Influence of structural parameters of venturi on internal flow field changes

Chuanmao Lv 1*, Puhao Wang 1, Xiaoguang Zhang 1 and Haifeng Lv 1

1 School of Mechanical Engineering, North University of China, Taiyuan, Shanxi, 030051, China
*1196567784@qq.com

Abstract. The influence of the inlet angle and the outlet angle of the venturi on the fluid flow state in the tube was studied. The control variable method was used to simulate the flow of the fluid inside the venturi by COMSOL software. The results show that when the inlet angle changes from 10.3° to 55°, the fluid flow velocity at the throat of the universal venturi is 19.5m/s, and the pressure varies from 1121.1Pa. When the outlet angle is changed from 10.3° to 55°, the fluid flow velocity inside the venturi varies by 0.8 m/s, and the pressure varies from 6060.2 Pa. Therefore, it can be concluded that changing the angle of the outlet has a greater influence on the negative pressure at the throat of the venturi. The change in the negative pressure caused by changing the inlet angle is weak, but the flow rate changes greatly.

1. Introduction
The venturi is a tubular structure that is firstly contracted and expanded. It consists of an inlet tube, a shrink tube, a throat tube, a diverging tube, and an outlet tube. The fluid flows in at the inlet tube and flows out at the outlet tube. Since the cross-sectional area of the venturi at the shrink tube is reduced, the flow state of the internal fluid becomes an increase in the flow velocity and a decrease in the pressure, which is the Venturi effect. Cases of the use of venturi adsorption in today's production activities are everywhere. Li [1] pointed out that installing a venturi structure in the intake system of a car to form a low static pressure zone is beneficial to exhaust gas recirculation. It can effectively reduce the emission of exhaust gas. Zhou [2] used the self-priming venturi scrubber as the research object, and analyzed the main factors affecting the amount of ejector, and analyzed and verified each factor through experiments. M. Wang studied the pressure drop characteristics of the Venturi scrubber in self-priming mode [3]. Due to the wide application range of venturi tube in practical production, some experts and scholars [4-6] studied and analyzed the structure of venturi tube, and concluded that the structural parameters of venturi tube had an impact on the fluid flow characteristics inside. For example, when the diameter of the throat tube becomes smaller, the flow velocity of the fluid is increased and the pressure is reduced. Changes in inlet angle and outlet angle also affect the flow rate and pressure of the internal fluid. However, no research has pointed out the law of the influence of these two factors on the internal flow field.

Therefore, by using COMSOL software to numerically simulate the general venturi structure, the law of the change of the angle of the shrinkage tube and the gradually expanding tube to the internal flow field is obtained, which provides a basis for the design of the venturi.
2. Basic structural model of universal venturi
The universal venturi is formed by changing the angle of the shrinkage port and the angle of the flare on the basis of the classic venturi. It not only has the characteristics of the venturi, but also has the advantages of shortening the length of the body and effectively reducing the pressure loss. In this paper, the solid venturi structure model shown in Figure 1 is established using Solidworks 3D modeling software.

In order to analyze the change in the internal medium flow rate and pressure caused by the change in the angle of the shrinkage port and the angle of the flare, the intermediate section of the internal fluid region model is simplified to the schematic shown in Figure 2. D is the diameter of the round tube on both sides of the venturi tube 50 mm, d is the diameter of the round tube at the throat of the venturi tube is 30 mm, and B is the length of the round tube at the throat of the venturi tube is 40 mm. Where α is the inclination of the venturi’s constricted opening and β is the dip of the venturi’s divergent opening.

3. Mathematical model
In the numerical simulation process, the flow medium inside the venturi is selected from air, and it is assumed that the flow of air in the venturi is a steady-state incompressible flow, and the fluid conforms to the law of conservation of mass and momentum during the flow process. The equation consists of a continuity equation and a Navier-Stoke equation.

The continuity equation is:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]  

The Navier-Stokes equation is:

\[ \rho \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + \rho w \frac{\partial u}{\partial z} = -\frac{\partial P}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \]

\[ \rho \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} + \rho w \frac{\partial v}{\partial z} = -\frac{\partial P}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \]

\[ \rho \frac{\partial w}{\partial x} + \rho v \frac{\partial w}{\partial y} + \rho w \frac{\partial w}{\partial z} = -\frac{\partial P}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \]

In the above formula: \( \rho \) is the density of air \( (Kg/m^3) \), \( \mu \) is the dynamic viscosity coefficient of air \( (Pa\cdot s) \), \( u, v \) and \( w \) are the velocity vectors on the \( x, y \) and \( z \) axes respectively, and \( P \) is the pressure \( (Pa) \).

In this paper, the diameter D of the cylinder on both sides of the venturi is selected as 50 mm. When the gas flow rate at the inlet flows into the venturi at a speed of 50 m/s, the Reynolds number of the
fluid can be calculated according to the inlet velocity and the diameter of the cylinders on both sides. Its Reynolds number is:

\[ Re = \frac{VD}{\nu} = \frac{50 \times 50}{1.48 \times 10^{-5}} = 1.48 \times 10^5 \]  
(3)

Among them, \( \nu \) is the kinematic viscosity of air \( (m^2/s) \). The above calculations show that the flow state of the fluid in the venturi is turbulent, so the \( K-\varepsilon \) turbulence model suitable for high Reynolds number turbulence is selected for numerical simulation.

4. Numerical Simulation

Firstly, the structural model of the internal fluid domain of the venturi is established in the 3D modeling software, and then numerically analyzed by COMSOL software. In this paper, the numerical simulation method is used to study the flow of fluid inside the venturi. It can be seen from the above that the flowing medium is air and the internal fluid is steady-state incompressible. The turbulence model was adopted. The boundary conditions were: inlet flow rate was 50 m/s, outlet pressure was 0 Pa, and the remaining wall surfaces were set to have no slip wall surface. The mesh division adopts the automatic division of the grid controlled by the physical field, and the size selection of the grid unit is coarser. The calculation is terminated with 1000 iteration steps.

When constructing a three-dimensional model of the internal fluid domain of a venturi, the structural models of different parameters will have a one-to-one corresponding throat flow rate and negative pressure value. The simulation results were sorted and fitted to investigate the influence of the structural parameters of the outlet and inlet angles on the flow velocity and negative pressure of the fluid inside the throat of the venturi.

4.1 Influence of inlet inclination

The influence of the inlet inclination angle of the venturi on its internal flow field was studied, and the internal fluid domain geometry model of the venturi with 11 different inlet inclination angles was established. When the outlet inclination angle is 21.8° under the same working conditions, the different inlet inclination angles are simulated to obtain the velocity values and pressure values of their respective throat fluids. The results are shown in Table 1.

| Entrance inclination α(°) | Throat fluid velocity(m/s) | Throat fluid pressure(KPa) |
|--------------------------|-----------------------------|---------------------------|
| 10.3                     | 143.556                     | -5.492                    |
| 14.0                     | 143.969                     | -5.385                    |
| 18.4                     | 144.635                     | -5.300                    |
| 21.8                     | 145.396                     | -5.272                    |
| 24.9                     | 146.109                     | -5.085                    |
| 29.1                     | 147.471                     | -4.800                    |
| 33.7                     | 149.571                     | -5.268                    |
| 39.8                     | 152.821                     | -4.690                    |
| 45.0                     | 155.749                     | -4.570                    |
| 50.6                     | 159.173                     | -4.450                    |
| 55.0                     | 163.060                     | -4.371                    |

Regression analysis was performed on the data in Table 1, and the relationship between the inlet inclination and the velocity and pressure values of the fluid at the throat was obtained as follows:

\[ V(\alpha) = -3.854 \times 10^{-6} \alpha^3 + 8.741 \times 10^{-3} \alpha^2 - 0.1248 \alpha + 144 \]  
(4)

\[ R^2 = 0.9994 \]
\[ P(\alpha) = -9.976 \times 10^{-6} \alpha^3 + 8.68 \times 10^{-4} \alpha^2 + 4.943 \times 10^{-3} \alpha - 5.621 \]
\[ R^2 = 0.9939 \]

Where: \( \alpha \) is the inlet inclination (°); \( V \) is the fluid velocity at the throat (m/s); \( P \) is the fluid pressure at the throat (KPa); \( R^2 \) refers to the degree of regression of the regression equation.

Figures 3 and 4 are drawn by simulation results and regression analysis curves obtained by changing the inlet inclination.

![Figure 3. Speed versus inlet angle.](image1)

![Figure 4. Negative pressure value versus inlet angle.](image2)

It can be seen from Fig. 3 and Fig. 4 that when the other structural parameters of the venturi remain unchanged and the inlet inclination angle ranges from 10.3° to 55.0°, the flow velocity and negative pressure of the fluid at the throat of the venturi will follow. As the angle of the entrance increases, the rate of change of the velocity increases, while the rate of change of the pressure increases first and then decreases.

4.2 Impact of exit dip

Under the condition that the inlet inclination angle is 21.8° and the working conditions are the same, the above analysis method is used to study the influence of the change of the outlet inclination angle on the fluid flow state inside the venturi, and the numerical simulation results are analyzed and integrated to obtain the data shown in Table 2.

| Entrance inclination \( \alpha \) (°) | Throat fluid velocity (m/s) | Throat fluid pressure(KPa) |
|-------------------------------------|-----------------------------|-----------------------------|
| 10.3                                | 144.726                     | -8.522                      |
| 14.0                                | 144.623                     | -7.117                      |
| 18.4                                | 144.731                     | -5.471                      |
| 21.8                                | 144.680                     | -5.011                      |
| 24.9                                | 144.846                     | -4.543                      |
| 29.1                                | 144.881                     | -3.736                      |
| 33.7                                | 145.086                     | -3.126                      |
| 39.8                                | 145.261                     | -2.852                      |
| 45.0                                | 145.310                     | -2.669                      |
| 50.6                                | 145.561                     | -2.541                      |
| 55.0                                | 145.508                     | -2.462                      |

The data in the above table were collated and analyzed to obtain the relationship between the velocity and pressure of the fluid at the throat of the venturi as a function of the inclination of the outlet.

\[ V(\beta) = -3.615 \times 10^{-5} \beta^3 + 2.756 \times 10^{-3} \beta^2 - 0.06483 \beta + 145.1 \]
\[ R^2 = 0.9805 \]
\[ P(\beta) = -8.426 \times 10^{-3} \beta^3 + 0.01254 \beta^2 + 0.6421 \beta - 13.85 \]

\[ R^2 = 0.9964 \]

Where: \( \beta \) is the outlet inclination angle (°); \( V \) is the fluid velocity at the throat (m/s); \( P \) is the fluid pressure at the throat (KPa); \( R^2 \) refers to the degree of regression of the regression equation.

The following figure is drawn from the above results:

![Figure 5. Speed versus exit angle.](image1)

![Figure 6. Negative pressure value versus exit angle.](image2)

It can be seen from Fig. 5 and Fig. 6 that when only the structural parameter of the venturi outlet inclination is changed, the flow velocity and pressure of the fluid at the throat of the venturi are changed. When the outlet inclination angle ranges from 10.3° to 50°, the fluid velocity at the throat of the venturi will decrease first and then rise and eventually stabilize as the angle becomes larger. The negative pressure value becomes larger as the angle becomes larger, and the rate of change is gradually decreased.

5. Conclusion
In this paper, the influence of inlet angle and exit angle of venturi on its internal fluid flow state is studied. It is found that the flow velocity and negative pressure of the fluid at the throat are positively correlated with the inlet inclination. At the same time, the negative pressure value is positively correlated with the outlet inclination angle, and the speed fluctuates with the increase of the outlet angle.

The inlet angle has a large effect on the flow rate of the internal fluid of the universal venturi, while the outlet angle has a greater influence on the pressure of the fluid at the throat of the venturi.

References
[1] Li, J.X. (2003) Heavy Duty Turbocharger with EGR. J. Vehicle Engines, 2:48-48.
[2] Zhou, Y.M., Sun, Z.N., Gu, H.F. (2003) Ejection characteristics of self-priming venturi scrubber and its influencing factors. J. CIESC Journal, 66: 99-104.
[3] Wang, M., Sun, Z.N., Gu, H.F. (2012) Experimental Study of Pressure Drop Characteristics of Venturi Scrubber Working at Self-priming Mode. J. Atomic Energy Science & Technology, 46:1353-1356.
[4] Wang F.J. (2005) Computational fluid dynamics analysis. Tsinghua University Press, Beijing.
[5] Sun, Y.Q., Niu, W.Q. (2010) The influence of structural parameters of venturi on its water performance. J. Journal of Northwest A&F University, 38: 211-218.
[6] Tan, J.G., Liu, J.H., Wang, Z.G. (2010) A Dynamic Model of Venturi Tube for System Simulation. J. Journal of System Simulation, 12: 2788-2790.