



An Experimental and Comparative Investigation into the Influence of Manifold Configurations on Air Intake Efficiency

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Abstract. Dissolved oxygen content is a paramount indicator of water quality, directly linked to water remediation processes. Aeration processes enhance dissolved oxygen levels in water treatment through hydraulic structures that increase interfacial area between water and air. This study investigates the aeration efficiencies of pressurized flow systems equipped with Venturi devices of two different orifice diameters (12.7 mm and 19.05 mm) connected to four distinct manifold pipe systems. Experiments were conducted at four flow rates (0.60, 0.75, 0.85, and 1.0 m³/h) corresponding to Reynolds numbers ranging from 16,850 to 27,663. The findings demonstrate that orifice diameters and manifold configurations significantly influence aeration efficiency. Venturi type 2 (19.05 mm) exhibited superior air suction performance at higher flow rates, while optimal performance was observed at main flow velocities between 1.5-2.0 m/s. Empirical correlations were developed linking air-to-water flow ratios (Q_{air}/Q_{water}) with jet lengths, yielding R^2 values ranging from 0.87 to 0.99, indicating strong predictive capabilities for system design optimization.

Keywords: Atmosphere, Aeration, Dimensional Analysies, Manifold, Venturi,

1 Introduction

Dissolved oxygen (DO) concentration in water is a critical parameter determining water quality and ecosystem health. In water treatment systems, adequate oxygenation is essential for biological processes, chemical oxidation, and maintaining aquatic life. Aeration systems facilitate oxygen transfer from the atmosphere to water through various mechanisms, including mechanical aerators, diffusers, and hydraulic structures. Among these, Venturi-type aerators have gained prominence due to their energy efficiency, simplicity, and cost-effectiveness. The Venturi principle, based on Bernoulli's equation, creates a pressure differential when fluid flows through a constricted section, drawing air into the system through negative pressure at the throat region. This mechanism offers approximately 20% energy savings compared to conventional suction methods [1]. The straightforward design of Venturi devices, consisting of a converging inlet section, throat, and diverging outlet section (Figure 1), makes them attractive for various water treatment applications.

Previous research has established the fundamental performance characteristics of Venturi aerators. Baylar and Emiroğlu [2] demonstrated that water jets can significantly increase DO levels when jet impact velocity exceeds critical thresholds. Their experimental study on Venturi devices equipped with air holes in the throat section revealed that air mixing ratio and oxygen transfer efficiency values were substantially higher than those for circular nozzles. The aeration characteristics influenced jet expansion, shape, bubble penetration depth, and consequently oxygen transfer efficiency.

Bagatur [3] investigated Venturi pipe parts (VPPs) designed to enhance DO levels in irrigation water, demonstrating that elevated DO levels can accelerate nutrient absorption by plant roots, potentially boosting plant growth rates by up to 30%. Optimal inlet flow velocities for the aeration process were determined to range between 1 and 4 m/s, with a minimum velocity of 0.80 m/s necessary to initiate the air vacuum process. The study emphasized the importance of throat-to-inlet diameter ratio (0.5) and air vent-to-throat diameter ratio (0.3) in VPP design.

Gökgöz et al. [4] investigated the impact of hole location on air intake performance in circular conduits, concluding that hole position does not significantly affect air intake rate. Conversely, Hamed [5] demonstrated through experimental investigations that geometric configuration parameters substantially influence aeration efficiency in Venturi systems, including water flow rate, air inlet orifice diameters, throat length, and inlet/outlet angles.

Kantarıcı [6] focused on optimizing nozzle designs for maximum air intake efficiency in pressurized water jet systems. The research indicated that increasing jet impact distance led to higher air intake rates, with optimal performance achieved using a nozzle size four times the jet diameter and an air hole diameter of 4 mm. Turgut [7] examined circular Venturis with varying diameters (36, 42, and 54 mm) and throat configurations, finding that DO levels varied systematically with Venturi diameter.

The geometric influence on aeration efficiency was further explored by Mobasher and Mahmoud [8], who developed empirical correlations to predict air and water flow rates based on Venturi dimensions, angles, and Reynolds numbers. Their experiments on transparent polycarbonate Venturi models demonstrated that geometric characteristics significantly influence aeration performance. Baylar et al. [9] compared perforated and non-perforated Venturi and circular orifices, finding that perforated Venturi orifices exhibited higher oxygen transfer efficiency. The negative pressure in air holes influenced bubble expansion, shape, and penetration depth, consequently affecting oxygen transfer efficiency. Yadav et al. [10] investigated Venturi aerator performance in a 200-liter water tank, observing that moderate to high discharge rates yield optimal standard oxygen transfer rate (SOTR) and standard aeration efficiency (SAE), while excessive discharge rates can diminish performance.

Despite extensive research on Venturi aeration, limited studies have systematically investigated the interaction between Venturi device geometry and manifold configuration on air entrainment performance. This study addresses this gap by experimentally examining two Venturi types with different orifice diameters across four manifold configurations, providing comprehensive empirical correlations for system optimization.

The objective of this research is to: (1) quantify air suction performance for two Venturi types across varying flow rates; (2) investigate the influence of manifold port configurations on air-water flow characteristics; (3) develop empirical relationships between air-to-water flow ratios and jet lengths; and (4) determine optimal operating conditions for maximum aeration efficiency.

2 Materials and Methods

2.1 Experimental Setup

The experimental apparatus was constructed and tested in the Hydraulics and Environmental Laboratory, Department of Civil Engineering, Dicle University, Turkey. The system comprised a 300-liter water tank, circulation pump (0.75 kW, Pedrollo Model), manifold pipe system (250 cm length, 12.7 mm internal diameter), two Venturi devices, water flowmeter (0-6 m³/h, 101.325 kPa), air flowmeter (0.3-3.0 L/min, LZT 6-M), and measurement instruments (Figures 1).

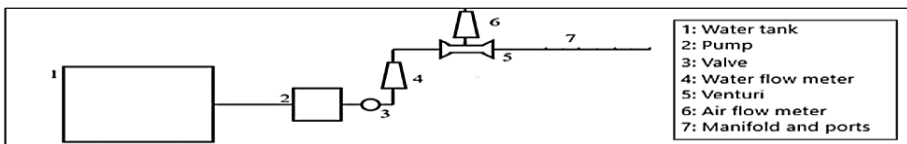


Fig. 1. Schematic diagram of experimental setup with venturi device

Water was circulated through the horizontally oriented manifold system at controlled flow rates using a flow control valve. The system was precisely leveled using a water

level to ensure accurate measurements. Temperature was monitored using a thermometer (WTW Tetra Con 325 Model), maintaining water temperature at 20°C throughout experiments.

2.2 Manifold Configurations

Four manifold configurations with varying port outlet configurations were investigated to assess the influence of discharge distribution on air entrainment characteristics. Each manifold system was equipped with ports at specific intervals along the 250 cm length, allowing two-phase air-water flow to discharge through multiple outlets.

2.3 Experimental Procedure

Experiments were conducted at four flow rates: $Q_1 = 17 \times 10^{-5} \text{ m}^3/\text{s}$ (0.60 m³/h), $Q_2 = 20.8 \times 10^{-5} \text{ m}^3/\text{s}$ (0.75 m³/h), $Q_3 = 23.6 \times 10^{-5} \text{ m}^3/\text{s}$ (0.85 m³/h), and $Q_4 = 27.8 \times 10^{-5} \text{ m}^3/\text{s}$ (1.0 m³/h). Corresponding manifold flow velocities were $V_1 = 1.34 \text{ m/s}$, $V_2 = 1.64 \text{ m/s}$, $V_3 = 1.86 \text{ m/s}$, and $V_4 = 2.20 \text{ m/s}$.

For each experimental configuration, water was circulated from the tank through the manifold system. Air entrainment was measured using the air flowmeter positioned at the Venturi throat air inlet. The two-phase air-water mixture discharged through manifold ports, and jet lengths were measured and recorded.

2.4 Dimensional Analysis

A theoretical investigation was undertaken to explore the functional relationships between the air injection flow rate (Q_{air}) and various geometric and fluid dynamic parameters. Dimensional analysis was utilized to identify these relationships [11]. Q_{air} was treated as the dependent variable, while the following parameters were considered as independent variables:

$$Q_{\text{air}} = \varphi(Q_w, \rho, \mu, v, d_s, d_t,) \quad (1)$$

Where: Q_w : Water flow rate through the venturi, φ : Fluid density, μ : Dynamic viscosity,

v : Velocity, d_s : Hole diameter, d_t : Throat diameter

Using Buckingham's π -Theorem, nine variables and three repeated changes were obtained. These changes can be easily coordinated in the following non-dimensional π -terms.

$$\pi_1 = \frac{Q_{\text{air}}}{vd_t^2}, \pi_2 = \frac{Q_{\text{water}}}{vd_t^2}, \pi_3 = \frac{\mu}{\rho vd_t}, \pi_4 = \frac{d_s}{d_t} \quad (2)$$

In accordance with Buckingham Pi theorem, the general functional relationship between these variables can be represented as:

$$\varphi = \left(\frac{Q_{\text{air}}}{vd_t^2}, \frac{Q_{\text{water}}}{vd_t^2}, \frac{\mu}{\rho vd_t}, \frac{d_s}{d_t} \right) \quad (3)$$

Considering the properties of the π -terms, the following equation was derived:

$$\frac{Q_{air}}{Q_{water}} = \varphi(Re, \frac{d_s}{d_t}) \tag{4}$$

Where, Re is Reynold’s number.

3 Results and Discussion

3.1 Air Suction Performance Across Manifold Configurations

3.1.1 Manifold Type 1

Air entrainment measurements for Manifold 1 revealed linear correlations between air suction flow rate and main pipe flow rate for both Venturi types (Figure 2). Initially, both Venturi devices exhibited comparable performance at lower flow rates. However, as flow rate increased, Venturi type 2 demonstrated superior air suction capacity compared to Venturi type 1. This performance differential is attributed to the larger throat diameter of Venturi type 2 (19.05 mm vs. 12.7 mm), which creates enhanced pressure differential and consequently greater air entrainment.

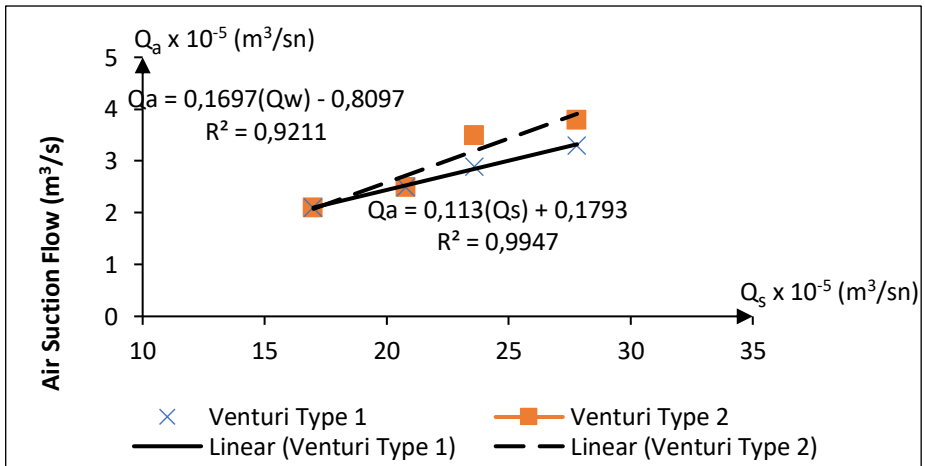


Fig. 2. Relationship between air suction flow rate and main pipe flow rate for Manifold Type 1]

Manifold 3 results (Figure 3) demonstrated that while Venturi type 1 exhibited superior initial performance at lower flow rates, Venturi type 2 achieved higher air suction capacity at elevated flow rates. The linear relationship between air suction and water flow rate remained consistent across both Venturi types, supporting the dimensional analysis predictions.

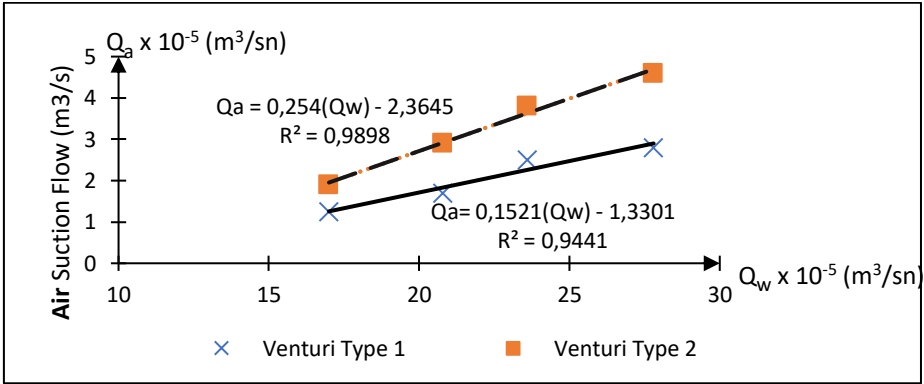


Fig. 3. The relationship between the air suction flow rate and the main pipe flow rate

3.2 Jet Length Analysis – Venturi Type 1

Jet length measurements provide insight into the momentum and energy distribution of the two-phase flow exiting manifold ports. The relationship between Q_{air}/Q_{water} ratio and jet length exhibited characteristic behavior across manifold configurations.

3.2.1 Manifold Type 1 with Venturi Type 1

Analysis of Figure 4 reveals direct proportionality between jet length and Q_{air}/Q_{water} ratio. A notable inflection point occurred at $V_2 = 1.64$ m/s, beyond which jet lengths increased linearly with flow rate. This inflection indicates a transition in flow regime characteristics, likely associated with the development of fully turbulent two-phase flow patterns.

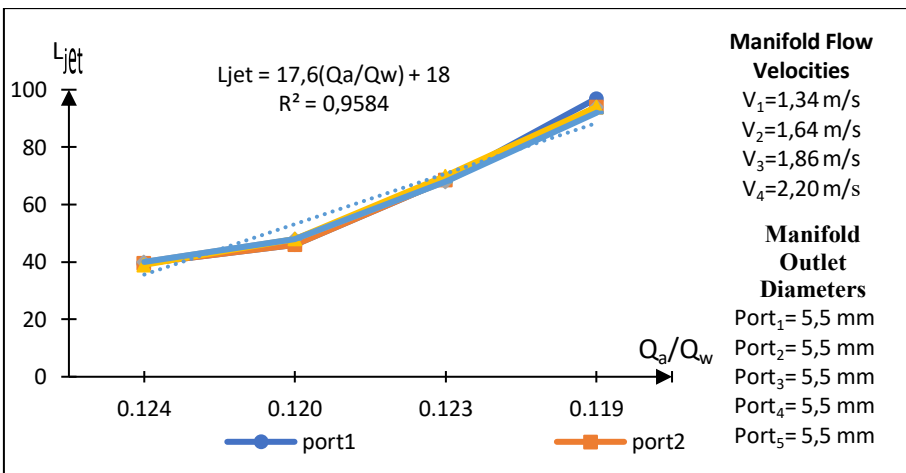


Fig. 4. Relationship between Q_{air}/Q_{water} ratio and L_{jet} in Venturi type 1, manifold type 1

3.2.2 Manifold Type 3 with Venturi Type 1

Manifold 3 exhibited dual inflection points at $V_2 = 1.64$ m/s and $V_3 = 1.86$ m/s (Figure 5), indicating more complex flow development influenced by port configuration:

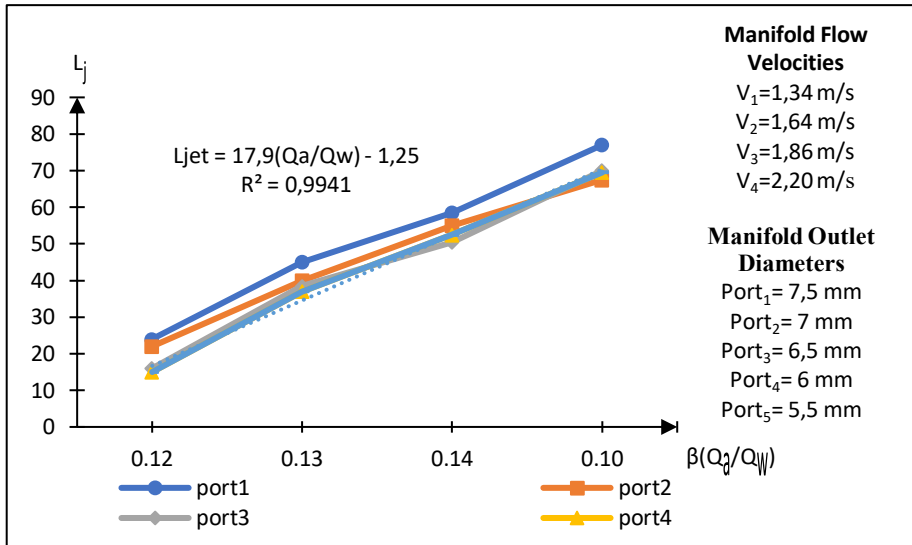


Fig. 5. Relationship between Q_{air}/Q_{water} ratio and L_{jet} in Venturi type 1, manifold type 3

3.3 Jet Length Analysis

3.3.1 Manifold Type 1 with Venturi Type 2

Venturi type 2 with Manifold 1 showed inflection at $V_3 = 1.86$ m/s (Figure 6), occurring at higher velocity compared to Venturi type 1, suggesting delayed flow regime transition:

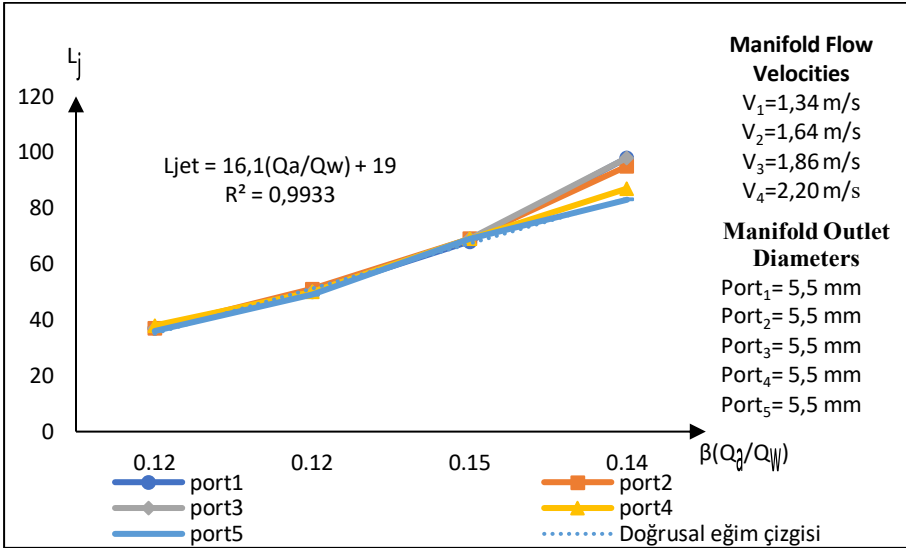


Fig. 6. Relationship between Q_a/Q_w ratio and L_{jet} in Venturi type 2, manifold type 1

3.3.2 Manifold Type 3 with Venturi Type 2

Single inflection point at $V_2 = 1.64$ m/s (Figure 7):

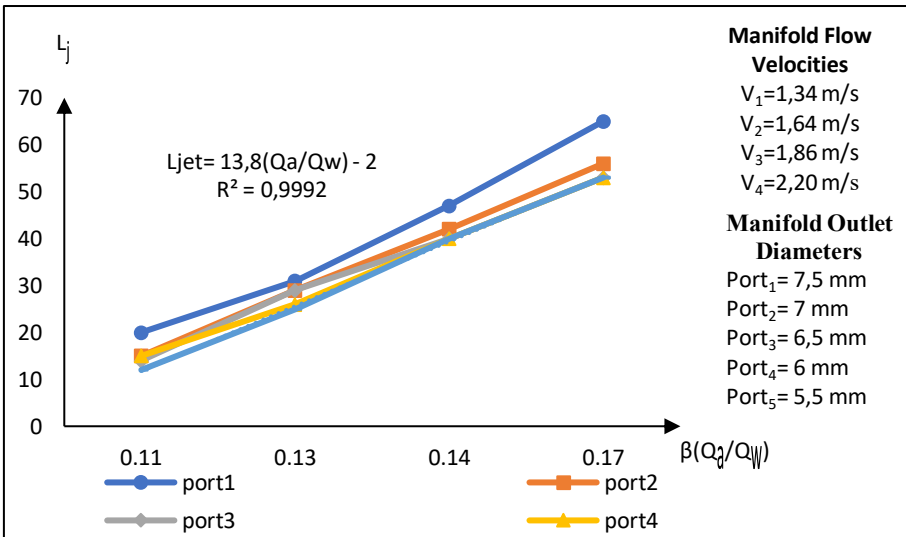


Fig. 7. Relationship between Q_a/Q_w ratio and L_{jet} in Venturi type 2, manifold type 3

3.4 Comparative Performance Analysis

The experimental results demonstrate several key findings:

Geometric Influence: Throat diameter ratio significantly affects air entrainment performance. Venturi type 2, with larger throat diameter, generally achieved superior air suction at higher flow rates, consistent with findings by Hamed and Mobasher and Mahmoud .

Reynolds Number Dependency: Air suction efficiency increased with Reynolds number, confirming the dimensional analysis predictions. The transition from lower to higher efficiency occurred around $Re \approx 20,000$ ($V \approx 1.64$ m/s), suggesting optimal operating conditions in the range of 1.5-2.0 m/s.

Manifold Configuration Effects: Different port outlet configurations substantially influenced both air suction characteristics and jet length behavior. Manifold 4 showed unique performance patterns, highlighting the complex interaction between Venturi geometry and downstream flow distribution.

Empirical Correlations: Strong correlations ($R^2 = 0.87-0.99$) between Q_a/Q_w ratios and jet lengths enable predictive modeling for system design optimization. These empirical equations can facilitate engineering applications requiring specific aeration performance characteristics.

Critical Velocity Thresholds: Inflection points at $V_2 = 1.64$ m/s and $V_3 = 1.86$ m/s indicate flow regime transitions associated with two-phase flow development. These critical velocities should be considered in system design to optimize performance.

The ratio d/D (air hole diameter to throat diameter) plays a crucial role in system performance. Previous work by Tumur et al. established a critical value of $d/D = 0.433$, below which dual-phase flow conditions are not sustained. The current study confirms that maintaining appropriate geometric ratios is essential for optimal aeration performance.

4 Conclusion

This experimental investigation systematically evaluated the air entrainment performance of two Venturi types across four manifold configurations. The following conclusions can be drawn:

Venturi Performance: Venturi type 2 (19.05 mm throat diameter) demonstrated superior air suction capacity at higher flow rates ($Q > 0.75$ m³/h) across most manifold configurations, attributed to enhanced pressure differential created by larger throat diameter. However, Venturi type 1 showed competitive or superior performance at lower flow rates and in specific manifold configurations.

Optimal Operating Conditions: Maximum aeration efficiency was achieved at manifold flow velocities between 1.5-2.0 m/s, corresponding to Reynolds numbers of 20,000-25,000. This velocity range represents optimal balance between energy input and air entrainment capacity [12].

Manifold Configuration Influence: Port outlet configuration significantly affects air suction characteristics and jet behavior. The experimental data revealed that manifold design must be integrated with Venturi selection to optimize overall system performance.

Empirical Correlations: Strong empirical relationships ($R^2 = 0.87-0.99$) were established between Q_a/Q_w ratios and jet lengths for all experimental configurations.

Flow Regime Transitions: Critical velocity thresholds at $V_2 = 1.64$ m/s and $V_3 = 1.86$ m/s mark significant transitions in two-phase flow behavior, characterized by inflection points in jet length curves. These transitions reflect developing flow patterns influenced by air-water interaction dynamics.

Geometric Ratios: The experimental results confirm the importance of maintaining appropriate d_s/d_t ratios (air hole to throat diameter) for effective air entrainment. The dimensional analysis successfully predicted the functional dependence of air-water flow ratio on Reynolds number and geometric parameters.

Practical Applications: The findings provide design guidance for water treatment systems, irrigation applications, and industrial processes requiring efficient aeration. The empirical equations can be directly applied to predict system performance and optimize design parameters.

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