Detection of Cavitation in a Venturi Injector With a Combined Method of Strain Gauges and Numerical Simulation

The fertilizer suction capability of a Venturi injector is dependent on the vacuum pressure in the throat portion. As the vacuum level drops below the saturation vapor pressure, the pressure decreases to a particular value corresponding to the maximum pressure difference ($\Delta p_{\text{max}}$) between inlet and outlet pressures, and critical cavitation is likely to occur, leading to an unstable suction flow rate and low fertilization uniformity. A new method of using strain gauges to detect cavitation in Venturi injectors was explored experimentally and verified numerically under various operating conditions. The standard deviation (SD) of the measured strain values and the simulated values of the vapor-phase volume fraction ($V_r$) were used to evaluate the influence of cavitation. The results showed that both the rate of increase ($\eta_r$) of the average SD and the average growth rate (AGR) of the simulated cavitation length reach relatively large values at the maximum pressure difference ($\Delta p_{\text{max}}$), where the measured suction flow rate simultaneously reaches a maximum. In addition, SD and $V_r$ shared similar variation trends at pressure differences larger than the corresponding $\Delta p_{\text{max}}$ under various conditions. This new cavitation detection method has been proved to be feasible and reliable. It helps to determine accurately the value of $\Delta p_{\text{max}}$ at different inlet pressures and to ensure that the Venturi injector runs in a safe operating-pressure range. [DOI: 10.1115/1.4026879]

Keywords: Venturi injector, cavitation, detection, strain gauge, numerical simulation

1 Introduction

With the growing shortage of water resources and increasing investment in agricultural infrastructure, high-efficiency water-saving irrigation technology has become very popular in China. According to the statistical bulletins of the Chinese government [1], the national area under water-saving irrigation has increased from 16.0 to 28.7 million hectares during the period from 2000 to 2011. Because fertilization technology in drip irrigation systems has enabled high yield, quality, and efficiency in crop production [2], the application area of this technology had increased to 2 million hectares by the end of 2011 in China. Among all kinds of fertilizer injection devices, the Venturi injector has been widely used in drip irrigation systems due to its distinct advantages of simple structure, convenient operation, and not needing an extra power supply [2, 3].

Unlike the well-known Venturi tube, the Venturi injector has a suction orifice in its throat portion that is connected to a fertilizer solution tank by a flexible pipe. The suction capability for fertilizer solution was found to be dependent on the pressure and vacuum level in the throat portion of the Venturi injector. The suction flow rate increases with increasing inlet pressure ($p_1$) and increasing difference between inlet and outlet pressure ($\Delta p$) [4]. In practice, a minimum pressure difference ($\Delta p_{\text{min}}$) is required to initiate suction at a given inlet pressure. However, as the vacuum level reaches a certain value below the saturated vapor pressure, critical cavitation may occur, which dramatically affects the internal flow patterns in the Venturi injector [5]. Abrasion caused by critical cavitation in the minimum-diameter point of the Venturi injector throat could lead to reduction of the suction flow rate for given operating conditions and eventually affect fertilization uniformity and drip-irrigation system efficiency. Therefore, a Venturi injector should function within an appropriate operating-pressure range to prevent critical cavitation. Predicting and detecting the occurrence of critical cavitation therefore becomes an important issue in Venturi injector design and operation.

Recently, researchers have studied cavitation in Venturi injectors and its relationship to injection characteristics and structural parameters. Jing et al. [6] found that when the flow-rate ratio (ratio of suction flow rate to outlet flow rate) was greater than 10%, cavitation initially occurred in the Venturi injector and the corresponding pressure ratio (ratio of inlet pressure to outlet pressure) decreased rapidly. Yan et al. [7] found that if the flow-rate ratio exceeded a certain value, the injection capacity appeared to become unstable and even to decrease. Barre et al. [8] studied Venturi tubes with diffusion angles of 4 deg and 8 deg and found that cavitation varied periodically for a diffusion angle of 8 deg and occurred with small fluctuations for a diffusion angle of 4 deg. Ardiansyah et al. [9] reported that cavitation accelerated abrasion on the internal surface of a Venturi tube. In fluid engineering, several methods are used for cavitation detection, including photographic methods, coating corrosion, static-pressure measurement, and vibration measurement [10]. Cudina et al. [11] used noise changes to analyze cavitation initiation in pumps. They found a strong correlation between the length of discrete noise within the audible wavelength and cavitation development. Pu et al. [12] and Liu et al. [13] explored a method based on wavelet entropy for cavitation initiation monitoring and status identification. Al-Hashmi [14] used both noise signals and
vibration signals recorded by an accelerometer to analyze cavitating flow in centrifugal pumps. In his study, SD and probability density distribution were calculated to analyze the vibration signal. Yazici et al. [15] used high-speed cinematography and particle-image velocimetry (PIV) techniques to demonstrate bubble shedding and cavitation processes in a transparent Venturi tube. However, few studies on cavitation detection in Venturi injectors are available in the recent literature. For Venturi injectors made of nontransparent plastics, it is impossible to observe internal flow using imaging and PIV techniques. It is also difficult to use vibration measurement because it is impractical to put an accelerometer sensor on a Venturi injector. In addition, cavitation detection in Venturi injectors using acoustic techniques may be disturbed by ambient noise, leading to inaccurate results [10].

During the short period of initiation, increase, and collapse of cavitation bubbles, the induced energy transformation can impact the internal surface of a Venturi injector and lead to body deformation caused mainly by imposed bending moment. Bending-moment variation can be accurately measured with strain gauges that are directly attached onto the external surface of an object for detection without any damage to object structures. The bending-moment variation can reflect the influence of cavitation on the body [16–18]. Hence, a new method of cavitation detection in Venturi injectors using strain gauges was initially proposed in the present study. In addition, numerical simulation using the FLUENT software was also carried out under the same experimental conditions to verify to a certain extent the measurement accuracy of this new detection method because other available direct-detection methods could not be used in this situation. Although few papers have been found on numerical simulation of cavitation in Venturi injectors, a certain number of publications related to similar fluid instruments (e.g., Venturi nozzles, inducers, tubes, and so forth) are available [19–23]. These scientific findings can help to develop a numerical simulation of cavitation in a Venturi injector.

The main objectives of this study were: (1) to explore and test a new method for cavitation detection in Venturi injectors based on strain gauges and (2) to verify this new method through numerical simulation using the FLUENT software. This study provides a simple way to determine accurately the maximum pressure value \( \Delta p_{\text{max}} \) which corresponds to critical cavitation in a Venturi injector.

2 Materials and Methods

2.1 Structure of a Venturi Injector. The Venturi injector (Fig. 1) studied here had an inlet diameter of 15.6 mm, an outlet diameter of 22 mm, and a minimum diameter of 4 mm in the throat-constriction portion. It was made of acrylonitrile butadiene styrene (ABS) plastic, with wall thicknesses of 3.0 mm at the throat portion and 7.8 mm at the diffusion portion, which is a little thicker than products currently on the market.

2.2 Cavitation Detection Based on Strain Gauges

2.2.1 Experiment Setup and Procedures. The experiment was conducted at the College of Water Resources and Civil Engineering, China Agricultural University. The Venturi injector was installed horizontally (Fig. 2). All connected pipes were made of unplasticized polyvinyl chloride (UPVC). The inner diameter of the main pipes was 36 mm. The inner upstream and downstream diameters of the Venturi injector were 21 mm and 28 mm, respectively. A flexible 8-mm-diameter pipe, through which the fertilizer solution could be injected, was connected to the suction orifice. Two turbine flow meters (types LWGY-15 and LWGY-25; components 4 and 8 in Fig. 2) were installed on the upstream and downstream pipes to measure inlet and outlet flow rates. The suction flow rate \( Q_s \) was calculated by subtracting the inlet flow rate \( Q_i \) from the outlet flow rate \( Q_o \). Two pressure gauges (components 5 and 7 in Fig. 2) were installed to control inlet and outlet pressures in the Venturi injector. Clean water was used to replace fertilizer solution in the supply tank during the test. The vertical distance between the axis line of the Venturi injector and the water level in the supply tank was maintained at 350 ± 10 mm during the whole experiment using a water supply pipe with a continuous water supply.

Two pairs of strain gauges were attached to the external surfaces of the throat and the diffusion portion of the Venturi injector. Each pair was symmetric to the axis line of the Venturi injector and was connected to a dynamic strain indicator by a half-bridge (Fig. 1). The X-axis of the coordinate system coincided with the center line of the injector inlet and outlet, while the Y-axis coincided with the center line of the suction orifice. Dynamic strain indicators were used to measure strain values in the throat and diffusion portions simultaneously. The variations in the strain signals were expected to reflect changes in the internal flow inside the Venturi injector.

Various experimental scenarios were implemented by adjusting the valves in the experimental system. According to actual operating conditions, inlet pressure was set to 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, and 0.45 MPa. While keeping inlet pressure at a given constant value, outlet pressure was gradually decreased from the suction-initiation outlet pressure by steps of 0.025 MPa to create the required pressure difference. According to the authors’ experience, when a rapidly rising noise was heard, critical cavitation was assumed to be occurring. Then the pressure decrement was adjusted to 0.01 MPa to achieve more informative and accurate detection. In each scenario, two 1000-Hz channels in the dynamic strain indicator were used to record the strain signals for at least 20 s.

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Fig. 1 Internal structure of the Venturi injector with strain gauges attached to its surface. Dimensions in millimeters (mm).

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2.2.2 Statistical Indicators. Strain values over a period of 20 s, or 20,000 values for each channel, were obtained for each scenario. The standard deviation of the 20,000 values was calculated using the following formula:

\[
SD = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (e_i - \bar{e})^2}
\]

where \( e_i \) is the \( i \)th strain value in the 20-s period, \( \bar{e} \) is the average value of all strain values in the 20-s period and SD. As an eigenvalue of these 20,000 strain values, the value of SD reflects the degree of deformation in the throat and diffusion portions.

The rate of increase (\( \eta_m \)) of the average SD was calculated as follows:

\[
\eta_m = \frac{SD_m - \frac{1}{m} \sum_{j=1}^{m-1} SD_j}{\frac{1}{m} \sum_{j=1}^{m-1} SD_j} \times 100\%
\]

where \( SD_1 \) is the first SD value measured for each inlet pressure which corresponds to suction initiation; \( SD_j \) is the value of SD in...
constants were three cavitation models: the Schnerr and Sauer model [25], the two models after the same number of iterations. Therefore, the standard k-ε model was used in this study. The relevant simulation constants were $C_{1k} = 1.44$, $C_{2k} = 1.92$, $C_{mu} = 0.09$, $\sigma_k = 1.0$, $\sigma_r = 1.3$ [24].

2.3.2 Cavitation Model. The FLUENT software module offers three cavitation models: the Schnerr and Sauer model [25], the Singhal model [26], and the Zwart–Gerber–Belamri model [27]. The Schnerr and Sauer model has been used for cavitation simulation of Laval and injection nozzles, which are structurally similar to Venturi injectors, and obtained good simulation results [28,29]. Therefore, this model was used in this study. This model includes an exact expression of net mass transfer from liquid to vapor. The only parameter that needs to be determined is the number of spherical bubbles per volume of liquid. In the simulation, liquid water was set as the first phase and water vapor as the second. It was assumed that there was no heat transformation, mass transfer, or slide between these two phases. The vaporization pressure constant was 3540 Pa, and the bubble density was 10$^{15}$.

2.3.3 Computational Mesh. Geometric modeling and mesh generation for the internal computation domain of the Venturi injector were conducted using the Gambit software. The domain was separated into three portions: constriction, throat, and diffusion. The constriction and throat portions were respectively meshed using a Cooper grid with a density of 0.4 mm and a T grid grid with a density of 1 mm. For the front of the diffusion portion, a boundary layer 0.1 mm in thickness was defined to obtain better computational precision. The whole computation domain contained a total of 152,932 grid cells and 108,605 nodes.

2.3.4 Boundary Conditions. Velocity boundaries were defined at both inlet and suction orifices of the Venturi injector. Initial inlet and suction velocities ($v_1$ and $v_3$) could be calculated as follows:

$$v_1 = \frac{4Q_1}{\pi d_1^3} \quad (3)$$

$$v_3 = \frac{4Q_3}{\pi d_3^3} \quad (4)$$

where $Q_1$ and $Q_3$ are the measured inlet and suction flow rates under a given scenario and $d_1$ and $d_3$ are the diameters of the inlet and suction orifices respectively.

The pressure boundary was set at the outlet of the Venturi injector and the initial pressure was set to be the same as the measured outlet pressure ($p_2$) in the experiment described above. Four inlet pressures (0.30, 0.35, 0.40, and 0.45 MPa) were investigated in the present study.

2.3.5 Computational Region Selection. The volume integral of the vapor phase, referred to as average $V_v$, was selected as the eigenvalues of cavitation in the computational domain. During simulation post-processing, two spherical volume domains were selected to compute $V_v$: volume–throat [with center coordinates of (0,0,0)] and volume–diffusion [with center coordinates of (28,0,0)], corresponding to the throat and diffusion portions of the Venturi injector as shown in Fig. 2. The diameters of the volume–throat and volume–diffusion domains were 30 and 60 mm, which roughly covered the experimental domains detected by the strain gauges (Fig. 3).

Fig. 5 Relationship between the SD ratio ($SD_m/SD_1$) at the throat portion and the diffusion portion and the pressure difference ($\Delta p$) at an inlet pressure of 0.40 MPa. Three eigenvalues, $\Delta p_1$, $\Delta p_2$, and $\Delta p_3$. Maximum pressure difference $\Delta p_{\text{max}}$.

Fig. 6 Relationship between SD of strain values at the throat portion and suction flow rate ($Q_s$) at inlet pressures of (a) 0.30–0.45 MPa and (b) 0.15–0.25 MPa.
values varied according to an M-shaped curve (Fig. 4). Taking the 0.45 MPa inlet pressure as an example, SD declined slightly after \( \Delta p \) increased to \( \Delta p_1 \). Afterwards, \( \Delta p \) continuously increased to \( \Delta p_2 \), and then the SD value increased rapidly. When \( \Delta p \) reached the value of \( \Delta p_2 \), the SD value began to decrease until \( \Delta p \) increased to its maximum measured value. In general, the SD values varied according to a M-shaped curve (Fig. 4). According to Sayyaadi’s research on cavitation in Venturi reactors [30], this M-shaped effect corresponds to cavitation fluctuations in a Venturi injector, which may be caused by complex physical activity of cavitation bubbles in the injector.

Because the thickness was different between the throat and diffusion portions, and because the attachment quality and sensitivity of the strain gauges were not entirely identical, no comparison of SD values was made between the two portions. However, the change in the SD ratio SD\(_1\)/SD\(_2\) for the two portions appeared to be very similar (Fig. 5). For an inlet pressure of 0.40 MPa, the SD\(_1\) value was calculated at a \( \Delta p \) of 0.15 MPa. The values of \( \Delta p_1 \) and \( \Delta p_3 \) in the diffusion portion were in accord with those in the throat portion. When \( \Delta p \) varied from \( \Delta p_1 \) to \( \Delta p_2 \), the downward trend of SD in the diffusion portion was more obvious than that in the throat portion. The SD also increased when \( \Delta p \) became larger than \( \Delta p_2 \) and changed slightly at \( \Delta p_1 \).

3.1.2 Relationship Between SD and \( Q_3 \). The SD value in the throat portion was relatively stable, with an approximate value of 0.8 as \( Q_3 \) increased from 0 to 0.15 m\(^3\)/h (Fig. 6). It increased rapidly as \( Q_3 \) varied from 0.15 to 0.16 m\(^3\)/h. Because a smaller inlet pressure has a relatively narrower range of \( \Delta p \), the measured maximum SD also became smaller. Hence, the maximum SD at an inlet pressure of 0.45 MPa was much greater than at 0.25 MPa (Fig. 6). The maximum \( Q_3 \) values for all inlet pressures were around 0.15–0.16 m\(^3\)/h (Fig. 6). This finding was similar to the results obtained by other researchers [7], which indicated that the suction flow rate did not increase, even slightly, when critical cavitation occurred in the Venturi injector. The value of SD did not rise sharply at an inlet pressure of 0.15 or 0.20 MPa (Figs. 4 and 5), which indicated that critical cavitation may not occur in the Venturi injector under these two scenarios. Therefore, an operating pressure below 0.20 MPa can be considered effective and safe for operation of the Venturi injector investigated in this study.

3.1.3 Relationship Between \( \Delta p_{\text{max}} \) and \( p_1 \). When \( \Delta p \) increased to a certain value, the Venturi injector began to inject fertilizer solution. The corresponding \( \Delta p \) and \( Q_1 \) were called the minimum pressure difference (\( \Delta p_{\text{min}} \)) and the minimum inlet flow rate (\( Q_{1\text{min}} \)), respectively. The suction flow rate of the Venturi injector stopped increasing and remained relatively stable at a certain value of \( \Delta p \), at which the values of \( \Delta p \) and \( Q_1 \) were called the maximum pressure difference (\( \Delta p_{\text{max}} \)) and the maximum inlet flow rate (\( Q_{1\text{max}} \)), respectively, and where critical cavitation was expected to impact the flow in the Venturi injector [7]. The values of \( \eta_\text{min} \) [Eq. (2)] at \( \Delta p_{\text{max}} \) for inlet pressures of 0.30, 0.35, 0.40, and 0.45 MPa were calculated to verify the theory that \( \Delta p_{\text{max}} \) also corresponds to critical cavitation. In the present study, the values of \( \eta_\text{min} \) at \( \Delta p_{\text{max}} \) were approximately 20% (Fig. 5), which was greater than neighboring values and could be regarded as a criterion indicating critical cavitation.

![Fig. 7 Relationship between maximum pressure difference (\( \Delta p_{\text{max}} \)) and inlet pressure (\( p_1 \))](image)

3 Results and Discussion

3.1 Experimental Results

3.1.1 Relationship Between SD and \( \Delta p \). The SD of the measured strain values at the throat portion varied with \( \Delta p \) (Fig. 4). SD was relatively stable when \( \Delta p \) varied from 0.05 to 0.20 MPa at all inlet pressures. However, it rose sharply when \( \Delta p \) was greater than 0.20 MPa.

Taking the 0.45 MPa inlet pressure as an example, SD declined slightly after \( \Delta p \) increased to \( \Delta p_1 \). Afterwards, \( \Delta p \) continuously increased to \( \Delta p_2 \), and then the SD value increased rapidly. When \( \Delta p \) reached the value of \( \Delta p_2 \), the SD value began to decrease until \( \Delta p \) increased to its maximum measured value. In general, the SD values varied according to an M-shaped curve (Fig. 4). According to Sayyaadi’s research on cavitation in Venturi reactors [30], this M-shaped effect corresponds to cavitation fluctuations in a Venturi injector, which may be caused by complex physical activity of cavitation bubbles in the injector.

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![Fig. 8 Schematic diagram of internal flow in a Venturi injector for the section Z = 0, inlet pressure of 0.40 MPa, and outlet pressure of 0.011 MPa](image)
A distinct linear relationship was found between $\Delta p_{\text{max}}$ and $p_1$ (Fig. 7). Because no critical cavitation was observed at an inlet pressure of 0.15 MPa, the linear equation was fitted to six inlet pressures from 0.20 to 0.45 MPa. From the fitted equation, the $\Delta p_{\text{max}}$ value below which the Venturi injector can operate safely increases linearly with the inlet pressure.

### 3.2 Numerical Simulation

#### 3.2.1 Internal Flow Fields

When the inlet pressure was 0.40 MPa and the outlet pressure was 0.011 MPa (Fig. 8), the turbulence kinetic energy in the constriction portion was small, which indicated that the flow in the constriction portion was steady. The turbulence kinetic energy in the diffusion portion was relatively larger than in the throat portion because two liquid fluxes were mixing asymmetrically to form a new flux. Besides, the diameter along the diffusion portion varied, which resulted in violent turbulence in the throat and diffusion portions and larger values of turbulence kinetic energy. The flow gently slowed down near the internal tube walls of the throat and diffusion portions with relatively lower velocity and larger pressure gradient, which led to a larger vapor volume fraction (Fig. 8).

#### 3.2.2 Cavitation Length

To explain the cavitation characteristics of the Venturi injector, the cavitation length (mm) was introduced, which was used to measure the distance between $X = 0$ and the boundary of $V_f$ in the flow direction (Fig. 9). With an inlet pressure of 0.40 MPa, the distribution of $V_f$ in the Venturi injector expanded from the front end of the diffusion portion to the back end as outlet pressure decreased from 0.100 to 0.013 MPa (Fig. 9).

Taking the inlet-pressure scenarios of 0.30 and 0.40 MPa as an example, the cavitation length expanded with $\Delta p$. The average growth rate of cavitation length (AGR) represents the average gradient of cavitation-length variation with $\Delta p$, AGR$_{\text{below}}$ represents AGR between the minimum value of $\Delta p$ corresponding to suction initiation ($\Delta p_{\text{min}}$) and $\Delta p_{\text{max}}$, and AGR$_{\text{above}}$ represents AGR between $\Delta p_{\text{max}}$ and the maximum measurable value of $\Delta p$ (Fig. 10). AGR$_{\text{above}}$ with an inlet pressure of 0.30 MPa was slightly larger than with 0.40 MPa, which means that inlet pressure might affect the value of AGR$_{\text{above}}$. However, for an inlet pressure of 0.40 MPa, when $\Delta p$ varied from $\Delta p_{\text{min}}$ (0.15 MPa) to $\Delta p_{\text{max}}$ (0.26 MPa), AGR$_{\text{below}}$ reached a value of 95.5 mm/MPa, or 58.6% of its AGR$_{\text{above}}$ (162.8 mm/MPa). For an inlet pressure of 0.30 MPa, AGR$_{\text{below}}$ between $\Delta p_{\text{min}}$ (0.11 MPa) and $\Delta p_{\text{max}}$ (0.22 MPa) was only 84.1 mm/MPa, or 38.0% of its AGR$_{\text{above}}$ (221.4 mm/MPa). It can be concluded that the AGR becomes much larger at pressure differences above $\Delta p_{\text{max}}$, where critical cavitation occurs.

#### 3.3 Comparison Between SD and $V_f$

Taking the inlet pressure of 0.40 MPa as an example, the simulated $V_f$ shared a similar trend with the measured SD when $\Delta p$ was greater than $\Delta p_{\text{max}}$ (Fig. 11). When $\Delta p$ was smaller than $\Delta p_{\text{max}}$, $V_f$ did not immediately drop to zero until $\Delta p$ decreased to 0.20 MPa. However, whether or not cavitation occurs, the internal flow will always induce a certain deformation of the throat and diffusion portions. Therefore, SD at any $\Delta p$ less than $\Delta p_{\text{max}}$ can also be measured. In this study, all the measured SD values at pressure differences above $\Delta p_{\text{max}}$ for inlet pressures of 0.30, 0.35, 0.40, and 0.45 MPa were selected and analyzed. The correlation coefficient ($R^2$) between the measured SD and the corresponding simulated $V_f$ was 0.541 (Fig. 12). The relatively small $R^2$ might have resulted mainly from the influence of wall thickness on measured SD. According to the variations of SD and $V_f$ in Fig. 11, the values of both $\eta_{\text{mass}}$ and AGR showed significant increases at a pressure difference of $\Delta p_{\text{max}}$. Therefore, the relationship between SD and $V_f$ showed that cavitation detection in a Venturi injector using strain gauges was reliable.
In this study, both laboratory experiments and numerical simulation were conducted to test and verify a method for cavitation detection in Venturi injectors during fertilizer injection. SD was measured by strain gauges attached on the external body of the Venturi injector. Changes in SD can indicate internal flow characteristics. When critical cavitation occurred in the Venturi injector, the suction flow rate stopped increasing, and the rate of increase (ηm) of SD rose sharply, with its largest value at a pressure difference of Δpmax for various inlet pressures.

4 Summary and Conclusions

In this study, both laboratory experiments and numerical simulation were conducted to test and verify a method for cavitation detection in Venturi injectors during fertilizer injection. SD was measured by strain gauges attached on the external body of the Venturi injector. Changes in SD can indicate internal flow characteristics. When critical cavitation occurred in the Venturi injector, the suction flow rate stopped increasing, and the rate of increase (ηm) of SD rose sharply, with its largest value at a pressure difference of Δpmax for various inlet pressures.

\[ V_f \] of the internal flow in a Venturi injector was calculated to simulate cavitation using the FLUENT software. The curves of both simulated \( V_f \) and measured SD versus Δp exhibited M-shaped characteristics during the cavitation process. This M-shaped effect was presumably caused by complex physical activity of cavitation bubbles, which could indicate cavitation propagation from the throat portion into the diffusion portion. The simulated \( V_f \) for pressure differences greater than Δpmax agreed well with the measured SD. In addition, both the AGR of cavitation length and the value of ηm reached relatively large values at Δpmax. Therefore, this new method of cavitation detection in a Venturi injector using strain gauges has been verified and can be used for these fluid devices with no damage to any component or testing in complex environments.

Critical cavitation in a Venturi injector results in unstable outlet pressure and suction flow rate, which reduces fertilization uniformity in drip-irrigation systems. Therefore, determination of Δpmax using this method can provide a safe operating-pressure range for Venturi injectors to prevent critical cavitation.

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Nomenclature

\[ \text{AGR} = \text{average growth rate of cavitation length, } \text{mm/MPa} \]
\[ \text{AGR}_{\text{above}} = \text{AGR between } \Delta p_{\max} \text{ and the maximum measured value of } \Delta p, \text{ mm/MPa} \]
\[ \text{AGR}_{\text{below}} = \text{AGR between } \Delta p_{\min} \text{ and } \Delta p_{\max}, \text{ mm/MPa} \]
\[ d_1 = \text{inlet diameter, m} \]
\[ d_4 = \text{outlet diameter, m} \]
\[ p_1 = \text{inlet pressure, MPa} \]
\[ p_2 = \text{outlet pressure, MPa} \]
\[ Q_1 = \text{inlet flow rate, } m^3/s \]
\[ Q_2 = \text{outlet flow rate, } m^3/s \]
\[ Q_3 = \text{suction flow rate, } m^3/s \]
\[ Q_{1\text{max}} = \text{maximum inlet flow rate, } m^3/s \]
\[ Q_{1\text{min}} = \text{minimum inlet flow rate, } m^3/s \]
\[ \text{SD} = \text{standard deviation of strain values} \]
\[ \bar{\varepsilon} = \text{average strain values in } 20 \text{ s} \]
\[ \varepsilon_i = i\text{th strain value in } 20 \text{ s} \]
\[ \eta_{\text{lin}} = \text{rate of increase of average SD} \]
\[ \eta_m = \frac{1}{m-1} \sum_{j=1}^{m-1} \text{SD}_j \times 100\% \]
\[ \text{SD}_j = \text{standard deviation of strain values} \]

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\[ v_1 = \text{inlet velocity, m/s} \]
\[ v_1 = 4Q_1/(\pi d_1^2) \]
\[ Q_1, m^3/s \]
\[ d_1, m \]
\[ v_3 = \text{suction velocity, m/s} \]
\[ v_3 = 4Q_3/(\pi d_3^2) \]
\[ Q_3, m^3/s \]
\[ d_3, m \]

References