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HYDRAULIC PERFORMANCE ANALYSIS OF DIAGONALLY ALIGNED CIRCULAR LABYRINTH WEIRS USING COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

Weirs are among the most critical hydraulic structures employed for the con-trolled conveyance of water in open channel systems. In conventional free over-flow weirs, the discharge capacity is predominantly a function of the upstream head. However, for operational efficiency and stability, it is often undesirable for the upstream water level to vary significantly with changes in flow rate. To over-come this limitation, labyrinth weirs—particularly sharp-crested types—have gained prominence in recent years due to their ability to increase the effective crest length within a limited channel width. The extended crest length enhances the discharge capacity at a given head, making labyrinth weirs more efficient than linear-crested weirs. Over the years, various labyrinth weir geometries, including trapezoidal, triangular, and piano key configurations, have been explored to improve hydraulic performance. Recently, new forms such as circular and diagonally stepped labyrinth weirs have been introduced. Circular labyrinth weirs offer improved discharge efficiency by minimizing nappe interference and reducing submergence at the weir cycles. On the other hand, diagonally stepped labyrinth weirs aim to enhance flow capacity at a constant head and crest length through steep downstream alignments. This study combines on the hydraulic performance of circular and diagonal stepped labyrinth weirs. Numerical model validation was conducted based on established findings from previous studies. Utilizing these validated models, a novel nappe breaker configuration was introduced and the discharge performance of stepped circular labyrinth weirs was comparatively assessed in plan view.

Keywords: Labyrinth weir, Hydraulic performance, Discharge coefficient, CFD, Stepped circular labyrinth weirs.

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1 INTRODUCTION

The efficient and safe management of water resources has become increasingly critical in recent decades due to growing population pressure, intensified urban development, and the evolving impacts of climate change. As a result, the hydraulic design and performance of existing dam and reservoir systems must be reconsidered to address modern flood control demands and water storage requirements. In particular, spillways -key structures responsible for conveying excess water- play a vital role in dam safety. However, conventional linear spillways often fall short when greater discharge capacities are needed, especially in regions with limited space and strict elevation constraints [1-4]. To address these challenges, labyrinth weirs have gained attention as an alternative design approach due to their ability to increase the effective crest length without expanding the dam width, thereby enhancing discharge efficiency [3, 5]. Labyrinth and stepped-labyrinth weirs also enhance discharge and energy dissipation while offering retrofit potential for constrained spillways, gate integration, and debris passage, with arced and projecting forms achieving higher unit discharge per plan width than linear designs [6, 7].

Despite their advantages, traditional labyrinth weirs, commonly designed in triangular, trapezoidal, or rectangular geometries, are subject to a significant limitation: the occurrence of nappe interference. This phenomenon, resulting from the collision of converging flow jets, can reduce the effective discharge coefficient and overall hydraulic efficiency, particularly under higher total head conditions [8-10]. In response, researchers have explored novel geometrical configurations aimed at minimizing interference zones and optimizing flow behavior. Among these innovations, circular-section labyrinth weirs arranged in a harmonic plan present a promising alternative. Their geometry is designed to align the flow more perpendicularly to the crest surface, thereby mitigating flow collisions and improving overall performance. The performance of these structures depends on parameters such as curvature, side wall angles, and geometric arrangement, and numerical and experimental studies show that S-shaped weirs with convex curvature increase the discharge capacity [11]. Computational fluid dynamics (CFD) is widely used in the design process, and although elements like Nappe breakers improve the flow structure, they can only lead to a limited reduction in the discharge coefficient [12]. However, since the effects of nappe interaction and aeration conditions are not yet fully understood, future studies should focus on investigating more efficient geometries.

Recently, Yildiz et al. [10] aims to experimentally investigate the hydraulic characteristics of asymmetrically placed circular labyrinth weirs with harmonic plan alignment. By analyzing the effects of varying weir height (P = 0.20 m, 0.30 m, 0.40 m) and the number of labyrinth cycles (N = 2, 3, 4), the study provides a comprehensive evaluation of discharge behavior, coefficient of discharge (C_d), and energy dissipation capacity. The results are compared with both conventional linear weirs and earlier designs of triangular and trapezoidal labyrinth weirs. Findings reveal that while the circular weirs experience a modest reduction in discharge coefficients (approximately 13%) compared to linear weirs, they offer a significant increase (up to 57%) in net crest length (L_{net}), and a reduction in nappe interference, resulting in better hydraulic performance under self-aerated nappe flow conditions [13-16]. These outcomes highlight the potential of circular labyrinth weirs as a practical and efficient solution for modern dam rehabilitation and flood mitigation strategies.

This study presents several novel design features aimed at enhancing the performance of harmonic circular labyrinth weirs in plan view. Numerical model validation was conducted based on previous studies in the literature, and using these validated models, a new nappe breaker design was proposed and comparatively analyzed alongside the discharge performance of stepped circular labyrinth weirs in plan view.

2 MATERIAL AND METHOD

Computational Fluid Dynamics (CFD) has become an indispensable tool for analyzing complex hydraulic phenomena in open channel systems, where free surface dynamics play a critical role. Among the available CFD platforms, FLOW-3D stands out for its specialized capabilities in simulating transient, multiphase, and free surface flows. One of the core strengths of FLOW-3D is its implementation of the Volume of Fluid (VOF) method, known in this software as the TruVOF technique, which accurately captures the evolution of fluid interfaces in open channel scenarios [17]. The VOF method operates by solving a volume fraction equation that tracks the interface between immiscible fluids:

$$\frac{\partial F}{\partial t} + \nabla.(F\vec{u}) = 0 \tag{1}$$

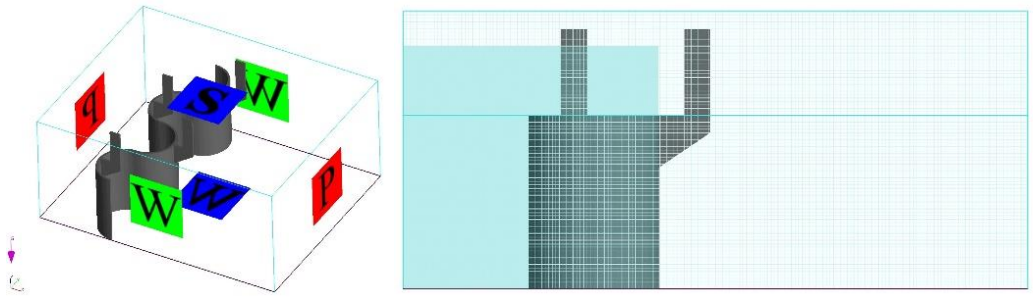
where F represents the volume fraction of the fluid (e.g., water), and u is the local velocity vector. This transport equation is coupled with the continuity and Navier-Stokes momentum equations:

$$\nabla . \vec{u} = 0 \tag{2}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla . (\rho \vec{u} \vec{u}) = -\nabla p + \nabla . (\mu \nabla \vec{u}) + \rho \vec{g} + \vec{F_s} \tag{3}$$

here, ρ is the fluid density, μ is the dynamic viscosity, p is pressure, g represents gravitational acceleration, and Fs includes surface tension and interfacial forces. FLOW-3D solves these equations using a structured grid and advanced boundary condition treatments, enabling high-resolution simulations of hydraulic jumps, weir flows, energy dissipation structures, and other complex open channel behaviors [17, 18].

This study utilizes FLOW-3D to explore the performance of open channel systems under various flow regimes and structural configurations. The aim is to demonstrate the effectiveness of the TruVOF method in capturing critical flow features, thereby supporting the design and optimization of hydraulic infrastructure through physically realistic simulations.



(a) **(b)**

Figure 1. Preparation of the numerical model, a) Boundary conditions, b) Mesh structure

Fig. 1 shows the boundary conditions and mesh structure of the numerical models. In Fig. 1a, the boundary conditions are defined as follows: *W* represents the wall condition, where the no-slip condition is applied, assuming zero relative velocity between the fluid and the wall surface. *P* represents the pressure inlet/outlet, where specific conditions such as pressure values or flow level and flow rate are prescribed to enable fluid entry and exit from the computational domain. The upper surface of the solution domain, denoted by S, represent symmetry planes, where the normal component of velocity is set to zero. This effectively reduces the computational domain and enhances numerical efficiency without compromising the accuracy of the flow representation. Fig. 1b presents the mesh structure employed in the simulations. A structured mesh composed of rectangular prismatic (hexahedral) elements was used to discretize the computational domain. Mesh sensitivity analyses were performed using various grid densities to ensure solution accuracy while maintaining computational efficiency.

Consequently, the number of elements used in the simulations ranged from approximately 2,088,000 to 2,952,000. This range was found to offer an optimal balance between computational cost and numerical accuracy. Using a structured hexahedral mesh is critical in capturing the physical phenomena accurately, particularly in regions with high velocity or pressure gradients, while also supporting numerical stability and convergence.

2.1 Dimensional Analysis

The discharge coefficient is a dimensionless parameter that quantifies the difference between the theoretical and actual flow capacities of hydraulic structures. It plays an important role in the design and scaling of flow mechanics studies. The dimensional analysis method is used to systematically examine the geometric, kinematic, and dynamic quantities that determine this coefficient. The parameters related to the discharge coefficient are given in Eq. 4:

$$C_d = f(P, W, H_t, N, L, B, \rho, g) \tag{4}$$

where, C_d is the discharge coefficient, P is the weir height, W is the channel width, H_t is the total head, N is the number of cycles, L is the crest length, B is the nappe breaker, ρ is density of water and g is the gravitational acceleration. P, ρ and g are repetitive parameters. The channel width and crest length were kept constant in all models. Therefore, the parameters affecting the flow coefficient were determined as follows within the scope of the study:

$$C_d = f\left(\frac{H_t}{P}, N, B\right) \tag{5}$$

2.2 Validation of the Model

Yildiz et al. [10] conducted an experimental investigation on the discharge performance of harmonic (combined circular) weirs with varying heights (P = 0.20, 0.30, and 0.40 m) and different numbers of cycles (N = 2, 3, and 4) within an open channel flume with a width of W=0.60 m. We employed a subset of the experimental data corresponding to the two-cycle harmonic weir reported by Yildiz et al. [10] as a benchmark to validate the numerical models developed (Fig. 2).



a) **b)** **c)**

Figure 2. a) Plan view, b) Benchmark model used for validation the numerical model [10], c) Validated numerical model visualization

Accordingly, the comparison of discharge coefficients (C_d) obtained from the experimental and numerical models is presented in the graph shown in Fig. 3. As seen in the figure, the numerical results closely follow the experimental data across the range of relative heads (H_t/P), with only minor deviations. The verification test yielded an average numerical error of approximately 4%, indicating that the discharge performance values predicted by the numerical models used in this study can be obtained with an accuracy better than 5%. To further strengthen these findings, future work will focus on experimental validation of the proposed configurations, enabling direct comparison between numerical predictions and physical model behavior.

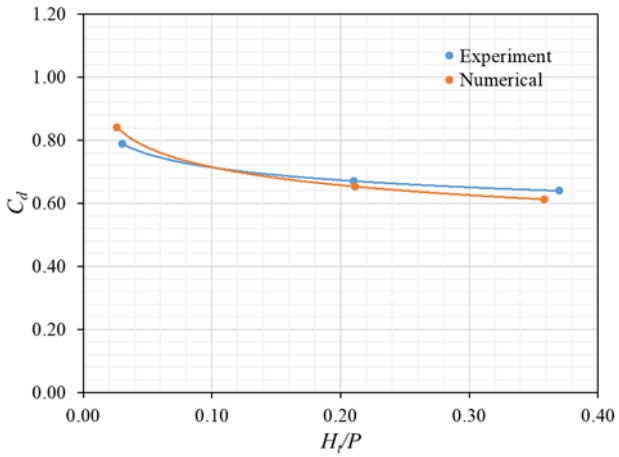


Figure 3. Comparison of experimental and numerical discharge coefficients for the harmonic weir with N=2 cycles

3 RESULTS AND DISCUSSION

In addition to previous studies on harmonic (combined circular) weirs, the designs proposed in the present study have two primary objectives. The first is to reduce nappe adhesion

on the downstream face of the weirs caused by sub-atmospheric pressures, thereby mitigating flow-induced vibrations and oscillations. The second is to enhance discharge performance by minimizing downstream nappe interference. In this respect, four harmonic circular weirs were considered as illustrated in Fig. 4. Here, CNB, DNB, SNNB, and SDNB refer to the circular weir with nappe breaker, down-stream nappe breaker, stepped non-nappe breaker, and stepped downstream nappe breaker configurations, respectively.

Bilhan et al. [13] conducted numerical analyses on circular labyrinth weirs and investigated the pressure fluctuations beneath the nappe on the downstream face, which are known to cause flow-induced oscillations and vibrations. Their findings demonstrated that the use of nappe breakers mounted on the weirs significantly reduced these sub-atmospheric pressure fluctuations. However, it was also noted that the presence of nappe breakers had a slight adverse effect on discharge efficiency. Within the scope of the present study, the effects of nappe breakers placed on harmonic weirs—arranged in plan view—on discharge performance were investigated (Fig. 4a,b,d). On the order hand, Aydin et al. [19] utilized stepped weirs with a sharp-cornered geometry, arranged diagonally in the flow direction, to improve the discharge performance of labyrinth weirs. Their study reported substantial performance enhancements compared to linear weirs, with discharge efficiency increasing by approximately 27% to 49%. However, it was also observed that increasing the number of steps led to the development of dead zones—characterized by flow separation and recirculation—upstream of the corners, which in turn caused a relative decline in discharge efficiency. In the present study, it is hypothesized that the use of diagonally arranged harmonic weirs with rounded corners can lead to improved discharge efficiency by reducing flow separation and nappe interference. For this purpose, diagonally oriented circular harmonic weirs (referred to as BNNB weirs) were employed in the design (Fig. 4c). The geometric and hydraulic conditions used to assess the performance of the harmonic circular weirs shown in Fig. 4 were determined in accordance with the limits of the empirical Eq. (6) introduced by Yildiz et al. [10].

$$C_d = 0.581 \times (H_t/P)^{-0.121} \times (W/P)^{-0.035} \times N^{-0.047} \quad (6)$$

In our models, W and P were kept constant at 0.60 m and 0.20 m, respectively, while the ratio H_t/P was varied between 0.1 and 0.5.

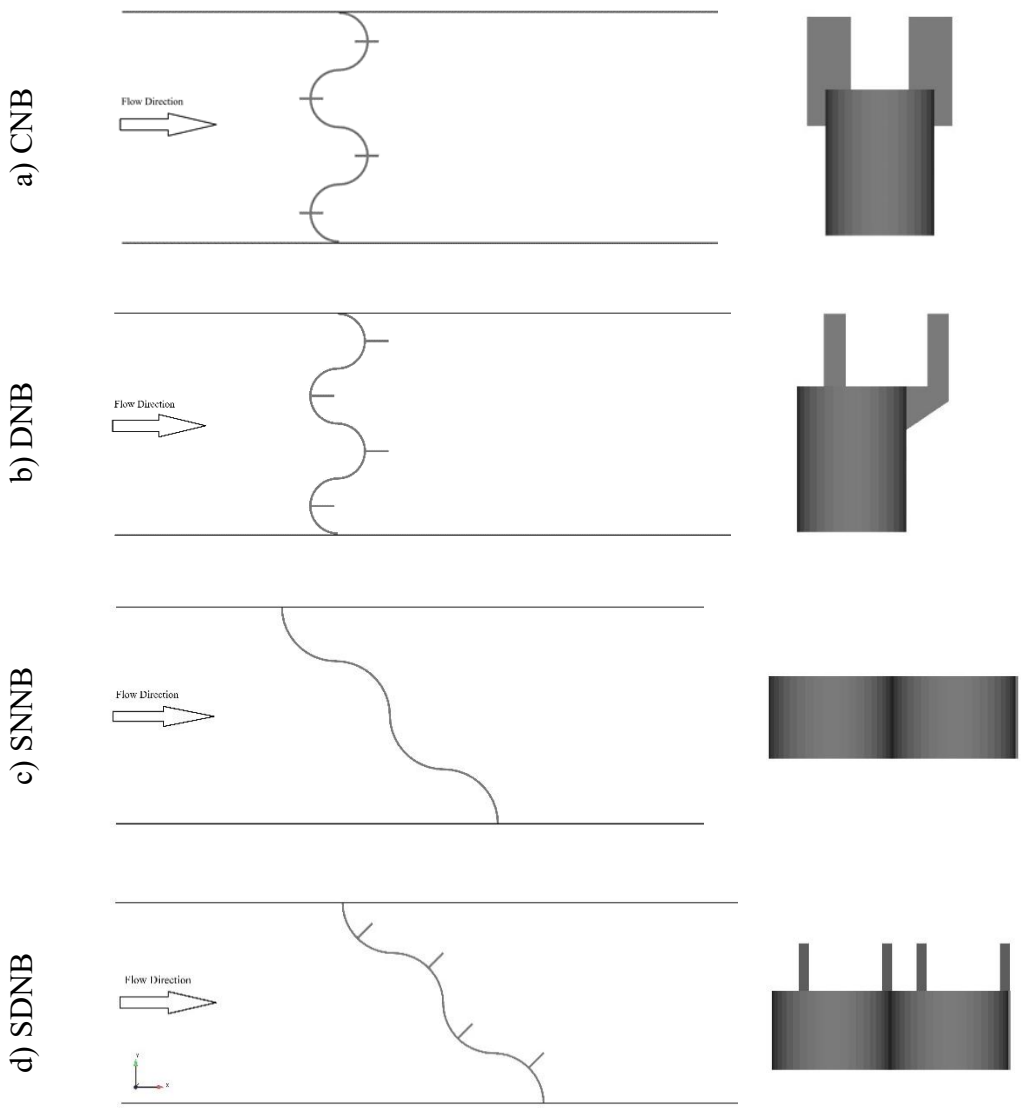
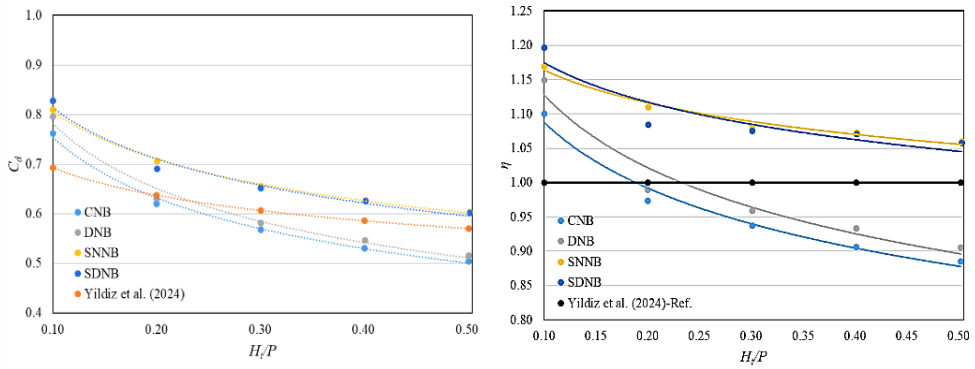


Figure 4. Schematic representation of the harmonic circular weir configurations

Based on the specified parameter ranges, the discharge efficiencies of the weir configurations shown in Fig. 4 were compared with the results of Yildiz et al. [10] and are presented in the graphs in Fig. 5a. According to these graphs, the stepped designs (SNNB and SDNB) exhibited the highest discharge efficiency for all Ht/P values. The negligible difference between the SNNB and SDNB configurations (<1%) indicates that the adverse effects of nappe breakers on discharge efficiency are minimal and can be considered negligible. Considering that nappe breakers eliminate pressure fluctuations responsible for undesirable oscillations and vibrations on the weir crest [13], the version with nappe breakers (SDNB) can be considered a more favorable design.

On the other hand, when evaluating the performances of CNB and DNB—where the effects of nappe breakers are observed—it is seen that DNB performs approximately 3% better than CNB. When compared with the no-nappe breaker configuration results presented by Yildiz et al. [10], an interesting trend emerges. For lower relative heads ($H_t/P < 0.2$), the designs with nappe breakers outperform their no-nappe breaker counterparts [10]. However, for relatively high head ratios ($H_t/P > 0.2$), the configurations equipped with nappe breakers (CNB and DNB) have a lower discharge capacity than the plain configuration. This reduction is due to the increased interference of the nappe breakers with the free nappe trajectory. This effectively shortens the aerated flow length and alters the pressure distribution along the crest. Conversely, at lower heads, nappe breakers mitigate nappe adhesion to the downstream face by maintaining local aeration under low-pressure conditions. This enhances discharge efficiency and flow stability.



(a) **(b)**

Figure 5. a) Comparison of the variation in discharge coefficients with relative head for different configurations, b) Comparison of the efficiency factor for different weir configurations

The discharge coefficients were normalized with respect to the reference values considered as Yildiz et al. [10]. To better characterize the variations in discharge efficiency, Fig. 5b presents the normalized efficiency factors (η=Cd/Cd,ref), where the nappe-free data from Yildiz et al. [10] were taken as the reference. According to these graphs, compared to the nappe-free version and under equal crest length and relative head conditions, the stepped circular weirs provide a maximum efficiency increase of approximately 17% (SNNB) and 20% (SDNB) at low head ratios. For both weir types, the average improvement is around 10%.

In terms of nappe breakers, under low relative head conditions, the CNB and DNB configurations exhibited maximum efficiency increases of approximately 10% and 15%, respectively. However, when considering average values, discharge efficiency decreased by

about 4% for CNB and 1% for DNB. These results indicate that the downstream-extended nappe breakers (DNB) do not lead to a significant reduction in average discharge efficiency compared to the no-nappe breaker condition. Moreover, they offer a notable advantage by significantly reducing vibrations and oscillations on the weir wall. This improvement suggests that downstream-extended nappe breakers not only help stabilize sub-nappe pressures but also do not adversely affect the effective crest length. Therefore, they are considered more advantageous and preferable over conventional flat nappe breakers due to their minimal impact on discharge performance. The streamlines generated by the flow over the crest for the different weir configurations are compared in Fig. 6. The figure shows the streamlines taken from the crest levels of the models with an H_t/P ratio of 0.4. In the stepped circular weir configuration, neither significant flow separation nor nappe interference is observed, unlike in the standard circular weirs where the flow-separating effect of nappe breakers is clearly evident.

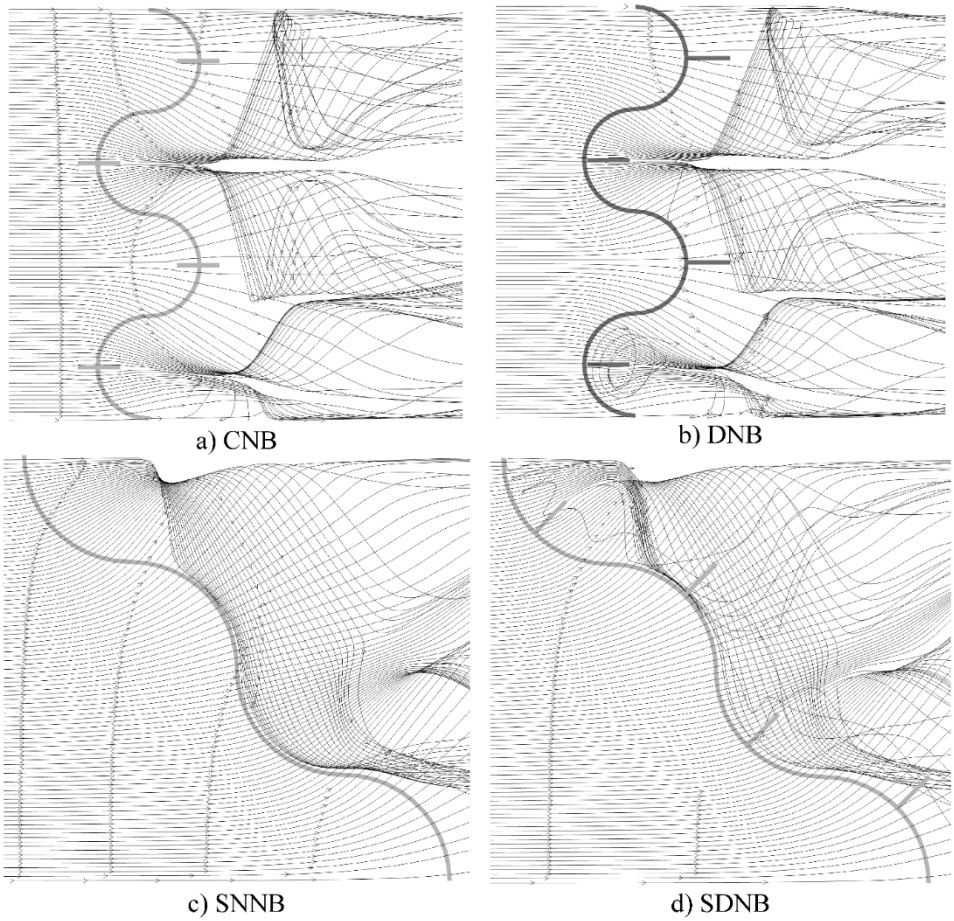


Figure. 6 (a-d). The streamlines over the crest for the different weir configurations (Ht/P = 0.4)

4 CONCLUSION

This study introduces several novel design features aimed at improving the performance of plan-view harmonic circular labyrinth weirs. Numerical model validation was carried out based on previous literature, and using these validated models, a new type of nappe breaker design and the discharge performance of stepped circular labyrinth weirs in plan view were comparatively analyzed. The results indicate that, compared to conventional flat nappe breakers mounted on the crest, the newly pro-posed downstream-extended nappe breakers have a minimal negative impact on discharge efficiency. With this new nappe breaker type, pressure fluctuations beneath the nappe—responsible for structural vibrations and oscillations—can be mitigated, particularly in labyrinth weirs with long crest walls, without causing significant reductions in discharge capacity. Furthermore, in diagonally stepped circular configurations, a noticeable improvement in discharge efficiency was observed due to reduced nappe interference. As a result, among the weir configurations examined in this study, the diagonally stepped circular labyrinth weirs with rounded corners and equipped with downstream-extended asymmetric nappe breakers offer the most favorable performance from both structural and hydraulic perspectives.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

Concept of the manuscript planned by M.C.A. Numerical analysis conducted by A.E.U. Results collected by M.C.A and A.E.U. M.C.A wrote the first draft of the manuscript. Both two authors contributed and approved the last version of the manuscript.

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