} refers to the last point measurement on the right hand side of the control volume), normalised velocities decreased about 40% to 50% compared to the velocity in the middle section of the control volume.

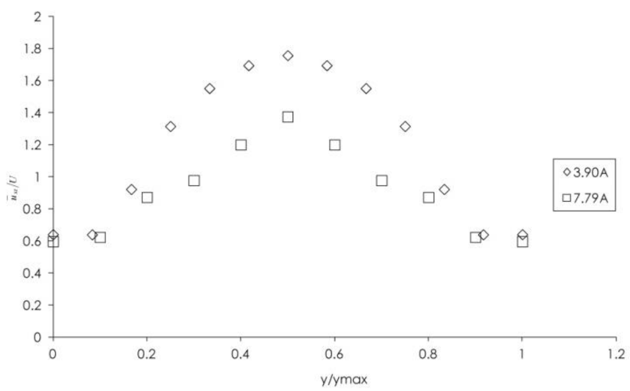
The transverse profile for normalised longitudinal velocity for the staggered vegetation arrangement is presented in Figure 2(b). 0.97SH created the highest normalised velocity profile, followed by 3.90SH, then 0.97SL and 3.90SL produced the lowest normalised velocity profiles. Between the same densities, the vegetation with higher water level generated greater velocity.

The highest longitudinal velocity for the aligned rod arrangement is located at the centreline between the two cylinders (labelled Y6 for test 3.90A and Y5 for test 7.79A see Figure 1) and the lowest velocity is located near the cylinders either at the left or right hand side of the control volume. For the staggered arrangement the highest velocity is located at Y3 which is along the longitudinal centreline between the cylinders and the lowest velocity is located at longitudinal section Y6, the longitudinal section closest to the cylinders.

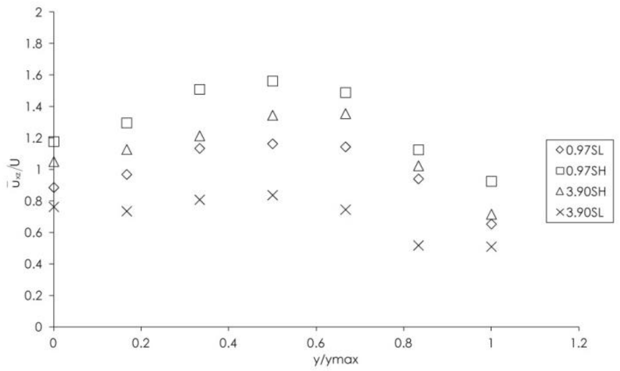
In relation to the above observations, Nepf [3] and White and Nepf [7] divided the velocity field into three regions. The first is the recirculation zone of width *d* (stem diameter) and length γd where according to Gerrard [8], γ is a function of the stem Reynolds number. The second is the wake area downstream of the recirculation zone, where the velocity is positive but diminished from the spatially average velocity. The drag imposed by the surrounding arrays causes the wake profile to decay over the length scale of $C_d a^{-1}$; where C_d is the drag coefficient; and a is the number of vegetation per unit area. Finally the flow in the gaps between the wakes area and recirculation zone, by the conservation of mass must be greater than U.

Velocity deficit (i.e. $\bar{u}_{xz}/U$ lower than 1) in the wake zones and the velocity enhancement (i.e. $\bar{u}_{xz}/U$ greater than 1) zone can be observed in the experimental results. However, the experiment was not able to capture the recirculation zone due to instrument limitation. The nearest possible sampling measurement was about 3 cm or approximately 1*d* (one diameter space) immediately after a dowel.

Another observation is that for the same solid volume fraction, for example test 3.90A and 3.90S with different arrangements of vegetation it was found that aligned vegetation contained higher longitudinal velocity relative to staggered arrangement for the same density. This is according to Li and Shen [9] where the staggered pattern generates more resistance than aligned configuration because the flow has to follow a more tortuous path.



(a) Transverse variation of normalised longitudinal velocity for 3.90A and 7.79A tests



(b) Transverse variation of normalised longitudinal velocity for 0.97S and 3.90S test

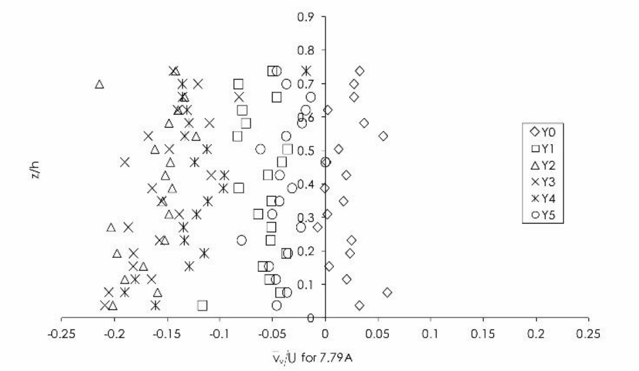
Figure 2 Transverse variation of normalised longitudinal velocity for aligned and staggered vegetation arrangement

3.2 Vertical Variation In Transverse Velocity

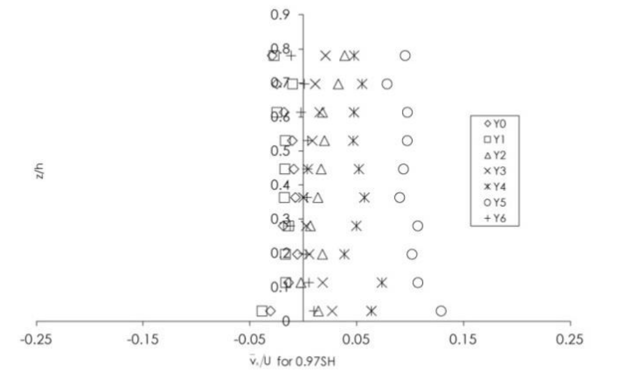
Figure 3(a) and (b) display the normalised transverse velocity for the vegetation density of SVF 7.79% (aligned vegetation) and SVF 0.97% (staggered vegetation), respectively. In the x-y plane, the transverse velocity was spatially-averaged over each longitudinal section and then normalised by the cross-sectional area velocity. The process of averaging the transverse velocity involves positive and negative values of the transverse velocity. Therefore, the spatial averaging process may suppress the true magnitude of the transverse velocity. Hence, a tactful interpretation or analysis of the one dimensional results is definitely required. Vertical profiles of transverse velocities for each cylinder density and arrangement presented in Figures 3(a) and 3(b) are based on regular averaging process, nevertheless the display results will give some indication on the vertical variation of the transverse velocity across the control volume.

The difference in the magnitude and direction of the transverse velocity in the vertical direction reflects the transverse shear within the control volume. According to Zong [10], the positive transverse velocity represents the flow diversion away from the vegetation and the negative transverse velocity implies that there is a flux towards the centre of the wake. Zong [10] conducted an experimental study on the interaction between flow and sediment deposition in the vegetated channel.

Transverse velocities for test 7.79A in aligned arrangement are mostly negative compared to the transverse velocity for test 0.97S in staggered arrangement. This is because in aligned arrangement the wake area dominates both left and right hand sides of the control volume. Possibly due to the difference of the pressure within the wake area which is lower compared to the middle section of the control volume, the transverse velocity will be driven towards the wake area. As previously mentioned by Zong [10] the negative transverse velocity indicates the movement of flux to the centre of the wake. Meanwhile in staggered arrangement, the farthest cylinder is located on the left hand side of the control volume and the nearest cylinder is located on the right hand side of the control volume (looking downstream). Therefore, it is suspected that the recovery wake area is on the left hand side of the control volume and the wake deficit area is on the right hand side of the control volume and the faster velocity area is within the middle section of the control volume. For that reason, probably there is a more positive transverse velocity in the staggered arrangement compared to that in the aligned arrangement.



(a) Profiles of the normalised spatially-averaged transverse velocity for 7.79A test



(b) Profiles of the normalised spatially-averaged transverse velocity $\overline{v}_x/U$ for 0.97 SH test

Figure 3 Profiles of the normalised spatially-averaged transverse velocity $\overline{v}_x/U$ for aligned and staggered vegetation

3.3 Vertical Variation Of Turbulence Intensity

Figure 4(a) presents the vertical variation of the normalised turbulence intensities for 3.90A test (SVF = 3.90%, aligned). The highest turbulence intensity is located at *Y2* (see Figure 1) and there is a possibility that *Y2* is situated within the boundary of the wake area and the fast flowing region. Zavistoski [4] used the term wake edges where the turbulence intensity peaks occur at the locations corresponding to the largest velocity gradient (*du/dy*). The lowest turbulence intensity for 3.90A is positioned at *Y6* at the middle section of the control volume with the fastest longitudinal velocity for the aligned vegetation arrangement. Results from the experiment also show that for aligned arrangement, larger vegetation density (SVF = 7.79%) generated more turbulence intensities compared to the lower vegetation density (SVF = 3.90%). Zavistoski [4] also found similar results where the turbulence intensity increases as the vegetation density increases.

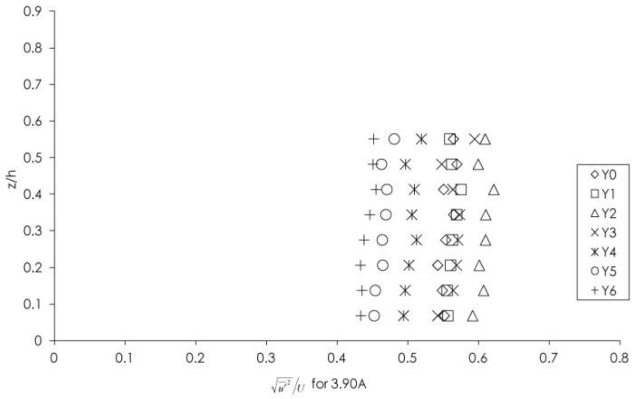
Figure 4(b) shows the vertical variation for the normalised turbulence intensities for 0.97SH test (SVF = 0.97%, staggered, high water level). In this test it was observed that turbulence intensities at *Y5* which are situated at the longitudinal section near to the upstream cylinders produced the highest normalised turbulence intensities. Meanwhile, *Y3* at the middle section of the control volume presents the lowest normalised turbulence intensities. Lui [5] also observed the same situation where the highest turbulence intensities are found immediately downstream of a dowel and the weakest ones are in the free stream region. The former is caused by eddies shedding from the side of the cylinder in an alternating fashion.

The analysis shows that for larger vegetation density more turbulence intensities are generated compared to the lower vegetation density. Zavistoski [4] found similar results where the turbulence intensity also increases as the vegetation density increases. Also it was found that the vegetation with higher water level for the same vegetation density produces more turbulent intensities relative to the vegetation with lower water level. However in Toth *et al.* [11] found the opposite where the vertical average of turbulence intensity increases with the flow depth of the given site. Toth *et al.* [11] examined the turbulent energy dissipation rate based on the instrumentally monitored turbulence intensity under different water levels in relation to the zooplankton community of Lake Balaton, Hungary.

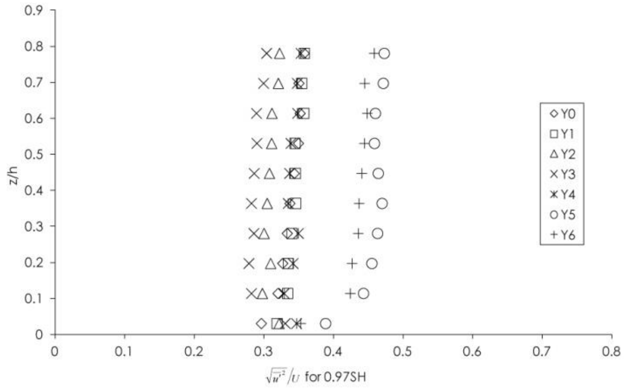
Figure 5(a) presents the average normalised turbulent intensities against vegetation density where the turbulent intensities were spatially-averaged in the longitudinal, transverse and vertical directions and each turbulent intensity was then normalised by the cross-sectional area velocity. Figure 5(a) indicates that there is a positive relation between turbulence intensity and vegetation density, where the turbulent intensities increase with the vegetation density. As previously discussed, this result are similar to Zavistoski [4] and Stoesser *et al.* [12] where the spatially-averaged turbulence intensity increases with the vegetation density because there are more wakes present to generate more turbulence [4].

Figure 5(b) displays the relation between the averaged normalised turbulent intensities and the stem Reynolds number where turbulent intensities decrease with the increment of the stem Reynolds number. In this experiment the stem Reynolds numbers were between 1000 and 3000 and based on the flow structure past a single emergent cylinder, for stem Reynolds number up to 1000, an increase in the Reynolds number corresponds to an increase in the turbulence level within both the free stream and the cylinder wake but as the turbulence levels in the free stream increase (up to stem Reynolds number 200000) the contribution of the cylinder wake to the total turbulence level of the flow decreases [13], [1].

Figure 5(c) shows that there is a weak positive relation between the averaged normalised turbulent intensities and the flow depth, h. Flow depth is often used in the open channel study as the characteristic length scale because the flow depth determines the size of the turbulence eddies which transport mass [14]. However, according to Nepf [15] and Tanino and Nepf [16] the integral length scale of turbulence is set by the canopy scale; i.e. the stems diameter, *d* and the nearest-neighbour stems spacing, *S*. If the stems diameter is smaller than the nearest-neighbour stems spacing, the integral length scale is stems diameter. Likewise if the stems diameter is larger than the nearest-neighbour stems spacing, the integral length scale is the nearest-neighbour stems spacing.

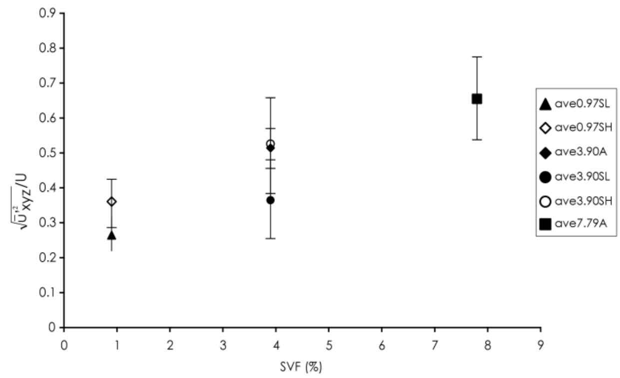


(a) Normalised turbulent intensities for 3.90A test

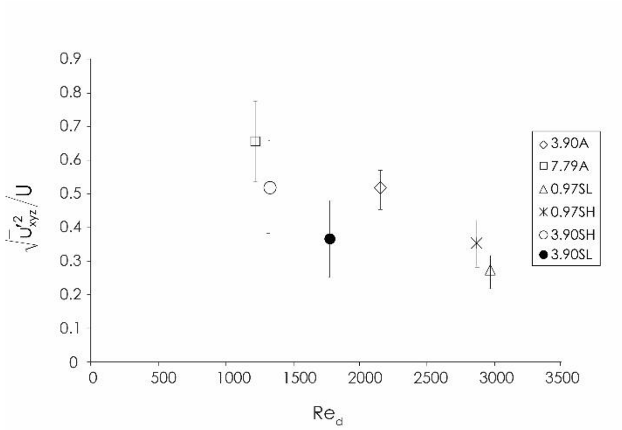


(b) Normalised turbulent intensities for 0.97SH test

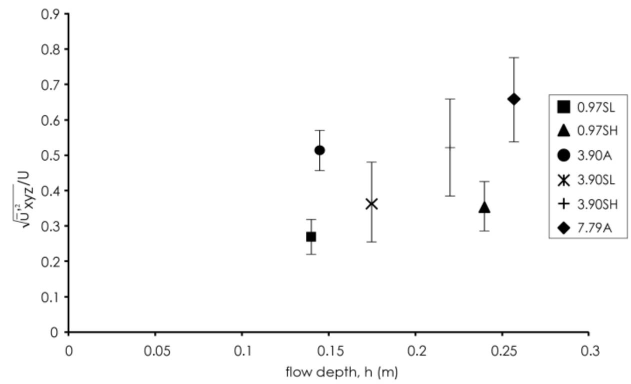
Figure 4 Normalised turbulent intensities $\sqrt{u_x'^2}/U$ for aligned and staggered vegetation



(a) Normalised turbulent intensities plotted against SVF



(b) Normalised turbulent intensities plotted against Reynolds number



(c) Normalised turbulent intensities plotted against flow depth

Figure 5 (a) Normalised turbulent intensities plotted against SVF, stem Reynolds number and flow depth

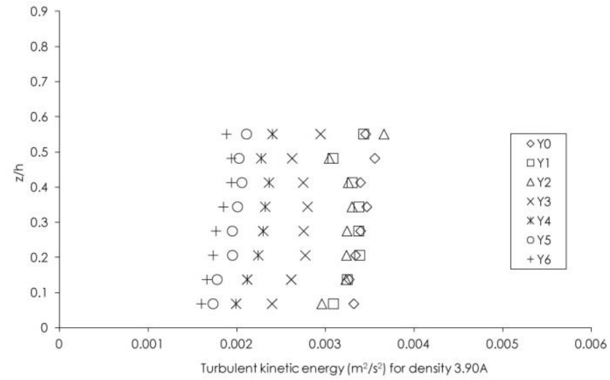
3.4 Vertical Variation Of Turbulent Kinetic Energy

Figure 6 represents the vertical profiles of longitudinal-averaged turbulent kinetic energy for (a) 3.90A test and (b) 3.90SH test. The lowest turbulence kinetic energy for aligned arrangement located at the central section of the control volume (Y6 for 3.90A test) and the magnitude of the turbulent kinetic energy increases towards the dowels at Y0. Meanwhile for the staggered arrangement (3.90SH), the highest turbulent kinetic energy is located at Y6 for 3.90SH which was located at the longitudinal section closest to the upstream cylinder. However, the lowest turbulence kinetic energy for the vegetation density of 3.90SH was not at the centre line of the control volume but shifted to Y1 which is more to the left hand side of the control volume (looking downstream).

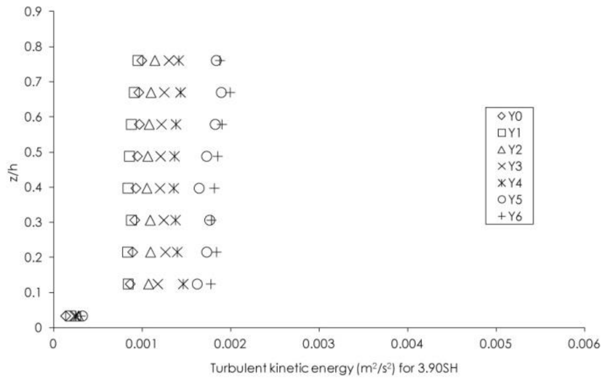
Figure 7(a) shows the spatially-averaged turbulent kinetic energy (TKE_{xyz}) against the stem Reynolds number which reflects a weak positive correlation (the turbulent kinetic energy increases as the stem Reynolds number increases) between the turbulent kinetic energy and stem Reynolds number. This positive correlation would be expected as higher stem Reynolds number is associated with higher turbulence level.

Meanwhile 7(b) plots the spatially-averaged turbulent kinetic energy (TKE_{xyz}) against the flow depth and there is no observable trends that can be captured between TKE_{xyz} and flow depth. In an unobstructed open channel, the flow turbulent length scale is set by flow depth; however in the vegetated channel the stems impinge on the channel scale eddies and these eddies are broken apart and the turbulence is then rescaled to the stem geometry [17].

Figure 7(c) presents the spatially-averaged turbulent kinetic energy against the solid volume fraction and the results display a weak negative relation (the turbulence kinetic energy decreases as the solid volume fraction increases) between the spatially-averaged turbulent kinetic energy and vegetation density. According to Nepf [17] changes in the turbulent kinetic energy reflect the competing effects of reduced velocity and increased turbulence production. These opposing tendencies produce a nonlinear response in which the turbulence levels initially increase with the increasing stem density, but eventually they decrease as the vegetation density increases further.

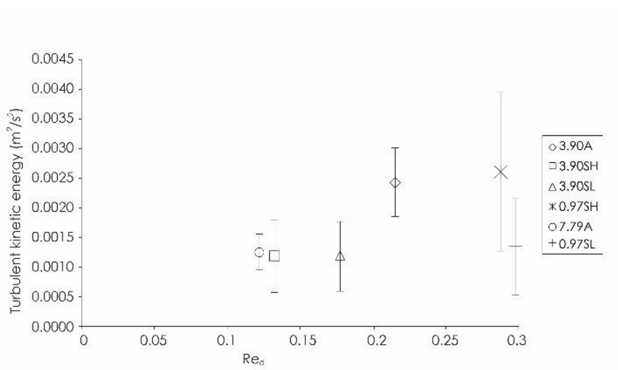


(a) Turbulent kinetic energy in X-axis for 3.90A test

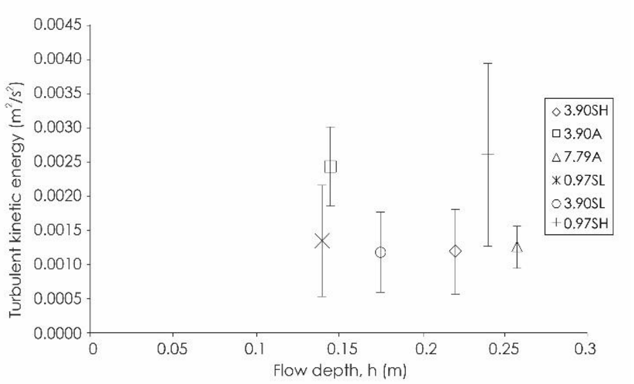


(b) Turbulent kinetic energy in X-axis for 3.90SH test

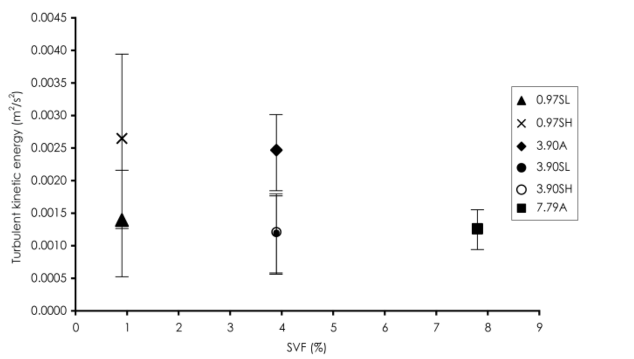
Figure 6 Profiles of the turbulent kinetic energy (TKE_x) for aligned and staggered vegetation



(a) Turbulent kinetic energy for axis X, Y and Z (TKE_{xyz}) plotted against stem Reynolds number



(b) Turbulent kinetic energy for axis X, Y and Z (TKE_{xyz}) plotted against flow depth



(c) Turbulent kinetic energy for axis, X, Y and Z (TKE_{xyz}) against SVF

Figure 7 Turbulent kinetic energy for axis X, Y and Z (TKE_{xyz}) plotted against stem Reynolds number, flow depth and SVF

4.0 CONCLUSIONS

Detailed and systematic velocity measurement was carried out to study the velocity profile for flow through vegetation. The analysis shows that normalised longitudinal velocity reduces around 50% as the vegetation density doubles and shallow water depth generates greater flow resistance compared to high water depth. Further analysis reveals that the negative transverse velocities dominate in aligned vegetation and positive transverse velocities dominate in staggered vegetation. Positive transverse velocity represents the flow diversion away from the vegetation and the negative transverse velocity indicates the flux of flows toward the centre of the wake. Normalised longitudinal turbulence intensity displays the highest magnitude at the wake edge. Also, the normalised longitudinal turbulence intensity presents a negative trend with the stem Reynolds number which indicates lower magnitude of turbulence in the fast flowing region. This is similar to the turbulent kinetic energy that is lowest at the fast flow region located at the centre of the control volume. Meanwhile, the magnitude of the turbulent kinetic energy increases in the wake area downstream the vegetation. To conclude the present experimental study manages to capture the wake area (velocity deficit zone) and the fast flow region.

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