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Enhancing Hydraulic Performance and Discharge Efficiency of a Type-C Piano Key Weir Through Stage Incorporation

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Abstract

Weirs are hydraulic constructions typically employed in dam spillways and channel control structures. The shape and size of the crest will determine whether the weir is linear or non-linear. Of the two types, non-linear weirs are often selected due to their ability to allow different discharge levels at the minimal heads. A recently introduced variation of the non-linear kind is the piano key weir. This research undertakes a comprehensive analysis of the hydraulic functionality of the type-C piano key weir under conditions of free flow. The research methodology involved modifying the models by adding stages to the sides and monitoring the effect on the efficacy of discharge, represented by the discharge coefficient. The study further extrapolated formulae linking critical variables to the discharge coefficient, using dimensional analysis and SPSS software. The findings of this study revealed that the introduction of stages significantly bolstered the discharge coefficient in the altered models compared to the standard model. This enhancement was reflected in a 6% and 11% ascent with length expansion of the stages and a 6% and 8% rise with height increase of the stages. Additionally, the model's performance was augmented with a drop in the total head ratio.

Keywords: Control structures; Dimensional analysis; Discharge coefficient; Piano key weir; Stage; Type-C

1. Introduction

In combination with control structure discharge equations like weirs, the discharge, and equipped head share a direct relationship where an increase in the equipped head corresponds to boosted discharge [1],[2]. The idea arises to double the length of the weir edge to the same available field required for the hydraulic structure, whether by providing different depths of the weir or the action of a zigzag pattern of the edge. The squandering of the labyrinth weir is a basic type of folding edge that is easy to put up and gives better discharge than a linear weir, but the negative part of the labyrinth weir must provide a greater space for the foundation.

Lempérière and Ouamane [3] transformed the labyrinth weir into a piano key weir by making the entrance and exit inclined with overhangs of the same available area as the linear weir, resulting in high discharge with low heads that can be used to rehabilitate the dam or for high discharges in channels. The Piano key weir was assigned based on the top view, the folded edge of which is identical to the piano keys.

Piano key weir (PKW) can give discharge up to four times as much as linear weir of the same head and width [4]. In recent years, piano key weir research to enhance discharge and water efficiency has been increased. Fig. 1 depicts each dimension of the piano key weir that was named in the main part of the study that was consolidated based on what was previously published by Lempérière and Ouamane [3]-[5] and as demonstrated in [6],[7]. Various piano key weir constructions have been completed, and the hydraulic design was based on an approach comparable to a physical model. Piano key weir has also been investigated in various studies such as Lempérière and Jun [5]. According to Paxson et al. [8], piano key weirs can provide a superior and unique alternative to improve the current dams' capacity for outflow and storage. The piano key weir has a significantly distinct hydraulic behavior from conventional labyrinth weirs. In the study by Leite Ribeiro et al. [9], performance for low heads (low H/P ratios) is increased by around 50% when L/W (from 3 to 7) is increased. An experimental study was conducted by Kabiri and Javaheri [10] to better understand the effects of a PKW's geometry on Cd in both free and immersed flow circumstances. As reported by Cicero and Delisle [11] and Ribeiro et al. [12], type C can be up to 15% less efficient than type A for free flow and up to 20% less efficient than type A for submerged flow while operating under constant flow circumstances (L/W=4.6, Wi/Wo=1, B/P=2.6). Rdhaiwi et al. [13] examined the scour for three discharges using a type C trapezoidal piano key weir with a stilling basin. However, there is no study for type-C with side stage. The effects of the PKW geometry on the weir flow discharge coefficient were investigated by Bhukya et al. [14]. Mero et al. [15] examined PKW (Type A) models to find out how the intake-to-exit width ratio (Wi/Wo) affected the PKW hydraulic efficiency. In a study by Li et al. [16] observations, the PKW flow patterns demonstrate the device's strong overflow capacity. The impact of PKW geometry on flow capacity for two types (A and D) was investigated by Raheem and Aurahman [17]. Using a small set of experimental data, Kadia et al. [18] discovered the current formulas for the discharge coefficient of PKW type-A. Rezaei et al. [19] used Flow-3D software and models to assess the parameters influencing the discharge coefficient of PKW models. Bekheet et al. [20] evaluated the impact of the form and type (A and B) of PKW on the flow performance for various inlet and output key width ratios. Type-A piano key weir's discharge coefficients might be evaluated according to the intriguing results presented by Javaheri et al. [21]. In many experimental investigations, Erpicum et al. [22] looked into the primary variables affecting PKW type-A hydraulic performance to determine their ideal value. Khanh et al. [23] provided an initial account of the commencement of studies in laboratories on PKW in 2004. Experiments on the discharge coefficient in PKW type B were conducted by Al-Shukur and Al-Khafaji [24] to assess the impact of PKW shape. The energy dissipation and discharge rate of two trapezoidal PKW types (B and C) were examined by Rdhaiwi et al. [1].

There are many forms of piano key weir, Type-C has only overhang from the side of the exit against the entrance to be vertical, and the standard type has less efficiency than the other types of piano key weir manifestation [25], so it was taken in this study to see how effective it is to add stages on the sides as the reason for increasing the value of discharge coefficient (Fig.1).

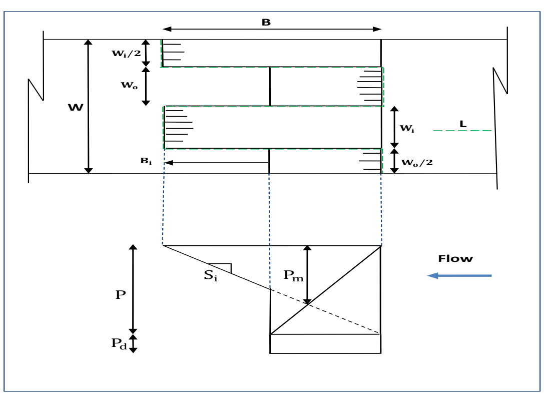

Figure 1. Standard rectangular piano key weir type-C (Top and Side view).

Standard models were employed, based on the dimensions of the Model-B previously investigated in [5], and the discharge factor C_d was analyzed using a ratio of W_i/W_o equal to 1.25. The effective length of the weir edge affects the increased weir efficiency in passing more discharge when increased and to the same head. This is an important reason for the desire to use non-linear weir. In this study, emphasis was placed on increasing the length of the weir edge by providing side openings that increase the amount of discharge passed either in the high or low head of models similar to the standard models and comparison between them in the value of the discharge factor.

2. Physical Models and Experimental work

The material models are made of acrylic material with a thickness (of 2.5 mm), the special dimensions of each model are equipped with a laser device with a high resolution of ($\pm$0.01) before the parts are assembled with silicon material and a base containing screws to stabilize them with satisfactory laboratory channel and rubber bands placed on the piano key weir's sides stabilize some parts of the object to prevent water leaking. The channel used is 15 meters long, 30 cm wide, and 40 centimeters high, with glass sides and two reservoirs, one for channel water processing in the front and the other for water collecting in the back, with expenditures ranging from 6 to 36 liters per second. The physical model is inserted in the center of the channel to avoid turbulence in the front (Fig.2). Several models with specific non-dimension groups according to Table 1 have been created.

Figure 2. Material of piano key weir (left) and channel (right).

Table 1. Limitation of non-dimensional groups for discharges (12-32 liters/ second)

L/W	B/P	B_i/P	P_d/P	d_P/P	d_L/L
5	2.4	0.5	0.7	0.2	0.06
5	2.4	0.5	0.7	0.3	0.06
5	2.4	0.5	0.7	0.2	0.12
5	2.4	0.5	0.7	-	-

The same models have been modified by adding side stages and comparing hydraulic performance between the models. Then an equation that connects the dimensional variables resulting from the dimensional analysis with the discharge coefficient has been discovered. A digital instrument positioned on the channel measures velocity as it goes both vertically and horizontally to any location. A point gauge with an accuracy of ($\pm$0.01) is used to measure the heads. In each procedure, the levels and velocities are measured at a distance of approximately (90 cm) to avoid drawdown of water in the upstream piano key weir and at the backside at a distance of (250 cm) to avoid disturbances occurring in the downstream piano key weir. An electrical device connected to the pump with a digital panel to insert the desired discharge controls the quantity of discharge inside the channel (Fig. 3).

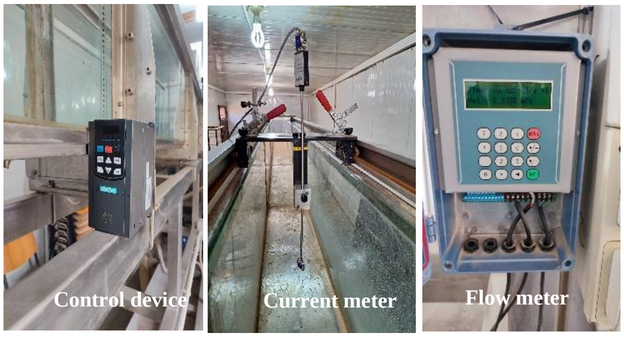

Figure 3. Measuring instruments.

Discharge over a piano key weir is computed by equating discharge to a non-linear weir and using the effective length of the edge (L) as in (1), or by equating discharge to a sharp-edged weir and using the channel width (W) as in (2). Because of the complexity of the flow through the piano key weir of the measurements where the front (W_i) and rear key (W_o) and side edges (B) [26], and the difficulties of measuring the coefficient of discharge are taken into account in the calculation, apply (2).

$$Q_{non-linear\ weir} = C_d\ L\sqrt{2g}H^{1.5} \quad (1)$$

$$Q_{linear\ weir} = C_d\ W\sqrt{2g}H^{1.5} \quad (2)$$

So:

$$C_d = Q_{linear\ weir}/W\sqrt{2g}H^{1.5} \quad (3)$$

Each model has lasted around 20 discharges and the heads and velocities are obtained at each discharge (velocity to extract the total head H, Fig. 4 depicts the measured levels.Where H is equal to ($h+v^2/2g$) and Q is equal to ((P_d+P+h)×W×V).

The value of each transient discharge is calculated through a calibrated rectangle weir standard at the front of the channel and the flow device, velocity is measured using a current meter, and equation 3 is used to compute the discharge coefficient for each model. Fig. 5 illustrates the form of certain standard and modified versions with side-stage additions.

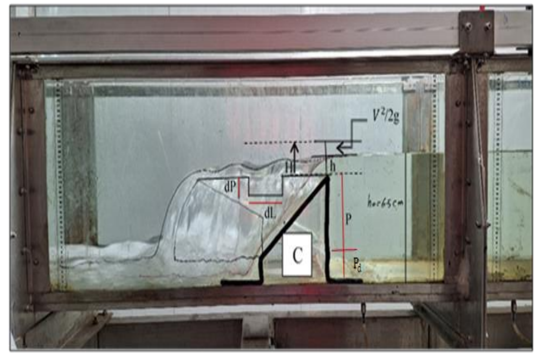

Figure 4. A picture of a piano key weir type-C during one experience

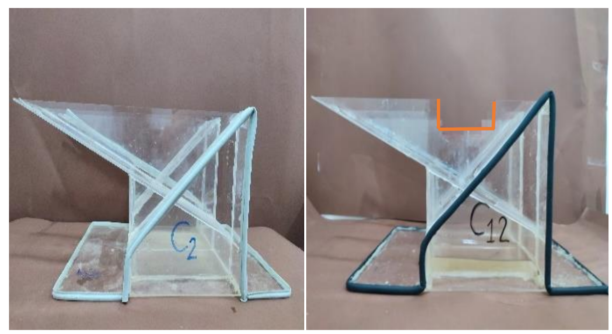

Figure 5. Standard model (C_2) and modified model (C_{12}).

Rectangular piano key weirs are the only models used; the standard model is based on the dimensionless variables taken in [5]. Fig. 6 displays the models' dimensions and flow conditions.

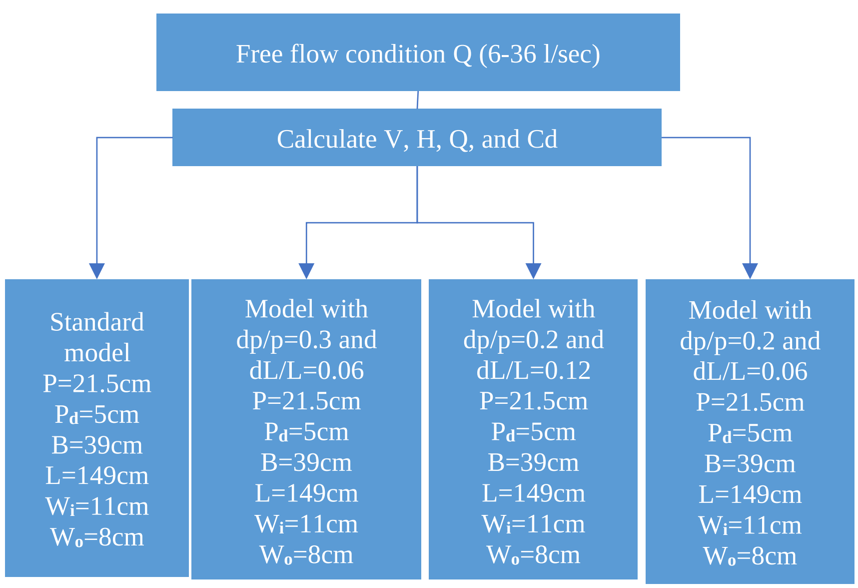

Figure 6. Flow chart.

3. Results and Discussion

A link was created between the total heads on the piano key weir and the discharge coefficient of the standard piano key weir model (SPKW) and modified models to show the impact of adding stages to the piano key weir sides.

Fig. 7 demonstrates that adding stages to the sides greatly enhances piano key weir efficiency by raising the discharge coefficient when side stages offer a longer impact crest, particularly at the lower head where the influence of the stages is greater. Increase in discharge coefficient up to (8%) when (d_P/P= 0.3) and (11%) when (d_L/L= 0.12).

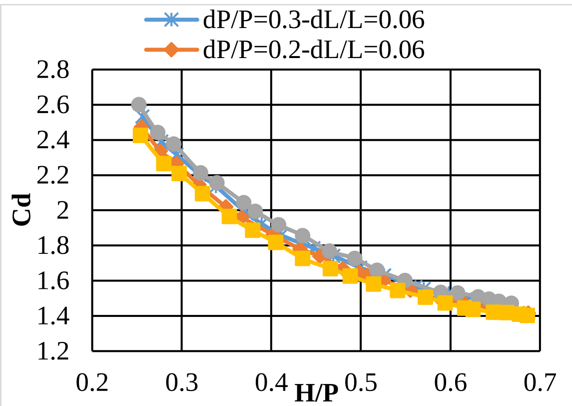

Figure 7. Change in C_d with H/P of the standard (SPKW) and modified models of piano key weir Type-C

When the grade length is raised, the quantity of discharge moving through the sides improves (so increases the coefficient of discharge), particularly at low heads, where the majority of the discharge flows through the degree at the head (h) below (5 cm). Fig.8 demonstrates how increasing stage length increases piano key weir efficiency by raising the discharge coefficient.

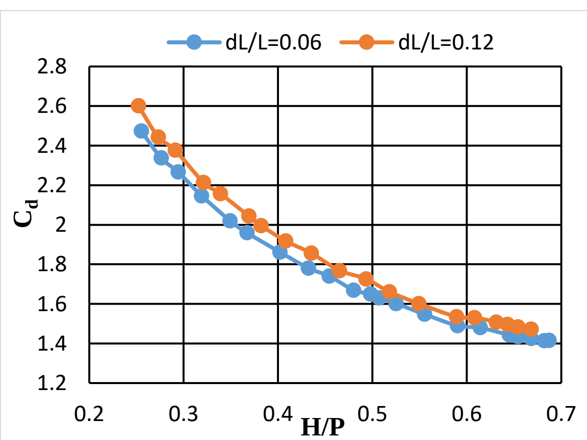

Figure 8. Change in the discharge coefficient as the stage length increases for piano key weir type-C

Fig.9 depicts the effect of increased grade height on the quantity of discharge flowing through the piano key weir on the sides. The stage acts as a side gate, increasing the efficacy of the piano key weir's effective length at the same head as it does when the stage's height is increased, which in turn increases the quantity of discharge going through.

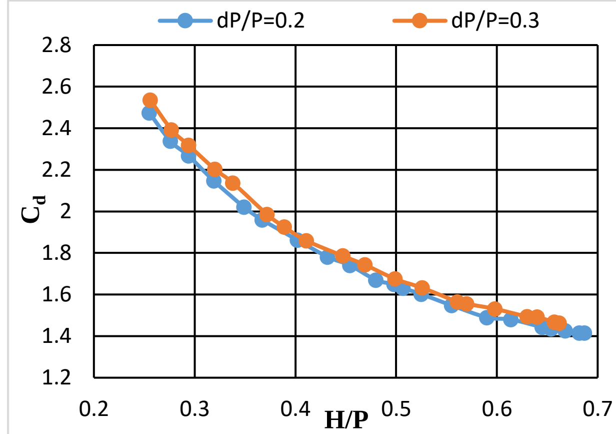

Figure 9. Change in the discharge coefficient as the high stage increases for piano key weir Type-C

Fig. 10 shows how the effect of stage length is higher to increase the amount of discharge than the effect of stage height. As compared to the rest of the model, the modified model with ratios (d_P/P=0.2 and d_L/L=0.12) has a larger discharge, and it exceeds the standard model (SPKW) by 6.03%.

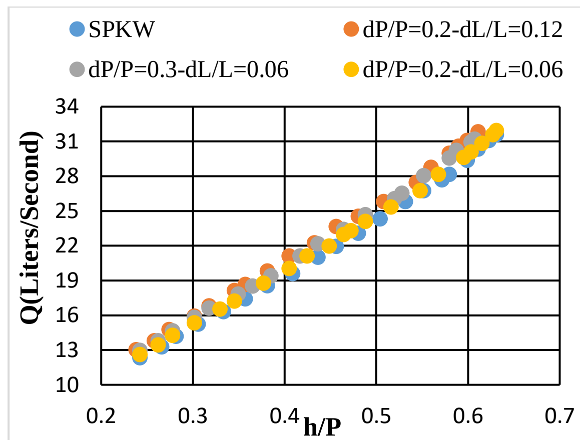

Figure 10. Change in discharge (Q) with Head ratio (h/P).

The standard model's flow pattern differs from that of modified models as well (Fig.11). Side stages alter the form of the aeration area beneath the overhang and add curves to the flow surface.

Using the dimensional analysis method and statistical software (SPSS) to extract the non-dimensional groups impacted in the study, a relationship was derived between the discharge coefficient and the variables that affected it as demonstrated by (4), (5), (6) and (7), and the determination coefficient (R^2) was equivalent to (0.997).

$$C_d = f(H, \rho, g, \mu, \sigma, P, L, d_P, d_L) \quad (4)$$

As a result of the higher turbulence as well as the value of h above (3cm), the Reynolds number and Weber number were neglected so the dimensionless relationship is:

$$C_d = f\left(\frac{H}{P}, \frac{d_P}{P}, \frac{d_L}{L}\right) \quad (5)$$

$$C_d = b_0 * (H/P)^{b1} * (dP/P)^{b2} * (dL/L)^{b3} \quad (6)$$

Where: b_0=0.765, b_1= -0.3, b_2=0.383 and b_3=1 so:

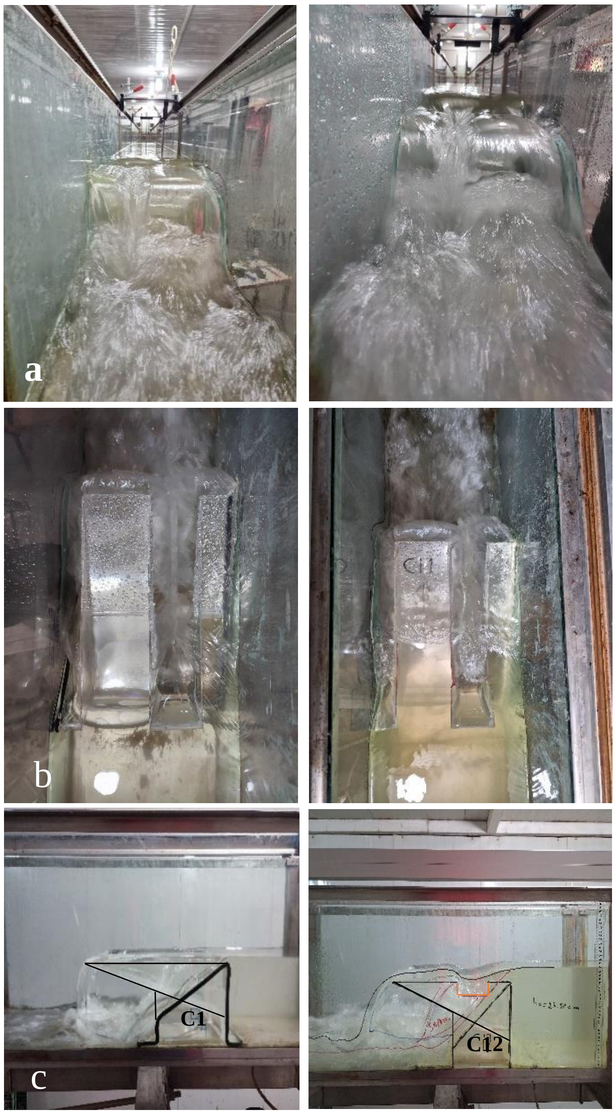

Figure 11. Flow over piano key weir a) Front view b) Top view c) Side view.

$$C_d = 0.765 * (H/P)^{-0.3} * (dP/P)^{0.383} * (dL/L)^{1} \quad (7)$$

About 20% of the data did not enter the equation extraction process and was utilized to evaluate the predictive equation (verification process), which found a satisfactory fit between the actual outcomes and the data obtained from (7) and Fig.12 depicts this.

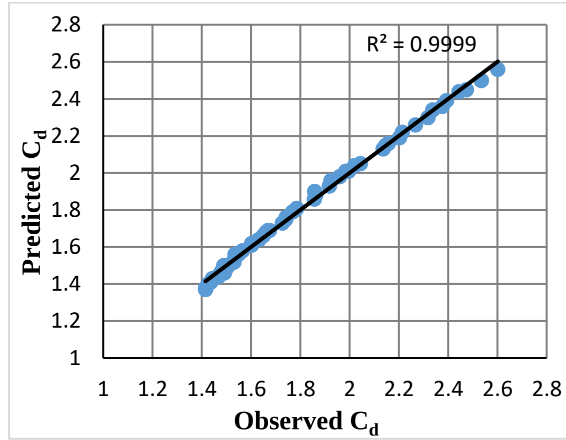

Figure 12. Comparison of the equation (5) with the discharge coefficient's experimental findings

4. Conclusions

The study investigated the effect of adding a side stage to the side crest of a piano key weir Type-C and varying the length and height of the side stage (d_P, d_L) then comparing it with the standard piano key weir. There are four models taken. One standard model is used, and the other models are modified by adding stages with long-stage ratios (d_L/L=0.06 and 0.12) and high-stage ratios (d_P/P=0.2 and 0.3).

By analyzing the practical experiments, it was discovered that adding stages to the sides of the piano key weir increases the efficiency of the piano key weir discharge (C_d) compared to the standard model. With the rates of increase (C_d) with increased stage length (6% and 11%) and the increase rates with increased stage height (6% and 8%) in sequence. The stage also affects the shape of the flow surface and the aeration area . Increased weir efficiency in discharge increases its importance. Reading the data, the least efficient type of piano key weir was chosen, and the stages enhanced their efficiency so that this addition will raise the discharge efficiency of the other types of piano key weirs. In future studies, energy dissipation can be studied in this type of modified model PKW.

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Abbreviations

B	The side length of the piano key weir edge, m
B_i	Length of overhang, m
C_d	dimensionless coefficient of discharge
d_L	High stage, m
DP	Stage length, m
g	gravitational acceleration, m.s^{-2}
V	Velocity, m.sec^{-1}
h	Level from the crest of the piano key weir to the surface of the water, m

H	Total head $((V^2/2g) + h)$, m
L	The effective length of the piano key weir edge, m
P	High piano key weir, m
P_d	Height of the dam, m
P_m	Vertical distance between the edge of the piano key weir and the junction mile entrance and exit, m
Q	discharge, $m^3. Sec^{-1}$
W	Channel width, m
W_i	Piano key weir entrance width, m
W_o	Piano key weir exit width, m
ρ	The mass density of water, $Kg.m^{-3}$
μ	Dynamic Viscosity of water, $Kg.\ s^{-1}\ m^{-1}$
σ	Surface tension of water, $Kg.s^{-2}$

Subscripts

d	dam
i	inlet
m	middle
o	outlet

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

The authors proposed the research problem, developed the theory and performed the computations, investigated and supervised the findings of this work.

Both authors discussed the results and contributed to the final manuscript.

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