# Design of rotor air-operated pump mechanism and dynamics analysis

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**Abstract**

The study combines the merits of pump transportation mechanism and swivel mechanism in Concrete Wet Abrasive Blasting Machine, designs new air-operated spring-piston mechanism to complete the transportation of concrete, deduces the calculation formula of loss in pressure of concrete vertical pump transportation mechanism, completes dynamic analysis of the machine, establish the relevant equations.

*Keywords*: wet abrasive blasting machine, rotor, air-operated, spring-piston mechanism

## 1 Introduction

According to the working principle, domestic Concrete Wet Abrasive Blasting Machine can be divided into pump transportation type and wind transportation type. Wet Abrasive Blasting Machine of pump transportation type is transported by concrete pump and a nozzle is installed on the outlet of the delivery pipe. With high-pressure gas passing through the nozzle, concrete is ejected. The main types are piston pump type, screw type, extrusion pump, etc. Pump transportation has complex structure, requiring high pressure levels, the larger models, mobile inconvenience, but long distance transportation. Common domestic products are YSH type, XBS piston type, SPL spiral type and GJB-S type extrusion Wet Abrasive Blasting Machine. Through compressed air, Wet Abrasive Blasting Machine of wind transportation type transports the concrete material to the nozzle in delivery pipe in the form of "rarefied flow" to spray. The main types are rotor type, spiral type, rotary piston type, tank type, impeller type, etc. Wind transportation has short transportation distance, poor maintainability and mobility, as well as return air phenomena [1]. Common domestic products are SPZ-6 type from Beijing General Research Institute of Mining and Metallurgy, HSP6 type from Shandong Dezhou Shengjian Machinery Co. LTD, HTS300 type from Anqing Special Engineering Machinery Research Institute.

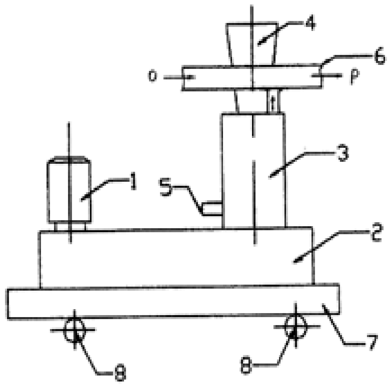
## 2 Current situation of rotor blasting machine

Rotor Wet Abrasive Blasting Machine has a simple structure, stable performance, light weight, etc., so it is well received by the operators [2]. It is widely studied in our country and has grown to nearly 20 kinds of models through continuous improvement. However, due to constraints of the working principle and structure of it, on-the-spot operating conditions in coal mine, the space environment, underground construction methods and workers' operation level and other aspects, rotor Wet Abrasive Blasting Machine needs to be further optimized designed to accommodate the requirements of working conditions in coal mine.

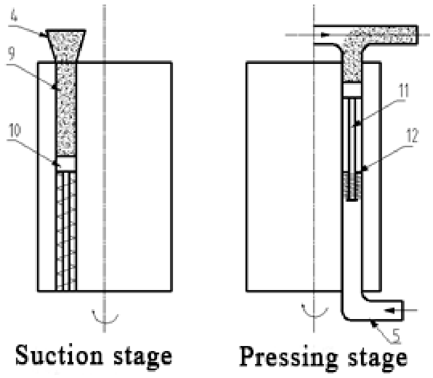
The key components of the machine is rotor block mechanism, and the working principle is that in the space that is formed by rotor block and coupling plate, when working, wet mixing concrete in the hopper falls into the material hole, and when the rotor rotates, the material hole and compressed air inlet are connected. Under the pressure, the concrete material is transported to the nozzle in delivery pipe in the form of "rarefied flow" to spray. Common domestic structure of rotor block mechanism has varied forms, but regardless of its location, or the changes of its structure or its configuration with other components, their fundamentals are still similar to the blasting type I or type II. Therefore, based on Rotor Wet Abrasive Blasting Machine and the air leakage and grouting off target problems of traditional air-operated machine, this study designs new rotor block mechanism which is air-operated piston Concrete Wet Abrasive Blasting Machine.

## 3 Working principle of air-operated piston concrete wet abrasive blasting machine

The newly designed air-operated piston rotor mechanism combines the features of the traditional rotor and pump transportation mechanism with a spring piston mechanism set in the rotor material pipe, and the structure is shown in Figure 1. Its main components include rotor block, spring piston, guide mechanism, coupling plate and so on. The interval of the feeding pipe and discharge pipe of Wet Abrasive Blasting Machine and is set on the top of air-operated piston rotor, which has 6 to 12 even-distributed piston cylinders inside. When working, the air-operated piston rotor rotates driven by transmission device, and when the piston cylinder rotates to the mouth of the feeding pipe, the piston rod moves downward under the effect of the restoring force of the return spring. Under the negative pressure of internal piston cylinder, wet mixing concrete in the feeding pipe is sucked into the piston cylinder. When the fully-stuffed piston cylinder rotates to the mouth of the tube, the mouth of the pipe in the bottom of piston cylinder corresponds to the mouth of air inlet pipe of high-pressure gas, and driven by the gas, the concrete is transported to discharge pipe by pump. With accelerating agent added into the delivery pipe, under the pressure of wind, the wet concrete is sprayed to the sprayed surface so that the blasting is completed.




Gripping material phase




Crushing material phase

1-motor; 2- transmission device; 3- air-operated rotor; 4- feeder hopper; 5- air inlet pipe; 6- delivery pipe; 7- chassis; 8-wheel; 9- piston cylinder; 10- piston; 11-piston guide rod; 12-guide ring

FIGURE 1 Diagram of rotor air-operated wet abrasive blasting machine

## 4 The feature and kinetic analysis of air-operated piston pump transportation

The newly designed air-operated piston pump transportation mechanism has the features of common two-cylinder reciprocating pumping transportation mechanism, but under effect of the external power of new mechanism and a return spring. The feature and kinetic analysis of air-operated piston pump transportation must be studied to obtain the relationship of parameters of the pressure of high-pressure gas and the blasting pressure of concrete at the outlet of the piston cylinder. The diameter of the piston cylinder, the length of the piston cylinder, slump of concrete, flow rate of high-pressure gas, and the stiffness of spring so as to provides a theoretical basis for the design of pumping mechanism.

### 4.1 PRESSURE LOSS ANALYSIS OF PUMP TRANSPORTATION OF CONCRETE

Concrete fluid is similar to Bingham fluid [3], and the study on pump transportation concrete can be considered as the fluid along the pipe under the effect of Bingham fluid. Concrete Wet Abrasive Blasting starts from the overcoming of the adhesion of concrete (i.e., yield stress Sy) starts, and driven by the piston, due to the pressure difference between the concrete plug flow, concrete is transported to the discharge pipe of the blasting machine. This requires maximum pressure applied to plug flow and it must overcome the delivery resistance and maintain a certain moving speed of the plug flow, besides, delivery pressure mixed with high-pressure blasting gas is needed to ensure that the wet mixed concrete can be transported to blasting pipe to complete the blasting.

For air-operated piston mechanism shown in Figure 1, the concrete plug flows along the tilted straight pipe, and plug flow fills the whole pipe section. In a closed cavity, concrete is generally assumed incompressible, so the pressure of the concrete is basically a fixed value, and the flow rate is related to piston motion. When the piston pushes concrete, the resistance can be regarded as the combination of two parts, adhesion force and friction force. The resistance can be collectively referred to as the loss of resistance of fluid along the way, and the formula S.Morinaga [4, 5] applies to calculation. Plug flow model is shown in Figure 2, and the formula of pressure loss per unit length dx generated by the concrete flow is shown in Equation (1).

$$\Delta P_b = \left[\frac{2}{R}(K_1 + K_2\bar{\upsilon}) + \gamma \sin\varphi\right] N \qquad (1)$$

In the Equation: $\Delta P_b$-coefficient of resistance along the way per unit length; $R$-radius of concrete delivery pipe, m; $K_1$- adhesion coefficient, Pa; $K_2$- speed coefficient, Pa·s/m; $\bar{\upsilon}$ -average flow rate of concrete in the delivery pipe, m/s; $\gamma$- volume weight of concrete, N/m$^3$, $\gamma=\rho g$; $\rho$ - density of concrete ($\rho$ =240kg/m$^3$); g - acceleration of gravity, ($g$=9.8N); $\varphi$ - the angle between the axial and the horizontal delivery pipe; $N$ - the ratio of radial thrust and axial compressive force, 0.90 is applied to common concrete.

In the Equation, sticking coefficient K1 and speed coefficient K2 reflects the friction of concrete and inner wall of pipes, and they are affected by the ratio of concrete proportion and the roughness of the inner wall of pipes, in addition, it is also influenced by the material of straight pipe and temperature. However, the greatest impact is slump S of concrete, which can be calculated according to the empirical Equation (2).

$$\bar{K}_1 = (3.00 - 0.10S)\cdot 10^2$$
$$\bar{K}_2 = (4.00 - 0.10S)\cdot 10^2 \qquad (2)$$

In the Equation, $S$- slump of concrete, cm.

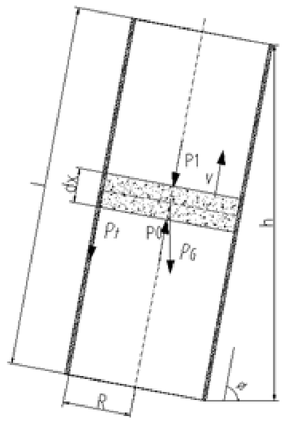


FIGURE 2 Model of concrete plug flow

When the straight pipe works vertically (angle between the straight pipe and horizon is 90 degrees), resistance loss caused by the concrete flow in the working process of piston pressing concrete is as follows:

$$P_l = I \cdot \Delta P_b = \left[ \frac{2}{R}(K_1 + K_2\bar{\upsilon}) + \gamma \right] NI \,. \tag{3}$$

In the Equation: *I*-length of concrete delivery pipe, m.

When the thrust force of piston is fixed, under the effect of the pressure of the thrust force of piston $P_0$, the maximum vertical height of delivery concrete is:

$$h_{\max} = \frac{P_0 R}{2N\left[(K_1 + K_2\bar{\upsilon}) + \gamma\right]} \,. \tag{4}$$

4.2 PRESSURE MOVEMENT BY PUMP TRANSPORTATION

According to Figure 1, the piston is located in the zero position in the cylinder if it isn't at work, at which the reset spring is in free extension. In the pressure stage, the piston pushes the concret to move upward under high-pressure gas and simutaneously compresses the reset spring. When it reaches the top limit, the pressing process is finished. Because the piston works vertically, it has no positive pressure against the cylinder wall. The friction between the piston ring and the cylinder, that between the piston rod and guide ring and the influence of guide ring on wind pressure can be neglected. It is suggested in the working state of the air-operated piston that the piston moves at only one degree of freedom, whose total force can be reduced to a vertically forced vibration of the spring oscillator. The mechanical model is shown in Figure 3.

Because the flow and pressure of the high-pressure air is in a constant value, the average speed of piston movement is approximately constant. The concrete outlet pressure can be inferred by the force equilibrium conditions.

$$P_0 - P_\psi - P_h = \frac{F_t + G_s + G_h}{S} \,, \tag{5}$$

$$P_h = \Delta P_h \cdot (I - dx) = (I - dx) \cdot \left[ \frac{2}{R}(K_1 + K_2\bar{\upsilon}) + \gamma \right] N \,, \tag{6}$$

$$F_t = k \cdot dx \,. \tag{7}$$

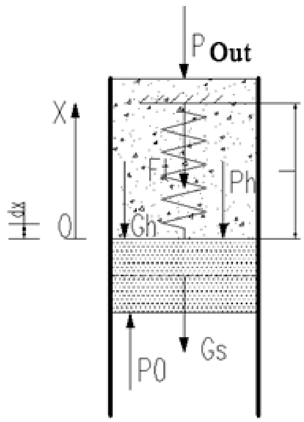


FIGURE 3 Mechanical model of spring oscillator of air-operated pistion (pressure stage)

In the for Equation, $P_0$-wind pressure of high-pressure air, Pa; $P_\psi$ flow pressure of the concrete in the piston outlet, Pa; $P_h$-resistance loss of concrete flow, Pa; $F_t$ -spring compressive force, N; $G_s$-piston gravity, *N*; $G_h$ -concrete gravity, N, Gh=γ (I-dx); *S*-sectional area of piston cylinder, m2; *K*-stiffness coefficient of the spring, N/m; *I*- working stroke of the piston, m; $\bar{\upsilon}$ -average flow speed of the concrete mixture in the conveying pipe, m/s, $\bar{\upsilon} = Q/S$ ; *Q*-flow of high-pressure air, m$^3$/s.

All these substituted into the equation, we can get a formula calculating the injection pressure of the concrete in the piston cylinder outlet, as in Equation (8).

$$P_\psi = P_0 - (1 - dx) \cdot \left\{ \frac{2}{R}\left[ K_1 + K_2 \cdot \frac{Q}{S} \right] + \gamma \right\} N - \frac{kdx + \gamma(I - dx) + G_s}{S} \tag{8}$$

The Equation shows the injection pressure of concrete is greatly influenced by piston movement distance, slump of the concrete, cylinder diameter and length and the spring stiffness. The return force of the spring is small in the initial movement of the piston, when the friction pressure loss in the concrete movement is the key influential factor. With the movement of the piston, the less the friction pressure loss becomes, the more the return force of the spring. In the late movement, the return force of the spring has a crucial influence on the injection pressure.

4.3 SUCTION MOVEMENT BY PUMP TRANSPORTATION

In the suction stage, the relief hole under the piston cylinder is connected with the external. Under the force produced by return force of the restoring spring and its gravity, the concrete mixture in the hopper goes into the cylinder and finishes the suction process when the piston moves downward to the middle zero position. When the piston rotor turns the transposition and if the piston cylinder seals well and the compressed spring doesn't move, the piston dynamic model can be formulated as in Figure 4.

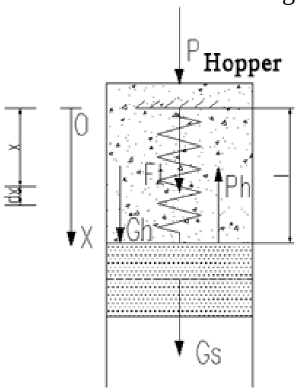



FIGURE 4 Dynamic model of air-operated piston spring viberator (suction stage)

When the piston moves downward, the piston cyclinder bottom is connected with the external air and its speed is in an inconstant value. The movement parameter can be inferred by Lagrange Equation. Given the pressure of the hopper on the piston is constant and neglecting the quality of the spring, take linear displacement x as generalized coordinates and the position of maximum compressed state of the spring as common energy zero point, and then we can have Kinetic energy of he system:

$$T=\frac{1}{2}M\dot{x}^2+\frac{1}{2}\gamma x\dot{x}^2 . \quad (9)$$

Potential energy of the system:

$$V=-Mgx-\gamma x^2-\frac{1}{2}k(I-x)^2 . \quad (10)$$

Generalized force:

$$Q=[P_{\mu 4}-G_h]S=[P_{\mu 4}-\Delta P_h\cdot x]S= \left\{P_{\mu 4}-xN\left[\frac{2}{R}\left(K_1+K_2\dot{x}\right)+\gamma\right]\right\}S \quad (11)$$

Movement Equation the system:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right)-\frac{\partial L}{\partial x}=Q . \quad (12)$$

Substitute $L=T-V$ into the equation, we can get:

$$P_{\mu 4}S+Mg-kI=\left(M+\gamma x\right)\ddot{x}+\frac{1}{2}\gamma\dot{x}^2+2\pi RNK_2x\dot{x} +\left[2\pi RN\left(\gamma+K_1\right)-2\gamma-k\right]x \quad (13)$$

In the Equation: $M$-piston quality, kg.

This Equation can be applied to analyze the displacement and speed of the piston movement in suction stage and get the relationship among such parameters among the gray between Stiffness coefficient of the spring and the concrete, the slumping degree of the concrete, piston quality, the length and diameter of the piston cylinder and the stepping and switching time of the rotor, providing theoretical foundation for optimizing relevant parameters and ensuring successful working stage of concrete pressure and suction.

## 5 Conclusion

Take air-operated piston rotor as pump transportation of concrete wet shotcreting machine to replace traditional pumping system of hydraulic cylinder, effectively reducing the whole volume. Multiple piston cylinder can decrease the discontinuous injecting problem.

This paper has studied the movement of pump transportation and formulated movement equations in pressure and suction stages of wet shotcreting machine, providing foundations for optimizing relevant parameters of pump transportation and improving overall system performance.

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