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Characteristics of momentum transfer depend on the focus geometry for waterjet rock cutting

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ABSTRACT

Abrasive waterjet is used in civil engineering such as tunneling, concrete demolition, and rock excavation. The main energy of abrasive waterjet for rock cutting is the accelerate abrasives. Since the momentum transfer efficiency differs according to the waterjet system configuration and abrasive flow rate during mixing and acceleration, different cutting performance is shown. In this study, the influence of the focus geometry such as diameter and length on the momentum transfer was evaluated according to flow rate and abrasive input mass by rock cutting experiment. As a result, characteristics of the optimum abrasive flow rate and the momentum transfer parameter by focus geometry were evaluated. The results of this study are expected to be applied to operational optimization of waterjet for civil engineering

1. INTRODUCTION

Waterjet is tool for cutting and cleaning by using high-pressure water and abrasive. Since this technology uses only water and abrasive, waterjet is environmentally friendly, and is applicable for many civil engineering cases. Nowadays, it is used for urban rock cutting of tunnel excavation due to its low noise and low vibration feature (Cha, Tae-Zin, & Cho, 2017; Kim, Song, Han, & Lee, 2012; Oh & Cho, 2013).

The main energy of abrasive waterjet for rock cutting is accelerated abrasives. The energy of abrasive is determined by whole waterjet conditions such as pump pressure, water flow rate and abrasive flow rate, and system configurations (Momber, 1997). The abrasives are accelerated by high-velocity water stream after pressurized water passing through the orifice. By passing through the orifice of the pump pressurized high-pressure water, the high-pressure water become the high-velocity stream with consideration of resistance parameter (μ) for orifice shape. By Bernoulli

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theorem, the velocity of the water stream is:

$$v_{w,0} = \mu\sqrt{\frac{2 \cdot p_{wp}}{\rho_w}} \qquad \text{Eq. (1)}$$

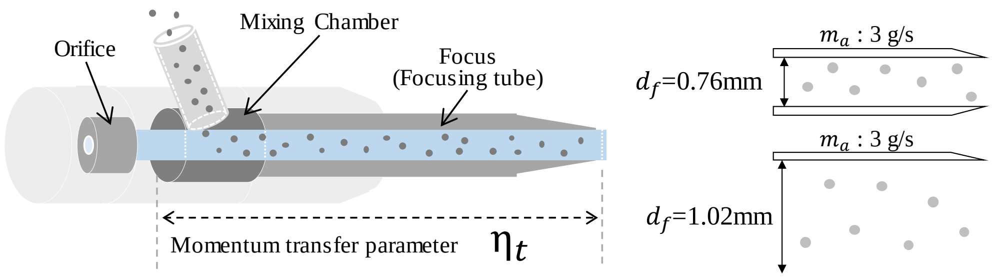
Where $v_{w,0}$ is velocity of water stream p_{wp} is pump pressure, ρ_w is the density of water. During acceleration of abrasives, the momentum of water stream transfer to that of abrasives. In accordance with the law of the conservation of energy, the velocity of abrasive-water mixture is:

$$v_t = \eta_t \frac{v_{w,0}}{1+\left(\dot{m}_a/\dot{m}_w\right)} \qquad \text{Eq. (2)}$$

Where v_t is velocity of the mixture, $\dot{m}_a$ and $\dot{m}_w$ are flow rate of abrasive and water respectably, and η_t is momentum transfer parameter which means mixing efficiency (Figure 1.(a)).

The energy for rock cutting is calculated by velocity of the mixture and mass of abrasive

$$E_{et} = \frac{1}{2} \cdot \dot{m}_a \cdot t \cdot \left(\eta_t \frac{v_{w,0}}{1+\left(\dot{m}_a/\dot{m}_w\right)}\right)^2 \qquad \text{Eq. (3)}$$



(a) abrasive acceleration in focus (b) mixing efficiency of focus
Fig 1. Schematic drawing of abrasive mixing and acceleration

The momentum parameter is key parameter for rock cutting energy, and this parameter is determined by shape of orifice, focus geometry, and abrasive flow rate (Blickwedel, 1990; Hloch, Gombar, & Valicek, 2007; Momber, 1997). However, there is lack of an approach to evaluate the effect of waterjet configuration (e.g. orifice diameter, focus diameter; Figure 1.(b)) due to complicated mechanisms (Babu & Chetty, 2006; Hashish, 1991; Oh & Cho, 2013). Therefore, it is necessary to evaluate the rock cutting performance depending on the focus geometry on the consideration of abrasive flow rate to be used properly in civil engineering. In this study, characteristics of maximum cutting depth and momentum parameter is evaluated by experiment with various focus diameter. The optimum abrasive flow rate features were reviewed by experiment result, and the change of the momentum parameter was evaluated by estimating the change of the cutting energy according to abrasive and water flow rate. As a result, the influence of focus length on the rock cutting performance was assessed. Through this study, the optimum abrasive flow rate of proper focus installation can be selected for economic reason. The results of this study are expected to be used for optimization waterjet operation for civil engineering.

2. EXPERIMENTAL PROGRAM

Experimental setup for evaluation of focus effect for rock cutting is shown in figure 2. In order to evaluate the focus diameter effect, experiment was conducted with 3 different diameter (e.g. 0.76, 0.91, and 1.02 mm) at 3 different water flow rate (10.67, 29.50, 50.00 ml/s). The abrasive flow rate changed from 10 to 70 g/s and the details of experimental cases such as pressure, standoff distance, and traverse speed are shown in table 1.

The properties of abrasive and intact rock specimen are shown in table 2 and 3. The garnet ($Fe_2O_3Al_2(SiO_4)_3$) is used, garnet is the common abrasive in waterjet industry, and used mean particle size is 80 mesh (0.18mm) considering optimum abrasive particle size (Mozurkiwicz, Fincuan, & Ferguson, 1988). Granite, classified very strong rock by ISRM standard, is target. This rock type is the mostly encountered at construction site in Korea.

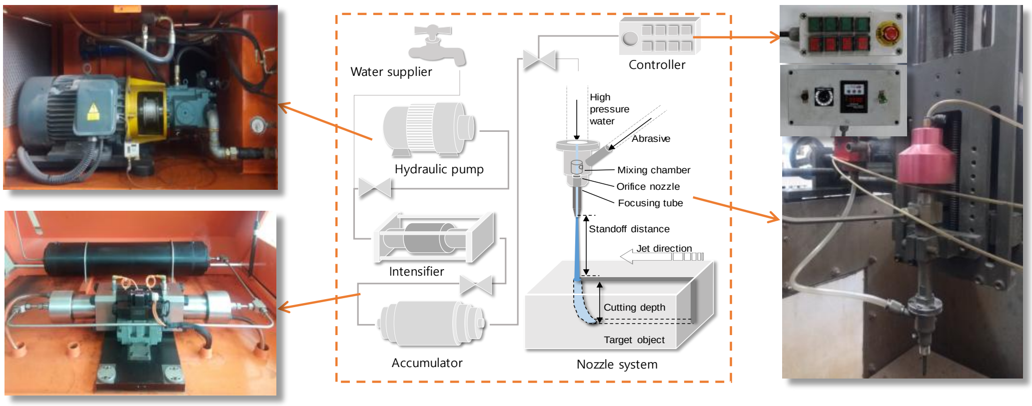


Fig. 2. waterjet assembly for focus effect experiment

Table 1. Experimental conditions and cases

Water pressure (MPa)		320	
Standoff distance (mm)		10	
Traverse speed (mm/s)		1.9	
Orifice diameter (mm)	0.15	0.254	0.33
Water flow rate (ml/s)	10.67	29.5	50.0
Length of focus (mm)	76.2	76.2	7.2
	0.76	0.76	0.76
Diameter of focus (mm)	0.91	0.91	0.91
	1.02	1.02	1.02
Abrasive flow rate (g/s)		10-70	

Table 2 Abrasive property

Abrasive type	Component	Mohs hardness	Specific gravity	Particle size
Garnet	Pyrope	7.1	3.1-4.3	80 mesh

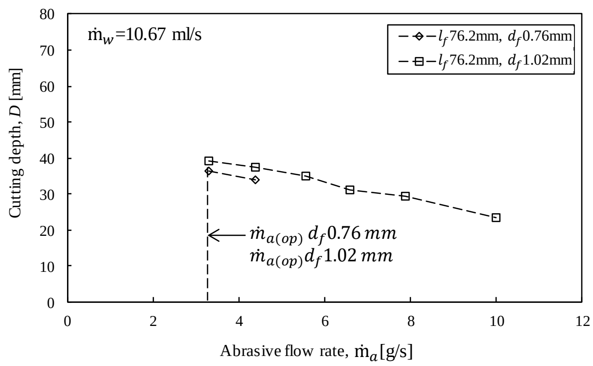
Table 3 Rock specimen property

Rock type	Density (kN/m^3)	UCS (MPa)	Shear strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
Granite	26.50	236		10.2	56.5

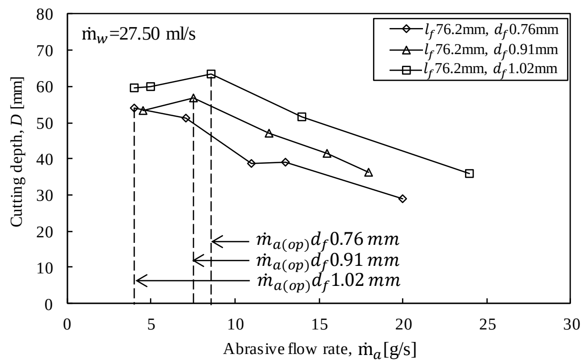
3. EXPERIMENT RESULT

3.1 Characteristics of optimum abrasive flow rate depend on the focus diameter

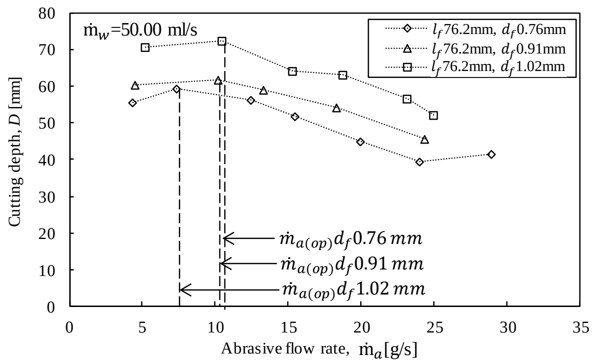
Fig. 3 (a) shows the cutting depth by focus diameter according to the abrasive flow rate. The larger focus diameter at the same abrasive flow rate, the better the rock cutting performance. The optimum abrasive flow rate (m_{op}), which is the input mass for the best cutting depth, increase as the focus diameter increases. This is explained that larger the focus diameter, the focusing internal space is widened and the interferences between the abrasive particle are reduced. The maximum cutting depth also increases with a larger focus diameter. On the other hand, optimum abrasive flow rate was not observed at 10.67 ml/s of water flow rate, and it was observed as the focus diameter increased as a larger water flow rate of 27.5 ml/s. With that tendency, at a flow rate of 50.00 ml, optimum abrasive flow rate is observed at all focus diameter.



(a) 10.67 ml/s of water flow rate



(b) 27.50 ml/s of water flow rate



(c) 50.00 ml/s of water flow rate

Fig. 3 Effect of focus diameter on the optimum abrasive flow rate

3.2 Characteristics of momentum transfer parameter change

Figure 4 shows the result of the cutting depth with the focus length 76.2 mm and the diameter 1.02 mm, by water flow rate according to the abrasive flow rate. Based on these result, abrasive kinetic energy is estimated by the momentum transfer parameter change (equation 2, 3) in accordance with the change in abrasive flow rate. In this way, the change of momentum transfer parameter according to abrasive flow rate was obtained, and the result is shown in figure 5. The lower the water flow rate, the greater the change in momentum transfer parameter. The reason for this is that the higher the abrasive-water mass ratio, the greater the influence of the abrasive velocity (equation

2). Meanwhile, the larger the focus diameter, the greater the change in momentum transfer parameter. It is demonstrated that the larger the focus, the higher the mixing efficiency and the greater variation.

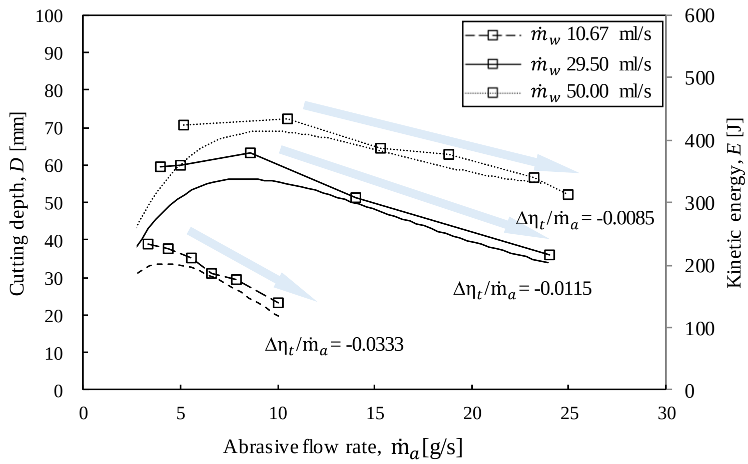


Fig. 4 Rock cutting energy and abrasive kinetic energy

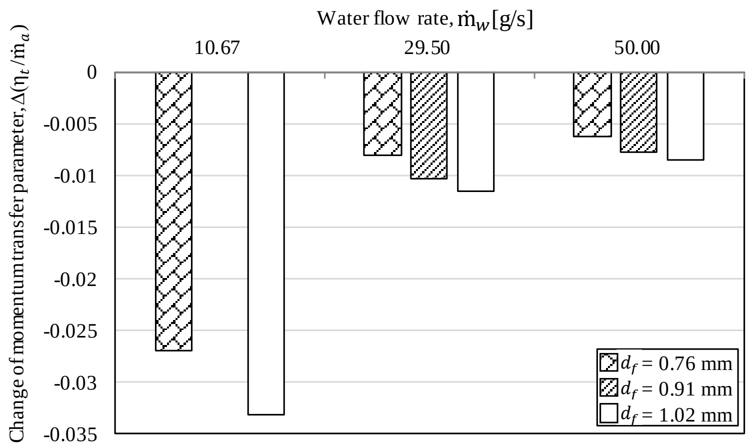


Fig. 5 Momentum transfer change depend on focus diameter

4. CONCLUSIONS

In this study, the effect of the focus diameter on the rock cutting performance was evaluated. The characteristics of optimum abrasive flow rate was assessed according to focus diameter and water flow rate. In addition, by estimating the abrasive kinetic energy based on the cutting result, the momentum transfer parameter was evaluated. The result of the experiment and the considerations are as follows.

- The larger the focus diameter, the greater the abrasive flow rate and maximum cutting dep. It is explained that a certain internal space of focus is required for abrasive acceleration
- In the conditions such as low water flow rate and small focus diameter, that the cutting efficiency is decreased, the optimum abrasive flow rate is not observed and the cutting depth is decreased as the abrasives are input. This is because

the number of abrasive particles are increased, the mixing efficiency is reduced, and the momentum of the fluid is further decreased.

- The abrasive kinetic energy is estimated on the basis of the experimental result, and the momentum transfer parameter changes are evaluated as the mixing efficiency
- The larger the focus diameter or the lower the water flow rate, the larger the MTP changes. This is the result of the degree of influence on the abrasive velocity and the initial mixing efficiency. This is the same result as the cutting experiment.

These results are expected to be applied for more economical use of abrasive waterjet rock cutting.

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