Research on Numerical Simulation and Structural Optimization of Dual-Throat Venturi Fertilizer Injectors

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Abstract: Fertilization equipment is a crucial component of irrigation systems, and its performance directly impacts irrigation quality. To address the issues of low suction flow and excessive head loss in existing Venturi fertilizer injectors, the team employed numerical simulation techniques. Through single-factor experiments, we analyzed the effect of the suction pipe angle of the dual-throat Venturi fertilizer injector on its suction performance, ultimately determining the optimal structural parameter combination for the injector. The study utilized software such as Tecplot and CFD to analyze the influence of various structural parameters on the internal pressure, turbulent kinetic energy, and vortex distribution within the dual-throat Venturi fertilizer injector, examining the patterns of internal flow field variations. The angle of the suction pipe significantly affects suction performance; adjusting the suction pipe to the optimal angle helps reduce turbulent kinetic energy at the throat, increase negative pressure, and decrease both the area and intensity of vortices. This, in turn, minimizes the intensity of multidirectional velocity collisions and the head loss caused by vortices, leading to a substantial enhancement in both suction and hydraulic performance.

1 Introduction

Fertilizers play a crucial role in modern agricultural production, serving as a fundamental resource that significantly impacts food production. The efficient utilization of water and fertilizers is a pressing issue that needs to be addressed. Integrated water and fertilizer management[1] has opened new avenues for optimizing their use. Commonly available integrated water and fertilizer equipment on the market includes Venturi tubes, pressure differential fertilization tanks, and mixing tanks. Among these, the Venturi fertilizer injector is widely utilized in agricultural irrigation due to its simple structure, ease of use, affordability, and the absence of the need for external power sources.[2, 3] Traditional Venturi injectors typically feature an asymmetric single-throat design; however, this structure often leads to excessive energy loss and low fertilizer absorption efficiency. Therefore, this paper focuses on the study of a dual-throat Venturi fertilizer injector,[4] analyzing the impact of the angle of the absorption tube on its structural performance through model experiments. This research is significant for enhancing water and fertilizer utilization efficiency and improving crop quality and yield.

2 Introduction to the Experimental Apparatus

The Venturi fertilizer injector is an agricultural irrigation device designed based on the Venturi principle. It primarily consists of a converging section, throat, diverging section, fertilizer suction tube, and inlet and outlet straight pipe segments. Water flows from the inlet straight pipe segment into the device, passing through the converging section where the flow path narrows, resulting in an increase in flow velocity and a gradual decrease in pressure. At the throat, the cross-sectional area reaches its minimum, creating a negative pressure that allows the fertilizer solution to be drawn into the suction tube under atmospheric pressure. The fertilizer solution then mixes with the water flow in the throat and diverging section. Key structural parameters include the convergence angle, divergence angle, throat diameter, orientation of the suction tube, structural form of the diverging section, and the position of the central axis.[5] However, traditional Venturi fertilizer injectors exhibit significant turbulent kinetic energy at the throat, and there are pronounced and intense vortices generated in the diffuser section. These vortices can lead to friction between flow layers, increasing localized head loss.[6] Based on this, Hu Ronggui proposed a dual-path coupling optimization approach, utilizing slight counteraction to eliminate or reduce the vortices in the dispersion section, resulting in a dual-throat Venturi fertilizer injector. This study aims to conduct an in-depth investigation based on this foundation, employing numerical simulation techniques to analyze the impact of the angle of the suction pipe in the dual-throat Venturi fertilizer injector on fertilization performance, with the objective of maximizing suction efficiency and determining the optimal structural parameter combination for the dual-throat Venturi fertilizer injector.[4]

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3 Numerical simulation and structural design of two parameters

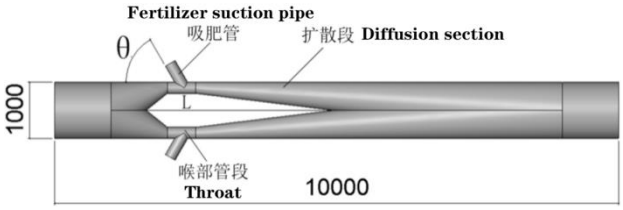

Figure 1: Dual-throat Venturi Fertilizer Injector.

Figure 1 shows the structural schematic diagram of the double-throat Venturi fertilizer applicator. In this study, the numerical simulation model was constructed using Revit, while the three-dimensional numerical analysis was conducted with Fluent software. This research focuses on the structural optimization of a dual-throat Venturi injector, emphasizing the enhancement of suction efficiency and identifying the optimal structural parameter combinations for the dual-throat Venturi fertilization device. In the experimental design, our team analyzed the effects of varying the suction pipe angle θ, setting multiple control groups for each configuration to investigate internal pressure, turbulent kinetic energy, and vortex distribution.

4 Analysis of the impact of three single-factor structural parameters

This experiment focuses on the angle of the suction pipe as the sole variable, establishing multiple control trials to investigate how variations in the suction pipe angle affect nutrient absorption efficiency. To enhance the reliability of the experimental results and eliminate the influence of random factors, this study designed three groups with different flow rate levels for testing, ensuring the accuracy and scientific validity of the experimental data.

4.1 Distribution of Turbulent Kinetic Energy

The magnitude and distribution of turbulent kinetic energy reflect the flow state of the fluid; a greater turbulent kinetic energy indicates a more complex flow regime, characterized by intense collisions between flow layers, frequent multi-directional velocity interactions, and significant head loss.

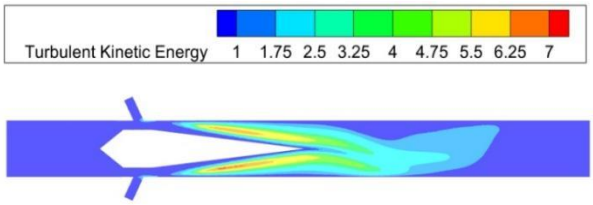

Figure 2: Turbulent kinetic energy distribution cloud diagram of the dual-throat Venturi fertilizer injector (θ=63°, v=1m/s).

As illustrated in Figure 2, the turbulent kinetic energy within the Venturi fertilizer injector begins to increase at the throat and exhibits a banded distribution at the diffuser end. The peak turbulent kinetic energy is observed at the intersection of the throat and the suction pipe's rear end, as well as at the front section of the diffuser. This indicates that the flow conditions in this region are the most complex, resulting in the highest localized head loss, primarily because the front section of the diffuser serves as the main area for the mixing of water and fertilizer.

With the objective of reducing turbulent kinetic energy and minimizing head loss, Figure 3 reveals that under varying inlet flow velocities, the trend of turbulent kinetic energy at the throat remains similar. Specifically, as the angle of the suction pipe increases, there is a noticeable decline in turbulent kinetic energy. At an angle of 42°, the model with a flow rate of 0.5 m/s exhibits the minimum turbulent kinetic energy of 1.38 m²/s²; at 48°, the model with a flow rate of 0.8 m/s reaches a minimum of 3.78 m²/s²; and at 60°, the model with a flow rate of 1 m/s shows a minimum of 5.59 m²/s². Beyond the optimal angle, there is a rising trend in turbulent kinetic energy. This phenomenon can be attributed to the increased collision intensity between the two streams of water as the angle of the suction pipe increases, along with heightened wall collisions, leading to a significant rise in localized head loss and a decrease in energy conversion efficiency.

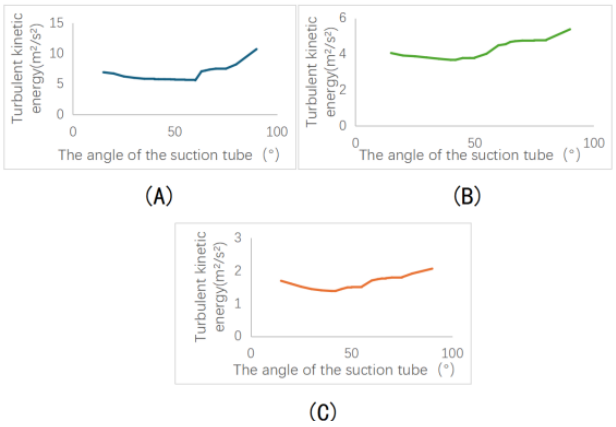

Figure 3: Comparison of turbulent kinetic energy in dual-throat Venturi fertilizer injectors under varying flow rates. Models (A), (B), and (C) correspond to flow velocities of 1 m/s, 0.8 m/s, and 0.5 m/s.

4.2 Distribution of stress fields

The pressure distribution along the central axis has been extracted. As illustrated in Figure 4, The pressure gradient at the throat is the most obvious. As the pressure difference between the inlet and outlet increases, the fertilizer - suction flow rate gradually increases until critical cavitation is reached.[7, 8] The pressure reaches its minimum at the throat, after which it begins to increase, with the maximum negative pressure occurring at the rear end where the throat intersects with the suction pipe. This phenomenon is attributed to the mixing of the water flow in the throat with that in the suction pipe, leading to a complex flow state and significant local head loss [4].

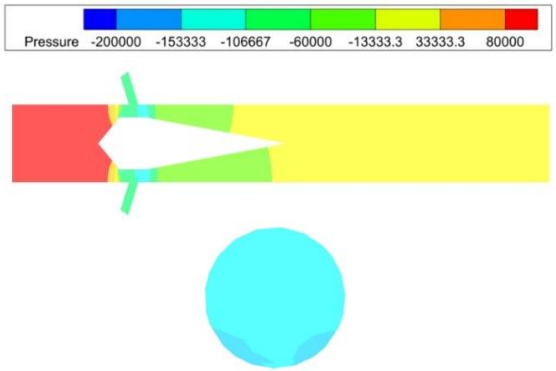

Figure 4: Pressure field distribution cloud map of a dual-throat Venturi fertilizer injector (θ=63°, v=1m/s).

Figure 5 indicates that negative pressure is primarily concentrated on the side adjacent to the suction pipe, while the pressure values on the side further away from the suction pipe are higher. Taking the section at the lower throat of the Venturi suction pipe, positioned at an angle of 63°, as an example, the negative pressure near the suction pipe is measured at 180 kPa, whereas the negative pressure on the side further from the suction pipe is 110 kPa. This discrepancy arises because the structure on the side of the double-throat Venturi fertilizer applicator that is distant from the suction pipe is more stable, resulting in lower collision intensity between flow layers. In contrast, the side closer to the suction pipe experiences rapid flow direction changes and greater head loss. This also indicates a higher utilization rate of negative pressure in the throat of the double-throat Venturi fertilizer applicator.

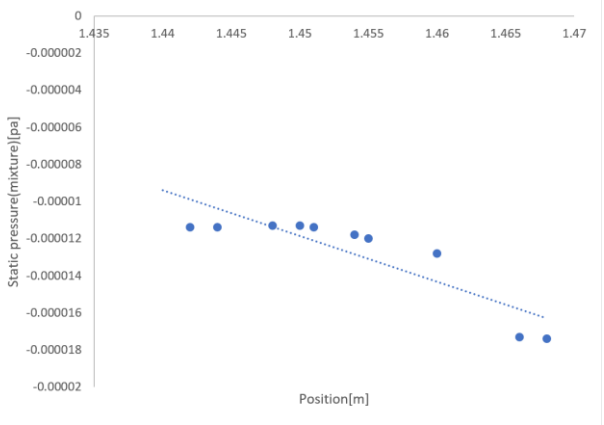

Figure 5: Cross-sectional pressure diagram of a dual-throat Venturi fertilizer injector at the throat (θ=63°, v=1m/s).

Upon comparing the negative pressure at the throat under three different flow velocity levels (Figure 6), it can be observed that as the angle of the fertilizer suction pipe increases, the negative pressure initially increases and then decreases. When the angle is set at 48°, the model with a flow rate of 0.5 m/s reaches a maximum negative pressure of 86.9 kPa. At an angle of 55°, the model with a flow rate of 0.8 m/s achieves a peak negative pressure of 221 kPa. Finally, at an angle of 65°, the model with a flow rate of 0.5 m/s attains a maximum negative pressure of 340 kPa. This phenomenon can be attributed to the fact that before reaching the optimal angle, the flow rate at the throat increases with the angle of the suction pipe, leading to an increase in negative pressure as described by Bernoulli's equation. However, beyond the optimal angle, the flow rate gradually decreases, resulting in a reduction of negative pressure at the throat.

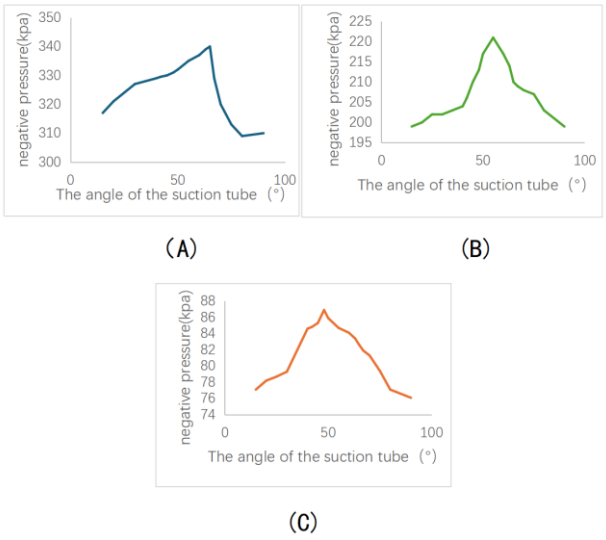

Figure 6: Comparison of maximum negative pressure in dual throat Venturi fertilizer injectors under varying flow rates. Models (A), (B), and (C) correspond to flow velocities of 1 m/s, 0.8 m/s, and 0.5 m/s.

4.3 Vortex distribution

The area and intensity of vortices within the Venturi suction pipe significantly affect suction efficiency. An increase in the area and intensity of these vortices leads to greater energy loss and reduced energy conversion efficiency. This study analyzes the impact of varying the angle of the suction pipe on the internal vortices of the suction device under a flow rate of 1 m/s.

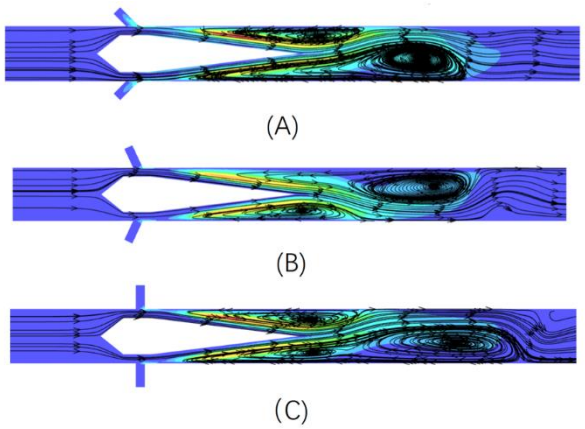

Figure 7: Comparison of Flow Lines in a Double-Throat Venturi Fertilizer Injector at Different Fertilizer Suction Angles. (A), (B), and (C) correspond to models with angles of 45°, 60°, and 90°.

As shown in Figure 7, when the angle of the fertilizer suction pipe is 45°, there are obvious and vigorous vortices present in the diffusion section of the fertilizer

sucker. As the angle increases to 60°, the influence of the vortices in the diffuser section diminishes, and their intensity decreases. When the angle is further increased to 90°, the range of vortex influence significantly expands. Thus, it is evident that the angle of the suction pipe greatly affects the vortices in the diffuser section of the suction device. Selecting the optimal angle for the suction pipe can help minimize the range of vortex influence and reduce vortex intensity.

5 Conclusions

To enhance the suction performance of a Venturi fertilizer injector, this study employs numerical simulation techniques. It uses a dual-throat Venturi injector as the research basis. By analyzing the impact of the suction pipe angle on the internal flow field of the dual-throat Venturi injector, we propose an optimized structural design. This design yields the optimal structural parameters for the dual-throat Venturi injector. We compare various dual-throat Venturi injectors with different parameters to validate the feasibility of structural design and suction performance optimization. The main conclusions are as follows:

1. At the same flow rate, the suction pipe angle does not correlate positively with the negative pressure and turbulent kinetic energy at the throat. As the suction pipe angle increases, the negative pressure at the throat first increases and then decreases, while the turbulent kinetic energy first decreases and then increases. The range and intensity of vortices in the diffusion section also show a trend of first decreasing and then increasing. This indicates that selecting an appropriate suction pipe angle is more beneficial for enhancing suction performance.

2. At different flow rates, the optimal suction pipe angle increases with the flow rate. At a flow rate of 0.5 m/s, the optimal angle is 48°; at 0.8 m/s, it is 55°; and at 1 m/s, it is 65°. Furthermore, the variations in negative pressure, turbulent kinetic energy, and vortex distribution exhibit similar patterns across different flow rates, thereby eliminating experimental randomness and enhancing the reliability of the tests.

6 Prospects

Current research on Venturi fertilizer injectors primarily focuses on symmetric designs, while studies on asymmetric injectors and other structural forms remain limited. Due to constraints related to undergraduate studies and personal capacity, this paper acknowledges certain shortcomings in the research process. Future investigations could delve deeper into the following areas:

1. The low utilization of throat negative pressure contributes to the limited suction performance of Venturi injectors. Therefore, future studies may explore modifications to the throat structure, designing it for omnidirectional suction or alternative configurations to enhance the suction efficiency of Venturi injectors.

2. Vortices significantly impact the suction performance of Venturi injectors. This paper has only examined a few parameter variations affecting vortex formation within the Venturi tube. Subsequent research could consider additional methods to reduce vortex area and intensity or increase the distance between the vortex and the throat. For instance, incorporating guide plates in the diffusion section could mitigate head loss caused by the collision of two water flows in that region.

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