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**A comparison of two-dimensional and three-dimensional flow structures
over artificial pool-riffle sequences**

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Abstract

Experiments have been carried out in a flume with one 2D pool-riffle sequence and one 3D pool-riffle sequence, respectively. Objectives of this study are to determine whether or not the convergence of lateral flow exists. Variations of the near-bed shear stress have been studied. The characteristics of the secondary currents along a pool-riffle sequence have been investigated. Results showed that for the 3D pool riffle sequence, the near-bed velocity decreases along convective deceleration flow (CDF) and increases convective acceleration flow (CAF), respectively. It is found that the shear velocities estimated from the slope of the velocity gradient in the inner layer, decreases in the CDF section, and increases in the CAF section in the 3D pool riffle sequences. The Reynolds shear stress is highest at the CDF section along longitudinal lines with distances of 10 cm and 20 cm away from the channel wall.

Keywords: accelerating flow, decelerating flow, pool riffle sequence, secondary current, shear stress.

1. Introduction

Although the pool-riffle sequence has been widely studied by many researchers, several key aspects of pool-riffle bed form have not been investigated, such as the 3D flow structures over pool-riffle sequences. Both pools and riffles are three dimensional bed forms. These bed forms have been resulted as the stream flow structure alternates from areas of relatively shallow to deeper water. As a consequence, the interactions with three-dimensional flow and complex patterns of sediment transport lead to the formation of the pool-riffle sequence. Furthermore, pools and riffles are usually not well defined, resulting in the possible discrepancies between experimental studies and what actually exists in the field.

Up to date, researchers have investigated some important hydrodynamic processes including the reverse relationship between flow velocity near channel bed and the stage (Keller 1971; Clifford and Richards 1992), the generation of turbulent vortices (Hassan and Woodsmith 2004; Thompson 2002, 2006, 2007), and the lateral convergence and divergence of flow (Booker et al. 2001; MacWilliams et al. 2006; Sawyer et al. 2010) with associated phase shifts in shear stress (Wilkinson et al. 2004). As claimed by Clifford and Richards (1992) and Thompson et al. (1996), the flow convergence and divergence normally occur in the pool head section and pool tail section, respectively. Hassan and Woodsmith (2004) pointed out that sediment particles tend to be delivered with lower shear stresses in the pool than those in other channel sections. Clifford (1996) observed that the pool head section has higher turbulence intensity. Thompson (2002, 2004) found a shear zone at the downstream section of the obstruction in a forced pool which tends to generate turbulent vortices that may also be important for pool scour (Thompson 2006, 2007). In a pool-riffle sequence which is forced to get formed by a fallen tree, at the bankful discharge, MacVicar and Roy (2007a, 2007b) presented a reverse relationship between the near-bed flow velocity and stage, turbulent vortices and lateral convergence and divergence of flow. Their results indicate that multiple processes may occur simultaneously (MacWilliams et al. 2006; Thompson and Wohl 2009).

To link research results based on field measurements with concepts of hydraulics of open channels, experimental study in laboratory is an useful method for investigating the influence of a non-uniform channel boundary on the distribution of mean flow and turbulence. As we known, characteristic vertical profiles of both flow velocity and Reynolds stress develop due to a balance between the driving force caused by gravity and the resistance force resulted from the channel bed and channel walls. Flow depth in a pool will first increase and then

decrease from the pool head to pool tail, and thus, it leads to a decelerating flow (DF) with a positive pressure gradient, followed by an accelerating flow (AF) with a negative pressure gradient. The inertial effect of flow showed that, in the outer flow zone farther away from the channel bed, flow velocity in the stream-wise direction remains relatively high in the DF section and relatively low in the AF section (Coles 1956; Perry and Joubert 1963; Kironoto and Graf 1995; Song and Chiew 2001; Yang and Chow 2008).

Imbalances between the production and dissipation of turbulence far away from the boundary lead the distribution of turbulence to have different patterns in non-uniform channels (Best and Kostaschuk 2002; Blanckaert 2009; Van Balen et al. 2009). The Reynolds stress, which is a criterion for assessing the turbulent exchange of momentum, tends to increase above the channel bed in the DF section compared to that for uniform flow due to the production of new turbulence; and decrease in the AF section due to the suppression of turbulence (Kironoto and Graf 1995; Krogstad and Skåre 1995; Warnack and Fernholz 1998; Song and Chiew 2001; Yang and Chow 2008; Lee and Sung 2009; Lee et al. 2010).

Einstein and Shen (1964) demonstrated that a meandering thalweg has been generated on the bed of a straight laboratory channel. Einstein and Shen (1964) claimed this meandering thalweg has been formed by the action of twin surface convergent cells of secondary flow, induced purely by wall turbulence. The appearance of the cellular secondary flow may cause lateral sediment transport, which can in turn enhance and maintain longitudinal bedforms (Karcz 1966; Nezu et al. 1988). Müller and Studerus (1979) reported that up-flows occur over the smooth strips and down-flows over the rough strips forming a pair of counter-rotating flow cells with a diameter which is the same as the flow depth. Nezu and Nakagawa (1984) carried out experiments over artificial longitudinal ridges of 45° trapezoidal cross-section. They found a pair of counter-rotating flow cells, the up-flows occurred over the ridge and down-flows over the trough. Experimental studies in laboratory regarding cellular secondary flows have also been conducted by Wang et al. (2003 and 2004) and Wang and Cheng (2005), among the others. Onitsuka and Nezu (2001) found that the established fluid movements and the associated sediment transport occurred alternatively on movable plane sand. They also claimed that the cells of secondary-currents became stable in the entire cross section, and this lead to the formation of sand ridges. Wang and Cheng (2006) conducted experiments in laboratory with six artificial rigid bed forms including alternate bed strips with different roughness heights. Wang and Cheng (2006) found that down-flow occurred

over rough strip or trough whereas up-flow occurred over smooth strip or ridge. Their results suggested that the time-mean secondary flows could be reasonably described by simple analytical expressions in the sinusoidal form, which could be applied for various secondary flow structures with different patterns.

Bed forms are defined by changes in bed elevation that will produce accelerating, decelerating and more uniform sections (Radhakrishnan et al. 2006). Over dunes, steps and bumps, transitions between three mentioned sections commonly are characterized by flow separation and reattachment point of the boundary layer (Best 2005). Some researchers claimed that in macro scale pools, bed gradients were normally milder and a fully developed flow separation was not expected to occur (Carling and Orr 2000; MacVicar and Roy 2007b, MacVicar and Rennie 2012).

Most researchers focused their research work on the pool-riffle morphology based either on one-dimensional or two-dimensional flows, ignoring the effect of lateral variability in non-uniform open channels; such as, over dunes (Best and Kostaschuk 2002; Venditti 2007; Macvicar and Rennie 2012), over bumps (Webster et al. 1996) and in numerical studies (Grigoriadis et al. 2009; Lee et al. 2010), to mention only a few. Since lateral and vertical variability of flow characteristics play a very important role in the evolution of a pool-riffle sequence in nature, the existing pool hydrodynamics based on either one-dimensional or two-dimensional flows remains unclear.

Along a river reach with a natural pool-riffle sequence, channel width changes; lateral bars may appear; channel sinuosity exists; bed particles get delivered, etc. A lot of aspects regarding the pool-riffle sequence need to be further investigated. In present study, the objectives are (1) to determine whether or not the convergence of lateral flow exists, and if the increased turbulence appears in the simplified pool-riffle sequence morphology; (2) to investigate variations in near-bed shear stress over the pool-riffle sequence; (3) to study the characteristics of the secondary flows along a river reach with pool-riffle sequence.

2. Experiment setup

Experiments have been carried out in a rectangular flume that is 16m long, 0.9m wide and 0.6m deep in the hydraulic laboratory, Isfahan University of Technology, Iran. The channel

bed and sidewalls of the flume were made of glass, and the flume bed is horizontal with the bed slope of zero. A tailgate located at the end of the flume was used to control water level during experiments. Flow depths were measured by using a point gauge with 1mm increment. A pump with a maximum discharge of 50Liter/s (with the accuracy of $\pm 0.5\%$) was used to circulate water from a sump. The flow discharge was measured by an electromagnetic flow meter. The normal flow depth of 0.26cm in the channel, measured before bed forms when channel-bed slope is zero and the corresponding width-depth ratio (aspect ratio) was 3.5. Flow conditions have been chosen in such a way to compare our results to those of other studies. The median diameter of sediment (d_{50}) was 10mm with the geometric standard deviation $\sigma_g = (d_{84}/d_{16})^{0.5}$ of 1.14, where d_{84} and d_{16} are 84% and 16% finer particle diameters, respectively. To compare our results to those of existing research works (e.g., Fazlollahi et al. 2015b), sediment grain size in our study was similar to those of others. The flexible carton-plast sheets were used to shape the channel bed. Then, gravel grains were attached to the channel bed. The gravel grains were flattened by applying pressure on carton-plast sheets to eliminate large scale variations of bed form topography. The channel section of a riffle-pool-riffle sequence started at the cross section 9.5 m downstream from the flume entrance. To compare our results to those of other researchers, dimensions of bed form in our study have been decided based on the existing studies (e.g. Fazlollahi et al. 2015b; MacVicar and Rennie 2012). The wavelength of the artificial bed form sequence was 2 m from the upstream wave-crest to the downstream wave-crest. In the stream wise direction, both entrance slope and exit slope of the pool were constructed with a slope of 15° . Flow depth changes along the following 5 sections, namely, flow depth above the upstream wave-crest was shallow, then increased along the entrance slope of pool, increased to a constant of deepest in the middle of the pool, decreased along the exit slope of pool and then became the shallowest over downstream wave-crest. In total, 22 cross sections for measurements have been set up along this riffle-pool-riffle sequence. The spacing distance between adjacent cross sections was 10 cm. Data collections have been conducted at these 22 cross sections for all experimental runs. In present research, as shown in Figure 1a and Figure 1b, two types of bedform were used to represent two-dimensional and three-dimensional pool-riffle sequences, respectively. For the 2D pool-riffle sequence, two profiles were measured at each cross section, one profile was measured at the center of channel and another one located at a distance of 20 cm from the left channel wall of channel. However, for the 3D pool-riffle sequence, the thalweg was centered along pool-riffle sequence. In addition to collecting data along the central axis (thalweg), data were also collected along other three lines which were located at a distance of 10cm, 20cm

and 30cm from the left channel wall, respectively. Therefore, along each longitudinal axis, 22 profiles were obtained, as shown in Figure 1c. For each bed form with different geometries, experiments have been carried out with following three discharges, 21.4L/s, 25L/s and 30L/s. However, due to space limitation, only research results under flow condition with the maximum discharge (30 Lit/s) are presented in this study.

In this experimental study, a period of two-minutes for data collection has been set up. Three-dimensional velocity components were recorded using a downward looking 3D Acoustic Doppler Velocimeter with a frequency of 200 Hz. The down looking ADV sensor is equipment which is able to use to collect data near the bed (for example, 3mm near the bed, depending on the sampling volume selection). However, the down looking ADV device is unable to collect data in the zone from water surface to a depth of 5 cm below water surface. Measured data showed that there is no difference between results using 2-minutes data sampling and those using 5-minutes data sampling. Velocity spikes were removed using the phase-space despiking algorithm in the free software package WinADV (Goring and Nikora 2002). Velocity profiles were visually inspected to remove improper data. Sometimes, improper data occurred near the rough bed where minor variations in gravel position and location might affect signal quality for collecting data, especially about 10 cm from the boundary, where the reflectance from the bed contained poor quality data series (MacVicar and Rennie 2012). The pool-riffle morphology used in present experiments was measured by using a ruler, with the accuracy of $\pm 1\text{mm}$, installed on the frame which was set up at tracks above the flume.

3. Theoretical background

3.1. Statistical description of velocity and turbulence

Instantaneous velocity in the stream-wise (u), lateral (v), and vertical (w) directions were decomposed into time-averaged components ($\bar{u}$, $\bar{v}$, $\bar{w}$) and turbulent components (u' , v' , w'):

$$u = \bar{u} + u' \quad v = \bar{v} + v' \quad w = \bar{w} + w' \quad (1)$$

In the zone close to the channel bed (i.e., the inner zone), the stream-wise velocity follows the law of the wall, and can be written as following (Mac vicar and Rennie 2012):

$$\frac{u}{u^*} = \frac{1}{\kappa} \ln \left(\frac{z}{z_0} \right) \quad (2)$$

Where, u^* is the shear velocity, κ is the von Karman coefficient ($\kappa=0.4$), z is the height above the bed, and z_0 is the reference bed level ($z_0=d_{50}$). In this study, the calculated shear velocity by means of the wall law is named u_{in}^* .

Equation 2 is a universal equation. As pointed out by White (1991) that Equation (2) is independent of the pressure gradient. Therefore, changes of flow condition due to changes in geometric conditions do not affect the validity of this universal law. In addition, as stated Barenblatt (1982) that this law is an empirical law and its validity does not justify any theoretical base for its development.

The important component of Reynolds stress was calculated from turbulent fluctuations in the stream-wise and vertical directions:

$$\tau_R = -\rho \overline{u'w'} \quad (3)$$

where, ρ is the fluid density. The Reynolds stress at the bed (τ_R) was estimated at the bed reference level from the shear stress profile which is the output of WinADV. This gave a second estimate of the shear velocity ($u_R^* = \sqrt{\tau_R/\rho}$). This method, sometimes, is sensitive to measurement errors due to steep gradients in Reynolds stress in non-uniform flow at the bed (Song and Chiew, 2001; Yang and Chow, 2008). Also, shear stress was estimated from a calibrated relation with the turbulent kinetic energy (MacVicar and Rennie 2012):

$$\tau_{tke} = 0.5 \rho c_2 (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (4)$$

where, c_2 is a constant with an approximately value of 0.2. From Equation 4, the shear velocity can be also estimated as $u_{tke}^* = \sqrt{\tau_{tke}/\rho}$. As pointed out by Biron et al. (2004), this method was recommended for the complex flows because it does not assume a particular shape for the velocity profile. This method is similar to Reynolds stress method (u_R^*), using turbulent fluctuations, however, u_{tke}^* applies all three velocity components in the stream-wise, lateral, and vertical directions.

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231 3.2. Secondary flow mechanism

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The characteristics of secondary flows are hard to obtain because they easily fluctuate and change under different flow conditions. Therefore, a coefficient can be used to describe the rotational direction and the intensity of the secondary flows. All three components of velocity vector change along the vertical axis and the maximum value of stream wise velocity component often appears below the free surface because of the dip phenomenon due to the influence of the secondary currents (Yang et al. 2004). All three velocity components can be used to effectively represent secondary flow. It is assumed that all components could be expressed, in terms of the depth-averaged stream wise velocity (U_d), as following:

$$u = m_1 U_d, \quad v = m_2 U_d, \quad w = m_3 U_d \quad (5)$$

or

$$m_1 = \frac{u}{U_d}, \quad m_2 = \frac{v}{U_d}, \quad m_3 = \frac{w}{U_d} \quad (6)$$

where, m_1 , m_2 and m_3 are dimensionless coefficients. Then, the product of each couple velocity components can be expressed as follows:

$$uv = m_1 m_2 U_d^2 \quad vw = m_2 m_3 U_d^2 \quad uw = m_1 m_3 U_d^2 \quad (7)$$

By integrating each part of Equation 7 from zero to the maximum measured depth (H), the depth-averaged of uv , vw and uw can be obtained as follows:

$$\begin{aligned} (uv)_d &= \frac{1}{H} \int_0^H uv dz = \left[\frac{1}{H} \int_0^H m_1 m_2 dz \right] U_d^2 = M_{12} U_d^2 \\ (vw)_d &= \frac{1}{H} \int_0^H vw dz = \left[\frac{1}{H} \int_0^H m_2 m_3 dz \right] U_d^2 = M_{23} U_d^2 \\ (uw)_d &= \frac{1}{H} \int_0^H uw dz = \left[\frac{1}{H} \int_0^H m_1 m_3 dz \right] U_d^2 = M_{13} U_d^2 \end{aligned} \quad (8)$$

where, M_{12} , M_{23} and M_{13} are defined as the secondary flow coefficients:

$$M_{12} = \frac{(uv)_d}{U_d^2} \quad M_{23} = \frac{(vw)_d}{U_d^2} \quad M_{13} = \frac{(uw)_d}{U_d^2} \quad (9)$$

3.3. Basic equation for production term of secondary currents

The turbulence induced by secondary currents in an open channel flow is explained well by the longitudinal vorticity equation. The distribution of the velocity difference ($v^2 - w^2$) plays an essentially important role, as was pointed out by Einstein and Li (1958). The differences in secondary currents can be explained by the difference of the ($v^2 - w^2$) distribution, in the

following way. The longitudinal vorticity equation in a fully-developed turbulent flow is given as follows:

$$v \frac{\partial \xi}{\partial y} + w \frac{\partial \xi}{\partial z} = \frac{\partial^2}{\partial y \partial z} (v'^2 - w'^2) - \left(\frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} \right) \overline{v'w'} + \nu \left(\frac{\partial^2 \xi}{\partial y^2} + \frac{\partial^2 \xi}{\partial z^2} \right) \quad (10)$$

where, $\xi = \partial w / \partial y - \partial v / \partial z$. The last term of in Equation 10, the viscous term, is neglected except very near the wall. The convection term of the left-hand side can be approximately neglected, according to the examination of Nezu and Nakagawa (1984). The Reynolds shear stress $-\overline{v'w'}$ can be expressed using the eddy viscosity model as follows:

$$-\overline{v'w'} = \varepsilon_{yz} \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \quad (11)$$

where, ε_{yz} is the eddy viscosity coefficient. Then, the secondary current velocity components v and w are expressed using stream function ψ as follows:

$$v = -\frac{\partial \psi}{\partial z}, \quad w = \frac{\partial \psi}{\partial y} \quad (12)$$

Substituting Equations 11 and 12 into Equation 10, the following equation can be obtained:

$$\left(\frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} \right) \varepsilon_{yz} \left(\frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} \right) + \nu \left(\frac{\partial^4 \psi}{\partial z^4} + 2 \frac{\partial^4 \psi}{\partial y^2 \partial z^2} + \frac{\partial^4 \psi}{\partial y^4} \right) = \frac{\partial^2}{\partial y \partial z} (v'^2 - w'^2) \quad (13)$$

ε_{yz} remains unknown, since it is quite difficult to determine $-\overline{v'w'}$ in open channel flows. Therefore, the distribution of ε_{yz} is assumed to be given as a parabolic function. It is the distribution of $(v'^2 - w'^2)$ that controls the structure of the secondary currents, as pointed out by Gerard (1978).

4. Results and discussions

4.1. Stream-wise velocity

In the constructed pool riffle sequence, the velocity distribution changes as a result of accelerating flow (AF) and decelerating flow (DF). Figures 2a-2d displayed the velocity profiles along the longitudinal lines with a distance of 10 cm, 20 cm, 30 cm and 45 cm from left channel wall of the 3D pool riffle sequence (facing downstream), respectively. Along all these four longitudinal lines, the near-bed velocity decreases along the convective deceleration flow (CDF) section as flow depth increases. Also along all these four

longitudinal lines, near-bed velocity is relatively high along the convective acceleration flow (CAF) section as flow depth decreases. Results showed that, velocities near channel bed along the central line for the 2D pool riffle sequence (Figure 2e) are larger than those for 3D pool riffle sequence (Figure 2d) in all parts. Also, for 2D pool riffle sequence, the near-bed velocities decreased along the decelerating flow (DF) section, similar to that for the 3D pool riffle sequence.

Flow separation did not occur along the longitudinal line of 10cm which is the closest to the channel wall, but separation zone appeared with increasing distance from the channel wall. For the longitudinal line of 20 cm away from the channel wall, flow separation started at the decelerating flow section. For the longitudinal line of 30 cm away from the channel wall, flow separation started from the upstream riffle, and was extended to the beginning deepest part of the pool. However, for the longitudinal line of 30 cm away from the channel wall, the separation zone develops and covered one-half of the deepest part of the pool. While along the central longitudinal line of the pool riffle sequence (45 cm away from channel wall), and the area of flow separation zone decreased and was almost limited to the channel section from the end of the entrance slope to the middle of the deepest part of the pool, with a distance of 120 cm from the beginning part of the upstream riffle. In contrast of all mentioned above, along the central line of the 2D pool riffle sequence, there is a small separation zone started near the end of entrance slope, and disappeared in the deepest part of the middle of the pool.

Despite the differences in shear velocities estimated from the slope of velocity gradient in the inner layer (u_{in}^*), generally, shear velocity decreases in the DF section, and increases as flow depth decreases (AF section) along all longitudinal lines with different distances from the channel wall (Figure 2f). Results indicated that, with the exception of the longitudinal line of 20 cm away from the channel wall, the u_{in}^* trend along other longitudinal lines was nearly symmetric to the middle point of the pool, which would indicate that shear velocity is mainly a function of flow depth. This finding is in accordance of the research work performed by MacVicar and Rennie (2012), however, their research result was only along the central axis of the channel. Results showed that, along the longitudinal lines of 30 cm and 45 cm away from the channel wall, shear velocities in the AF section are greater than the corresponding values in the DF section. This finding is reasonable, because near-bed velocity in the AF

section is greater than that in the DF section. Along the longitudinal lines of 10 cm and 20 cm away from the channel wall, however, trends of velocity values were not similar to those of along the longitudinal lines of 30 cm and 45 cm away from the channel wall. It is found that, along the longitudinal lines of 10 cm and 20 cm away from the channel wall, there were little differences between shear velocities in the AF section and those in the DF section.

4.2. Turbulence along the channel central line

Due to the presence of bed form as pool riffle sequence, it resulted in the CAF and CDF in the channel. Thus, the shape of Reynolds shear stress profiles deviated from the shape of Reynolds shear stress profiles for uniform flow, as showed in Figures 3a-3e. For both 2D pool riffle sequence and 3D pool riffle sequence, when the distance from the start upstream riffle (x) is in the range of 20-50 cm, under condition of normal flow, shear stress is typically highest near the bed surface and linearly approaches zero at the water surface, as is expected in uniform flow (Nezu and Nakagawa 1993). For the 3D pool riffle sequence, however, with approaching to the channel wall, shear stress profiles were more deformed than those for uniform flow. The presence of strong secondary flow and cross currents might be responsible for this deformed shear stress profiles. For both the 3D pool riffle sequence and the 2D pool riffle sequence, and for all distances from the channel wall, along the entrance slope of the pool, the maximum Reynolds shear stress occurs at a large distance away from the bed surface. This effect occurs in the CDF due to positive stream-wise pressure gradients that leads to increased shear (Krogstad and Skåre 1995; Yang and Chow 2008; Lee et al. 2010). For the 3D pool riffle sequence, the magnitude of Reynolds shear stress is the highest at the CDF section along the longitudinal lines of both 10cm and 20 cm from the channel wall, as shown in Figures 3a and 3b. However, along other two longitudinal lines of 30 cm and 45 cm (central line) away from the channel wall for the 3D pool riffle sequence, and also along the channel central line for 2D bed form, the highest shear stress is moved toward the middle of pool (Figures 3c, 3d and 3e, respectively). At the end of the exit slope of pool, although the shear stress profile is still affected from CAF section, the distribution of shear stress at the downstream of the pool tends toward the distribution observed at the upstream limit of the pool.

The shear velocity at the reference bed level (u_R^*) estimated from Reynolds shear stress displays similar trends to u_{in}^* , as shown in Figure 3f. In general, u_R^* decreases in the CDF section, approaches a minimum in the middle of the pool, and increases in the CAF section. It is noteworthy that only along the longitudinal lines of 30 cm away from the channel wall, u_R^* is greater in CDF section than that in CAF section. Along all other longitudinal lines, there is a reverse trend. However these differences are small along other longitudinal lines. These results aren't consonant to the u_{in}^* results; as along the longitudinal lines of 30 cm and 45 cm away from the channel wall, the shear velocities (u_{in}^*) are higher along the exit slope of the pool comparing to those along the upstream slope of the pool. However, there are reverse results along other longitudinal lines. Results indicated that, along the entrance slope of the pool and the pool section, the shear velocities estimated from turbulence is higher than the shear velocities estimated from time-averaged velocities. However, along the exit slope of the pool, the values of u_{in}^* are higher than u_R^* . Along both upstream and downstream riffle sections, along all longitudinal lines, shear velocities estimated from the velocity gradient are higher than those estimated from Reynolds shear stress.

It is not expected that, when flow passes through the pool, the maximum Reynolds stress happen at the bed surface. As shown in Figure 3g, for the 3D pool riffle sequence, the shear velocity was calculated from the maximum Reynolds shear stress in each profile (u_{Rmax}^*) along all four longitudinal lines with different distances away from the channel wall. The maximum value of u_{Rmax}^* was different along different longitudinal lines away from the channel wall. Along the central line, the maximum u_{Rmax}^* appeared at a distance of 130 cm from the beginning upstream riffle. With approaching to the channel wall, the location of the maximum u_{Rmax}^* is moved to the transition from the normal flow to the CDF. However, there are some irregularities along the longitudinal line of 10 cm away from the channel wall, and the maximum u_{Rmax}^* appeared in the middle of the pool. Regarding the trend of u_{Rmax}^* values, despite the irregularities, the higher u_{Rmax}^* values generally occurred in the middle of pool and the u_{Rmax}^* values decreased toward both the upstream riffle and downstream riffle. The minimum values of u_{Rmin}^* along the channel central line, occurred just at the transition from

CAF back to the downstream riffle, while along other three longitudinal lines, the minimum values of $u_{R\min}^*$ values occurred at the upstream riffle.

Changes in lateral component of turbulence does not appear in the principal Reynolds shear stress but is included as v'^2 term in u_{tke}^* , as shown in Figure 3h. The trends of both u_R^* and u_{tke}^* are similar. Although there are some irregularities in u_{tke}^* values, the lowest u_{tke}^* occurred at the pool. The comparison between u_R^* and u_{tke}^* along the channel section from the upstream riffle to the middle of exit slope of pool showed that, the values of u_{tke}^* are less than u_R^* along all four longitudinal lines. Whilst, along the channel section from the middle of pool exit to the downstream riffle, the values of u_{tke}^* are more than u_R^* , along longitudinal lines of 10 cm and 30 cm away from the channel wall. It is found that lateral turbulence exchanges are important in these zones. Overall, u_{tke}^* values indicate that shear stresses as a result of three-dimensional turbulence are higher than shear stresses calculated from the principal Reynolds stress (u_R^*) along the channel section of the final 30% of pool riffle sequence.

4.3. Mechanism of the secondary flow

For the 3D pool riffle sequence, the dimensionless coefficients, m_1 , m_2 and m_3 are calculated for different parts of pool riffle sequences, as the calculation example showed in Figure 4. Results showed that, everywhere along this 3D pool riffle sequence, the dimensionless coefficient m_1 is dominant and the fluctuation of this coefficient profile is larger than two other dimensionless coefficients. This is expected because the velocity gradient in the stream wise direction is larger than those of along other two directions for velocity components. The dimensionless coefficient m_1 has the same results along the 2D pool riffle sequence.

Investigation of the products of dimensionless coefficients of m_1m_2 , m_2m_3 and m_1m_3 has been performed for all profiles. Figure 5 showed an example of the products of dimensionless coefficients for the 3D pool riffle sequence. Results of these profiles indicated that, for the 3D pool riffle sequence, the maximum gradient of m_1m_2 profiles, are larger than those of m_2m_3 and m_1m_3 profiles for almost all sections of the pool riffle sequence (except for entrance slope of pool) and all longitudinal lines away from the left channel wall. It has been proved

that the intensity of the secondary flow is much stronger at the x-y surface. Also it has been demonstrated that the changes from the channel bed to the water surface have almost the same trend as those of m_2 . Whereas, except at the upstream riffle, for all other parts of the 2D pool riffle sequence, the product of dimensionless coefficient of m_1m_3 had the largest gradient.

Except for downstream riffle, for all other parts of the 2D pool riffle sequence, results showed an increasing trend in the intensity of secondary currents. It has been noticed that there exists little difference between the trend in the intensity of secondary currents along the 2D pool riffle sequence and that along the 3D pool riffle sequence. At the upstream riffle of the 3D pool riffle sequence, in the direction of flow, regular trend for intensity of the secondary flow has not been noticed. However, in the section of the entrance slope of the pool, along all longitudinal lines away from the left channel wall, the intensity of the secondary flow is increased with the highest increase along the longitudinal line of 20 cm away from the left channel wall. The increase in the intensity of secondary flow is continued to the end of the entrance slope of pool. Then, the intensity of secondary flow decreases in the deep pool along all the longitudinal lines away from the left channel wall, except the longitudinal line of 10 cm. However, the biggest decrease occurs along the longitudinal line of 20 cm away from the left channel wall. Along the channel section from the end of deep pool to the end of the exit slope, the intensity of secondary flow varies depending on the distance from the channel wall. The intensity of secondary flow is increased along the longitudinal lines of 20 cm and 30 cm away from the channel wall, however, it is decreased along the longitudinal lines of 10cm and 45 cm away from the channel wall. Results showed that the decreasing trend is very mild, and increasing trend along the longitudinal line of 20 cm is the largest among all cases. It is also found that, along the channel section of the downstream riffle, the intensity of secondary flow has an additive trend along all longitudinal lines, except for the longitudinal line of 10 cm away from the left channel wall.

The “M” value together with its sign has special physical meanings. As pointed out by Liu et al. (2013), the sign and the absolute value of “M” represents the rotational direction and the intensity of the secondary flows, respectively. Along the central line of the 3D pool riffle sequence, assessment of the absolute values of M in the stream direction indicated that the values of M_{13} had the largest values than other two coefficients, followed by M_{12} and M_{23} , as shown in Figure 6a. By approaching to the channel wall, however, the M_{23} is remained low;

the difference becomes small for other two coefficients, so that, along the longitudinal line of 10 cm away from the left channel wall, the absolute values had nearly the same amounts. Investigation of the M_{13} absolute values along the channel central line showed that, the intensities in the flow direction along the entrance slope are increased; the intensities in the deep pool are constant and had the highest values; and the intensities in the following exit slope are decreased along the channel, as shown in Figure 6b. By approaching to the channel wall, an obvious trend as mentioned above has not been noticed. Results showed that the intensities are increased but appeared some irregularity.

As showed in Figure 6a, in the decelerating flow section of the 3D pool riffle sequence, the negative M_{13} -values along the channel central line, indicate that the rotational direction of the secondary current cell is counter-clockwise. Therefore, the dominant vertical component of flow is directed toward the channel bed. However, the M_{12} -values had lower values, the negative sign of this coefficient showed the oriented lateral component of flow toward the channel central line, thus the reported convergence of flow by MacVicar and Rennie (2012) is confirmed.

Results showed that, although M_{13} and M_{12} are in the order of magnitudes near the channel wall, there are some differences. In the 3D pool riffle sequence, M_{13} -values are negative, thus, the rotational direction of the secondary current cell is counter-clockwise. It means that the dominant vertical flow is oriented toward the channel bed. However, M_{12} -values are positive, this means that the secondary flow rotates in the direction of clockwise. It is represented that the dominant flow is directed toward the channel wall.

These findings indicated that the divergence of flow is not in agreement with the conceptual model mentioned by MacVicar and Rennie (2012). On the other hand, along the channel central line in the section of accelerating flow, the negative sign of M_{13} -values represented a downward vertical flow, and the positive sign of M_{12} -values indicated an oriented lateral flow toward the channel wall. Therefore, the divergence of flow is confirmed the conceptual model reported by MacVicar and Rennie (2012). Also along the section of accelerating flow, all M_{12} and M_{13} values near the channel wall are in the order of magnitudes and positive, representing a clockwise rotating secondary flow and divergent flow in this section of the 3D pool riffle sequence. Results showed that the intensities of the secondary flows increase by

increasing the flow discharge. It means that increase in three-dimensional velocities due to the constant flow depth lead to stronger secondary current cells.

Along the 2D pool riffle sequence, assessment of secondary flow coefficient (M) has been done. Along the decelerating flow section, the values of M_{12} and M_{13} had negative sign. The physical meaning of these values demonstrated the counter-clockwise rotational secondary current cell and indicated downward and central line oriented flow, as shown in Figure 6c. Therefore, the convergence of flow occurred in the decelerating flow section (MacVicar and Rennie 2012). However, along the accelerating flow section, M_{13} has negative values yet, but the values of M_{12} have the positive sign. From a physical point of view, it is showed that the rotational direction of the secondary current cell is counter-clockwise and clockwise for M_{13} and M_{12} , respectively. These results confirmed the divergent flow reported by MacVicar and Rennie (2012). Also, from the Figure 6c, one can see that along the entire sequence of pool-riffle, the maximum intensity of the secondary currents occurred at the middle of pool.

4.4. Distribution of production term of secondary currents

Figure 7 illustrated distribution of $(v'^2 - w'^2)$ for different parts of the 2D pool riffle sequence. Results showed that along the upstream riffle section, the production term of secondary currents has low values near the vertical wall close the water surface. Large values of the production term of secondary currents are found to be located near the center of the channel bed, as showed in Figure 7a. Along the entrance slope of the pool (the decelerating section), a small spot with the low values of $(v'^2 - w'^2)$ is found near the channel bed, but cross the channel from the left wall to the right. In return, a wide region with the low values of $(v'^2 - w'^2)$ is diffused at the water surface across the whole channel, as showed in Figure 7b. In the deep pool, a zone with low values of production term of secondary currents is located near the bed, and zones with high values of production term of secondary currents appear near the water surface and close to the channel wall (Figure 7c). Along the channel section from the end of the deep pool to end of the accelerating slope, zones with low values of production term of secondary currents are noticed near channel walls from channel bed to water surface. Zone with high values of production term of secondary currents appears along the channel central line of, as shown in Figure 7d. Along the downstream of riffle, spots with low values of production term of secondary currents move toward the channel central line, in contrast, spots with high values occur near channel walls, especially close to the channel bed (Figure 7e).

Figure 8 displayed the distribution of production term of secondary currents in the 3D pool riffle sequence. Along the section of the upstream riffle, spots with high value of production term of secondary currents are located near the channel bed, very close to the longitudinal line of 20 cm away from the channel wall, as indicated by Figure 8a. However, the values of this parameter decrease toward the central line of channel and water surface. Once water enters the decelerating section of the 3D pool riffle sequence, zones contain negative and zero values have not been noticed. Ten centimeters after entering the decelerating section, a zone of approximately 10 cm wide contains negative and zero values is located near the channel central line. This zone has been developed in such a way that the zero values appear from water surface to the channel bed, but the negative values is covered about $2/3$ of depth from water surface toward the bed (Figure 8b). However, as shown in Figure 8c, at the boundary between entrance slope and the deep pool, the coverage area with negative and zero values is decreased to a small zone located in the middle flowing water. The high values of production term of secondary currents have been assessed. It is found that, along the decelerating flow section, zones with high values have been developed from the near-bed and near-channel wall toward water surface vertically. By approaching to the end of decelerating flow section, the size of zones with high values decreases.

Along the deep pool section of the 3D pool riffle sequence, zones with low values of production term of secondary currents still remain around the channel central line. These zones with low values are located not only near water surface but also near channel bed, also the size of these zones with low values increases. By approaching to the border between the deep pool section and the accelerating flow section, also the size of these zones with low values decreases. It is also found that, zone with high values of production term of secondary currents is extended near the channel wall. Toward the accelerating flow section of the pool riffle sequence, the size of zone with high values increases and occupies a large portion of flow cross section near water surface (Figure 8d).

At the start of accelerating flow section, the size of zone with low values of production term of secondary currents is expanded nearly throughout the whole water depth around the channel central line. However, along the accelerating slope section, zones with high values production term of secondary currents allocated over a large portion of flow cross section and moved toward the channel central line. In the mean time, zones with low values of the

production term of secondary currents moved toward the vertical walls near the channel bed, as indicated by Figure 8e. This distribution pattern of zones with low values of production term continued to the end of accelerating section. At the border between the end of accelerating section and downstream riffle, two zones with high values of production term are produced. The first zone is located around the channel central axis near water surface centered, and the second one is developed near the channel bed oriented toward the channel wall. By further moving to the downstream riffle, the effect of the zone with high values of production term near the channel bed decreases, and this zone with high values disappears at the last cross section for measurement, as showed in Figure 8f. However, the other zone with high values of production term at the water surface still exists, and the size of this zone becomes small. At the last cross section, a large portion of the cross section is covered by zone with low values of production term. It has been observed that along the downstream riffle, the negative values of production term disappear and the zone with values close to zero occupy a small area.

Assessment of distribution of the zero isoline of $(v'^2 - w'^2)$ showed that, along the decelerating flow section of the pool-riffle sequence, this zero isoline of $(v'^2 - w'^2)$ is located around the channel central line and extended to about 60% of the total flow depth. However, at the border between the entrance slope and the deep pool, the zero isoline of $(v'^2 - w'^2)$ is limited to the middle of flow depth and near the channel central line. Results show that in the deep pool, zero isoline of $(v'^2 - w'^2)$ moves away from central line toward the channel walls and locates in the middle of flow depth. Along the accelerating flow section of the pool-riffle sequence, the zero isoline of $(v'^2 - w'^2)$ covers a small region and is located near the channel bed. As showed in Figures 8a and 8f that zero isoline of $(v'^2 - w'^2)$ and the negative values of $(v'^2 - w'^2)$ disappear along both the upstream riffle and downstream riffle.

5. Conclusions

Results showed that for the 3D pool riffle sequence, the near-bed velocity decreases and increases along convective deceleration flow (CDF) and convective acceleration flow (CAF), respectively. Along the 2D pool riffle sequence, the near-bed velocity also decreases and increases along CDF and CAF, respectively, but have larger values than those for the 3D pool riffle sequence. Along the 3D pool riffle sequence, flow separation has not been observed along the longitudinal line of 10 cm away from the left channel wall. However, but by getting

away from the channel wall, flow separation has been observed. Additionally, the length of the flow separation zone increases up to the distance of 30 cm from the channel wall, and then decreased toward the channel central line (45 cm from the channel wall). It means the longest flow separation length is occurred along the longitudinal line of 30 cm away from the channel wall. It is found that the shear velocities estimated from the slope of the velocity gradient in the inner layer (u_{in}^*), decreases in the CDF section, and increases in the CAF section at any distances from the channel wall in the 3D pool riffle sequences.

Investigation of shear stress profiles showed that, for normal flow in both 2D and 3D pool riffle sequences, shear stress near channel bed has the highest value and linearly decreased to zero at water surface. Also, for flow in the 3D pool riffle sequence, the Reynolds shear stress is highest at the CDF section along longitudinal lines with distances of 10 cm and 20 cm away from the channel wall; however, for distances of 30 cm and 45 cm away from the channel wall, the highest shear stress moves toward the deep pool. For flow in the 2D pool riffle sequence, the highest shear stress moves toward the channel central line in the deep pool. At the end of the exit slope of pool, the shape of the shear stress profile is still affected from the CAF section. For flow in the entrance slope section and deep pool, the shear velocities estimated from turbulence intensities is higher than those estimated from time-averaged velocities. However, for flow in the exit slope section of the pool riffle sequence, values of u_{in}^* are higher than u_R^* . Despite the irregularities, the higher values u_{Rmax}^* occur in the deep pool and decreased toward both upstream riffle and downstream riffle. The values of u_{tke}^* indicates that shear stresses calculated from all three components of turbulence (u_{tke}^*), are higher than shear stresses calculated from Reynolds stress (u_R^*) along the channel section of the final 30% of pool riffle sequence.

Analyses of secondary flow in both 2D and 3D pool riffle sequences have been conducted. It is found that m_I is the dominant coefficient which has the highest fluctuation. The absolute values of M_{13} along the channel central line showed that, along the entrance slope of the pool riffle sequence, the intensity increased in the flow direction, the intensity was constant and the largest in the deep pool, and decreased along the exit slope. From these results, one can say that secondary currents along the decelerating flow section indicated convergence of flow along the channel central line. In contrast of the decelerating flow section, divergence of flow along the central line channel in the accelerating flow section has been observed. Our

findings confirmed the results of MacVicar and Rennie (2012). Also near the channel wall, secondary flow and divergence rotated counter-clockwise.

For flow in the 2D pool riffle sequence, assessment of distribution of production term of secondary currents showed that zones with low values of production term are near the channel wall in the upstream riffle section and are located near the channel bed in the entrance slope. While zones with high values of production term appear around the channel central line. In contrast, for flow in the 3D pool-riffle sequence, zones with low values of production term in the upstream riffle are located at water surface along the channel central line. For flow in the decelerating flow section, a zone of approximately 10 cm wide contains negative and zero values is located near the channel central line. In this section zones with high values are observed near the channel wall. In the deep pool zone with low values of production term of secondary current still remains around the channel central line.

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Figure 1: (a) Two dimensional (2D) pool riffle; (b) three dimensional (3D) pool riffle; (c) locations for measurements

Figure 2. (a – d) Streamwise velocity profiles along the channel, for distances 10cm, 20cm, 30cm and 45cm away from channel wall for 3D pool riffle, respectively; (e) streamwise velocity at a distance 45cm (central line) away from channel wall for 2D pool riffle; (f) trend of shear velocity (u^*_{in})

Figure 3: (a-d) Reynolds shear stress profiles along the channel, for distances of 10cm, 20cm, 30cm and 45cm away from the left channel wall, respectively; (e) shear stress at a distance 45cm (central line) away from channel wall for 2D pool riffle; (f) trend of shear velocity (u^*_R); (g) trend of shear velocity (u^*_{Rmax}); (h) trend of shear velocity (u^*_R)

Figure 4 An example of dimensionless coefficients for 3D pool riffle sequence

Figure 5 An example of multiplied of dimensionless coefficients for 3D pool riffle sequence

Figure 6: (a) Absolute M-values along the stream direction at the center line for 3D pool riffle; (b) M13 absolute values along the stream direction for four different distances from channel wall for 3D pool riffle; (c) Absolute M-values along the stream direction at the center line for 2D pool riffle;

Figure 7: Distribution of $(v^2 - w^2)$ for 3D pool riffle sequence: (a) upstream riffle; (b) decelerating section; (c) deep pool; (d) accelerating section; (e) downstream riffle

Figure 8. Distribution of $(v'^2 - w'^2)$ for 3D pool riffle sequence: (a) upstream riffle; (b) decelerating section; (c) boundary between entering slope and the deep pool; (d) at the pool toward the accelerating section; (e) accelerating section; (f) downstream riffle