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Variations of Flow Separation Zone at Lateral Intakes Entrance using Submerged Vanes

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ABSTRACT: Flow Separation in the upstream of the intake channel is a critical issue causing eddy flow into the intake entrance. It reduces the intake efficiency and the effective width of flow in intake. Therefore, it is essential to identify the dimensions of the flow separation zone. Installation of submerged vanes in intake entrance is a method which is usually applied to reduce the size of flow separation zone. In this study the dimensions of flow separation zone were measured in presence of submerged vanes with five arrangements including parallel, stagger, compound, piney and butterflies (the piney and butterflies models were provided for the first time that is our innovation in present paper) by four discharges of 15, 20, 25 and 30 *L/s* in main channel entrance. Multivariate regression equations were extracted for investigated flow separation zone using SPSS software. R^2 of these equations changes from 0.87 to 0.96, which statistically, can be considered as valid equations in hydraulic flow studies at lateral intake entrance. These results are also comparable with other studies which all of them show a reducing of the size of flow separation zone with increasing ratio of lateral intake discharge. Piney submerged vanes were selected as the best model that reduced the size of flow separation zone and made proper flow profile in main channel and intake entrance. Comparing with pilot model tests, this model reduced the length and width of flow separation zone 36.34%, 32.53%, 34.37%, 30.72% and 27.46%, 31% , 31.33 % , 30% respectively at four different discharges of 15, 20, 25 and 30 *L/s*. Results showed that the ratio of width to length of separation zone (shape index of zone) was between two values 0.2 and 0.28 in the all models.

Key words: Intake channel, Flow separation zone, Submerged vanes, Shape index of zone, Piney model.

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INTRODUCTION

Making lateral intakes is one of the most ancient methods of utilization of rivers. In hydraulic and environmental engineering, one commonly comes across branching channel flows. Some of the distinctive characteristics of a dividing flow in an intake are illustrated in Figure 1. They include a zone of separation immediately near the entrance of the lateral intake (separation zone), a contracted flow region in the branch channel (contracted flow), and a stagnation point near the downstream corner of the junction (stagnation zone). In the region downstream of the junction, along the continuous far wall, separation due to flow expansion may occur (Ramamurthy, 2007) that is a separation zone. It can both reduces intake efficiency and the effective width of flow and increases sediment deposition in the intake entrance (Jalili et al., 2011). Therefore, it is essential to identify dimensions of flow separation zone. Installation of submerged vanes in intake entrance is a method which is usually applied to reduce the size of flow separation zone. Submerged vanes (Iowa vanes) are designed in order to modify the near-bed flow pattern and bed-sediment motion in transverse direction in the river. The vanes are installed vertically on the channel bed, at an angle of attack which is usually oriented at 10 to 25 degrees to the local primary flow direction. Vane height is typically 0.2 to 0.5 times the local water depth during design flow conditions and vane length is 2 to 3 times its height (Odgaard and Wang, 1991). They are vortex-generating devices that generate secondary circulation, thereby redistributing sediment within the channel cross section. Several factors affected on flow separation zone such as the ratio of lateral intake discharge to main channel discharge, angle of lateral channel with respect to the main channel flow direction and size of applied submerged vanes.

Nakato et al. (1990) conducted sediment management in intake entrance with using submerged vanes in Station 3 of Plant Council Blafsz is located on the Missouri River for the first time. The results show submerged vanes are appropriate solution for reduction of sediment deposition in intake entrance. Ramamurthy (2007) investigated the flow was treated as 3D and test results were obtained for the flow characteristics of dividing flows in a 90°, sharp-edged, rectangular open-channel junction formed by channels of equal width. The predicted flow characteristics were validated using experimental data. The results indicate the width and length of separation zone increase with the increase in the discharge ratio Qr, (ratio of outflow per unit width in intake channel to inflow per unit width in main channel).

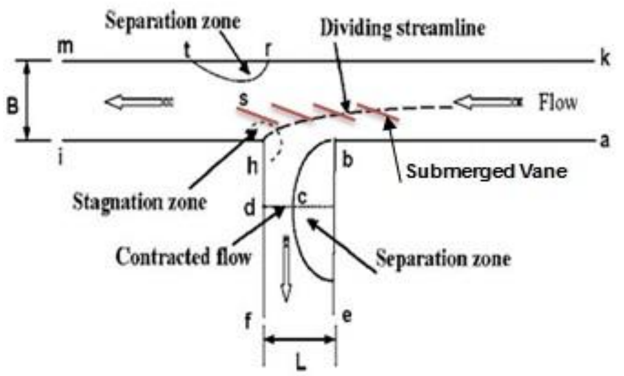

Figure 1. Flow characteristics of a dividing flow in open channels (Ramamurthy. 2007)

Ouyang (2009) studied the sediment control effectiveness of a vane as a function of its size and shape, with the expectation of an optimal combination of dimensions and shape. A model for calculation of transverse bed profile in a cross section of a straight alluvial channel induced by a single submerged vane was developed. The model was utilized to investigate the performances of three types of vanes: 1- rectangular plates with various height and length; 2- tapered plates with linear decreasing in length from the base to the top; and 3- Plates in the shape of parallelogram with the top of the plates swept forward or backward. For a rectangular vane, studies showed that the optimal vane height is related to the length of the vane and is within 0.58–0.70 of water depths. In other words, with increasing the vane length the possible of occurrence the flow separation may be less but costs grow. Hence it cannot be considered an optimal description for vane length. Samimi Behbahan (2011) investigated effect of vane-shapes on river banks protection. Using measured data, the canal and related vanes were modeled by ANSYS and SURFER software. Results showed that the curved and angled vanes compared to flat vanes were more effective in river-bank protection by 35% and 20% respectively.

Barani and Shahrokhi Sardo (2013) investigated the shape effect of vanes on stability of river bend; a physical model had been constructed. All the 28 experiments were performed, using three shapes of submerged vanes (flat, angled and curved). These vanes were installed on the bed of 90° and 180° bends of model with arrays of one, two and three vanes in parallel and zigzag patterns. According to results, three curved vanes installed in parallel pattern on 90° bend and zigzag pattern on 180°bend can be more effective in river bank protection.

Abbasi et al. (2004) performed experiments for investigating dimensions of flow separation zone at lateral intake entrance. They demonstrate with increasing the ratio of lateral intake discharge, the length and width of separation zone decrease. Also with decreasing angle of lateral intake, the length of separation zone increases and width of separation zone decreases. Then they compared their observations with results of Kasthuri and Pundarikanthan (1987) which conducted in open-channel junction formed by channels of equal width and angle of lateral intake in 90°, which showed dimensions of separation zone in their experiments were fewer than previous studies.

Karami Moghaddam and Keshavarzi (2007) analyzed flow characteristics in intakes with angle of lateral intake 55° and 90°. They presented results based on increasing separation zone with decreasing the ratio of lateral intake discharge. Studies about flow separation zone can be found in Jalili et al. (2011), Nikbin and Borghei (2011), Seyedian et al. (2008).

There is less related research about submerged vanes arrangements effect on flow pattern and separation zone at lateral intake entrance. so, The present study is focused on investigating dimensions of flow separation zone in presence of submerged vanes with five arrangements including parallel, stagger, compound, piney and butterflies. The piney and butterflies models were provided for the first time that is our innovation in present paper.

MATERIALS AND METHODS

Test setup

The experiments were performed in a 55° horizontal dividing flow channel. The main channel is 8.4 m long, 0.4 m wide and 0.5 m high and the branch channel is 2m long, 0.28 m wide and 0.5 m high, as shown in Figure 2. Both main channel and branch channel have slope of 0.0001 with side walls of glassy. The vanes were made of Galvanized sheets with thickness of 1mm. A subsurface reservoir supplies the required water flow (*Q*). A pump with power 100hp discharges the water into the stilling basin at the entrance of the main flume. The discharge is measured by using a rectangular weir with compaction of 19cm in two sides. In this study 64 experiments were carried out at range of $0.26<F_r<0.31$ (Froude numbers in main channel and upstream of intake) and five vane shapes, as shown in Figure 3. Some sawdust was sifted in the main channel upstream to measure dimensions of separation zone. As

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follows, when sawdust had approached to lateral intake entrance a photo of separation zone is made in intake entrance had taken that it was from top view.

By using photo, maximum width and length of separation zone calculated in AutoCAD software. Submerged vanes were installed in the region be limited to 20cm distance from upstream wall of intake channel and 24cm distance from downstream wall of intake channel. The Length and height of vanes are shown with signs L_v and h_v respectively. As well as they were placed on channel floor with long distance vanes (δ_s) and width distance vanes (δ_n). They placed in distance 10 cm from Wall of the main channel be located in upstream of intake (δ_b).

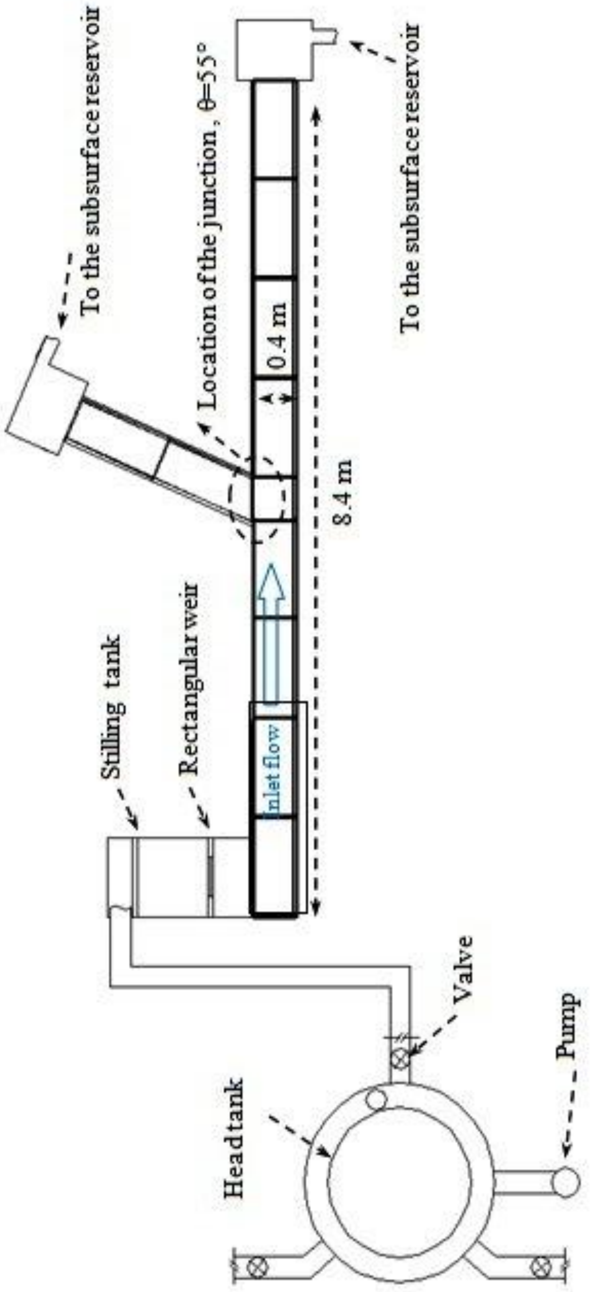
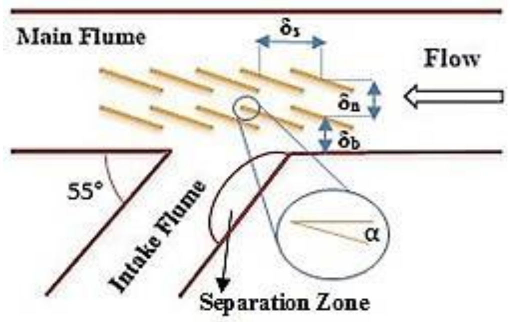
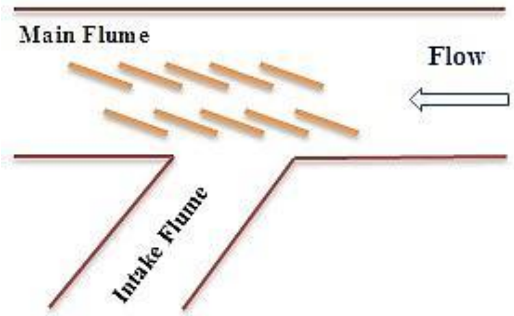


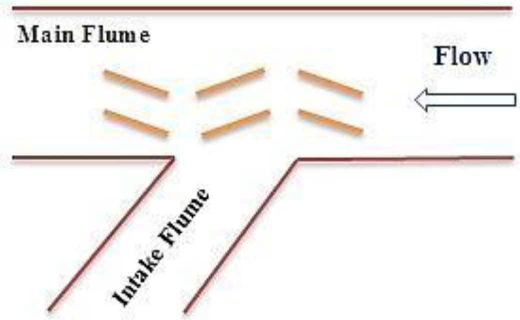
Figure 2. Sketch showing experimental setup



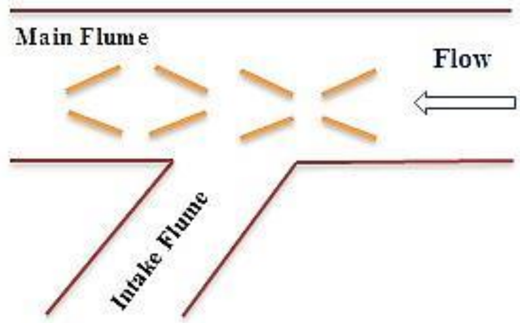
a. Parallel



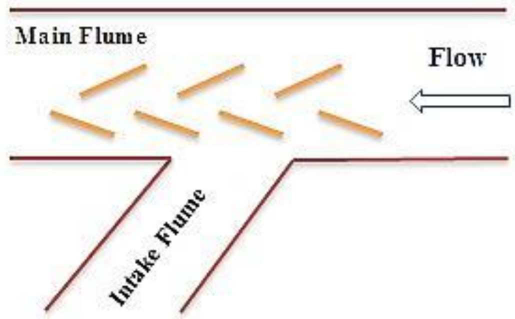
b. Stagger



c. Compound



d. Butterflies



e. Piney

Figure 3. Submerged vanes arrangements

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RESULTS

Dimensional analyses

The variable involved in the flow separation zone in presence of submerged vanes at intake channel entrance are inflow per unit width in main channel (q_1), outflow per unit width in intake channel (q_0), the flow density (ρ), the dynamic viscosity of flow (μ), gravitational acceleration (g), the width of intake channel (B_2), flow depths in main channel upstream and downstream of branch channel; y_1, y_0 respectively, channel slope (S_0), angle of attack to the local primary flow direction(α), number of rows of submerged vanes(N), length and height of submerged vanes; L_v and h_v respectively, distance of vanes along the flow (δ_s), distance of vanes across the flow (δ_n), distance from wall of the main channel in upstream of intake (δ_b), angle of lateral intake (θ), length of separation zone (L_s) and width of separation zone (W_s). By applying the Pi theorem (Buckingham Method) and by eliminating fixed variables such as θ, S_0, α, N; the result is the following relationship among non-dimensional parameters:

$$f(Re_1, Fr_1, \frac{q_0}{q_1}, \frac{y_0}{y_1}, \frac{\delta_b}{y_1}, \frac{\delta_s}{y_1}, \frac{\delta_n}{y_1}, \frac{L_S}{y_1}, \frac{W_S}{y_1}, \frac{L_V}{y_1}, \frac{h_V}{y_1}, \frac{B_2}{y_1}) = 0 \quad (1)$$

By assuming a high degree of turbulence (i.e., large Reynolds numbers), the influence of Re_1 can be considered negligible in the flow distribution and will not be accounted for in this case, for the sake of simplicity. Finally, rearranging parameters are provided as follows:

$$\frac{L_S}{B_2} = f\,(Fr_1, \frac{q_0}{q_1}, \frac{y_0}{y_1}, \frac{\delta_s}{y_1}, \frac{\delta_n}{y_1}, \frac{\delta_b}{y_1}, \frac{L_V}{y_1}, \frac{h_V}{y_1}) \quad (2)$$

$$\frac{W_S}{B_2} = f\,(Fr_1, \frac{q_0}{q_1}, \frac{y_0}{y_1}, \frac{\delta_s}{y_1}, \frac{\delta_n}{y_1}, \frac{\delta_b}{y_1}, \frac{L_V}{y_1}, \frac{h_V}{y_1}) \quad (3)$$

Range of variable parameters in experiments and specifications of submerged vanes are provided in Table 1 and 2, respectively.

Table 1. Range of used parameters

Range of variable parameters	Parameters	Range of variable parameters	Parameters
0.76-0.99	$(\frac{q_1}{q_0})\ q_r$	0.0375-0.075	$(m^2/s) q_0$
0.26-0.31	Fr	0.037-0.057	$(m^2/s) q_1$
10.33-16.51	$(cm)\ y_1$		

Table 2. The specifications of submerged vanes

Parameter	The recommended range Odgaard and Wang 1991)	The used value
α	15-25	20
L_v	(2-3) h_v	$3h_v$
H_v	(0.2-0.5)y_1	6 and 5.5
δ_s	(8-10)h_v	(2,3,4) h_v
δ_n	(2-3)h_v	$2h_v$
δ_b	Less than 4 times of vane height	10

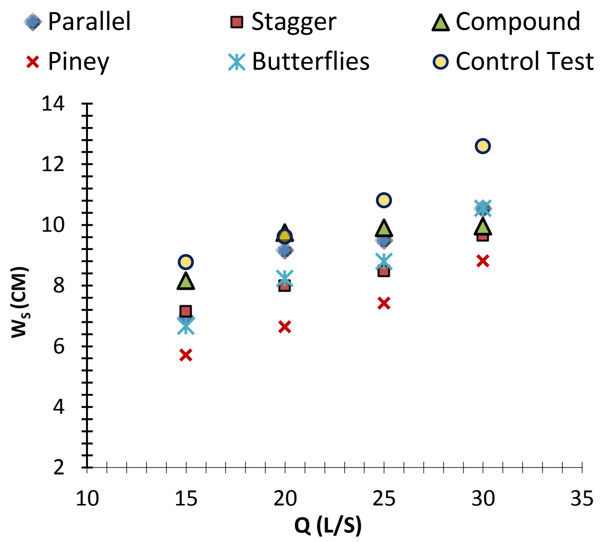
It should be noted that unit of hv, Lv, δs, δn and δb is cm.

DISCUSSION

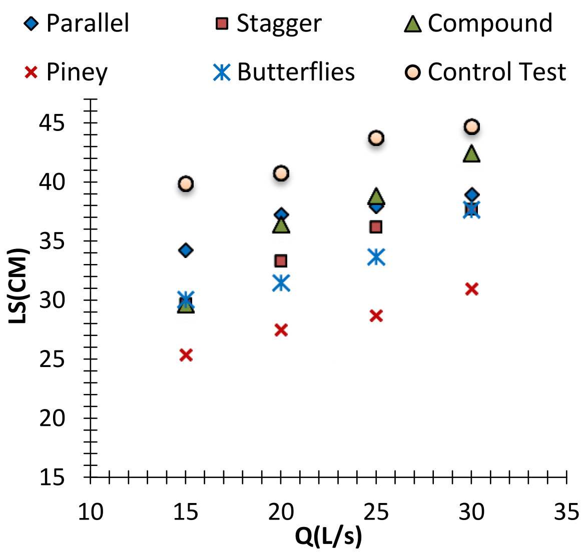
Variation of flow separation zone

In order to see the effect of Q_1 on dimensions of flow separation zone, some photos had taken that they were from top view. By using photos, maximum width and length of separation zone calculated in AutoCAD software. Then, variation trends W_s and L_s versus q_r provided.

In all models of submerged vanes arrangements, dimensions of separation zone are increased with increase of Q_1. This trend is provided in Figure 4a and 4b. when discharge change from 15 to 30 L/s , flow velocity increase and, flow passes faster in downstream of main channel than intake flume. So, entered discharge to intake flume reduces.



a.



b.

Figure 4.a,b. Effect of discharge Q_1 on dimensions of flow separation zone.

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Reduction of flow separation zone

In this study 64 tests were conducted for reduce the size of separation zone by using of submerged vanes with five arrangements including parallel, stagger, compound, piney and butterflies at lateral intake entrance.

Tables 3 to 6 are provided in order to compare submerged vane arrangements effect on reduction of dimensions of separation zone. As can be seen, dimensions of separation zone increase with increase of discharge from 15 to 30 *L/s* which is true for all models. Submerged vanes reduce width and length of separation zone at all model compared with control tests. This result is not apply about width of separation zone in compound model for discharges of approximately fewer than 20 L/s.

Table 3. The dimensions of separation zone in different arrangements of vanes (Q=15 *L/s*)

Type	Dimension $\frac{W_s}{L_s}$	$\frac{W_s}{B_2}$	$\frac{L_s}{B_2}$
Butterflies(δ_S=15cm)	0.202	0.211	1.044
Piney(δ_S=15cm)	0.214	0.212	0.99
Compound(δ_S=15cm)	0.287	0.288	1.0046
Stagger(δ_S=10cm)	0.259	0.232	1.091
Parallel(δ_S=15cm)	0.186	0.239	1.286

Table 4. The dimension of separation zone in different arrangements of vanes (Q=20 *L/s*)

Type	Dimension $\frac{W_s}{L_s}$	$\frac{W_s}{B_2}$	$\frac{L_s}{B_2}$
Butterflies(δ_S=20cm)	0.241	0.303	1.26
Piney(δ_S=15cm)	0.195	0.193	0.992
Compound(δ_S=20cm)	0.26	0.34	1.32
Stagger(δ_S=10cm)	0.214	0.275	1.28
Parallel(δ_S=15cm)	0.237	0.315	1.327

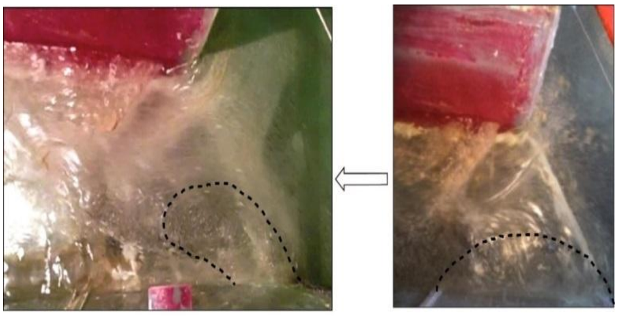
Table 5. The dimensions of separation zone in different arrangements of vanes (Q=25 *L/s*)

Type	Dimension $\frac{W_s}{L_s}$	$\frac{W_s}{B_2}$	$\frac{L_s}{B_2}$
Butterflies(δ_S=13cm)	0.255	0.292	1.143
Piney(δ_S=19.5cm)	0.23	0.24	1.07
Compound(δ_S=13cm)	0.248	0.351	1.416
Stagger(δ_S=13cm)	0.231	0.293	1.268
Parallel(δ_S=26cm)	0.226	0.306	1.351

Table 6. The dimension of separation zone in different arrangements of vanes (Q=30 *L/s*)

Type	Dimension $\frac{W_s}{L_s}$	$\frac{W_s}{B_2}$	$\frac{L_s}{B_2}$
Butterflies(δ_S=13cm)	0.293	0.345	1.178
Piney(δ_S=13cm)	0.268	0.316	1.18
Compound(δ_S=26cm)	0.229	0.351	1.536
Stagger(δ_S=13cm)	0.244	0.337	1.383
Parallel(δ_S=19.5cm)	0.25	0.34	1.383

According to tables, piney model is the best model that can reduce dimensions of separation zone at lateral intake entrance. It makes a flow appropriate length profile in main channel and branch channel and reduces flow turbulence at intake place. Comparing with other tested models, this model reduces the length and width of flow separation zone 36.34%, 32.53%, 34.37%, 30.72% and 27.46%, 31%, 31.33 %, 30% respectively at four different discharges of 15, 20, 25 and 30 *L/s*. because of the type of submerged vanes arrangements in piney model, when flow reaches to vanes the eddy flow be created that causes more water flow enters to intake channel. Increase of turned discharge to intake in this model prevents expansion of separation zone and makes a different shape of flow separation zone compared with other submerged vanes, according to Figure 5.



b. Separation zone in *Q*=20*L/s* , δ_s = 20cm(piney model)

a. Separation zone in *Q*=20*L/s* (control test)

Figure 5. Dimensions of separation zone

Multivariate regression equations are extracted for investigated flow separation zone using SPSS software. R^2 of these equations changes from 0.87 to 0.96, which statistically, can be considered as valid equations in hydraulic flow studies at lateral intakes entrance.

In general, non-dimensional equations for length and width of separation zone in each model are provided in accordance with equations 4 and 5(Parameters are provided in table 7). The observed value versus predicted value dimensions of separation zone are provided in Figure 6 and 7 in Piney model, for example.

$$\frac{W_s}{B_2} = A{q_r}^a + B(\frac{y_0}{y_1})^b + C\,{F_{r1}}^c + D(\frac{\delta_S}{y_1})^d + E(\frac{\delta_n}{y_1})^e + F(\frac{H_V}{y_1})^f + G(\frac{L_V}{y_1})^g + H(\frac{\delta_b}{y_1})^h \quad (4)$$

$$\frac{L_s}{B_2} = I{q_r}^i + J(\frac{y_0}{y_1})^j + K{F_{r1}}^k + L(\frac{\delta_S}{y_1})^l + M(\frac{\delta_n}{y_1})^m + N(\frac{H_V}{y_1})^n + O(\frac{L_V}{y_1})^o + P(\frac{\delta_b}{y_1})^p \quad (5)$$

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Table 7. Used parameters in equations 4 and 5

Parallel Model							
A	2.1	***a***	-0.256	***I***	3.5	***i***	-0.165
B	1.42	***b***	-0.251	***J***	1.53	***j***	-0.482
C	-1	***c***	-0.477	***K***	-1.3	***k***	-0.684
D	+1	***d***	-0.035	***L***	+1	***l***	0.0051
E	+1	***e***	-0.502	***M***	-2.2	***m***	-0.414
F	-1	***f***	-1.041	***N***	+1.96	***n***	-0.36
G	-1	***g***	1.94	***O***	+1.6	***o***	-0.008
H	+1	***h***	1.213	***P***	-2.8	***p***	0.342
R^2= 0.961				R^2= 0.89			

Stagger Model							
A	1.3	***a***	-0.906	***I***	2.1	***i***	-0.119
B	+1	***b***	-0.287	***J***	-1.6	***j***	-0.278
C	-1.97	***c***	-0.36	***K***	-2.3	***k***	0.128
D	+1	***d***	0.025	***L***	+1	***l***	-0.101
E	1.6	***e***	0.692	***M***	-1.5	***m***	1.154
F	-1.51	***f***	-0.642	***N***	+1	***n***	-1.149
G	-2.7	***g***	0.654	***O***	+1	***o***	2.203
H	1.4	***h***	-0.16	***P***	+2.6	***p***	-0.227
R^2= 0.944				R^2= 0.941			

Compound Model							
A	+1	***a***	-0.22	***I***	1.9	***i***	-0.411
B	+1	***b***	4.851	***J***	1.6	***j***	-0.427
C	-1	***c***	-0.121	***K***	-1.3	***k***	-0.938
D	+1	***d***	-0.004	***L***	+1.2	***l***	0.021
E	+1	***e***	0.922	***M***	-2.7	***m***	2.402
F	+1	***f***	-0.059	***N***	-1.4	***n***	-0.012
G	-1	***g***	1.052	***O***	2.71	***o***	-4.121
H	-1.1	***h***	-0.412	***P***	-2.1	***p***	-2.413
R^2= 0.943				R^2= 0.941			

Piney Model							
A	1.7	***a***	-1.127	***I***	1.3	***i***	13.28
B	1.5	***b***	0.159	***J***	-1	***j***	-0.469
C	-1.75	***c***	-0.408	***K***	+1.3	***k***	-1.216
D	+1	***d***	0.085	***L***	+1	***l***	0.182
E	-1.12	***e***	-1.096	***M***	-0.9	***m***	-8.456
F	+1	***f***	-0.231	***N***	+1.57	***n***	-0.676
G	-1	***g***	3.075	***O***	+1	***o***	-0.54
H	2.88	***h***	4.286	***P***	+1	***p***	-8.277
R^2= 0.87				R^2= 0.89			

Butterflies Model							
A	+1	***a***	-0.641	***I***	+1	***i***	0.396
B	+1	***b***	-0.21	***J***	-1	***j***	-0.234
C	-1	***c***	0.047	***K***	-1	***k***	0.149
D	-1	***d***	-0.08	***L***	-1	***l***	-0.327
E	2.21	***e***	2.315	***M***	1.35	***m***	-0.265
F	+1	***f***	-0.256	***N***	+1	***n***	-0.424
G	-2.22	***g***	1.345	***O***	+1.5	***o***	-0.962
H	-1	***h***	-0.767	***P***	+1	***p***	1.613
R^2= 0.932				R^2= 0.915			

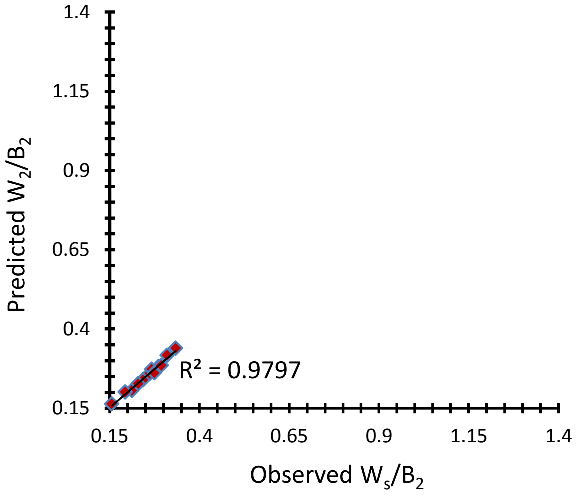

Figure 6. Observed versus predicted width of separation zone (Piney model)

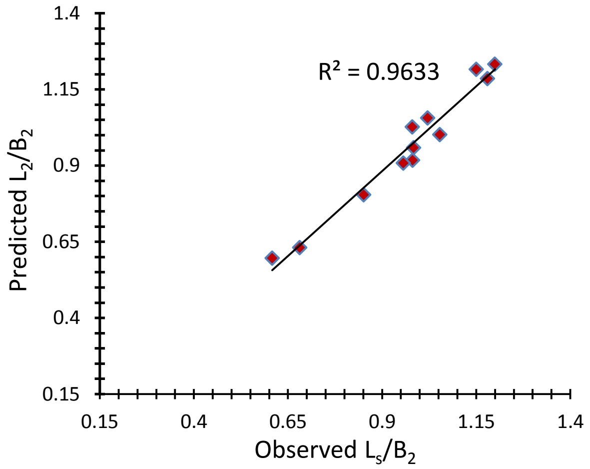

Figure 7. Observed versus predicted length of separation zone (Piney model)

Variation of surface contour in intake flume

In order to see variations of surface contours in intake entrance, they are provided using surfer software in piney model and discharges of 30 L/s in main channel entrance for example and compared with pilot model test, as shown in Figure 9. In which H_w is water depth in *x* and *y* locations shown in Figure 8.

It can be concluded from figures that applying submerged vanes increase water depth than control experiment. The least of its value is Approximately 5 cm.

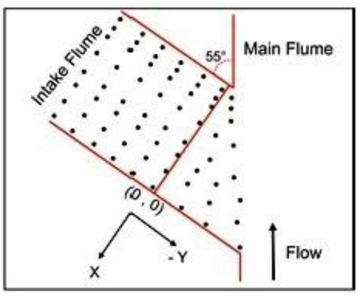

Figure 8. The locations of x and y for measure water depth

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Shape index of separation zone

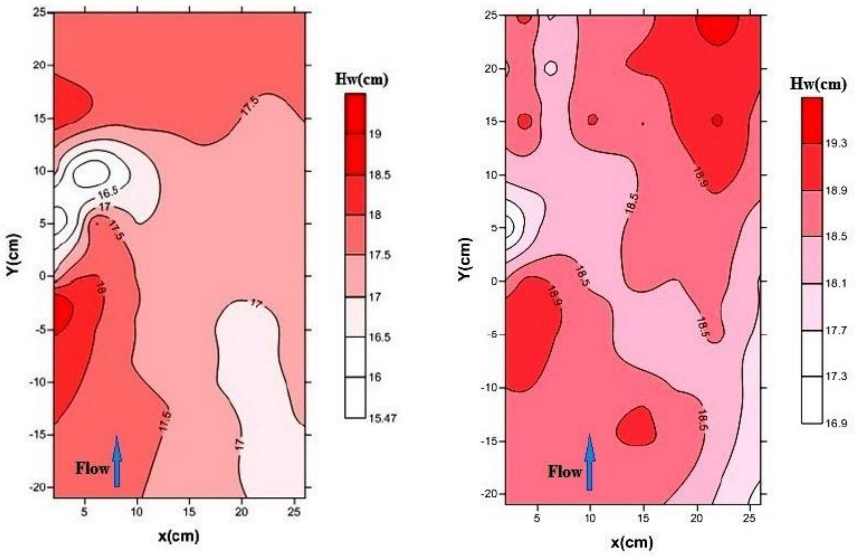
Shape index of zone is the ratio of width to length of separation zone that provides a general state of separation zone shape. According to previous studies, the average value of index was between 0.17 up to 0.19 (Ghobadian et al., 2006). In present study, results shows that it is between two values 0.2 and 0.28 in all models.

Comparison with other studies

Abasi et al. (2004) and Kasthuri and Pundarikanthan (1987) investigated dimensions of separation zone in lateral intake entrance. In their studies W_r and L_r were ratio of $\frac{W_S}{B_1}$ and $\frac{L_S}{B_1}$, respectively. In which W_s and L_s are both width and length of separation zone and B_1 is width of intake channel.

Intake entrance radius effect on size of separation zone, were investigated in another study that was conducted by Karimi Moghaddam and Keshavarzi (2007). They provided a non-dimensional parameter R/W_b which R *and* W_b are intake entrance radius and width of intake channel equal with 25 cm, respectively.

The results are compared with other studies which all of them show a reducing of the size of flow separation zone with increasing ratio of lateral intake discharge, as shown in Figure 10 a and b. The difference in graphs is because of different ratio of discharge and variable height of submerged vanes in present study.



b. Control Test, Q=30L/s a. Piney Model, δ_S=13cm ,Q=30L/s

Figure 9. Three-dimensional profile of the water surface in lateral intake entrance

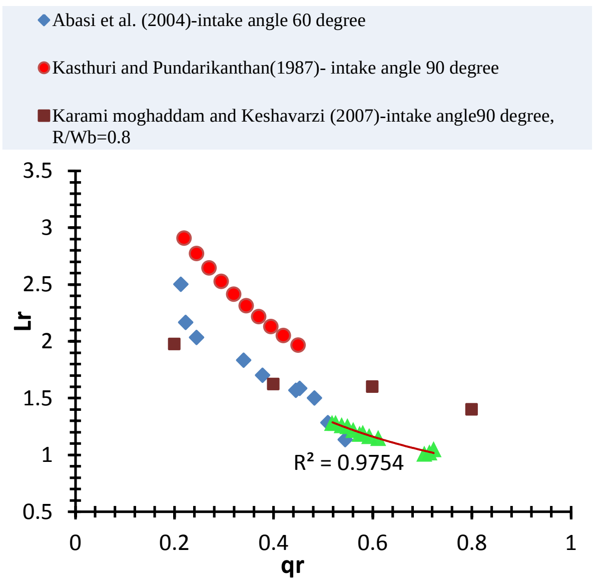


Figure 10a. Non- dimensional Length of separation zone variations in present study compared with other studies

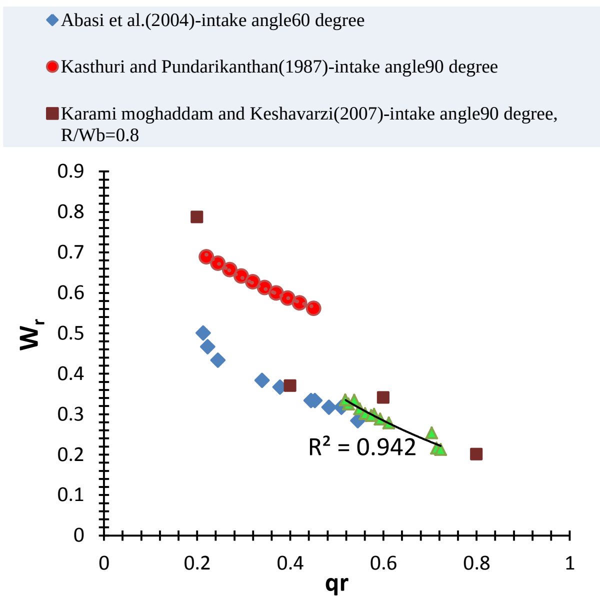


Figure 10b. Non- dimensional width of separation zone variations in present study compared with other studies

CONCLUSION

This study measured dimensions of flow separation zone in presence of submerged vanes with five arrangements including parallel, stagger, compound, piney and butterflies (piney and butterflies models were used for the first time). A summary of the results is as follows:

The dimensions of separation zone decrease with increase of non-dimensional parameter of qr.

When discharge increase from 15 to 30 L/s (Q_1), dimensions of separation zone because of reduction ratio of intake discharge increase in all experiments.

Multivariate regression equations were extracted for investigated flow separation zone using SPSS software. R^2 of these equations changes from 0.87 to 0.96, which statistically, can be considered as valid equations in hydraulic flow studies at lateral intake entrance.

Piney model selected as the best model that can reduce dimensions of separation zone at lateral intake entrance. It makes a flow appropriate length profile in main channel and branch channel and reduces flow turbulence at intake place. Comparing with other tested models, this model reduces the length and width of flow separation zone 36.34%, 32.53%, 34.37%, 30.72% and 27.46%, 31%, 31.33 %, 30% respectively at four different discharges of 15, 20, 25 and 30 L/s.

Shape index of separation zone is obtained between two values of 0.2 and 0.28 in all models too.

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Competing interests

We have read and understood JCEU policy on declaration of interests and declare that there is no conflict of interests regarding the publication of this paper.

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