Enhancing the aggressive intensity of a cavitating jet by introducing a cavitator and a guide pipe

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Abstract
In order to enhance the aggressive intensity of a cavitating jet for practical applications, such as cavitation peening, a nozzle equipped with an additional nozzle upstream from the main nozzle, i.e., a cavitator, and a guide pipe downstream from the main nozzle was proposed and optimized. The aggressive intensity of the jet was evaluated by the residual plastic deformation, i.e., the radius of curvature, in duralumin plate specimens subjected to the jet perpendicularly. The radius of curvature can be considered to be directly related to the aggressive intensity of the jet, as the plastic deformation such as introduction of compressive residual stress and/or work hardening in metallic materials is important parameters on cavitation peening. The deformation occurs because the pressure due to cavitation impacts is beyond the yield stress of the specimens. It was demonstrated that a nozzle equipped with an optimized cavitator and optimized guide pipe increased the aggressive intensity of the jet by a factor of 4.2 without an increase of the jet power, compared to the jet obtained with a conventional nozzle with neither cavitator nor guide pipe, as the cavitator fed cavitation nuclei for the jet and the guide pipe enlarged the cavitation clouds of the jet.

Keywords: Cavitation, Jet, Nozzle, Aggressive intensity, Cavitator, Guide pipe

1. Introduction

It is well known that the collapse of cavitation bubbles can generate large impact pressures of up to several GPa, which can cause severe damage in hydraulic machinery, such as pumps and propellers (Jones and Edward, 1960; Soyama et al., 1992; Brennen, 1995). However, the impact can be controlled and used effectively by means of a cavitating jet, i.e., a submerged high speed water jet, for practical applications such as underwater rock cutting, to aid chemical reactions and for peening metallic materials (Johnson et al., 1981; Kalumuck and Chahine, 2000; Soyama and Sekine, 2010). In order to further improve the operational efficiency and to reduce processing times, enhancement of the aggressive intensity of the jet is required.

In order to achieve this, many kinds of nozzles have been proposed and applied. These nozzles can be divided into two categories; those that have features that excite the jet acoustically, and those that have features to increase the supply of cavitation nuclei. Acoustic excitation of an air jet on the upstream side of the nozzle is known to modulate the jet and generate large pressure fluctuations and vortex structures (Crow and Champagne, 1970). This theory has been applied to cavitating jets by using acoustically tuned nozzles, i.e., resonating nozzles (Johnson et al., 1984; Chahine et al., 1987; Soyama, 2011a). Johnson et al. (1984) and Chahine et al. (1987) reported an improvement in the erosion rate by using a cavitating jet utilizing an organ pipe nozzle, the shape of which had been optimized to generate large pressure fluctuations as a result of acoustic excitation of the jet on the feed side. Soyama (2011a) proposed a nozzle with an outlet bore at the nozzle exit, which was expected to work as an open ended Helmholtz resonator (Morel, 1979), and with which an improvement in the aggressive intensity of the jet was demonstrated (Soyama, 2011a). On the other hand, as is well known, cavitation initiation is sensitive to the distribution of nuclei in the test liquid, since cavitation bubbles grow from those nuclei in the core of the vortex. A feature which can improve the supply of cavitation nuclei is called a cavitator, which is known to augment the generation of cavitation bubbles that can produce more severe
Taking those reports into consideration, in this study, in order to enhance the aggressive intensity of a cavitating jet, we propose using a nozzle equipped with an additional nozzle plate upstream from the main nozzle plate, i.e., a cavitator, and a guide pipe downstream from the nozzle, as shown in Fig. 1(a). A spacer was used to separate the cavitator from the main nozzle, which would allow the cavitation bubbles generated within the shear layer to grow and collapse before being fed to the nozzle as nuclei. On the other hand, the guide pipe is expected to excite the jet in a similar way to the nozzle outlet, so the same theory can be applied to each (Soyama, 2011a). However, in order to apply this proposed nozzle for practical usage, the geometry of the cavitator, spacer and guide pipe need to be optimized so that the maximum aggressive intensity of the jet can be obtained.

In this paper, an experimental investigation of the aggressive intensity of the jet obtained using the proposed nozzle was carried out with various geometries for the cavitator, the spacer and the guide pipe. The aggressive intensity of the jet was evaluated by the residual plastic deformation produced in a duralumin plate specimen subjected to the jet, since this deformation is caused by cavitation impact pressures beyond the yield stress of the specimen, and which can be considered to be directly related to the aggressive intensity of the jet. The deformation was quantified by measuring the radius of curvature of the test specimen, as the single sided plastic deformation of a thin plate is similar to that produced in an Almen strip by shot peening. In addition, high-speed observations of the cavitating jet were made in order to investigate the mechanisms by which the proposed additions to the nozzle enhance the aggressive intensity of the jet.

2. Experimental Facilities and Procedures

A schematic diagram of the cavitating jet apparatus used in the experiments is shown in Fig. 2. The high-speed water jet is perpendicular to the specimen, with both the specimen and the nozzle immersed in water in the test section. A plunger pump that can generate a maximum pressure of 35 MPa and a maximum discharge of \(3.0 \times 10^{-2} \text{ m}^3/\text{min}\) is used to generate the jet. The test section is a rectilinear tank 1200 mm in length, 600 mm in width and filled to a depth of 700 mm with water, which is open to the atmosphere. The water level is maintained at a constant level by an overflow control, so that the nozzle is about 100 mm beneath the surface. In order to prevent a suction vortex being generated by the jet, a floating plate is placed around the nozzle. The specimens used were Duralumin JIS A2017-T3 plates, 200 mm in length, 50 mm in width and 5 mm thick. The standoff distance, \(s\), which is the distance from the upstream side of the main nozzle plate to the test specimen, is controlled by the height of the base. The nozzle is mounted on a motorized stage and is scanned parallel to the longitudinal direction of the test specimen at a scanning speed, \(v\), of 1 mm/s. The injection pressure of the jet, \(p_1\), is controlled by the speed of an inverter motor connected to the plunger pump, and is kept constant at 30 MPa. The ambient pressure of the jet, \(p_2\), is approximately equal to atmospheric pressure (0.1 MPa), since the depth to which the test section is immersed is sufficiently shallow to be

Fig. 1  Tested cavitating jet nozzles. The proposed complete nozzle consists of a cavitator, a spacer and a guide pipe.
Fig. 2  Cavitating jet apparatus. The submerged high speed water jet is injected to the specimen perpendicuerly and scanned parallel to the longitudinal direction of the specimen.

Fig. 3  Cavitator with rounded edge. In order to investigate effect of edge of the cavitator, the round edged cavitator is also tested, as normal cavitator has the sharp edge.

safely ignored. The test water is recirculated into the header tank after removal of residual bubbles by a partition plate with holes. A pressure transducer is placed on the upstream side of the nozzle in order to measure the injection pressure. The water temperature is controlled by a chiller, and kept constant at 300±3K.

The cavitation number, \( \sigma \), is the main parameter of a cavitating jet as shown in ASTM G135-95 (2006). Generally, the cavitation number is defined by the ratio of the hydrodynamic pressure to the static pressure in the cavitating flow (Brennen, 1995). In the case of cavitating flow through a nozzle or orifice, the hydrodynamic pressure is expressed by the pressure difference between the upstream and downstream sides of the nozzle or orifice. Thus, the cavitation number of a cavitating jet is given by Eq. (1),

\[
\sigma = \frac{p_2 - p_v}{p_1 - p_2} \cong \frac{p_2}{p_1}
\]  

where, \( p_1 \) is the injection pressure, \( p_2 \) the ambient pressure, and \( p_v \) the vapor pressure of the test water. The cavitation number can be simplified, as in Eq. (1), since in the present case \( p_1 \approx p_2 \approx p_v \). As the injection pressure \( p_1 \) and ambient pressure \( p_2 \) in this study are 30 MPa and 0.1 MPa, respectively, the cavitation number is 0.003.

The nozzle proposed and developed in this study is shown in Fig. 1 (a). The complete nozzle consists of a cavitator, a spacer, nozzle cap, and a guide pipe, whose geometries could be varied, and a nozzle plate with a hole with a fixed diameter, \( d \), of 2 mm. The guide pipe was fixed to the nozzle cap by four bolts, whose size were 5 millimeter in diameter. Each nozzle is cylindrical in shape. The nozzle outlet bore, \( D \), and length, \( L \), were each selected to be 16 mm, which are the optimum sizes determined in a previous report (Soyama, 2011a). The optimum geometry of the cavitator and spacer which maximizes the aggressive intensity of the jet was studied without the guide pipe. The spacer diameter, \( D_s \), and length, \( L_s \), were varied as shown in Table 1, with a fixed cavitator throat diameter, \( d_c \), of 3 mm. In addition, a cavitator with a rounded upstream edge, as shown in Fig. 3, was tested, in order to investigate the effect of the edge geometry of the cavitator on the aggressive intensity of the jet, since the generation of cavitation nuclei should depend on the shape of the edge of the cavitator. The throat diameter of the rounded cavitator was chosen to be 2.3 mm, so that the flow rate would be similar to that of the cavitator with the sharp edge (Soyama and Lichtarowicz, 1996). Since the aggressive intensity of the jet has a local maximum depending on the standoff distance, \( s \), this was varied in order to determine this for each nozzle (Soyama, 2011a).

The jet power, \( P \), depends on the flow rate, \( Q \), and the injection pressure, \( p_1 \), as shown in Eq. (2). The effective throat diameter of the nozzle, \( d_e \), and the flow coefficient, \( c_e \), are described by Eqs. (3) and (4), so the jet power is proportional to \( c_e \). The relationship between the aggressive intensity of the jet and the flow coefficient, \( c_e \), was...
investigated, as the cavitator and the spacer both affect $c_e$.

\[ P = Q p_1 = \frac{\pi d^2}{4} c_e p_1 = \frac{\pi d^2}{4} p_1 \]  
\[ d_e = d \sqrt{c_e} \]  
\[ c_e = \frac{4Q}{\pi d^2 U} \]  

In this paper, $c_e$ was calculated from $d$, $Q$ and $U$, where $d$ was measured by microscope, $Q$ was measured by the volume of the overflow from the test section per unit time, and $U$ was calculated to be 245 m/s using Bernoulli’s equation with $p_1 = 30$ MPa.

After the optimum geometries of the cavitator and the spacer had been obtained, the guide pipe was mounted on the nozzle with the optimized cavitator and spacer. The guide pipe diameter, $D_p$, and length, $L_p$, were varied as shown in Table 2 and the values that maximize the aggressive intensity of the jet were found.

In order to evaluate the aggressive intensity of the jet obtained using the proposed nozzle, the radii of curvature of duralumin plate specimens treated by the jet at a scanning speed, $v$, of 1 mm/s were measured by stylus type surface roughness measurement equipment. Five measurements were made at different points, and the average of 3 points without the highest and lowest values was used to determine the radius of curvature, $R$. The measurement length and scanning speed of the stylus was 50 mm and 1 mm/s, respectively. Generally, peening intensity is evaluated by the arc height of an Almen strip used in shot peening. Greater peening intensity gives larger arc height. The relationship between arc height, $h$, and radius of curvature, $R$, can be described by Eq. (5), where $l$ is the length of the test specimen, which, in this study, was 200 mm.

\[ h = R \left(1 - \cos \frac{l}{2R}\right) \]  

Figure 4 shows the relationship between the arc height, $h$, and the inverse of the radius of curvature, $1/R$, where $l$ is 200 mm, which is shown to be almost linear in the range between 0.1 m$^{-1}$ and 1 m$^{-1}$. This shows that the aggressive intensity of the cavitating jet increases as $1/R$ becomes larger. The optimum nozzle geometry is that geometry which maximizes the inverse of the radius of curvature of the test specimen.

In order to clarify why the proposed nozzle increases the aggressive intensity of the jet, the jet was observed through a clear Lucite window in the test section with a high-speed video camera. During the high-speed observations, the specimen and specimen base were removed. Two halogen lamps and one xenon lamp were placed on the same side as the camera, so the cavitation bubbles around the jet appeared white in the image. In order to observe the jet clearly, an exposure time of 2 μs, a frame rate of 20,000 fps and a frame size of 128×512 pixels were chosen. The shedding frequency of the cavitation clouds was evaluated from the fluctuations in the gray scale value at the analysis point in the image in the same way as described in a previous report (Nishimura et al., 2012). The analysis point was set 100 mm downstream from the upstream side of the nozzle plate, at the center of the jet.
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Fig. 4  Linear relationship between arc height and the inverse of the radius of curvature. As the inverse of the radius of curvature 1/R is proportional to the arc thight, 1/R can express the aggressive intensity of the jet.

3. Results

3.1 Optimization of cavitator

Figure 5 shows the effect of the spacer diameter $D_s$ and length $L_s$ on the aggressive intensity of the jet as a function of the standoff distance $s$. Note that the results presented in Fig. 5 were obtained with nozzles without the guide pipes. Clearly, the aggressive intensity of the jet, which is related to the inverse of the radius of curvature, has a local maximum at a certain standoff distance for each nozzle. Thus, the aggressive intensity of the jet at the optimum standoff distance, $1/R_{opt}$, for each nozzle can be obtained from Fig. 5. For example, in the case of $D_s = 4$ mm and $L_s = 4$ mm, the value of $1/R$ is 0.203 m⁻¹ at $s = 182$ mm. Therefore, $1/R_{opt}$ is 0.203 m⁻¹. The aggressive intensity of the jet induced by the conventional nozzle is also shown in Fig. 5, for which $1/R_{opt}$ is 0.101 m⁻¹ at 192 mm. For the case of $D_s = 6$ mm, $1/R_{opt}$ is 0.228 m⁻¹ at $L_s = 6$ mm and $s = 162$ mm. $1/R_{opt}$ for $D_s = 8$ mm and $L_s = 8$ mm at $s = 152$ mm is 0.216 m⁻¹ and $1/R_{opt}$ for $D_s = 10$ mm and $L_s = 8$ mm at $s = 162$ mm is 0.205 m⁻¹. That is, when the geometry of the spacer is optimized, the aggressive intensity of the jet for the nozzle with the cavitator can be enhanced by a factor of about 2.3 compared with that of the conventional nozzle without a cavitator.

Figure 6 shows the effect of the spacer geometry on the aggressive intensity of the jet at the optimum standoff distance. It can be seen that the spacer length, $L_s$, has an optimum value for each spacer diameter, $D_s$. For example, the optimum spacer length is 4 mm for $D_s = 4$ mm, 6 mm for $D_s = 6$ mm, 8 mm for $D_s = 8$ mm and 8 mm for $D_s = 10$ mm. Thus, it can be concluded that the preferred ratio of $D_s : L_s$ is 1:1, except for the case of $D_s = 10$ mm. This tendency can be explained from the viewpoint of the supply of cavitation nuclei to the downstream nozzle. According to a previous report (Soyama, 2011a), it was found that a specific vortex structure developed around the nozzle exit that encouraged the growth of cavitation bubbles that produced more severe erosion when the ratio of the nozzle outlet bore $D$ to the nozzle outlet length $L$ was 1:1. In the same manner, when the ratio of the spacer diameter $D_s$ to spacer length $L_s$ is 1:1, this specific vortex structure might appear within the volume surrounded by the spacer, and generate such cavitation bubbles downstream from the nozzle. On the other hand, it might be that the absolute length of the spacer is also an important factor, since the aggressive intensity of the jet at $D_s = 6$, $L_s = 6$ is greater than that of $D_s = 4$, $L_s = 4$ and $D_s = 8$, $L_s = 8$. If the spacer length, $L_s$, is too short, the cavitation bubbles cannot collapse and develop into cavitation nuclei before being fed to the downstream nozzle plate. In contrast, if the spacer length is too long, the generated cavitation nuclei might peter out before reaching the downstream nozzle. The fact that the optimum spacer length, $L_s$ is 8 mm instead of 10 mm for $D_s = 10$ mm can be explained by the same reasoning. It was observed that the optimum spacer geometry was $D_s = 6$ and $L_s = 6$, and the aggressive intensity of the jet induced by the nozzle equipped with a cavitator and an optimized spacer was 2.3 times larger than that of the conventional nozzle without neither cavitator nor spacer.

Figure 7 shows the results of Fig. 6, sorted by the flow coefficient, $c_e$, of each nozzle, as the aggressive intensity of the jet is known to be proportional to the jet power, $P$, which in turn is proportional to $c_e$ at constant injection pressure as shown by Eq. (2). Therefore, the following equation can be regarded as representing the relationship between the
Fig. 5  Effect of spacer diameter $D_s$ and length $L_s$ on the aggressive intensity of the jet. The aggressive intensity of the jet has a local maximum at certain standoff distance. The optimized spacer enhances the aggressive intensity of the jet by a factor of 2.3 compared with that of the conventional nozzle without cavitator.

Fig. 6  Variation of the aggressive intensity of the jet with spacer diameter $D_s$ and spacer length $L_s$. The preferred ratio of $D_s : L_s$ is 1:1, except for the case of $D_s = 10$ mm.

aggressive intensity of the jet, $1/R_{opt}$, and the flow coefficient, $c_e$, which is shown as the broken line in Fig. 7.

$$1/R_{opt} \propto c_e \tag{6}$$

From Fig. 7, although the aggressive intensity of the jet through the nozzle equipped with the cavitator is significantly larger than that of the conventional nozzle, it can be seen that $c_e$ is only slightly affected by the diameter and the length.
of the spacer. In other words, the flow coefficient is not the main factor that determines the aggressive intensity for a nozzle equipped with a cavitator. This result suggests that the main factor determining the aggressive intensity of the jet is the supply of cavitation nuclei, as already suggested by the results in Fig. 6. It is worth noting that the aggressive intensity of the jet induced by the nozzle equipped with the cavitator and optimized spacer of 6 mm in diameter and 6 mm in length is about 2.3 times greater than that induced by the conventional nozzle, regardless of the flow coefficient.

In order to investigate the effect of the upstream edge of the cavitator on the aggressive intensity of the jet, Fig. 8 shows $1/R$ as a function of standoff distance for the nozzle equipped with the sharp edged cavitator and the rounded cavitator illustrated in Fig. 3. These are compared with the conventional nozzle without a cavitator. In each case, $1/R$ has a maximum at a certain standoff distance and the maximum value for the sharp edged cavitator is greater than that for the round edged cavitator. Note that the flow coefficients for each nozzle are nearly equivalent as the nozzle diameters were chosen to equalize the flow rate. The results demonstrate that the shape of the cavitator has a considerable effect on the aggressive intensity of the jet. As is well known, in the case of hydrodynamic cavitation, the flow separates at the edge of the cavitator, and a cavitator with a sharp edge produces more cavitation bubbles than one with a rounded edge for the same constant upstream pressure. In the present case, as the downstream pressure of the cavitator is 30 MPa, the cavitation bubbles from the cavitator collapse, and the ensuing residual bubbles shed towards the nozzle plate as cavitation nuclei. That is, the sharp edged cavitator feeds the nozzle with many more cavitation nuclei compared with the round edged cavitator, so that the aggressive intensity of the jet through the nozzle equipped with the sharp edged cavitator is larger than that with the round edged cavitator.

In order to clarify the mechanism by which the aggressive intensity of the jet is enhanced by the cavitator, Fig. 9 shows $1/R$ has a maximum at a certain standoff distance and the maximum value for the sharp edged cavitator is greater than that for the round edged cavitator.

![Graph](image-url)

**Fig. 7** Variation of the aggressive intensity of the jet with flow coefficient $c_e$. As $c_e$ is only slightly affected by the spacer diameter $D_s$ and length $L_s$, $c_e$ is not the main factor that determines the aggressive intensity of the jet for a nozzle equipped with a cavitator.

![Graph](image-url)

**Fig. 8** Effect of the shape of the edge of the cavitator on the aggressive intensity of the jet. $1/R$ has a maximum at a certain standoff distance and the maximum value for the sharp edged cavitator is greater than that for the round edged cavitator.
3.2 Optimization of guide pipe

In the next step, we investigate the effect of the guide pipe on the aggressive intensity of the jet. In order to determine the optimum geometry of the guide pipe diameter, \( D_p \), and length, \( L_p \), the inverse of the radius of curvature was measured for various values of \( D_p \) and \( L_p \). For this, the nozzle equipped with the optimum cavitator and spacer was used. The inclusion of the guide pipe affected the optimum standoff distance, so the inverse of the radius of curvature as a function of standoff distance, \( s \), is plotted in Fig. 10. As in Fig. 5, it can be seen that the aggressive intensity of the jet has a local maximum at a certain standoff distance, i.e., the optimum standoff distance. With the guide pipe, the optimum standoff distance was increased in all cases. As shown in Fig. 10, the inverse of the radius of curvature also varies with \( D_p \) and \( L_p \). For the optimal guide pipe, the value of \( 1/R \) is 0.42 m\(^{-1}\) with \( D_p = 44 \text{ mm}, L_p = 46 \text{ mm}, \) and \( s = 262 \text{ mm} \). On the other hand, without the guide pipe \( 1/R \) was 0.23 m\(^{-1}\), indicating that the guide pipe almost doubled the aggressive intensity of the jet.

In order to investigate the effect of the geometry of the guide pipe on the aggressive intensity of the jet, Fig. 11 shows \( 1/R_{opt} \) at the optimum standoff distance as a function of guide pipe length for each guide pipe diameter. The broken line in Fig. 11 represents the aggressive intensity of the jet induced by the nozzle without a guide pipe. Thus, for each guide pipe diameter, the aggressive intensity of the jet has a local maximum at a certain guide pipe length. For example, for \( D_p = 44 \text{ mm}, \) the aggressive intensity of the jet has a maximum at \( L_p = 46 \text{ mm}, \) while for \( D_p = 54 \text{ mm}, \) the maximum is at \( L_p = 56 \text{ mm}. \) The most suitable guide pipe length in each case is almost equal to or slightly larger than the guide pipe diameter. The optimum guide pipe geometry that gives the maximum aggressive intensity of the jet is \( D_p = 44 \text{ mm} \) and \( L_p = 46 \text{ mm}, \) where the aggressive intensity of the jet is 1.8 times larger than that of the nozzle without the guide pipe.
Fig. 10  Aggressive intensity of the jet through a nozzle equipped with a cavitator as a function of standoff distance for various guide pipe lengths $L_p$ and diameters $D_p$. The optimum standoff distance is increased by using the guide pipe. The guide pipe almost doubles the aggressive intensity of the jet.

Fig. 11  Effect of guide pipe length $L_p$ and diameter $D_p$ on the aggressive intensity of the jet. The aggressive intensity of the jet has a local maximum at a certain guide pipe length. The most suitable guide pipe length in each case is almost equal to or slightly larger than the guide pipe diameter. The optimum guide pipe geometry that gives the maximum aggressive intensity of the jet is $D_p = 44$ mm and $L_p = 46$ mm, where the aggressive intensity of the jet is 1.8 times larger than that of the nozzle without the guide pipe.
Fig. 12  Effect of guide pipe geometry on the shedding frequency of cavitation clouds. The shedding frequencies of cavitation clouds induced by nozzles equipped with guide pipes are lower than that of the nozzle without the guide pipe.

In order to clarify the reason why the optimum nozzle guide pipe increased the aggressive intensity of the jet, high-speed observations were carried out. Figure 12 illustrates the effect of the guide pipe geometry on the shedding frequency of the cavitation clouds, $f_{shed}$. The horizontal axis in the figure gives the ratio of the guide pipe diameter to the guide pipe length. The broken line represents the shedding frequency of cavitation clouds induced by the nozzle without the guide pipe. It can be seen that the shedding frequencies of cavitation clouds induced by nozzles equipped with guide pipes are lower than that of the nozzle without the guide pipe. In addition, the shedding frequency increases with the diameter to length ratio of the guide pipe. These features suggest that the shedding frequency of cavitation clouds plays an important role in determining the aggressive intensity of the jet. When the shedding frequency of the cavitation clouds is low, larger clouds develop and then collapse. It is understandable that the collapse of larger cavitation clouds produce larger impact within the present experimental condition. The fact that the standoff distance increased after introducing the guide pipe supports this tendency, as larger cavitation clouds need greater distances to collapse. That is, the optimum guide pipe maximizes the size of the cavitation clouds and they produce large impacts. As is well known, if the shedding frequency is too low, the number of the impacts will be too small. Thus, the aggressive intensity of the jet was at its maximum with $D_p = 44$ mm and $L_p = 46$ mm as mentioned above.

4. Conclusions

In order to enhance the aggressive intensity of a cavitating jet for practical applications such as cavitation peening, a nozzle equipped with a cavitator and spacer upstream from the nozzle and a guide pipe downstream from the nozzle was proposed and optimized by experiment. The nozzle throat diameter in these experiments was 2 mm. The aggressive intensity of the jet was evaluated by the plastic deformation it produced in a duralumin plate. The mechanisms by which the aggressive intensity of the jet was enhanced by the cavitator and the guide pipe were discussed while considering the effect of the edge of the cavitator and taking account of the results of high-speed observations of the cavitating jet. The main results obtained are summarized as follows.

1. The aggressive intensity of the jet was affected by the geometry of the cavitator, the spacer and the guide pipe. The optimum standoff distance for the maximum aggressive intensity also changed with the geometries of the cavitator, the spacer and the guide pipe. The optimum cavitator, spacer and guide pipe increased the aggressive intensity of the jet by a factor of about 4.2 compared to a conventional nozzle, which had neither cavitator nor guide pipe.

2. The optimum geometry of the spacer for the 3 mm diameter sharp edged cavitator was 6 mm in diameter and 6 mm in length. The aggressive intensity of the jet through the nozzle equipped with this combination was 2.3 times greater than that of the nozzle without the cavitator.

3. The optimum geometry of the guide pipe for the nozzle equipped with the optimized cavitator and spacer was 44 mm in diameter and 46 mm in length. The aggressive intensity of the jet through the nozzle equipped with the
cavitator, spacer and guide pipe was 1.8 times larger than that of this combination without the guide pipe.

4. The guide pipe affected the shedding frequency of the cavitating clouds, which is related to the aggressive intensity of the jet. The frequency was decreased by the guide pipe, allowing larger cavitating clouds to develop which generate larger impacts.

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Nomenclature

\( c_e \) = Flow coefficient
\( D \) = Nozzle outlet bore diameter
\( d \) = Nozzle diameter
\( d_c \) = Cavitator diameter
\( d_e \) = Effective nozzle throat diameter
\( D_s \) = Spacer diameter
\( f_{shedd} \) = Shedding frequency of the cavitation cloud
\( h \) = Arc height of the test specimen
\( L \) = Nozzle outlet bore length
\( l \) = Length of the test specimen
\( L_s \) = Spacer length
\( P \) = Jet power
\( p_1 \) = Injection pressure
\( p_2 \) = Ambient pressure
\( p_v \) = Vapor pressure
\( Q \) = Flow rate
\( R \) = Radius of curvature of the test specimen
\( R_{opt} \) = Radius of curvature of the test specimen at the optimum standoff distance
\( s \) = Standoff distance
\( U \) = Velocity of the jet at the nozzle exit
\( v \) = Scanning speed
\( \sigma \) = Cavitation number

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