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Experimental and numerical studies of the jet tube based on venturi effect

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ABSTRACT

Venturi has been widely used in the production and daily life due to its simple structure and low cost. This paper presents a jet tube, which is based on the venturi theory. The characteristic of the jet tube is that a rectangular opening is opened in the wall of the tube, which is linked to the outside of the tube. We conduct research and make a design to the structure of the rectangular opening. Then, a mathematical model is established for the analysis of the velocity on the rectangular opening. A careful study has been done on the relationship between the different parameters by experiments and simulations. SC/Tetra, the fluid analysis software, has been used in the simulation. The experimental study verifies the suction of the jet tube, the velocity distribution and size of the rectangular opening. Besides, the model has been improved by experiments and simulations. It provides the theory basis for analyzing the suction within the jet tube.

1. Introduction

When gas or liquid flows in the venturi, dynamic pressure reaches the peak, and static pressure is the lowest in the throat. Thus, pressure difference generates in the throat, which is used to measure flow or produce suction force. Relationship between the tube diameter and angle of the inlet has been obtained by experiments and theoretical analysis. Therefore, venturi has been widely utilized in production, such as vacuum cleaners, powder conveying, cooler, flow meter, dryer etc [1–3]. What's more, it has been extensively applied in the venturi scrubber [4–10].

The fundamental structure of the venturi is throat. For example, flow meter is based on the pressure difference between the throat and tube. Cong XU [11,12] designed a compact reverse flow diverter pumping system and a compact pneumatic pulse-jet pump improved on the venturi, which was used for transferring liquid–solid mixtures and lifting or transporting a hazardous fluid through a narrow mounting hole.

In this paper, the performance of the jet tubes with different sizes is analyzed. Some tubes are designed, manufactured and tested with a certain amount of airflow. The aim of design is that reduce the diameter of the throat, which will contribute to increase the velocity of airflow and improve the suction ability. Firstly, we make a theoretical analysis on the jet tube by simulations and experiments. Secondly, we derive a mathematical model through simulation results. Finally, we analyze performance of the jet tube and calculate the force generated by the suction effect. This paper presents a simple suction device whose aim is to make a small screw enter into the tube by the suction force. This device is based on the venturi effect, and it has several features: low cost, small size and high efficiency. With the development of industrial automation technology, orderly delivery of micro parts is an urgent issue, while the jet tube can offer an effective method to solve this problem.

2. Structure and principle of the jet tube

This paper presents a jet tube (shown in Fig. 1), which has a rectangular opening in the wall of the tube. L is its length and b width. The diameter of the inlet tube is D_1, the angle of taper hole is θ, the diameter of the throat tube is d, the length is S, and the diameter of the outlet tube is D_2. The working principle of the jet tube is that compressed air enters into the tube whose radius is D_1, and then gets through the throat. As a result, the pressure of the airflow decreases and produces a suction effect. Supersonic of the jet can be reached at the throat by reasonable design of the tube [13]. The situation of the venturi, when the throat diameter is a few millimeters, has been analyzed [14–16].

When jet flow enters into the tube (diameter is D_2), it will take away the air from the tube and generate suction effect. The larger the jet velocity is, the greater the suction force becomes. The

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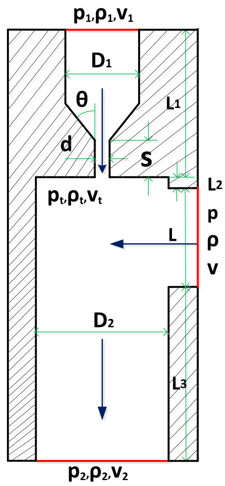

Fig. 1. The structures of the jet tube.

velocity of the jet plays an important role in improving the work performance of the jet tube, it is connected with tube diameter (D_1), the angle of the taper hole (θ), the throat diameter (d), and the inlet velocity (V_1) and pressure (P_1). The jet velocity and suction ability are improved by narrowing the throat diameter. Fig. 2 is the working principle of the jet tube. Little screws refer to the type of M1 or M2. It is quite tricky to delivery by traditional ways.

3. Airflow acceleration phase

The pressure loss, caused by the changes of the tube diameter, doesn't consider in the traditional analysis [17]. When the changes of the diameter are small, the pressure loss is not considered, but the changes of the diameter are larger, the pressure loss has to be considered. Standard and non-standard contraction angles of the venturi have been researched by experiments [18]. Most of the researches focus on the changes of the contraction angle, but less focus on the throat diameter when it's a few millimeters. The simulation of the tube with different angles by using fluid simulation software SC-Tetra. SC-Tetra is large-scale general analysis software CFD, an unstructured grid based on flexible and adaptive grid technique solution. SC/Tetra is commonly used in the laminar flow and turbulent flow, heat flow, multiphase flow, rotating machinery etc. The type of fluid is air. The simulation uses the standard turbulence model (k-ε). The number of mesh is 1,000,000, and the mesh type is octree. The conditions of the inlet are controlled by the airflow velocity, rectangular opening and outlet, by pressure, and its reference pressure is zero. The other wall is the stationary wall. All parameters in the process of solving are stable, and this is the convergence condition. $D_1 = 5$ mm, $d = 1$ mm, $L_1 = 15$ mm, $V_1 = 10$ m/s, $S = 1$ mm is model parameters. Results are presented in Table 1. It can be clearly observed that with the increase of contraction angle, the velocity of throat increase is very small. However, as the contraction angle increases, the inlet pressure increases are rapid. When the angle increases every 15°, the pressure increases 2000 Pa approximately. Therefore, when the tube length L_1 is constant, we should narrow the contraction angle, in order to reduce pressure loss.

Length of the throat has an important influence on the jet velocity as well. Table 2 displays the length changes of the throat influence on the jet velocity. The model parameters are $D_1 = 5$ mm, $d = 1$ mm, $V_1 = 10$ m/s, $L_1 = 14$ mm, $\theta = 45°$.

We can see from Table 2 that with the increase of the throat length, the velocity of the outlet increases not obviously, but inlet pressure increases sharply. Therefore, the throat length should be fixed as small as possible under the condition of working requirements.

The jet tube can't avoid pressure loss in the process of airflow acceleration, which caused by diameter changes, so set a constant λ and make it meet the formula

$$v_t = (1-\lambda)\left(\frac{p_t}{p_1}\right)^{-1/r}\left(\frac{A_1}{A_t}\right)v_1 \quad (1)$$

In order to calculate λ on a certain range of tube diameters, we get the pressure loss data by simulations, and then analyze the changes of λ. Tube diameter ratios of the six models are $D_1/d = 5/3$, 5/2, 5/1, 5/0.8, 5/0.6, 5/0.4 (mm), $\theta = 45°$, $S = 1$ mm, $V_1 = 10$ m/s. Relationship between λ and tube diameter ratio are shown in Fig. 3.

In Fig. 3, λ increases with the rise of the tube diameter ratio. Relationship between the two parameters are obtained by the least square fitting method, show as

$$\lambda = 0.083\frac{D_1}{d} - 0.18 \quad (2)$$

The mathematical model can be utilized in the calculation of the throat velocity. Combining Eq. (1) and Eq. (2), resulting in

$$v_t = \left(1.18 - 0.083\frac{D_1}{d}\right)\left(\frac{p_t}{p_1}\right)^{-1/r}\left(\frac{A_1}{A_t}\right)v_1 \quad (3)$$

Then the velocity of throat exit can be calculated by Eq. (3), and it was used in the situation when the tube diameter changes a lot.

4. The experiment and simulation

Four tubes of different sizes have been used in the experiments. The structure of the jet tube is illustrated in Fig. 4. It is divided into two parts, upper and lower are connected with a close fit. Air compressor provides airflow during the experiment, and maintains the pressure at 0.8 MPa. Compressed-air machine is linked with pipe (outer diameter Ø6 and inner Ø4, length 605 mm), and another tube (outer diameter Ø4 and inner Ø2 lengths 185 mm), the test tube and pipe are combined by pneumatic fitting M5 thread. Fig. 5 is the experimental setup. It mainly contains the following components: compressed air tanks, pressure gauge, flow meter, jet tube, valve, filter, reducing valve, measuring device, etc. Hot wire anemometer, a measuring device, is used to measure the velocity of the rectangular opening. Experiments are conducted to measure the velocity of the rectangular opening.

The structure parameters of the test tube are shown in Table 3.

Based on the above experiments, it can be concluded that the velocity of the rectangular opening is decided by the tube parameters. Table 3 indicates the changes of tube parameters. Fig. 6 depicts the velocity of the rectangular opening, which is the average velocity at points of each 2 mm distance.

We conduct simulations by the fluid software SC/Tetra. All of the simulation models are 3D, the mesh model and the simulation result (Fig. 7), whose parameters is $D_1 = 5$ mm, $S = 1$ mm, $\theta = 90°$, $L = 16$ mm, $b = 6$ mm, $D_2 = 6$ mm, $V_1 = 10$ m/s, $L_2 = 0.5$ mm, $d = 0.6$ mm. The simulation uses the standard turbulence model (k-ε). The mesh number is about 2,000,000, and the mesh type is octree. The conditions of the inlet are controlled by the airflow velocity, rectangular opening and the outlet, whose reference pressure is zero, controlled by pressure. The other wall is the stationary wall. All parameters in the process of solving are stable, and this is the convergence condition. Mesh of the throat is refined, which different from tube mesh. Fig. 7 is the result of the velocity vector.