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Study of relative energy dissipation of trapezoidal and arced piano key weirs equipped with baffles

Hooman Farhadi[a], Mehdi Karami Moghadam[b,*], Touraj Sabzevari[a] and Shabnam Noroozpour[c]

[a] Department of Civil Engineering, Estahban Branch, Islamic Azad University, Estahban, Iran
[b] Department of Agriculture, Payame Noor University (PNU), Tehran, Iran
[c] Young Researchers and Elite Club, Estahban Branch, Islamic Azad University, Estahban, Iran
*Corresponding author. E-mail: m.karami.mo2014@pnu.ac.ir

TS, 0000-0003-3965-1751

ABSTRACT

Energy dissipation is one of the important issues in piano key weirs (PKWs). Excessive energy at the weir's toe can cause scouring. In the previous studies, energy dissipation of the arced piano key weirs (APKWs) has not been investigated. In this experimental study, the effect of weir height as well as the height and arrangement of the baffles located on the outlet key slope on the amount of dissipated energy were examined in trapezoidal piano key weirs (TPKWs) and APKWs. Experiments were performed on models with two weir height to the width of a cycle ratios equal to 0.9 and 1.2, three baffle height to the width of a cycle ratios equal to 0.06, 0.12 and 0.18 and two A and B-arrangements. The results showed that with the increase in discharge, the amount of relative energy dissipation decreases. The amount of relative energy dissipation is higher in weirs with higher height and also in weirs with larger baffles. Also, the arrangements of the baffles located on the outlet key slope has a significant effect on the amount of dissipated energy.

Key words: baffle blocks, extra energy, nonlinear weirs, relative energy dissipation, residual energy, scouring

HIGHLIGHTS

- The relative energy dissipation of piano key weirs equipped with baffles is higher than the ones without baffles.
- The baffle blocks with higher height and B-arrangement dissipate more flow energy.
- Under the same conditions, a weir with greater height has a greater effect on energy dissipation.

LIST OF SYMBOLS

Parameter	Definition
B	PKW total streamwise length (m)
B_i, B_o	Lengths of the upstream and downstream overhangs (m)
B_b	Weir foot length (m)
S_i, S_o	Slopes of the inlet and outlet keys apron (m/m)
L	Total crest length (m)
W_i, W_o	Inlet and outlet keys' widths (m)
P	Weir height (m)
T_s	Wall thickness of the weir (m)
W	Total width of the PKW (m)
W_u	Width of a cycle (m)
θ	Central angle of APKW (degree)
R	Parapet wall's height (m)
n	Number of PKW units (cycles)
h	Baffles height (m)
H	Upstream head (m)
H_t	Total upstream head (m)
σ	Surface tension (N/m)
g	Gravity acceleration (m/s^2)

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μ	Water viscosity (kg/m.s)
ρ	Water density (kg/m^3)
Q	Discharge (m^3/s)
y_0	Water depth at PKW upstream (m)
y_1	Water depth at PKW downstream (m)
y_2	Secondary depth of hydraulic jump (m)
y_c	Critical depth (m)
V_d	Flow velocity at PKW downstream (m/s)
V_u	Flow velocity at PKW upstream (m/s)
C	Discharge coefficient
Re	Reynolds Number
We	Weber Number
E_0	Total upstream energy (m)
E_1	Total downstream energy (m)
E_{min}	Minimum possible value of specific energy (m)
ΔE	Total dissipated energy (m)
ΔE_{max}	Maximum possible amount of energy dissipation (m)
TPKW	Trapezoidal Piano Key Weir
APKW-53	Arced Piano Key Weir with central angle of 53 degree
A-h/W_u	Baffles with A-arrangement and h/W_u ratio
B-h/W_u	Baffles with B-arrangement and h/W_u ratio

INTRODUCTION

Weir's insufficient discharge capacity can endanger dam's safety especially during severe floods (Akbari Kheir-Abadi *et al.* 2020a). Using nonlinear weirs is a common way to resolve this issue (Leite Ribeiro *et al.* 2012). Labyrinth weirs (LWs) as one of the vastly used nonlinear weirs disclosed the large-sized foundation weakness limiting their use on gravity dams (Lempérière & Ouamane 2003). Recently, piano key weirs (PKWs) considered as an innovative and optimized type of labyrinth weirs (Figure 1).

PKWs have inlet and outlet keys featuring sloped floors alternately towards upstream and downstream. The use of overhangs in upstream and/or downstream of PKWs has led to a smaller footprint relative to the labyrinth weirs (Akbari Kheir-Abadi *et al.* 2020b). Also, key's sloped floors of PKWs compared to the horizontal-vertical walls of labyrinth weirs improve the hydraulic efficiency (Anderson & Tullis 2011, 2012). Many studies have so far been completed on PKWs (Khassaf & Al-Baghdadi 2015; Mehboudi *et al.* 2016; Kumar *et al.* 2019; Seyedjavad *et al.* 2020). The main goal of most of these studies has been to achieve the hydraulic efficiency enhancement. Researchers have also considered areas of applied research to strengthen the correlation between researchers and authorities (Crookston *et al.* 2019). Some of the most important studies on the non-linear weirs and their findings are given in Table 1.

Energy dissipation is one of the important issues in the piano key and labyrinth weirs. Excessive energy at the weir's toe can cause scouring (Jüstrich *et al.* 2016; Truong Chi & HoTa Khanh 2017). In addition to the techno-hydraulic advantages of

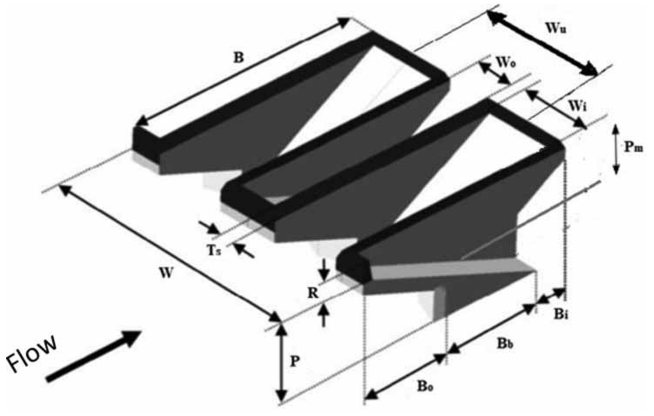

Figure 1 | Geometric overview of piano key weir.

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Table 1 | The most important studies on the non-linear weirs and their findings

Researcher (s)	Subject	Findings
Cordero Page *et al.* (2007)	Investigation of the performance of arced weirs	The discharge capacity of the arced labyrinth weirs is almost same as the linear labyrinth weirs.
Crookston (2010)	Investigation of the performance of arced weirs	The arched weirs have a higher discharge capacity.
Leite Ribeiro *et al.* (2012)	The head-discharge relationship of a Type-A piano key weir with a half-circular crest	The crest length and relative head are the primary parameters affecting the discharge capacity.
Machiels *et al.* (2012)	Study of three parameters of piano key weir's height, keys' widths and overhangs' lengths	These parameters affect the discharge capacity.
Karimi Chahartaghi *et al.* (2019)	Investigation of the performance of arced piano key weirs	The arced piano key models perform better at the upper heads.
Akbari Kheir-Abadi *et al.* (2020a, 2020b)	Investigation of the effect of the key angle and parapet walls on performance of a TPKW	The existence of parapet walls along with the increase of the key angle would escalate the weir discharge efficiency.
Abhash & Pandey (2021)	Investigation of the head – discharge relationship of a PKW with CFD	The numerical model can accurately simulate nappe depths close to the PKW's crest.

PKWs, the nappe flows cascading from the side walls colliding at the outlet key and eventually contributing to energy dissipation. This energy dissipation caused by turbulence can reduce the size of structures such as apron and the downstream energy dissipators (Eslinger & Crookston 2020). In a laboratory study, Lopes *et al.* (2011) examined the flow characteristics including air entrainment, characteristic depths, and energy dissipation at the downstream of the chute of a trapezoidal labyrinth weir. Their results showed a three-dimensional flow near the weir merged with air entrainment and shockwaves. Also, the number of cycles or the shape of the crest had no significant effect on the amount of dissipated energy and residual energy. Merkel *et al.* (2018) studied experimentally the relationship between drop height, discharge and the energy dissipation rate in the labyrinth weir. Depending on the length of the hydraulic jump, they showed that the presence of a concrete apron or a riprap protection can protect erodible river beds. Also, labyrinth weirs can act as an energy dissipator due to their special geometry. Erpicum *et al.* (2011) compared the energy dissipation over the stepped spillway downstream of the piano key and Ogee weirs. The results showed that although the relative energy dissipation in the two models is almost the same, however, the flow is fully aerated in a PKW-equipped stepped spillway unlike an Ogee-equipped stepped spillway. Leite Ribeiro *et al.* (2011) examined the experimental model of the St-Marc dam in France along with PKW. They used a ski-jump gutter to investigate energy dissipation at the downstream of the weir. They exhibited the uselessness of the PKW in this dam where acted as a gravity structure. To reach maximum energy dissipation in the small gravity dam, Ho Ta Khanh *et al.* (2011) suggested using a PKW at the crest and a downstream small stilling basin. Also, in addition to the use of PKW and small stilling basin, using steps downstream of PKW can increase energy dissipation in medium to large dams. Al- Shukur & Al- Khafaji (2018) results showed that the amount of energy dissipation of the piano key weir is directly related to the slope of the keys. They also calculated energy dissipation values based on the hydraulic jump distance from the weir's toe. Qanavati *et al.* (2019) investigated the effect of height and distance of the first row of blocks on the outlet key of the PKW. They used blocks with a height of 8 and 12 cm and the distance of the first row of blocks equal to one-third and one-fourth of the length of the outlet key. Their results indicated that the energy dissipation was slightly higher over the model with a block height of 12 cm compared to the 8 cm, and about 10% more than the model without blocks. Also, energy dissipation over the model with the distance of one-third of the outlet key length was 4% higher than the one-fourth distance. Eslinger & Crookston (2020) investigated the effect of the W_i/W_o ratio on the energy dissipation rate of a type-A PKW. Their results showed that the energy dissipation of the PKW is higher in low discharges and decreases in a logarithmic-like manner as the discharge increases. Despite the increase of the PK weir efficiency, they also found the amount of dissipated energy decreases slightly resulted from an increase in W_i/W_o within the range of $0.2 \leq H/P \leq 0.8$. However, energy dissipation is independent of W_i/W_o ratio outside this range. Singh & Kumar (2021) modeled the type-B PKW weir and concluded that at low heads, the energy dissipation of this type of weir is higher than other types. Also at a constant width, energy dissipation increases with increasing number of cycles.

Energy dissipation of the PKWs, especially arced type, has been rarely addressed despite many studies on performance of the PKWs. Furthermore, most studies on energy dissipation have been performed on chutes or stepped spillways located

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downstream of the PKW, while less attention has been paid to the energy dissipation over the PKW outlet key slopes. In the PKW-equipped spillways, if energy dissipation over the chute as well as the PKW is considered to estimate the total dissipated energy, the structure could be improved economically and estimate a performance safety factor accurately determining the exact size of the apron or stilling basin (Eslinger & Crookston 2020). On the other hand, experiments and findings of the United States Bureau of Reclamation (USBR) have shown applying the baffles, which cause separation of the overflow jet followed by flow turbulence, could effectively dissipate the kinetic energy of the flow (Barani & Abbasi-Parvin 2009). Hence, one of the objectives of this research is to study the effects of the weir's height, height and the arrangement of baffle blocks located on the slope of the outlet key on the energy dissipation of the trapezoidal piano key weir (TPKW) and arced piano key weir (APKW) with a 53 degrees' central angle (APKW-53).

MATERIALS AND METHODS

Dimensional analysis

According to Figure 1, the parameters affecting the energy dissipation of PKW can be presented as Equation (1) (Leite Ribeiro *et al.* 2012; Qanavati *et al.* 2019):

$$F(\Delta E, V_u, y_0, \rho, g, \mu, \sigma, H, P, W_u, W_i, W_o, B_i, B_o, n, S_i, S_o, h, A) = 0 \tag{1}$$

In this equation, ΔE is the difference between the upstream and downstream energy of the weir (total dissipated energy); V_u is the flow velocity at upstream of the weir; y_0 is upstream flow depth; ρ and μ represent specific density and fluid viscosity, respectively; g is the acceleration of gravity; σ is surface tension; H is upstream water head over the weir; P is weir's height; W_u designates the width of one cycle; W_i and W_o are inlet and outlet key widths, respectively; B_i and B_o are upstream and downstream overhangs' lengths, respectively; n represents the number of cycles; S_i and S_o are inlet and outlet key slopes respectively; h designates the height of the baffle and A shows the arrangement of the baffles.

Using Buckingham's π theory, dimensionless parameters are obtained:

$$F\left(\frac{g\Delta E}{V_u^2}, \frac{V_u^2}{gy_0}, \frac{\mu g}{V_u^3\rho}, \frac{g\sigma}{\rho V_u^4}, \frac{V_u^2}{gH}, \frac{V_u^2}{gP}, \frac{V_u^2}{gW_u}, \frac{V_u^2}{gW_i}, \frac{V_u^2}{gW_o}, \frac{V_u^2}{gB_i}, \frac{V_u^2}{gB_o}, n, S_i, S_o, \frac{V_u^2}{gh}, A\right) = 0 \tag{2}$$

As we know, the reciprocal of a dimensionless parameter is itself a dimensionless parameter. Also, by multiplying two or more dimensionless parameters, another dimensionless parameter is obtained. For example, we have:

$$\Pi_2 \times \Pi_3 = \frac{V_u^2}{gy_0} \times \frac{\mu g}{V_u^3\rho} = \frac{\mu}{\rho V_u y_0} = \frac{1}{\mathrm{Re}} \Rightarrow \Pi = \mathrm{Re}$$

$$\Pi_2 = \frac{V_u^2}{gy_0} = Fr^2 \Rightarrow \Pi = Fr$$

$$\Pi_4 \times \Pi_5 = \frac{g\sigma}{\rho V_u^4} \times \frac{V_u^2}{gH} = \frac{\sigma}{\rho V_u^2 H} = \frac{1}{We} \Rightarrow \Pi = We$$

$$\Pi_7 \times \frac{1}{\Pi_6} = \frac{V_u^2}{gW_u} \times \frac{gP}{V_u^2} = \frac{P}{W_u}$$

$$\Pi_7 \times \frac{1}{\Pi_{15}} = \frac{V_u^2}{gW_u} \times \frac{gh}{V_u^2} = \frac{h}{W_u}$$

$$\Pi_6 \times \frac{1}{\Pi_5} = \frac{V_u^2}{gP} \times \frac{gH}{V_u^2} = \frac{H}{P}$$

$$\Pi_{11} \times \frac{1}{\Pi_{10}} = \frac{V_u^2}{gB_o} \times \frac{gB_i}{V_u^2} = \frac{B_i}{B_o}$$

$$\Pi_{13} \times \frac{1}{\Pi_{14}} = \frac{S_i}{S_o}$$

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With operations such as multiplication and inversing the dimensionless parameters and eliminating fixed parameters in this research (input and output key widths ratio, the overhangs' slope length ratio and the number of cycles), new parameters are obtained as follows:

$$F\left(\frac{P}{W_u}, \frac{h}{W_u}, \frac{H}{P}, \frac{y_c}{E_0}, \frac{\Delta E}{E_0}, A, Fr, \mathrm{Re}, We\right) = 0 \tag{3}$$

where *Fr* is the Froud number, *Re* is the Reynolds number, *We* is the Weber number, $\Delta E/E_0$ represents the relative energy dissipation where E_0 is the upstream total energy of the weir. Since the surface tension was negligible and the flow was turbulent in all experiments, the effect of Weber number and Reynolds number could be discarded. Also, the flow was subcritical in the upstream in all experiments. As a result, the dimensionless parameters affecting the relative energy dissipation can be expressed by Equation (4):

$$\frac{\Delta E}{E_0} = f\left(\frac{P}{W_u}, \frac{h}{W_u}, \frac{H}{P}, \frac{y_c}{E_0}, A\right) = 0 \tag{4}$$

Experimental setup

The experiments were conducted at the hydraulic laboratory of Khuzestan Water and Power Authority (KWPA). The experimental tests were performed on a rectangular flume with a cross section of 0.6 m wide and a height of 0.5 m. Figure 2 depicts a schematic representation of the experimental setup.

The flow was supplied by a pump from an underground reservoir. The flow discharge was adjusted by a control valve, a triangular weir and the head-discharge manometers. After entering the flume, the flow passed over the PKW model and went out at the end of the flume. Finally, after passing through a triangular weir, the flow was directed into the primary reservoir through a return channel system. The range of discharge variations of the experiments was between 4 and 50 L/s. In this study, the TPKW and APKW-53 models with heights of $P = 15$ and 20 cm ($P/W_u = 0.9$ and 1.2) were utilized (Figure 3). All weir models accommodate three cycles and 1.41 m long total crest (L). The weirs were type-D (without overhangs in upstream and downstream) and the width of the inlet and outlet key were considered to be the same. The dimensionless geometric parameters of the weir models are as in Table 2.

To investigate the effect of baffles located at the outlet key's slopes on the relative energy dissipation, three baffle height to the width of a cycle ratios (h/W_u) equal to 0.06, 0.12 and 0.18, and two A and B-arrangements were used. In A-arrangement, the number of baffles increases from top to bottom along the slope. In B-arrangement, the number of baffles in all rows is the same and equal to 3. However, the total number of baffles of A and B-arrangements is the same and equal to 15. Also, the space between the first row of the baffles and weir's crest was equally distanced. The weir models and baffles were made of transparent Plexiglas. Figure 3 represents several weir models with two A and B-baffles arrangements. PKW models with $A\text{-}h/W_u$ and $B\text{-}h/W_u$ represent the weirs with A and B-baffles arrangement and a height ratio of h/W_u, respectively.

Method of experiment

To perform the experiments, the baffles were first installed with a specific arrangement on the outlet key's slopes. The flow with a specified discharge was established in the flume using a pump and a calibrated triangular weir (±2% accuracy). After the flow was stabilized (5 to 10 min), the flow depths at section 1 at the upstream (y_0) and at section 2 at the downstream (y_1) were measured using point gauge (±0.1 mm) at a distance of *3P* and *8P* from the PKW center line, respectively (Figure 2). The location of section 2 was selected based upon the downstream distance needed for the flow to return to gradually varied with a quasi-constant flow depth. Also, the upstream flow velocity (V_u) and downstream flow velocity (V_d) were calculated using the continuity equation. Next, the weir upstream total energy (E_0) and weir downstream total energy (E_1) could be obtained using Equations (5) and (6), respectively:

$$E_0 = y_0 + \frac{V_u^2}{2g} \tag{5}$$

$$E_1 = y_1 + \frac{V_d^2}{2g} \tag{6}$$

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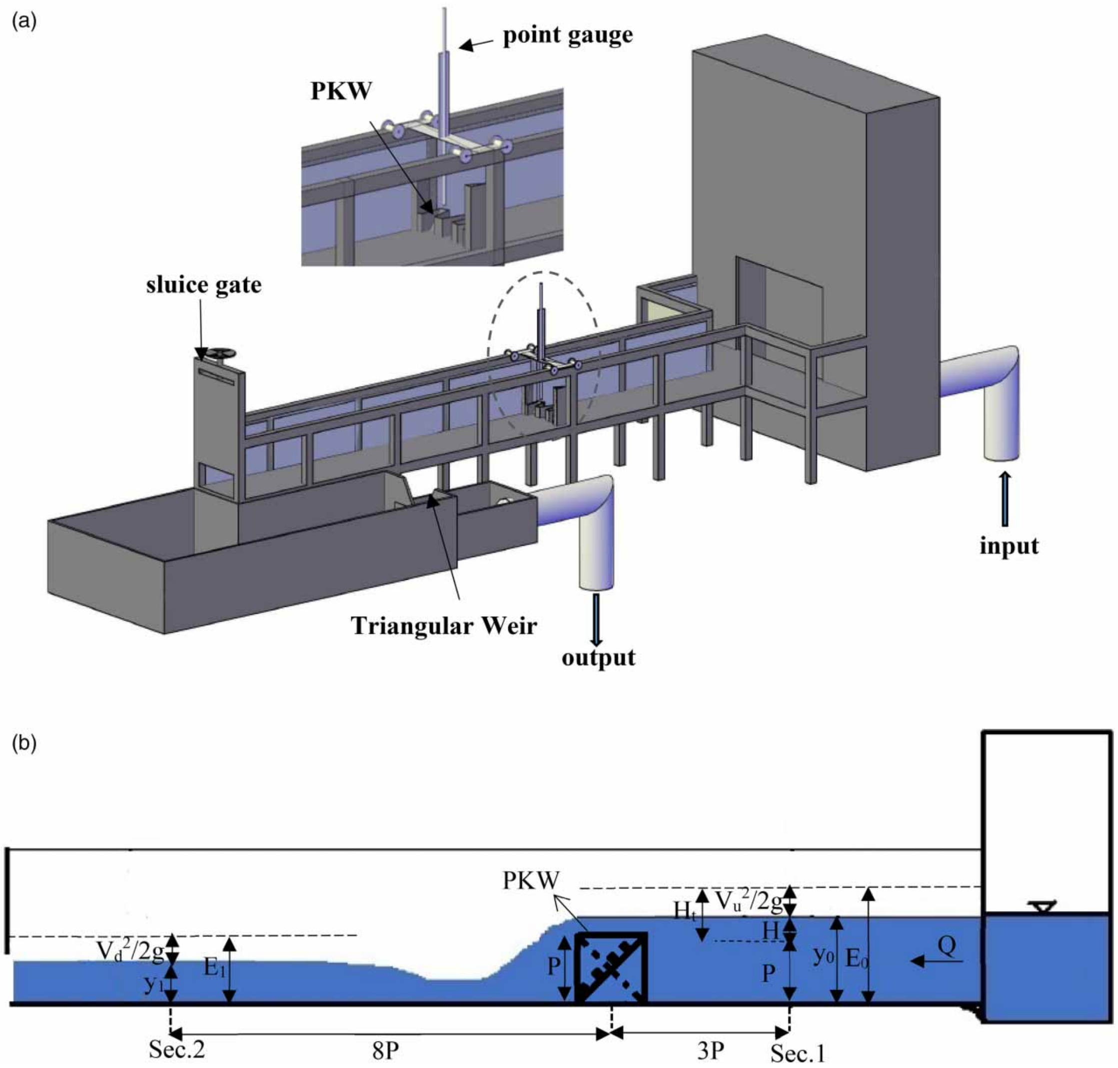

Figure 2 | Schematic representation of (a) the physical model; (b) energy measurement plot.

In this study, tail water was not artificially controlled by a sluice gate. At a certain discharge, the hydraulic jump occurred before section 2. It should be noted that the amount of energy dissipated by hydraulic jump is negligible compared to energy dissipated by PKW (Eslinger & Crookston 2020).

Finally, the percentage of the relative energy dissipation is calculated from Equation (7):

$$\frac{\Delta E}{E_0} = \frac{E_1 - E_0}{E_0} \times 100 \tag{7}$$

where ΔE is the total dissipated energy (m) and $\Delta E/E_0$ is the percentage of the relative energy dissipation (%).

When the upstream head (H) is low, the effect of the surface tension force increases causing differences between the model and prototype results. Such discrepancies are referred to as size-scale effects. Machiels (2012) and Erpicum *et al.* (2016) studies showed that for Weber number (We) above 50, the effect of surface tension is negligible and size-scale effects are refrained. In order to avoid the scale effects, these criteria were considered in this study.

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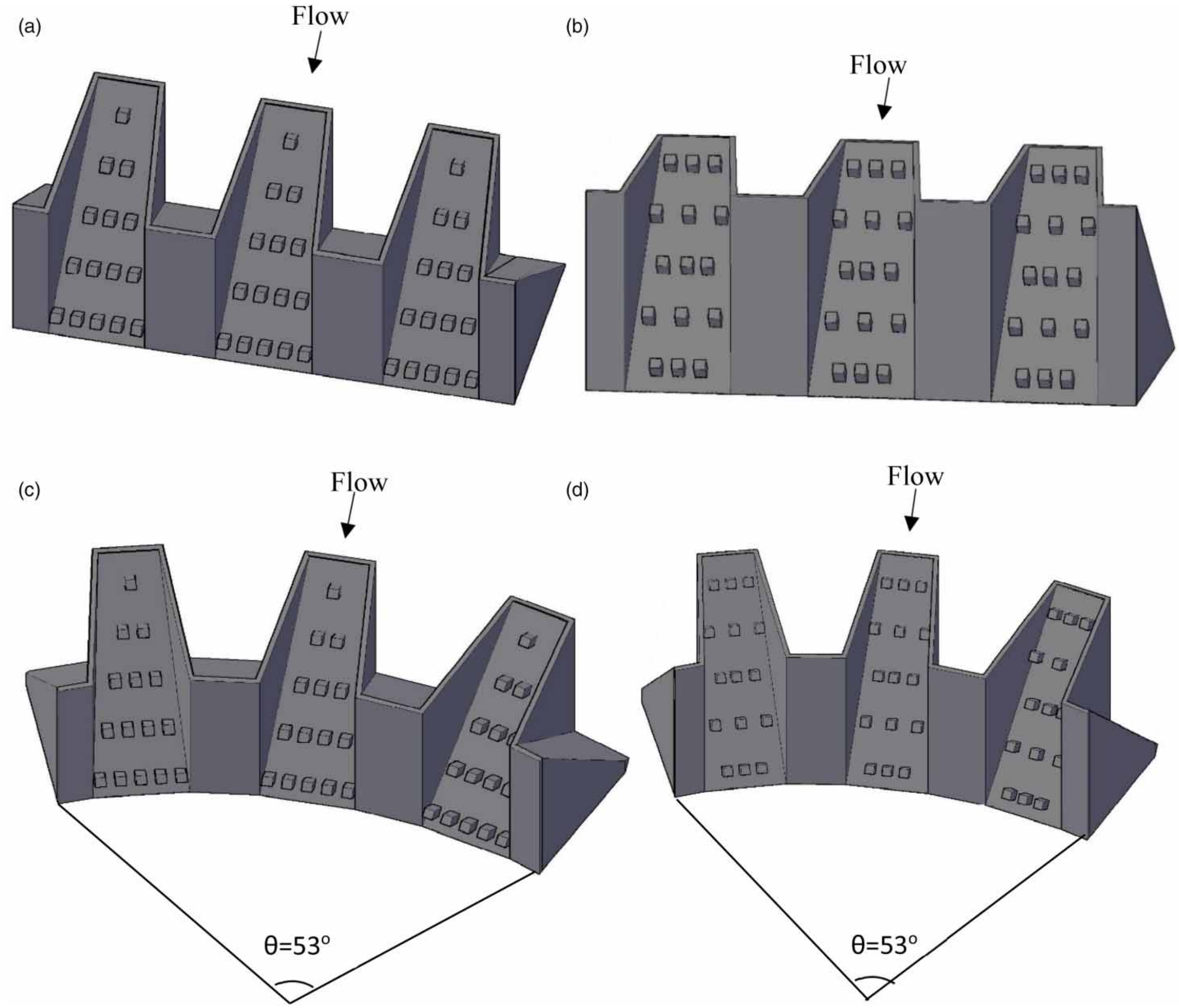

Figure 3 | Piano key weir models with baffles, (a) Model M_2 with $A\text{-}h/W_u = 0.06$; (b) Model M_2 with $B\text{-}h/W_u = 0.06$; (c) Model M_3 with $A\text{-}h/W_u = 0.06$; (d) Model M_4 with $B\text{-}h/W_u = 0.06$.

RESULTS

In this section, dimensionless parameters H/P and y_c/E_0 were explored to study the effect of weir's height, height and the baffle blocks arrangement on the range of relative energy dissipation percentage ($\Delta E/E_0$) change compared to the control model. After that, the results of the current study were compared with previous studies.

Energy dissipation in different discharges

The relative amount of dissipated energy is varied in different discharges. The data analysis in this research showed that the amount of relative energy dissipation is different between discharge range of 4 to 17 L/s and discharge range of 17 to 50 L/s. Table 3 shows the average increase of relative energy dissipation in different discharges from 4 to 17 L/s and from 17 to about 50 L/s in comparison with the control model.

According to Table 3, it can be seen that the increasing rate of relative energy dissipation in the baffle mode compared to the control model is lower in discharge range of 4 to 17 L/s than in discharge range of 17 to 50 L/s. For instance, for APKW-53, height ratio of $P/W_u = 0.9$ and discharge range of 4 to 17 L/s, the relative energy dissipation compared to the control model increase by 2.5, 3.1 and 5.2% for $B\text{-}h/W_u = 0.06$, $B\text{-}h/W_u = 0.12$ and $B\text{-}h/W_u = 0.18$, respectively. For the same set-

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Table 2 | Dimensional parameters of piano key weir models used in this study

Model number	Weir type	Θ(degree)	P(m)	P/W_u	W_i/W_o	Cycles number	L/W
M1	TPKW	-	0.15	0.9	1	3	2.83
M2	TPKW	-	0.2	1.20	1	3	2.83
M3	APKW-53	53	0.15	0.9	1	3	2.92
M4	APKW-53	53	0.2	1.20	1	3	2.92

up and for discharge range of 17 to 50 L/s the relative energy dissipation increase by 10.2, 14.3 and 18%, respectively. In both types of weirs and for both A and B-arrangements, the relative amount of dissipated energy increases compared to the control model when the baffles' heights enlarge. As it is observed for TPKW, $P/W_u = 1.2$ and A-arrangement, increase in blocks height ratio from $h/W_u = 0.06$ to $h/W_u = 0.18$, would increase the relative energy dissipation 1.2 to 3.6% at discharge range of 4 to 17 L/s and 4 to 12% at discharge range of 17 to 50 L/s. It can be derived that the relative energy dissipation intensifies as the baffles' height increases due to the increase in resistance against the flow (Qanavati *et al.* 2019).

In both TPKW and APKW-53, the relative energy dissipation in baffles with B-arrangement is greater than A-arrangement. For example, for APKW-53, $P/W_u = 1.2$ and discharge range of 17 to 50 L/s, the relative energy dissipation compared to the control model increase by 9, 13 and 16% for $A\text{-}h/W_u = 0.06$, $A\text{-}h/W_u = 0.12$ and $A\text{-}h/W_u = 0.18$, respectively, compared to 12.5, 17.4 and 20% for $B\text{-}h/W_u = 0.06$, $B\text{-}h/W_u = 0.12$ and $B\text{-}h/W_u = 0.18$, respectively. In general, at higher discharges, the amount of dissipated energy increase of B-arrangement is 2 to 5% more than A-arrangement.

Relationship between H/P and $\Delta E/E_0$

One of the dimensionless parameters involved in relative energy dissipation is the H/P ratio, where P is the height of weir and H is the upstream head above the crest of the weir. Figure 4 shows the relationship between H/P and $\Delta E/E_0$ of TPKWs and APKWs with a 53 degrees' central angle (APKWs-53) for two height ratios of $P/W_u = 0.9$ and $P/W_u = 1.2$ for two set-ups, one case featuring baffle blocks with three height ratios of h/W_u and A and B-arrangements, and second case without baffle blocks, called in this paper control model (CM).

According to Figure 4, the amount of dissipated energy decreases with increasing H/P ratio in all models. In weir models with different arrangements and baffle heights, the amount of energy dissipation is neighboring closely at lower H/P ratios. When the H/P ratio rises, the effect of baffles height and arrangement increases where energy dissipation variation becomes distinguishable which shows a consistency with Qanavati *et al.* (2019) results.

By installing baffle blocks with different height and arrangement, an increase is observed in the relative energy dissipation compared to the control model (CM). It can be seen also for both weir types and height ratios (P/W_u), the B-arrangement and block height ratio of $h/W_u = 0.18$ have a greater effect on increasing the relative energy dissipation. For instance, for TPKW,

Table 3 | The average increase of the relative energy dissipation (%) at the outlet key with baffle blocks compared to the control model

		P/Wu = 0.9		P/Wu = 1.2	
PKW Type	Arrangement and height of baffles	$4 < Q < 17$	$17 < Q < 50$	$4 < Q < 17$	$17 < Q < 50$
TPKW	$A\text{-}h/W_u = 0.06$	0.9	3	1.2	4
	$A\text{-}h/W_u = 0.12$	1.5	5	2.16	7.2
	$A\text{-}h/W_u = 0.18$	2.4	8	3.6	12
	$B\text{-}h/W_u = 0.06$	1.65	5.5	2.22	7.4
	$B\text{-}h/W_u = 0.12$	2.61	8.7	3.21	10.7
	$B\text{-}h/W_u = 0.18$	3.6	12	4.29	14.3
APKW-53	$A\text{-}h/W_u = 0.06$	1.9	7.6	2.7	9
	$A\text{-}h/W_u = 0.12$	2.7	10.4	3.9	13
	$A\text{-}h/W_u = 0.18$	3.5	13	4.8	16
	$B\text{-}h/W_u = 0.06$	2.5	10.2	3.75	12.5
	$B\text{-}h/W_u = 0.12$	3.1	14.3	3.75	17.4
	$B\text{-}h/W_u = 0.18$	5.2	18	6	20

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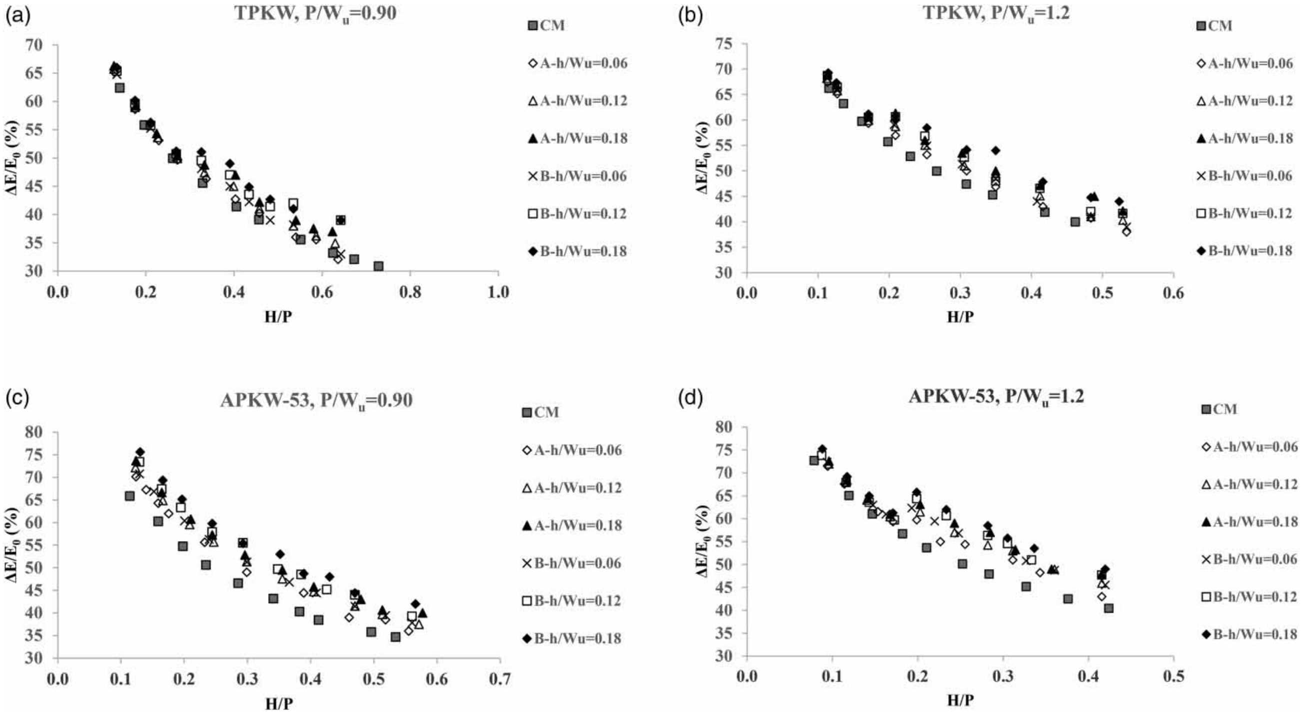

Figure 4 | H/P and $\Delta E/E_0$ relationship of (a) TPKW with $P/W_u = 0.9$; (b) TPKW with $P/W_u = 1.2$; (c) APKW-53 with $P/W_u = 0.9$; (d) APKW-53 with $P/W_u = 1.2$.

$P/W_u = 1.2$ and a constant H/P ratio, the amount of dissipated energy of $A\text{-}h/W_u = 0.06$, $A\text{-}h/W_u = 0.12$ and $A\text{-}h/W_u = 0.18$ models are 1.7, 3 and 4.5% higher than the control model, respectively. The energy dissipation at the similar ratios of P/W_u and H/P for the models $B\text{-}h/W_u = 0.06$, $B\text{-}h/W_u = 0.12$ and $B\text{-}h/W_u = 0.18$ are 3, 4 and 5.5% higher in comparison to the control model, respectively. The same trend can be observed for APKW-53 with $P/W_u = 0.9$, the models $A\text{-}h/W_u = 0.06$, $A\text{-}h/W_u = 0.12$ and $A\text{-}h/W_u = 0.18$ result in 5.6, 6 and 7.4% more dissipated energy amount compared to the control model and 6, 7.4 and 9.11% more for the same set-up and B-arrangement.

For instance, Figure 5 shows a comparison of the H/P and $\Delta E/E_0$ relationship for different height ratios of TPKW and APKW-53 at $A\text{-}h/Wu = 0.12$ and $B\text{-}h/Wu = 0.18$ and control model.

It can be observed in Figure 5, that the relative energy dissipation at the $P/W_u = 1.2$ is greater than at $P/W_u = 0.9$ at a constant H/P, occurring because of the greater outlet key slopes of the weir at the $P/W_u = 1.2$ (Heydari Orojlo *et al.* 2011). In the baffle-free state (CM), the difference between the values of relative energy dissipation for the two weir types at different P/W_u ratios is minor while, at a same height ratio, the relative energy dissipation of APKW-53 is seen to be higher than TPKW for the models equipped with baffle blocks. The following equations are suggested for calculating the percentage of relative energy dissipation for different models.

For TPKW – without baffle:

$$\frac{\Delta E}{E_0}(\%) = 28.984\left(\frac{P}{W_u}\right)^{0.057}\left(\frac{H}{P}\right)^{-0.393} \tag{8}$$

For APKW – without baffle:

$$\frac{\Delta E}{E_0}(\%) = 28.476\left(\frac{P}{W_u}\right)^{0.054}\left(\frac{H}{P}\right)^{-0.387} \tag{9}$$

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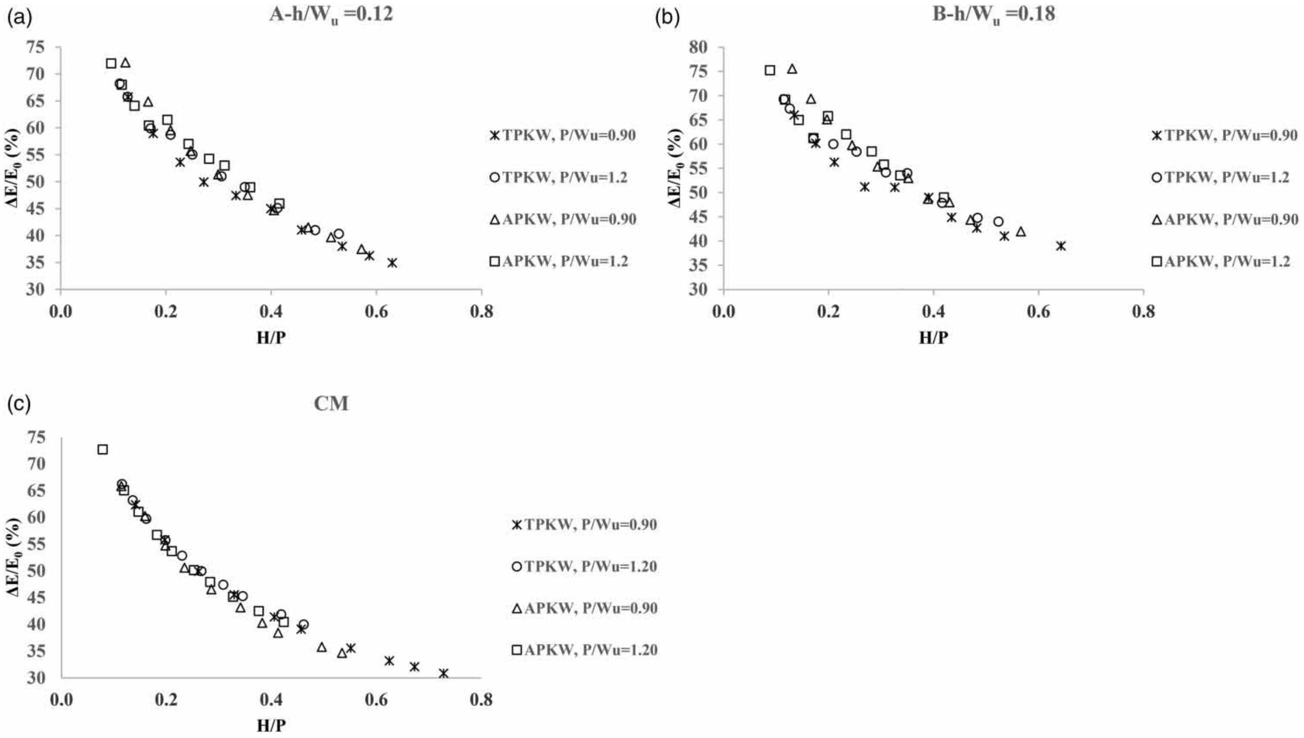

Figure 5 | Comparison of H/P and $\Delta E/E_0$ relationship of TPKW and APKW-53 of (a) $A\text{-}h/Wu = 0.12$; (b) $B\text{-}h/Wu = 0.18$; and (c) control model (CM).

For TPKW – baffles with A-arrangement:

$$\frac{\Delta E}{E_0}(\%) = 35.184\left(\frac{P}{W_u}\right)^{0.13}\left(\frac{H}{P}\right)^{-0.349}\left(\frac{h}{W_u}\right)^{0.041} \tag{10}$$

For TPKW – baffles with B-arrangement:

$$\frac{\Delta E}{E_0}(\%) = 37.432\left(\frac{P}{W_u}\right)^{0.116}\left(\frac{H}{P}\right)^{-0.326}\left(\frac{h}{W_u}\right)^{0.044} \tag{11}$$

For APKW – baffles with A-arrangement:

$$\frac{\Delta E}{E_0}(\%) = 36.875\left(\frac{P}{W_u}\right)^{-0.044}\left(\frac{H}{P}\right)^{-0.348}\left(\frac{h}{W_u}\right)^{0.043} \tag{12}$$

For APKW – baffles with B-arrangement:

$$\frac{\Delta E}{E_0}(\%) = 40.323\left(\frac{P}{W_u}\right)^{-0.075}\left(\frac{H}{P}\right)^{-0.325}\left(\frac{h}{W_u}\right)^{0.053} \tag{13}$$

Figure 6 shows the results of relative energy dissipation ($\Delta E/E_0$) and downstream relative residual energy (E_1/E_0) of this study for the control model (CM) and $B\text{-}h/W_u = 0.18$ model at $P/W_u = 0.9$ compared with the results of the previous studies. Eslinger & Crookston (2020) studied the relative energy dissipation of type-A PKW with $P/W_u = 0.96$. Magalhaes & Lorena (1994) investigated energy dissipation over Labyrinth weirs (LW) with $L/W = 2$ and $L/W = 3$. The results of Rajaratnam & Chamani (1995) and Chanson (1995) are concerned with the energy dissipation over the vertical drops. As observed in Figure 6, the results of this study of the baffle-free state (control model) are coherent with Eslinger & Crookston (2020)

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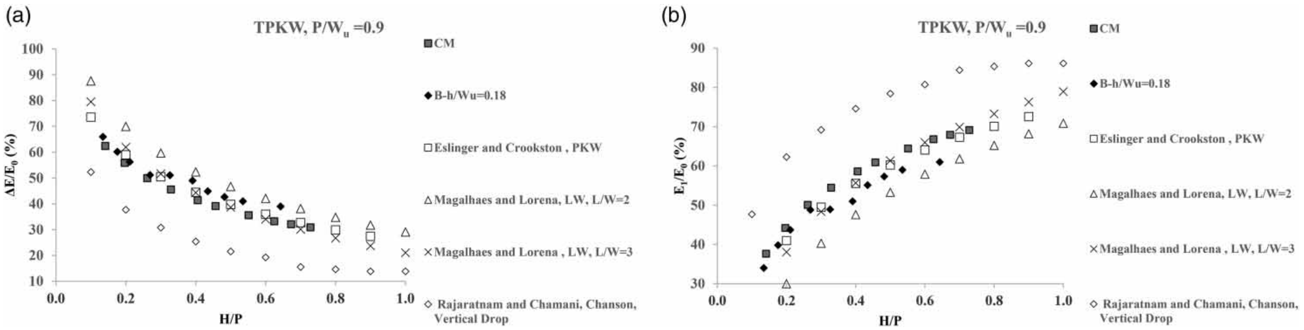

Figure 6 | Comparison of the results of this study with previous studies (a) $\Delta E/E_0$ and (b) E_1/E_0.

findings. However, their results are slightly higher than the present study which is because of the different weir types as well as the P/W_u ratios. As the Magalhaes & Lorena (1994) study on labyrinth weirs, the relative energy dissipation decreases as the L/W ratio increases. The current study model L/W ratio is equal to 2.92. The results of relative energy dissipation of the current study are less than the results obtained by Magalhaes & Lorena at $L/W = 2$ and closer to those with $L/W = 3$. The relative energy dissipation of piano key and labyrinth weirs are greater than of vertical drops associating the results of Rajaratnam & Chamani (1995), and Chanson (1995). According to Figure 6, the relative energy dissipation of piano key weirs at a constant H/P ratio is on average 63% higher than vertical drops. Also, the results related to residual energy in this research show a good agreement with previous studies. The residual energy of vertical drops is considerably greater than PKWs and LWs.

Relationship between y_c/E_0 and $\Delta E/E_0$

Assuming an upstream constant energy, the relative energy dissipation will be maximum when the downstream residual energy is minimized. The minimum possible value of the specific energy (E_{min}) would occur at the critical depth equal to $E_{min} = 1.5\ y_c$ (Mohammadzadeh-habili *et al.* 2018). Therefore, the maximum possible amount of energy dissipation (ΔE_{max}) and the maximum percentage of relative energy dissipation ($\Delta E_{max}/E_0$) are obtained from Equations (14) and (15) below (Mohammadzadeh-habili *et al.* 2018):

$$\Delta E_{max} = E_0 - E_{min} = E_0 - 1.5y_c \tag{14}$$

$$\Delta E_{max}/E_0 = (1 - 1.5y_c/\mathrm{E}_0) \times 100 \tag{15}$$

Figure 7 shows the y_c/E_0 and $\Delta E/E_0$ relationship at different height ratios of TPKW and APKW-53.

In all sub-figures of Figure 7, the line pertaining to the $\Delta E_{max}/E_0$ relationship is also drawn. As can be seen, the relative energy dissipation values in all models with different blocks' arrangements and heights are less than the maximum relative energy dissipation. The relative energy dissipation values in the APKW-53 models are closer to the maximum relative dissipation line than in the TPKW. For example, at $P/W_u = 1.2$, $y_c/E_0 = 0.25$ and $B\text{-}h/W_u = 0.18$, the amount of relative energy dissipation of APKW-53 is about 96% of the maximum energy dissipation compared to 86% of TPKW.

DISCUSSION

Based on the results, in the PKWs without baffle, the amount of dissipated energy at low discharges is significant. At high discharges, the amount of energy dissipation contrarily decreases where there is a possibility of scouring downstream of the weir. On the other hand, introducing baffles to the model (Figure 4), would increase the amount of dissipated energy compared to the control model at high discharges. Therefore, using baffles in weirs with high discharge capacity is essential. This can reduce the size of the downstream stilling basin and consequently reduce the cost of the project.

The nappe flows cascading from the side walls colliding at the outlet key result in energy dissipation at the PKWs. The results also showed that the amount of relative energy dissipation of APKW and TPKW is different. Therefore, the shape of the weir and the flow pattern over it affect the energy dissipation. In this study, experiments were performed on type-D piano key weir (without overhangs in upstream and downstream). Due to the different flow patterns in different types of

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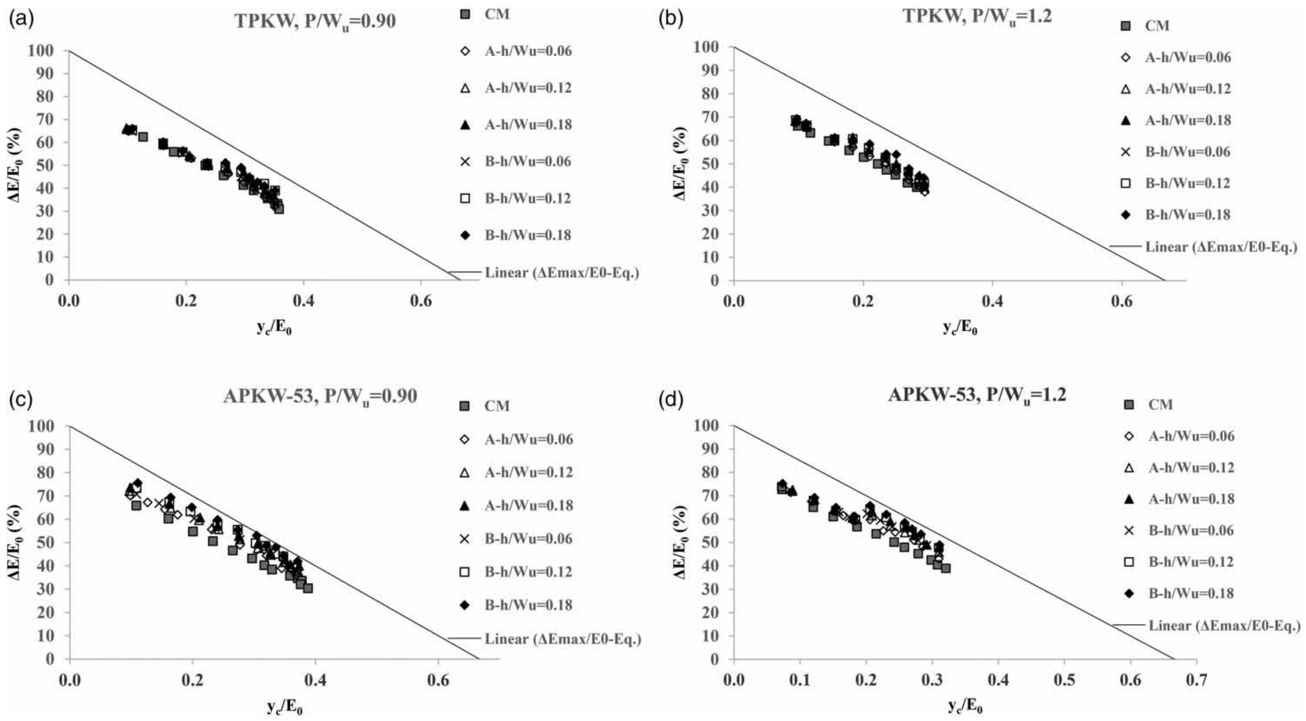

Figure 7 | y_c/E_0 and $\Delta E/E_0$ relationship of (a) TPKW with $P/W_u = 0.9$; (b) TPKW with $P/W_u = 1.2$; (c) APKW-53 with $P/W_u = 0.9$; and (d) APKW-53 with $P/W_u = 1.2$.

piano key weirs, relative energy dissipation can also be different. Therefore, it is suggested to investigate the effect of baffles on energy dissipation over other types of weirs in future studies.

Before conducting experiments in this study, various options for selecting the shape and arrangement of the baffle blocks were examined. Considering the purpose of this study to investigate the performance of different baffle arrangements at the same cost, two A and B-arrangements were selected, including the same number of cube-shaped baffles. The results showed better performance of B-arrangement in increasing energy dissipation. Since the shape, number and location of the baffles on the output key slopes affect the amount of dissipated energy and also the cost of the project, it is suggested to examine the effect of other arrangements with different number of baffles on energy dissipation in future studies.

CONCLUSION

One of the most important issues in PKWs is the downstream extra energy which can lead to destruction of the structure. In this experimental study, the influence of weir's height, arrangement and height of the baffle blocks located on the outlet keys slopes on the energy dissipation were investigated. A TPKW and an APKW with a 53 degrees' central angle (APKW-53) with two height ratios of P/W_u equal to 0.9 and 1.2 were used. Three height ratios of h/W_u equal to 0.06, 0.12 and 0.18 and two A and B-arrangements were selected for the baffle blocks. The most important findings of this study are as follows:

- In all models (with or without baffles), the relative energy dissipation decreases when the discharge increases.
- At high discharges and with the B-arrangement baffles, the amount of increase in relative energy dissipation compared to the control model is 2 to 5% higher than those with A-arrangement.
- The relative energy dissipation at the $P/W_u = 1.2$ is greater than at $P/W_u = 0.9$ at a constant H/P, occurring because of the greater outlet key slopes of the weir at the $P/W_u = 1.2$
- $B\text{-}h/W_u = 0.18$ type baffles installed on APKW-53 demonstrating 96% of the maximum relative energy dissipation showed the highest increase in energy dissipation.

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AUTHORS' CONTRIBUTIONS

M.K.M and T. S. writing and editing the paper, H. F. collected the data and revised original draft preparation.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or the corresponding author can provide more information to the reader.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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