Journal of Microfluidic and Nanofluidic Research 2 (2025), 114 – 119

Journal of Microfluidic and Nanofluidic Research

Journal homepage: https://jmnr.sku.ac.ir

Research Article

Numerical Study of Fluid Flow in Venturi Scrubbers

Amireh Nourbakhsh [a*], Mohsen Parsa [b]

[a] *Department of Mechanical Engineering, Faculty of Engineering, Bu-Ali Sina University, Hamedan, Iran*

[b] *Department of Mechanical Engineering, Faculty of Engineering, Bu-Ali Sina University, Hamedan, Iran*

ARTICLE INFO

Article history:

Received: 2025-05-01

Revised: 2025-06-18

Accepted: 2025-06-20

Keywords:

Venturi scrubber;

Turbulent flow;

Mass flow rate;

Pressure drop.

ABSTRACT

Venturi scrubbers are among the most efficient and widely employed devices in industrial air pollution control, designed to remove suspended particles and gaseous pollutants from gas streams by exploiting the Venturi effect to enhance gas-liquid contact. This study investigates the influence of varying gas mass flow rates and geometric parameters, including converging and diverging angles and section dimensions, on pressure drop and velocity distributions in five distinct Venturi scrubber designs. Numerical simulations using Ansys Fluent under turbulent, steady-state conditions with Reynolds numbers from 1.37×10^5 to 2.81×10^5 reveal that increasing gas flow rate raises pressure drop in a nonlinear fashion due to enhanced pressure recovery in the diverging section. The throat section consistently exhibits maximum fluid velocity, largely governed by throat cross-sectional area and gas flow rate, whereas variations in converging angle have minimal impact. Diverging angle significantly affects pressure behavior: larger divergence angles lead to greater pressure drops from flow separation and vortices, while smaller angles improve pressure recovery and reduce pressure loss. Enlarging geometric dimensions by 30% decreases pressure drop by 65.5% and lowers throat velocity by 40.9%, indicating potential energy savings at the cost of reduced mixing intensity.

1. Introduction

The venturi scrubber is a highly efficient and widely utilized device in air pollution control, designed to separate suspended particles and pollutant gases from gas streams. It functions by establishing effective contact between the polluted gas and a washing liquid, typically water, leveraging the venturi effect as its fundamental operating principle [1].

A key advantage of Venturi scrubbers is their superior removal efficiency for particles smaller than one micron, which is crucial in industries such as metallurgy, chemical processing, thermal power generation, and combustion. Furthermore, their ability to simultaneously capture both particulate and gaseous pollutants offers a distinct edge over many conventional pollution control methods [2]. However, a notable limitation is the relatively high pressure drop associated with their operation, which increases the energy demand for fans. Fine particle presence is a significant concern in many industrial settings due to its potential harm to industrial processes and human health. In the textile industry, for instance, fiber dust poses serious health risks to workers [3].

Wet scrubbers provide a viable alternative to dry filters or cyclones, which are often the primary choice for particle removal. The collection efficiency of wet scrubbers depends on the particle size distribution in the gas stream, generally decreasing as particle size diminishes. Consequently, achieving higher

* **Corresponding author.**
E-mail address: nourbakhsh@basu.ac.ir

Cite this article as:

Nourbakhsh, A. and Parsa, M., 2025. Numerical Study of Fluid Flow in Venturi Scrubbers. *Journal of Microfluidic and Nanofluidic Research*, 2(2), pp. 114-119. https://doi.org/10.22034/jmnr.2025.15490.1017

collection efficiency requires increased electrical energy input, which rises as particle diameter decreases. Among wet particle collectors, Venturi scrubbers stand out for their efficiency, incorporating atomization mechanisms and collision-prevention strategies to control the emission of particulate and gaseous pollutants into the atmosphere [4].

Venturi scrubbers have a history of over 50 years, initially developed for agricultural applications such as corn collection, but now predominantly used in industrial plants for particulate removal from gas streams. Extensive research has been conducted to model and optimize their performance. Advantages of these scrubbers include high efficiency for relatively small particles, low capital costs, and the capability to handle wet and corrosive gases. The main drawback remains their high operational cost due to the significant pressure drop, leading to increased power consumption. Proper Venturi scrubber design must balance particle collection efficiency against pressure drop. Structurally, these scrubbers consist of a converging section, a narrow throat area, and a diverging section, where gas velocity and turbulence increase in the converging region. Despite their established use and extensive performance studies across various industries, the continuous evolution in applications justifies ongoing research into their operational parameters, such as particle removal efficiency and pressure drop [5].

Recent investigations have examined their use in nuclear power plants for iodine removal, including experimental studies on contaminant particle removal, absorption efficiency modeling, and CFD simulations that align closely with experimental data. Innovations include new Venturi scrubber designs aimed at improving desulfurization by integrating shaped bodies within rectangular ducts, mimicking parallel Venturi scrubbers for enhanced dust and sulfur oxide removal. The rising industrial pollution in the chemical, mining, and energy sectors over recent decades has underscored the importance of effective air pollution control equipment like Venturi scrubbers. These devices operate by generating a pressure drop that induces intense collisions between gas and scrubbing liquid, efficiently removing suspended particles and pollutant gases [6].

The use of venturi scrubbers dates back to the 1950s, initially applied in mining and chemical industries for fine particle and dissolved gas removal.

Early research (1950–1970) focused on fundamental fluid mechanics and thermodynamics principles, with pioneers like Calvert and Leith providing basic models that linked Venturi throat size, gas velocity, and washing liquid flow rate to particle removal efficiency [7].

From 1970 to 2000, advancements were driven by mathematical modeling and simulation tools, alongside high-speed imaging that enhanced understanding of liquid atomization in the Venturi throat. These studies demonstrated that increasing relative gas-liquid velocity improves particle capture.

Since 2000, research has prioritized optimizing energy usage, enhancing pollutant removal efficiency, and minimizing pressure drop. Innovations include the use of nanofluids, bio-based scrubbing liquids, and CFD analyses for design improvements. For example, Zhao et al. [8] showed through CFD that adjusting the liquid inlet angle boosts efficiency by up to 15%. Studies on acid gas removal, such as SO2 and NH_3, confirm that well-designed Venturi scrubbers can simultaneously remove particles and gases. The evolution of Venturi scrubber technology reflects a progression from basic designs to sophisticated, optimized systems addressing growing demands for efficient, low-energy pollution control.

In this paper, five 3D Venturi scrubber geometries were designed and simulated using Ansys Fluent to examine internal flow behavior. Air is modeled as an incompressible gas under steady-state, turbulent conditions with Reynolds numbers at the Venturi inlet between 1.37×10^5 and 2.81×10^5, using the Spalart-Allmaras turbulence model. Heat transfer between the gas and the walls was neglected. The present paper aims to investigate two aspects: (1) the impact of varying gas mass flow rate at the venturi inlet on pressure drop and velocity, and (2) the influence of geometric changes (dimensions and angles) on pressure drop and velocity at a constant mass flow rate. Simulations were performed on five venturi meters (Fig. 1) with a mass flow rate of 0.736 kg/s, alongside studies at different mass flow rates (0.483, 0.736, 0.861, and 0.987 kg/s) for a v175 venturi scrubber. Flow data are extracted from seven sections (P_1 to P_7) for graphical analysis. For each case, pressure, velocity, turbulent viscosity contours, and performance graphs are generated and compared to understand the effects of flow rate and geometry on the venturi scrubber's hydraulic behavior. The dimensions of Venturi V175 are as follows: d_1 = 250 mm, d_2 = 122.5 mm, l_1 = 212.6 mm, l_2 = 300 mm, l_3 = 742.95 mm, $\alpha_1 = 17^0$, and $\alpha_2 = 5^0$. The dimensions of Venturi V55 are as follows: d_1 = 250 mm, d_2 = 122.5 mm, l_1 = 742.5 mm, l_2 = 300 mm, l_3 = 742.95 mm, $\alpha_1 = 5^0$, and $\alpha_2 = 5^0$.

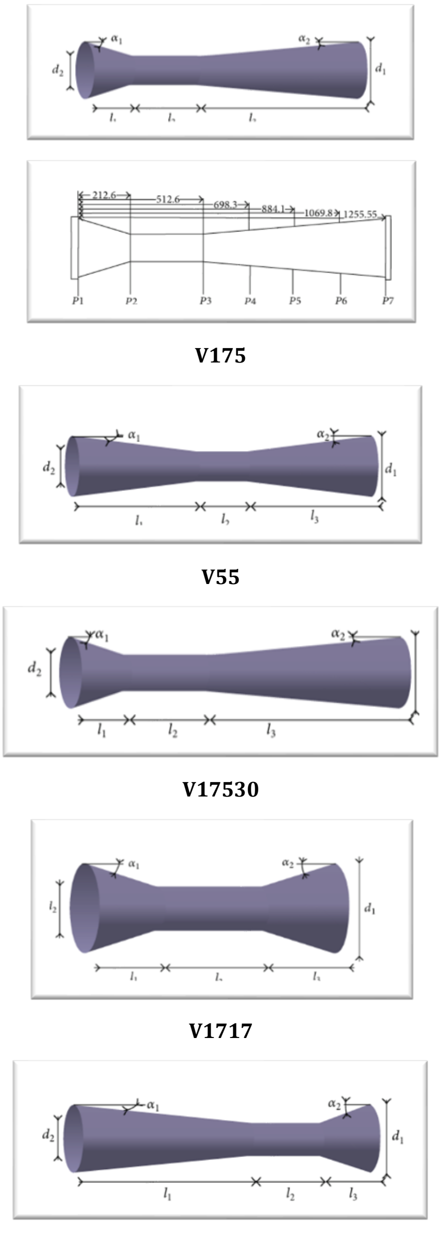

Fig. 1. Schematic of venturi scrubbers.

The dimensions of Venturi V17530 are as follows: d_1 = 325 mm, d_2 = 159.25 mm, l_1 = 276.4 mm, l_2 = 390 mm, l_3 = 965.8 mm, $\alpha_1 = 17^0$, and $\alpha_2 = 5^0$. The dimensions of Venturi V1717 are as follows: d_1 = 250 mm, d_2 = 122.5 mm, l_1 = 212.6 mm, l_2 = 300 mm, l_3 = 212.6 mm, $\alpha_1 = 17^0$, and $\alpha_2 = 17^0$. The dimensions of Venturi V517 are as follows: d_1 = 250 mm, d_2 = 122.5 mm, l_1 = 742.5 mm, l_2 = 300 mm, l_3 = 212.6 mm, $\alpha_1 = 5^0$, and $\alpha_2 = 17^0$.

2. Governing Equations

The governing equations include the mass conservation equation:

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0 \quad (1)$$

Momentum equation:

$$\rho\left(\frac{\partial \boldsymbol{V}}{\partial t} + \boldsymbol{V} \cdot \nabla \boldsymbol{V}\right) = -\nabla p + \mu \nabla^2 \boldsymbol{V} + \rho \boldsymbol{g} \quad (2)$$

Here, $\boldsymbol{V}$ is the velocity vector, p is pressure, μ is dynamic viscosity, and ρ is the density.

3. Results

Figs. 2 and 3 illustrate the variations of pressure and velocity with mass flow rate for ventory V55. Increasing the gas mass flow rate leads to an increase in total pressure drop, but this increase is "non-linear"; that is, as the flow rate increases, the growth of the pressure drop decreases (the recovery efficiency in the diverging section increases, and a larger portion of the energy is recovered). The maximum fluid velocity in all cases was located in the throat area, and changing the converging/diverging angles did not have a significant impact on the maximum velocity value. This indicates that geometric parameters such as the ratio of inlet diameter to throat diameter and gas flow rate are determining factors for maximum velocity. The longitudinal pressure distribution showed that a significant portion of the pressure drop generated in the convergent section and throat (a portion of the energy) is recovered in the divergent section; in other words, pressure recovery in the divergent section plays a key role in the net pressure drop.

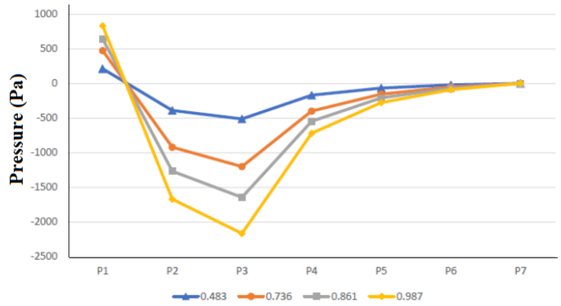

Fig. 2. Pressure changes along venturi V175 for different mass flow rates.

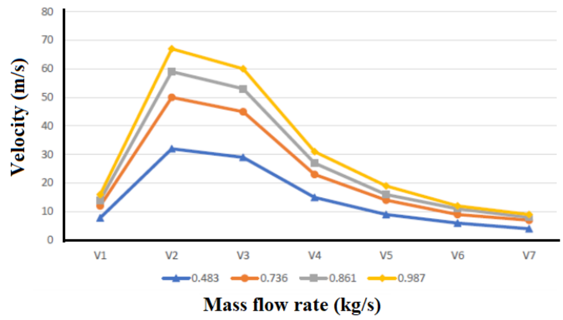

Fig. 3. Velocity distribution along venturi V175 for different mass flow rates.

Figs. 4 and 5 depict the cariation of pressure and velocity along various venturies. The impact of each section is analayzed af follows. Figs. 6 and 7 show the changes in pressure and velocity contours for various venturies.

Convergent Angle: Changing the convergent angle had no significant effect on the overall pressure drop or maximum velocity. The reason for this is that the final velocity at the throat is more dependent on the throat cross-section and the gas flow rate, rather than the converging angle. Therefore, geometries with different convergence angles showed very similar pressure drop results. Divergence angle: The divergence angle had a much greater impact on flow behavior. Geometries with a large divergence angle (such as v517 and v1717) produced a higher overall pressure drop because flow separation and vortices occur in the divergence, reducing pressure recovery. In contrast, geometries with a small divergence angle (like v55) had lower pressure drops because the flow was more stable and pressure recovery was better. Dimensions: Geometry v17530 is the same as v175, but all its dimensions are 30% larger. The overall pressure drop was reduced by approximately 65.5%. The maximum velocity at the throat decreased by approximately 40.9%. Due to the increase in cross-sectional area (proportional to the square of the length), the flow velocity decreased for a constant flow rate. This result is important because it shows that increasing the geometry reduces energy costs (fan power), but on the other hand, mixing intensity and particle removal efficiency may decrease. In this project, by simulating five different venturis with the same mass flow rate, it was observed that all tested geometries behave the same regardless of the divergence angle, and the lowest value of gage pressure is observed in the throat section. Additionally, geometries with the same divergence angle exhibit very similar pressure values. Therefore, it can be said that divergent angle values have a greater impact on the scrubber pressure behavior compared to convergent angle values.

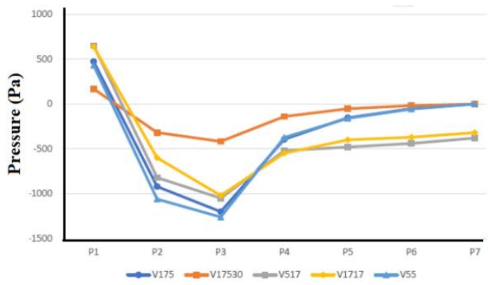

Fig. 4. Pressure changes along different venturies for a mass flow rate of 0.736 kg/s.

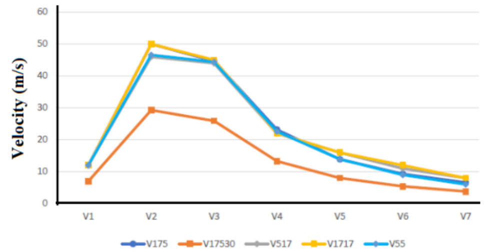

Fig. 5. Velocity distribution along different venturies for a mass flow rate of 0.736 kg/s.

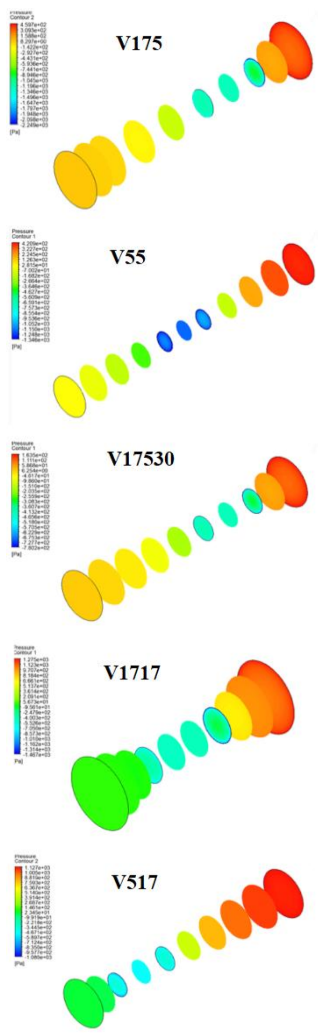

Fig. 6. Pressure contours along different venturies.

As expected, the contours show that the fluid velocity increases as the fluid passes through the converging section and reaches its maximum value at the throat. As the gas exits the throat section, the velocity decreases as the fluid passes through the diverging section of the Venturi.

The divergence angle has a very significant impact on the values of total pressure and pressure drop. Geometric configurations with the same divergence angle values have similar total pressure drop values. Also, increasing the length of different sections and the diameter values by up to 30% reduces the pressure drop by 65.5%.

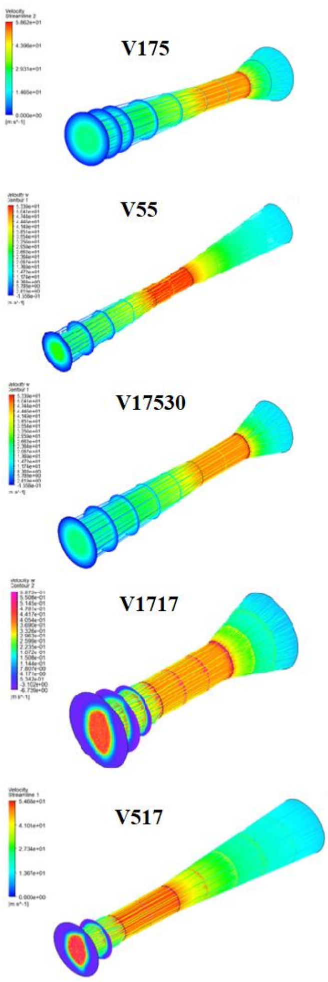

Fig. 7. Velocity contours along different venturies.

It can also be observed that as the divergence angle increases, the total pressure drop also increases. The highest total pressure drop (1010.6 Pascals) was obtained with the v517 geometry. However, only 21.12% of this pressure drop occurs in the bottleneck section. Although the v55 geometry has the lowest total pressure drop (429.7 Pascals), the pressure drop in the throat section alone accounts for 36.67% of the total. Therefore, 63.33% of the total pressure drop occurs in the converging and diverging sections. It is required that we have the maximum possible pressure drop in the throat section while minimizing the total possible pressure drop, as it is in the throat section that phase mixing occurs. Considering this, the best performance is found in geometry v175 because the pressure drop in its bottleneck section represents 42.31% of the total pressure drop.

4. Conclusions

The present study elucidates how gas mass flow rate and Venturi scrubber geometry intricately influence pressure drop and velocity profiles within the device. Increasing the gas flow rate leads to a nonlinear increase in total pressure drop, as a larger portion of the pressure is recovered in the divergent section. The maximum fluid velocity consistently occurs at the throat, primarily determined by throat diameter and flow rate. While variations in the converging angle have a negligible impact on pressure drop and velocity, the diverging angle exerts a pronounced effect, with larger angles causing higher pressure drops due to flow separation and vortex formation, thereby reducing pressure recovery efficiency. Enlarging all geometrical dimensions by 30% significantly reduces pressure drop and throat velocity, offering energy savings but potentially diminishing mixing performance critical for pollutant capture. A key design criterion identified is optimizing the partitioning of pressure drop to maximize it in the throat section, where effective gas-liquid mixing and particle collection predominantly occur, while minimizing losses in converging and diverging sections. Among the simulated geometries, V175 best met this criterion, with over 42% of the pressure drop concentrated in the throat, coupled with moderate total pressure loss.

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