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Simulation of thermal stress effects in submerged continuous water jets on the optimal standoff distance during rock breaking

Mukun Li [a], Hongjian Ni [a,*], Guan Wang [a], Ruihe Wang [b]

[a] Research Institute of Unconventional Oil & Gas and New Energy, China University of Petroleum, Qingdao 266580, China
[b] School of Petroleum Engineering, China University of Petroleum, Qingdao 266580, China

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ABSTRACT

Although many hypotheses of rock breaking of water jets have been proposed, effects of thermal stresses on the jet-based rock breaking hasn't been systematically analyzed yet. A fluid-solid coupling analysis module in ANSYS was employed in the article to reveal the effects of thermal stresses on the water-jet rock breaking and prove the existence of the optimal standoff distance. It is found that the trend of the temperature is in accordance with the existence of the optimal standoff distance. The coupling effect of the temperature and pressure fields can enlarge the breaking area of water jets. The effects of thermal stresses on soft rock with the low elastic modulus are minor, and no optimal value exists, with regard to the standoff distance. Nevertheless, as for hard rock such as granite, the optimal standoff distance is about ten times the nozzle diameter and the value will decrease with the increase of jet time. The findings of this research can offer a novel research starting point and method for the effective application of high-pressure water jets to cut metal and rock.

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1. Introduction

High pressure water jetting has been widely used in rock crushing in many fields, such as mining, petroleum drilling, rock cutting and tunnel excavation [1–6]. However, no unified theory on water-jet rock breaking has been commonly accepted, since breaking rock with water jets involves multiple disciplines, including fluid mechanics, solid mechanics, and fluid-solid coupling [2,7]. Currently, the rock breaking theories can mainly be attributed to the static elastic breaking, stress-wave breaking, cavitation erosion breaking, crack-propagation-induced breaking and the damage theory [8–10].

In a view of the static elastic breaking, the maximum shear stress on the rock occurs right below the striking zone of water jets, and around the boundaries of the striking zone occurs the tensile stress [11]. When the tensile stress or the shear stress exceeds the tensile or shear strength of the rock, the rock will then fail. The dense core-splitting tensile breaking theory, which explains the evolution of radial cracks into volumetric breaking of brittle rock, is one of the most representative theories from such perspectives [12]. The static elastic breaking theory well explains the existence of the threshold pressure during the continuous water-jet rock breaking. However, its results strongly differ from the experimental results of large volumetric rock failure and other parameters under pulsed jetting or supersonic jetting.

The stress-wave breaking theory holds the view that the rock impacted by water jets is initially under compression due to the water hammer pressure, and then the water hammer pressure rapidly decreases to the stagnation pressure, which causes the reflection of the compression wave and tensile failure of the rock [2,7,13–19]. The stress-wave breaking theory mainly describes the rock breaking mechanisms of the pulsed jetting and supersonic jetting. However, further studies are needed as for the occurrence of stress waves in the medium-low speed jetting and submerged jetting.

The cavitation erosion breaking theory believes that the bubbles inside the jets generate simultaneous high pressures and high temperatures as they burst on the solid surface, which break the rock [20–23]. Yet, there haven't been theoretical models about the cavitation erosion breaking theory, due to the unavailable experimental data about the damage of cavitation jet to rocks as well as the discrepancy concerning the understanding of the initiation, evolution and destruction of cavitation under confined conditions.

In the crack propagation breaking theory, it is proposed that the rock fails because of the propagation of natural cracks under the effects of impact stresses of water jets or tensile water wedging [8,9]. It is found that many experimental results support this theory, while there lack persuasive evidences for the contribution of the pore pressure to the rock failure. Therefore, the theory fails to well describe the relationship between the crack propagation and crushed zone.

The damage theory uses the damage variable as the criteria of the rock failure, which is a function of tension, pressure, strain rate and damage. On the basis of Johnson Holmquist constitutive model [2,3,7]

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* Corresponding author.
E-mail address: nihj@upc.edu.cn (H. Ni).

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and Lemaitre isotropy continuous damage model [24,25], the dynamic rock breaking process of jets is simulated [9]. It is found that the water-jet rock breaking can be divided into two stages, which are respectively dominated by the impulse load that leads to rock damage and the pseudo-static pressure that results in the secondary development of micro pores and cracks [9,26]. Such opinion agrees with the previous experimental result by Daniel [14]. But the method simplifies the water properties and the contact between the fluid and rock, and can't reflect the thermal effect on the rock breaking.

To sum up, the existing water-jet rock break theories do not consider effects of thermal stresses. The standoff distance is an important factor affecting the metal or rock cutting of water jets, but its mechanism is not clear so far. Experimental studies have proved that the standoff distance has an optimal value. As the standoff increases, the rock removal volume increases until a turning point appears where the rock removal volume starts dropping. Liao et al. did lots of studies on the optimal standoff distance of rock breaking for a submerged water jet (jetting in the water). It was found that the optimum standoff distance under submerged condition changes from 15 times the nozzle diameter to 20 when the driven pressure varies from 100 MPa to 200 MPa and nozzle moving speed is 2.5 mm/s [27]. Under a pressure difference of 20 MPa, the optimum standoff distance for both conical water jet and cavitating jet was produced at near 4 times the nozzle diameter with an ambient pressure of 0 MPa, 10 MPa and 20 MPa [28]. Also, they found through experiments that the optimal standoff distance of a multi-orifice nozzle with a pressure difference of 25 MPa is about 5 to 6 times the equivalent nozzle diameter at atmosphere submerged conditions and a jet time of 3 min [29]. The reasons they gave are as follows. On one hand, in a short standoff distance, rock erosion increases slowly because of the return flow counteracting parts of the jet energy. On the other hand, the jet effective impinging area enlarges as an increment of standoff distance at a certain range. But the above explanations were not proven by experiments or calculations. And it can't explain the big difference of optimal standoff distance for nozzle moving and not moving. Tian et al. found that the optimal standoff distance of chaos nozzle and cavitation nozzle is about 10–14 times the nozzle diameter at a jet time of 60 s [30]. They thought that the optimal standoff distance of a cavitation nozzle is produced by the erosion effect of cavitation, and for chaos nozzle the continuous jet needs time to become a discontinuous jet. But it is only an assumption without further proof, and couldn't explain why the optimal distance of the two kinds of nozzles are close to each other. Li et al. found that the optimal standoff distance for the premixed abrasive water jet and the pulsed abrasive water jet under atmosphere submerged conditions is 10 times the nozzle diameter [31], which is the same as the optimal distance of a particle jet [32]. The results showed that pulse pressure is not a key parameter influencing the optimal standoff distance, and a common factor having no relations with abrasive or particle effects on the optimal standoff distance. Ozcelik et al. found that when standoff distances for water jets in the air increases, the width of cut increases whereas the depth of cut decreases [33], and that the optimum distance is near 62.5 times the nozzle diameter at a nozzle moving speed of 4 m/min and pressure difference of 60 MPa [34]. Oh et al. found for abrasive water jet in the air, that the optimum distance for cutting volume is near 118 times the nozzle diameter at a pressure difference of 314 MPa and nozzle moving speeds of 1.9 mm/s, 8.4 mm/s and 14.1 mm/s [35]. It was also found that as the standoff distance increases, the cutting depth decreases while the cutting width increases, and thus an optimal standoff distance exists. Oh et al. contributed the change of depth and width to the increase of pressure impact area induced by jet diffusion. To the contrary, through tests and calculations of the impact force of jets versus the standoff distance, some found that the impact force decreases with the growing standoff distance, and therefore there is no so-called optimal standoff distance [36]. The researches mentioned above suggest that there are still unrevealed influential factors in rock breaking by high-pressure water jets.

Viscous heating can be easily produced in high shearing distortion flows because the action of shear forces is transformed into heat [37–39]. Because the water jet on the rock can produce high pressure gradients, high shearing flow is easy to form. Exploratory simulation study in this paper indicates that high temperatures over 70 °C are generated in the jet central zone on the rock surface because of viscous heating. Li et al. found that thermal stress is the main factor for the better rock breaking performance of a supercritical carbon dioxide jet than that of a water jet [40]. It shows that thermal stress may be an ignored factor in previous research of water jet. Massive studies have been carried out on the thermal breaking of rock under the effect of temperature loads. There are mainly two reasons contributing to thermal breaking. One is the rock stress induced by the thermal gradient, and the other one is the stress caused by the varied thermal expansion coefficients of different minerals in the rock. Previous studies found that micro cracks can initiate in the igneous rock under relatively low temperatures as the heat rate exceeds several degrees per minute [41–43]. It is also found that the thermal breaking of the American Westerly granite can occur under 75 °C or so and meanwhile the count rate of the acoustic emission grows with an increasing heating rate [44,45]. Moreover, the thermal breaking temperature of the Westerly granite was found to range from 60 °C to 70 °C [46]. It was also suggested that the carbonate rock permeability grows by 8–10 times after going through the temperatures of 110 °C–120 °C [46]. Previous studies also demonstrated that the cracking threshold temperature of granite from Pingyi, Shandong Province, China is 65 °C and that of fine-grained sandstones from Yongcheng, Henan Province, China is 170 °C [47,48]. From the above analyses, it is safe to say that thermal breaking may happen to hard rock similar to the granite as it is heated to 70 °C. In fact, hard rock such as stiff marbles and granite is often used in high-pressure water jetting test. The rock breaking process of water jet lasts for only several milliseconds during the high-pressure water jetting [9,14]. Moreover, the severe convection in jetting leads to the rapid temperature variation on the rock surface, while the thermal conductivity of rock is low and the internal temperature transfer within the rock is a slow process. Therefore, relatively great thermal gradients exist between the rock surface and the internal part during jetting. The high thermal gradient can lower the threshold value of the thermal breaking. In a word, thermal stress can very possibly play an important role in rock breaking of water jet.

To investigate the effects of thermal stresses on the optimal standoff distance of water-jet rock breaking, the rock stress field under water jets was analyzed using the fluid-solid coupling analysis module, Fluent-Static Structural in ANSYS. The static elastic breaking theory was adopted as the criteria for the water-jet rock breaking, which assumed that the rock would crush if the tensile or shear stress exceeds the ultimate value. Simulation results show that the thermal stress is a critical influential factor on the optimal standoff distance. The findings of this research offer a novel research idea and method for the effective applications of high-pressure water jets to rock breaking in petroleum drilling and mining. It's particularly helpful for the development of water jet cutting without abrasives [7], which show that thermal stress is another way to save the cost of abrasive material except increasing the water jet cutting pressure. High pressure water jet comminution (HPWJM) is a branch of high pressure water jet technology [49], and it has been proved in material powder production with advantages of low energy consumption, high comminution efficiency, no pollution and lower equipment wear [50–53]. The HPWJM process is the jet of the mixture of water and particles on the plate [49–53], which is similar to that of the water jet on the rock. Current research for coating removal [54,55] and powder production with HPWJM such as powder of metal [56–58], rubber [56,57,59] and coal [50], has not taken thermal effect into use and mechanism explanation. Because thermal stress is easy to produce between different components of materials having different thermal properties, the thermal effect of high water jet could be useful for the development of using water jet in coating removal [60] and powder production.

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