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Study on aeration performance of different types of piano key weir

Deepak Singh and Munendra Kumar*
Dept. of Civil Engineering, Delhi Technological University, Delhi-110042, India
*Corresponding author. E-mail: munendrakumar@dtu.ac.in

MK, 0000-0003-3922-424X

ABSTRACT

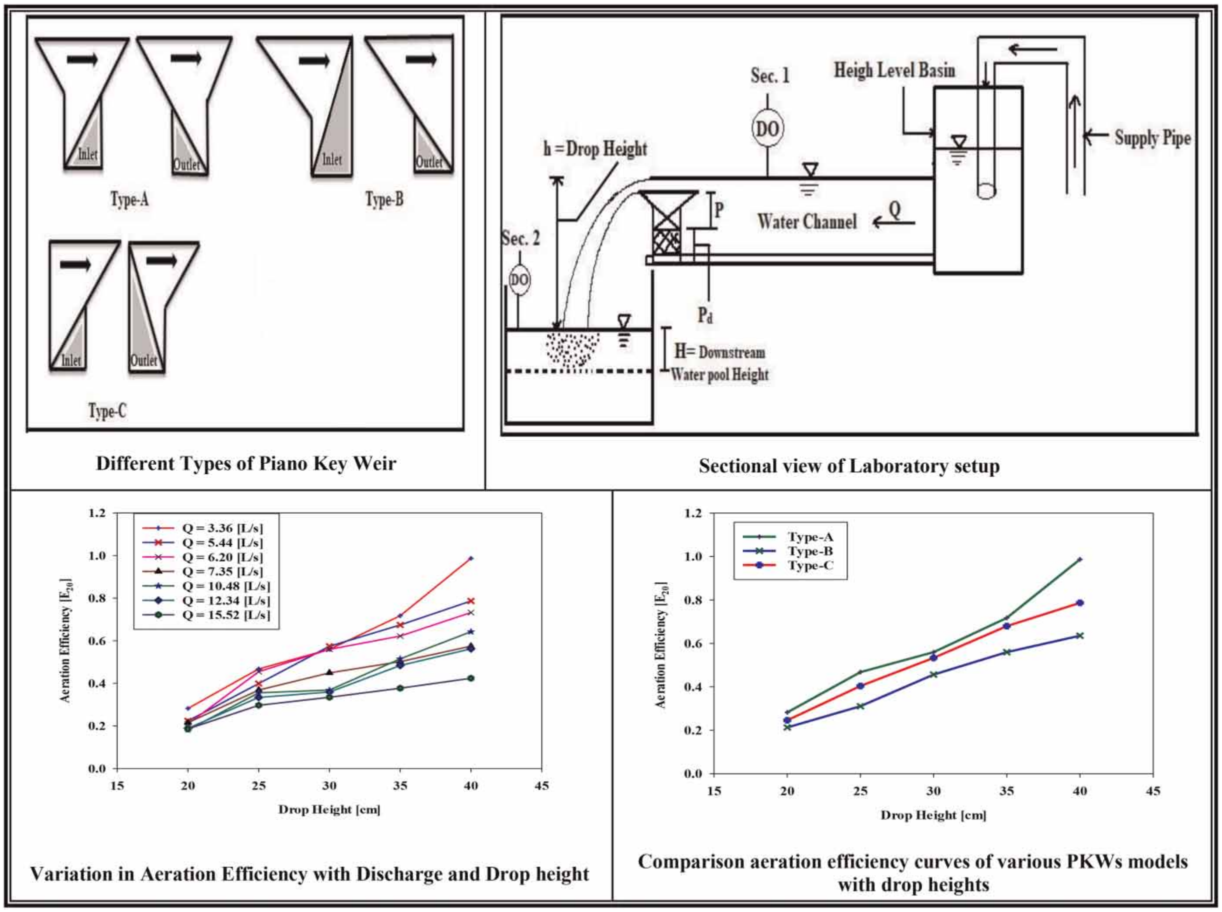
Aeration is the process of increasing the dissolved oxygen (DO) content of water, which is an important water quality parameter for the survival of aquatic life. In this process, large amounts of air bubbles develop; as a result, contact surface area increases, and hence the water-air-mass transfer accelerates. There are numerous methods for increasing DO concentration in water, including self-aeration, mechanical aeration, chemical aeration, and hydraulic structures. The hydraulic structures are an economical and efficient way of enhancing stream/river water aeration. Even though the water only comes into contact with the structure for a short while, it increases the amount of DO in a river system. In this study, an experimental investigation has been carried out to determine the aeration performance of different types of piano key weir (PKW). To this end, three different types (type-A, type-B, and type-C) of PKW laboratory-scaled models were tested. The results demonstrated that the type-A PKW created maximum oxygen transfer efficiency of the three PKW types. In addition, the results show that the aeration efficiency of all PKW models increases with drop height but decreases with increasing discharge over the weirs.

Key words: aeration efficiency, DO concentration, drop height, oxygen transfer rate, PKWs

HIGHLIGHTS

- This study is based on a comparative analysis of aeration performances of different types of piano key weir, which has not yet been published elsewhere.
- Studying and comparing the aeration capacity of the different types of piano key weirs.
- Studying the effects of drop height on aeration performance of piano key weirs.

GRAPHICAL ABSTRACT



Different Types of Piano Key Weir

Sectional view of Laboratory setup

Variation in Aeration Efficiency with Discharge and Drop height

Comparison aeration efficiency curves of various PKWs models with drop heights

LIST OF SYMBOLS

A	Surface area associated with the volume (V) of water over which the transfer occurs
B	Length of side weir ($B_i + B_b + B_o$)
B_b	Base length
B_i	Length of overhang portions at the inlet side
B_o	Length of overhang portions at the outlet side
C	DO concentration
C_d	DO concentration d/s of hydraulic structure
C_S	DO concentration at the saturation level
C_u	DO concentration u/s of hydraulic structure
E	Oxygen transfer or aeration efficiency
H	Downstream water pool height
h	Drop/fall height
K_L	Coefficient of liquid-mass transfer
L	Total developed crest length
N	Number of cycles
P	PKW height
P_d	Dam height
Q	Discharge over the PKW
R	Oxygen deficit ratio
S_i	Inlet key slope
S_o	Outlet key slope
t	Time

T Temperature during measurement in °C.
W Channel width/Width of PKW
W_i Inlet key width
W_o Outlet key width

1. INTRODUCTION

Aeration is the phenomenon by which air is mixed with or dissolved in a liquid. Aeration of hydraulic structures reduces the risk of cavitation and aids in maintaining the required dissolved oxygen (DO) concentration in the flowing water. Today, the world is suffering from a severe freshwater shortage, which hurts both human health and aquatic life. The current scenario is critical for keeping water quality parameters within acceptable limits because daily life, climatic conditions, and pollution levels contribute to the problem on a global scale, either directly or indirectly. According to environmental experts, the DO concentration varies from creature to creature, and the deficiency of DO concentration in any stream or river may create a hazard to the natural aquatic cycle (Baylar & Bagatur 2000). The amount of dissolved oxygen required for aquatic animals such as bottom feeders, crabs, and oysters is 4 mg/L, while shallow water fish need a higher amount of 4–15 mg/L (Baylar & Bagatur 2000; Emiroglu & Baylar 2003).

In the last decade, several studies have investigated the aeration performances of various types of free-flow structures such as rectangular, triangular, trapezoidal, semi-circular, labyrinth, and piano key weirs (PKWs). However, it still requires more in-depth research to assess the aeration performances of labyrinth type weir structures. There are numerous methods for increasing DO concentration in rivers, streams, lakes, ponds, and reservoirs. Nonetheless, aeration is one of the most cost-effective and efficient methods. The aeration process over the hydraulic structures reduces cavity formation while maintaining the required DO concentration in the flowing water (Rathinakumar *et al.* 2014). There is no additional working expense to keep the head, achieve aeration in the river/stream water, and make weir aeration economically viable compared to other artificial oxygen accelerators, such as mechanical aerators. Even though they are only in contact with water for a short time, hydraulic structures help boost DO concentration to a large extent (Wormleaton & Tsang 2000; Emiroglu & Baylar 2003; Guenther *et al.* 2013).

Gameson (1957) was the first researcher to demonstrate the weir's ability to circulate air in rivers. Since then, various experimental studies have been conducted to investigate the aeration potential of different types of weirs, particularly by Van der Kroon (1969a, 1969b), Apted & Novak (1973), Ervine & Elsawy (1975), Avery & Novak (1978), Nakasone (1987), Baylar & Bagatur (2000), and Baylar *et al.* (2001). Gulliver & Rindels (1993) investigated issues concerning field estimations of oxygen transfer and the vulnerability levels of hydraulic structures. Further, Wormleaton & Soufiani (1998) found that the labyrinth weir has better aeration efficiency than the equivalent length linear weir. A comparative study over the sharp, broad crested, and labyrinth weirs was done by Emiroglu & Baylar (2003) for their air entrainment rate. Bagatur & Sekerdag (2003), Baylar & Bagatur (2006), Baylar *et al.* (2008), Baylar & Ozkan (2006), and Baylar *et al.* 2010, 2011) have all conducted studies to determine the air/water flow ratio (Q_a/Q_w) and aeration efficiency (E_{20}) in various hydraulic structures. A systematic review on aeration performances of the different weirs was presented by Jaiswal & Goel (2019). Komal *et al.* (2017) investigated the use of linear regression and adaptive neuro-fuzzy interference systems in predicting the aeration efficiency of the PKW. In addition, Jaiswal & Goel (2020) assessed the triangular weir's aeration efficiency using Gaussian and M5P techniques and concluded that both predicted and measured values agreed with this technique.

Many studies of PKWs have demonstrated that the water flowing over the weir is naturally aerated, but only for low head flows (Hien *et al.* 2006; Laugier *et al.* 2013). One of the main concerns identified by the previous studies is oscillating negative pressures behind the overflow nappe, the potential of these oscillations causing structural vibrations, and the effect of artificially aerating the overflow nappe (Leite Ribeiro *et al.* 2007; Erpicum *et al.* 2013a). A critical review of the hydraulic design and analysis of the PKW was presented by Singh & Kumar (2021). Crookston & Tullis (2012a) proposed an intermediate step in determining the impact of nappe impedance on labyrinth weir hydrodynamics, such as neighborhood submergence. In addition, Crookston & Tullis (2012b) analyzed four specific nappe air circulation conditions of the labyrinth weir during laboratory analysis: clinging, aerated, partially aerated, and drowned. This study provides new hydrodynamics and knowledge about nappe conduct, vibrations, instability, and ventilation (e.g., nappe breakers, aeration vents). Nappe oscillations mainly occur under partially aerated nappe conditions rather than under aerated and drowned nappe conditions (Crookston & Tullis 2012b, 2012c). Although artificial aeration may reduce the nappe instability (Crookston & Tullis 2012b), it does not necessarily prevent vibrations from occurring (Crookston & Tullis 2011). Lodomez *et al.* (2017) addressed the two dominant approaches for describing aeration issues or nappe oscillation over the PKW, images and sound approaches.

The hydraulic performance of the weirs depends on the nappe geometry and aeration conditions (Crookston & Tullis 2012b). For PKW, the flow over the sideways and downstream inlet key crests forms a continuous curtain with a contained air pocket, i.e., a nappe (Denys *et al.* 2017; Lombaard 2020). The air pocket behind the nappe was found to serve only as an amplification and stabilization factor, and it has no effect on the incidence of vibrations (Lodomez *et al.* 2018). By estimating the fall height, one can determine the nappe thickness. When there are high flows or narrow outlet keys, the opposite lateral ridges collide, but they are unlikely to affect discharge efficiency significantly (Machiels 2012). Three typical nappe behaviors are observed for PKWs (free-flow conditions). They can all coincide at different locations along the lateral crests for a specific flow (Machiels *et al.* 2009, 2011).

A nappe is a water jet that flows through a weir structure. The behavior of the nappe must be examined during the design/planning of weirs and spillways in order to ensure optimal hydraulic performance while accounting for flow-induced vibrations, turbulence, noise, and flow surging (Falvey 1980). Aeration issues for various linear weirs have been thoroughly discussed and investigated (Kandaswamy & Rouse 1957; Chow 1959). Recently, Singh *et al.* (2021) conducted an experimental investigation to determine the aeration efficiency of various plan-forms of the labyrinth weirs and used the data to develop the various models and validate their accuracy. They concluded that oxygen transfer efficiency (E_{20}) rises with the number of keys and drop height. The energy dissipation downstream across the PKW has also affected the air circulation rate (Singh & Kumar 2022). In addition, the scouring near the hydraulic structures affects aeration over the hydraulic systems (Pandey *et al.* 2020a, 2020b). Aeration will not influence the shape of the scouring pit; it mitigates the scouring and the effect of air concentration on scouring depth (Pandey *et al.* 2019). The aeration influences the scour hole's shape mainly by decreasing the scour depth. Scour depth depends on bed material and tailwater depth and is affected very little by the air concentration itself in the test range (Pandey *et al.* 2021; John *et al.* 2021a, 2021b). The suspended sediment transport usually ranges from dilute to hyper-concentrated during flooding, depending on the local flow and ground conditions (Pu *et al.* 2021).

This paper presents an experimental investigation over different types of PKWs (type-A, type-B and type-C (see Figure 1)) to determine their aeration performance. The experiments in this study were carried out or designed with the channel flow approach (i.e., experiments were carried out over PKW models in a laboratory flume); thus, this study's application consists primarily of PKWs set up at river barrages or as a control structure in a canal.

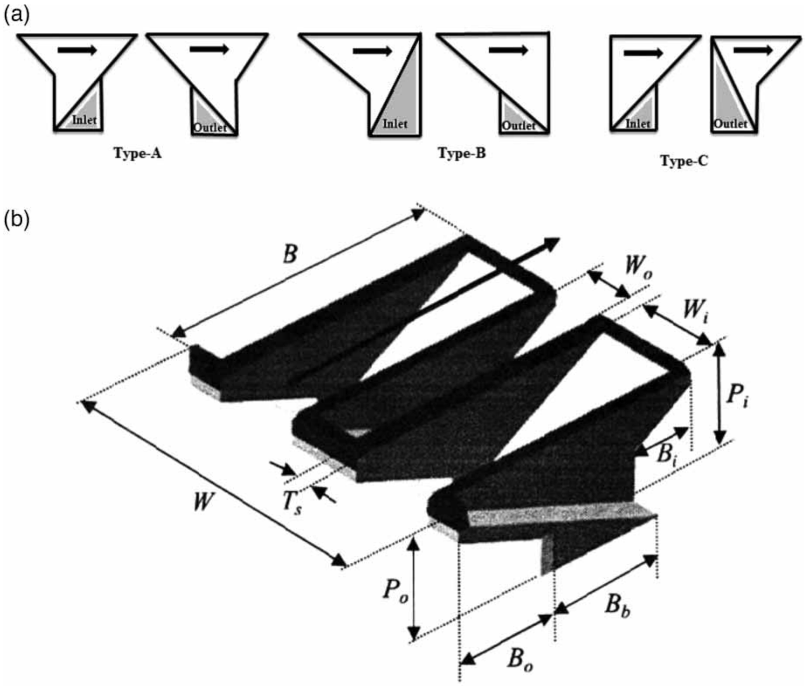


Figure 1 | (a) PKW types [Type-A, Type-B, and Type-C] (Adapted from Lempérière *et al.* 2011). (b) Fundamental parameters of a type-A PKW – 3D view (Pralong *et al.* 2011).

2. MATERIALS AND METHODS

2.1. Experimental setup

Tests were conducted utilizing a tilting rigid steel flume of dimensions (10 m × 0.516 m × 0.6 m) in the Fluid Mechanics and Hydraulics Research Laboratory at Delhi Technological University. The flume is equipped with a 4–20 mA electromagnetic flowmeter (accuracy ±0.2%) for discharge measurement (see Figure 2). The water jet from the test weir was directed into a downstream water pool, which was raised using a base/dam height mechanism (see Figure 3). The depth in the downstream water pool was kept above the bubble penetration depth to ensure optimal aeration throughout the process. A calibrated Thermo Scientific Orion Star A223 Dissolved Oxygen Portable Meter was used to measure DO and temperature upstream and downstream of the PKW. The DO meter was calibrated using either water-saturated air or air calibration method, and calibration steps followed those recommended by the manufacturer. The calibration was carried out in humid air under ambient conditions. The flowing water over the weir was clean water. Each experiment was started by filling the storage tank with clean water.

The models were fabricated using a transparent acrylic sheet with a thickness of 8 mm and affixed with chloroform. The models' configurations are as follows: the relative width ratio (W_i/W_o) is 1.28. The L/W ratio is 6, the height of all models (P)

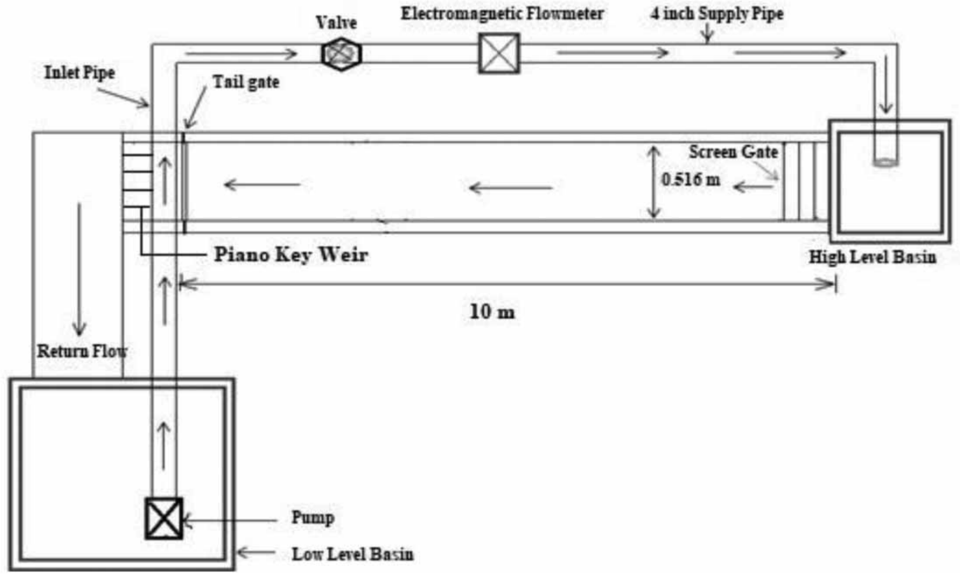


Figure 2 | Schematic plan view of the experimental setup.

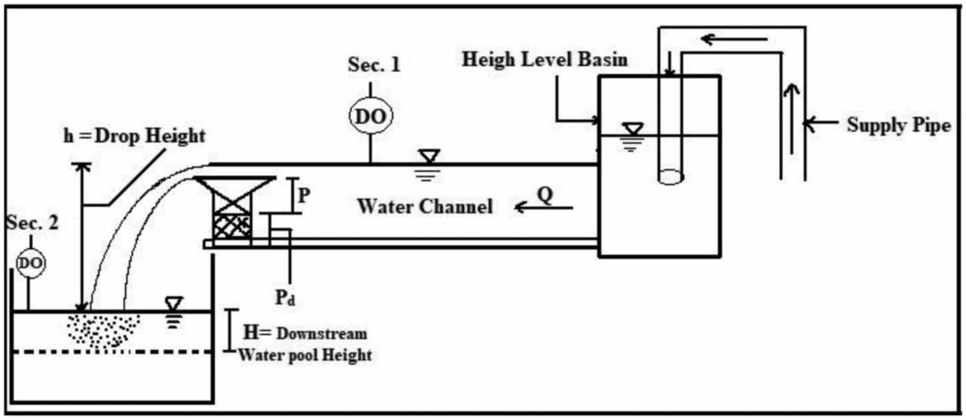


Figure 3 | Laboratory schematic PKW aeration apparatus.

is 20 cm. The inlet-outlet key slopes are 45° ($S_i = S_o = 1$) for Type-A, $S_i = 1$, and $S_o = 0.37$ for Type-B, and $S_i = 1$, $S_o = 3.2$ for Type-C. The two overhang portions are such that $B_i = B_o$, are alike for Type-A, whereas $B_i = 0$, $B_o = 2/3\ B_b$, for Type-B, and $B_i = 2/3\ B_b$, $B_o = 0$, for Type-C. The testing discharges were varied over the model in the range $0.003\ \mathrm{m^3/s} \leq Q \leq 0.0155\ \mathrm{m^3/s}$ on five different drop heights (20 cm, 25 cm, 30 cm, 35 cm, and 40 cm) of the models. The drop height is the difference between the water level upstream and downstream of the weir (see Figure 3). The ranges of the data set collected in this study are shown in Table 1.

2.2. Methodology

The efficiency of aeration depends on the quality of air intake in the form state of water. DO is incongruent with an entirely liquid-controlled gas-water transfer rate. Thus Gameson (1957) and Gulliver *et al.* (1990) stated that the concentration rate of oxygen changes over time in the air-water phase system as water passes over hydraulic structures and can be expressed as,

$$\frac{dC}{dt} = K_L \frac{A}{V}(C_S - C) \tag{1}$$

where $C =$ DO concentration; $K_L =$ coefficient of liquid-mass transfer; $A =$ surface area associated with the volume of water (V) over which the transfer occurs; $C_S =$ saturation concentration at the equilibrium with the air phase is achieved; and t is the time. By integrating Equation (1) we get the aeration efficiency.

$$E = \frac{C_d - C_u}{C_s - C_u} = 1 - \frac{1}{r} \tag{2}$$

$E =$ oxygen transfer or aeration efficiency, $C_d =$ DO concentration d/s of hydraulic structure, $C_u =$ DO concentration u/s of hydraulic structure, $C_s =$ DO at a saturated level for a given ambient condition, and $r =$ oxygen deficit ratio. Aeration efficiency $E = 1.0$ indicates that complete exchange up to the saturation value occurred at the structure, while $E = 0.0$ indicates no transfer occurred. Typically, the saturation concentration is calculated using charts or equations and is set to the local atmosphere value.

The temperature profoundly affects aeration efficiency, so researchers use a temperature correction factor to estimate aeration efficiency. Gameson *et al.* (1958) specified the most commonly used temperature correction factor for hydraulic structures. Gulliver *et al.* (1990) developed the mass exchange comparability relationship to adjust aeration efficiency to 20°C and signified it as E_{20}.

$$E_{20} = 1 - (1 - E)^{\frac{1}{f}} \tag{3}$$

where exponent f depends on the in-situ temperature and is expressed as follows:

$$f = 1 + 0.02103(T - 20) + 8.261 \times 10^{-5}(T - 20)^2 \tag{4}$$

where $T =$ temperature during measurement in °C.

Table 1 | Ranges of data collected in the present study

Model No.	Range of Q ($\mathrm{m^3/s}$)	$\frac{W_i}{W_o}$	W_i (m)	W_o (m)	P (m)	$\frac{L}{W}$	B (m)	B_i (m)	B_o (m)	Range of drop height h (m)	Range of aeration efficiency (E_{20})	N (No. of cycles)
PKW-A	0.003–0.0155	1.28	0.088	0.069	0.20	6	0.427	0.142	0.142	0.20–0.40	0.185–0.983	3
PKW-B	0.003–0.0155	1.28	0.088	0.069	0.20	6	0.427	0	0.2842	0.20–0.40	0.157–0.631	3
PKW-C	0.003–0.0155	1.28	0.088	0.069	0.20	6	0.427	0.2842	0	0.20–0.40	0.151–0.771	3

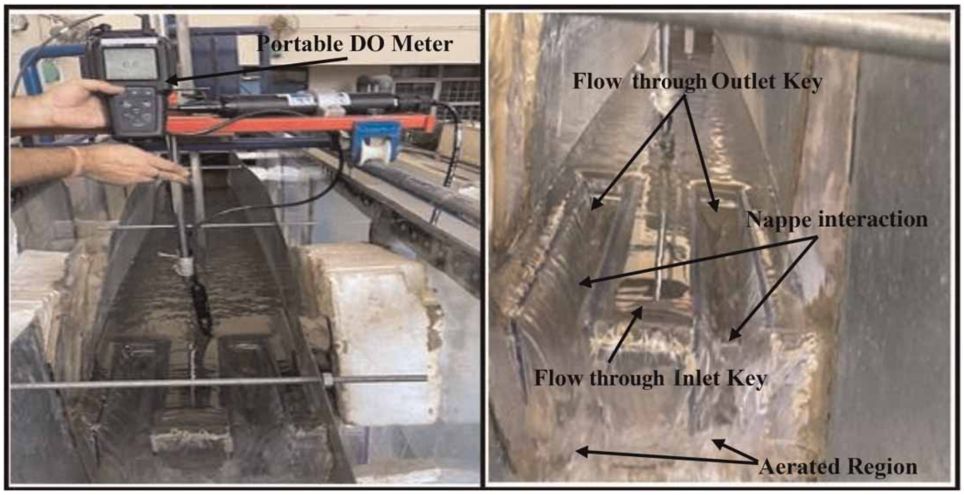


Figure 4 | Flow pattern over PKW.

3. RESULTS AND DISCUSSION

The basic concept of the flowing discharge over the PKW is that flow over a PKW comprises three major components: flow over the outlet key, inlet key, and lateral flow over the side crest (Machiels 2012; Khassaf *et al.* 2015). All three discharge parts interact, resulting in a complicated three-dimensional flow, as shown in Figure 4. With increasing head, water spilled from the side crest enters the outlet key more readily, reducing hydraulic efficiency until the two discharging nappes clash and become one, resulting in the PKW assuming the characteristics of a linear weir. Water flowing over the crest of the sidewall revealed two nappes. In the first one, closer to the upstream side, there is no aeration. The second one is detached from the side crest and aerated, and the separation zone enhances as with discharge and moves downstream. Figure 4 shows that the flow across the PKW is immensely ventilated and three-dimensional, with splash and spray regions within the outlet keys and at the structure's bottom (Singh & Kumar 2022). In proportion to H_t's trajectory, the area of spray and sprinkling increased very little, and the planar jet began away from the crest. On the other hand, the air circulation region grew substantially with H_t, partly because the regional speed increased, resulting in higher advection levels and turbulent mixing. This flow behavior increases the aeration efficiency of the PKW because the complex flow nature creates more air bubbles for a greater time and longer path (Eslinger & Crookston 2020).

The main goal of this study was to gather information on the aeration performance of the different types of PKW. To this end, three different laboratory-scale PKW models were built and tested to assess the aeration performance. The dissolved oxygen upstream and downstream of the PKWs was measured by DO meter, and the oxygen transfer rate/efficiency was assessed based on Equations (2) and (3).

According to the literature, the aeration efficiency of the hydraulic structures depends on the flowing water temperature, water quality, tailwater depth, drop height, and water discharge. In the present study, it was seen that the drop height and discharge over the weir significantly affect the aeration efficiency of the weir. Greater time and longer path traveled by the air bubble in the downstream pool will increase the aeration efficiency. In order to achieve maximum aeration efficiency, Avery & Novak (1978) found that tailwater depth should equal 0.6 times drop height. Water quality is another crucial parameter affecting the aeration efficiency over the weir. If the water contains the active type of suspended solids, it will affect the aeration process. The dynamic suspended solids slow down the diffusion process and surface tension at the interface, thereby affecting the aeration in water.

The experimental data results were documented and plotted for each PKW model with different characteristics (i.e., drop height and discharges). The results demonstrate that the aeration efficiency of PKWs increases with increasing drop height but decreases with increasing flow rate over the weir. Generally, a higher drop height may result in deep bubble insertion into the water pool and longer contact time, increasing the oxygen transfer rate. However, for the greater drop height, a collapse of the jet was observed. Because the jet eventually collides into multiple droplets, the depth of bubble penetration and contact times decrease, enhancing the aeration efficiency. As discharge increases, bubble penetration and contact time in the downstream water pool decrease, reducing aeration efficiency.

The results show that the type-B PKW model yielded the lowest values of oxygen transfer efficiency. The maximum oxygen transfer efficiency of the type-B PKW model was 0.63, at a discharge of 0.00314 m^3/s and a fall height of 0.40 m. And the minimum aeration efficiency was 0.15, corresponding to 0.0125 m^3/s discharge and fall height of 0.20 m. Thus the type-B PKW was found to be less effective as an aerator (see Figure 5(b)). The oxygen transfer efficiency values for the type-C PKW model were generally consistent with those for the type-A weir. The greatest oxygen transfer efficiency of the type-C PKW model was 0.77, at a discharge of 0.0032 m^3/s and drop/fall height of 0.40 m, and the minimum aeration efficiency was observed 0.151, corresponding to 0.0152 m^3/s flow rate and drop height of 0.20 m (see Figure 5(c)). The oxygen transfer

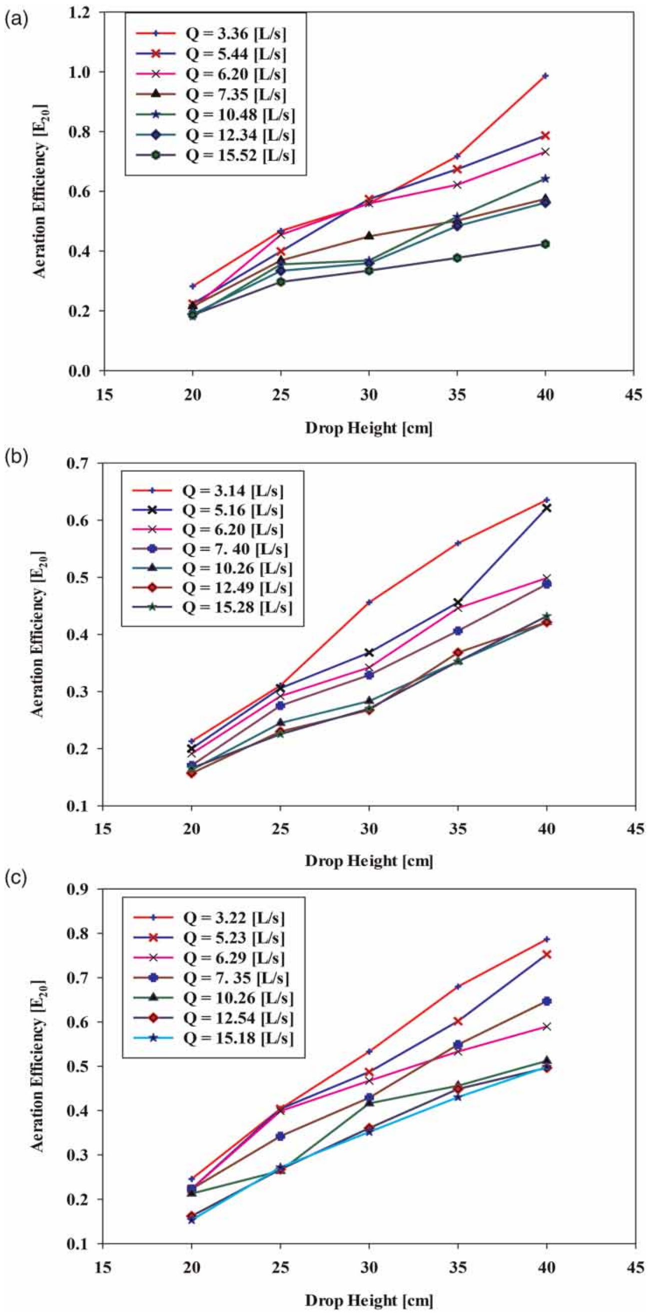


Figure 5 | Variation in aeration efficiency with discharge and drop height for (a) Type-A (b) Type-B, and (c) Type-C piano key weirs.

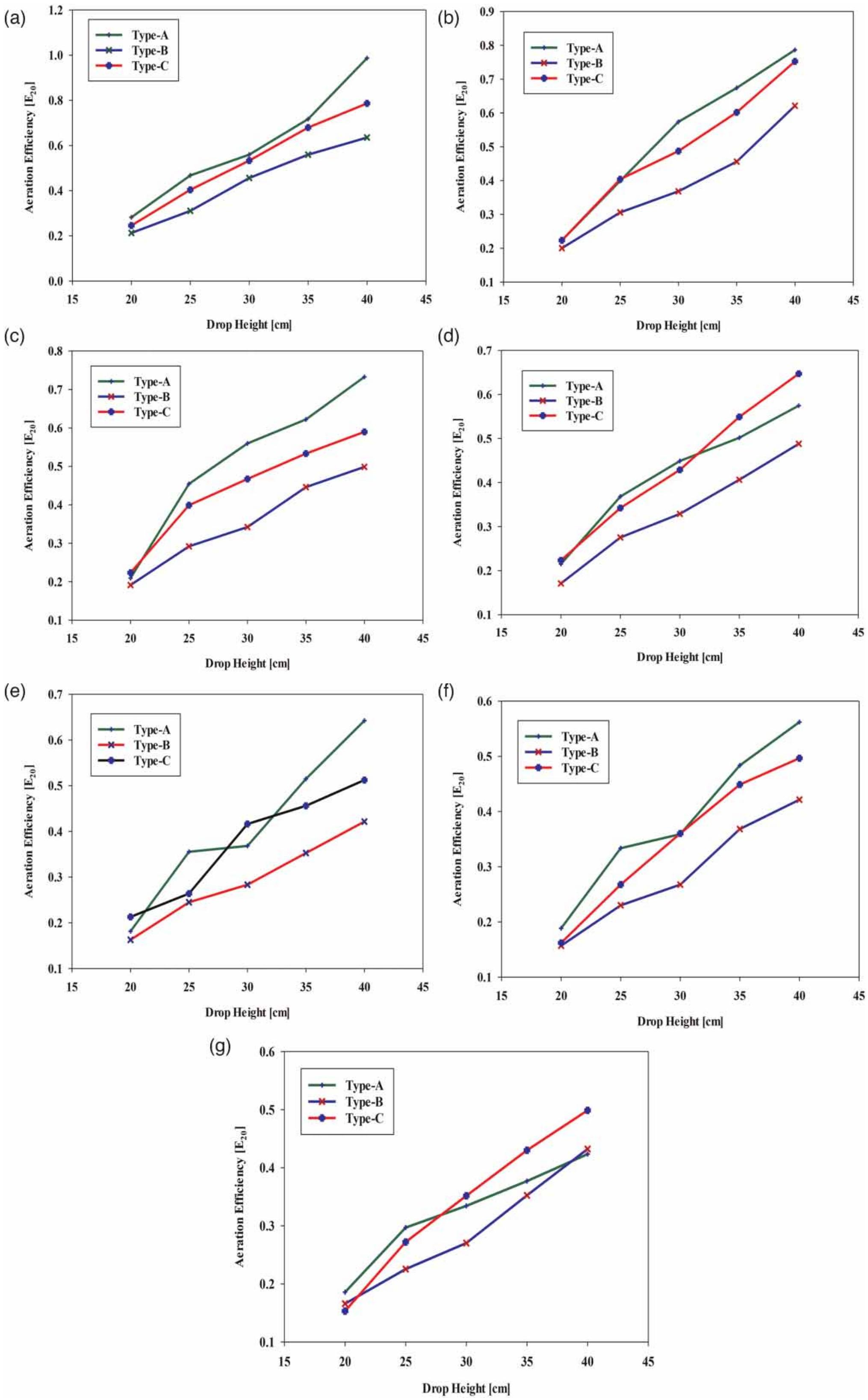


Figure 6 | Comparison aeration efficiency curves of various PKW models with drop heights. (a) Q = 3.2 [L/s], (b) Q = 5.3 [L/s], (c) Q = 6.2 [L/s], (d) Q = 7.4 [L/s], (e) Q = 10. 32 [L/s], (f) Q = 12.50 [L/s], (g) Q = 15.30 [L/s].

efficiency of the type-A PKW model was found to be the best. The maximum oxygen transfer efficiency of the type-A PKW model was 0.98, at a discharge of 0.0034 m^3/s and drop height of 0.40 m, and the minimum aeration efficiency was 0.185, corresponding to 0.0155 m^3/s discharge and drop height of 0.20 m (see Figure 5(a)).

Figure 6 shows the comparative aeration performances of different PKWs with different drop heights. From Figure 6, it is clear that the aeration efficiency of all three models is enhanced with the drop height but decreases with the increasing discharge. It concludes that the overall aeration performance of the type-B PKW is lesser than the type-C. The type-A has better aeration performance than type-C for almost all the discharges. The type-A PKW has shown a 22–28% higher aeration rate than the type-C at drop height 0.20–0.40 m and a 23 to 56% higher aeration rate than type B at the same drop height. The type-A and type-C PKW models have downstream overhang portions of free jet formation. As a result of this free jet falling on the downstream pool of water, turbulent mixing and air entrainment occur, increasing oxygen transfer rates. In the downstream collection, more oxygen is transferred because the hydrostatic pressure on the air bubbles is greater. The overhangs of PKW were noticed to be a significant factor influencing aeration efficiency.

During the investigation, it was noticed that as the drop height increases, the aeration efficiency of all the weirs increases. However, increasing the discharge decreases the aeration efficiency of all weir shapes. A similar trend was observed by Baylar & Bagatur (2000). They presented the experimental results of aeration performance of different shapes of weirs, with flow rates Q varying from approximately 1.0 to 4.0 m^3/s. The drop height was varied between 0.15 and 0.90 m. Therefore, the present experimental study shows good agreement with the published data.

4. CONCLUSIONS

The paper presents the results of an experimental study carried out to assess the aeration performance of different PKW type models. To this end, three different types of PKW models (type-A, type-B, and type-C) were tested across flow rates ranging from 0.0032 to 0.01552 m^3/s and drop heights ranging from 0.20 m to 0.40 m. The following observations, conclusions, and recommendations are made based on the findings of this study:

1. The type-A PKW has shown the highest aeration performance, and the type-B has the lowest. The type-A PKW has a 22 to 28% higher aeration rate than type-C at drop height 0.20–0.40 m and 23 to 56% higher than type B.
2. The type-A and type-C PKW models have downstream overhang portions, which leads to the maximum oxygen transfer rate. The PKW geometry defines nozzle shapes that are unique to each weir, and oxygen transfer appears to be strongly influenced by these jet shapes.
3. The drop height was the most significant parameter influencing oxygen transfer performance over the PKWs. In all cases, the air circulation efficiency increased with drop height.
4. The flow rate over the weir produced less explicit results than drop height experiments. Across the entire range of drop heights tested, the PKW's aeration efficiency decreased as the discharge enhanced.
5. Tailwater depth, drop height, and discharge are essential factors in weir air circulation. As a result, there should be a tailwater depth beyond which air bubbles can penetrate to an approximate deepest point.

Actual results are limited in defining the aeration performance of different types of PKW. However, they should give designers a clearer idea of the potential hydraulic impacts of labyrinth geometric designs that differ from the weir geometries specific to the design method used.

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DATA AVAILABILITY STATEMENT

The supporting data associated with the findings of this study can be obtained from the corresponding author on genuine request.

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