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Turbulence Measurements in Submerged Hydraulic Jumps with Baffle Blocks

Alireza Habibzadeh¹, Mark R. Loewen², and Nallamuthu Rajaratnam³

Abstract

Laboratory measurements of turbulence in submerged hydraulic jumps with blocks downstream of a sluice gate are presented. As observed previously two flow regimes were distinguished; the deflected surface jet (DSJ) and the reattaching wall jet (RWJ) regimes. In the DSJ regime considerable turbulent kinetic energy (TKE) was generated just downstream of the blocks and the rate of dissipation of TKE was found to be very high resulting in a rapid decay of TKE. In the RWJ flow regime the magnitude of both the TKE and the dissipation rate were considerably lower but because the TKE decayed more slowly higher levels of TKE persisted further downstream. This study provides insights into the production and dissipation of turbulence in submerged flows and helps to explain why a submerged jump with blocks with a low submergence factor; i.e. the DSJ flow regime, is as effective as a free jump in dissipating energy.

Keywords: Baffle block; submerged hydraulic jump; energy dissipation; turbulence.

1 Introduction

Hydraulic jumps are often used to dissipate energy downstream of hydraulic structures such as spillways, sluice gates and drops. These structures are generally designed to operate with

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a free jump, but when tailwater depths increase, the jump becomes submerged. In the past, submerged hydraulic jumps were generally believed to be less efficient in dissipating energy and thus less effective at reducing the downstream velocity compared to free jumps (Rajaratnam 1967). Recent studies have shown that the use of baffle walls (Wu and Rajaratnam 1995) or baffle blocks (Habibzadeh et al. 2012 and 2014) significantly increases the amount of energy dissipated in a submerged jump. However, these studies only included observations of mean flow properties and time-averaged velocities and, as a result, the role baffle walls or blocks play in the generation and subsequent dissipation of turbulent kinetic energy is poorly understood. Furthermore, no information is available regarding the turbulence properties within a hydraulic jump with baffle blocks.

The turbulent flow field in free hydraulic jumps has been studied by numerous researchers. Rouse et al. (1958) were the first to conduct detailed measurements of turbulence in a hydraulic jump. The structure of the turbulence in free hydraulic jumps was studied more recently using Particle Image Velocimetry (PIV) (Lin et al. 2012), Laser Doppler Anemometer (LDA) (Svendsen et al. 2000) and Acoustic Doppler Velocimeter (ADV) (Mignot and Cienfuegos 2011, Liu et al. 2004). The flow downstream of a hydraulic jump has also been studied experimentally to identify the required length for the transition to open channel flow (Zobeyer et al. 2010, Wu and Rajaratnam 1996). These studies have shown that a length equal to ~ 10 times the subcritical sequent depth is required for the momentum dominated flow in the jump to make the transition to an open channel flow.

Long et al. (1990) were the first to study the turbulence properties in submerged hydraulic jumps using an LDA. The decay of the turbulence intensities and Reynolds stress in the streamwise direction was found to be more rapid than a wall jet. Dey and Sarkar (2008) studied

the effect of bed roughness on the turbulence properties in a submerged jump, and observed that roughness causes the turbulence intensities and Reynolds stress to decay more rapidly.

The mean flow in a submerged jump with a baffle wall was studied by Wu and Rajaratnam (1995). They found that, depending on the flow properties and the baffle wall height and location, the flow could either be deflected towards the water surface or reattach to the bed just downstream of the baffle. These two flow patterns were called the deflected surface jet (DSJ) and the reattaching wall jet (RWJ) flow regimes, respectively. The time-averaged flow characteristics were studied and it was observed that in the DSJ flow regime, the maximum longitudinal velocity component decayed more rapidly. As a result, they concluded that the DSJ flow regime could potentially be used as an energy dissipator downstream of submerged outlets.

A study of the submerged hydraulic jump with 3D baffle blocks downstream of a sluice gate was conducted by Habibzadeh et al. (2012). The flow patterns were studied and they found that the flow classification proposed by Wu and Rajaratnam (1995) was also valid for submerged jumps with baffle blocks. Therefore, following Wu and Rajaratnam (1995), they classified the flow into two regimes, the deflected surface jet (DSJ) and reattaching wall jet (RWJ) regimes. Habibzadeh et al. (2012) concluded that the DSJ regime dissipates energy as efficiently as the corresponding free jump. In a second series of experiments Habibzadeh et al. (2014) investigated the time-averaged properties of the two flow regimes in submerged hydraulic jumps with blocks. The mean flow field, decay of the maximum longitudinal velocity and bulk energy dissipation were compared and the DSJ regime was found to be more effective than the RWJ regime in reducing the longitudinal component of the velocity and dissipating the excess energy of the incoming flow.

These studies conducted by Habibzadeh et al. (2012 and 2014) covered a wide range of flow parameters but were limited to time-averaged quantities by design. This data could not then be used to examine the spatial and temporal properties of the turbulence within the two flow regimes. Such a data set; i.e. spatial and temporal time series of the turbulent flow properties within a submerged jump with blocks, is, to the knowledge of the authors, missing from the literature. Therefore, a new series of experiments was designed to investigate the properties of the turbulence produced in submerged hydraulic jumps with blocks. Habibzadeh et al. (2012) had previously studied the effects of the flow parameters (e.g. Froude number and block arrangement) and therefore the current study is focused on the turbulence properties for a given baffle block arrangement. In order to quantify the effect of the blocks on the turbulent flow field, measurements were also made in the corresponding submerged jumps without baffle blocks. The experiments were designed to cover practical ranges of the Froude number and submergence factor, and to encompass both flow regimes. This required a longer duration of the turbulent velocity sampling at each measurement point to ensure accurate turbulence data was acquired. The turbulence properties of the flow field and the effects of the blocks on turbulence intensity, Reynolds stress, kinetic energy, and energy dissipation rate were investigated in detail. The effect of the blocks on the dissipation of turbulent kinetic energy was of particular interest. The experimental data presented herein is the first set of data collected in this type of flow and fills the gap in the available data on turbulence properties of submerged jumps with blocks. Furthermore, the results provide an insight into the mechanism of energy dissipation and elucidate why a flow regime with a smaller submergence factor; i.e. the DSJ regime, is more efficient in dissipating energy by rapidly reducing the mean kinetic energy.

2 Experimental Setup and Procedures

The experiments were conducted in a flume located in the Hydraulics Laboratory of the Department of Civil and Environmental Engineering at the University of Alberta. A schematic view of the experimental setup is shown in Fig. 1. Submerged hydraulic jumps were generated using a sluice gate with a streamlined edge and an opening of $y_I=19.1$ mm that produced a supercritical stream with an approximately uniform velocity distribution that flowed into a horizontal flume with a width of 0.467 m, height of 0.60 m, and length of 7.5 m. A more detailed description of the experimental setup can be found in Habibzadeh et al. (2014).

Three Froude numbers of $F_I \approx 3.4, 5.3, \text{ and } 6.9$ were evaluated. Here, the Froude number at the gate opening is defined as $F_I = U_I / \sqrt{gy_I}$, where U_I is the velocity at the gate opening and g is the gravitational acceleration. For each Froude number two submergence factors (S) were tested such that both flow regimes; i.e. DSJ and RWJ regimes, were covered. Submergence factor S is defined as $S = (y_I - y_2) / y_2$; where y_I is the tailwater depth and y_2 is the subcritical sequent depth of the corresponding free jump, computed from the Belanger momentum equation (Chow 1959). Also, each flow condition was tested with baffle blocks (BB series) and without baffles blocks (NB series). The experimental parameters for all runs are tabulated in Table 1. A discussion of the estimated uncertainty in the measurements can be found in Habibzadeh et al. (2012).

For the BB series, five baffle blocks were fabricated using the design guidelines of the USBR for the standard USBR Basin III (Peterka 1984). The height and width of the blocks were $h_b=3.8$ cm ($h_b/y_I=2.0$), and $w_b=4.5$ cm, respectively and the space between the blocks (w_s) was equal to the block width; i.e. $w_b = w_s$ (see Fig. 1). The blocks were mounted on the bed with their upstream face located at $x_b=19.1$ cm from the gate, which corresponds to $x_b/y_I=10$. The Reynolds

number at the sluice gate (R_I) was larger than 27,000 in all cases, where R_I was defined as $R_I = U_I y_I / \nu$, and ν is the kinematic viscosity of water.

Velocity measurements were made using a Nortek Vectrino acoustic Doppler velocimeter (ADV) at a sampling frequency of 100 Hz. The ADV has a cylindrical control volume with a diameter of 6 mm and a height that is adjustable from 2 mm to 15 mm. The control volume is located 5 cm below the transmitting probe. Velocities were measured in two longitudinal planes; the centerplane at $z=0$ of the flume (passing through the center of the central block) and the off-centerplane, the plane passing between the blocks at $z=w_b$ (see Fig. 1), and at eight longitudinal stations measured from the gate, starting at $x/y_I=5$ (upstream of the blocks) and ending at $x/y_I=60$. Velocity time series were sampled for a duration of five minutes based on a sensitivity analysis that demonstrated that this duration was sufficient for accurate computation of the turbulence parameters of interest (e.g. Reynolds stresses). Spikes were removed from the sampled time series by the iteration-free method recently developed by Islam and Zhu (2013). The time series at each point were, then, corrected for Doppler noise and filtering effects, using the method developed by Romagnoli et al. (2012). Further details on data analysis can be found in Habibzadeh (2013).

In the presence of a 3D obstacle, the flow field is disturbed such that the turbulence field is inhomogeneous and highly anisotropic and estimates of the dissipation rate typically require the measurement of a number of component gradients (Hussein and Martinuzzi, 1996). As a result, a method based on dimensional analysis was used to estimate the rate of dissipation of turbulent kinetic energy per unit mass (ϵ). This method has been developed for highly turbulent mixing flows; e.g. mixing tanks (Wu and Patterson 1989). In this method, energy dissipation is related to a characteristic turbulent velocity (V_t) and length scale (L_t) as follows,

$$\varepsilon = A \frac{V_t^3}{L_t} \quad (1)$$

where, V_t is the characteristic velocity, L_t is the integral time scale and $A=0.85$ is a constant. The characteristic velocity (V_t) is defined as the square root of the time-averaged turbulent kinetic energy (k) and is given by,

$$V_t = \sqrt{k} = \sqrt{\frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})} \quad (2)$$

where, u' , v' , and w' are the fluctuating velocity components in the longitudinal (streamwise), vertical (normal to the bed) and transverse directions, respectively. The overbar represents a time-averaged quantity.

The characteristic length is defined as,

$$L_t = \sqrt{\frac{1}{2}(L_x^2 + L_y^2 + L_z^2)} \quad (3)$$

where, L_x , L_y , and L_z are the turbulence integral length scales in the longitudinal, vertical, and transverse directions, respectively. The integral time scale is defined as the area under the autocorrelation function up to the first zero crossing (Pope 2000). The autocorrelation function was computed as the inverse fast Fourier transform of the corrected power spectrum and Taylor's frozen turbulence hypothesis (Taylor 1935, Hinze 1959, Pope 2000) was used to transform from the temporal domain to the spatial domain.

Using the dimensional analysis approach (i.e. Eq. 1), to estimate the energy dissipation rate in turbulent flows is common in highly turbulent flows such as mixing tanks. The flow field being studied herein is 3D in nature and highly turbulent, which resembles the flow field within a mixing tank; hence, this method was used to compute estimates of the dissipation rate. Irrespective of the method used to calculate the dissipation rate, it is necessary to convert the

measurements from the time domain to the space domain, using Taylor's frozen turbulence hypothesis (Taylor 1935). This hypothesis requires that the turbulence intensity be small compared with the mean flow velocity. That is, the advection velocity of turbulence needs to be much greater than the velocity scale of the turbulence itself, such that the changes at a fixed point are simply due to the passage of an unchanging pattern of turbulent motion past the fixed point (Townsend 1976). As it will be shown in the following, this assumption is satisfied in this flow field. That is, the ratio of the turbulent fluctuations to the mean velocity, is on average ~ 0.07 . Taylor's frozen turbulence hypothesis has been widely used to approximate turbulence scales when measurements were made using single-point measuring instruments such as ADV or LDA. For example, the frozen turbulence hypothesis has been formerly applied in hydraulic jumps to approximate eddy sizes and energy dissipation rates (e.g. Mignot and Cienfuegos 2011, Liu et al. 2004). Furthermore, the frozen turbulence hypothesis has also been used to estimate dissipation in shear flows; e.g., boundary layer flow and fully developed pipe flows (Azad and Kassab, 1989), as well as wall-bound flows (Piomelli et al. 1989). To assess the applicability of this approach to the flow conditions in the current study, the estimated energy dissipation rates were used to calculate the dissipative eddy sizes; i.e. the Kolmogorov's length scale L_K , using the following relation (Pope 2000);

$$L_K = \left(\frac{\nu^3}{\varepsilon} \right)^{1/4} \quad (4)$$

The estimated dissipative eddy sizes varied between ~ 0.02 to ~ 0.15 mm, which is in agreement with the range found by Liu et al. (2004) for free hydraulic jumps. Baki et al. (2015) estimated that the size of dissipative eddies varied from 0.06 mm to 0.15 mm in fishways and Nikora and Smart (1997) found the sizes varied from 0.05 mm to 0.1 mm in turbulent flow in gravel bed

rivers. The fact that the estimated dissipative eddy sizes in this study are within the same range as these previous studies confirms that the estimated dissipation rates are reasonably accurate.

The moving block bootstrap method with 1000 repetitions was used to evaluate the confidence intervals of all turbulence parameters (Garcia et al. 2006, and Politis and White 2004).

3 Results and Discussion

An example of vertical profiles of the longitudinal turbulence intensities in the centerplane and off-centerplane and the corresponding submerged jump without baffles (NB series) are shown in Figs. 2a and b for the DSJ and RWJ flow regimes, respectively. The longitudinal and vertical turbulence intensities (I_x and I_y) are defined as,

$$I_x = \frac{\sqrt{u'^2}}{U_1}, \quad I_y = \frac{\sqrt{v'^2}}{U_1} \quad (5)$$

where, x and y refer to the longitudinal (streamwise) and vertical (normal to bed) directions, respectively (see Fig. 1). The random error associated with I_x was estimated to be less than 4% based on the moving block bootstrap technique (error bars are not shown on the figure for simplicity). At the blocks ($x/y_I=10$), the measured time series just above the blocks in the centerplane consisted of a large percentage of spikes (more than 60%). This can be attributed to the large velocity gradients created by the deflected jet in this region. As a result, the measurements at this station in the centerplane were excluded from subsequent analysis. Furthermore, the presence of air bubbles upstream from the blocks (i.e., $x/y_I=5$) near the water surface (i.e., $y/y_I>5$) in the DSJ regime resulted in poor quality data which were also excluded from subsequent analysis. Also, the data sampled furthest from the bed for the NB series at stations $x/y_I=15$, 20, and 30 were not included because of the presence of spikes due to the shear

layer formed at the lower edge of the recirculating surface roller. This is why the vertical profiles at these stations are shorter.

It can be observed in Fig. 2a that the magnitude of I_x in the DSJ flow regime is significantly influenced by the blocks. I_x values in the centerplane and off-centerplane are considerably different just downstream of the blocks; i.e. for $12.5 \leq x/y_l \leq 25$. At $x/y_l = 15$, I_x values in the centerplane are smaller than those in the series without blocks; but values of I_x in the off-centerplane are larger than the NB series. Moving downstream, the intensities in the off-centerplane decrease and for $x/y_l \geq 30$, the intensities are almost identical in the two planes. It is observed in Fig. 2b that in the RWJ regime there are only minor differences between the I_x intensities in the two planes, except near the blocks at $10 \leq x/y_l \leq 15$ and $y/y_l < 5.0$. In this region, the intensities in the centerplane have a maximum at $y/y_l \approx 3.0$, which coincides with the shear interface created by flow separation at the leading top edge of the block. The location of the maximum I_x behind bluff bodies such as spheres has been reported to occur at the shear interface (e.g. Dey et al. 2011). It can be observed in Fig. 2 that the magnitude of I_x at the furthest station downstream (i.e. $x/y_l = 60$) is approximately 0.03 and 0.08 in the DSJ and RWJ flow regimes, respectively. This indicates that the DSJ regime is much more effective at reducing the turbulence intensity compared to the RWJ regime. It should be noted, that these turbulence intensities are higher than the average values observed in open channel flows. The turbulence intensity, scaled using the local depth-averaged velocity, in a fully-developed turbulent open channel flow is typically $\sim 5\%$ (Nakagawa and Nezu, 1993), which corresponds to $I_x \approx 0.005$ when it is scaled using the velocity at the gate as it is here. Urban et al. (2005) reported that downstream of a stilling basin the turbulence decays to open channel flow levels in a distance of ~ 50 times the tailwater depth, which corresponds to $x/y_l > 200$.

A comparison of the profiles in Figs. 2a and 2b, shows that, when compared to the submerged jumps without blocks, larger turbulence intensities are generated by the blocks in the DSJ regime. However, turbulence intensities in the DSJ regime decay considerably faster than the RWJ regime. This is clearly seen at the furthest downstream station, where the turbulence intensities in the DSJ regime are considerably smaller than the submerged jump without blocks (Fig. 2a); while the turbulence intensities at this station in the RWJ regime have comparable magnitudes to those of submerged jumps without blocks (Fig. 2b). Typical profiles of the vertical turbulence intensities I_y (not shown here), followed a similar trend to that of the longitudinal turbulence intensities I_x .

Vertical profiles of the normalized Reynolds stresses ($\hat{\tau}_R$), defined as,

$$\hat{\tau}_R = \frac{-\overline{u'v'}}{U_1^2} \quad (6)$$

are plotted in Figs. 3a and b for the DSJ and RWJ regimes, respectively. Also plotted for comparison in these figures are profiles for the corresponding submerged jumps without blocks (NB series). It can be observed in Figs. 3a and b that three profiles of $\hat{\tau}_R$ upstream of the blocks at $x/y_I=5$, are all similar with a peak at the shear interface which is typical in submerged jumps (Dey and Sarkar 2008, Long et al. 1990). Comparing, Figs. 3a and b, it is clear that the largest difference between the magnitudes of the Reynolds stress in the centerplane and off-centerplane of both flow regimes occurs just downstream of the blocks at $x/y_I=12.5$. The difference is more pronounced in the DSJ regime because of the significant shear interface generated between these two planes in this regime. In the RWJ regime, the region of high Reynolds stress; i.e. $x/y_I=12.5$ and 15 in the centerplane, coincides with the boundary of the eddy formed downstream of the blocks due to flow separation. Further downstream, at $x/y_I \geq 15$, the location of the maximum

Reynolds stress in both planes in the RWJ regime moves towards the bed due to reattachment of the flow, and the peak in the Reynolds stress curve gradually diminishes at $x/y_I=20$ to 30. This observation is consistent with the previous findings (Habibzadeh et al. 2013, and Castro and Robins 1977).

The turbulent kinetic energy (k) is defined as the mean kinetic energy per unit mass in the fluctuating velocity field (Pope 2000). The magnitude of k is a measure of turbulence intensity and decreases in its magnitude are an indication of energy dissipation. In Fig. 4, typical profiles of the normalized time-averaged turbulent kinetic energy ($\hat{k}$) are plotted for the two flow regimes and the corresponding submerged jump without blocks. Here, $\hat{k}$ is given by,

$$\hat{k} = \frac{k}{\frac{1}{2}U_1^2} = \frac{\frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})}{\frac{1}{2}U_1^2} \quad (7)$$

In Fig. 4a, the largest magnitudes of $\hat{k}$ are observed in the DSJ regime downstream of the blocks in the off-centerplane where the magnitude of $\hat{k}$ in the off-centerplane at $x/y_I=12.5$ and 15.0 is approximately four times larger than in the centerplane. Large magnitudes of $\hat{k}$ indicate a high rate of conversion of mean flow kinetic energy to turbulent kinetic energy in the off-centerplane of the DSJ regime. A peak in the value of $\hat{k}$ in the RWJ regime is observed in the centerplane just behind the blocks at $x/y_I=12.5$, which coincides with the shear interface located at the boundary of the standing eddy behind the block (see Fig. 4b). The magnitudes of $\hat{k}$ in the RWJ regime are, in general, smaller than those in the DSJ regime, representing the lower rate of decay of the mean kinetic energy in the former flow regime, as reported in a previous study (Habibzadeh et al. 2014).

Comparing Figs. 2 to 4, it is evident that the turbulence characteristics are significantly different in the centerplane and off-centerplane of the DSJ flow regime. Downstream of the

blocks, the turbulence intensities and turbulent kinetic energy are smaller in the centerplane, and larger in the off-centerplane, compared to the submerged jump without blocks. But, this difference rapidly diminishes and for $x/y_I \geq 30$, the magnitudes in the two planes are less than those in the submerged jump without blocks. This rapid recovery of the flow is similar to that observed in wall-wakes behind spherical obstacles (Dey et al. 2011). In the RWJ flow regime, however, the difference between the two planes is only significant (i.e. more than 5%) in the vicinity of the blocks, that is, for $y/y_I \leq 4$ at $10 \leq x/y_I \leq 20$. Therefore, the blocks have a much larger impact on the flow field in the DSJ regime compared to the RWJ. In the DSJ regime more shear-induced mixing occurs and therefore significantly more turbulence is generated.

Vertical profiles of the dimensionless turbulent kinetic energy dissipation rate per unit mass, $\varepsilon/\varepsilon_{ave}$, are plotted in Fig. 5. The average dissipation rate per unit mass of the corresponding free jump ε_{ave} following Liu et al. (2004) is given by,

$$\varepsilon_{ave} = \frac{\rho g Q \Delta h}{\rho L_j B (y_1 + y_2) / 2} \quad (8)$$

where, Q is the discharge, Δh is the head loss in the free jump, L_j is the length of the free jump assumed to be equal to $6y_2$ following Peterka (1984), and $B=0.467$ m is the width of the channel. The ratio $\varepsilon/\varepsilon_{ave}$ represents the relative magnitude of the local energy dissipation rate per unit mass compared to the volumetric average of the energy dissipation in the corresponding free jump. In Fig. 5, it can be seen that the maximum energy dissipation rate in the DSJ regime, $\varepsilon/\varepsilon_{ave} \approx 4$, occurs in the off-centerplane at $x/y_I = 12.5$ and 15. Also, at these stations, the energy dissipation rates are approximately 5 to 6 times larger than those in the corresponding NB series. In the RWJ regime, however, the maximum value of $\varepsilon/\varepsilon_{ave} \approx 4$ occurs at only one point, in the centerplane just downstream of the blocks at $x/y_I = 12.5$ at a height of $y/y_I \approx 2.0$, which coincides with the upper boundary of the reattaching jet. At other locations, the energy dissipation rate in the RWJ regime

is comparable to the NB series and negligible compared to the corresponding free jump. Comparing the two flow regimes in Figs. 5a and b, it is clear that, in the DSJ flow regime, the maximum dissipation occurs over a greater vertical extent in the off-centerplane and persists for a longer distance downstream compared to the RWJ regime.

The normalized vertically-averaged turbulent kinetic energy $\hat{k}_0$ is defined as,

$$\hat{k}_0 = \frac{1}{\frac{1}{2}U_1^2} \left[\frac{1}{y_0} \int_0^{y_0} k \, dy \right] \quad (9)$$

where y_0 is the height of the highest point at which velocity measurements were conducted. It should be noted that the “vertically-averaged” magnitude herein refers to the representative magnitude averaged over the depth which was covered in the measurements and not the total depth of the flow. The average longitudinal variations of $\hat{k}_0$ are plotted in Fig. 6 for the DSJ and RWJ flow regimes. Each curve is the result of averaging over the three experimental runs for each flow regime. The error bars in this figure represent the range of observed values at each location. In Fig. 6 the magnitudes of $\hat{k}_0$ in the centerplane of the DSJ regime increase slightly at $x/y_I \approx 20$ and then steadily decrease moving downstream. For $12.5 \leq x/y_I \leq 30$, the magnitudes of $\hat{k}_0$ in the centerplane of the DSJ regime are, on average, 30% to 50% of those in the corresponding submerged jump without blocks. The peak of $\hat{k}_0$ in the off-centerplane of the DSJ regime occurs at $x/y_I = 12.5$, with a magnitude approximately twice of that in the corresponding submerged jump without blocks. This is followed by a rapid reduction for $12.5 \leq x/y_I \leq 30$ and a more gradual decreasing trend for $x/y_I > 30$. For $x/y_I < 30$, $\hat{k}_0$ magnitudes are considerably different in the two planes of the DSJ flow regime but this difference decreases moving in the streamwise direction. The maximum difference between the two planes occurs at $x/y_I = 12.5$, where $\hat{k}_0$ is approximately

five times larger in the off-centerplane compared to the centerplane. For $30 \leq x/y_1 \leq 60$ the values of $\hat{k}_0$ in the two planes are approximately equal and their magnitudes are approximately 20% of those in the corresponding submerged jump without blocks.

The values of $\hat{k}_0$ in the centerplane of the RWJ regime decrease gradually downstream of the blocks in Fig. 6. The values in the off-centerplane, however, first increase to a peak at $x/y_1 \approx 20$, and then gradually decrease. In both planes of the RWJ regime, the values of $\hat{k}_0$ are larger than those of the corresponding submerged jump without blocks (except at $x/y_1 = 60$). At $x/y_1 = 60$, $\hat{k}_0$ magnitudes in the two planes of the RWJ regime are ~ 0.015 , which is comparable to the value observed in the submerged jump without blocks and approximately nine times larger than the values observed in both planes of the DSJ regime.

The region $12.5 \leq x/y_1 \leq 20$, where large values of $\hat{k}_0$ are observed in the off-centerplane of the DSJ regime, plays an important role in extracting kinetic energy from the mean flow and converting it into turbulent kinetic energy. It is within this reach that a rapid reduction of the longitudinal velocity is observed; i.e. mean kinetic energy is significantly reduced (see Habibzadeh et al. 2014, Fig. 13). Also, the large difference in $\hat{k}_0$ values in the two planes of the DSJ regime indicates the presence of a large shear interface in the off-centerplane which creates intense turbulent mixing. As a result, in a short distance; i.e. $12.5 \leq x/y_1 \leq 30$, the turbulent kinetic energy decays and reaches the same value in the two planes which is appreciably less than the corresponding values in the RWJ regime and the submerged jump without blocks; e.g. $\hat{k}_0$ magnitudes at $x/y_1 = 40$ in the DSJ regime are approximately four and seven times smaller than the RWJ and submerged jump without blocks, respectively. This indicates that kinetic energy of

the mean flow is being converted to turbulent kinetic energy in the region $12.5 \leq x/y_I \leq 30$ in the off-centerplane of the DSJ regime.

The dimensionless vertically-averaged turbulent kinetic energy dissipation rate per unit mass $\hat{\varepsilon}_0$ is defined as,

$$\hat{\varepsilon}_0 = \frac{1}{\varepsilon_{ave}} \left[\frac{1}{y_0} \int_0^{y_0} \varepsilon dy \right] \quad (10)$$

This parameter is the average energy dissipation rate per unit mass at each station with respect to the average value of the energy dissipation rate in the corresponding free jump. Average curves of $\hat{\varepsilon}_0$ are presented in Fig. 7 for the DSJ and RWJ regimes and the corresponding submerged jump without blocks. The vertical average was calculated in the same manner as described previously and the error bars in Fig. 7 represent the range of values at each point. The magnitudes of $\hat{\varepsilon}_0$ in the centerplane of the DSJ flow regime are seen to be relatively small in Fig. 7 ($\hat{\varepsilon}_0 < 0.33$) at all locations. In the off-centerplane, however, the magnitude of $\hat{\varepsilon}_0$ is significantly larger just downstream of the blocks; for i.e. $12.5 \leq x/y_I \leq 20$, with a peak value of $\hat{\varepsilon}_0 \approx 2.5$ at $x/y_I = 15$. The dissipation rate in the corresponding submerged jump without blocks reaches a maximum value of $\hat{\varepsilon}_0 \approx 0.68$ at $x/y_I = 15$ and then gradually decreases downstream. In the range $10 \leq x/y_I \leq 20$, the dissipation rate in the off-centerplane of the DSJ regime is significantly larger compared to the corresponding submerged jump without blocks but for $x/y_I > 30$ it is smaller. Fig. 7 also shows that the dissipation rate in the off-centerplane of the RWJ regime and the corresponding submerged jump without blocks follow a similar trend with magnitudes of $\hat{\varepsilon}_0$ not exceeding 0.2. In the centerplane, the values of $\hat{\varepsilon}_0$ are larger, 0.65 and 0.38 at $x/y_I = 12.5$ and 15, respectively and this coincides approximately with the location of the eddy behind the

blocks. An interesting feature in Fig. 7 is that the energy dissipation rates are larger than the corresponding free jump; i.e. $\hat{\epsilon}_0 > 1$, only in the off-centerplane of the DSJ regime within the region $12.5 \leq x/y_I \leq 20$. That is, within this reach, the local energy dissipation rate is 1.5 to 2.5 times larger than the average dissipation rate of the corresponding free jump.

The difference between the two flow regimes can be explained by comparing the turbulence parameters downstream of the blocks; i.e. $x/y_I > 10$. In the DSJ flow regime, the longitudinal and vertical turbulence intensities (I_x and I_y) are, on average, 50% larger in the off-centerplane compared to the centerplane for $12.5 \leq x/y_I \leq 20$. This difference between the two planes is because of a shear interface located between the two which leads to intense mixing. The shear interface is caused by the fact that in the centerplane, the flow deflects sharply upwards and in the off-centerplane it deflects at a smaller angle as reported by Habibzadeh et al. (2014). This leads to large mean velocity differences between the two planes hence a shear layer or interface. As a result of the intense mixing associated with this shear interface, the difference in the intensities in the two planes becomes negligible in a short distance downstream. In the RWJ flow regime, however, the turbulence intensities are of the same order in the two planes and comparable to the submerged jump without blocks even at the furthest downstream station at $x/y_I = 60$. This is due to the fact that no large shear interface occurs as the extent of the flow field which is disturbed by the blocks in the RWJ regime is limited to approximately the size of the eddy behind the blocks. This clearly demonstrates that in the DSJ flow regime the blocks are much more effective at generating turbulence compared to the RWJ regime. This is also evident from the fact that in the DSJ flow regime considerably larger turbulent kinetic energy levels are observed just downstream of the blocks. This increase in turbulent kinetic energy is associated with extraction of energy from the mean flow, as was reported by Habibzadeh et al. (2014) who

observed a rapid reduction of the mean kinetic energy. The production of large amounts of turbulent kinetic energy then leads to significant energy dissipation rates just downstream of the blocks. The kinetic energy of the mean flow supplies energy to the fluctuating flow components in the form of the turbulent kinetic energy (Pope 2000). That is, if the turbulent kinetic energy increases dramatically, the mean kinetic energy is expected to decrease and if the longitudinal velocity component is the dominant velocity component, then, this velocity component (and the mean kinetic energy) would be expected to decrease significantly as was observed by Habibzadeh et al. (2014).

4 Summary and Conclusions

This study is the first attempt to experimentally evaluate turbulence properties of the flow field within submerged hydraulic jumps with baffle blocks and to compare them with the corresponding submerged jump without blocks. The two flow regimes of submerged hydraulic jumps with baffle blocks; i.e. deflected surface jet (DSJ) and reattaching wall jet (RWJ), were examined at three different Froude numbers ranging from approximately 3.3 to 7.0. It was observed that the turbulence in both the centerplane and off-centerplane was influenced by the blocks in both flow regimes. The turbulence intensities, Reynolds stress and turbulent kinetic energy gradually decreased with distance downstream of the blocks in the centerplane of the DSJ. The turbulent kinetic energy in the off-centerplane of the DSJ regime reached its peak value just downstream of the blocks and then rapidly decreased with distance. The largest energy dissipation rates (up to ~2.5 times larger than the average dissipation rate in the corresponding free jump) were observed in the off-centerplane of the DSJ regime and this coincided with a rapid reduction of the turbulent kinetic energy.

The interaction of mean velocity gradients, created by the deflected flow in the DSJ regime, with the large Reynolds stresses, observed in the off-centerplane, resulted in the generation of significant amounts of turbulent kinetic energy via shear production. Generation of turbulent kinetic energy by shear production coincides with a decrease in the mean kinetic energy because turbulent shear production extracts energy from the mean flow. It follows then that if the transport and buoyant production terms in the turbulent kinetic energy equation are negligible compared to the production and dissipation terms, then large shear production of turbulent kinetic energy will be counter-balanced by large dissipation rates (Pope 2000). This process defined the patterns observed downstream of the blocks in the Reynolds stress, turbulent kinetic energy and the dissipation rate in the off-centerplane of the DSJ regime.

In the DSJ regime the presence of the baffle blocks resulted in the conversion of large quantities of mean flow energy into turbulent kinetic energy that is then dissipated a short distance downstream. As a result, the turbulence intensity and kinetic energy in the DSJ regime are reduced significantly (compared to their values just downstream of the blocks) within a short distance. In the RWJ regime, these processes occur but because the flow is not deflected sharply upward the mean velocity gradients and Reynolds stresses are smaller in magnitude resulting in less shear production and smaller rates of dissipation of turbulent kinetic energy.

In the absence of blocks, very large Reynolds stresses occur near the bed in the shear layer created by the wall-jet and these are associated with the production of significant turbulent kinetic energy and its subsequent dissipation. However, in this case the high turbulence levels persist much further downstream compared to the DSJ regime. It was found that turbulence intensities and turbulent kinetic energy in the DSJ regime are significantly reduced within a length approximately equal to 30 times the incoming supercritical flow depth which is

comparable to the length of a USBR Type III stilling basin. The turbulence intensities beyond downstream of this location in the DSJ regime are still larger than those of a fully-developed open channel flow; this, however, is also the case in free jump stilling basins. Somewhat elevated turbulence levels in the flow just downstream of a stilling basin is accepted in the design, so that a shorter and more economic stilling basin can be used. To prevent scouring by the remaining turbulence in the flow, the river bed just downstream of the stilling basin is typically protected using bed armor (e.g. riprap). The experimental data presented in this study provides insights into the processes responsible for the production and dissipation of turbulence in submerged flows and help to explain why a submerged jump with blocks with a low submergence factor; i.e. the DSJ flow regime, is as effective as a free jump in dissipating energy.

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Table 1. Range of the experimental parameters ($y_l=19.1$ mm for all runs).

Run	U_1	F_1	S	Flow Regime	ε_{ave}
	m/s				m ² /s ³
BB1	1.44	3.34	0.87	DSJ	0.43
BB2	1.47	3.41	2.61	RWJ	0.45
BB3	2.30	5.32	0.54	DSJ	1.04
BB4	2.27	5.25	1.55	RWJ	1.02
BB5	3.01	6.97	0.20	DSJ	1.59
BB6	3.00	6.94	0.79	RWJ	1.58
NB1	1.51	3.48	0.76	SJ	0.47
NB2	1.48	3.43	2.67	SJ	0.45
NB3	2.30	5.33	0.49	SJ	1.04
NB4	2.28	5.28	1.53	SJ	1.03
NB5	3.00	6.94	0.20	SJ	1.58
NB6	2.99	6.92	0.82	SJ	1.57

Fig. 1. Schematic view of the experimental arrangement; a) side view, b) top view.

Fig. 2. Variation of the longitudinal normalized turbulence intensity (I_x) with dimensionless longitudinal distance (x/y_l) and dimensionless depth (y/y_l) for a) the DSJ regime (run BB3, $F_l=5.32$, $S=0.54$) and the corresponding submerged jump without blocks (run NB3, $F_l=5.33$, $S=0.49$) and b) the RWJ regime (run BB4, $F_l=5.25$, $S=1.55$) and the corresponding submerged jump without blocks (run NB4, $F_l=5.28$, $S=1.53$).

Fig. 3. Variation of the normalized Reynolds stress ($\hat{\tau}_R$) with dimensionless longitudinal distance (x/y_l) and dimensionless depth (y/y_l) for a) the DSJ regime (run BB3, $F_l=5.32$, $S=0.54$) and the corresponding submerged jump without blocks (run NB3, $F_l=5.33$, $S=0.49$) and b) the RWJ regime (run BB4, $F_l=5.25$, $S=1.55$) and the corresponding submerged jump without blocks (run NB4, $F_l=5.28$, $S=1.53$).

Fig. 4. Variation of the normalized turbulent kinetic energy ($\hat{k}$) with dimensionless longitudinal distance (x/y_l) and dimensionless depth (y/y_l) for a) the DSJ regime (run BB3, $F_l=5.32$, $S=0.54$) and the corresponding submerged jump without blocks (run NB3, $F_l=5.33$, $S=0.49$) and b) the RWJ regime (run BB4, $F_l=5.25$, $S=1.55$) and the corresponding submerged jump without blocks (run NB4, $F_l=5.28$, $S=1.53$).

Fig. 5. Variation of the dimensionless energy dissipation rate with dimensionless longitudinal distance (x/y_l) and dimensionless depth (y/y_l) for a) the DSJ regime (run BB3, $F_l=5.32$, $S=0.54$)

and the corresponding submerged jump without blocks (run NB3, $F_I=5.33$, $S=0.49$) and b) the RWJ regime (run BB4, $F_I=5.25$, $S=1.55$) and the corresponding submerged jump without blocks (run NB4, $F_I=5.28$, $S=1.53$).

Fig. 6. Average curves for the streamwise variation of the vertically-averaged normalized turbulent kinetic energy $\hat{k}_0$. (Curves representing each flow regime are the average of the three runs in that flow regime, and error bars represent the range of observed values.)

Fig. 7. Average curves for the streamwise variation of the vertically-averaged normalized turbulence dissipation rate $\hat{\epsilon}_0$. (Curves representing each flow regime are the average of the three runs in that flow regime, and error bars represent the range of observed values.)

Fig. 1. Schematic view of the experimental arrangement; a) side view, b) top view.
65x71mm (300 x 300 DPI)

Fig. 2. Variation of the longitudinal normalized turbulence intensity (I_x) with dimensionless longitudinal distance (x/y_1) and dimensionless depth (y/y_1) for a) the DSJ regime (run BB3, $F_1=5.32$, $S=0.54$) and the corresponding submerged jump without blocks (run NB3, $F_1=5.33$, $S=0.49$) and b) the RWJ regime (run BB4, $F_1=5.25$, $S=1.55$) and the corresponding submerged jump without blocks (run NB4, $F_1=5.28$, $S=1.53$).

78x37mm (300 x 300 DPI)

Fig. 3. Variation of the normalized Reynolds stress ($\hat{\tau}_R$) with dimensionless longitudinal distance (x/y_1) and dimensionless depth (y/y_1) for a) the DSJ regime (run BB3, $F_1=5.32$, $S=0.54$) and the corresponding submerged jump without blocks (run NB3, $F_1=5.33$, $S=0.49$) and b) the RWJ regime (run BB4, $F_1=5.25$, $S=1.55$) and the corresponding submerged jump without blocks (run NB4, $F_1=5.28$, $S=1.53$).
78x37mm (300 x 300 DPI)

Fig. 4. Variation of the normalized turbulent kinetic energy (k^+) with dimensionless longitudinal distance (x/y_1) and dimensionless depth (y/y_1) for a) the DSJ regime (run BB3, $F_1=5.32$, $S=0.54$) and the corresponding submerged jump without blocks (run NB3, $F_1=5.33$, $S=0.49$) and b) the RWJ regime (run BB4, $F_1=5.25$, $S=1.55$) and the corresponding submerged jump without blocks (run NB4, $F_1=5.28$, $S=1.53$).

78x37mm (300 x 300 DPI)

Fig. 5. Variation of the dimensionless energy dissipation rate with dimensionless longitudinal distance (x/y_1) and dimensionless depth (y/y_1) for a) the DSJ regime (run BB3, $F_1=5.32$, $S=0.54$) and the corresponding submerged jump without blocks (run NB3, $F_1=5.33$, $S=0.49$) and b) the RWJ regime (run BB4, $F_1=5.25$, $S=1.55$) and the corresponding submerged jump without blocks (run NB4, $F_1=5.28$, $S=1.53$).
78x37mm (300 x 300 DPI)

Fig. 6. Average curves for the streamwise variation of the vertically-averaged normalized turbulent kinetic energy . (Curves representing each flow regime are the average of the three runs in that flow regime, and error bars represent the range of observed values.)

61x31mm (300 x 300 DPI)

Fig. 7. Average curves for the streamwise variation of the vertically-averaged normalized turbulence dissipation rate ϵ_0 . (Curves representing each flow regime are the average of the three runs in that flow regime, and error bars represent the range of observed values.)
64x34mm (300 x 300 DPI)