

Experimental and Numerical Dynamic Analysis of a Water Conservation Nozzle for Sustainable Water Management in Pakistan

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Abstract: The water crisis is a global issue, and the situation in Pakistan is no different. With rapid population growth, improper resource management and climate change effects, Pakistan is approaching a state of water scarcity. Tap water is a major contributor in residential water usage, presenting a significant opportunity for water conservation. The principal aim of this study is to propose a sustainable water management solution by introducing inventive household conservation devices. This research will identify the optimum parameters for the design of faucets at the maximum efficiency point, which will maximize water efficiency and reduce water consumption that can be precisely machined using traditional manufacturing processes. Using ANSYS, we performed Finite Element Analysis on the fluid flow through the prototype to observe pressurevelocity variation, and real-world testing was conducted to compare the performance of the prototype against the normal tap. Our study reveals that the prototype can conserve 70% of water by producing mist without affecting the functionality. It was also observed that the formation of mist is dependent on the distance between the screw and the nozzle. In conclusion, our research demonstrates that the domestic and commercial utilization of this prototype can restrain Pakistan's ongoing water crisis. Further, the prototype can be modified and utilized in the showerhead, to maximize water conservation.

1. Introduction

Imagine a world with no fresh water available for future generations. Urbanization, rapid population growth, climate change, and low rainfall have adversely affected the availability of fresh water [1]. The world possesses a huge threat of water scarcity, around 4 billion people could experience water scarcity all around the world, which will also increase energy prices [2], [3], [4], [5]. By the year 2050, it is anticipated that an extra billion individuals will reside in areas experiencing extremely high water stress [5]. In 1950, water availability in Pakistan was around 5,000 m³ which has been reduced to 1,000 m³ in 2015, and it is expected that if immediate actions are not taken, Pakistan will run dry in 2025 [6], [7], [8]. According to UN assessment 2023, Pakistan is ranked 18th in the critically water-stressed countries of the world [3]. A report of the World Research Institute 2019 indicates that Pakistan ranks 14 among 18 extremely high water-stressed Countries [9]. Poor management, lack of water storage capacity, water quality, urbanization, high population growth, and climate change are the main factors of water scarcity in Pakistan [10], [11], [12], [13]. The concept of sustainable water management involves a systematic approach to decreasing water usage and safeguarding our natural resources for the well-being of future generations [1]. Water being the most significant resource with 70% utilization in rural areas needs efficient sustainable management across

all potential sectors, which could result in a decline of water demand up to 50% [13], [7]. Implementing sustainable water management involves the adoption of water-saving technologies like low-flow faucets and efficient washing tanks, the introduction of gray water systems, and the collection of rainwater elements. [14]. The water requirements for basic human needs are 50 liters per person per day [15]. Among all indoor water usage, faucets and showers can conserve relatively more water than all other uses combined [16].

Water consumption is primarily concentrated in residential buildings within urban areas, with a significant portion attributed to the usage of faucets and taps. The adoption of low-flux faucets presents a valuable opportunity to decrease water consumption [17]. To reduce the water consumption, it was observed that by replacing conventional taps with water-saving taps, the amount of water consumption can be reduced by 50% [18]. For this purpose, we have analyzed the flowrate of conventional taps and water-saving nozzles. Depending upon the faucet type it is possible to conserve more than 50% of water, which will also reduce the energy requirement for heating and pumping [18], [19].

The efficiency of water conservation nozzle strongly depends upon certain parameters, which affect its performance and quality of atomization. Cavitation is a phenomenon that occurs when bubbles form in regions of low static pressure, where the pressure is below the saturated vapor pressure at a constant temperature [20], [21]. The parameter used to predict cavitation is Cavitation Number, which is given by [22]:

$$k = \frac{P_a - P_v}{\frac{1}{2} \rho v^2}$$

Cavitation produced within the nozzle improves the atomization characteristics [23]. As the cavitation number K decreases, the chances for cavitation phenomena occurring increase [21]. Flow speed at outlet and spray cone angle increases when cavitation phenomena occur [23]. [24]. Cavitating flow is classified into three regions: turbulent flow region, cavitating flow region, and hydraulic flip region [25]. The cavitation number exhibits an exponential decrease with rising Reynolds numbers. Water jets atomize quickly after discharge when Reynold's Number is high [26]. Keeping the Reynolds number greater than 10^5 and cavitation number less than 1, we can achieve better cavitation and atomization [27].

2. Methods

Design and Manufacturing

The assembly of the design consists of the twister, brass screw, main body, grub screw and O-rings as depicted by Fig. 1. The twister incorporates a centrally positioned conical-shaped cavity at its base which guides the intricate design of brass screw which is in the shape of a convergent nozzle. Fig. 1(a) and Fig. 1 (b) illustrate the assembled and disassembled view of the prototype respectively. The purpose of this innovative design is to provide precise shaping of the nozzle and to facilitate a rapid and controlled reduction in pressure which is a fundamental requirement for the generation of fine mist.

Grub screw is used to limit the axial motion of twister allowing for controlled transition between spray and mist mode and O-rings are employed to prevent the water leakage between the sleeve and the housing during mode switch. To achieve optimal compactness and proper alignment of all components, all parts are designed as cylinders. Moreover, the research adheres to the ISO 724:1993 standard for ISO general-purpose metric screw threads, which is the recognized benchmark in Pakistan, and it ensures compatibility with established industry norms and practices.



Fig. 1. Design of Dual True Mist Twister (Mist Nozzle) (a) Assembled View (b) Disassembled view - central conical-shaped cavity at the bottom of twister to guide the brass screw and shape the nozzle allowing sudden pressure to drop for mist creation.

Fig. 2 provides a more comprehensive illustration of fluid flow in mist mode. The restriction of flow from the periphery effectively channels the flow through a relatively small region at the center, creating a necessary environment for sudden pressure drop in mist mode. This sudden pressure drop is pivotal in reducing the cavitation number, a critical parameter for atomization of water molecules to generate mist in mist mode.

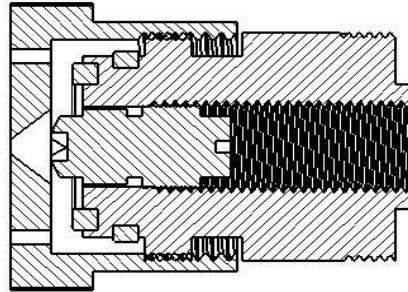


Fig. 2. Sectioned view of dual flow true mist twister – Flow restricted to central cavity creating a nozzle profile for fluid flow resulting in cavitation.

Finite Element Modelling

The fluid domain is the region of the fluid flow in the assembled part. We have generated a separate fluid domain for each mode i.e., spray mode and mist mode in SOLIDWORKS as shown in Fig. 3. In spray mode, the outlet is along the periphery and at the center of twister as illustrated in Fig. 3(a) whereas in mist mode, the outlet is only at the center of the twister as shown in Fig. 3(b).



Fig. 3. Fluid domain (a) Spray mode – fluid flow is allowed from all holes/pores/cavities (b) Mist Mode – fluid flow is allowed only from the central cavity.

These fluid domains are then imported and modelled in ANSYS 2020 R1 for further analysis. To simplify geometry and reduce the mesh count, a quarter portion of geometry is created by considering two symmetric planes, one on the YZ-plane with an offset of -0.030891 m from the Global X-axis, and the other on the XZ-plane with an offset of 0.031444m from the Global Y-axis. Meshing is performed on each fluid domain and the quality of mesh is improved by the patch conforming method. A visual representation of the meshed geometry is shown in Fig. 4. To ensure improved result accuracy, it is advisable to maintain mesh quality greater than 0.1, skewness less than 0.95, and aspect ratio below 100. In the spray mode, as depicted in Figure 4(a), the total number of elements is 943,242, with 170,329 nodes. The maximum aspect ratio of the mesh element is 8.3776. The minimum element quality is 0.26116. The maximum skewness of the mesh is 0.79954. In mist mode (Fig. 4 (b)), the total number of elements are 221,041 and nodes 42,822. The maximum aspect ratio is 7.8086. The minimum element quality is 0.27893. The maximum skewness of the mesh is 0.79774. Based on the convergence check, all the parameters are within limits for both modes.

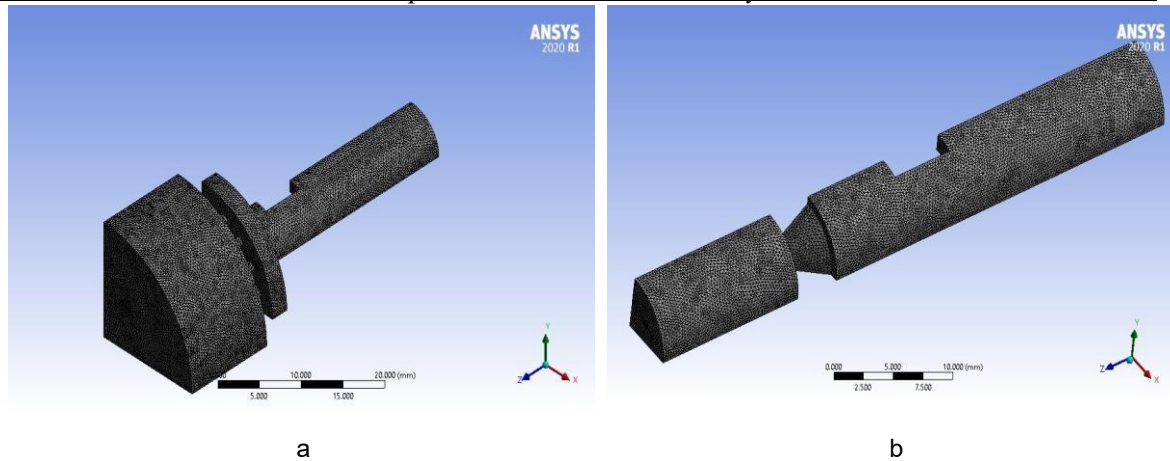


Fig. 4. Mist formation study on fluid domains with inlet total gauge pressure of 300,000 Pascal and turbulent intensity of 5% (a) Axisymmetric fluid domain in spray mode with elements size of 0.3mm. Total elements are 943,242 (b) Axisymmetric fluid domain in mist mode with elements size of 0.3mm. Total elements are 221,041.

The inlet is provided with a total gauge pressure of 300,000 Pascal with the turbulent intensity of 5%, and the hydraulic diameter is 0.0095m, and the output parameters are observed at STP conditions for both spray and mist mode. The outlet hydraulic diameter considered for spray mode is 0.030m, which is larger than the hydraulic diameter for mist mode, i.e., 0.0095m, a necessary condition to observe flow from the periphery in spray mode.

Material Selection and Manufacturing

The material chosen for all components is stainless steel except for screw which is made of brass. Conventional lathe machine is used for all the cylindrical components while CNC milling is used for convergent nozzle feature in the brass screw.

Test Setup and Performance Evaluation

The performance of the fabricated prototype is evaluated by mounting the prototype on the faucet and observing the volume flowrate for each mode. Three readings each for 5 seconds are taken for both spray and mist mode, and the most repeated value is selected. The readings are then compared with the volume flow rate of the normal tap to calculate the percentage reduction in flow rate of the prototype in comparison with the normal tap.

3. Results

FEA

Following the computational modeling of fluid domains using ANSYS, a comprehensive analysis was conducted to scrutinize the influence of geometric parameters on mist formation, a phenomenon pivotal for the conservation of water resources. This analysis encompassed an examination of pressure distributions, velocity profiles, and volume fraction contours within the system.

The investigation is performed in both spray and mist modes, recognizing the distinct dynamics at play in each operational state. By conducting this multifaceted analysis, we gained valuable insights into the underlying mechanisms governing mist formation and, by extension, water conservation. These insights are vital not only for our specific research objectives but also hold broader implications for the advancement of environmentally responsible technologies and practices.

Spray Mode

Fig. 5 depicts the flow pattern in spray mode which is achieved through the strategic manipulation of the nozzle's position, specifically by shifting it in a manner precisely equal to the distance between the grub screw cavity and the periphery of the twister. This spatial adjustment plays a pivotal role in facilitating the outflow of water from all cavities within the twister. As the water traverses from the prototype's inlet to its outlet, a discernible static pressure reduction is observed, decreasing from 300,000 Pascal at the inlet to 90,000 Pascal at the outlet as shown in Fig. 5(a). This pressure drop accelerates the water flow resulting in high velocity of the water molecules at the outlet, which is observed to be around 11m/s as shown in Fig.5 (b). This observation holds significant implications for practical application, as it ensures the prototype's capacity to deliver water at a velocity deemed optimal for effective utilization

within household faucets. The outcome is a testament to the prototype's efficiency in promoting water conservation, a matter of great importance in contemporary environmental discourse.

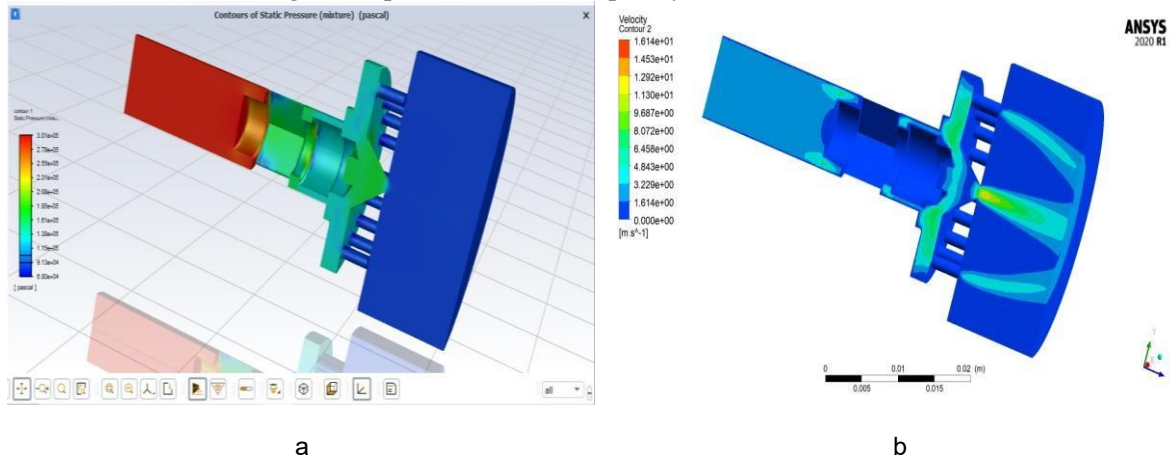


Fig. 5. Post Processing flow analysis through the prototype in spray mode with inlet total gauge pressure of 300,000 Pascal and output at STP conditions. (a) Pressure variation contour (Pa) (b) Velocity variation contour (m/s) - Hydraulic diameter at outlet is 0.030m. Comparatively low pressure drop due to larger distance between screw and the nozzle. Velocity observed is 1m/s.

Mist Mode

Fig. 6 illustrates the intricate dynamics of water flow only from the central cavity of the twister, which is achieved through precise reduction in distance between the nozzle and the central cavity with the help of the twisting mechanism of the twister. The consequence of this geometrical adjustment is the deliberate restriction of water flow from the peripheral regions of the twister to establish the requisite conditions for a crucial phenomenon - the abrupt drop in static pressure at the nozzle's orifice which is responsible for the generation of mist, a vital objective in our study aimed at conserving water, as vividly illustrated in the figure.

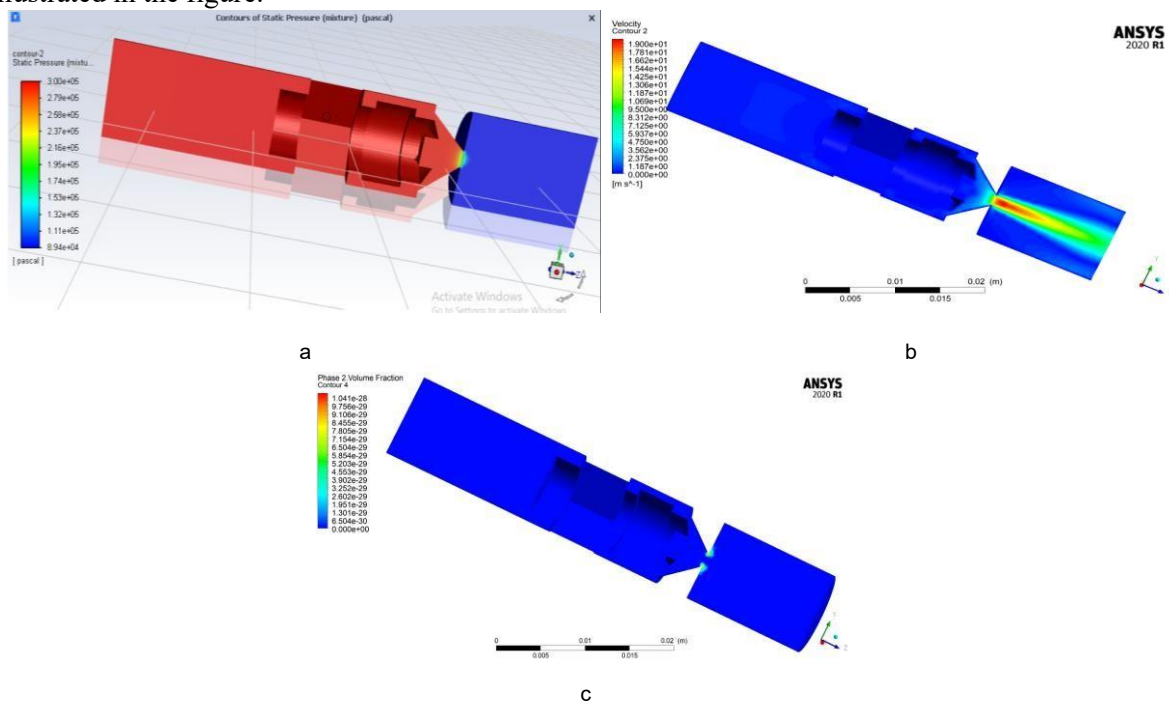


Fig. 6. Post Processing flow analysis through the prototype in mist mode with inlet total gauge pressure of 300,000 Pascal and output at STP conditions. (a) Pressure variation contour (Pa) (b) Velocity variation contour (m/s) (c) Volume fraction contour - Hydraulic diameter at outlet is 0.0095m. A sudden drop in static pressure drop across the nozzle resulting in high velocity mist across the orifice. Velocity observed is 14m/s.

As the water progresses from the nozzle to the outlet, there is a rapid conversion of static pressure to dynamic pressure (Fig. 6(a)) leading to a substantial increase in velocity of the water as it exits the prototype, which is observed to be approximately 14m/s underscoring the efficacy of the prototype as shown in Fig. 6 (b). An intriguing observation arises when we compare the outlet velocities in the mist mode and the spray mode. The mist mode exhibits a significantly higher outlet velocity. This discrepancy can be attributed to a more substantial static pressure drop within the system. We can also observe the augmented spray cone angle which is a direct consequence of mist generation. It ensures the optimal utilization of water resources while simultaneously maintaining the prototype's efficacy in household applications. Moreover, Figure 6(c) provides empirical evidence of mist formation, a minute quantity of liquid water undergoes a phase transition, becoming water vapor precisely at the nozzle's orifice. This vapor, upon mixing with the liquid component, gives rise to the mist observed at the outlet. This tangible observation underscores the intricate interplay of fluid dynamics within our experimental setup and substantiates the core objectives of our study.

In order to ensure the validity of our results, we have performed calculations for the Reynolds and Cavitation Number both in the mist mode of operation. Reynolds Number:

$$Re = \frac{\rho v d}{\mu}$$

$$Re = \frac{998.4 \times 14 \times 0.0095}{0.00089}$$

$$Re = 1.49 \times 10^5$$

Cavitation Number:

$$k = \frac{P_a - P_v}{\frac{1}{2} \rho v^2}$$

$$k = \frac{90000 - 2338}{\frac{1}{2} \times 998.4 \times 14^2}$$

$$k = 0.895$$

The calculated result for both the Reynolds Number and Cavitation Number agrees with the minimum requirement for cavitation substantiating the results of mist generation in mist mode.

Water Conservation

The validity of the results obtained through Finite Element Analysis (FEA) was further substantiated by empirical testing of the prototype, thereby ensuring the robustness of our findings. It was observed that within a brief 5-second interval, the prototype consumed 220 milliliters of water in spray mode, while in mist mode, a significantly reduced consumption of 120 milliliters was recorded. This translated to volume flow rates of 0.044 liters per second (l/s) and 0.024 l/s for spray and mist modes, respectively. Our tests revealed that a conventional faucet in Pakistan yielded 400 milliliters of water in 5 seconds, equivalent to a flow rate of 0.088 l/s.

The flow rates for both spray and mist modes were then compared against the flow rate of a standard faucet, the results underscored substantial water conservation potential in both operational states with mist mode exhibiting the highest water conservation efficiency, boasting a remarkable 70% reduction in water consumption, as detailed in the accompanying table.

Extrapolating from this data, the study provides insights into the average water utilization in a normal household, which is 16gpcd, which is approximately 5840 gallons in a year of a complete household [28]. Faucet utilization will be 917 gallons in a year [16]. The application of our prototype in a hypothetical scenario involving 100 households reveals its transformative potential. With its deployment, this prototype has the potential to conserve up to 64,190 gallons of water annually. This holds exceptional significance for a water-stressed nation such as Pakistan, where sustainable water management practices are of paramount importance.

4. Conclusion

This research aims to address the pressing issue of water scarcity in Pakistan by providing an innovative solution. Through extensive literature review, detailed design, and rigorous simulations, we have proposed a design that has the potential to substantially reduce water consumption. The proposed solution, known as the Dual True Mist Twister, demonstrates remarkable efficiency, with the capacity to conserve a significant portion of water resources. In mist mode, this device has proven capable of conserving up to an impressive 70% of water, while in spray mode, it achieves a commendable 55% reduction in water usage, as indicated by the results obtained in our performance evaluation. We are already aware that 15.7% household water consumption is through faucets. The widespread adoption of this innovative solution, both in domestic and commercial settings, has the potential to play a pivotal role in mitigating Pakistan's water crisis. Furthermore, the adaptability of this research extends to showerheads, where it can effectively reduce water consumption by approximately 16.8%.

Thus, the represents a tangible step towards addressing a critical water scarcity issue faced by Pakistan. Its potential applications and proven water-saving capabilities make it an asset in the quest for sustainable water resource management.

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