Arabian Journal of Geosciences (2019) 12: 137
https://doi.org/10.1007/s12517-019-4287-2

ORIGINAL PAPER

Diamond core drilling process using intermittent flushing mode

Xin Cao[1,2] · Anatolii Kozhevnykov[3] · Andrii Dreus[4] · Bao-Chang Liu[1,2]

Received: 14 March 2018 / Accepted: 25 January 2019 / Published online: 15 February 2019

Abstract

Core drilling has been the main method for exploration of solid mineral deposits, also used widely for drilling engineering geological boreholes, hydrogeological wells, etc. But the efficiency of rock destruction during diamond drilling remains fairly low, especially in some difficult conditions. The main part of power on bottom-hole is wasted to heat generation. Diamond core drilling efficiency can be improved by using pulse flushing modes, particularly with pulse drilling fluid supply. A broad classification for possible drilling methods using pulse drilling fluid supply to the downhole has been presented herein. Among the wide variety of pulse flushing options, particular attention is paid to intermittent flush drilling with alternated on/off drilling fluid supply. Proposed technology is characterized by using standard diamond drilling bits and drilling equipment. Thus, transition to the proposed technology does not require significant technical re-equipment of the process and material costs. The results of bench drilling tests with intermittent flushing were presented. A criterion for drilling with intermittent flushing was introduced. Test results had shown that transition to intermittent flushing mode allows considerably improved penetration rate (by 1.18 to 2.2 times). Power on bottom-hole value and intermittency factor will affect drilling efficiency by using intermittent flushing. It is suggested that directional utilization of frictional heat energy in the bottom-hole used for rock destruction is one of physical principles that govern improving efficiency of drilling with intermittent flushing. The technology considered allows to utilize diamond drilling's latent reserves and can become the key technologies to improvement of efficiency of the diamond core drilling.

Keywords Diamond drilling · Intermittent flushing · Bench test · Efficiency of drilling · Frictional heat energy

Introduction

Rotational drilling with constant operating parameters is widely used at the moment in prospecting for mineral deposits. In the meantime, further improvement of this method requires new design and technology solutions. Transition to technologies using pulsed variation of drilling process parameters is one of such solutions.

Particularly, the developers of rotational drilling technologies manifest a keen interest to pulsed well flushing methods recently. For example, a mud-pulse rotational technology for drilling deep wells with abnormal formation pressure has been developed in the US (Kollé and Marvin 1999). An ability to increase penetration speed by use of intermittent jets for well flushing has been studied (Wang 2005; Liu et al. 2015). Results of experimental studies mentioned and numeric modeling allow assuming that rock destruction is performed more efficiently due to its weakening by jet mechanical impact and bottom-hole cavitation. Hydraulic pulse generators used to form frilling fluid supply mode has been considered (Qu et al. 2016; Shi et al. 2015).

A positive experience of application of pulsed flushing during diamond and hard-alloy drilling bits has been obtained in (Tungusov 2009). Authors have shown that using pulsed flushing promotes for better rock destruction and improves well cuttings removal efficiency (Filimonenko 2007; Gorshkov and Gorelikov 1992).

Editorial handling: Murat Karakus

✉ Bao-Chang Liu
liubc@jlu.edu.cn

1 College of Construction Engineering, Jilin University, Changchun 130012, China

2 Key Laboratory of Drilling and Exploitation Technology in Complex Conditions of Ministry of Land and Resources, Changchun 130000, China

3 Techniques Prospect of Deposits Department, "National Mining University", Dnipro, Ukraine

4 Fluid Mechanics and Energy & Mass Transfer Department, Oles Honchar Dnipro National University, Dnipro, Ukraine

It has been shown by Fassahov et al. (Fassahov et al. 2005) that pulsed flushing allows saving power and resources in oil field operation. Therefore, using alternating drilling fluid supply allows boosting rock destruction as well as improving other drilling process conditions.

Taking into account that diamond drilling is one of the most common ways of prospecting for solid commercial deposits ((Wang et al. 2015).), research held for its improvement is considered a very important task.

General characteristic of pulsed flushing modes

Well drilling using pulsed flushing belongs to pulsed drilling technologies. Concepts, definitions, and classification of pulsed drilling technologies were proposed first by A. Kozhevnykov in investigation report of National Mining University (former Dnipropetrovsk Mining Institute) according to the agreement with National Institute for Exploration Methods and Technology performed. These results are presented in the form of a report at "Drilled rock mechanics" international conference (Kozhevnykov 1992). This issue is detailed by Kozhevnykov and Filimonenko (Kozhevnykov and Filimonenko 2010), the brief characteristics of pulsed drilling technologies are summarized as a chart in Table 1.

According to chart in Table 1, there are three variants of pulsed flush drilling technology:

- one single-parameter, with only one variable parameter Q;
- two double-parameter, with two variable drilling parameters taken in pairs, Q and n or Q and F;
- one triple-parameter (when all three drilling parameters are variable at a time, Q, n, and F)

In this way, pulsed flushing can be carried out independently as well as with other transient parameters. Consideration of pulsed well flushing leads to four possible ways of its implementation (see Fig. 1).

The following factors have been introduced to characterize pulsed well flushing.

Pulse factor k_{pulse}, the ratio of fluid feed flow variation ΔQ to max fluid feed flow Q_{max}:

$$k_{pulse} = \frac{\Delta Q}{Q_{\max}} \tag{1}$$

Steadiness factor k_{st}, the ratio that characterizes min fluid feed rate Q_{min} to max flow rate:

$$k_{st} = \frac{Q_{\min}}{Q_{\max}}. \tag{2}$$

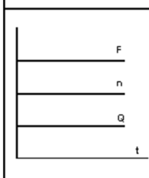
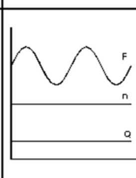
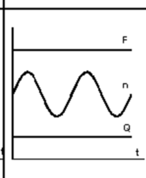
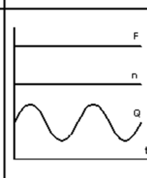
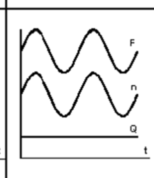
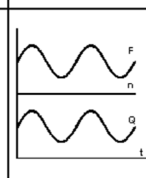
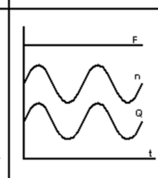
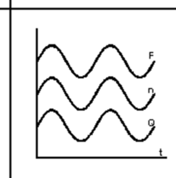
Pulse and steadiness factors are mutually-dependent, because

$$k_{pulse} = \frac{\Delta Q}{Q_{\max}} = \frac{Q_{\max} - Q_{\min}}{Q_{\max}} = 1 - \frac{Q_{\min}}{Q_{\max}} = 1 - k_{st}. \tag{3}$$

Hence,

$$k_{pulse} + k_{st} = 1.$$

Table 1 Classification of pulsed drilling technologies

Constant	Pulse						
	single parameter			double-parameter			triple-parameter
F= const	F=var	F= const	F= const	F=var	F=var	F= const	F=var
n= const	n= const	n=var	n= const	n=var	n= const	n=var	n=var
Q= const	Q= const	Q= const	Q=var	Q= const	Q=var	Q=var	Q=var
							
Rotational drilling	Rotational-Percussion drilling						

Q flushing liquid flow rate, n rotational speed, F axial load

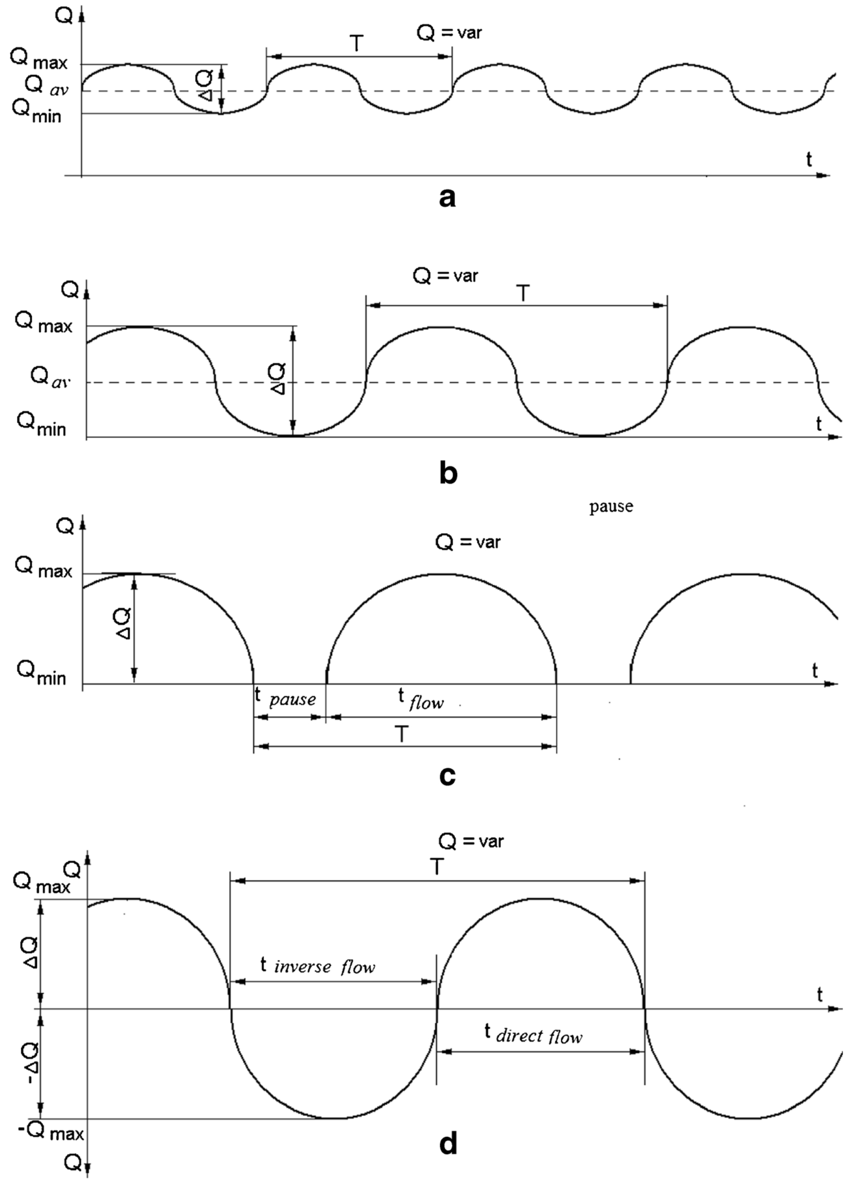


Fig. 1 Pulsed flushing methods: with variable fluid flow (**a**); with pulsed fluid flow (**b**); with intermittent fluid flow (**c**); with revertive fluid flow (**d**)

Steadiness factor is also functionally constrained with fluid flow rate, because

$$k_{st} = \frac{Q_{\min}}{Q_{\max}} = \frac{Q_{\max} - \Delta Q}{Q_{\max}} = 1 - \frac{\Delta Q}{Q_{\max}} = 1 - k_{pulse}. \quad (4)$$

Intermittency factor k_{int} shows ratio of fluid feed pause duration t_{pause} to fluid feed duration t_{flow}

$$k_{int} = \frac{t_{pause}}{t_{flow}} \quad (5)$$

Reversibility time factor k^{t}_{rev} shows ratio of times of fluid direct t_{dir} and inverse feed t_{inv}

$$k^{t}_{rev} = \frac{t_{dir}}{t_{inv}} \quad (6)$$

Reversibility flow factor k^{Q}_{rev} shows ratio of fluid direct (t_{dir}) and indirect feed flow values (t_{inv}).

$$k^{Q}_{rev} = \frac{Q_{dir}}{Q_{inv}} \quad (7)$$

Bench testing of diamond core drilling with pulse flushing

One of pulsed well flushing methods, namely, intermittent flushing, has been held in bench-scale conditions in Drilling laboratory at Department of Technic Prospecting Of Deposits in National Mining University (Dnipro, Ukraine) (Kozhevnykov et al. 1990).

Drilling has been performed with a single-layer diamond core type 01A3, 59 mm dia, shown in Fig. 2, with four flushing channels.

Drilling was performed on a granite block with IX drillability category (Fig. 3). Water was used as drilling fluid.

Rig type ЗИФ-300 (ZIF-300) equipped with auxiliary gear box together with drilling pump type НБ-3 (NB-3) are the test bench main components. ЭМР-2 (EMR-2) flowmeter was used additionally for recording and control of drilling conditions (Fig. 4).

Fig. 3 Granite block used in a bench test drilling

Test results of diamond drilling using intermittent flushing mode

Flushing mode was being changed during drilling with 01A3 core bit. Drilling was held using continuous flushing, respective intermittency factor $k_{\text{int}} = 0$, as well as intermittent flushing with intermittency factor values of $k_{\text{int}} = 0.2$ and $k_{\text{int}} = 1$. Drilling was held with different rotation speed and axial load values. Results of experimental investigation of intermittent flushing impact on mechanical penetration speed are shown in Table 2.

As it can be seen from Table 1, all examined intermittently flushed drilling modes provide penetration speed increase as compared to continuous flushing mode. Drilling efficiency is affected not only by flushing mode features, but also by numeric values of drilling parameters that provide resultant power on bottom-hole (Karakus and Perez 2014). There was no significant wear on the drill bit due to the relatively shorter drilling depth and the high performance of natural diamond in the bit.

Table 3 shows power values on bottom-hole that correspond to numeric values of rotational speed and axial load in this investigation.

Efficiency of drilling using intermittent flushing as compared to continuously flushed drilling can be evaluated with an efficiency criterion K_{eff} that presents a ratio of penetration rate using intermittent flushing V_{int} to penetration speed using continuous flushing V_{const}.

$$K_{eff} = \frac{V_{\text{int}}}{V_{const}} \tag{8}$$

Penetration speed is connected with power on bottom-hole P by the relation.

$$V = \frac{P}{A \cdot S}. \tag{9}$$

where A is specific energy consumption on rocks destruction process, S area of working face of borehole.

Let us write (1) by taking in account (2), in the form of

$$K_{eff} = \frac{A_{const}\ P_{int}}{A_{\text{int}}\ P_{const}} \tag{10}$$

where subscript index "int" means the parameters taken at intermittent flushing mode, and index "const" means the parameters taken at constantly flushing mode. Let us introduce the coefficients which show ratio of downhole power and energy consumption by using intermittent and constant flushing mode

$$k_P = \frac{P}{P_{const}} \tag{11}$$

$$k_A = \frac{A_{\text{int}}}{A_{const}} \tag{12}$$

Fig. 2 Diamond drilling bit type 01A3; **a** general view; **b** top view; **c** side view

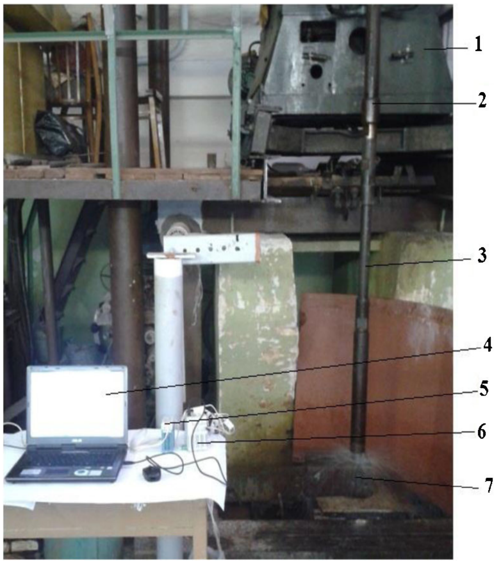


Fig. 4 Test bench general view. 1, rock drilling machine type ЗИФ-300 (ZIF-300); 2, kelly stem; 3, drilling tool; 4, computer; 5, power supply unit; 6, electronic interface; 7, granite block

Then the criterion of drilling efficiency with intermittent flushing depends on the ratio of these factors

$$K_{eff} = \frac{k_N}{k_A}. \qquad (13)$$

According to data provided in Table 2, efficiency factor varies from 1.18 to 2.2. Intermittent flushing with intermittency factor $k_{\text{int}} = 1$ affects drilling more than with intermittency factor $k_{\text{int}} = 0.2$. At the same time, power on bottom-hole value affects penetration speed increase. Efficiency factor increase is shown as a function of power on bottom-hole for different intermittency factor values is shown in Fig. 5.

As it can be seen from the data shown in Fig. 5, greater relative increase of penetration speed is achieved with lower power on bottom-hole values. At the same time, as it can be seen from Fig. 6, greater increase of absolute penetration speed corresponds to greater power on bottom-hole values.

Table 2 Results of test banch diamond drilling using core type 01A3 with intermittent flushing

Rotational speed (min^{-1})	Axial load (kN)	Flushing mode	Intermittency factor	Penetration speed (cm/min)
239	7	Intermittent	1	1.23
		Intermittent	0.2	1.15
		Stationary	0	0.58
239	7	Intermittent	1	1.07
		Intermittent	0.2	0.99
		Stationary	0	0.48
377	9	Intermittent	1	4.47
		Intermittent	0.2	3.64
		Stationary	0	3.06

Table 3 Test bench values of power on bottom-hole

Rotational speed (min^{-1})	Alial load (kN)	Power on bottom-hole (kW)
239	7	1.7
377	9	3.4

It has been shown by Dreus et al. (Dreus et al. 2016a; Dreus et al. 2016b) that intermittent flushing provides bottom-hole surface temperature change during diamond core drilling. Therefore, as it has been shown in investigations ((Vettegrena et al. 2013)), conditions for intensified rock disintegration can be provided due to thermal weakening by intermittent impact of high and low temperatures.

Intermittency factor impact on efficiency criterion is presented in Fig. 7.

The results shown in Fig. 7 confirm that frictional thermal power performs more efficiently at operating conditions assumed.

Some more advantages of transition to intermittent diamond drilling mode need to be mentioned. Average liquid flow under intermittent flushing is defined by expression

$$Q_{av} = \frac{\int_0^T Q(t)dt}{T} \qquad (14)$$

where $Q(t)$ is a function of fluid flow variation under constant feed rate, t time, and T period (see Fig. 1). Therefore, transition to intermittent mode allows reducing of flushing liquid, and consequently, saving drilling mud. Furthermore, the pump pressure and the power to drive the pump reduces allows to save power.

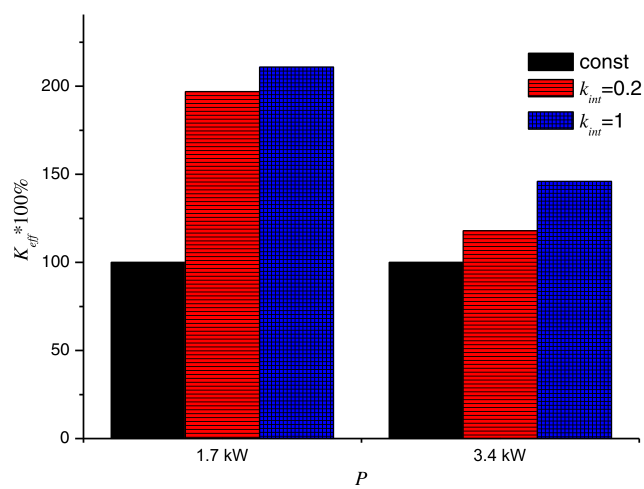


Fig. 5 Efficiency factor increased as a function of intermittency factor and power on bottom-hole

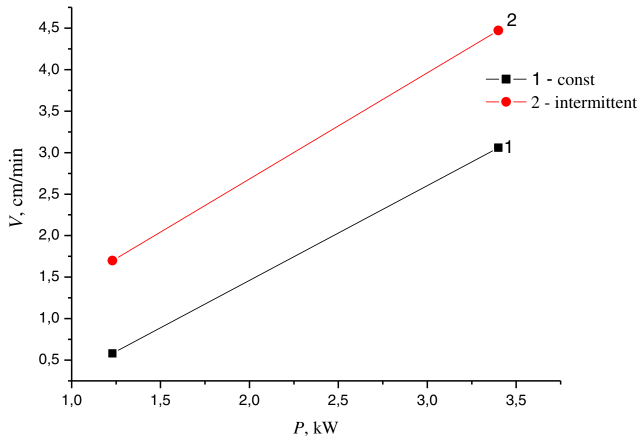


Fig. 6 Dependence of penetration speed on power on bottom-hole for different flushing modes

Conclusions

The results of performed research show that diamond drilling using intermittent flushing proves to be an efficient method of penetration speed improvement.

The research showed that the penetration speed increased with the consideration of varying operating conditions. Penetration speed increase constituted 1.18 to 2.2 times, depending on intermittency factor value. Increase in intermittency factor provides increase in penetration speed.

It has been shown that improvement in rock destruction efficiency during diamond drilling using intermittent flushing has been higher in relative values at a lower power on bottom-hole values. In absolute values, penetration speed increase after transition to intermittent flushing mode is directly proportional to the power on bottom-hole level.

Utilization of intermittent flushing allows not only to increase penetration speed, but to improve other performance indicators, such as reduction of flow rate of flushing liquid at absorption and save power.

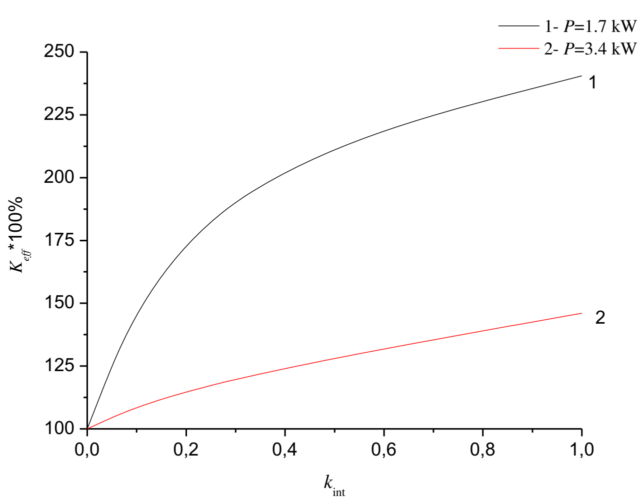


Fig. 7 Intermittency factor k_{int} impact on efficiency criterion on intermittent flushing for different power values

Funding information This work was supported by Research Foundation of Key Laboratory of Deep Geodrilling Technology, Ministry of Land and Resources, China (No.KF201808).

References

Dreus AYu, Sudakov AK, Kozhevnikov AA, and Vakhalin YN (2016a) Study of thermal strength reduction of rock formation in the diamond core drilling process using pulse flushing mode. *Natsional'nyi Hirnychyi Universytet. Naukovyi Visnyk*. (3), 5–10

Dreus A, Kozhevnikov A, Lysenko K, Sudakov A (2016b) Investigation of heating of the drilling bits and definition of the energy efficient drilling modes. Eastern-European Journal of Enterprise Technologies (7):3, б 41–б 46. https://doi.org/10.15587/1729-4061.2016.71995

Fassahov RH, Faizulin IK, Sahapov YaM, Badretdinov AM, Yeldashev DA, Prokoshelnikov DV, Gurianov AI (2005) Energy efficiency in hydro-pulse impact on the bottomhole formation zone *Izvestiya vuzov «Problemyi energetiki»*. №9–11. 56–60. (in Russian)

Filimonenko NT (2007) The movement of the cut debris in a pulsing flow, which circulating in the bottom-hole of the well. *Naukovi pratsi Donetskogo derzhavnogo tehnichnogo universitetu*. Seriya: girnicho-geologichnayu 6(125):125–130 (in Russian)

Gorshkov LK, Gorelikov VG (1992) Temperature regimes of diamod drilling. Nedra, Moscow (in Russia)

Karakus M, Perez S (2014) Acoustic emission analysis for rock-bit interactions in impregnated diamond core drilling. Int J Rock Mech Min Sci 68:36–43

Kollé J, Marvin M (1999) Hydropulses increase drilling penetration rates. Oil Gas J 97(Issue 13):33–37

Kozhevnykov AA (1992) Pulse technology of drilling wells. *Proceedings International Conference "Rocks mechanics at drilling"*– Groznyi. 43 – 44. (in Russian)

Kozhevnykov AA, Filimonenko NV (2010) Ways of impulse washing of wells *Natsional'nyi Hirnychyi Universytet. Naukovyi Visnyk* 6:28–32 (in Russian)

Kozhevnykov, A.A., Vyrvinsky, P.P., Dyachenko, Yu.G., Yacenko N.D. (1990) Bench drilling research with impulse flushing // *Proceedings V Vsesouznoi Conference « Destruction of rocks at wells drilling»*. – Ufa – C.43–44. (in Russian)

Liu Y, Wei J, Ren T, Zhaohui L (2015) Experimental study of flow field structure of interrupted pulsed water jet and breakage of hard rock. Int J Rock Mech Min Sci 78:253–261. https://doi.org/10.1016/j.ijrmms.2015.06.005

Perez S, Karakus M, Pellet F (2017) Development of a tool condition monitoring system for impregnated diamond bits in rock drilling applications. Rock Mech Rock Eng 50(5):1289–1301

Qu H, Li G, Jiang D (2016) Mechanisms and application for hydraulic pulsed cavitating jet generator. Advances in Petroleum Exploration and Development 12(2):1–12. https://doi.org/10.3968/pdf

Shi H, Li G, Guo B, He Z (2015) Hydraulic pulse jet: test of characteristics and field applications in ultra-deep wells. J Nat Gas Sci Eng 27:200–206. https://doi.org/10.1016/j.jngse.2015.08.053

Tungusov SA (2009) Improving the efficiency of drilling wells by pulsed flushing. *Razvedka I ohrana nedr* 8:42–47 (in Russian)

Vettegrena VI, Mamalimova RI, Sobolevb GA, Kireenkovab SM, Morozovb YA, Smul'skaya AI (2013) Temperature-induced phase transition in quartz nanocrystals dispersed in pseudotachylite. Phys

Solid State 55(5):1063–1069. https://doi.org/10.1134/S1063783413050338

Wang Z (2005) Discussion on theory and methodology of suction-pulse drilling technique. Oil Drill Prod Technol 27(6):13–15

Wang D, Zhang W, Zhang X, Zhao G, Zuo R, Ni J et al (2015) The China continental scientific drilling project: CCSD-1 well drilling engineering and construction. Springer, Berlin