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Importance of early adjustment of rotary-percussion drilling tool to mineral mining conditions

VN Karpov,* VV Timonin**

Chinakal Institute of Mining SB RAS,
Novosibirsk, Russia

E-mail: *karpov@misd.ru, **timonin@misd.ru,

Abstract. The authors discuss the technical and economic criteria for the evaluationof efficient application of rotary-percussion drilling tools. The determinants of efficiency of downhole pneumatic drilling hammers are identified. The authors set conditions of high-velocity hole-making and find maximum indices of long-term performance for downhole pneumatic rotary-percussion drilling tools.

The application of the modern high-tech *main active members* of rotary-percussion drilling rigs, namely, down-hole percussion machines equipped with rock-cutting tools is a promising condition to lower mining costs in production of ore and construction materials when the rotary-percussion process is employed to make holes. The use of modern high-automated drilling complexes allows prompt auxiliary operations and optimal adjustment of operation parameters through the control panel, but does not eliminate the need in modification of the machinery and their adaptation to mining conditions of a mineral deposit [2, 3]

The term “main active or working member” is introduced by researchers working for IM, SB RAS, who were the first to introduce the full-scale rotary percussion drilling by downhole drilling tools as an ore-breaking process with deep blasthole charges in Russian mines in 1954–1955 [1].

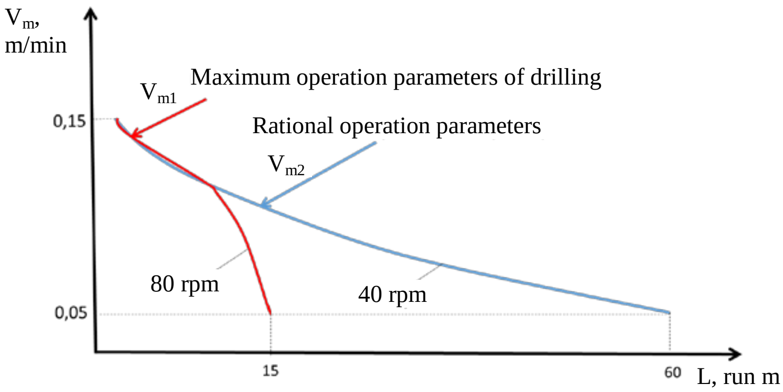
Research reports on application of different versions of active members of rotary-percussion drilling machines, actually, air hammers and their rock-cutting tools are not systemized and unified. As a rule, available publications on new versions of down-hole percussion machines is restricted with such specifications as average mechanical drilling velocity, rock strength by Protodiakov's scale, rated energy-carrier pressure, production rate per a shift and general description of a mineral deposit, perhaps, in terms of the full-scale production experience and acting standards based on rock drillability classification [4, 5]. The reports disregard physical-mechanical properties of a rock mass in view to the recommended rated drilling parameters and complete auxiliary devices sets in order to gain rational technical and economic hole-making parameters with account for mining-geological and technical conditions of a specific mineral deposit. The lack of so-called efficient drilling pattern and “route chart”, which could guarantee technical and economic indices of rational application of main active rotary-percussive drilling members under conditions of a specific mineral deposit constitutes one of acute challenges in domestic drilling practice in quarries and mines [6].

Let consider the technical and economic criteria for evaluation of rational application scope of main drilling rig executives on the down-hole air hammers as an example to make deep blast holes. The production cost of one running meter drilling of a blast hole in combination with the drilling capacity per a shift basically depends on intensity of rock breakage, viz., mechanical drilling velocity V_m, route rate of drilling V_r and sinking per a trip L_s considering the effects of natural, technical and technological factors.

Moreover, it is next to impossible to find the maximum feasible productivity of down-hole air hammers based on average mechanical drilling velocity and sinking length per a run, because the parameters are under strong effects of variable natural or technogenic factors. In this connection one of parameters of the maximum drilling productivity can be the maximum feasible velocity of sinking $V_{r\,max}$ at optimal time of mechanical drilling t_{opt} per a run under rated operation parameters of rock cutting.

It is important that established correlation relations between physical-mechanical properties of rocks and average penetration speed $V_{av\text{-}p}$ of pneumatic drilling is of restricted scientific and practical value, as a velocity can be calculated based on different time parameters possible during a route run. This peculiarity is typical of most research works, where empirical relationships are derived based on average mechanical drilling velocity which does not match the maximum drill velocity $V_{r\,max}$, viz. $V_{av\text{-}p}= L/t$, where $t \neq t_{opt}$, $L \neq L_{opt}$. This feature is specific for earlier mentioned standards based on classification of rocks by their drillability, where an average penetration speed of drilling is presented with no justification of sinking length per a run L provided that $V_{r\,max}$ is gained per a run.

As practice shows the normalization of drilling operations is an actual and rather acute issue at quarries and mines. Performance norms used to be set without proper account for qualitative parameters of drilling. To be precise, the well known mine machines NKR-100M are not equipped with devices to measure operation parameters of drilling. A drill operator quantitatively feels working pressure, forward force, rotation velocity, in brief, responsibility for hole-making norms lies on a drill operator, his motivation, his skills. This leads to excess- or understated production norms. The human factor remains a constitutive factor in evaluation of productivity norms for a drill crew at a certain drill section, no matter whether there is the detailed information on physical-mechanical properties of a rock mass, and a high-tech powerful pneumatic hammer. Figure 1 demonstrates a general view of the first characteristic sinking of a blasthole by two drill operators by the same air hammer under the rest identical conditions, excluding a choice of operation parameters capable to affect a character of rock failure.



Fugure 1. Relationships of mechanical-economic parameters of drilling versus a choice of maximum and rational operation parameters of blasthole making.

In [7] the researchers established that in rotary-percussion hole-making under the constant nominal pressure of energy carrier (air) there is a wide zone of tool rotation angles between percussion loads within which productivity of a drilling machine is maximum and practically the same. Thereto, the zones have boundary parameters in regard to a rock mass, but drill bits have differing resistance. This problem becomes evident in making deep blastholes since the first sinking run.

In hard and abrasive rocks the pressure of energy carrier is low within 0.5 MPa and indentors of drill bits are underloaded relative to the rated parameters because of low capacity parameters of production air hammers, and the surface failure is realized and then it transfers to a fatigue wear as a result of indentor wear-out [3]. Increase in rotations causes increase in angle between impact loads, and this leads to drastic wear of hard drill-bit alloy, as the reduced effects of impacts per every rotation of the tool and enhanced cutting effect like in rotary drilling. The hard alloy of drill bit is subjected to drastic wear because it is not intended for this drilling process [8, 9].

This situation results in greater number of runs: up to 6 runsper 50 running meters in making deep blastholes, thus boosting total drilling costs because of excess energy-carrier consumption by a drill rig making multiple runs. The typical case of the maximum rotation frequency of the rig (80 rpm) in drilling an upper-layer blasthole semi-ring of 105 mm in diameter is the use of P105PM air hammer in NKR100MA rig, Starooskolsky Mechanical Plant Co., Russia, on weakly mineralized quartzites in Gubkina Mine. The field tests of Starooskolsky machines with electric motor of MO-5 swivel head in NKR-100 modified versions justified that they do not have variants of column rotation variations other than design ones from 1.25 Hz and higher [10 –13]. This state of things does not enable to realize rational principles of rotary-percussion hole drilling by downhole air hammers, as the principles are based on provision of the maximum durability of drill bits at the minimum power-intensity of drilling in executing runs in blastholes [14 – 16]. That is the reason why the known global companies Mitsubishi (Japan) and Rock More Internationale (USA, Austria) proposed their services to solve the problem and developed their own tool for domestic down-hole machines, but did not manage to find solution to this problem.

The penetration speed of drilling can not serve a constitutive factor in evaluation of performance of downhole air hammers and its maximum indices, in particular, as a choice of operation conditions providing high V_m can promote excessive wear of drill bits and incidents (jamming of drill strings, and even its loss, breakdown of main parts of the rig, etc.). Herewith, with increasing depth of a blasthole a high penetration speed becomes less beneficial than a footage per a run because the duration of round-trip operation tends to grow with increase in blasthole depth. Alternatively, increase in footage per a bit run L sharply reduces a number of round-trip operations cuts down specific operation costs per 1 run m of drilled holes. Therefore, it is reasonable to consider the choice of optimal modes of drilling providing the minimal energy-intensity of rock cutting at the maximum durability of the rock-cutting tools when researchers develop and master the methods for evaluation of performance of the principal executive members with armament considering the mechanical properties of rocks. This issue is to be discussed in details in other publications by the present authors.

Let consider specific operation costs C, the general formula to calculate production cost of 1 run m of drilled holes is:

$$C = \frac{C_{dr} \cdot (t_{dr} + t_{auh}) + C_b + C_{ah} \cdot K_{hw}}{L}, \text{ as } \frac{L}{t_{dr+t_{aux}}} = V_p, \text{ expression is } C = \frac{C_{dr}}{V_p} + \frac{C_b + C_{ah} \cdot K_{hw}}{L}$$

where C_{dr} is working cost of a drill rig, RUB/h; C_b is cost of bit of air hammer, RUB; C_{ah} is cost of air hammer, RUB; L is run length per a bit of air hammer to drill a hole in a rock mass, run m; K_{hw} is coefficient of air hammer depreciation, calculated from ratio L/L_{gl}; L_{gl} is guaranteed life of air hammer, run m.

It is important to state that in some Russian publications the drilling cost for an air hammer is calculated disregarding the cost of a downhole air hammer, namely, index C_b is considered and index C_{ah} is disregarded,the reliability of such calculations is low and the cost of 1 running meter of a drilled hole is under-evaluated. The adoption of calculation formulas for rotary hole-making process is explicit. As a rule, the wear life of downhole tools is few times higher than for bits $L_{gl} > L$; as is the case with the cost. For example, the cost of modern high-pressure air hammers of Atlas Copco Co. with the rate of application 0.23 u/1000 run m. is 6–8 times higher than the cost of a bit of the same producer (according to data of ZAO "UGMKRugormash-Voronezh") [17]. Respectively, it is possible to obtain reliable results in calculations of production costs provided that coefficient K_{hw} is used to specify the costs of application of downhole tools. Unfortunately, there are cases in the actual practice when rates of application for air hammers are higher or comparable to rates of their rock-cutting tool at $L_{gl} \leq L$, $K_{hw} \geq 1$ [6].

Figure 2 demonstrates the model of diagram for technical and economic assessment of hole-making efficiency by downhole percussion machines on rotary-percussion drilling machines developed at Chinakal Institute of Mining SB RAS.

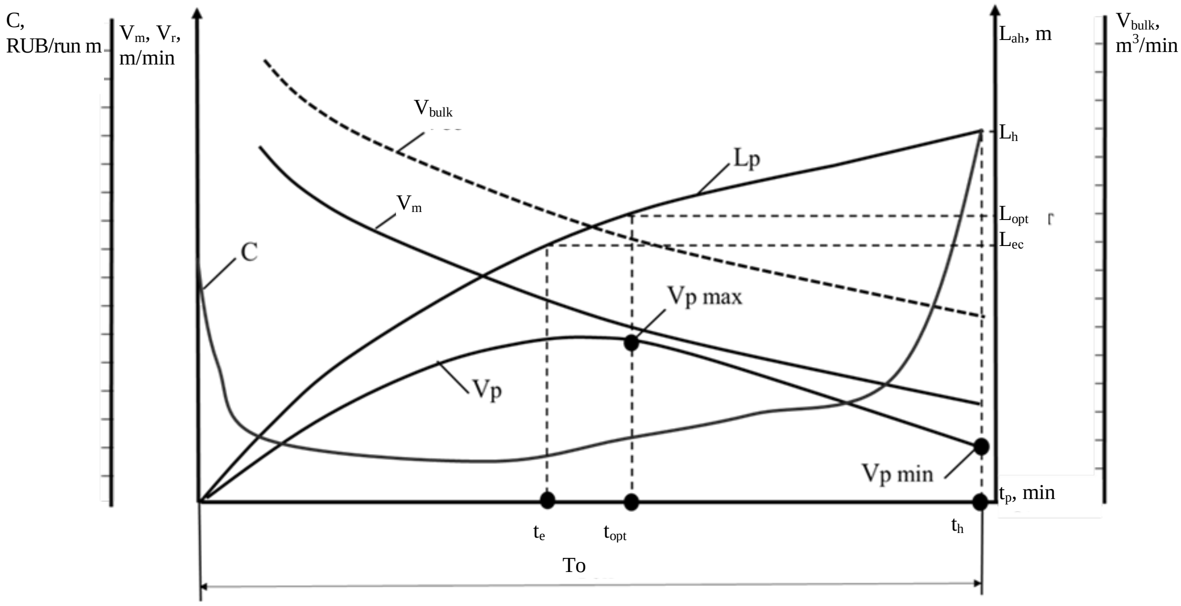


Figure 2. Model of diagram plotted based on the full-scale research data to evaluate the technical-economic efficiency of blasthole-making by downhole air hammers on the rotary-percussion drilling rigs in underground conditions.

The diagram represents variations in penetration V_p, run V_r and bulk V_{bulk} speeds of drilling; the run length executed by the air hammer L_{ah}, and working cost C of one running meter of drilling under preset drilling conditions for operation time T_o per a hole. Intervals for calculation of proposed parameters and plotting of relationships do not exceed length of drilling strings used in operation. In the diagram t_e – economic penetration time for a downhole air hammer; $t_p = t_e$, where $L_{ah} = L_{er}$, L_{er} – economic run of air hammer in a drilled hole; top–optimal penetration time for downhole air hammer $t_p = t_{op}$, where $L_{ah} = L_{op}$, L_{op} – optimal penetration of executive member into a geomedium; t_h – drilling time to failure for air hammer or to a depth preset by drilling-blasting pattern $t_p = t_h$, where $L_{ah} = L_{hr}$, L_{hr} – run of air hammer to failure or to a wanted depth according to drilling-blasting pattern or to above 50 % decline in drilling productivity because of drill bit wear or network pressure fall which makes drilling hazardous or uneconomic.

The most unfavorable combinations of drilling parameters reach critical values at $V_r = V_{r\ min}$, $t_p = t_h$, $L_{ah} = L_h$, at the maximum costs, curve C (Figure 2). It is important to emphasize that parameter C is always the highest in the case of accident-free termination of the run, as dismounting of the drilling string is an energy-intensive operation and in most depends on the drill rig automation.

The model of the technical-economic diagram to evaluate efficiency of pneumatic percussion drilling under full-scale production conditions is elaborated based on theoretical experience of Russian prominent researchers in rotary drilling of large-depth production and geological holes [18].

It is essential that Russian researchers engaged in investigation into rotary-percussion drilling with the use of downhole percussion machines did not pay proper attention to the bit run speed in making deep blast holes of 50–80 m, in particular. Drilling by light-weight rotary-percussion machines in essence represents a physical model of boring of deep oil, geological and other-type holes by applying stationary drilling complexes withlarge number of rods in a drill string and in a less degree by geological rock mass diversity. Field research of technical-economic characteristics of drilling machines revealed that the bit run speed in making lower blasthole semi-ring at a routine failure-free mode repeats the trend of penetration rate practically from the beginning to the end of the run. This means that the rig crewneglects a forced cleanout of a hole in the course of drilling by every drill rod and performs the hole cleanout only before extention of a flight. This state of things and the lack of manometers capable to assess loss of metering characteristics of downhole tools, as well as a fall in an ascending-air-flow speed during the hole cleaning lead to frequent break-downs and even loss of downhole tools and complete drill strings [6]. In production drilling in oil and gas fields such situation is impossible and prohibitive, as the cost of a lost borehole of several thousand meters in length amounts to millions roubles.

The model of the diagram for technical-economic evaluation of efficiency of downhole air hammers is reasonable to apply during runs of a drilled hole in making deep blastholes. The proposed model is also applicable in making deep oil, gas, and exploration holes by rotary-percussion drilling. The equipment assessment in terms of the mine geology permits to make rational choice, adaptation of downhole tools, facilities and drilling conditions to specific local rock characteristics, to work out adaptive measures for years in advance at the planning stage with the aim to solve technological problems specified by mining systems and boring-blasting patterns. The high-class grade guaranteed by domestic and foreign producers of the respective equipment is of prime importance as well. The application of the new-proposed model in full-scale production conditions is reported in [10–12].

Let consider the modern approaches to adaptation of downhole tools at open pit mines. When drilling blastholes by the modern high-tech air hammers [19–21] at consumption rate 0.05–0.5 run m per 1000 run m (foreign data) the service life of the equipment is not specified. For example, in the case study the Table 1 contains drilling specifications with a wide range of working air pressure on rocks of 203 MPa in strength with the use of DM45HP machine (Sweden) and air hammer QL65QM equipped with a bit 6-3/4 Q6FE (171.4 mm in diameter) according to database of Mining Solutions Co., a distributor of Atlas Copco, but the Table 1 does not contain such parameters as energy of a single impact A_{ah} for air hammer, applicable for the cited operation pressure range and capacity N_{ah}. These very parameters would be helpful in calculations of the single impact energy applied to hole bottom in order to break a rock mass. It is known that in rotary-percussion drilling the drilling thrust is required to provide the permanent contact of an air hammer and rocks. The drilling thrust is selected with regard to minimum parameters to eliminate vibration effects generated by an actuated air hammer. Respective penetration speed resulted from a dynamic effect on a rock mass mainly depends on a single impact energy of an air hammer executing mechanical failure of rocks, cutting structure of a bit, impact frequency, rod rotation, hole cleaning from slime and last but not least physicomechanical properties of rocks.

Table 1. Specifications of hole making by DM45HP drill rig with QL65QM downhole hammer

Air pressure	MPa	2.4	2.3	2.2	2.1	2
Air flow rate	m^3/min	27.3	25.8	24.4	23.0	21.6
Drilling speed	m/h	46.0	44.3	42.7	41.1	39.3
Impact frequency	imp/min	1876	1844	1813	1783	1751
Rotation speed	rpm	40	39	37	36	34
Thrust	kgs	1308	1262	1222	1181	1137
Blow rate	m/min	2626	2482	2341	2212	2086
Service life of an air hammer	m	9853	11029	12400	13852	15769
Service life of a bit	m	1793	1726	1664	1601	1532

The lack of the above parameters can be easily explained. The single impact energy of the first and last runs (on the achievement of the critical service life level for an air hammer) can differ greatly in drilling with the use of the same drill bit model in the failure-free period in a certain drilling area with a set of physicomechanical properties of local rock mass and other identical conditions. One of reasons for difference can be catastrophic wear of basic parts of an air hammer. As a result there are two absolutely different tracks of drilled holes passed by a new drill bit and a new air hammer and a track passed by a worn-out air hammer with low energy parameters, a rock failure pattern varied from the bulk- to fatigue- or surface-type rock failure.

In [22] it is reported that the cumulative cross-section areas of gaps exert negative influence on both impact energy and impact frequency. Reduction in these parameters lowers capacity of the machine and drilling productivity as a whole. Researchers of IM SB RAS focus on this problem in development, design and investigation into high-pressure air hammers under both laboratory and production conditions. In [23] the full-scale research data on the problem under consideration are presented for PV-170M air hammer. The similar situation is observed if two machines of the same type-size line with differing energy parameters and the identical drill-bit models are used under the same operation conditions. Failure energy requirements and respective costs of 1 run m drilling are different and described in detail in [10–12].

The users should know optimal intermediate parameters between the first and conventionally "last" run of a drilled hole. It is essential for timely replacement of principal parts of air hammer or a worn-out downhole tool for a new one. Respectively, air hammers of the same type-size line and identical cutting structures under rest identical conditions can have quite different energy parameters after the equal service life intervals. In other words air hammers used to have their own specific parameters.

Figure 3 demonstrates relationships of service life parameters for QL65QM air hammer and 6-3/4Q6FE drill bits versus working pressure of compressed air at σca = 203 MPa.

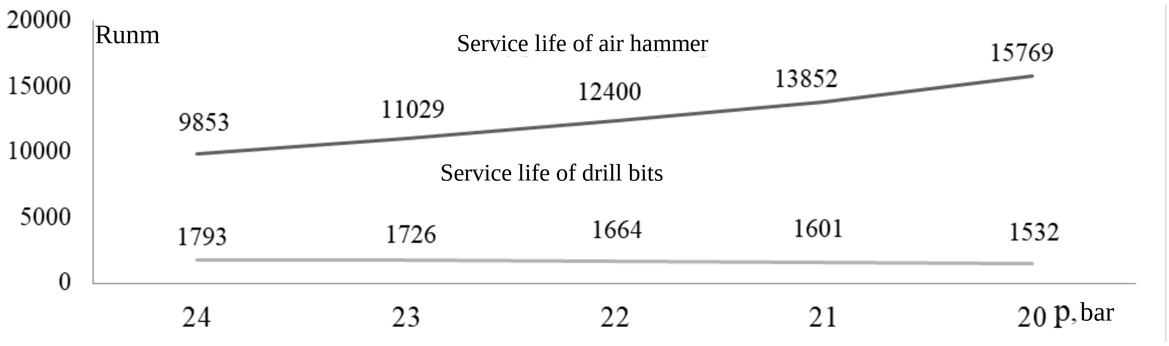


Figure 3. Relationships of service life parameters for QL65QM air hammer and 6-3/4Q6FE drill bits versus working pressure of compressed air at σ_{ca} = 203 MPa.

The present paper is intended to potential users of Atlas Copco products. There are issues to solve, let say, how many repair sets per a downhole machine in cost equal to 50% of the air hammer cost (8 - 10 thousand EURO per a unit of the mentioned type-size line) are required to a user, provided that according to producer's certificate the machine is capable to make holes of at least 5000 run m in length before it reaches the final service life parameters. Nobody can guarantee that a repair set is capable to maintain the design capacity of the machine without reduction in drill penetration speed, excessive consumption of drill bits, increased maintenance costs of compressors and as a consequence of increased costof 1 run m of drilled holes.

Assessment of technical-economic performance of downhole air hammers at open pit mines has specific features. Higher drilling performance, limited number of drill strings, as a rule no more than three, minute time of auxiliary operations in the course of a run (string removal velocity being 0.5–09 m/s) leads to a large number of runs of drilled holes per a shift. Inasmuch as it makes sense to assess the technical-economic performance based on run meterage before the replacement of a rock-breaking tool of a downhole air hammer. In theworld practice of drilling at open pit mines the decline of drilling performance by 30% because of wear-out of hard alloy of drill bits is an attribute to replace a rock-cutting tool from the economic point of view. At mines this parameter can be higher in drilling of large-length blastholes, as it is not reasonable to replace a drill bit in last 5-10 meter interval of the total 60 m length of a blasthole to be made. Dismounting of a drill string is energy-intensive operation. Thereto, the decline in performance is often due to not abrasive wear-out of a drill bit, but due to a fall of pressure in mine network (in tool input), or leakage of energy carrier during a run of a drill string to a downhole machine or through watered levels, variance in mining-geological conditions. In making large-length blastholes by downhole tools the critical fall in drill penetration speed is equal to 70% of rated parameters. Moreover, this fall occurs in making the second half of a blasthole length with downhole machines and a tool with the minimum service period, namely, new tools.

In Figure 4 the technical-economic diagram for open mining processes was worked out at IM SB RAS. In the diagram the research data are on drilling performance of PV170M downhole air hammer to make blastholes of 172 mm in diameter and 18 m in length at SWDB165 machine at the rated air pressure p = 1.2 MPa in Borok quarry, Novosibirsk.

Drilling was performed without reconditioning of the rock-cutting drill-bit insertions. The estimated parameters in this diagram are similar to the previous one, but considering the specific character of drilling operation, viz., large number of runs of a drilled hole per a shift, etc., the given data on technical-economic parameters were plotted for every collared hole, for operative drilling duration, for T_o per every shift. Within a shift the actual operative drilling time amounted to 91.6% of a shift time, excluding personal needs, and preparatory operations. T_o is a precise time of drilling operation at the quarry under the RF normative acts. Thus exclusively operative hole-drilling time per a shift before replacement of a drill bit is reported in the diagram..

It is explicit in Figure 4 that it is reasonable to replace a drill bit according the design drilling specifications at the quarry and its mechanical properties in the drilling area when $L_p = L_{opt}$ after 14 holes are made; their total length being 252 run m, the time of cost-effective drilling tэis gained at area $L_p = L_e$. In this case it would make sense to use a tool grinding facility for drill bits and to substantiate expediency of its acquisition for future research projects or to test other procedures for improvement of drilling performance. Assessment of cost-performance ratio on pilot units in terms of producer’s specifications under full-scale production conditions makes sense before decision making on purchase of new equipment.

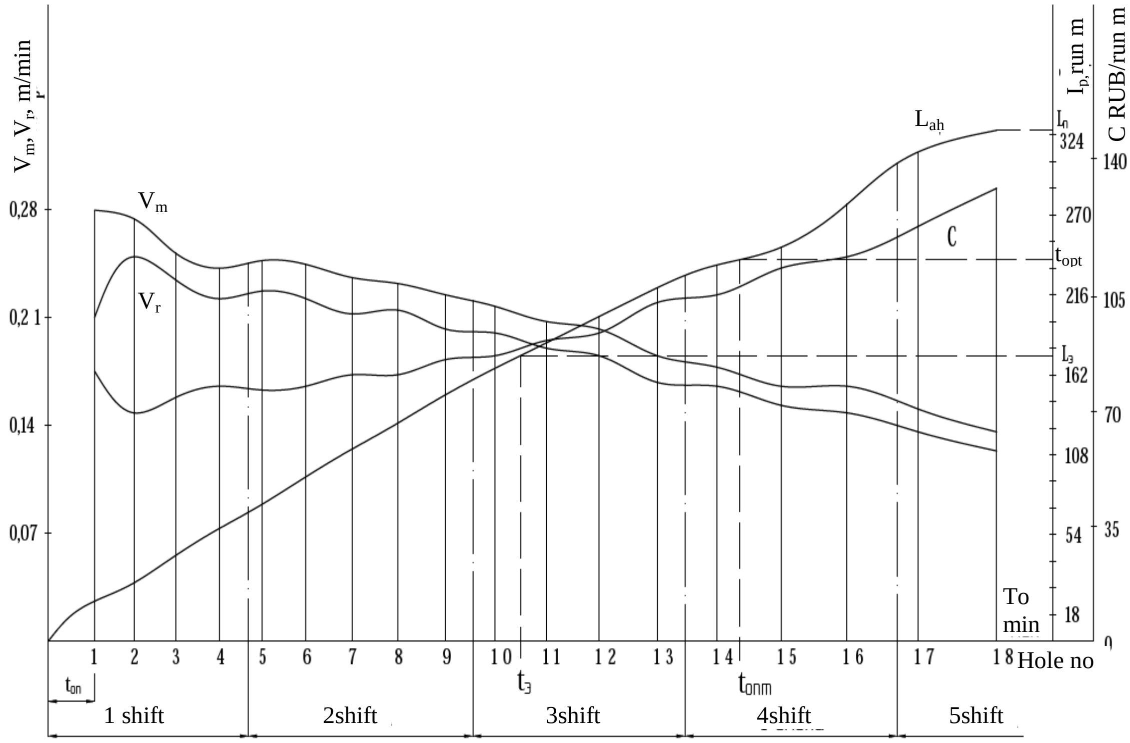


Figure 4. Diagram of technical and economic assessment efficiency of blasthole making by downhole air hammers in open pit mines.

Investigations in terms of the same mineral deposit are preferable to assess the service life parameters of serial and experimental downhole air hammers including replacement for new machines or individual important parts in order to gain optimal capacity specifications. In the new-proposed approach investigation into runs of drilled holes followed with further replacement of bits of downhole air hammer (or in the design replacement intervals) makes it feasible to establish “the last final” run, in other words, the range of non-failure operation life when the downhole hammer should be replaced for a new one. The above diagram of technical-economic efficiency of air hammers in openpit mines can be helpful in underground mines to make short-length blastholes by high-power rotary-percussion drill machines (high-pressure air hammers (2–3.5 MPa), hydroperforators, hydropercussion units).

Researchers working for IM SB RAS elaborated the procedure for evaluation of performance of rotary-percussion drilling machines under production conditions in terms of physical-and-mechanical properties and drillability with account for environment, technical, technological factors affecting the drilling capability. In the procedure evaluation of technical-and-economic parameters by the new-proposed diagrams is one of the basic but not single analytical criterion of evaluation. The detailed description is reported in [10–12] and later publications by authors.

Available methods for determination of rational application scope for air hammers and drilling bit cutting structure under production conditions imply industrial tests intended to determine experimentally the drilling penetration speed, run length, or total run of air hammer and bits in rocks with differing physical-and-mechanical properties, disregarding proper studies of variations in technical-economic indices in the course of hole-making. In specific tests the researchers focused on essential number of runs (30–60) with the minimal penetration per a run no more than 2-3 meters. The test data are used to make approximate calculations of production rate per a shift, cost of 1 running meter hole and to establish the optimal application scope for air hammers and rock-cutting tools [18, 24, 25]. In the case under consideration a large number of short runs leads to overestimated values of drillability and underestimation of actual cost of 1 run m of made hole. The similar state of things is observed in laboratory tests which results should be treated as preliminary evidence requiring correction in terms of environment, technical and technological factors, influencing the penetration speed under conditions of a certain mineral deposit [2].

Conclusion

Adaptation of controllable drilling parameters: drilling pattern, capacity of an air hammer, and others in terms of uncontrollable parameters of a mineral deposit: rock properties, geological and structural specific features makes it feasible to improve drilling productivity in rotary-percussion hole-making with application of downhole percussion machines, thereto the maximum service life of the main active members is gained.

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