Justification of pneumatic percussion machine performance in formation of main cracks from holes in natural stone

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Abstract. The study focuses on a percussive machine for directional fracturing of natural stone. The impact machine forces a rock-breaking tool to make a hole and penetrate it. Stone is propped as a result, and a main crack is formed finally along the row of holes. For the gravity-type pneumatic percussion machines, the circuit design is justified, and the numerical analysis of structural constants and performance of the machines is carried out based on the modeled dynamics of basic units. The operating cycle of the machine was evaluated by blow energy, blow frequency and compressed air flow rate. It is found that the operating cycle of the gravity-type pneumatic percussion machine with elastic valve ensures effective consumption of compressed air and high energy of impact. The numerical modeling data are proved by experimental results at the Institute of Mining, SB RAS.

1. Introduction
The Institute of Mining, SB RAS is developing the method of directional fracturing of solid rocks to be applicable in dimension stone production [1–3]. The method consists in creation of oriented cracks in rock mass by percussive penetration of rock-breaking tools in operating holes. The tool (Figure 1) is made as a twin cylinder with a conical crossover which reams out a hole; ad the tool penetrates in rocks to a depth of the hole, the rock mass gets propped and a main fracture is propagated. For rapid commercial introduction of the method, it is required to design simple and reliable equipment, i.e. the simplest rock-breaking tool and percussion machine.

The real impact fracturing of rocks follows a certain sequence of step [4]: drilling of idling and operating holes; mechanical installation of rock-breaking tools and percussion machines in the holes; operation of the machine in creation of the main fracture; removal of the machine to the next operating site.

The majority of the machine time-of-use is spent during preparatory periods of installation of the rock-breaking tool and re-arrangement of the machine. The period of initiation and growth of the main crack takes a short span of time (5–100 blows, or 1–2 min), and it has no essential influence on the total time of the technological cycle. Operation at the preparatory stage, when the rock-breaking tool is coursed into a hole and has yet no gripping and friction with the hole walls can be complicated by a recoil force. For this reason, it is preferable to fracture natural stone with a tool without recoil.

It is possible to eliminate recoil with a piston accelerated by gravity. The review of the existing pneumatic percussion machines [5, 6] shows that the known design fail to meet the condition of no
recoil. To meet the objective, it is suggested to use the gravity-type percussion machine with valve-type air distribution (Figure 1).

The machine consists of piston 1, driving cylinder 2, elastic valve 3 on the piston, working chamber 4, anvil 5 with hole 6, distribution cavity 7, slide valve 8, main line 9 and exhaust holes 10.

First, the machine is placed at the top end of the tool. Upon actuation, compressed air enter working chamber 4 through cavity 7 and hole 6 in anvil 5. Under the air pressure, the piston moves upward and accumulates kinetic energy before the compressed air exhaust through exhaust holes 10 in driving cylinder 2. At the same time, under the pressure difference, slide valve 8 is displaced upward and shuts compressed air flow to chamber 4. After that, the piston moves by inertia upward to a certain height until gravity returns it to initial position, and the piston hits the anvil.

Simultaneously with percussion, the piston with elastic valve seam working chamber 4 and affects slide valve 8 by displacing it and opening the channel for compressed air from distribution chamber 7 to chamber 4. The cycle is repeated.

Owing to the elastic valve included in the design, air compression in the back stroke chamber is essentially reduced, the piston deceleration is weakened, and the problem of the operating chamber compaction and accurate coupling of the piston and diving cylinder is eliminated. The resultant advantage is simple structure and low manufacture cost. The details of the elastic valve operation are given in [7–9].

2. Research method and results
The aim was to design a percussion machine capable to break highly strong granite rocks. From experimentation, granite fracturing requires blow energy not less than 7–8 kJ per rock-breaking tool [2]. Pre-blow velocity of pneumatic percussion machines usually ranges as 4–6 m/s, the piston has mass \( m = 600 \text{ kg} \), and the pressure (excessive) in the compression plant is \( p = 0.6–1.2 \text{ MPa} \).

The work process of the gravity-type pneumatic percussion machine was studied using a computer-aided numerical model [10]. The model was inserted with values of physical and structural parameters \((p_i, T_i, m, V_i, J_i, S_{ij})\). The operating cycles of the machine were evaluated by blow energy, blow frequency and compressed air flow rate in the settled mode of the machine operation.

The analytical models of the machine with basic structural and physical parameters are depicted in Figure 2. Figure 3 shows the characteristic diagrams of operating cycle with internal dynamic processes displayed. The diagrams are obtained with machine with effective structural parameters as follows: \( m_1=600 \text{ kg} \), \( m_2=7 \text{ kg} \), \( S_{21}=583 \text{ cm}^2 \), \( S_{12}=S_{22}=200 \text{ cm}^2 \), \( S_{41}=779 \text{ cm}^2 \), \( J_{m0}=J_{01}=5.3 \text{ cm}^2 \) (8.5 cm²), \( J_{d0}=210 \text{ cm}^2 \), \( V_0=22670 \text{ cm}^3 \), \( V_1=5800 \text{ cm}^3 \), \( V_2=6690 \text{ cm}^3 \), \( V_3=2700 \text{ cm}^3 \). Table 1 provides outputs of the modeling at the varied values of the main line pressure as 0.6, 0.8, 1.0 and 1.2 MPa and the main line cross section areas of 5.3 and 8.5 cm².

3. Discussion
The operating cycle of the studied gravity-type pneumatic percussion machine features that (Figure 3): compressed air is shut off the back stroke chamber before the exhausts starts (Figures 3a and 3b); compressed air in the work chamber expands (curve \( p_2 \), Figure 3a); compressed air resistance to the forward travel of the piston is minimized (section of curve \( p_2 \), Figure 3a).
Figure 2. Analytical models of pneumatic percussion machines (left—structural layout; right—pneumatics): $V_i$—volumes of chambers; $J_i$—air channel areas; $m_i$—masses of mobile elements; $S_{ij}$—effective areas of the masses $m_i$; $T_i$, $T_{ml}$—absolute temperatures in an i-th chamber and in the main line; $p_{m}$, $p_i$, $p_{atm}$—absolute air pressure in the main line, i-th chamber and in the atmosphere.

Figure 3. Calculated diagrams of operating cycles of pneumatic percussion machine: time change of (a) absolute compressed air pressure $p_i(t)$ in i-chambers; (b) travels of piston $x_1(t)$ and slide valve $x_2(t)$; (c) velocities of piston $v_1(t)$ and slide valve $v_2(t)$; (d) instantaneous compressed air consumption $G(t)$; $t$—time, s; $T_C$—cycle time; $T_B$ and $T_F$—periods of the back and forward stroke.
Table 1. Expected performance of gravity-type pneumatic percussion machine

| Description                      | Value       |
|----------------------------------|-------------|
| Excessive pressure $p$, MPa      | 0.6 0.6 0.8 1.0 1.0 1.2 |
| Main line area $J_m$, cm$^2$     | 5.3 8.5 5.3 8.5 5.3 8.5 5.3 |
| Cycle period $T_c$, s            | 0.77 0.80 0.82 0.85 0.87 0.92 0.95 |
| Back stroke period $T_b$, s      | 0.40 0.42 0.41 0.45 0.44 0.48 0.50 |
| Forward stroke period $T_f$, s   | 0.37 0.38 0.39 0.4 0.41 0.44 0.45 |
| Piston travel $H_m$, s           | 800 870 1000 1100 1180 1300 1370 |
| Blow velocity $v$, m/s           | 3.86 4.2 4.46 4.63 4.95 5.18 5.35 |
| Blow energy $A$, J               | 4470 5292 5968 6431 7351 8050 8587 |
| Blow frequency $n$, Hz           | 1.30 1.25 1.22 1.17 1.15 1.09 1.05 |
| Percussion capacity $N$, W       | 5812 6615 7280 7524 8453 8774 9016 |
| Absolute air flow rate $Q$, m$^3$/min | 6.30 5.92 6.66 6.62 7.07 7.48 7.80 |
| Specific consumption $q$, m$^3$/J | 18.0×10$^{-6}$ 15.0×10$^{-6}$ 15.2×10$^{-6}$ 14.6×10$^{-6}$ 13.9×10$^{-6}$ 14.1×10$^{-6}$ 14.4×10$^{-6}$ |

Due to specificity of the machine, the top place amongst the output characteristics below to the blow energy (blow velocity, Figure 3c). The blow frequency is of no critical influence on the technological process, and is low (1.05–1.3 Hz) the piston is mostly moved by gravity during the operating cycle. This also explains the relatively low flow rate of compressed air ($Q$), the average consumption of which was found from Figure 3d. The blow energy, average air flow rate and percussion capacity as functions of the main line pressure are presented in Figure 4.

![Figure 4](image)

**Figure 4.** Curves of blow energy $E$, compressed air flow rate $Q$, percussion capacity $N$ and main line pressure $p$ at different cross sections of the main line: 1—$j_0=5.3$ cm$^2$, 2—$j_0=8.5$ cm$^2$.

According to Figure 4, the increase in the main line pressure from 0.6 to 1.2 MPa elevates linearly the blow energy from 4470 to 8587 J at $j_m=5.3$ cm$^2$ and from 5292 to 8050 J at $j_m=8.5$ cm$^2$. Regarding the air flow rate and percussion capacity $p_m=0.6–1.0$ MPa, the air flow rate grows from 6.3 to
7.8 m$^3$/min at $j_m=5.3$ cm$^2$ while the percussion capacity rises from 5811 to 9016 W. Thus, it is possible to adjust the blow energy, average flow rate of compressed air as well as the percussion capacity of the machine by varying the compressed air pressure in the main line.

4. Conclusions

The gravity-type pneumatic percussion machine with valve-type air distribution ensures high blow energy at efficient consumption of compressed air. The computer-aided modeling shows that, depending on air pressure in the main line in the range of 0.6–1.2 MPa and at the main line cross section $j_m=5.3$ cm$^2$, the machine with the piston 600 kg in weight provides the blow energy of 4470–8587 J at the piston travel of 800–1370 mm, percussion capacity of 5811–9016 W, absolute compressed air flow rate of 6.3–7.8 m$^3$/min and specific air consumption not higher than $18.0\times10^{-6}$ m$^3$/J. The expected performance of percussion machine satisfies the conditions of impact to be applied to rock-breaking tool penetrated in a hole for the assured generation of a main fracture in highly strong rock mass composed of natural stone.

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