Instantaneous Photographic Observation of Abrasive Water Suspension Jets*
(Influence of Abrasive Particle on Jet Structure)

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Experimental studies are performed in order to clarify the effects of abrasive particle on the structure of the abrasive water suspension jet. Observations of jets are conducted at the injection pressure of 12 MPa for seven types of abrasives: two types of steel bead, two types of alumina, two types of glass bead, and one type of plastic shot. The experiments show that the jet structure is greatly affected by the particle type and the concentration of the abrasive. By using smaller abrasive particles, the jet can be made more compact, whereas larger abrasive particles tend to promote jet breakup. These tendencies are noticeable in the case of high-density abrasive.

Key Words: Multi-Phase Flow, Jet, Nozzle, Water Jet Technology, Abrasive Suspension Jet, Flow Structure

1. Introduction

The abrasive water suspension jet (AWSJ), in which an abrasive suspension jet is formed by propelling a premixed abrasive suspension through a nozzle, has been shown to have a capacity for drilling and cutting that is greater than that of the conventional abrasive water injection jet[11]. Brandt et al.[20] studied the cutting capability of the AWSJ in air. A comparative analysis of the AWSJ and the abrasive water injection jet (AWIJ) was conducted by Hashishi[25], and various studies on the AWSJ, such as application of the AWSJ in the dismantling of nuclear power plants[9] and in fine detail profiling[7], have been reported.


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The cutting and drilling capability of the AWSJ is closely related to the structure of the jet, and the jet structure is greatly affected by the concentration and type of abrasive, the injection pressure, and the nozzle shape. Thus, the relationship among the jet structure, the type of abrasive, the abrasive concentration, the injection pressure and the nozzle shape must be clarified in order to develop a more efficient AWSJ. One of the authors (Shimizu) has shown experimentally[4-8], using two types of alumina having different grain sizes, that smaller abrasive particles tend to maintain the compactness of the jet, whereas larger abrasive particles tend to promote jet breakup. The effects of nozzle shape on the flow structure of the AWSJ were also clarified.

In the present investigation, observations of jets are conducted at the injection pressure of 12 MPa using seven types of abrasives: two types of steel bead, two types of alumina, two types of glass bead, and one type of plastic shot. The densities of the abrasives range from 1400 kg/m³ to 7500 kg/m³. The effects of abrasive density, abrasive concentration, and abrasive particle size on jet structure are investigated based on instantaneous photographs of the jets.
2. Experimental Apparatus

Figure 1 shows a schematic diagram of the experimental apparatus. Pressurized water supplied by a pump discharges through a mixing nozzle into a pressure vessel (volume of $20 \times 10^{-3}$ m$^3$) containing abrasive stored under pressure. The water flow issuing from the mixing nozzle stirs up the abrasive at the bottom of the pressure vessel and the resulting slurry flows into an AWSJ nozzle. Observations of the jets are conducted at the injection pressure of 12 MPa. For further details on the experimental apparatus, the reader may refer to Refs. (6) through (8).

A conical convergent nozzle followed by a constant-diameter straight section (focusing section) shown in Fig. 2 is used to observe the jets. Since the effects of abrasive particle size on the jet structure are noticeable for a nozzle having a short focusing section, the nozzle having the shortest focusing section is selected for use in the present experiments. The diameter of the nozzle $d$ and the focusing section length are 1.0 and 0.9 mm, respectively. In order to reduce nozzle wear, the outlet of the convergent section and the focusing section were constructed of sintered diamond.

Seven types of abrasives: two types of steel bead, two types of alumina, two types of glass bead, and one type of plastic shot, are used in the experiments. Figure 3 shows microscopic photographs of the abrasives. The steel beads and the glass beads are spherical, whereas the alumina and the plastic shot have irregular and angular shapes. The particle sizes of the abrasives are listed in Table 1. The two types of
alumina used in the present study (Showa Denkou Moradum A40 #100 and #220) are identical to those used in previous experiments. The density of the alumina is 3,980 kg/m³. The densities of the steel bead (Ito Kiko BPC-80 and BPC-300), the glass bead (Ito Kiko GS-110 and GS-30), and the plastic shot (Ito Kiko AA-200) are approximately 7,500, 2,500, and 1,400 kg/m³, respectively.

In order to investigate the macroscopic structure of the jet, instantaneous photographs were taken using a stroboscope and an exposure time of approximately 1.5 μs.

3. Experimental Results and Discussion

The abrasive concentration in the jet generated using the present apparatus depends on the injection pressure, the type of abrasive, the mass of the abrasive stored in the pressure vessel, and the jetting duration. Since real-time measurement of the abrasive concentration is difficult in the jet, the time variation of the abrasive concentration is obtained in preliminary experiments under prescribed experimental conditions for the injection pressure, the mass of the abrasive stored in the pressure vessel, and the settling duration before the jetting. The abrasive concentration is calculated from the measured mass and volume of the slurry collected for 5 to 10 seconds using a pipe catcher. Figures 4 through 6 show the time variations of abrasive concentration for the steel bead BPC-300, the glass bead GS-110, and the plastic shot AA-200, respectively. In the observations of the jets, the abrasive concentrations are estimated using the time variations of the abrasive concentration obtained through the preliminary experiments. In the case of the plastic shot AA-200, the measured concentration is widely scattered. However, the concentration does not exhibit a tendency to decrease during the jetting duration of approximately 80 s. Since the density ratio of plastic shot AA-200 to water is approximately 1.4, the error in the measured concentration of AA-200 is considered to be larger than the other errors.

Figures 7 and 8 show instantaneous photographs of the jets for the cases of steel beads BPC-80 and BPC-300, respectively. The abrasive concentration of the jet using BPC-80 is approximately 4 vol%. For the steel bead BPC-300, the concentrations are approximately 8, 6, and 1 vol%. Photographs of the jets using the alumina A40#100 at concentrations of approximately 7 and 1 vol% are shown in Fig. 9. Figures 10 and 11 are photographs of the jets using the glass beads GS-110 and GS-30, respectively. The
concentrations of GS-110 are approximately 8, 6, and 1 vol\%. When GS-30 is used, the concentration is approximately 4 vol\%, the jet using the plastic shot AA-200 at the concentration of approximately 8.5 vol\% is shown in Fig. 12. In order to provide compari-
son with the suspension jets, an instantaneous photograph of the pure water jet is shown in Fig. 13.

Based on the instantaneous photographs of the jets using steel bead BPC-80 of 4 vol\%, glass bead GS-110 of 6 and 1 vol\%, and plastic shot AA-200 of 8.5 vol\%, the effects of abrasive density on jet structure are discussed for the cases of relatively large particle size. Although the concentrations are not the same, the qualitative tendency can be obtained by considering the effects of the abrasive concentration, as discussed later in the present paper. For the steel bead BPC-80 of 4 vol\% shown in Fig. 7, the diameter of the jet increases as the standoff distance increases. The jet breakup occurs in the region near the nozzle exit, and relatively large liquid lumps disintegrate into small droplets. In the region of $x/d > 60$ the jet becomes a dispersed flow. For GS-110, shown in Fig. 10, the structures of the jets, especially the jet at the concentration of 8 vol\%, are similar to that of the pure water jet shown in Fig. 13. However, the continuous cores of the jets having the glass bead GS-110 at the concentrations of 6 and 1 vol\% disappear at $x/d = 70 - 80$. The disintegration of the jet is promoted by the particles, even for the glass bead having a concentration of 1 vol\%. The jet using the plastic shot AA-200 is similar to that using the glass bead GS-110.

One of the authors pointed out that smaller abrasive particles tend to maintain the compactness of the AWSJ, whereas larger abrasive particles tend to promote jet breakup\cite{9}. The accelerations of the abrasive particles in the nozzle are numerically investigated using the method of Ref. (9) for the abrasives BPC-80, GS-110, and AA-200. The particles are assumed to be spheres having diameters of 0.162 mm.
Fig. 14 Acceleration of abrasive particles in the nozzle (BPC-80), 0.128 mm (GS-110), and 0.175 mm (AA-200). The densities of BPC-80, GS-110, and AA-200 are assumed to be 7.500, 2.500, and 1.400 kg/m³, respectively. Figure 14 shows the numerically obtained variations in particle velocity \( V_A \) and the water velocity \( V_w \) in the nozzle. The velocity ratios of the particle and the water at the nozzle exit \( V_A/V_w \) are approximately 0.63, 0.81, and 0.94 for BPC-80, GS-110, and AA-200, respectively. In the case of BPC-80, the velocity difference between the particle and the water is much larger than the velocity difference between the other particles and the water. Accordingly, the turbulent motion of the water phase is enlarged and jet breakup is promoted by the steel bead BPC-80 particles.

As examples of small abrasive particles, the jet structures are compared for the cases of steel bead BPC-300 of 6 vol% shown in Fig. 8 and glass bead GS-30 of 4 vol% shown in Fig. 11. As mentioned in previous reports, small abrasive particles suppress turbulent motion of the water phase and the continuous structure of the jet persists up to the long-standoff-distance region. In the cases of steel bead BPC-300 (density: 7.900 kg/m³) and alumina A40#220 (density: 3.980 kg/m³), the jets are compact and the turbulence suppression by the particles is clearly recognizable. However, in the case of glass bead GS-30 (density: 2.500 kg/m³), the structure of the jet is similar to that of the pure water jet, and turbulence suppression is not evident.

The effects of abrasive concentration on jet structure are discussed for the cases of relatively large abrasive particles. By comparing the jets using alumina A40#100 at the concentrations of 7 vol% and 1 vol%, as shown in Fig. 9, the jet at 1 vol% is found to be much more compact than that at 7 vol%. However, the jet using A40#100 tends to disintegrate at a shorter standoff distance than the pure water jet, even if the concentration of the abrasive is 1 vol%. On the other hand, when glass bead GS-110 is used, the difference in jet structure for the concentrations of 6 and 1 vol% is slight, as shown in Fig. 10. Next, the effects of abrasive concentration are discussed for the cases of small abrasive particles. In the case of steel bead BPC-300, the higher the abrasive concentration, the more compact the jet, as shown in Fig. 8. However, the effects of the abrasive concentration are not clear when glass bead GS-30 is used.

The effects of abrasive particles on jet structure are evident for abrasives of higher density. Smaller abrasive particles tend to suppress the disintegration of the jet, whereas larger abrasive particles tend to promote jet breakup. These tendencies are clear when the abrasive concentration is high. However, the above mentioned results are obtained for a jet formed by a nozzle having a short focusing section. By using a nozzle having a focusing section of adequate length, a compact slurry jet can be formed even when using abrasives of relatively large particle size and high density.

4. Conclusions

Experimental studies are performed in order to clarify the effects of abrasive particle type on the structure of the abrasive water suspension jet. Observations of jets are performed at the injection pressure of 12 MPa using seven types of abrasives: two types of steel bead, two types of alumina, two types of glass bead, and one type of plastic shot. The findings of primary interest are as follows:

1. Smaller abrasive particles tend to suppress the disintegration of the jet, whereas larger abrasive particles tend to promote jet breakup.
2. The effects of abrasive particles on the jet structure are clear when using abrasive of high density.
3. When the density of the abrasive is high, the effects of abrasive concentration on the jet structure are more evident.

References

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