Abrasive-Entrained High-Frequency Pulsed Waterjet: Basic Study and Applications

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ABSTRACT

Experiments were conducted to photograph the structures of high-speed conventional (CWJ), forced pulsed (FPWJ) and abrasive-entrained forced pulsed (PAWJ) waterjets. The objective was to determine the effect of operating parameters (pressure, flow, amplitude of the vibrating probe, etc.) on the structures, which influence the performance. Paint removal tests were made to compare their efficiencies. The experimental study has clearly shown that these parameters have significant influence on performance, and that PAWJ is more effective than the other two types of waterjet.

1 INTRODUCTION

Although FPWJ has been successfully used for several industrial applications (**1 to 4**), the fundamentals of the technique have remained obscure (**1 to 4**). Pulsed waterjet is an extension of conventional (continuous) waterjet technology, consisting of a train of high-speed water pulses. When a pulsed water jet impinges on targets, the momentum flux through the nozzle is not transmitted as a steady force, but as a discontinuous sequence of impacts, creating high momentary stresses in the impingement zone. The peak pressure on the surface is then not the stagnation pressure, but the significantly higher water hammer pressure (**5**). Much lower pressure pumps can therefore be used to achieve the same erosion rates as a continuous water jet. Another method of enhancing the erosion capability of FPWJ is to add an abrasive to it. Recently Ren *et al.* (**6**) described a nozzle configuration that allows abrasive particles to be entrained into a pulsed water jet, creating a pulsed abrasive-entrained water jet (PAWJ). If one considers theoretical analysis (or, modeling) of the continuous abrasive-entrained waterjet (AWJ) to be complex (**7**), it is even more formidable in the case of FPWJ and PAWJ. The best recourse, as pointed by Vijay, *et al.* (**8**), is analysis by visualization, together with relevant experimental data. Therefore, an experimental study was undertaken to observe the effects of varying several operating parameters on the operation of the FPWJ and PAWJ. Both types of waterjets were photographed using a pulsed laser source of light (**8**). Observations were made on the effect of the vibrating probe position (indicated by ‘a’ in Fig. 1), abrasive flow rate and type, etc., on performance (for example, on the rate of paint removal from surfaces). In this paper, some important observations from this continuing study are described.

2 EXPERIMENTAL METHOD

The basic nozzle configuration for producing water pulses is shown in Fig. 1 (**3**). The technique involves using a probe to modulate the continuous stream. The jet is modulated when the probe tip vibrates axially with frequency *f* (typically 20 kHz) and amplitude *A* (a maximum of approximately 0.2 mm), creating slugs of water (**3**).

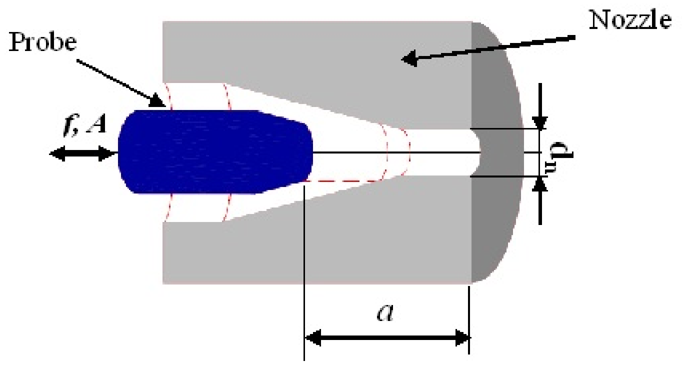


Fig. 1. Schematic diagram of the pulsed waterjet nozzle.

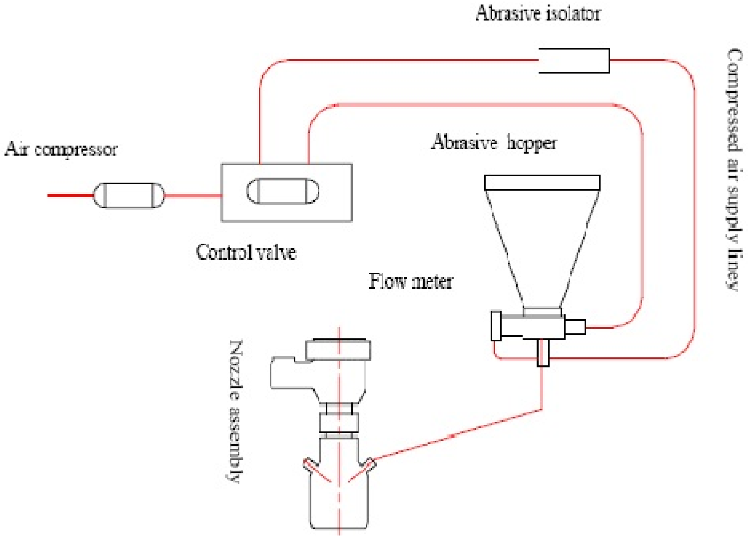


Fig. 2. A schematic diagram showing the method used to inject abrasives to produce PAWJ.

The PAWJ system, depicted in Fig. 2, consisted of the standard FPWJ system, to the exit of which was attached a mixing chamber connected by a tube to a hopper filled with abrasive powder. The high speed continuous or pulsed waterjet issuing from the nozzle created a partial vacuum in the mixing chamber, which entrained the abrasive powder (as in AWJ). The suction pressure was measured by attaching a vacuum gauge to the hose connected to the mixing chamber. A manually adjustable digital micro-meter connected to the abrasive hopper was used to set the flow rate of abrasives. Abrasive flow rates were measured by collecting particles in a drum placed underneath the exit of the nozzle and, dividing the mass of abrasive powder captured by the elapsed time. Two types of zeolite (abrasive) powders were used, obtained from Industrial Minerals Ltd., Calgary, Alberta: one was a fine powder, with an average particle size of 325 mesh (~0.04 mm) and the other were medium sized granules with average particle size 14 mesh (~1.4 mm). Briefly, zeolite (Clinoptilolite) is a naturally occurring mineral made of a special crystalline structure that is porous but remains rigid in the presence of water (**6**). Zeolites have been used for a variety of applications (aquaculture, agriculture, horticulture, household and industrial products, radioactive waste, water and wastewater treatments). Compositionally, zeolites are similar to clay minerals. More specifically, both are alumino silicates. They differ, however, in their crystalline structure. Many types of clay have a layered crystalline structure (similar to a deck of cards) and are subject to shrinking and swelling as water is absorbed and removed between the layers. In contrast, zeolites have a rigid, 3-dimensional crystalline structure (similar to a honeycomb) consisting of a network of interconnected tunnels and cages. Water moves freely in and out of these pores, but the zeolite framework remains rigid. Another special aspect of this structure is that the pore and channel sizes are nearly uniform, allowing the crystal to act as a molecular sieve (therefore, used as a filtering medium). The nozzle diameter d_n (Fig. 1) was kept constant at 1.37-mm in all tests.

Figure 3 shows a schematic diagram of the experimental apparatus used to photograph high speed waterjets. A Nd- Yag laser with 4-6 ns pulse duration was used to illuminate the waterjet and freeze its motion (**8**). A cylindrical lens converted the laser beam into a sheet of light and a digital Nikon D-100 camera was used to take a still photograph of the waterjets.

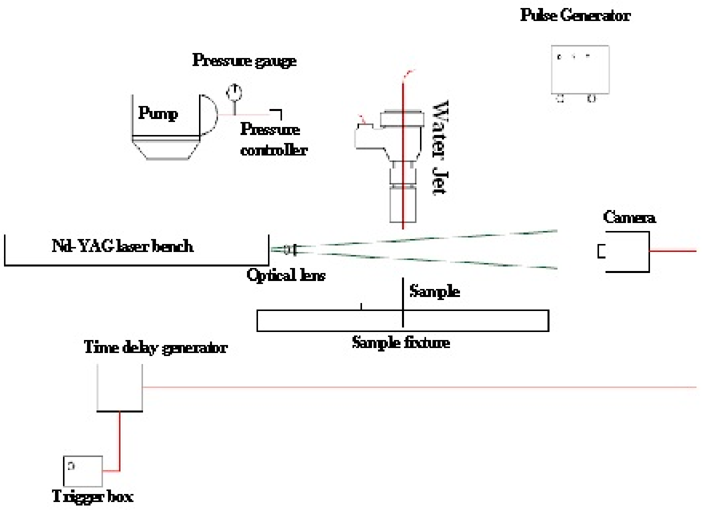


Fig. 3. A schematic diagram of the photographic system.

3 RESULTS AND DISCUSSION

Figure 4 shows a sequence of photographs showing the structure of pulsed water jets, with no mixing chamber attached. The nozzle diameter (d_n), pump pressure (P_p), and probe vibration amplitude (A_m) were kept constant respectively at 1.37-mm, 34.5-MPa and 50%. The distance of the probe tip from the nozzle exit (‘*a*’ in Fig. 1) was varied from 5.86-mm to 15.39-mm. At the smallest values of *a* there was a mist of water surrounding the jet and the water pulses were not well defined. Cavitation occurs in the wake of the probe (**9**), creating vapour bubbles in the water that atomize the jet when they exit the nozzle. When the distance between the probe and nozzle exit is increased, the bubbles collapse before they reach the exit. Atomization does not occur and the pulses in the water jet are then clearly defined (for values of $a > 9.04$-mm).

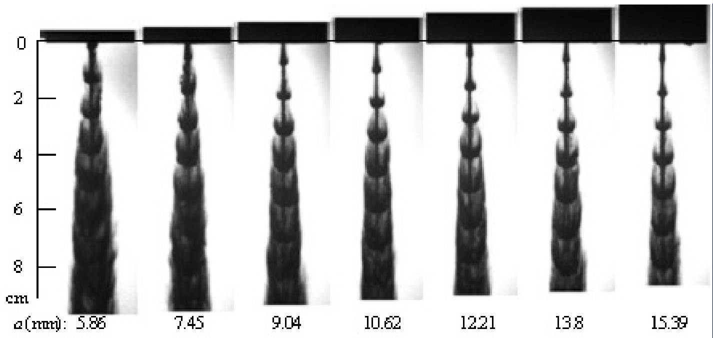


Fig. 4. A sequence of photographs showing the effect of the position of probe on the structure of pulses (d_n = 1.37-mm, P_p = 34.5-MPa, A_m = 50%).

a) with mixing chamber

b) without mixing chamber

Fig. 5. Photographs showing the effect of mixing chamber on the structure of pulses (d_n = 1.37-mm, P_p = 34.5-MPa, a = 13.8-mm, A_m = 50%).

The effect of attaching the abrasive mixing chamber to the exit of the pulsed water jet nozzle (without adding any abrasive) is shown in Fig. 5, for the case of a = 13.8-mm. The form of pulses can still be clearly seen (Fig. 5a), though the shape of pulses is not as well defined as it was without the chamber attached (Fig. 5b). The increased flow turbulence caused by the mixing

chamber distorts the shap
well-defined water pulses,
consequently the performan

The flow rate of air throug
mixing chamber at varying
pressures was measured us
flow meter, both with the
vibrating and with it
stationary. Figure 6 shows
when the probe is stationary
is, no pulses in the m
chamber), the airflow
gradually increases with pres
When the probe vibrates (th
when the pulses emerge fro
nozzle into the mixing chan
the airflow rates remain vir
constant at much higher valu
about 2.2-SCFM with pres
This finding indicates that p
in the chamber increase su
leading to an increased ai
rate which, in turn, increases the
flow rate of abrasive powders.

Figure 7 shows the effect of adding the medium sized zeolite powder to the water jet. Jets are shown both without (Fig. 7a) and with (Fig. 7b) abrasive, and also with the probe motion turned off. The concentration (C) of zeolite in water by weight was 9 percent. Since the concentration was relatively low, the particles had relatively little effect on the appearance of the water jet. There are water droplets visible in the pulsed water jets, which obscure the shape of the pulses. The probe vibration produced pulses and made the jets wider.

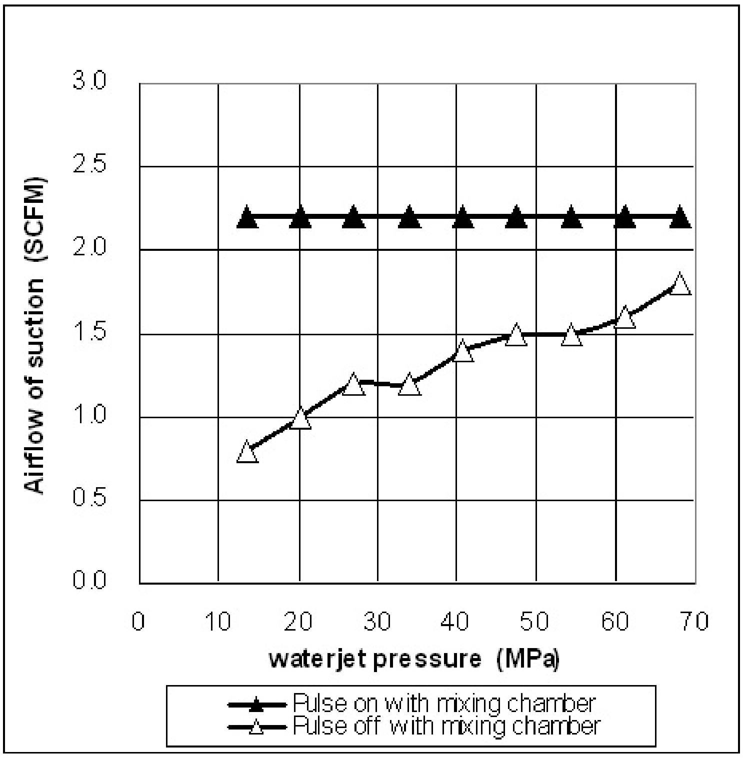


Fig. 6. Plot of airflow rate drawn into the mixing chamber as a function of pressure.

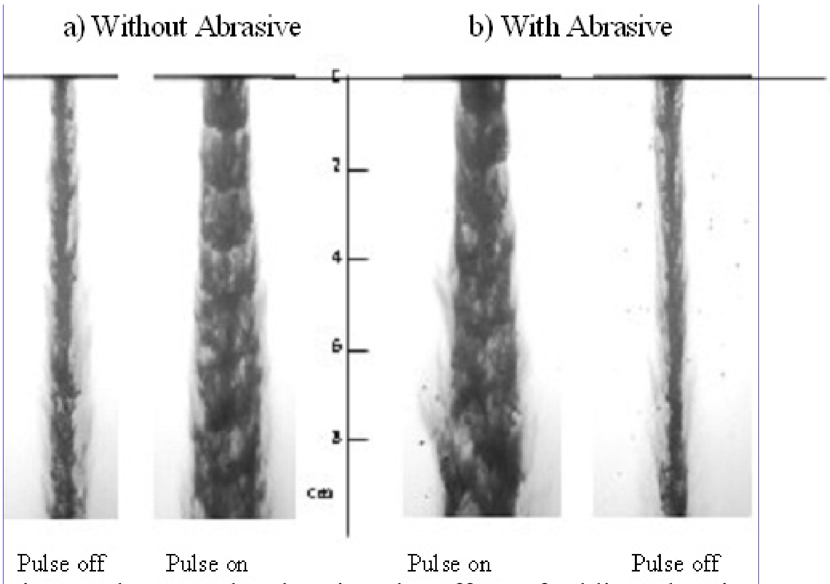


Fig. 7. Photographs showing the effect of adding abrasive (zeolite particles) on the structure of continuous and pulsed (d_n = 1.37-mm, P_p = 34.5-MPa, a = 9.04-mm, A_m = 50%, C = 9%).

Figure 8 shows the effect of changing probe tip position from *a* = 9.04 to 13.80-mm on PAWJ. Comparing the two images shows that with increasing *a,* the pulse pattern becomes more evident, the jet tends to become thinner, pulse size becomes smaller and the water pulse can survive longer. This is similar to that observed for the pulsed water jets without abrasives (Fig. 4). The abrasives remain near the jet centre at the nozzle exit and gradually disperse to the jet surface with increasing distance.

Paint (baked enamel) removal tests from aluminum strips were conducted to compare the performance of PAWJ against the continuous AWJ. Figure 9 shows typical results obtained (more details are given in Ref. **6**). In both cases the standoff distance (S_d) between the nozzle and substrate was 6 mm. While PAWJ removed the hard paint quite readily after a single pass (Fig. 9a), the AWJ did not remove any, except some spots (Fig. 9b). The low magnitude of 34.5-MPa must be noted.

Increasing abrasive flow rate enhanced the paint removal rate. Figure 10 shows the rate of paint removal as a function of abrasive flow rate. The increase was not linear; increasing abrasive flow rate above 0.7 kg/min produced only small further increases in paint removal rate. This was attributed to the loss of distinct pulse pattern with increased abrasive flow rates as illustrated in Fig. 11.

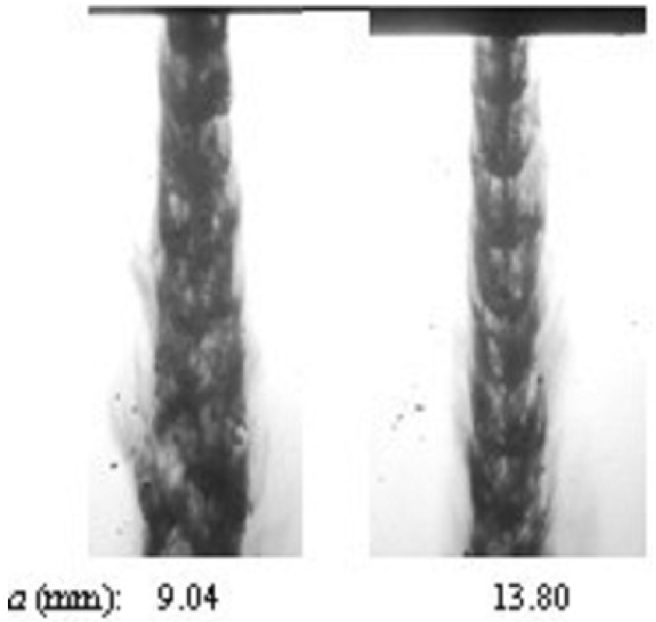
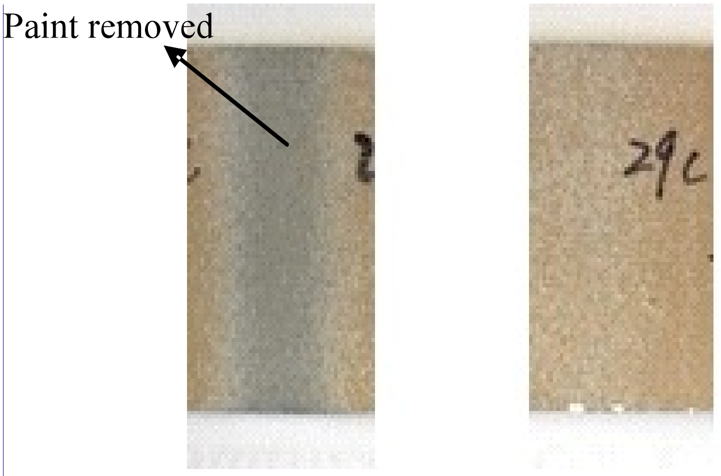


Fig. 8. Photographs showing the effect of position of probe on the structure of PAWJ (d_n = 1.37-mm, P_p = 34.5-MPa, A_m = 50%, Size of abrasive = 14-mesh).



a) Pulse on b) Pulse off

Fig. 9. Photographs showing the effectiveness of PAWJ compared to AWJ (d_n = 1.37 mm, P_p = 34.5 MPa, A_m = 60%, a = 9.04 mm, S_d = 6 mm, zeolite: 14-Mesh).

Another significant observation was the influence of the size of the abrasive particles. Reducing the size of the zeolite particle appeared to improve mixing between the particles and water. The appearance of PAWJ with the medium and fine particles is shown in Fig. 12. Despite the pulse pattern being less distinct, the fine particles mixed better with water than the medium size particles. Whereas medium size zeolite were visible on the jet surface, the fine particles were entrained into the core of the jet. The fine particles were also found to be more effective (and less aggressive) in removing the paint. Typical appearance of the strips from which the paint was removed after a single pass is shown in Fig. 13. The surface finish achieved with the fine particles was smooth to bare metal with well defined edges. On the other hand, the finish rendered by the medium size particles was quite rough, with considerable erosion (damage) on both sides of the width of the paint removed. Also at the operating conditions specified in Fig. 13, the concentration by weight of the finer particles was much less than the medium size (**6**).

4 APPLICATIONS

Several applications are in progress some of which are confidential at the time of writing this paper. However, in order to point out the potential benefits of using PAWJ, the following three are described herein.

As mentioned above, zeolite has the capacity to absorb radioactive particles (**6**). One of the requirements in radioactive decontamination (or, any other decontamination task) is to keep the amount of water used to a minimum (**10, 11**) to reduce the problem of wastewater disposal. Thus, the work on radioactive decontamination with PAWJ is pending to find out if the water consumption could be reduced to acceptable levels.

Removing epoxy coatings from the delicate aircraft skin is shown in Fig. 14. In such applications, erosion, warping and other problems caused by the impact of waterjet are not acceptable. Since the concentration of zeolite is quite low (≈ 10%), and the magnitude of pressure is of the order of 40-MPa, employing PAWJ for such applications, would be highly beneficial.

Figure 15 shows milling of the outer surface of the tubes used in nuclear reactors. Once again, keeping the pressure to minimum possible values is quite essential as the walls of the tubes are quite thin. Both garnet and zeolite were employed to establish their practicality for this application, the magnitude of pressure being approximately 30-MPa. Although results appear quite promising, acceptance of PAWJ for this application would depend on evaluation by the nuclear industry (subject to thorough testing of the surface and damage, if any, of the wall of the tube).

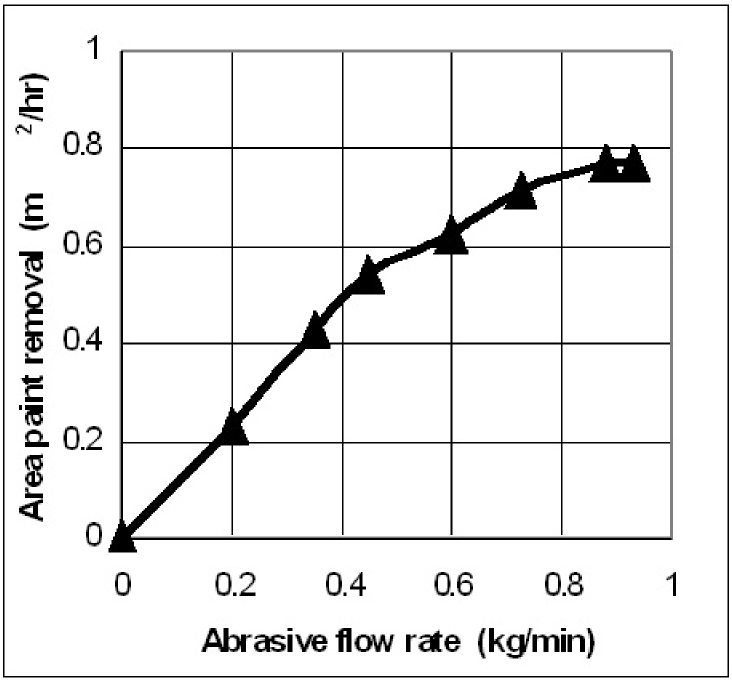


Fig. 10. Plot of area removal rate against abrasive flow rate (d_n = 1.37 mm, P_p = 34.5 MPa, A_m = 50%, zeolite: 14-Mesh).

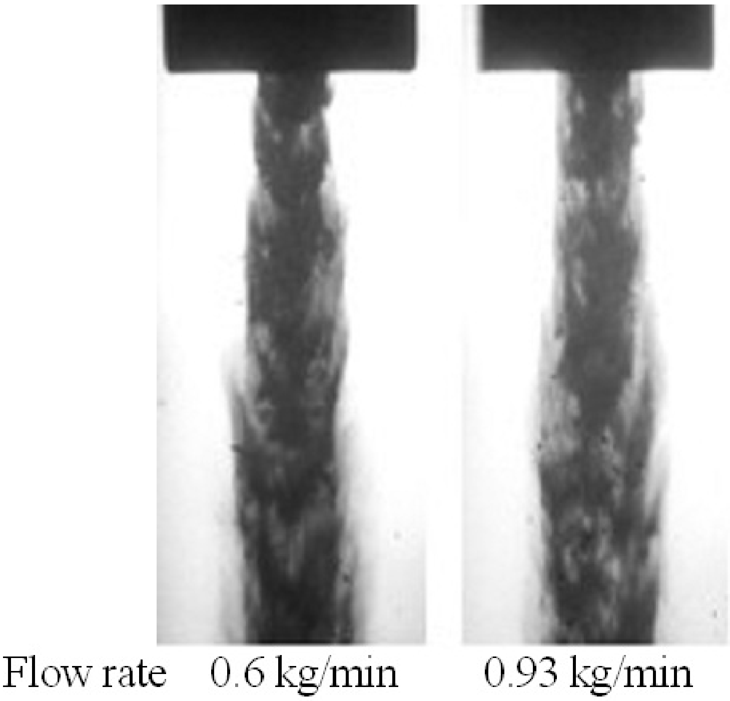


Fig. 11. Photographs showing the appearance of PAWJ at the abrasive flow rates indicated (d_n = 1.37 mm, P_p = 34.5 MPa, A_m = 50%, zeolite: 14-Mesh).

5 CONCLUSIONS

The following conclusions were drawn from the results of this study:

- As the vibrating probe in a pulsed water jet assembly is placed further away from the exit of the nozzle, the pulses become more defined.

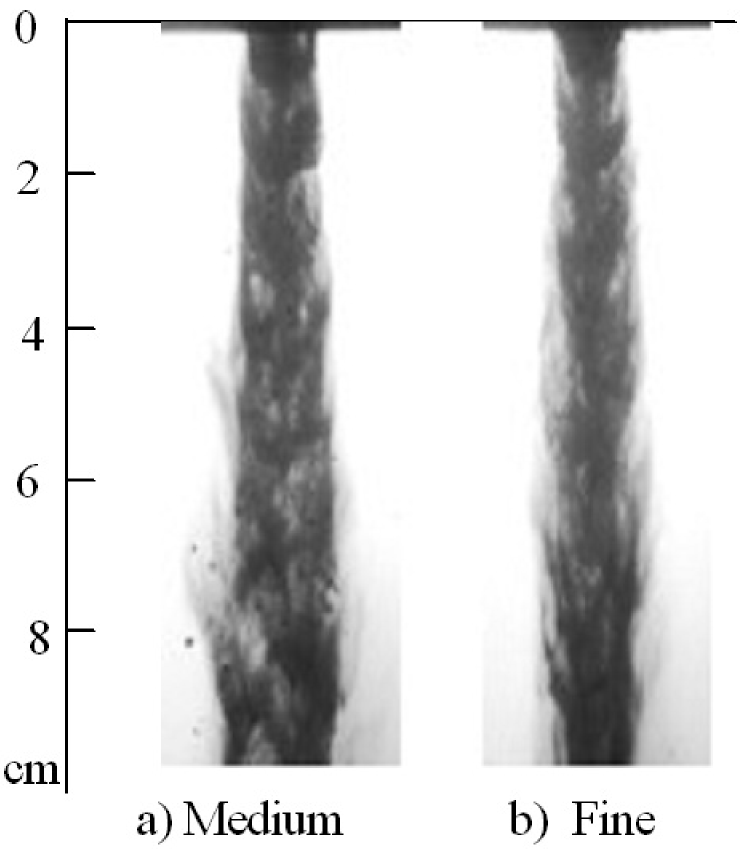
- Adding a mixing chamber to a pulsed waterjet nozzle and abrasive appear to have an adverse effect on pulses of water.

- Probe vibration enhances the abrasive suction in a PAWJ nozzle assembly.

- Pulsing an abrasive water jet increases its effectiveness in eroding layers of several types of coating.

- The fine size abrasive particles remove paint more effectively and uniformly than a coarser abrasive.

- PAWJ has great potential for several industrial applications, where low pressures and water consumption are required.



a) Medium b) Fine

Fig. 12. Appearance of PAWJ with medium and fine zeolite particles (d_n= 1.37 mm, P_p = 34.5 MPa, A_m = 50%, a = 9.04 mm).

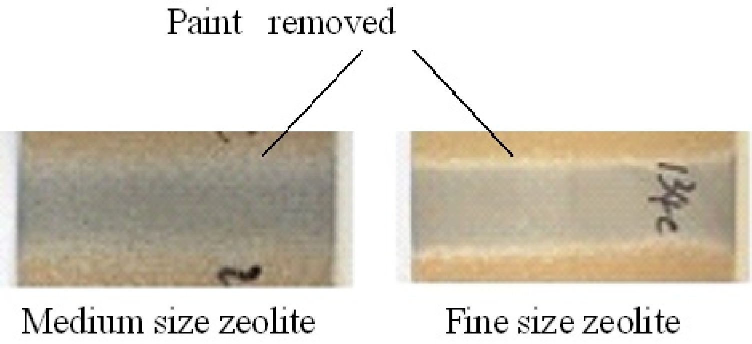


Fig. 13. Typical appearance of the swaths of paint removed with the medium and fine zeolite particles (d_n= 1.37 mm, P_p = 34.5 MPa, A_m = 60%, a = 9.04 mm).

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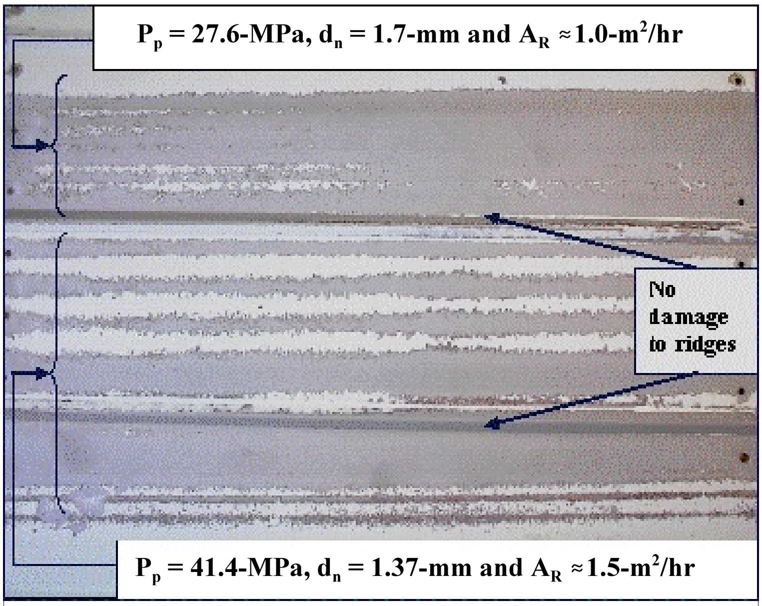

Fig. 14. Paint removal tsts conducted on aircraft skin test sample with PAWJ (fine zeolites) at conditions as indicated.

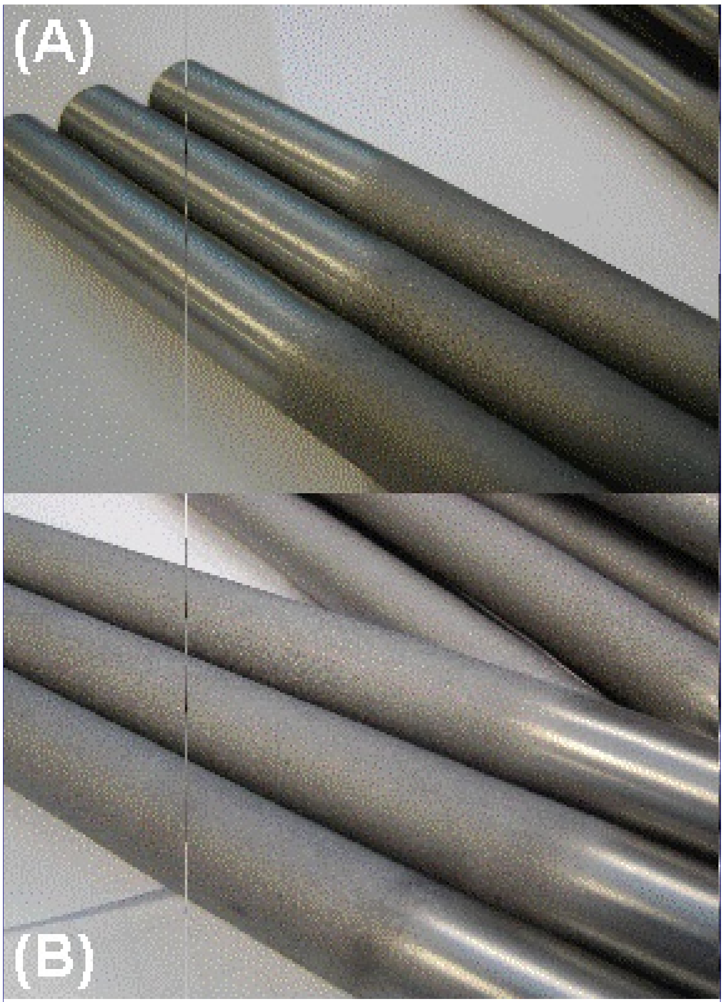

Fig. 15. Milling of the outer surfaces of the tubes used in nuclear reactors with the PAWJ (A) fine zeolites, (B) garnet ($P_p \leq$ 33-MPa).

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