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Numerical and Experimental Research on Convergence Angle of Wet Sprayer Nozzle

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Abstract

Shotcrete is a popular support method in construction of both ground projects and underground projects, such as tunnels, subways, slopes and roadway, etc. However, at present researches on the influence of nozzle structure parameters on the performance of concrete injection are insufficient. This research focuses on the influence of various parameters of nozzle structure on the evenness and dust generating, and conducts a systematic study on the flow characteristics of the concrete in the nozzle of wet spraying machinery and the quality control law, through a comprehensive research method combining theoretical analysis, numerical simulation and field tests. On the basis of dynamic analysis of the internal flow field of the nozzle, the mathematical model and numerical model of the internal flow field of the nozzle are establishes. Then the simulation calculation of the flow field of the wet spray nozzle is conducted with the FLUENT® software. The fluid's contour about velocity and phase volume fraction in the nozzle were obtained. On this basis this paper analyzed each phase's volume fraction of the mixed fluid in the outlet section. The convergent section of the nozzle is tested in the spray concrete impact force distribution system. The results are in good correspondence with the results of theoretical analysis and numerical simulation, which verifies the validity and reliability of the conclusion of numerical simulation. This paper provides the basis for the optimization of nozzle structure, and the improvement of the sprayed concrete construction quality.

Keywords: Shotcrete; Wet Spraying Machinery; Nozzle; Convergence Angle; Numerical Simulation.

1. Introduction

Shotcrete or sprayed concrete, a cement-based mixture projected pneumatically in high velocities [1], is often used in various constructions, such as mine tunnels, railway and highway tunnels, and water conservancy culverts [2-4]. The flexibility of shotcrete makes it an effective alternative to conventional concrete in rock support, tunnel lining, and concrete repair. For example, the pneumatic projection allows shotcrete to be applied quickly on the uneven substrate surfaces, acting as excavation stabilization and arch lining in mines [5]. There is a problem of uneven injection and large amount of dust on the shotcrete construction site. Ulvestad et al. [6] ever indicated that mean exposures to total dust and respirable dust in shotcreters were significantly higher than in drillers (13.6, 3.4 and 3.6, 1.2 mg/m^3). Georg et al. [7, 8] compared the exposure situation of shotcrete dust in heading face between Swiss road tunnel and Munich subway tunnel with similar shotcrete and ventilation, results showed that the average fine dust concentration of road tunnel (13.2 mg/m^3) and subway tunnel (11.6 mg/m^3) was still higher in fact, what's more, the peak of dust concentration during shotcrete can reach up to more than 100 mg/m^3 for the road tunnel and up to 70 mg/m^3 for the subway tunnel. Praml et al. [9, 10] measured dust concentration during the shotcrete in amine tunnel construction site. Results showed that the fine dust concentration were 4.2 mg/m^3 for mixer operator and 11.6 mg/m^3 for nozzleman. The peak loads of dust concentration can reach up to five times the mean value. These problems not only waste valuable wet spray materials,

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generate a large amount of dust, damage the support strength, reduce work efficiency, but also pose a threat to the health and safety of workers.

Currently, when it comes to shotcrete, a large amount of researches pay their attention on the pumpability and shootability of fresh concrete [11-13] or the mechanism of sprayed concrete [14, 15]. Lianjun Chen et al. [16] summarized the technologies for reducing cement dust during shotcrete from new process, new apparatus to new materials, as well as the pathological damage of cement dust. Zeng Xiantao et al. [17] indicated that the magnetized water can enhance the strength of shotcrete by 10% or so, and reduce the dust density by 50% in comparison with the ordinary shotcrete. The rebound rate of shotcrete mixed with magnetized water is greatly improved compared with that of the ordinary water shotcrete.

At present, there are few researches on the structure of wet spray nozzles, and in those researches the range of nozzle convergence angle is large lacking certain certainty, which has a great effect on the performance of nozzle [18]. This paper studies the effect of the shrinkage angle of the wet sprayer's nozzle on the uniformity of concrete injection and the reduction of dust through theoretical analysis, numerical calculation and experimental research. Based on the numerical calculation results, the specimen is made. The correctness of the numerical simulation results is verified in the experimental research and then applied to engineering practice.

2. Analysis and Calculation of Concrete Motion in Nozzle

2.1. Wet Sprayer Working Principle and Structure Characteristics of Nozzle

The construction of wet shotcrete refers to a process in which cement, water and aggregates are fully stirred in a certain proportion in blender, then pumped or air-conveyed to the nozzles, and finally, the concrete is accelerated with compressed air at the nozzle [19, 20]. The nozzle as the concrete exit is essential to the whole machine. In order to improve the technology and product quality of the wet sprayer, it is necessary to study the influence of the nozzle structure on the concrete flow in the nozzle. The nozzle is composed of convergent section, mixed core, air-induction ring, and connection snap ring, as shown in Figure 1, In practice, the compressed air and the accelerating agent enter the nozzle from the air induction ring (Part 2 in Figure 1). The concrete is pushed to the straight pipe (part 1) through the alternate delivery cylinder, and fully and evenly mixed in the material-gas mixing core (part 3) with high pressured air entering through the air induction ring (Part 2). The suspended concrete particles pass through the front convergent section (Part 5) and are sprayed from the outlet (Part 6) to the sprayed surface, completing the entire concrete spraying operation.

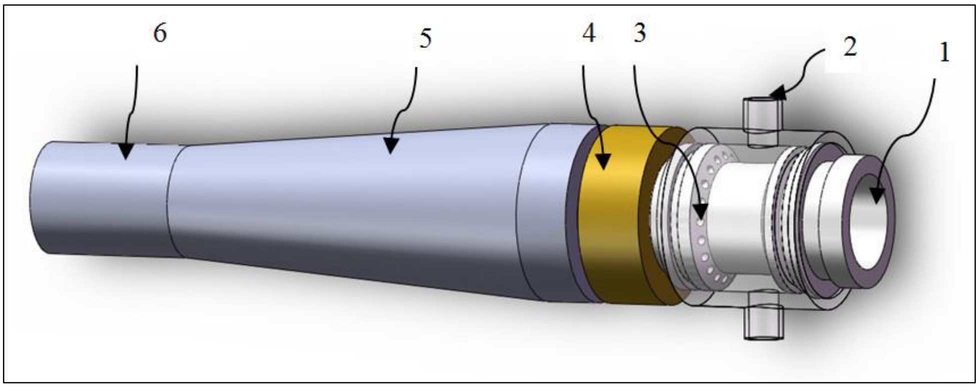


Figure 1. Diagram of nozzle structure

2.2. Differential Equations of Concrete Group Movement in Nozzles

According to the working principle of the wet sprayer, the concrete group is accelerated in the nozzle by the compressed air, and run in an axially-accelerated manner in the suspended state. At the same time, there is a circumferential rotational motion [21, 22]. That is to say, the concrete group is in a spiral motion in space and the axial and tangential forces are complex in the spraying process. However, the gravity and the levitation force balance each other in the vertical direction during the horizontal spray of concrete particles. The tangential force in the circumferential direction only produces a tangential rotational motion, without any effect on the axial movement of the concrete. Thus, the tangential force can be ignored when analyzing the axial movement of the concrete. The forces acting on the concrete group mainly include the axial flow thrust F_R and the frictional resistance T of the nozzle inner wall. Figure 2 briefly illustrates the forces on the concrete group in horizontal pipes in dl section [23, 24].

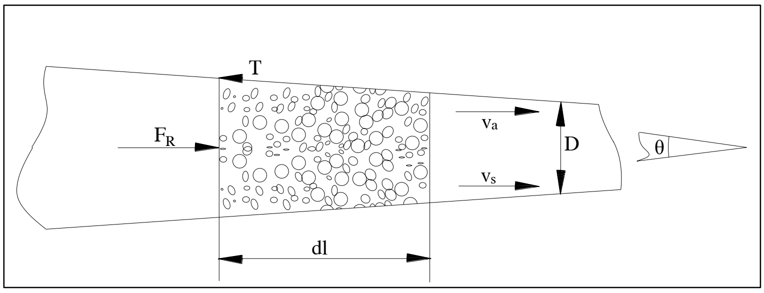


Figure 2. Force and motion diagram of concrete particle group in horizontal conical tube

Airflow thrust Equation 1:

$$F_R == C_s A_s \rho_a \frac{(v_a - v_s)^2}{2} \tag{1}$$

Where C_s refers to the flow resistance coefficient, and A_s is the total frontal area of concrete particle group in dl section.

Pipe wall resistance Equation 2:

$$T = \Delta P_l A = \lambda_s \frac{dl}{D} \rho_n \frac{v_s^2}{2} A \tag{2}$$

Where λ_s refers to the resistance coefficient of concrete group, and A is the cross section area.

Since:

$$\rho_n = \frac{q_{ms}}{Av_s} \tag{3}$$

$$C_s = C_n (\frac{v_n}{v_a - v_s})^{\mathrm{k}} \tag{4}$$

According to the previous analysis, the airflow resistance of the shotcrete particles is within the Newton resistance zone, i.e. K=0, thus it can be obtained;

$$C_n = g \frac{q_{ms}}{v_s} dl /(A_s \rho_a \frac{v_n^2}{2}) \tag{5}$$

Namely:

$$F_R = g \frac{q_{ms}}{v_s} gdl (\frac{v_a - v_s}{v_n})^{2-k} \tag{6}$$

$$T = g \frac{q_{ms}}{v_s} dl \frac{\lambda_s v_s^2}{2gD} \tag{7}$$

According to Newton's second law: $M_s \frac{dv_s}{dt} = F_R - T \cos\frac{\theta}{2}$, and combined it with Equation 2:

$$\frac{1}{g}\frac{dv_s}{dt} = (\frac{v_a - v_s}{v_n})^2 - \frac{\lambda_s v_s^2}{2gD(\theta)} \tag{8}$$

Where v_s stands for the transportation speed for concrete group (m/s); v_n suspension velocity (m/s); λ_s, flow resistance coefficient; v_a, air velocity (m/s); D, inner diameter of the nozzle (mm); and θ, convergence angle of the convergent section (°).

The Equation 8 is the differential equation of the motion of concrete group in horizontal nozzle, which reflects the change of actual velocity of the concrete with time in the spraying process, that is, with the increase of time, the actual velocity of the concrete group will accelerate from pumping speed to stable speed. The factors which affect the spray velocity of concrete include the convergence angle θ of the nozzle's convergent section, the suspension velocity v_n of the concrete group, the airflow velocity v_a, and the flow resistance coefficient λ_s of the concrete group. Among them, the convergence angle of the convergent section of the nozzle is crucial to the spray velocity of the concrete group. The motion of the concrete flow in the nozzle can be described in this way. The concrete group is pumped into the nozzle inlet, and under the action of high pressure wind, the decelerating acceleration movement is performed. When the material group acceleration is zero, the energy exchange between high pressure air and concrete group ends. At that moment, the concrete group gains the highest speed, and the material group is in evenness motion.

3. Modeling and Numerical Simulation of Wet Sprayer Nozzle

3.1. Geometry Model and Mesh Model of Nozzle Calculation Areashou

3.1.1 .Geometry Model

The nozzle model is composed of a front convergent section, a middle mixing core, an air-induction ring, and a connecting ring, as shown in Figure 1. The main parameters are listed in Table 1.

Table 1. Nozzle structure parameters

Nozzle parameters		Nozzle parameters	
Concrete inlet diameter D_1 (mm)	64	Nozzle length L_1 (mm)	595
Concrete outlet diameter D_2 (mm)	45	Convergence angle of convergent section θ °	4
Air inlet diameter D_3 (mm)	6×20	Straight pipe of concrete inlet L_3 (mm)	164
Air inlet declination β (°)	30	Straight pipe of concrete outlet L_4 (mm)	100

3.1.2. Mesh Model

As shown in Figure 3, the three-dimensional mesh of the nozzle is divided by ANSYS ICEM®. The model adopts a hexahedral core meshing format at the inlet of the concrete and the outlet of the mixed fluid to improve the accuracy of meshing. Due to the presence of 20 high-pressure air inlets in the intermediate mixing chamber, the model structure is complex. Therefore, an unstructured grid division format is used to ensure a reasonable balance between calculation accuracy and computational resources. The grid size is 0.002m and the total number of model grids is 1454508. The structural and unstructured grids are separated by the inter_face surface.

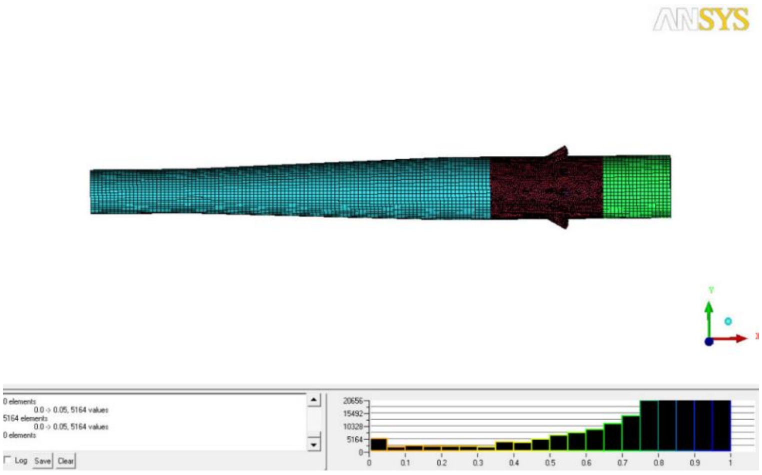


Figure 3. Diagrams of three mesh generation

3.2. Numerical Calculation

3.2.1. Assumptions

During the spraying process, the flow state of concrete and air in the nozzle is extremely complicated. In order to facilitate analysis and calculation, the following assumptions are made on the flow field:

- The working medium in the nozzle is a typical viscous fluid.
- The mixed fluid is a multiphase mixture of air, water, cement, gravel, etc. In order to simplify the study, only the continuous phase and the particle phase are considered in this paper.
- This research only focuses on the movement of the working medium, excluding the temperature change of the working medium, the hydration reaction of the cement, and the change of the internal energy of the working medium.
- All the components in the nozzle are absolutely rigid, ignoring the deformation caused by the interaction between the solid wall forming the flow area and the working medium.

3.2.2 .Boundary Conditions

The Operating environment is 101325 Pa; density of concrete particles is 2500 kg/m^3; concrete dynamic viscosity is 32 N·s/m^2; water-cement ratio is 0.48; thermal conductivity is 1.28 W/m·°C; specific heat capacity is 970 J/kg·K. The RNG k-ε model is more reliable and accurate than the standard k-ε model. What's more, since the high-pressure air supply process of the concrete pile group is in the square area of turbulent flow resistance and the turbulence is a fully developed strong turbulent turbulence with large intensity, the RNG k-ε model is more suitable. Therefore, this study used the RNG k-ε turbulent model to resolve the flow equations.

Its boundary conditions are set as follows:

1) **Concrete inlet conditions**

Concrete inlet conditions is adjustable where the velocity boundary condition can be implemented. Considering the actual conditions of the wet sprayer, the spray capacity of wet sprayer is 7 m^3/h, and concrete flow direction is perpendicular to the nozzle inlet cross section, i.e., $u_y=u_z=0$, $u_{int\_concrete} = u_x = 7/_{\pi D_1^2}$, where D_1 refers to the nozzle inlet cross section. The hydraulic diameter is 64 mm.

2) **Air inlet conditions**

The air inlet boundary conditions, considering the practical operating conditions, are selected as the pressure inlet pressure_inlet. The air flow direction is perpendicular to the air inlet section of the nozzle mixing chamber, i.e., $u_y=u_x=0$, $u_{int\_air}=u_x$. The field work wind pressure is 0.5MPa [25], while the hydraulic diameter is 6 mm.

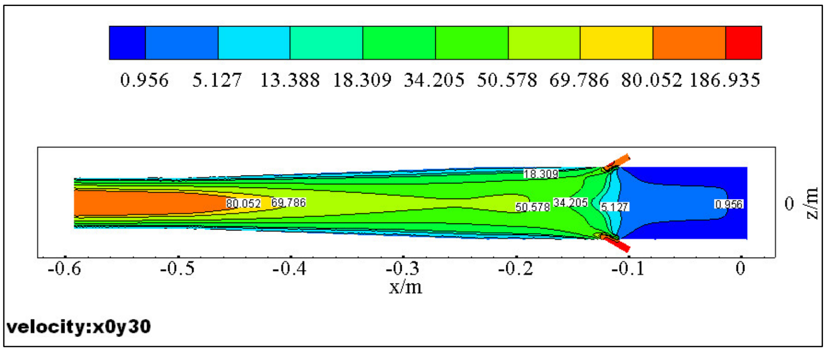
3) **Mixed fluid outlet conditions**

The nozzle outlet boundary conditions are selected to be free outlet Outflow. The fluid Reynolds number and turbulence intensity can be solved with $Re=u_{int}\rho d/\gamma$ and $I=0.16(Re)^{-1/8}$.

4. The Effect of Convergency Angle on wet Nozzle Performance

4.1. Numerical Calculation Results

In this study, modelling and numerical calculations were conducted with the convergency angles of convergent sections of 3°, 4°, 5°, 6°, and 7° respectively. Figure 4 shows the flow velocity isogram when the convergency angle of convergent section θ is 4°.



Unit: m/s

Figure 4. Velocity isogram on Y=0 cross section

In the x=-0.595 outlet section, 11 collection points were selected in the Y-axis direction in an isometric way within the flow field boundary (-0.0225m~0.0225m), as shown in Figure 5.

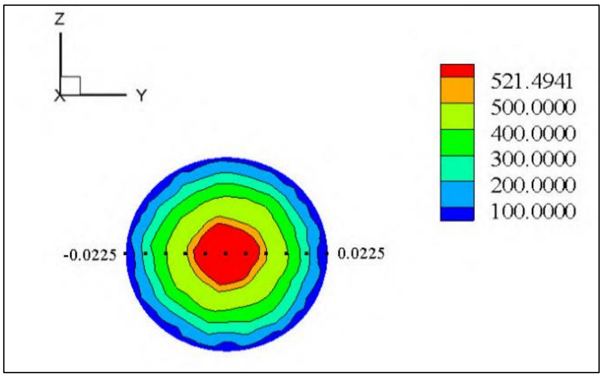


Figure 5. Collection points schematic diagram of x=0.595 cross section

4.2. Analysis of Resultant Velocity of Outlet Section

Under the condition that the air pressure of the wet sprayer and the pumping pressure of the concrete are constant, the greater the outlet velocity of the concrete jet is, the less energy consumption of the contact between the concrete group and the inner wall surface of the nozzle, and the small the wear of the nozzle will be. The average speed of the outlet section $\bar{U}$ (9) is regarded as an assessment index for the analysis of the outlet section velocity field, in the analysis of the average velocity of outlet section;

$$\bar{U} = \frac{1}{N}\sum_{i=1}^{N} U_i \quad (9)$$

Where U_i refers to the velocity of collection points in outlet section (m/s), and $\bar{U}$ is the mean velocity of collection points in outlet section (m/s).

Table 2 presents the mean velocity values of the outlet section collection points with various convergency angles of different nozzle models

Table 2. Mean velocity of outlet section collection points of different nozzle models

	Convergence angle （°）				
	3	4	6	6	7
Mean velocity（m/s）	40.64	37.70	36.47	35.40	19.66

Import the mean data into Origin9® to fit the data curve, as shown in Figure 6. It can be seen that when the convergence angle of the convergent section is less than 3°, it can be considered that the concrete group is transported in an approximately equal straight pipe, and the concrete outlet speed does not change much; when the convergence angle of convergent section is greater than 6°, the concrete transport velocity is very small and the nozzles are easily blocked.

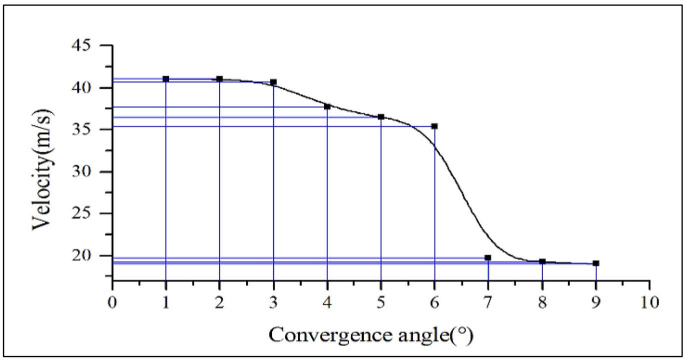


Figure 6. Mean velocity fitting curve of outlet section of different nozzle models

4.3. Analysis of Volume Fraction of Concrete Phase in Outlet Section

The distribution of the volume fraction of the concrete phase at the outlet of the nozzle is an important factor for judging the mixing effect of the nozzle structure on the mixed fluid. A reasonable distribution of the volume fraction of the concrete phase reflects the good mixing effect of the mixed fluid. In the past, the judgment of the mixing effect of the shotcrete flow can only be expressed indirectly based on the rebound rate of the sprayed wall surface. Through numerical simulation software analysis, the volume fraction of the concrete phase at the nozzle outlet of the mixed fluid is shown in Figure 7.

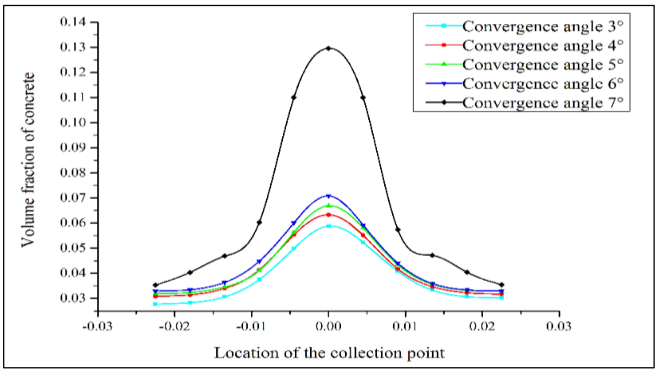


Figure 7. Volume fraction of the concrete phase in the outlet section x=-0.595 of different nozzle models

In order to objectively reflect the degree of mixing, both the standard deviation and the mean value are taken into account.

1. The degree of dispersion represents the ratio of the standard deviation to the measured mean value. The percentage expression is;

$$R = \frac{S}{\bar{x}} \times 100\% \tag{10}$$

2. Evenness represents the degree to which a set of measurements approaches the mean value of the measurements. The mathematical expression is;

$$H = 1 - R \tag{11}$$

The essence of dispersion and evenness is same, but just two different perspectives.

The analysis of the volume fraction of the concrete phase in the outlet section shows that both high concentration of concrete and low concentration fluctuation along the center of the nozzle are required in construction. Thus, suitable statistics to characterize this comprehensive evaluation index is necessary.

Define the comprehensive evaluation index Q as the product of the evenness and the measured mean values:

$$Q = \bar{x} \times H \tag{12}$$

Table 3. Concrete phase volume fraction analysis of outlet section

No.	Convergence angle (°)	Mean values (%)	Standard deviation (%)	Q value
1	3	3.82	1.08	2.73×10^{-2}
2	4	4.10	1.16	2.94×10^{-2}
3	5	4.24	1.24	3.00×10^{-2}
4	6	4.40	1.34	3.05×10^{-2}
5	7	6.48	3.45	3.03×10^{-2}

From Table 3, it can be seen that the best sample of the outlet section concrete spray evenness is the model with the convergence angle of 6° in the convergent section.

5. Experimental Study on Spraying Force Distribution Test of Shotcrete

5.1. Test System

Due to the limitation of test conditions, it is very difficult to directly measure the mixing quality of the concrete flow in the nozzle. Therefore, this study employed the method of measuring the impact force of the water jet flow abrasive on the object to indirectly determine the quality of the jet, and set up a shotcrete impact force distribution test system. Based on the field conditions of wet shotcrete as shown in Figure 8, an effective concrete spray force distribution test scheme is proposed by using LabVIEW® to curve the input and output characteristics of the sensor, and analyzing and processing the test data [26].

Figure 8. Typical shotcrete spray

5.2. Sensor layout

In order to measure the distribution of shotcrete impact force, a force transducer array system was designed. According to the characteristics of the central symmetrical structure of the shotcrete impact diffuse surface, taking into account the reduction of the test cost, 11 pressure transmitter collection points were arranged along a horizontal axis (-500 ~ 500 mm) at a distance of 1000 ×1000 mm, as shown in Figure 9, and fixed with nuts and the gaps were sealed with caulking glue. Collection points were evenly represented. The pressure transmitters in the array were numbered according to the distance from the centre of the bottom plate for the convenience of following test. From left to right, they were grouped by 0 ~ 10 in turn. The positions of 11 collection points in the coordinate system are 0 (-500, 0), 1 (-400, 0), and 2 (-300, 0) respectively, 3 (-200, 0), 4 (-100, 0), 5 (0,0), 6 (100,0), 7 (200,0), 8 (300,0) No. 9 (400, 0), No. 1 (500, 0).

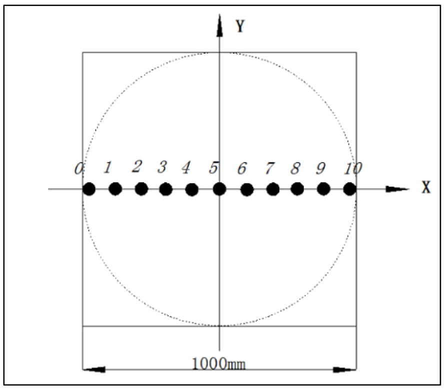


Figure 9. Sensor array distribution diagram

Figure 10 shows the assembly of the shotcrete test platform.

Figure 10. Assembly of the Shotcrete test platform

5.3. Nozzle Models Production and Testing

According to the previous analysis, the nozzle models with convergence angles of 4°, 5°, and 6° were fabricated as shown in Figure 11, and field tests were conducted.

Figure 11. Nozzle models

Figure 12 shows the shotcrete vehicle used in the site test manufactured by Xugong Group Schwein Machinery Co., Ltd.

Figure 12. Testing shotcrete vehicle

Figure 13 shows the site of field test of shotcrete impact force test system.

Figure 13. Field test

Setting LabVIEW®, the sampling frequency is 1000, which means that it is collected 1000 times per second. Since the output signal of the transmitter is 0~5V and the range is 0.5MPa, the output pressure and voltage conversion formula is shown as Equation 13, Test pressure:

$$P_{out} = \frac{V_{out}}{5} \times 0.5MPa \tag{13}$$

Multiple groups of test data have been obtained by replacing the convergent section to obtain.

Table 4. Mean values of test data of convergent section of different nozzle models

Collection point	Nozzle models (MPa)		
	4°	5°	6°
0	0.028224	0.029224	0.030264
1	0.030221	0.031171	0.032261
2	0.030931	0.031531	0.033331
3	0.032158	0.031898	0.035608
4	0.043221	0.044251	0.047961
5	0.051641	0.055231	0.059191
6	0.042998	0.045978	0.047088
7	0.032117	0.033807	0.034387
8	0.030873	0.031863	0.032123
9	0.029206	0.030226	0.030316
10	0.028128	0.029318	0.029398

The processed mean data was imported into Origin9® for data curve fitting, the results being showed in Figure 14.

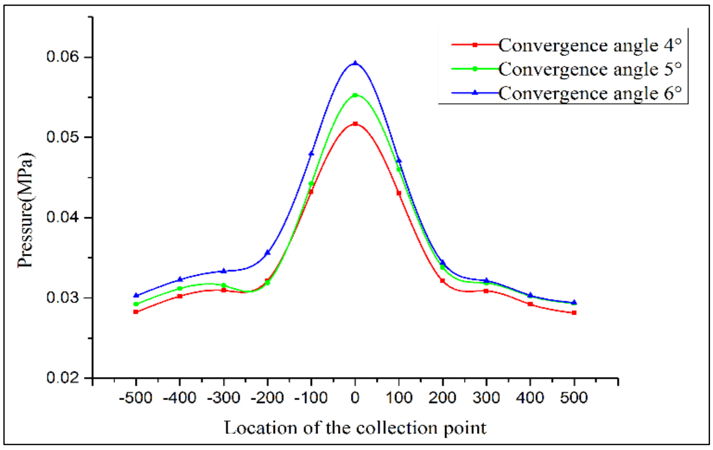


Figure 14. Mean test data curve of convergent section of different nozzle models

The distribution rule of the fitting curve is consistent with that of the volume fraction curve of the concrete phase of the nozzle outlet section shown in Figure 7.

According to the above analysis, Q values of nozzle models with different convergence angles in the convergent section were calculated.

Table 5. Test data analysis of convergent section of different nozzle models

No.	convergence angle (°)	Even value (MPa)	Standard deviation (MPa)	Q values
1	4	3.45×10^{-2}	3.03×10^{-5}	3.45×10^{-2}
2	5	3.59×10^{-2}	3.72×10^{-5}	3.58×10^{-2}
3	6	3.74×10^{-2}	4.64×10^{-5}	3.74×10^{-2}

By calculating Q value of the comprehensive evaluation index, the nozzle model with convergence angle of 6° in convergent section and Q value of more than 5° and 4° has the best performed, which is consistent with the theoretical analysis and numerical calculation results. The nozzle model with the convergence angle of 6° in convergent section has good shotcrete evenness and the test results is satisfactory.

6. Conclusion

In this study, the combination of numerical calculation and experimental research was employed to study the effect of the nozzle's convergence angle on the spraying performance of the concrete. According to the numerical calculation results, nozzle models were produced, and the shotcrete distribution test system was established to verify the numerical simulation, which then was applied to engineering practice. The study shows that when the convergence angle of the convergent section is less than 3°, the convergence angle has little effect on the shotcrete group; with the increase of the convergence angle, the shotcrete group jet velocity decreases and the nozzle wear increases; when the convergent section convergence angle is greater than 6°, the concrete outlet jet velocity is very small and the nozzle is easily blocked. The shotcrete impact force distribution test system was designed and assembled in line with the conditions of the wet shotcrete construction site, which can correctly collect the impact force of the sprayed surface and analyze the nozzle spray evenness. The test system provides an effective solution for on-site testing of the spraying performance of the wet sprayer nozzle. The force distribution test has a good consistence with the numerical simulation results.

7. Funding

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