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RESEARCH ON NEW ENERGY-SAVING VACUUM EJECTOR WITH FLOW SELF-REGULATION

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ABSTRACT

Jet vacuum ejectors currently used have a defect of large air consumption due to the need of continuous and constant air supply. To solve this problem, a novel technical structure of the jet vacuum ejector with flow self-regulation by an adjustable cone has been investigated. In this paper, the structure, key technologies and experiment of this new jet vacuum ejector are introduced. In the new ejector, by means of the adjustable cone, the effective cross section at the jet nozzle throat could be adjusted so as to realize the reduction of air supply and achieve energy saving. For this, a key technology for the new structure called chamber-separating pneumatic-magnetic driving is studied, in which a vacuum detecting-differential pressure actuating and non-contacting pneumatic-magnetic driving with a coaxial magnetic ring-axial structure are implemented. Experimental results for the flow self-regulated vacuum ejector have shown that the vacuum response time and maximum vacuum of new ejector are almost equivalent to the constant-area vacuum ejectors with the relative parameters, but the air consumption could save about 14.8%.

KEY WORDS

Vacuum ejector, Vacuum feedback, Magnetic actuating, Air consumption, Energy saving

INTRODUCTION

As a kind of operation form in automation, vacuum attraction technology is widely used in industry [1]. However, as a kind of locally-used vacuum generator, an ordinary jet vacuum ejector must be supplied continuously with constant air when working, so that large air consumption and large corresponding energy consumption are caused. It is an unsolved technology problem how to reduce the energy consumption but to maintain the original working performance in developing a new kind of energy-saving ejector.

Focusing on this problem, much research work has been done recently. For example, there is newly-developed vacuum-generating unit, which integrates vacuum nozzle, check valve and vacuum switch [2] and could control solenoid valve to shut off the air supply when system vacuum reaches at a set vacuum value. When removing workpieces with this vacuum unit, the air consumption could be decreased to 80% or so [3]. However, due to the increase of flow resistance brought by the check valve and corresponding up to 40% decrease of the exhaust flow, the vacuum response time of this unit would be obviously increased. Another example is a kind of energy-saving parallel-nozzle ejector [4~6]. In this ejector, two parallel nozzles which have different diameter have been used to realize quick vacuum response within the vacuum response stage. Within the vacuum maintaining stage, only the smaller nozzle is switched to work by a solenoid to maintain the vacuum for energy saving. But the parallel-nozzle ejector could not adapt various kinds of complex working conditions because there are only two fixed nozzles and therefore the energy saving effect of the parallel-nozzle ejector is still not so perfect. In this paper, a new energy-saving technology for jet vacuum ejector is presented. The research idea is to adjust the effective cross section of the nozzle by means of automatic technical operation so as to achieve the result to regulate the air supply and reduce the air consumption. For this, the structure, key technologies and experiments of this new jet vacuum ejector are introduced in following sections.

THE STRUCTURE AND KEY TECHNOLOGIES OF VACUUM EJECTOR WITH FLOW SELF-REGULATION

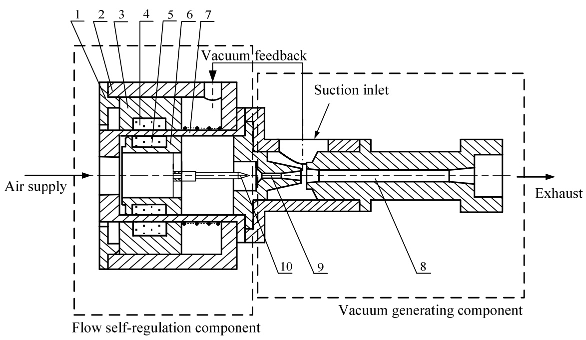
The Structure of Vacuum Ejector with Flow Self-regulation

The general structure of vacuum ejector with flow self-regulation is shown in Figure 1. (This new ejector with flow self-regulation has applied for China Paten). It is made of two components, one is the vacuum generating component and another is the flow self-regulation component, in which the working principle of the vacuum generating component is as same as that of a normal jet vacuum ejector, i.e., when the ratio of the pressure at the nozzle throat in the Laval duct 9 to the supply pressure exceeds a certain value, the supersonic jet flow could be formed at the outlet of the Laval duct. At the nozzle throat there is a vacuum to be produced. Then the flow from the suction chamber into the mixing chamber is formed and the ejecting gas is brought out of the ejector through the mixing duct. Therefore the local vacuum in the suction chamber could be formed. If the change of the supply temperature could be neglected, the supply flow rate q is in direct proportion to the effective cross section of the nozzle throat A_t [7].

In the flow self-regulation component, the adjustable cone 10 connected with the slave core is in the front of Laval duct and is coaxial with the Laval duct. The magnetic ring 4 and the magnetic ring 5 are installed on the active ring 3 and the slave core 6 respectively. The left chamber adjacent to the active ring 3 is open to the atmosphere and the right chamber is connected with the vacuum chamber of the ejector. When the ejector ceases working, the active ring, the slave core and the adjustable cone are all on the end of the left position where the adjustable cone keeps a distance away from the Laval duct throat (indicated with the real line in the Figure 2). When vacuum is generated by the ejector, a pressure difference on the two sides of the active ring could be formed and the active ring would be moved to the right. Thus the slave core and the adjustable cone would be driven towards the right and approaches the Laval duct throat by the magnetic force of the two magnetic rings (indicated with the broken line in the Figure 2). Therefore, the effective cross section of the nozzle throat could be adjusted so as to realize the reduction of air supply and achieve energy saving.

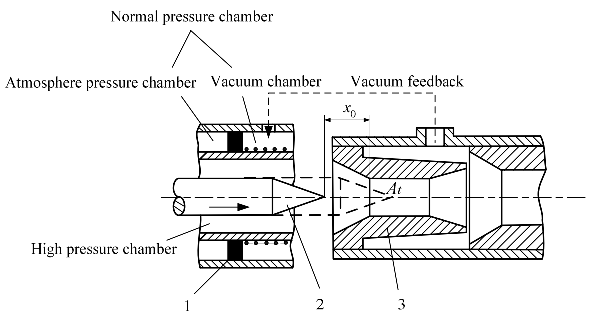
Technology of Vacuum Detecting And Differential Pressure Actuating

The driving force of the vacuum ejector with flow self-regulation is one of the key technologies in the structure design of the ejector. A vacuum feedback-differential pressure actuating technology has been presented which is illustrated in Figure 2. In this technical scheme, the working vacuum pressure is fed back directly to the vacuum chamber. The active ring is used to detect and amplify the differential pressure between vacuum and atmosphere pressure and the differential pressure is used for the driving force of the moving components. The merit of the scheme is that it directly utilizes the vacuum pressure to drive the moving components and could meet the work requirements of automatic flow regulation according to the real-time working vacuum. Moreover it has such advantages as rapid response speed, simple structure and good reliability.



1.cover 2.body 3.active ring 4,5.magnetic ring 6.slave core 7.sleeve 8.mixing duct 9.Laval duct 10.adjustable cone

Figure 1 The structure of vacuum ejector with flow self-regulation



1.active ring 2.adjustable cone 3.Laval duct

Figure 2 Scheme of the vacuum feedback-differential pressure actuating technology

Technology of Pneumatic-Magnetic Driving With Chamber-Separating

As above-mentioned, the driving force of the moving component is produced from the normal pressure chamber constituted of atmosphere pressure chamber and the vacuum chamber, while the adjustable cone acting as a flow regulation part is in the high pressure chamber where the supplied air flows through, so it is another key technology how to use the driving force coming from the normal pressure chamber to drive the adjustable cone in the high pressure chamber, as well as to keep reliable sealing between the two chambers. The normal mechanical transmission-mechanism is difficult to satisfy the sealing requirement between the two chambers. A pneumatic-magnetic driving with chamber-separating and coaxial magnetic ring-axial structure has been presented. As shown in Figure 1, the magnetic force between two magnetic rings which are embedded in the active ring 3 and the slave core 6 respectively could realize the non-contracting driving from the normal pressure chamber to the high pressure chamber. The merit of this technology is that under the condition of effective driving of the adjustable cone it could ensure that the two chambers are not connected through in structure and satisfy radically the sealing requirement between the two chambers.

THEORETICAL MODEL

Dynamic Model of Flow Self-Regulation Component

The force analysis of the flow self-regulation component is shown in Figure 3.

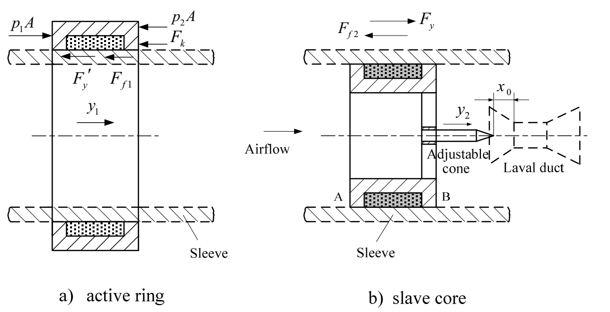


Figure 3 The force analysis of the active ring and the slave core

$$m_1 \frac{d^2 y_1}{dt^2} = p_1 A - p_2 A - k_t \left(y_0 + y_1 \right) - F_{f1} - F_y' \qquad (1)$$

$$m_2 \frac{d^2 y_2}{dt^2} = F_y - F_{f2} \qquad (2)$$

Where magnetic force F_y

$$F_y = \frac{-\sigma^2}{2\pi\mu_0} s[2\Gamma\left(\Delta y\right) - \Gamma\left(\Delta y + L\right) - \Gamma\left(\Delta y - L\right)] \qquad (3)$$

In Eq.(3), function $\Gamma\left(z\right)$

$$\begin{aligned}\Gamma\left(z\right) = \{&\left(c+h\right)\mathrm{tg}^{-1}\frac{c+h}{z} - 2c\mathrm{tg}^{-1}\frac{c}{z} \\ &+\left(c-h\right)\mathrm{tg}^{-1}\frac{\left(c-h\right)}{z} - \frac{z}{2}[\ln\left(\left(c+h\right)^2 + z^2\right) \\ &-2\ln c^2 + \ln\left(\left(c-h\right)^2 + z^2\right)]\}\end{aligned} \qquad (4)$$

In Eq.(1)~Eq.(4), m is mass of moving component,[kg], y is displacement of moving component,[mm], p is pressure,[MPa], A is area of the active ring,[mm^2], k_t is coefficient of resilience,[N/mm], y_0 is initial compressed displacement of spring,[mm], F_f is friction force,[N], F_y is magnetic force,[N], σ is induction density,[T], μ_0 is vacuum magnetic conductivity, s is average circumference of the magnetic ring couple,[mm], Δy is lag displacement with which little magnetic ring moves behind the big one,[mm], L is width of the magnetic ring,[mm], h is thickness of the magnetic ring,[mm], c is radial distance of center of cross section between two magnetic rings,[mm].

Effective Cross Section of Nozzle Throat

When the adjustable cone is not inside the nozzle, the effective cross section of the nozzle throat can be expressed as

$$A_t = \zeta \frac{\pi}{4} d_0^{\ 2} \qquad (5)$$

When the adjustable cone is inside the nozzle, as shown in Figure 4, the effective cross section of the nozzle throat can be expressed as

$$\begin{aligned}A_t = \zeta\pi\left(l - y_2 + x_0\right)\sin\alpha \times \\ \left[d_0 - \left(l - y_2 + x_0\right)\sin\alpha\cos\alpha\right]\end{aligned} \qquad (6)$$

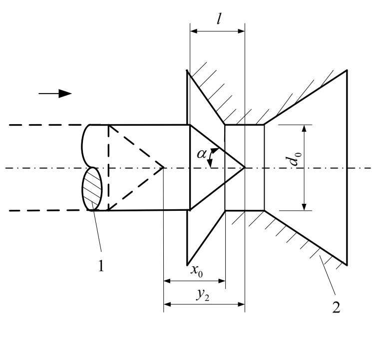


Figure 4 Relative location of adjustable cone and nozzle

In Eq.(5)~Eq.(6), d_0 is diameter of the nozzle throat,[mm], l is axial length of the cone for the adjustable cone,[mm], x_0 is initial design location of the adjustable cone,[mm], α is half angle of the cone for the adjustable cone,[°], ζ is correcting coefficient.

Air Consumption of Vacuum Ejector

The air consumption of vacuum ejector Q can be expressed as

$$Q = \int_0^t q\mathrm{d}t = \int_0^t \frac{p_s A_t}{\sqrt{T_s}} \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}\,\eta_p \mathrm{d}t \tag{7}$$

In Eq.(7), p_s is supply pressure,[MPa], T_s is supply temperature,[K], k adiabatic coefficient, R is gas constant, η_p correcting coefficient.

REGULATING STRATEGY OF THE ADJUSTABLE CONE

When the adjustable cone is inside the nozzle, the flow field of the vacuum ejector would tend to be bad due to the change of the structure parameter of the duct. If the regulating strategy of the adjustable cone is not reasonable, the performance of the ejector would be dropped greatly and as a result the ejector might not work normally. Therefore it is necessary to find a reasonable regulating strategy of the adjustable cone.

Force on the Adjustable Cone from Airflow

The forces that airflow exerts on the adjustable cone are shown in Figure 5.

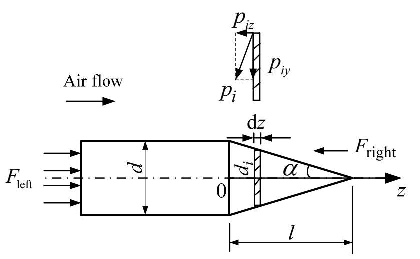


Figure 5 Forces that airflow exerts on the adjustable cone

The resultant force F could be expressed as

$$F = F_{\text{left}} - F_{\text{right}} = \frac{\pi}{4} p_s d^2 - \int_0^l 2\pi p_i \left(l - z\right) \sin\alpha \tan\alpha \mathrm{d}z \tag{8}$$

In Eq.(8), d is the column diameter of the adjustable cone,[mm], p_i is the airflow pressure distribution on the cone of the adjustable cone,[MPa].

When the distance x with which the adjustable cone enters the nozzle throat is 0 (i.e., the adjustable cone is not inside the nozzle), 0.5mm, 1.0mm, 1.5mm, 2.0mm, 2.5mm respectively, the airflow pressure distribution p_i on the cone of the adjustable cone obtained from simulation by CFD (Computational Fluid Dynamics) method is shown in Figure 6. It can be clearly seen that the bigger x is the shorter the high pressure range on the cone is and the longer the low pressure range is. Moreover, the gradient from high pressure range is gradually enlarged with the increase of x.

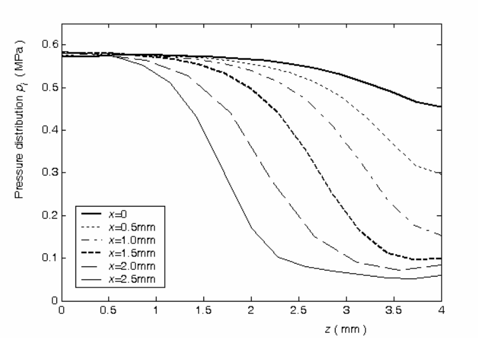


Figure 6 The airflow pressure distribution on the cone of the adjustable cone

The airflow resultant force F exerted on the adjustable cone for different x is shown in Figure 7. It can be seen that the resultant forces are all positive for different x and the bigger x is the larger the airflow resultant force is. Therefore, such conclusion could be drawn that the airflow force tends to push the adjustable cone into the nozzle throat.

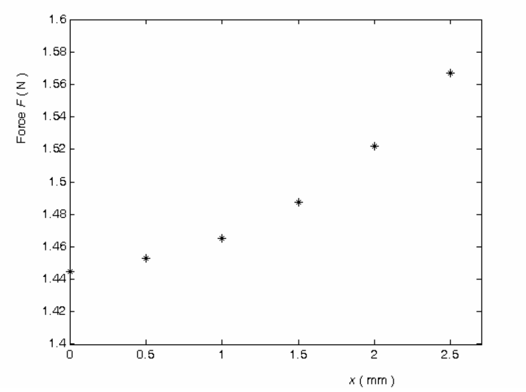
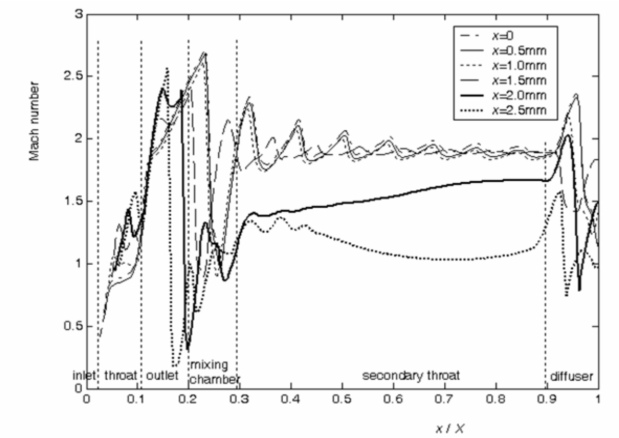


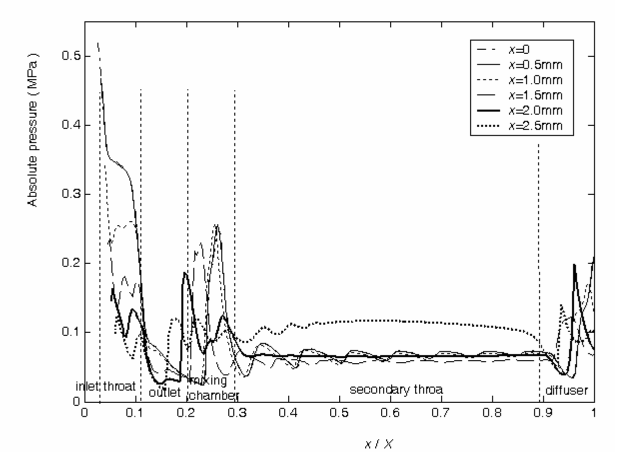
Figure 7 The airflow resultant force on adjustable cone

Study on Regulating Strategy of The Adjustable Cone

When the distance x is 0, 0.5mm, 1.0mm, 1.5mm, 2.0mm, 2.5mm respectively, Mach number and the static pressure along the axis of the 2-D flow field for vacuum ejector obtained from simulation by CFD are shown in Figure 8. It can be seen that Mach number of the nozzle throat is increased with the increase of x, the supersonic field shifts to an earlier position and the oscillation of Mach number is increased. Moreover, the



(a) Curves of Mach number



(b) Curves of static pressure along axis

Figure 8 Comparison of flow fields for different *x*

maximum vacuum field shifts from mixing chamber to the taper exit of the nozzle and the vacuum of the mixing chamber is gradually decreased. In addition, Mach number of the flow field in the secondary throat is also gradually decreased and the absolute pressure tends to increase. In simulation, when $x \leq 2.0$mm, the flow speed in the secondary throat is still sonic. For example, the maximum vacuum in the mixing chamber is about 65kPa when x=2mm. However, Mach number in the secondary throat is smaller than 1, while the absolute pressure is higher than 0.1MPa when x=2.5mm, i.e., the air flow in this field has been decreased to subsonic speed and the vacuum in the mixing chamber has been reduced to 40kPa. This indicates that the vacuum ability of ejector is too weak to maintain normal operation.

Therefore, regulating strategy of the adjustable cone should be suggested that the distance with which the adjustable cone enters the nozzle throat should be controlled within a range which is determined by the required minimum vacuum of the ejector in real operation. For example, when the minimum vacuum required by the real operation of the vacuum system is 65kPa, the distance with which the adjustable cone enters the nozzle throat should be controlled within 2mm under the given condition for tested prototype ejector.

EXPERIMENTAL RESULTS

The experimental studies have been conducted to measure the working performance of the flow self-regulated vacuum ejector (self-regulated ejector in short). For comparison, the vacuum generating component of the flow self-regulated vacuum ejector (constant-area ejector in short) has been measured too.

The experimental apparatus is shown in Figure 9. In the experiment, the supply pressure is 0.55 MPa, the volume of the vacuum chamber is 1 L and the diameter of the nozzle throat is 2 mm.

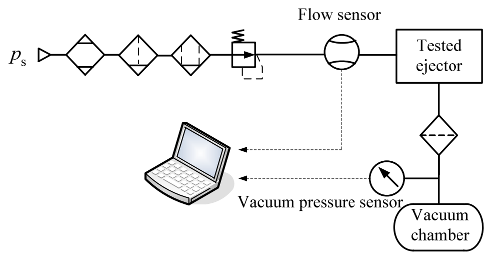
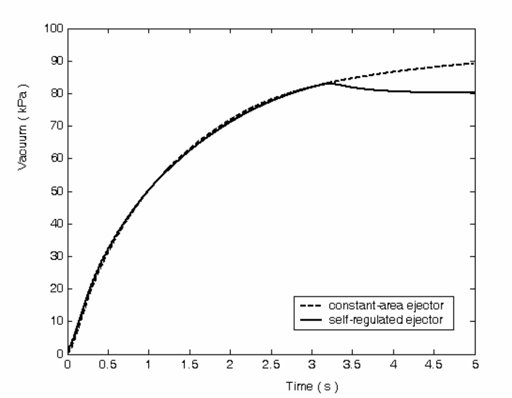
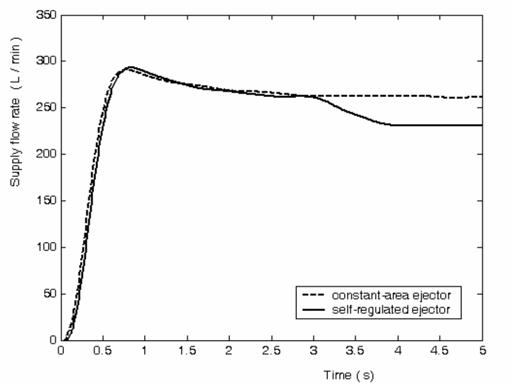


Figure 9 Experimental apparatus

The testing results for the self-regulated ejector and the constant-area ejector are shown in Figure 10.



(a) Curves of vacuum



(b) Curves of supply flow rate

Figure 10 Comparison of measured working performances for the self-regulated ejector and the constant-area ejector

Usually the normal vacuum range of the vacuum system is from 63% to 95% of the maximum vacuum. The time when the vacuum reaches 63% of the maximum vacuum 90 kPa is defined as the vacuum response time and in this case it is 57 kPa. From Figure 10 (a), it can be seen that the vacuum response times of the self-regulated ejector and the constant-area ejector are almost the same, about 1.25s. This indicates that the quick vacuum response performance of the self-regulated ejector is as good as that of the constant-area ejector. Moreover, although the maximum vacuum of the self-regulated ejector in the vacuum keeping stage is less than that of the constant-area ejector, this vacuum is still kept above 80kPa. This indicates that the vacuum of the self-regulated ejector could still maintain the normal operation. From Figure 10 (b), it can be seen that before 3 s curves of the supply flow rate of the two kinds of ejectors are almost coincident. However, after about 3 s, the supply flow rate of the self-regulated ejector is obviously less than that of the constant-area ejector. The supply flow rate of the constant-area ejector is 270 L/min at the vacuum keeping stage, while that of the self-regulated ejector is 230 L/min. As a result the air supply is reduced by about 14.8%.
The comparison of air consumption of the self-regulated ejector and the constant-area ejector on each time point within 20 s is shown in Figure 11. It can be seen that all the air consumption of the self-regulated ejector on every time point is less than that of the constant-area ejector. If the time of a working cycling is 20 s, the air consumption of the self-regulated ejector within one working cycling could be reduced by about 13.3 L compared to that of the constant-area ejector. It can be roughly figured out that the self-regulated ejector could reduce the air consumption about 12,768 L in every day if the time of a working cycling is 20 s, the time interval is 10 s and the whole working time of everyday is 8 h.

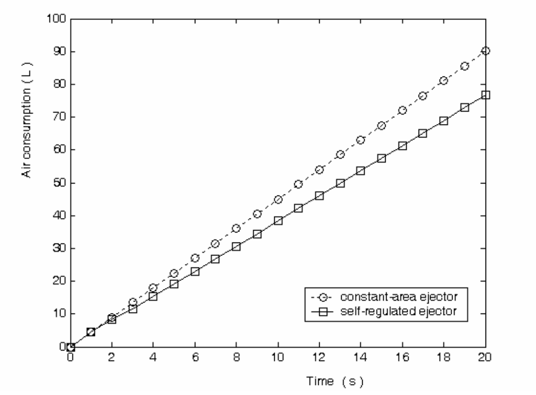


Figure 11 Comparison of the air consumption

CONCLUSION

Jet vacuum ejectors have a defect of large air consumption in use. To solve this problem, in this paper, a novel jet vacuum ejector with flow self-regulation by an adjustable cone has been presented and implemented for the first time. For this, research for the general structure, key technologies and experiment of this new jet vacuum ejector have been conducted. Some conclusions could be drawn as follows.
(1) The structure of the flow self-regulation ejector has been studied and realized. The vacuum feedback-differential pressure actuating technology and the chamber-separating pneumatic-magnetic driving with a coaxial magnetic ring-axial structure have been presented. The technical problem of non-contacting driving resulted from the sealing requirement between the high pressure chamber and the normal pressure chamber has been solved.
(2) The accurate forces that airflow exerts on the adjustable cone in the two-dimension flow field are analyzed. Then the regulating strategy of the adjustable cone has been studied and suggested, i.e., the minimum vacuum required by the normal operation of the vacuum system must be greater than 65kPa, while the distance with which the adjustable cone enters the nozzle throat should be controlled within 2mm under the given condition for tested prototype ejector.
(3) The basic working characteristics of the flow self-regulation ejector have been tested. Experimental results have shown that the vacuum response time and maximum vacuum of new ejector are almost the same compared to the constant-area vacuum ejectors with corresponding parameters, while the air consumption could be reduced by about 14.8%.

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