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Original Article

Modular Design and CFD-FEM Simulation of a Fog Collector for Atmospheric Water Harvesting

Heydi Karina Hinostroza Maravi[1], Nelfa Estrella Ayuque Almidon[2], Aron Jhonatan Aliaga Contreras[2], Jean Fernando Perez Montesinos[3]

[1]*Faculty of Engineering, Universidad Continental, Huancayo, Junín, Peru.*
[2]*Faculty of Engineering, Universidad Nacional del Centro del Peru, Huancayo, Junín, Peru.*
[3]*School of Civil Engineering, University of Idaho, Idaho, USA.*

[1]*Corresponding Author : 70345903@continental.edu.pe*

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Abstract - *The following study presents the design and simulation-based validation of a modular fog collector, which is structurally robust and aerodynamically optimized for high-altitude environments. By using CAD modelling, Finite Element Method Analysis (FEM), and Computational Fluid Dynamics (CFD), the system was evaluated under circumstances in which wind and gravity loads were combined. The results of this study show that the structure maintains safety factors greater than 2.6 and maximum displacements of less than 2 mm. In addition, CFD simulations revealed an effective interaction between the airflow and the collector surfaces, confirming its omnidirectional capture capability. When the present study was compared to conventional flat collectors, it was proven that the proposed design offers a better structural integrity as well as a better aerodynamic performance. As a result, this work brings a multidisciplinary approach to fog harvesting, with the potential for scalable implementation in different regions where the water source is scarce.*

Keywords - *Computational Fluid Dynamics (CFD), Design, Fog water harvesting, Modular collector design, Finite Element Method Analysis (FEM).*

1. Introduction

The systems for harvesting fog passively have emerged as a sustainable, resilient, and low-cost solution [1, 2] as a way to supply water resources to remote areas, fragile ecosystems, and areas that are hard to reach and where rainfall is scarce, irregular, or even seasonal [3, 4]. In regions that are very dry or arid, the condensation of atmospheric fog represents an alternative and viable method to obtain not only drinking water, but also water for agricultural use. This alternative does not necessarily compete with conventional water resources and does not require complex energy infrastructure either [5, 6].

A myriad of recent studies have considered fog water harvesting as a solution for obtaining water in rural communities, like in the Andes and other arid regions. The previous studies evaluated both the efficiency of the collection and the structural and technological viability of the used systems. For instance, in Ecuador, Toulkeridis et al. [7] developed a three-dimensional tower-type system in the community of Galte, and this tower-type system can yield up to 2.63 L/m² per day and a benefit/cost ratio of 1.90. This innovative, modular, and low-cost method developed by them proved the viability for partially supplying crops in vulnerable areas where water scarcity is high.

On the other hand, Chilón Tejada et al. [8] decided to focus on comparing mesh materials in collectors of two dimensions in the city of Celendín, Peru. Although their study did not address three-dimensional structure or mechanical validation, it provided evidence on the influence of mesh type on collection efficiency, highlighting the superiority of surgical mesh over Raschel and fique sackcloth. This methodological difference between the two studies, one focused on structural geometry and the other on surface material, reveals the fragmentation of the field and the need for comprehensive approaches.

In contrast, the work of Li et al. [9] offers a more technologically advanced viewpoint by Exploring Electrostatic Collectors (EFC), which surpasses, by far, the collection rates of the traditional passive systems. Even though this review of Li et al. does not focus on rural contexts or accessible materials, it ends up raising a promising line of research for future hybrid applications. Nonetheless, Li et al.'s work approach differs from previous studies that prioritize constructive simplicity and local replicability.

In his research, Regalado et al. [10] proposed an intermediate design that combines not only a biomimetic "stepped harp", but also the aerodynamic efficiency with structural robustness. Contrary to previous studies, this Regalado et al. study integrates CFD simulations and wind tunnel tests, allowing the validation of the system's behaviour under controlled conditions. However, the previous work mentioned does not include FEM structural analysis, and this situation limits the evaluation of its viability in the open field.

Finally, the work of Fernández et al. [11] compared the standard SFC collector with a dual FM-120 system; the results of this research demonstrated that the geometric configuration and orientation to the wind are the variables that significantly influence efficiency. Despite the fact that Fernandez et al.'s study was experimental and quantitative, it did not incorporate any simulations or structural analyses, turning that paper into a useful but partial reference.

Therefore, the decision of developing a scheme of a modular, structurally robust, and aerodynamically efficient fog collector that is capable of operating in circumstances of moderate and strong wind conditions is postulated [12]. The main difference with previous studies is that they focus primarily on collection efficiency [7, 8], or advanced technological mechanisms [9], while the present approach integrates digital design, Finite Element Method Analysis (FEM), and Computational Fluid Dynamics (CFD) with the purpose of evaluating mechanical stability and aerodynamic behavior within a unified framework. The implementation of this integrated methodology permits addressing a critical gap identified in the literature, where structural validation and airflow interaction are commonly treated as independent aspects [10, 11].

In order to attain the objectives of this study, a combined approach based on CAD modelling, Finite Element Method structural analysis (FEM), and Computational Fluid Dynamics (CFD) simulations was adopted. This previously mentioned approach allows performing the evaluation of mechanical strength under combined gravity and wind loads, as well as the analysis of airflow interaction with the fog collection surfaces. Through this dual validation, both the structural stability and the aerodynamic performance are adequately assessed within a single computational framework.

2. Methodology

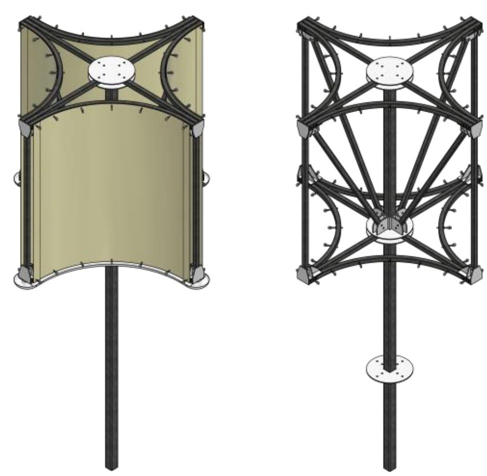
2.1. CAD Modeling

Autodesk Inventor was used to design the fog collector digitally, and different parametric geometries that enabled dimensional adjustments and modular replicability were used as well. The system presented in this paper comprises a square structural frame and a central porous mesh cylinder, which is designed to maximize fog collection from multiple airflow directions. The structure of this fog collector was conceived as a portable module, and then it was assembled using bolt-nut joints, with diagonal reinforcements so its rigidity could be improved against wind loads. In addition, the mesh was modelled as a thin solid without any physical perforations, so porous properties could be assigned to it in the CFD simulation.

It is essential to understand that the present study belongs to the stage of conceptual design, and it is focused on digital modeling and numerical validation. Despite the fact that the present system has not yet been physically implemented, the structural (FEM) and fluid-dynamic (CFD) simulations were conducted considering and employing realistic material properties, environmental conditions, and technical standards that were already reported in the literature. Consequently, experimental validation and field performance assessment, including quantitative water yield measurements, are identified as key for future stages to complement the computational findings presented in this research.

It is worth noting that this study is based on a digital model corresponding to the conceptual design phase. The system has not been physically implemented, but structural (FEM) and fluid-dynamic (CFD) simulations were performed using real parameters for materials, environmental conditions, and technical standards, to validate its technical feasibility.

Figure 1 shows the structural model used in the FEM analysis. View (a) shows the complete design with cylindrical meshes, while view (b) corresponds to the simplified model without meshes, used for the structural simulation. Additionally, Figure 2 provides an exploded view that details the individual components and their arrangement within the assembly.



(a) (b)

Fig. 1(a)Isometric view of the complete design and (b)Structural model.

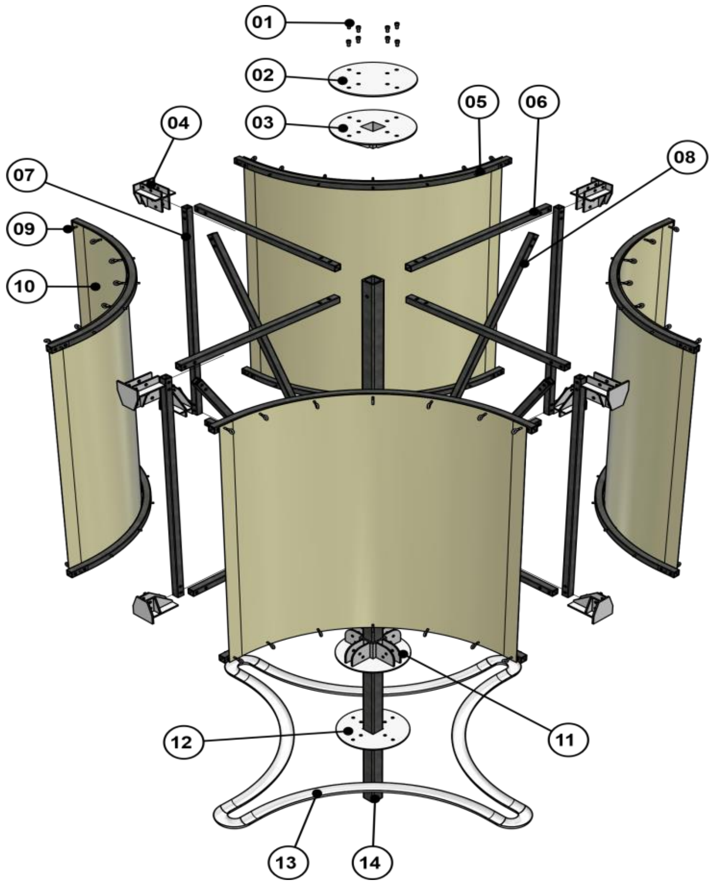


Fig. 2 Exploded view of the CAD model of the collector

Table 1 summarizes the materials assigned to each component, selected based on their strength, weight, and moisture resistance.

Table 1. List of components

No.	Component	Assigned Material	Structural Function
01	Bolts	Galvanized steel	Plate fastening and joints
02	Top plate	Aluminum 6061 T6 (hot-formed)	Upper square tube connection
03	Top plate with a square opening	Aluminum 6061 T6 (hot-formed)	Central tube passage, upper connection
04	Corner piece	Aluminum 6061 T6 (hot-formed)	Joint between bent and square tubes
05	Bent square tube	ASTM A36	Curved upper structure, mesh support
06	Horizontal square tube	ASTM A36	Lateral frame reinforcement
07	Vertical square tube	ASTM A36	Main vertical frame support
08	Diagonal square tube	ASTM A36	Diagonal reinforcement, torsional resistance
09	Hook	Galvanized steel	Mesh fastening and turnbuckle anchoring
10	Cylindrical mesh	Polypropylene (HDPP)	Fog collection; modeled as a solid surface in CFD
11	Bottom plate (for diagonal tube)	Aluminum 6061 T6 (hot-formed)	Bottom connection for diagonal reinforcement
12	Bottom plate with an opening	Aluminum 6061 T6 (hot-formed)	Central tube passage, bottom connection
13	Polypropylene gutter	Polypropylene	Collection and conveyance of harvested water
14	Central square tube	ASTM A36	Main vertical support for the entire structure

2.2. Structural Analysis (FEM)

To evaluate the mechanical resistance of the fog collector under real environmental conditions, a structural analysis was conducted using the Finite Element Method (FEM) within the Autodesk Inventor simulation environment. The structural model used excludes cylindrical meshes for geometric reasons, as their inclusion generated inconsistencies in the meshing. Instead, only the rigid elements of the frame, plates, tubes, and reinforcements were considered.

Two main loads were applied.

- Gravity: Acceleration of 9.81 m/s² over the entire model, considering the density of each assigned material.
- Wind pressure: 1.5 kPa applied on the front faces of the frame, simulating strong wind according to ASCE 7 standards for exposed lightweight structures [13, 14].

Equation (1) allows for calculating the pressure exerted by the wind on the exposed surfaces of the collector, where P is the dynamic wind pressure, ρ is the air density, and V is the incident wind speed.

$$P = \frac{1}{2} \cdot \rho \cdot V^2 \tag{1}$$

For this case, a wind speed of $50\ m/s$ was considered, corresponding to extreme conditions in exposed areas, an air density of $1.225\ kg/m^3$, and the equation was applied to obtain the dynamic pressure. Based on the considered values, the wind pressure was determined to be $P = 1.5\ kPa$. This value was applied as distributed pressure on the front faces of the structural frame, simulating the direct impact of the wind in a direction normal to the surface. Figure 3 illustrates the loads applied as boundary conditions in the FEM analysis, along with gravitational acceleration, to assess the mechanical response of the system under combined load conditions.

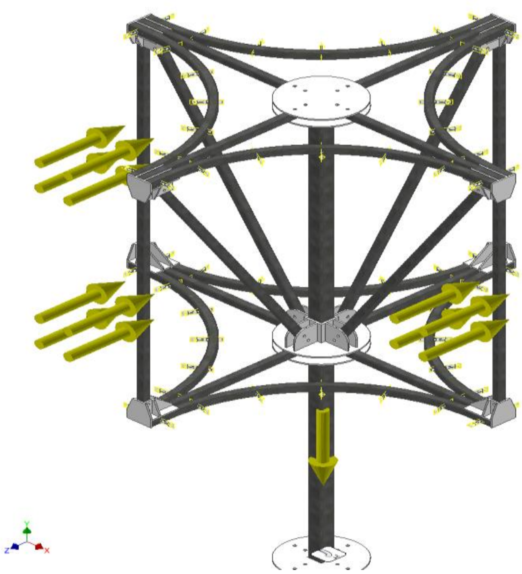


Fig. 3 Applied load diagram

2.3. Restrictions and Meshing

Restraint conditions needed to be defined at the support and fixing points, so we could accurately simulate the structural behaviour of the collector. In addition, the lower ends of the vertical tubes were restricted in their three degrees of freedom, giving them direct contact with the ground or installation base. To simulate the stabilizing function of the anchors against lateral loads induced by wind, restrictions were applied to the ends of the anchor tensioners.

The proposed model in this paper was discretized using tetrahedral solid elements that were selected for their ability to represent complex geometries with high precision. Local refinement was also applied in the joint areas, plates, and contact points because greater stress concentration is expected in those areas. The presented approach aimed to optimize the balance between numerical precision and computation time, ensuring adequate resolution in critical regions without overloading the global model.

In order to validate the quality of the mesh, it was necessary to use distortion and aspect criteria, which allowed the model to maintain a quality index above 0.75 in all regions. Figure 4 shows the mesh of the collector structure, where the total number of elements generated was approximately 1,170,526, and this allowed for obtaining reliable results in terms of stresses, displacements, and safety coefficients.

The approach selected for the refinement of the mesh was based on geometric complexity, as well as the expected stress concentration zones, in order to achieve adequate convergence of displacement and stress results. In spite of the fact that a formal mesh sensitivity analysis was not included in the present research, the mesh quality metrics and the high number of elements employed support the numerical reliability of the results. Thus, a detailed mesh sensitivity assessment is needed to perform as part of future work to further enhance the sturdiness of the computational framework.

Fig. 4 Meshing of the structure

2.4. Fluid Dynamics Simulation (CFD)

In order to evaluate the aerodynamic behavior of our model of fog collector and its interaction with the airflow, it was necessary to perform a CFD simulation using the Autodesk CFD environment. Unlike the structural analysis, the cylindrical meshes of this model were incorporated to act as porous media in this stage, so they could perform their function as a fog-capturing surface.

The design of the mesh that captures fog was modeled as a thin solid, to which porous media properties, equivalent to a commercial Raschel mesh, were assigned. This approach permits the representation of the resistance offered by the mesh to airflow without explicitly modeling individual perforations because these individual perforations would significantly increase the computational costs. In addition, the porous parameters were applied exclusively within the CFD environment, while the mesh elements were excluded from the FEM structural analysis due to meshing constraints. It was decided to opt for this modeling procedure because it ensures the consistency between aerodynamic representation and structural simplification. The following parameters were assigned.:

- Loss coefficient: $1.2 \times 10^5\ Pa.s/m^2$.
- Turbulence model: $k - \varepsilon$
- Input: uniform velocity of 10 m/s
- Output: atmospheric pressure (0 Pa gauge)
- Walls: non-slip condition

The standard k–ε turbulence model was selected since it is the most robust and suitable model for external flow simulations under fully developed turbulent conditions, which is also commonly reported in similar aerodynamic assessments of environmental structures. Besides, this model presents moderate Reynolds numbers that are also associated with the imposed inlet velocity, and the objective of this study is to evaluate the global flow patterns rather than near-wall micro-scale effects. Hence, all this evidence allows us to state that this model provides a reliable balance between numerical stability and computational efficiency.

CFD simulation identifies high-pressure zones, flow paths, and stagnation regions, helping to validate the design from an aerodynamic perspective. These results in sections are later presented in the results section, in more detail, and correlated with the structural analysis to indirectly assess fluid-structure interactions.

3. Results

3.1. Structural Analysis (FEM)

The performance of the structural analysis allowed us to evaluate the collector's resistance in the following loading conditions: dead weight and wind pressure. A surface pressure of 1.5 kPa was applied to the front faces of the frame; this allowed us to simulate strong winds according to ASCE 7 and NTP E.020 norms. Besides, gravitational acceleration was applied to the entire model, and for this, the density of the assigned materials was considered.

Table 2 shows the maximum and minimum values obtained in the performed structural analysis.

Table 2. FEM analysis results

Evaluated Magnitude	Maximum Value	Minimum Value
Von Mises stress	77.69 MPa	0 MPa
Total displacement	1.78 mm	0 mm
Safety Factor (SF)	15	2.66

Figure 5 exhibits the map of distributed von Mises stresses in the structural model of the present study. Concentrations are observed in different parts of the structural model, like the plates, corners, and joint areas, all within the permissible limits for the materials used (ASTM A36 and 6061 T6 aluminum). The maximum stress recorded was 77.69 MPa, and this indicates a safety factor greater than 2.6 in the areas that are critical.

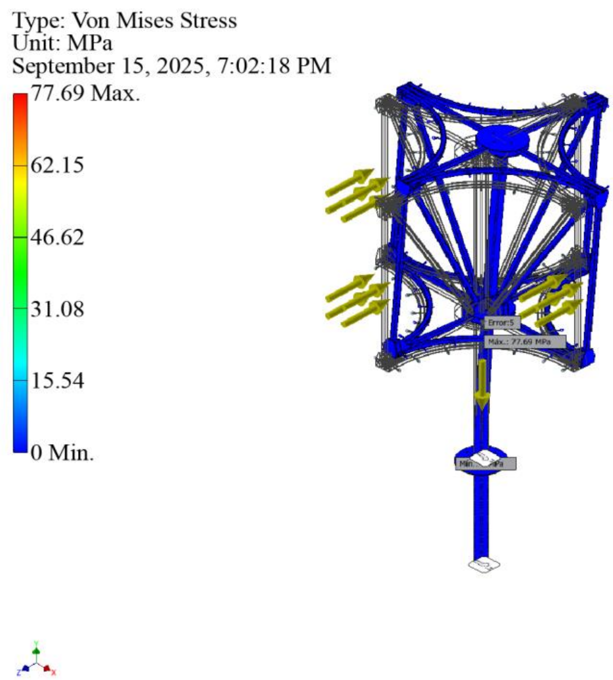


Fig. 5 Von Mises stress simulation

Figure 6 displays the map of total displacements. The maximum displacement found was 1.78 mm, located on the vertical axis (Z), which corresponds to the prevailing wind direction. This value is considered to be low for a lightweight, modular structure and does not compromise the stability of the system we present in this paper. The displacements on the X and Y axes were even smaller than the previous displacement mentioned, confirming the rigidity of the assembly under lateral loads.

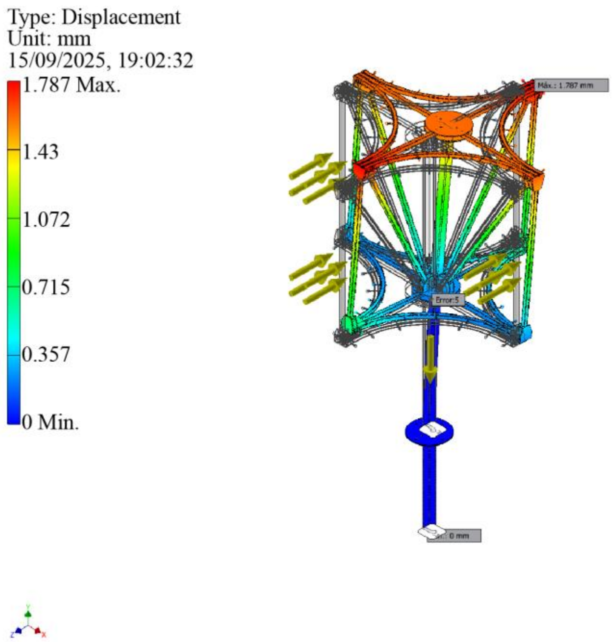


Fig. 6 Von Mises stress simulation

Figure 7 shows the Safety Factor (SF) scale throughout the entire model. All the structural areas have a Safety Factor (SF) greater than 2.6 (> 2.6), demonstrating that the design means are reliable even under demanding load conditions.

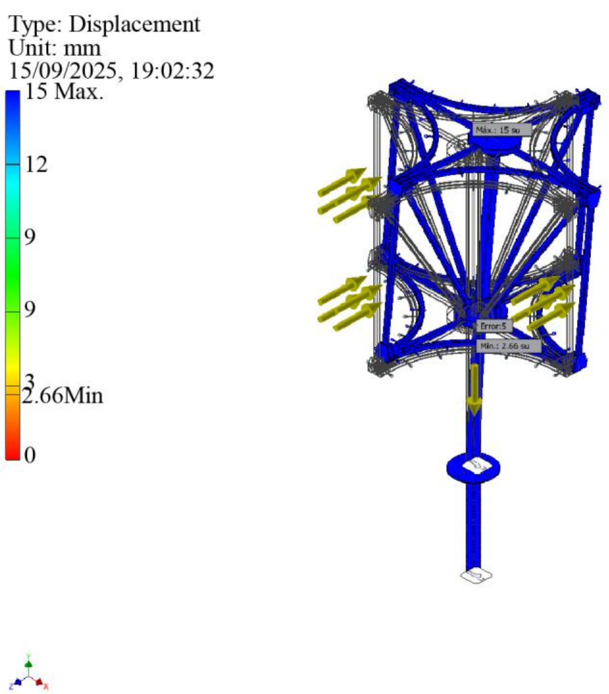


Fig. 7 Von Mises stress simulation

3.2. Fluid Dynamics Simulation (CFD)

CFD simulation allowed us to do the analysis of the airflow behavior around and through the collector, with the cylindrical meshes modeled as a porous medium. The model was processed in the Autodesk CFD environment; during this process, an inlet velocity of 10 m/s, atmospheric pressure at the outlet, and the standard k–ε turbulence model were applied. The meshes were defined with a porosity of 0.75 and a loss coefficient of $1.2 \times 10^5\ Pa.s/m^2$. Representing real-life collection conditions in high Andean areas.

Figure 8 presents the streamlines generated around the collector from a side view, demonstrating the aerodynamic envelope of the flow. Figure 9 shows the same distribution from a top view, highlighting the radial dispersion of air toward the mesh surfaces. Flow envelopes can be seen in the curved areas of the frame, as well as partial deflection through the meshes, which favours omnidirectional fog collection. Air trajectories are deflected toward the mesh surfaces, concentrating the flow in the most exposed regions.

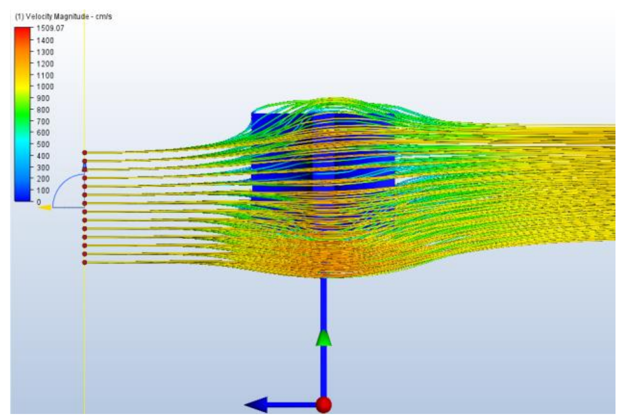


Fig. 8 Side view of the incident flow and its aerodynamic envelope

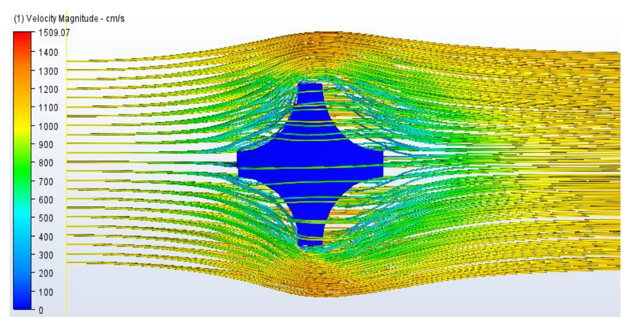


Fig. 9 Top view showing the radial dispersion of the flow towards the meshes

Figure 10 exhibits the pressure map that was obtained in the CFD simulation from a lateral perspective. This highlights the pressure concentration on the surfaces facing the flow. In addition, Figure 11 provides a top view, in which the spatial distribution of pressure on the collector is revealed. It was identified that the highest pressure areas are located on the exposed faces of the cylindrical meshes, coinciding with the direct impact of the wind. This distribution validates the geometric positioning of the system, as well as maximizing the interaction between the flow and the collection surfaces.

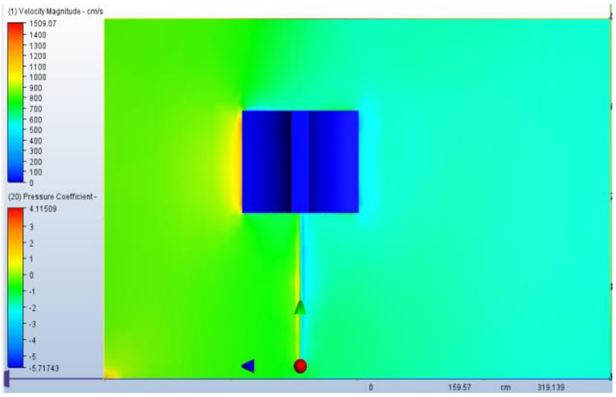


Fig. 10 Pressure map on the collector under a flow of 10 m/s from the side

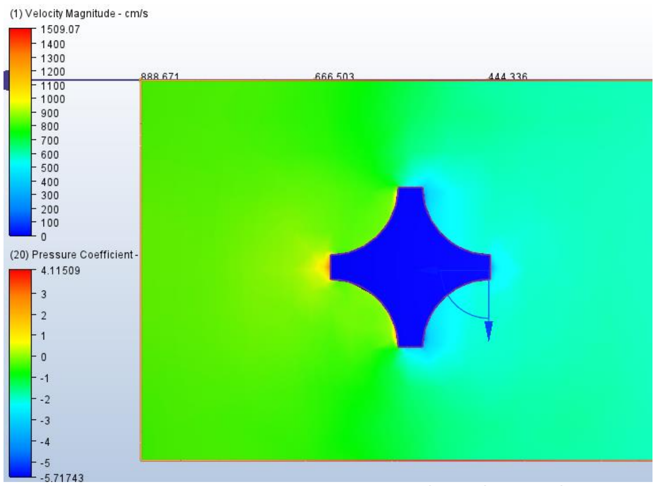


Fig. 11 Pressure map on the collector under a flow of 10 m/s from above

Although porous properties were not applied in this simulation, the results with regard to the pressure distribution that were obtained and observed allow us to make inferences about areas of greater interaction with the flow, which is useful for future design optimizations. Overall, the CFD results obtained from the performed simulations confirm that the proposed system in this research permits the effective interaction between the air flow and the collection surfaces, and as a consequence, the fog accumulation in moderate to strong wind conditions is stimulated.

4. Discussion

The results obtained in the present study from both the FEM and CFD simulations and analyses enabled us to get a comprehensive validation of the proposed fog collector design, not only from the structural perspective, but also from the aerodynamic one. With regards to the FEM analysis, it revealed that the Von Mises stresses remained, during the entire simulation, below the elastic limit of the used materials (ASTM A36 and aluminum 6061 T6), and the safety coefficient obtained from it exceeds 2.6 in all the critical areas. Regarding the displacements, the maximum ones observed were less than 2 mm, confirming the system's rigidity under wind loads and its own weight.

After performing the CFD simulation, it could be observed that an aerodynamic flow envelope around the collector, along with streamlines that were concentrated in the mesh areas, stimulated omnidirectional collection. Additionally, the pressure map obtained after the performed simulation revealed certain areas of direct impact on the exposed faces; these results validate the geometric orientation of the system. Although the meshes were modelled as solid surfaces, the distribution of the pressure obtained allowed us to infer and identify the areas of high interaction with the flow, which, of course, are helpful for future optimizations.

Departing from a quantitative perspective, the structural performance obtained in this study compares favorably with values reported for conventional flat fog collectors. While traditional systems typically lack mechanical validation or exhibit significant deformation under strong wind conditions [8, 11], this study proposes a modular design that maintains safety factors that are greater than 2.6, and its maximum displacements are below 2 mm when it is subjected to combined gravity and wind loads. These outcomes indicate a substantially higher structural reliability, which is critical for long-term operation in environments that are exposed to high altitudes. In spite of the fact that direct water yield measurements are not included at this stage, the outcomes present improved aerodynamic interactions in the CFD simulations, and these suggest a potential enhancement in collection efficiency when compared to two-dimensional configurations reported in previous literature [7, 10].

When considering the practical applicability of this modular configuration, this proposed collector facilitates scalability through the replication of standardized units, while also allowing its adaptation to different environmental conditions and water demand levels. The use of commercially available structural materials and simple bolted connections supports its ease of assembly, maintenance, and replacement of its components, even in rural contexts. From a preliminary economic perspective, this device does not require active energy systems, and the context of reliance on passive collection mechanisms suggests lower operational costs when compared to technologically complex solutions such as electrostatic collectors [9]. In addition, the addition of a detailed cost-benefit analysis and long-term maintenance assessment is identified as necessary for future steps to support large-scale implementation.

5. Conclusion

This study presents three important aspects of fog collectors: the design, the modelling, and its validation through a three-dimensional simulation, intended for it to be implemented in high Andean areas with favorable climatic conditions for passive water harvesting. Through the performance of structural (FEM) and fluid-dynamic (CFD) simulations, it was demonstrated that the present system is mechanically stable, aerodynamically efficient, and most importantly, it is adaptable to different modular configurations. The obtained results of this study confirm that the collector can operate under moderate to strong wind conditions without compromising its structural integrity. In addition, its geometry favours the interaction of the flow with the collection surfaces. The methodology used in this research allows for the replication of the presented design in other contexts and, even better, opens up the possibility of incorporating improvements such as porous materials, hydrophilic coatings, or hybrid collection systems. This study clearly contributes to the field of fog harvesting with a multidisciplinary approach. By integrating structural engineering, fluid dynamics, and environmental design, this system proposes a viable solution to address water scarcity in vulnerable rural communities.

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