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Hydraulic Performance for Combined Weir-Gate Structure

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A B S T R A C T

Combined hydraulic structure play an important role in controlling flow in open channels. This study was based on experimental and numerical modeling investigations for combined hydraulic structure. For this purpose three physical models of combined sharp crested trapezoidal weir with bottom opening and one physical model of sharp crested trapezoidal weir separately were used and tested by running eight different flow rates over each model. In which three configurations of bottom opening were tested; the first configuration is a rectangular gate while other two configuration were trapezoidal with two different side slopes of (1V:4H) and (1V:2H). The water surface profiles passing through weir-gate system were measured for all thirty two runs of all models which show uniform flow at 2.11h from the upstream of weir. The commercial computational fluid dynamic software ANSYS CFX was used to simulate flow numerically. The verification of the numerical model was based on water surface profiles and discharge which showed acceptable agreement. Also, the results showed that discharge coefficient Cd varies from (0.52-0.58). Furthermore, it was shown that both models with trapezoidal gate pass a higher discharge of flow than the model with rectangular gate with average percentage increase of discharge (40.78% and 19.40%) for trapezoidal side slopes (1H:2V and 1H:4V) respectively. In addition, the combined system with milder trapezoidal side slopes of bottom opening had a better performance for discharging weir flow which is about 40% as compared with traditional one. Finally, the empirical equations for stage-discharge relationship were estimated for all models and discharge coefficients were estimated for all runs.

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الأداء الهيدروليكي لمنشأ مكون من بوابة وهدار

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الخلاصة

تلعب المنشآت الهيدروليكية ذات الهدار والبوابة دورًا مهمًا في التحكم بالتصرف في القنوات المفتوحة. استندت هذه الدراسة إلى التجارب العملية والنمذجة العديدة للجريان المشترك المار خلال هذه المنشآت الهيدروليكية. لهذه الغاية ، تم استخدام ثلاثة نماذج للهدار شبه منحرف حاد الحافة و كل هدار يحتوي على فتحة بوابة في الاسفل . كانت البوابات مختلفة الاشكال، فالاولى مستطيلة أما البوابة الثانية والثالثة فكانتا على شكل شبه منحرف يختلف ميل جوانبهما 1H:2V والاخرى 1H:4V كما تم اختبار هدار شبه منحرف بدون بوابة. تم اختبار النماذج الاربعة عن طريق تمرير ثمانية تصاريف مختلفة على كل نموذج. تم قياس منسوب السطح الحر للماء على مسافات متقاربة لتحديد شكل السطح للماء المتكون لكل جريان وقد اتضح بان منسوب الماء يستقر على بعد 2.11h من حافة الهدار. وتم استخدام برنامج الديناميكا للموائع التجاري ANSYS CFX لمحاكاة التدفق عدديًا لتفسير ظاهرة الجريان. استند التحقق من مخرجات النموذج العددي على شكل سطح الماء وقيمة التصريف اللتين أظهرتا اتفاقا مقبولا، وأن قيمة معامل التصريف Cd تتراوح بين (0.52-0.58). وقد اتضح أيضا بأن كلا النموذجين ذاتا البوابة شبه المنحرفة تستطيع امرار تصريف أعلى من النموذج مع بوابة مستطيلة بمتوسط نسبة زيادة في التصريف (40.78 ٪ و 19.40 ٪) لكل من الهدارات ذات الفتحة شبه المنحرفة بميل جوانب (1H:2V)و(1H:4V) على التوالي. إضافة إلى ذلك ، فإن نظام الهدارات المركبة، الذي يكون فيه ميل البوابة الجانبي صغيرًا ، لديه قدرة على تصريف كمية أكبر وأداء أفضل بنسبة 40٪ بالمقارنة مع الانواع التقليدية. أخيرًا، تم استنباط معادلات وضعية لتقدير قيمة معاملات التصريف لجميع النماذج.

الكلمات الدالة: نظام مشترك، هدار شبه منحرف، الحسابات الديناميكية للموائع، تدفق بوابة، معامل التصريف.

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1. INTRODUCTION

Weirs and gates have been widely used in irrigation or open channels for flow control and discharge measurements. Weirs can be combined with gates at the bottom in one device system to solve the problems of sedimentation that accumulated upstream of this structure. The combined weir gate system represents the new hydraulic structure also the hydraulic characteristics in the combined system will be different. The use of the new system is the cheapest and easiest to construct as compared to the use of the weirs and gates separately. A combined rectangular sharp crested weir with inverted triangular opening at the bottom has been made by (Alhamid et al., 1996)[1] to obtain a nonlinear equation for simultaneous discharge. The test results found that the angle of the inverted triangle opening at the bottom has a significant effect on the discharge for the combined weir gate system and the larger capacity of flow founded with the increase of angle in the inverted V-notch gate. (Negm et al., 2002)[2] tested nineteen models with a horizontal bed and eighteen models with sloping bed of combined rectangular weir-gate system. A discharge equation is developed with an average absolute error of about 5%. Further, they presented the effects of surface tension and viscosity and both have significant effect on the combined discharge for narrow openings. The effect of dimensionless parameters on the performance of combined device has been studied by (Hayawi et al., 2008)[3] via testing nine combined models with rectangular weir and a semi-circular bottom opening. They estimated an equation of discharge coefficient for combined device with absolute percentage error 10%. (Dehghani et al., 2009)[4] investigated experimental work to study the scour characteristics at the downstream of combined flow over weir and through bottom opening. They founded that the ratio of the scour depth to the approaching water depth increased with the decrease of the ratio of head over weir and vertical distance between weir and gate to the gate opening. An experimental study was carried out by (Al-saadi, 2013)[5] to investigate the discharge coefficient for different cases of combined flow over weir and under gate, this study shows that the discharge coefficient Cd in the compound semicircular weir with semicircular gate performs the best in being Cd higher values of discharge coefficient than the other notches. (Khassaf and Habeeb, 2014)[6] studied the flow characteristics for combined trapezoidal weir and rectangular bottom opening for a wide range of trapezoidal weir angle and the vertical distance between lower edge of weir and upper edge of bottom opening. This study gives a new empirical formula of discharge coefficient with the relative the effect of trapezoidal weir and vertical distance. The hydraulic characteristics of Cipolletti weir with rectangular gate was conducted by (Al-Suhili and Shwana, 2014) [7]. For this purpose thirty models were tested experimentally and the discharge coefficient was founded for all configurations. The hydraulic characteristics of combined rectangular sharp crested weir-gate has been evaluated using numerical simulation (Fluent software) by (Arvanaghi, 2014)[8] showing that the flow of the combined weir-gate was divided into two parts, upper flow and lower flow and showing that discharge coefficient increased using the combined system. (Al-suhaili et al., 2014)[9] studied the flow characteristics of combined rectangular weir with three rectangular bottom opening using laboratory experiment. The discharge coefficient was founded for different flow cases showing the discharge coefficients for all three cases of flow increases with the increase of the head over the weir crest. (Duru, 2014)[10] conducted numerical modeling for contracted sharp crested weirs and combined weir-gate structure using Flow 3D, results show that computational fluid dynamic software is a powerful tool for simulating hydraulic problems related to the measurement structures of flow. A series of experimental models of combined curved weir and rectangular gate were conducted by (Obead and Hamad, 2014)[11], these models that the weir angle has a significant influence on the combined flow through the weir-gate system. They founded that the average value of discharge coefficient was decreased with the increase of weir angle. The (Parsaie et al., 2017)[12] proposed a cylindrical weir-gate structure to improve the performance of flow behavior of weir-gate structure. (Qasim et al., 2018)[13] studied the hydraulic characteristics for combined weir-gate of composite shape showing that the shape of weir and gate had an effective role in estimating the dimensional and non-dimensional factors.

As discussed above, many researchers developed a combined structure of weir with different shapes of bottom openings such as rectangular, circular and triangular gate opening. While, this investigation was carried on trapezoidal weir with inverted trapezoidal bottom opening. The hydraulic performance of flow through combined structure is studied, experimentally. Also deeper analysis of flow phenomena based on simulation may be introduced.

2. THEORETICAL BACKGROUND

To estimate the discharge through compound weir-gate system, the following theoretical equation (Q_{th}) is obtained by adding the discharge flowing over weir (Q_W) and through the gate (Q_g):

$$Q_{th} = Q_g + Q_w \quad (1)$$

The discharge through trapezoidal weir is obtained by (Bos, 1989)[14]:

$$Q_w = Q_{rectangular} + Q_{triangular}$$

$$Q_w = \frac{2}{3} b \sqrt{2g}\, h^{3/2} + \frac{8}{15}\sqrt{2g} \tan\left(\frac{\theta}{2}\right) * h^{5/2} \quad (2)$$

The discharge through the gate is calculated as following[14]:

$$Q_g = \sqrt{2gH} * A \quad (3)$$

From above consideration, the theoretical and actual discharge passing over weir and under gate is equal to:

$$Q_{th(combined)} = \sqrt{2g} \left(H^{1/2} A + \frac{2}{3} b h^{3/2} + \frac{8}{15} \tan\left(\frac{\theta}{2}\right) h^{5/2}\right) \quad (4)$$

$$Q_{act(total)} = C_d \sqrt{2g} \left(H^{1/2} A + \frac{2}{3} b h^{3/2} + \frac{8}{15} \tan\left(\frac{\theta}{2}\right) h^{5/2}\right) \quad (5)$$

where,
A: is cross sectional area of bottom opening,
b: bed width of weir,
g: acceleration due to gravity,
H: total head and it is equal to H = h + y + d
h: height of water over weir crest
y: vertical distance between weir and gate
d: height of gate, and
C_d: combined discharge coefficient (for flow over weir and under gate). All dimension parameters are defined in Fig. (1).

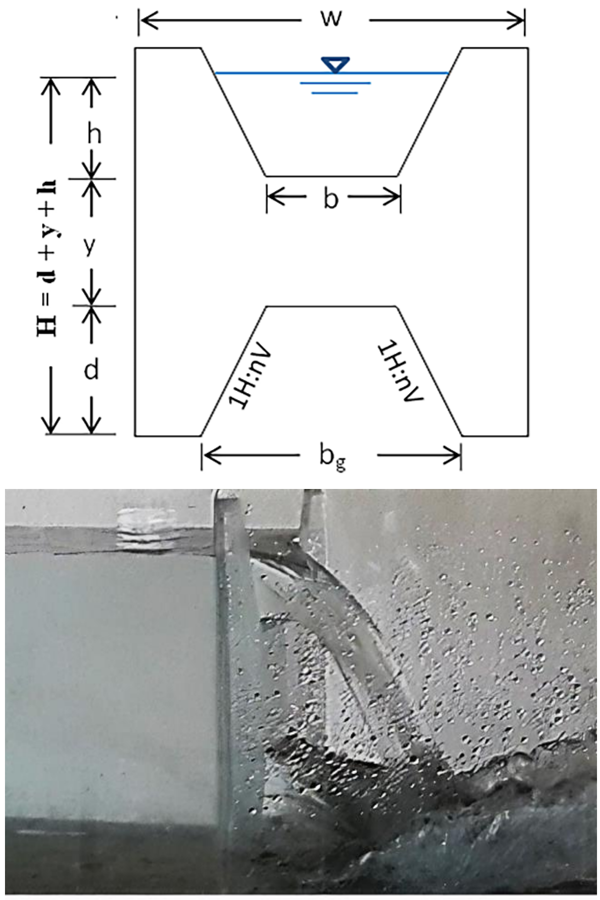


Figure. 1. Definition sketch for combined flow over weir and through gate where (n) is 0,2,4.

The computational fluid dynamic software was used to solve the Reynolds Averaged Navier-Stokes equations (RANS). The solution of equations was based on the finite volume technique discretization method [15]. These equations satisfy the mass and momentum conservation equations for the fluid flow [16]:

Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho U_i) = 0 \quad (6)$$

Momentum conservation equation

$$\frac{\partial(\rho U_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_i U_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho \overline{\acute{u}_i \acute{u}_j}\right) \quad (7)$$

where,
$\rho =$ The density of fluid, $t =$ time, $x =$ axis coordinates, $U_i =$ mean component of velocity, $P =$ means pressure, μ = dynamic viscosity and $\acute{u}_i =$ fluctuating part of the velocity.
The volume of fluid method VOF equation was applied to define the free surface between fluids (water and air) [17,18]:

$$\frac{\partial \alpha_w}{\partial t} + u_i \frac{\partial \alpha_w}{\partial x_i} = 0; 0 \le \alpha_w \le 1 \quad (8)$$

Where,

α_w: the volume fraction of water, and *ui*: is the velocity in *xi*-direction.
The sum of the water and air volume fractions is equal to unity; therefore the volume fraction of air (α_a) can be given as:

$$\alpha_a = 1 - \alpha_w \quad (9)$$

3. METHODOLOGY

The experimental setup of this study was carried out at the hydraulic laboratory of Engineering College of Duhok University. The experiments were conducted in a rectangular horizontal flume of a working length of 5 m with a cross section 0.3 m wide and 0.45 m deep. Three models of combined weir-gate system with one of weir model separately were constructed from 6 mm thick perspex plate with height and width of 0.3 m. The crest shape of the weir for all four models was kept as trapezoidal sharp crested weir with side slopes of (1H:2V). The bottom opening shape of the first two models was fixed trapezoidal and the third one is rectangular. The side slopes of trapezoidal bottom opening was changed two times as (1H:4V) and (1H:2V). The width of bottom opening were taken as (15 and 20 cm) respectively, while, the height of bottom opening was kept as 0.1 m. The height and width of third rectangular gate is 0.1 m. Details of the models tested during the experimental work are shown in Table 1.

Each model was set horizontally and fixed at the middle of the flume. The testing started by allowing eight different flow rates and the flow rates were recorded via a calibrated electromagnetic flow meter with an accuracy of 0.01 l/s. For each run, water surface profile measurements were recorded along the center line of the flume and the water depths were recorded at the upstream and downstream of weir-gate model using a point gauge with a scale reading up to 0.1 mm. A total of thirty two runs were conducted during the testing process.

To model the flow numerically, ANSYS Design Modeler was used to create 3D dimensional open channel with weir-gate system for the same dimensions as mentioned above. The automated mesh type which consists of tetrahedral elements was built with maximum element numbers of (467600), steady state with RNG k-ϵ turbulence model derived from the Navier stokes equations was selected [19]. The RNG k-ϵ turbulence model predicts more accurate performance for complex flows involving rotation, separation, and recirculation [16,20]. The initial conditions were adopted at the inlet using values of water volume fraction, air volume fraction, and pressure and velocity components. Non slip smooth walls have been selected as boundary conditions at the two sides and bottom of open channel flume. While, flow rate and pressure were selected at the inlet and outlet boundary respectively. At the top section, as shown in Fig. (2), the opening boundary condition with air entrainment was selected for the case of free surface flow. Further, mesh adaption was applied in order to make the mesh size finer in locations when solution variables change rapidly. After the mesh adaption the total number of elements became (1,809,582) see Fig. (3).

Table 1
Details of the tested models

Model Shape	Height of gate (d) (cm)	Bottom width of gate (b_g) (cm)	Bed width of weir (b) (cm)	Side slope of gate
Weir-rectangular gate	10	10	10	0
Weir-trapezoidal gate	10	15	10	1H:4V
Weir-trapezoidal gate	10	20	10	1H:2V
Trapezoidal weir	-	-	10	-

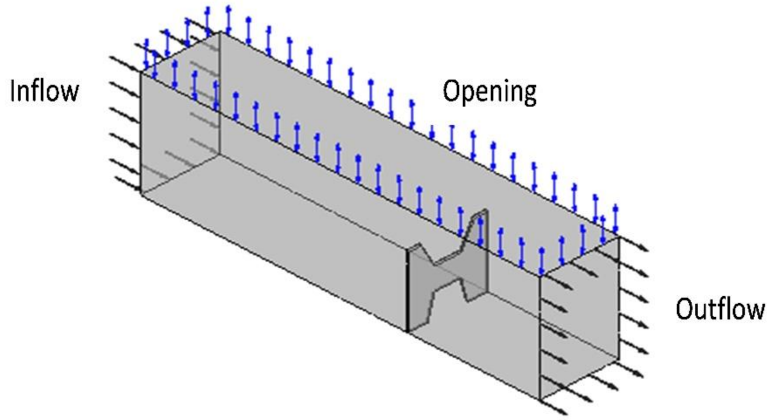


Figure 2. Three dimensional domain geometry with boundary conditions.

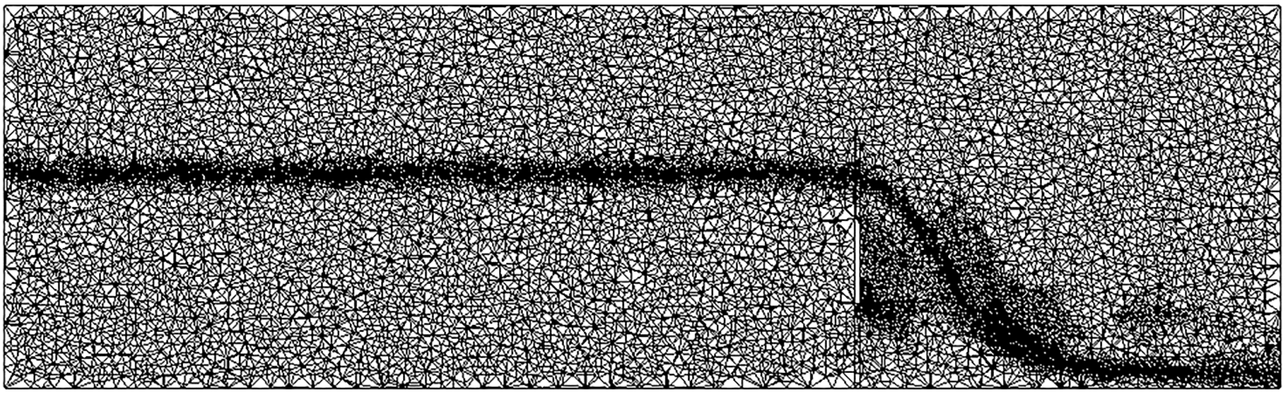


Figure 3. Mesh Adaption

4. RESULTS AND DISCUSSION

The experimental measurements of water surface profiles for all physical models for twenty four runs along the center line of channel were plotted in order to visualize flow shape and the upstream and downstream behavior of the crest model. The water surface profile shows approximately the uniform profile at the upstream locations with slight decrease near the upstream face of the combined weir-gate models. The water surface profile then drops sharply at the downstream of the model as shown in Fig. (4). Y is the upstream water depth measured above the flume bed at any distance X and X is the horizontal distance from the upstream face of the crest. The surface profiles fall into smooth curvature at the maximum distances of 2.11h from the upstream of weir crest for all combined weir-gate models. This distance indicates the nearest location to measure an accurate water depth above crest (h).

In this study the numerical model was verified by comparing the measured values experimentally and predicted numerically in terms of water surface profile and total discharge. Fig. (5) shows the acceptable agreement between experimental and numerical profile of water surface with average mean absolute percentage error equal to (1.98%) for all models.

Table 2 illustrates the measured flow rate experimentally and the summation of the predicted flow rate passing over weir (Q_w) and through the gate (Q_g) numerically. This table indicates that the difference between the measured discharge and predicted one was very small with average mean absolute percentage error (0.37%).

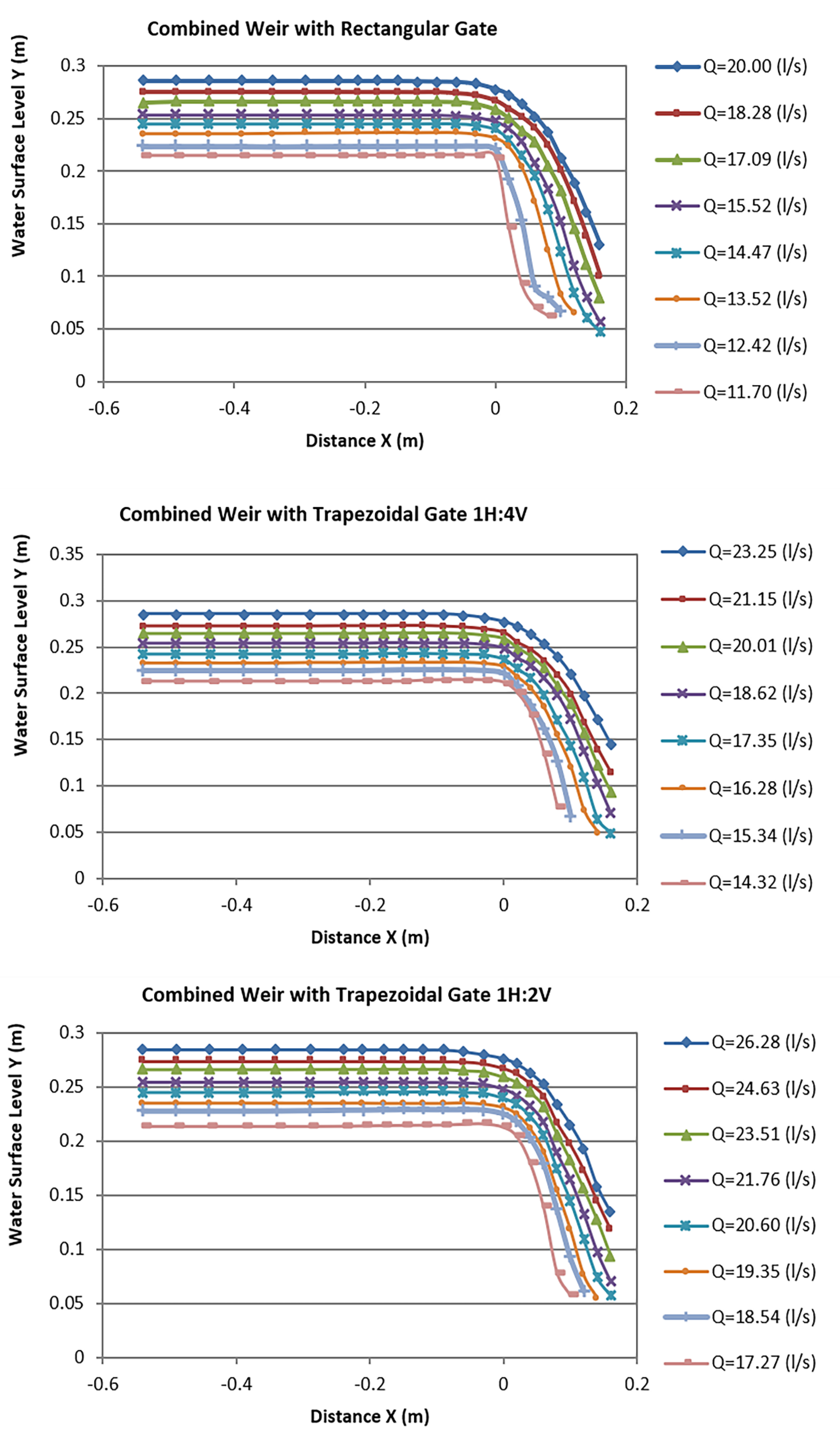


Figure. 4. Water surface profiles through combined weir-gate system

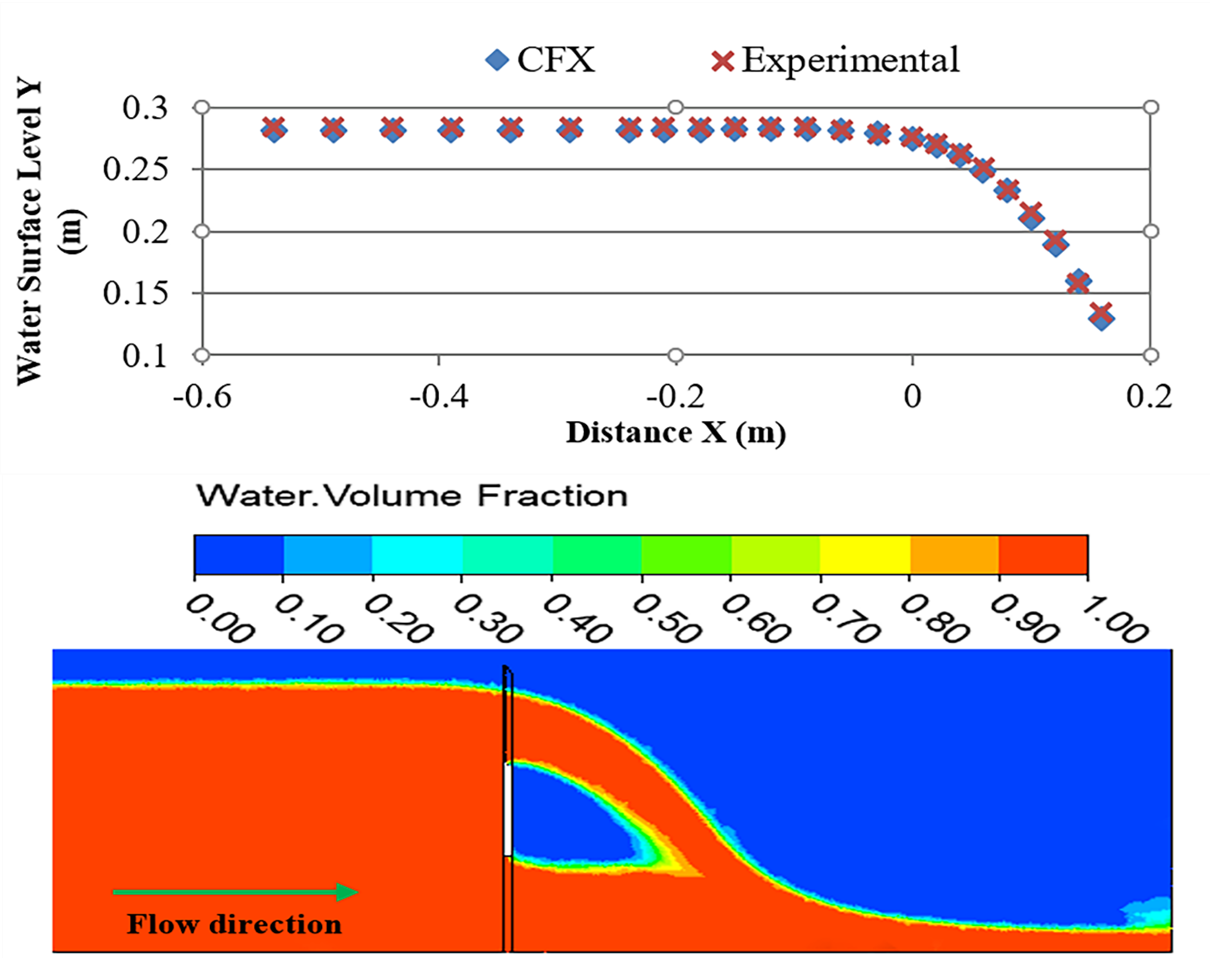


Figure. 5. Water surface profile comparison between experimental and numerical data for combined weir with trapezoidal gate (1H:2V), (h = 8.5 cm)

Table 2
Comparison of $Q_{measured}$ and $Q_{predicted}$ for the combined weir-gate system

Combined weir with rectangular gate	Q_w	6.58	5.14	4.26	2.98	2.22	1.57	0.85	0.63
	Q_g	13.35	13.08	12.77	12.48	12.19	11.89	11.53	11.01
	Q_w+Q_g	19.93	18.22	17.03	15.46	14.41	13.46	12.38	11.64
	$Q_{measured}$	20	18.28	17.09	15.52	14.47	13.52	12.42	11.70
	MAPE%	0.33	0.34	0.37	0.40	0.41	0.44	0.35	0.53
Combined weir with trapezoidal gate 1H:4V	Q_w	6.83	5.10	4.22	3.17	2.30	1.61	1.02	0.60
	Q_g	16.33	15.97	15.72	15.38	14.98	14.63	14.25	13.67
	Q_w+Q_g	23.16	21.07	19.94	18.55	17.28	16.24	15.27	14.27
	$Q_{measured}$	23.25	21.15	20.01	18.62	17.28	16.28	15.34	14.32
	MAPE%	0.37	0.38	0.34	0.35	-0.02	0.22	0.44	0.35
Combined weir with trapezoidal gate 1H:2V	Q_w	6.74	5.36	4.52	3.25	2.59	1.78	1.27	0.73
	Q_g	19.44	19.17	18.89	18.43	17.93	17.49	17.19	16.46
	Q_w+Q_g	26.18	24.53	23.41	21.68	20.52	19.27	18.46	17.19
	$Q_{measured}$	26.28	24.64	23.54	21.76	20.60	19.35	18.54	17.28
	MAPE%	0.38	0.44	0.57	0.37	0.37	0.41	0.43	0.50

The relationship between the head of water over crest (h) and the discharge (Q) is illustrated in Fig. (6). It is shown from this figure that the flow rate is increased with increasing the upstream head of water and both models with trapezoidal bottom opening have a higher capacity for discharging flow than model with rectangular bottom opening with average percentage increase of discharge (40.78% and 19.40%) compared with the actual increase in the surface area of the gate of (50% and 25%) for trapezoidal side slopes (1H:2V and 1H:4V) respectively. In addition, the model with milder side slopes gives higher percentages increase of flow about 17.86% as compared to steep side slopes. This demonstrates that gates of milder side slopes have larger area of bottom opening related to the head. From this figures, the best fit were determined to estimate equations for stage-discharge relationship for each models which was tested in this study as shown in Table 3.

The combined weir-gate system with milder trapezoidal side slopes of bottom opening has a highest efficiency for discharging weir flow Q_w which varies between 20% to 40% as compared to the traditional one and this is accepted with (Sarhan and Jalil, 2018) [21], see Fig. (7). This is one of the gate advantages in combined structure that increases the weir flow due to the reduction of separation zone at the downstream of combined structure.

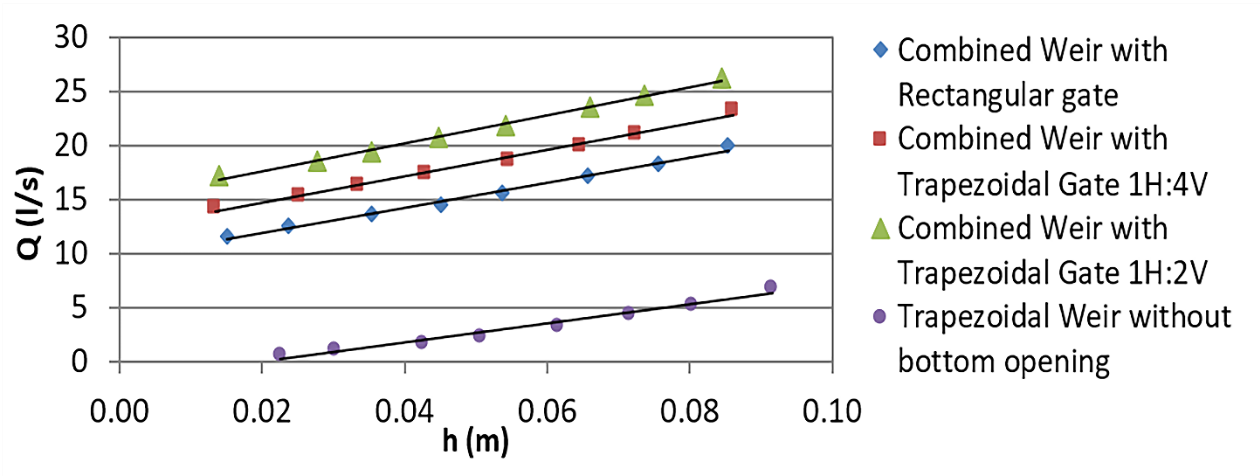


Figure. 6. Stage-Discharge relationships

Table 3
Stage-discharge equations for all models

Model	Empirical equation	R^2
Trapezoidal weir with rectangular gate	Q = 116.57 h + 9.5581	0.9889
Trapezoidal weir with trapezoidal gate 1H:4V	Q = 122.48 h + 12.288	0.9921
Trapezoidal weir with trapezoidal gate 1H:2V	Q = 130.06 h + 14.986	0.9925
Trapezoidal weir without bottom opening	Q = 88.033 h + 1.7683	0.9787

Where, h= head of water over crest (m) and Q= discharge (l/s)

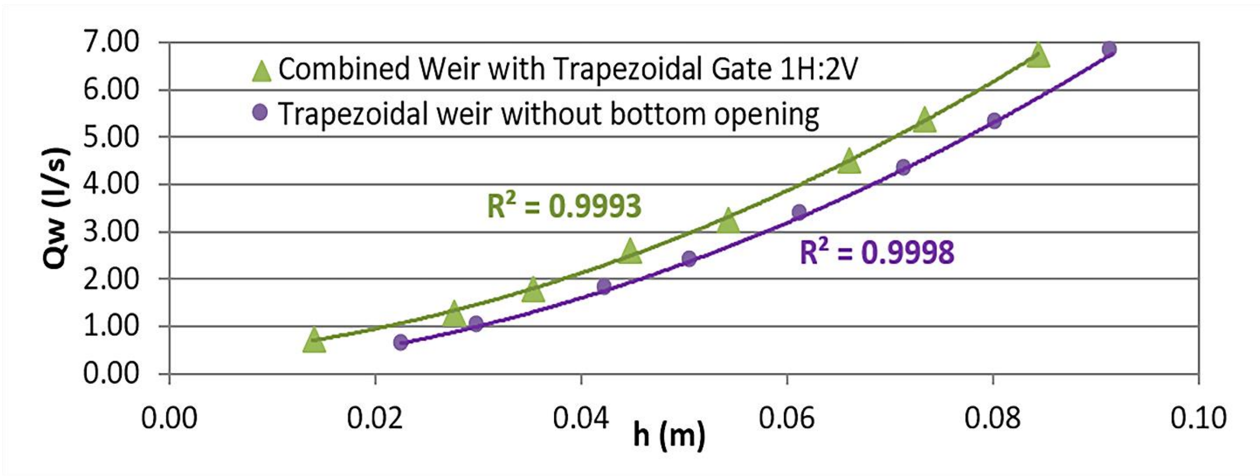


Figure. 7. Comparison of discharging weir flow between combined structure and traditional weir.

The flow structure and separation of vectors into two different zones is one of the essential points that affect the efficiency of weir discharge in combined structure. The percentage of separation depth to the total flow depth (Hs/H) is decreased about 7.57% with increasing the bottom opening area 50% for a constant head, see Fig. (8), and for more details see the relation between (Hs/H) and the percentage of flow depth over crest to the total flow depth (h/H) in Fig. (9). This means the reduction of lower separation depth Hs due to the increase of weir flow Q_w which increases the upper separation depth hs.

The variation of discharge coefficient with flow rate for all three models is plotted in Fig. (10). It is shown from this figure that the discharge coefficient C_d varies between (0.52 to 0.59) for all models of combined weir-gate system.

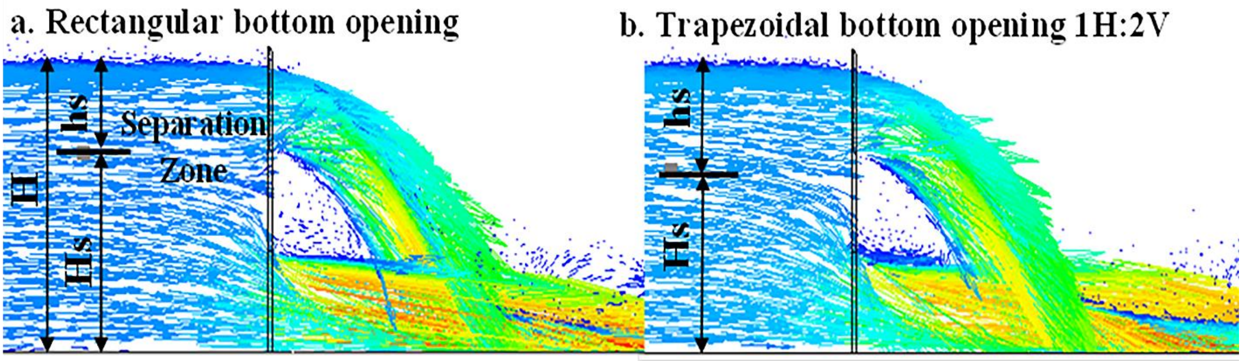


Figure. 8. Vector visualization for combined structure and constant head.

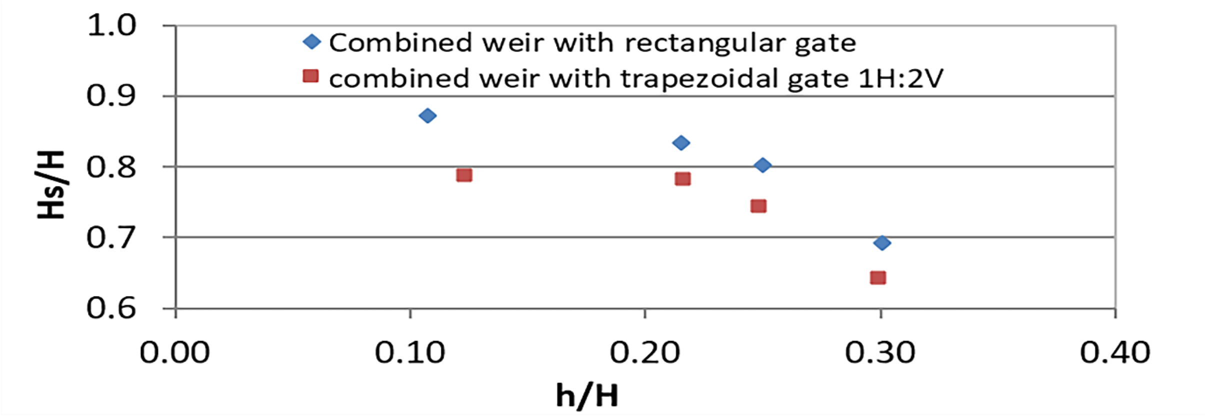


Figure 9. Relation between (h/H) and (Hs/H)

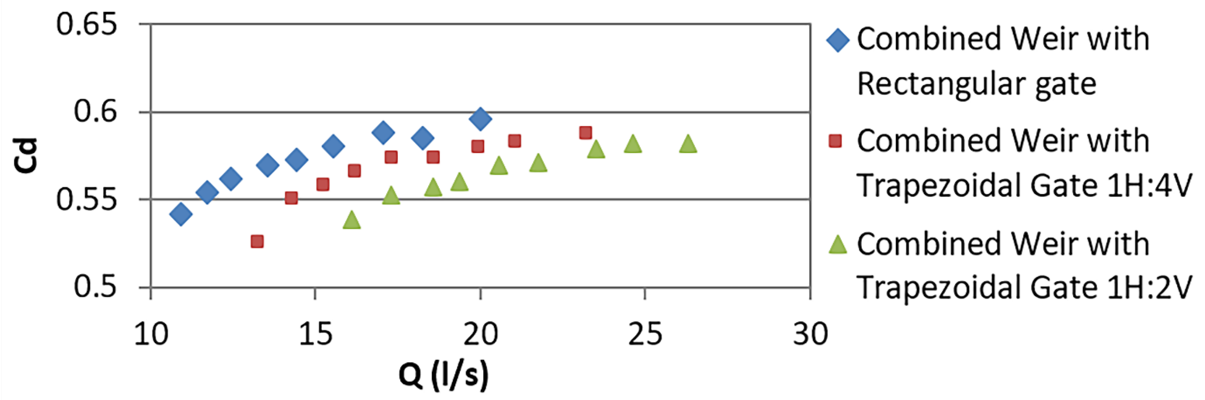
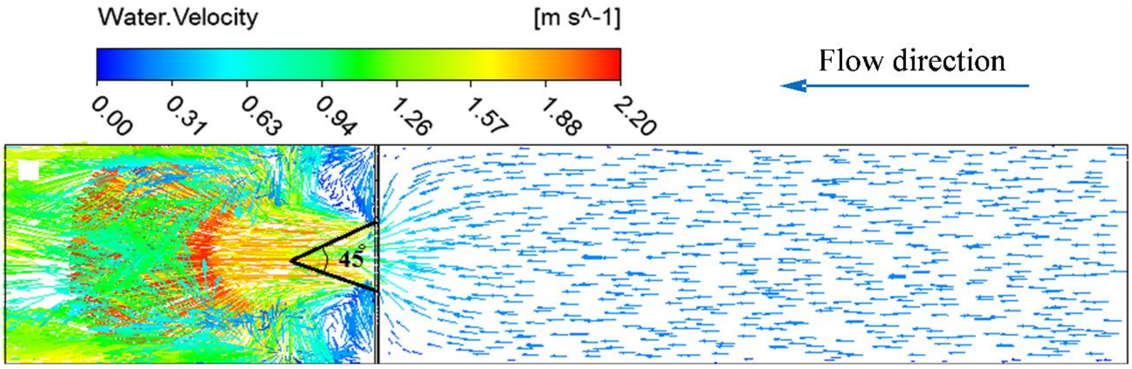
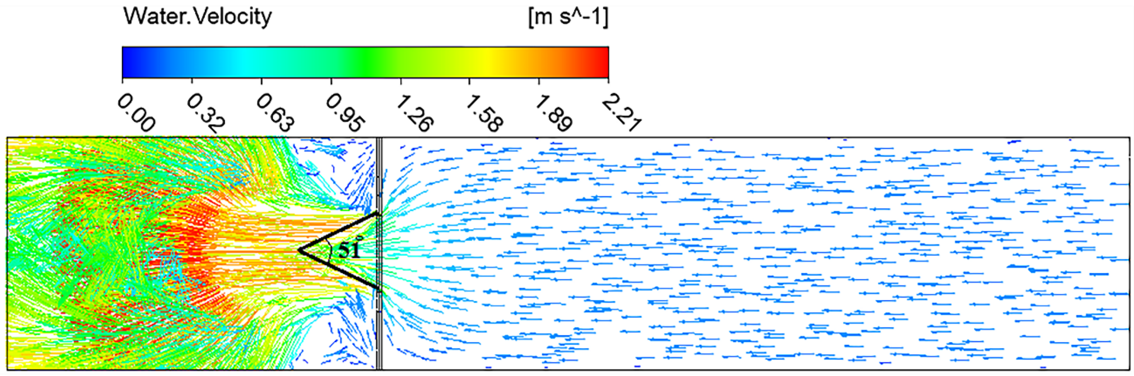


Figure 10. Relationship between discharge and discharge coefficient

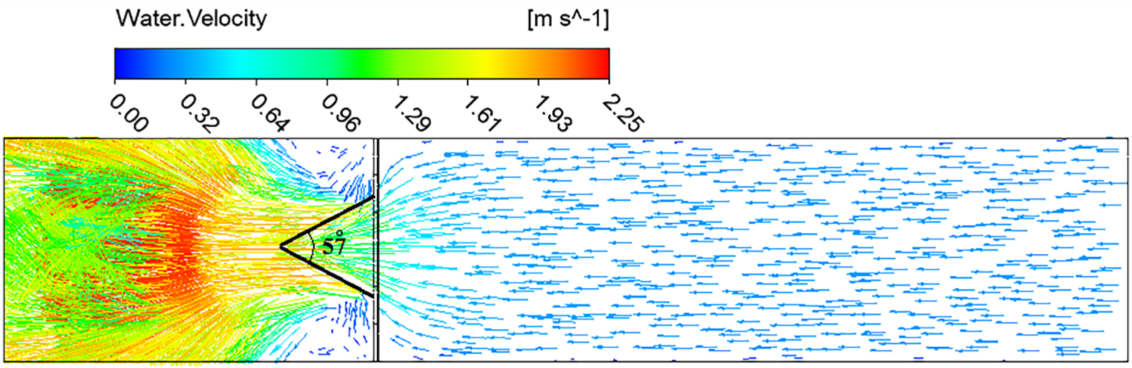
The water velocity vectors at the middle (d/2) of bottom opening for combined system are shown in Fig. (11). It is illustrated from this figure that the velocity vector directions have a direct effect on increasing the discharge for the same upstream head of flow. The combined weir with trapezoidal gate of side slopes (1H:2V) has a larger velocity jet area vector angle that happens from different directions of vectors to pass over weir and under gate. It is believed that the separation zone which reflects the energy losses is not proportional to the area of bottom opening. Moreover flow streamlines were drown at middle (d/2) of horizontal cross-section for combined weir-gate system in Fig. (12). This figure shows that the flow lines pass more smoothly under gates of larger area.



a. Water velocity vectors for combined weir - rectangular gate

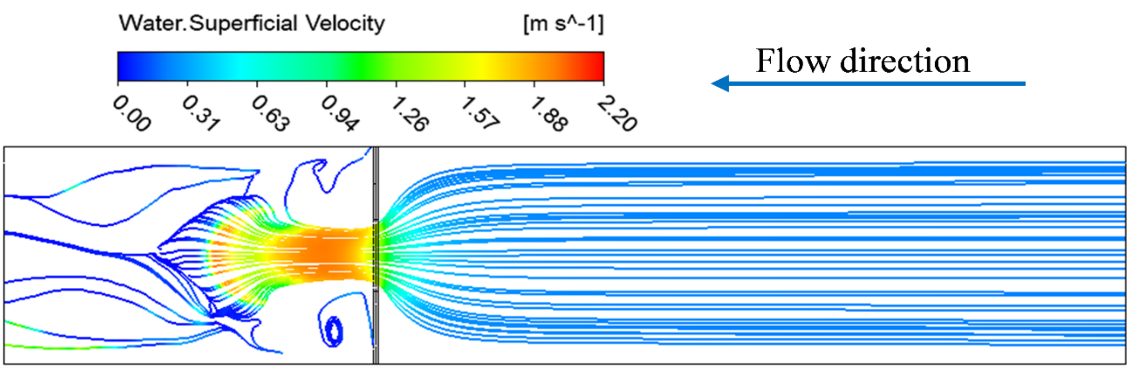


b. Water velocity vectors for combined weir - trapezoidal gate (1H:4V)

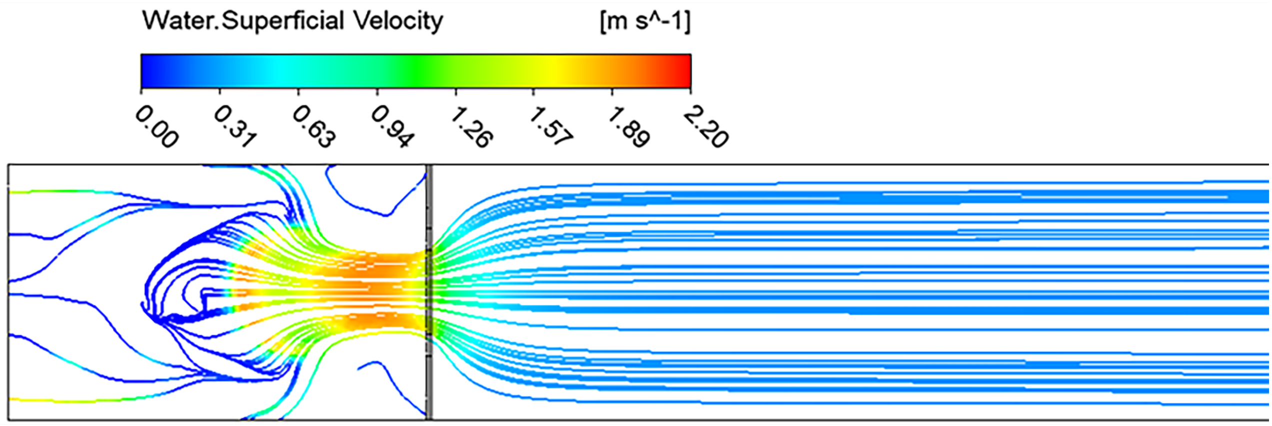


c. Water velocity vectors for combined weir - trapezoidal gate (1H:2V)

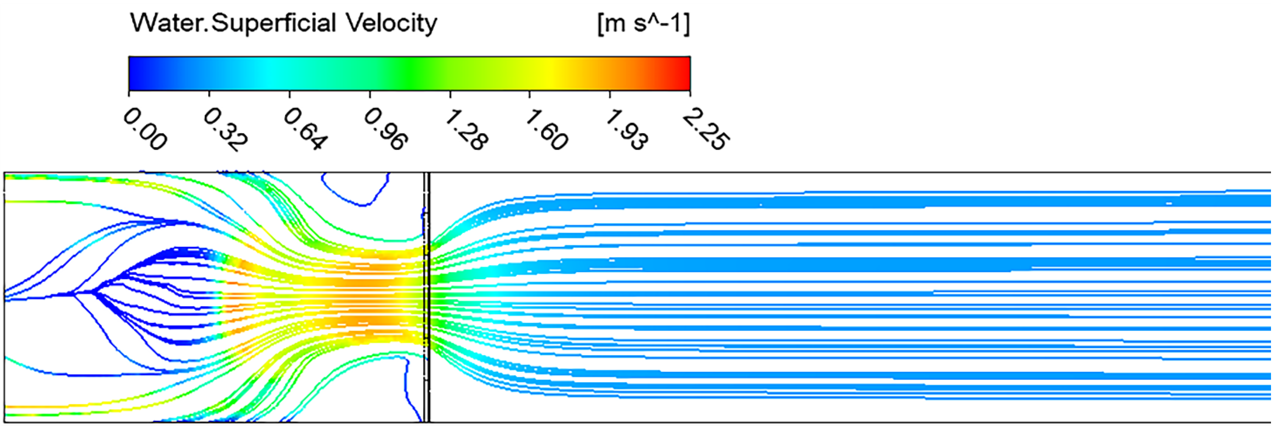
Figure. 11. Water velocity vectors at middle (d/2) of horizontal cross-section for combined weir-gate system (h = 8.5 cm)



a. Water velocity streamlines through rectangular gate



b. Water velocity streamlines through trapezoidal gate (1H:4V)



c. Water velocity streamlines through trapezoidal gate (1H:2V)

Figure 12. Water velocity streamlines at middle (d/2) of horizontal cross-section for combined weir-gate system (h = 8.5 cm)

5. CONCLUSIONS

From the experiments and as ANSYS-CFX was capable for simulating flow through combined weir-gate system with mean absolute percentage error of (1.98% and 0.37%) for water surface profile and total discharge respectively, the following conclusions can be summarized:

1. Water surface profiles through the center line of the flume were smooth and showing a slight decrease at the maximum distances of 2.11h from the upstream face of weir with a steep drop at the downstream.
2. Discharge coefficient C_d varies between 0.52 – 0.59 for all combined weir-gate models.
3. The combined weir with trapezoidal gate has a higher capacity for discharging flow than model of rectangular gate with average percentage increase of discharge (40.78% and 19.40%) for trapezoidal side slopes of (1H:2V and 1H:4V) respectively.
4. The combined system with milder side slopes of trapezoidal gate gives higher percentages increase of flow about 17.86% as compared to steep side slopes.
5. The combined system with milder trapezoidal side slopes of bottom opening has a highest efficiency for discharging weir flow Q_w which is about 40% as compared with weir model separately.
6. Empirical equations for stage-discharge relationship were developed for each model with good deterministic coefficient.

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