The 2022 World Congress on
Advances in Civil, Environmental, & Materials Research (ACEM22)
16-19, August, 2022, GECE, Seoul, Korea

Effect of Particle Shape Factor on Abrasive Kinetic Energy

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ABSTRACT

The rock excavation method using abrasive waterjet technology has the advantage of low noise and low vibration during construction, so various studies have been conducted to apply it to construction sites in downtown areas. The abrasive waterjet method is a technology that removes materials by mixing high-pressure water and abrasives and then spraying them on the target rock. The main principle of rock removal is that abrasives are accelerated by water impact and erode the target material. An important factor in the rock erosion mechanism of an abrasive is the abrasive kinetic energy, which is directly related to the abrasive velocity. Also, the abrasive velocity is affected by particle properties. However, it is difficult to observe the abrasive velocity according to particle properties experimentally. Therefore, this study observed the abrasive velocity for particle shape factors using ANSYS Fluent, a CFD program. Also, the kinetic energy of the abrasive was derived and analyzed. This study is expected to contribute effectively to the selection of abrasives when designing abrasive waterjet technology for rock excavation.

1. INTRODUCTION

Due to the overpopulation and lack of space in downtown areas, the development of underground spaces is required. However, several problems may cause inconvenience to citizens, such as road closure and traffic congestion due to

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construction during rock excavation in downtown areas. In particular, complaints from nearby residents caused by noise and vibration during rock excavation can delay or stop construction. Waterjet technology is a low-noise, low-vibration method that can solve these civil complaints when excavating rocks. Meanwhile, various studies have been conducted on material removals, such as rock cutting and drilling using waterjet technology (Summers 1995). Research on abrasive waterjet technology that mixes and sprays water and abrasives has been actively conducted (Momber and Kovacevic 1998, Hwang et al. 2019). High-pressure water is generated by the water pump and converted to high-velocity water through a small diameter orifice. This high-velocity water mixes with the abrasive in the mixing chamber and transfers momentum to the abrasive. The abrasive has kinetic energy in this process. Finally, it is sprayed into the air through the focusing tube (Fig. 1).

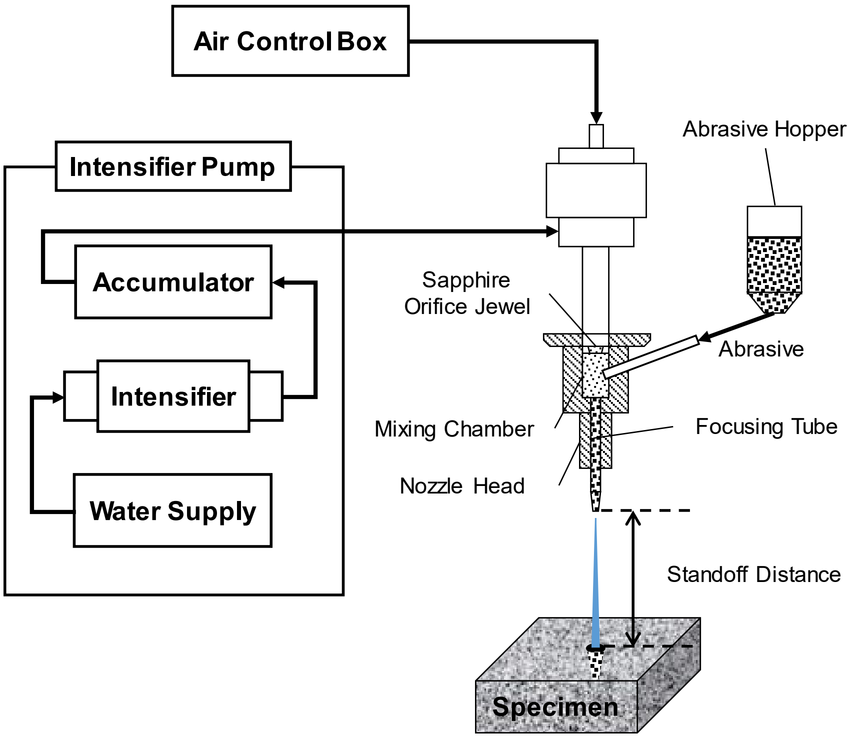


Fig. 1 Abrasive waterjet system (Hwang et al. 2019)

However, the main energy in rock excavation using an abrasive waterjet is the kinetic energy of the abrasive. First, the kinetic energy of water generated as it passes through an orifice with a tiny diameter decreases while accelerating the abrasive. In previous studies, it was assumed that the velocity of water and abrasive was the same as the terminal velocity just before being sprayed into the air from the tip of the focusing tube. In addition, the effective kinetic energy of the abrasive waterjet was defined as a function of abrasive flow rate and terminal velocity. However, Cha et al. (2019) showed that, depending on the size and density of the abrasive, the velocity of water and abrasive at the end of the focusing tube did not reach the same terminal velocity and were sprayed into the air (Fig. 2). Therefore, the effective kinetic energy that can be calculated for the actual abrasive waterjet rock excavation should use the abrasive velocity, not the terminal velocity. It is necessary to derive the abrasive velocity at the end of the focusing tube.

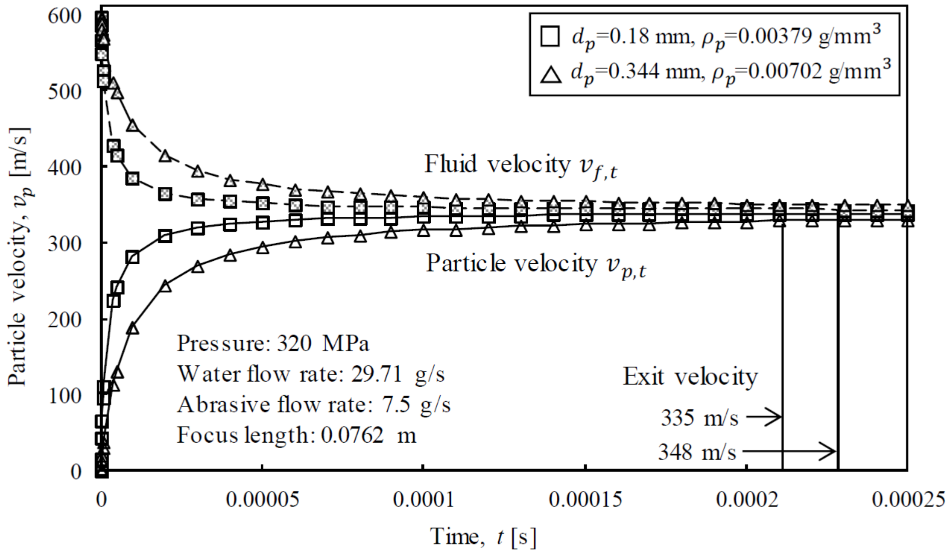


Fig. 2 Water and abrasive velocity in the focusing tube

Since the abrasive velocity before reaching the terminal velocity is difficult to observe experimentally, in this study, numerical analysis was used to observe it. The abrasive is mixed with water in the mixing chamber and collides with the wall while passing through the focusing tube, resulting in straightness. Since some energy is lost in this process, the restitution coefficient (E) was considered to represent a reasonable particle-wall interaction. Therefore, in this paper, the abrasive velocity at the tip of the focusing tube was observed by applying various particle shape factors to observe the effect on non-spherical abrasive particles.

2. NUMERICAL SIMULATION

2.1 Simulation Setup

This numerical analysis was conducted using ANSYS Fluent, a commercial Computational Fluid Dynamics (CFD) program. ANSYS Fluent is a Finite Volume Method (FVM) based analysis program that analyzes fluid flow by discretizing the control volume and calculating the physical quantity. ANSYS Fluent software was used in this study to observe the accelerated abrasive velocity before spraying into the air at the tip of the focusing tube.

The abrasive acceleration mechanism of the abrasive waterjet is a multiphase flow phenomenon and can be divided into a continuous phase (i.e., water and air) and a discrete phase (i.e., abrasive). For the continuous phase, the Volume of fluid (VOF) model was applied, and for the discrete phase, the Discrete phase model (DPM) was used (Hou et al. 2013, Nyaboro et al. 2018, Qiang et al. 2018). In addition, a discrete random walk (DRW) model was applied to consider the effect of turbulence in calculating the trajectories of abrasive particles in a fluid. These simulation setup models are suitable for complex geometries and mechanisms, such as abrasive waterjets, and can reasonably calculate multiphase fluid flow phenomena.

2.2 Geometry and Boundary Conditions

This numerical model implemented a three-dimensional abrasive waterjet system to observe the behavior of abrasives in three-dimensional space. Fig. 3 is the numerical analysis geometry of the abrasive waterjet system, and the abrasive is accelerated by the same mechanism as the abrasive waterjet system in Fig. 1 mentioned above. At the top, high-pressure water is injected, passes through an orifice with a tiny diameter, and is converted at high velocity. The abrasive injected through the abrasive inlet is mixed with water at high velocity in the mixing chamber to obtain momentum. As the mixed water and abrasives pass through the focusing tube, linearity is obtained, and a numerical model is constructed so that it is finally sprayed from the outlet.

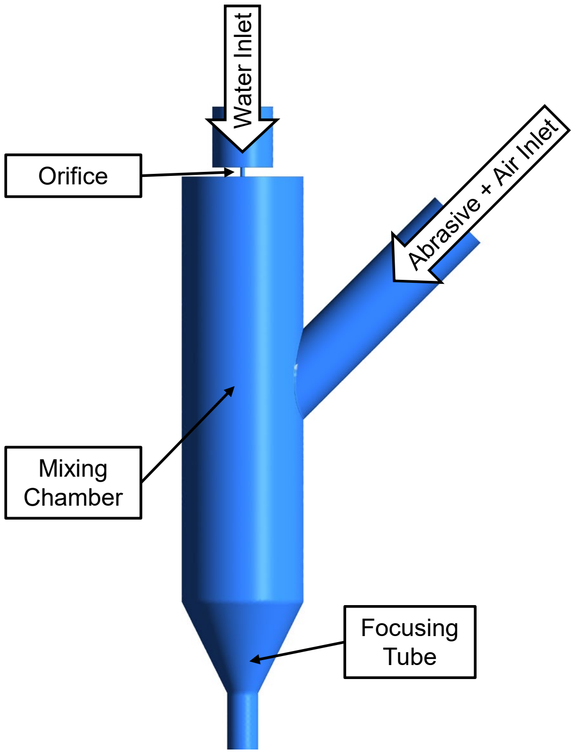


Fig. 3 Geometry of numerical simulation model

The location and input values of boundary conditions applied to this numerical analysis model are as follows. First, pressure conditions were input to the inlet and outlet sections. Specifically, 91.1 MPa for water inlet, 101.325 kPa for abrasive inlet, and 101.325 kPa for the outlet. This is because 101.325 kPa is a general atmospheric pressure condition, and in the case of abrasive inlet and outlet in an actual abrasive waterjet system, it is an atmospheric pressure condition, not arbitrarily applying external pressure. In addition, a restitution coefficient (E) was applied to consider the particle-wall interaction (Forder et al. 1998). The restitution coefficient is defined as a function of particle incidence angle, and the formula is as follows (Eq. 1, Eq. 2).

$$E_{\perp} = 0.988 - 0.78\theta + 0.19\theta^2 - 0.024\theta^3 + 0.027\theta^4 , \quad (1)$$

$$E_{/\!/} = 1 - 0.78\theta + 0.84\theta^2 - 0.21\theta^3 + 0.028\theta^4 - 0.022\theta^5 , \quad (2)$$

where $E_{\perp}$ is the restitution coefficient of normal direction, $E_{/\!/}$ is the restitution coefficient of tangential direction, and θ is the particle incidence angle.

2.3 Model Validation

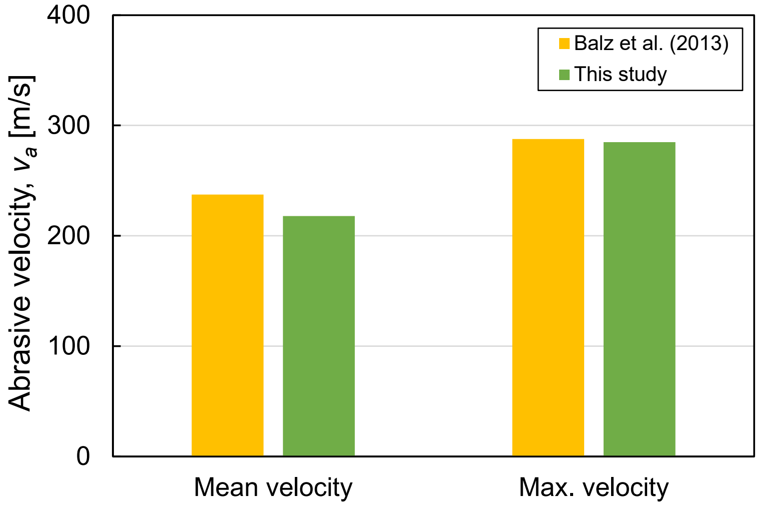


Fig. 4 Comparison of abrasive velocity between experimental test (Balz et al. 2013) and numerical simulation (This study)

Balz et al. (2013) experimentally measured the particle velocity of an abrasive waterjet using ultra-fast X-ray velocimetry. The numerical analysis model was verified by comparing the experimental results of their abrasive velocity with the results of this numerical analysis. For an accurate comparison, the specifications and boundary conditions of the abrasive waterjet system they used were applied equally when performing the numerical analysis. The specification of the abrasive waterjet system is as follows. It has an orifice diameter of 0.28 mm, focusing tube diameter of 0.80 mm, a focusing tube length of 76 mm, and an abrasive size of 0.20 mm. Also, for the boundary condition, a water pump pressure of 91.1 MPa, a water flow rate of 18.71 ml/s, and an abrasive flow rate of 3.667 g/s were applied. Numerical analysis was performed assuming that the particle shape factor was one and a perfect spherical shape. Fig. 4 is a graph comparing the abrasive velocity obtained numerically through this study with the experimental results and shows very similar results. Therefore, this numerical analysis model was judged to be valid.

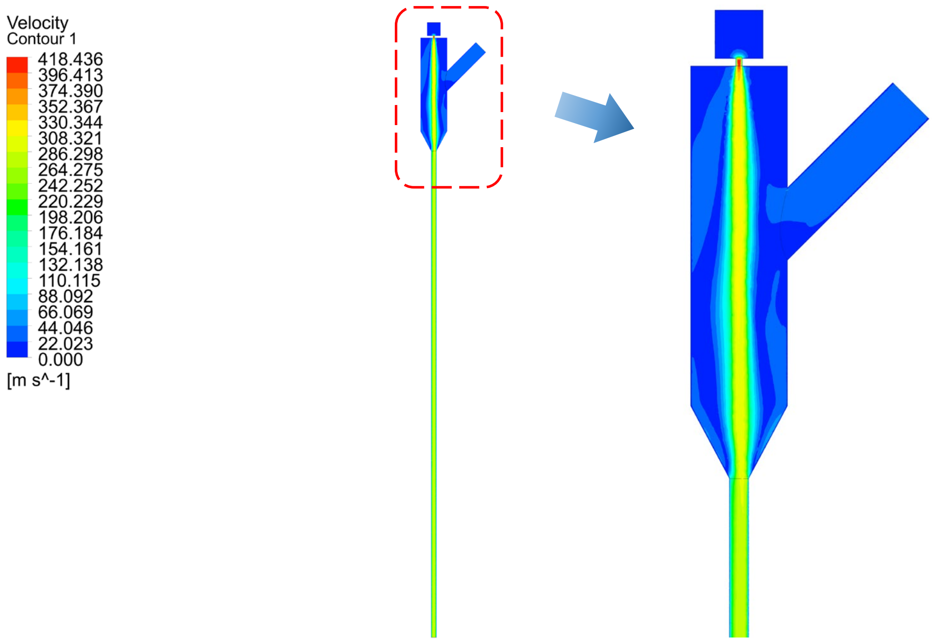
2.4 Simulation cases

In this numerical analysis, the case was constructed as shown in the following table to consider the effect of the particle shape factor on the abrasive velocity (Table 1). In addition, the abrasive was applied with a diameter of 0.2 mm and a density of 3790 kg/m^3. Nine cases were performed for particle shape factors ranging from 0.1 to 0.9.

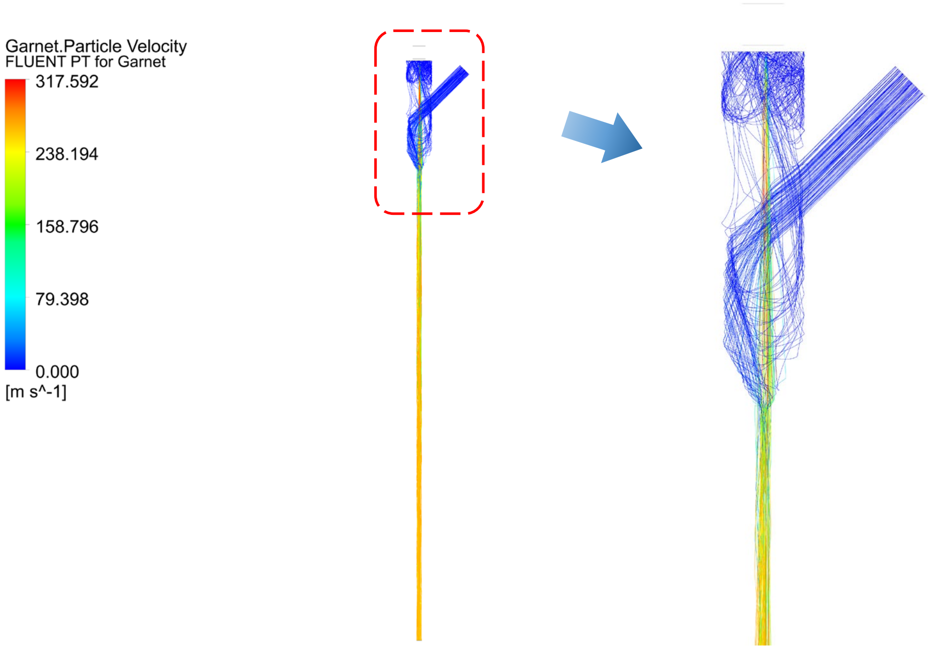
Table 1 Simulation cases and details

Water pump pressure [MPa]	91.1
Orifice diameter [mm]	0.28
Water flow rate [ml/s]	18.71
Abrasive flow rate [g/s]	3.667
Focusing tube diameter [mm]	0.80
Focusing tube length [mm]	76
Particle shape factor [-]	0.1 ~ 0.9

3. RESULTS AND DISCUSSIONS



(a)



(b)

Fig. 5 Velocity contour of (a) Fluid phase and (b) Discrete phase with particle shape factor = 0.4

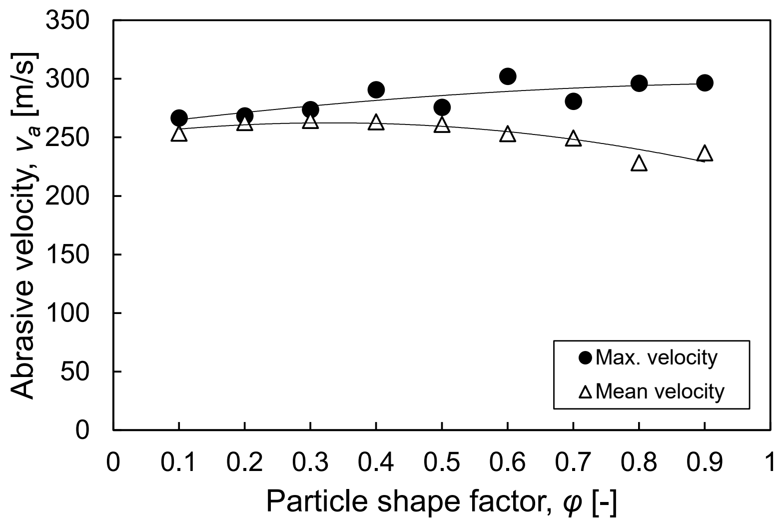


Fig. 6 Effect of particle shape factor on the abrasive velocity

Fig. 5 is an example of the numerical analysis result, showing the velocity contours of the fluid phase (i.e., water) and particle phase (i.e., abrasive) when the particle shape factor is 0.4. As shown in Fig. 5 (a), when high-pressure water enters from the top and passes through an orifice with a tiny diameter, it can be confirmed that it is converted to high-velocity water. Also, in Fig. 5 (b), it was confirmed that the abrasive particles were injected and mixed with high-velocity water, and the momentum was transferred and accelerated.

Also, Fig. 6 shows how the abrasive velocity at the tip of the focusing tube changes as the particle shape factor changes. Maximum abrasive velocity increased as the particle shape factor increased, while the mean velocity increased and then decreased. The decrease of the shape factor indicates the increase of particle sharpness and contributes to a larger drag coefficient. A large drag coefficient interrupts particle acceleration in the fluid, so the abrasive velocity should be small.

4. CONCLUSIONS

In this study, numerical analysis of abrasive waterjet system was performed considering particle shape factor and restitution coefficient. The results are summarized as follows.

- As a result of observing the abrasive velocity according to the change of the particle shape factor, there was a large difference. In order to derive a more accurate abrasive velocity, shape factor and restitution coefficient should be considered.

- It is necessary to derive a correlation between the drag coefficient and the restitution coefficient.

- This numerical analysis has limitations in that it does not consider the abrasive size and density, which will be carried out as a further study.

ACKNOWLEDGEMENT

This research was supported by UNDERGROUND CITY OF THE FUTURE program funded by the Ministry of Science and ICT and the technical support from ANSYS Korea.

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