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COMPARISON OF THE EFFECTS OF STANDARD NOZZLES AND EXTENSION TUBES ON THE EROSION OF PMMA USING PULSATING WATER JET TECHNOLOGY

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Abstract

The study of bone cement disintegration is important for advancing orthopedic and trauma surgery outcomes. Bone cement, commonly used in joint replacement procedures, plays a vital role in fixation implants. However, the long-term stability and integrity of bone cement are critical for the success of these procedures. This study focuses on the use of ultrasonic pulsating water jet technology for the selective removal of bone cement, aiming to provide a precise and efficient method for revision surgeries. The disintegration efficiency is measured in terms of depth, width and volume of the disintegrated bone cement as a result of variations in the nozzle geometry, supply pressure and traverse speed. Two different nozzle types, the standard nozzle insert and nozzle with an extension tube of 100 mm having a diameter of 0.3 mm, are used. Two supply pressure levels were taken as 10 and 20 MPa with five levels of traverse speeds as 0.5, 1, 1.5, 2 and 2.5 mm/s. The results showed an increased disintegration efficiency for all experimental conditions using an extension tube nozzle as compared to a standard nozzle (20 – 25% in terms of disintegration volume). Also, the disintegration efficiency increased with higher pressure level values (8.2 mm^3 and 4.85 mm^3 for p = 20 and 10 MPa, respectively) and lower traverse speed values. The results showed a promising direction in terms of the utilization of an ultrasonic pulsating jet with a modified nozzle type for higher bone cement disintegration efficiency.

Keywords:

Pulsating water jet, bone-cement disintegration, Extension tube nozzle

1 INTRODUCTION

Several methods are used for bone cement disintegration and removal (Xara-Leite et al., 2021). Mechanical methods, such as the use of drills, burrs, curettes, and osteotomes, are commonly used due to their effectiveness in breaking down cement. However, these techniques can be time-consuming and carry a risk of bone perforation and fracture. Ultrasonic devices (Liddle et al., 2019), like the Orthosonics System for Cemented Arthroplasty Revision (OSCAR), offer a more selective removal process, preserving the host bone and reducing the risk of cortical perforation. Despite these benefits, ultrasonic methods may result in weaker cement-in-cement bonds if not carefully managed. Laser-assisted techniques (Scholz et al., 1991; Zimmer et al., 1992) provide precision and minimal thermal damage to surrounding tissues, but they require specialized equipment and training. Chemical methods involving solvents to dissolve the cement are less invasive but can be slow and may not completely remove all cement residues. Each method must be chosen based on the specific clinical scenario, balancing the need for effective cement removal with the potential risks to the patient. Another experimental technique that overcomes the shortcomings of the above-discussed methods is the water jet technology. The high-speed water produced at the nozzle exit impacts the surface of the bone cement and induces compressive stresses into the sample to disintegrate from material failure (Perec et al., 2022). The advantage of the method for medical application is the absence of any heat-affected zone, and always a sterile condition is achieved (Dunnen & Tuijthof, 2014). Further, due to the absence of any solid tool, disintegration of the bone cement from the unreachable and smaller opening areas can also be possible (den Dunnen et al., 2017). Moreover, due to the inherent property of the technology and the water to follow the less resistant path, damage to neighbouring cells and tissues is also minimized. Several studies related to the feasibility of disintegration of bone cement using water jet technologies have been carried out in the last two decades starting from Honl et al. (Honl et al., 2000) using continuous water jet (CWJ) and abrasive water jet (AWJ) to disintegrate bone cement and observe the effect of the supply pressure on the erosion efficiency. Despite the numerous advantages supporting the use of water jet technologies for bone cement disintegration, certain limitations and challenges persist. Effective disintegration requires higher supply pressure (>35MPa) and flow rates (>4.8 l/min) (Kraaij et al., 2015). Current commercially available waterjet pumps are not able to deliver these ranges, and the higher hydraulic parameters raise safety concerns such as reducing the visibility of the working site, infections, and safety for the surgical personnel and the patient. Additionally, the abrasive particles typically employed in other abrasive water jet (AWJ) applications are not biocompatible, rendering them unsuitable for medical use (Schwieger et al., 2004). Therefore, some alternative methods to solve the problem are being searched.

Recently, there has been significant interest in the use of ultrasonic pulsating water jet (PWJ) technology for the selective removal of bone cement (Hloch et al., 2013). This cold selective technique utilizes high-frequency water pulses to disintegrate bone cement without generating excessive heat, thereby minimizing thermal damage to surrounding tissues (Hloch et al., 2019). The ultrasonic PWJ method is particularly advantageous due to its precision and selectivity, allowing for targeted removal of bone cement while preserving the integrity of the host bone (Honl et al., 2000, 2003). This approach holds promise for minimally invasive procedures, potentially reducing recovery times and improving patient outcomes. Studies (Nag et al., 2020, 2021) have demonstrated the effectiveness of this technique in creating controlled disintegration grooves in bone cement, highlighting its potential as a safe and efficient alternative to currently used methods. Moreover, handling with lower hydraulic conditions and without abrasives reduces the safety concerns associated with CWJ and AWJ.

Although some preliminary studies have shown the potential of PWJ to be used for the effective disintegration of bone cement, very limited attempts have been made to increase its reach during surgical procedures. In its current state, the instrument's reach is limited due to the bulky pulsating head assembly near the nozzle exit, reducing its manoeuvre around the working site. Therefore, in the present study, a newly designed 100 mm long straight cylindrical extension tube fitted at the nozzle exit of the pulsating head assembly is used for the disintegration of bone cement. The erosion efficiency of the extension tube nozzle in comparison to the standard nozzle was evaluated by systematically varying the supply pressure (p = 10 and 20 MPa) and traverse speed (v = 0.5, 1, 1.5, 2, 2.5 mm/s) for both nozzle configurations. The performance of each nozzle type was assessed based on the measured disintegration depth, width, and volume.

2 EXPERIMENTAL

2.1 Material

C-ment 1 bone cement, a product of Leader Biomedical, was selected to prepare a bone cement workpiece for the present study. The bone cement sample was prepared by manually mixing the polymer powder with the monomer liquid in a ceramic bowl using a ceramic spatula. The formation of dough and heat release due to the polymerization process starts after a few minutes of mixing, and the dough starts to solidify, which is then spread uniformly on an aluminium matrix cavity for better fixation during the experimental runs. Within 7 - 8 mins, the bone cement solidifies in the given shape and sticks to the aluminum matrix. C-ment bone cement was used due to its better compressive and bending strength, as per the manufacturer's claim, and also has better intrusion depth for longer service life.

2.2 Experimental conditions

The Bone-cement disintegration experiment was carried out using PWJ technology, where two types of nozzles were used, differentiated according to their functional length. Standard circular nozzle inserts with a diameter of d = 0.3 mm and a functional length of 5 mm directly fitted to the pulsating head assembly (Fig. 1a hereafter referred to as "standard nozzle") and a cylindrical tubular extension tube of 100 mm mounted at the nozzle exit of the pulsating head assembly (Fig. 1b hereafter referred to as "extension tube nozzle") were used. Hydraulic and kinematic parameters of the generated water clusters were varied by using supply pressure p = 10 and 20 MPa, to examine the effect of hydraulic parameters on the erosion potential of the PWJ. The generation of water clusters is ensured by means of a vibrating sonotrode firmly connected to a piezoceramic transducer. An electric harmonic signal, generated from an acoustic generator at a frequency of f_s = 41 kHz, is fed into the converter, which causes the expansion and contraction of the piezoceramic plates and, thus, their movement. For the maximum use of the erosion potential of each hydraulic pressure variation, it is necessary to set the optimal technological parameters such as the acoustic chamber length "l_c" and the distance of the jet exit and workpiece surface known as standoff distance "z". These optimal parameters were determined by using a methodology described in the author's previous studies (Nag et al., 2019), and the optimal values used for the present study can be seen in Tab. 1. After tuning the technology, the main experiment, which consisted of specific disintegration tests, was carried out. The target bone cement sample fixed in an aluminium matrix was fixed using fixation screws so that it doesn't move from its position during the test. Subsequently, the pulsating jet was traversed over the workpiece surface with the pre-determined technological parameters (standard and extension tube nozzle, p = 10 and 20 MPa and v = 0.5, 1, 1.5, 2 and 2.5 mm/s) and trajectory, generating the erosion grooves on the bone cement sample.

Tab 1: Hydraulic and technological parameters used for disintegration of bone cement sample

Hydraulic parameters				
p (MPa)	d (mm)	f_s (kHz)	v_w (m/s)	Q (l/min)
10	0.3	41	127	0.54
20			180	0.76
Technological parameters				
nozzle	*lc* (mm)	*z* (mm)	*v* (mm/s)	*Rep.*
Standard	6	5	0.5; 1; 1.5; 2; 2.5	5x
Extension tube	9			
Standard	8	11		
Extension tube	11			

A distance of 20 mm was selected as the length of the erosion trace for each experimental condition. A distance of 3 mm was kept between two consecutive erosion grooves to eliminate any influence of the previous groove on the new groove. For statistical relevance of the results and repeatability, each experimental condition was repeated 5 times. The realized trajectories of the experiment are shown in Fig. 2

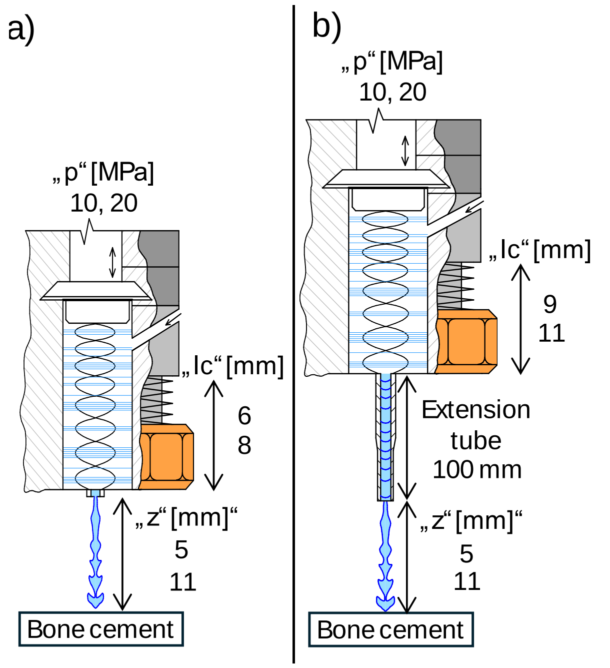

Fig. 1: Schematic representation of the PWJ head assembly with experimental conditions used for disintegration of bone cement.

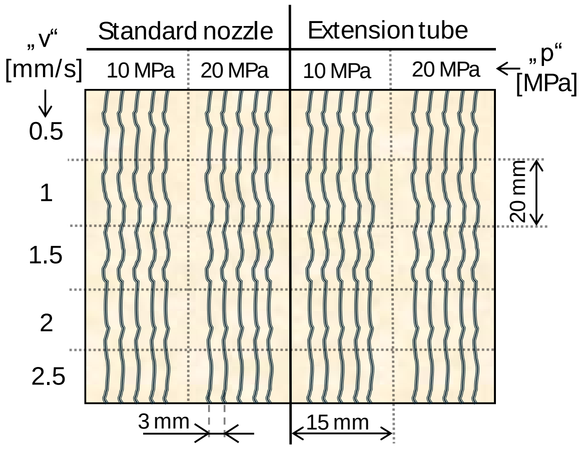

Fig. 2: Pictorial representation of the jet trajectory used during the disintegration of bone cement with different technological conditions.

2.3 Measurement

The measurement of the formed erosion grooves was carried out using an optical profilometer MicroProf from the company FRT. Each groove created was scanned for its width and depth (**Fig. 3**). These measurements were made at five different locations for each groove length for each nozzle, supply pressure, and traverse speed. As the experiments were repeated 5 times, this ultimately means 25 measurements of groove width and depth for each nozzle, pressure and feed rate were measured. Furthermore, the total erosion of the material in the form of the material volume removed was evaluated. In this case, each groove was individually scanned for a length of 20 mm and the volume of material removed was determined. All grooves from five replicates of the experiment were also scanned. The measured data were processed using the Mountains software, from which the data were extracted for statistical analysis. Subsequently, a statistical analysis of the measured data took place, which was processed into a graphic form together with the standard deviations of specific measured data to observe the effect of the input parameters on the output erosion responses.

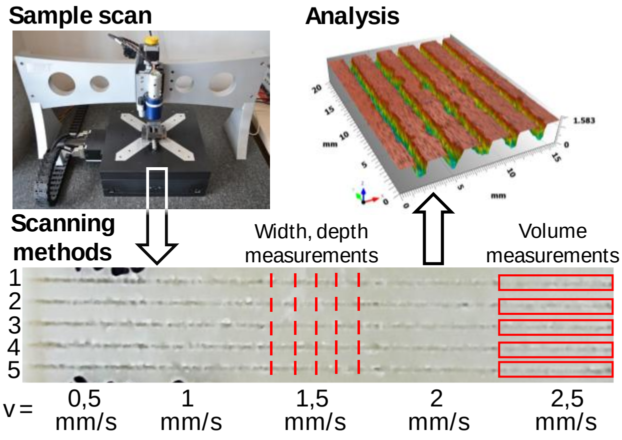

Fig 3: Measurement methodology to determine the disintegration depth, width and volume of the generated grooves formed using different experimental conditions.

3 RESULTS AND DISCUSSION

The disintegration responses measured from the generated grooves as a result of variation in the input parameters by the PWJ are plotted in Fig. 4, Fig. 5 and Fig. 6.

Fig. 4 shows the effect of traverse speed, supply pressure and nozzle type on the disintegration depth of the bone cement sample. It can be observed that for all experimental conditions, the erosion depth measured for the grooves generated using the extension tube nozzle is higher than compared to this counterpart standard nozzle. This increase in the efficiency of the jet can be attributed to the increase in the amplitude of the pressure fluctuation standing wave generated inside the high-pressure acoustic chamber and when propagating towards the nozzle exit. Due to the converging shape of the liquid waveguide, followed by the additional cylindrical tubular extension, the amplitude of the pressure fluctuation increases during its propagation, resulting in a bigger amplitude at the nozzle exit as compared to the nozzle exit of the standard nozzle insert fitted directly to the PWJ head assembly. This higher pressure fluctuation amplitude results in higher velocity fluctuation, resulting in well-developed water droplet clusters that interact with the bone cement surface. A second possible explanation could be that the elongated tube acts as a "damper" of unwanted fluctuations in the acoustic chamber. When inducing pressure fluctuations with the help of a sonotrode, water is constantly supplied to the acoustic chamber, which can carry with it subtle pressure fluctuations generated from the pump. This can cause, with a standard nozzle, that after exiting the nozzle, the water is not only divided into special dominant clusters (according to the frequency of the sonotrode), but the clusters themselves or their tail can be additionally slightly disturbed by subtle fluctuations generated from the pump. In this way, a disrupted cluster of water hits the target surface, which causes a lower impact pressure and stress on the target surface. On the other hand, passing through the tube extension causes the subtle oscillation to be eliminated or absorbed by the dominant oscillatory wave. This causes support and (or acceleration) of the energy of the dominant wave, which ultimately manifests as separate clusters of water after passing the nozzle without any disturbance. As a result, a greater impact load is applied to the material, which causes a higher erosion effect. When these repetitive water droplet clusters interact with the bone cement surface, compressive stresses are induced into the material. These stresses cause constant cyclic loading of the material, which, over time, leads to the appearance of the first cracks or separate microvoids. Moreover, at the onset of the interaction, lateral jetting takes place, which induces shear stresses on the bone cement sample surface. At the same time, the microcavities cause the lateral flow to enter the open spaces of the material, where a high accumulation of water pressure occurs. When these shear stresses exceed the ultimate strength of the material, brittle fracture takes place in the form of cracks. With subsequent droplet impacts, these generated micro-cracks propagate around the impact epicentre and merge with other cracks to cause brittle fracture and material disintegration. The intensity of the induced water hammer impact pressure depends on the impact velocity of the jet. Therefore, with the increase in the supply pressure, the magnitude of the disintegration depth measured increases proportionally. The disintegration depth for p = 20 MPa increases by 91.04% compared to the depth achieved using p = 10 and 20 MPa for traverse speed v = 0.5 mm/s. Also, the erosion depth magnitude depends on the traverse speed as it determines the distribution of the induced energy over a certain length of the material. For example, a jet with v = 0.5 mm/s induces 80,000 impacts per mm of the material compared to 16,000 impacts for v = 2.5 mm/s. This increased number of repetitive impacts at lower traverse speed is attributed to higher disintegration capability as compared to higher traverse speed. It can also be observed that with an increase in the traverse speed of v = 0.5 mm/s to 2.5 mm/s, the disintegration depth decreased by 142.7% for p = 20 MPa using an extension tube nozzle. The same decreasing trend is observed for another level of pressure and nozzle types with increased traverse speed.

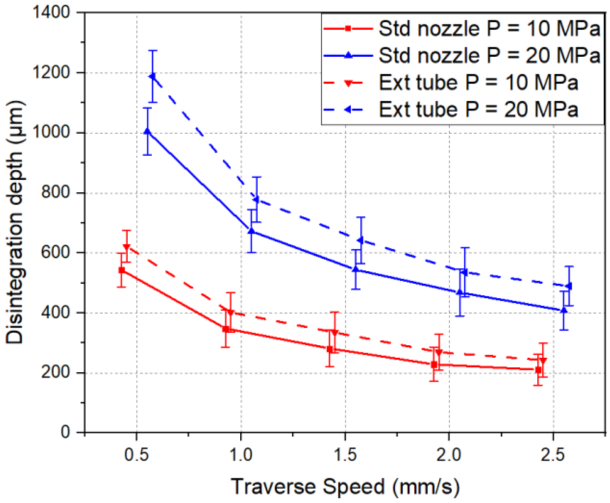

Fig. 3: Effect of traverse speed (v = 0.5 – 2.5 mm/s), supply pressure (p = 10 and 20 MPa) and nozzle type (standard nozzle and extension tube nozzle) on bone cement disintegration depth.

Fig. 4 shows the influence of the input parameters on the disintegration width generated by the PWJ on the bone cement sample. It can be observed that now much influence of the magnitude of the width was obtained with variation in the input parameters. However, the same trend as depth was observed when comparing the efficiency of the extension tube nozzle and the standard nozzle. The extension tube nozzle generated wider disintegrated grooves as compared to the standard nozzle. Also, with the increase in the supply pressure from p = 10 to 20 MPa, the groove width increased due to the increase in the hydraulic energy of the jet along with a higher magnitude of lateral jetting with higher impact velocity generating shear force to widen the generated groove away from the impact epicentre. Moreover, with an increase in the traverse speed, a narrower disintegration groove is achieved. For example, groove width generated with extension tube nozzle with p = 20 MPa and v = 0.5 mm/s measured as 548.3 μm compared to 345.2 μm for v = 2.5 mm/s. This is due to the lowering of the energy density of the jet over the length of the workpiece at a higher traverse speed. However, the difference in the disintegration width is not significantly large, as observed for the depth when using an extension tube nozzle over a standard nozzle. This can be attributed to the nozzle exit diameter, which was the same for both nozzles, which did not allow them to cover a significantly wider area compared to each other.

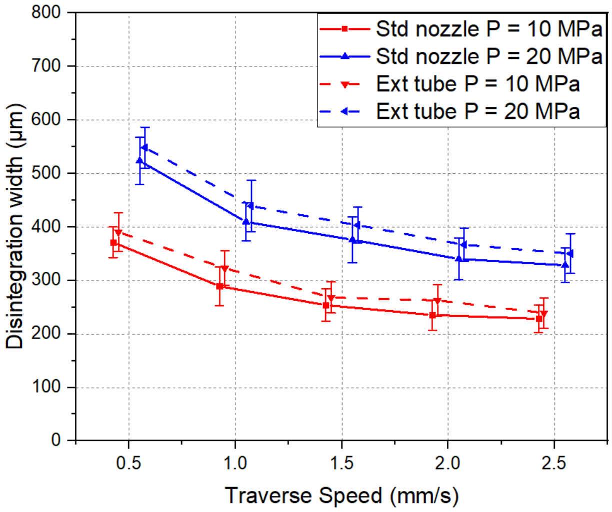

Fig. 4: Effect of traverse speed (v = 0.5 – 2.5 mm/s), supply pressure (p = 10 and 20 MPa) and nozzle type (standard nozzle and extension tube nozzle) on bone cement disintegration width.

Fig. 5 shows the disintegration volume of the bone cement as a result of variation in the input parameters. From the application point of view, this response is most important as it provides an overall view of the behaviour and efficiency of the jet depending upon the input parameters. This response also takes into account both the depth and the width responses to generate overall information. The trend of the input parameters remains similar to the depth and width discussed earlier. A higher disintegration volume is achieved by using an extension tube nozzle over the standard nozzle. An increase in 23.8% of volume removal was observed for the extension tube nozzle over the standard nozzle with *p* = 20 MPa and *v* = 0.5 mm/s. For supply pressure, with an increase in the pressure level, the overall bone cement disintegration volume also increases. For the disintegration groove generated using an extension tube nozzle with traverse speed, *v* = 0.5 mm/s disintegration volume 4.85 mm^3 and 13.05 mm^3 were measured for *p* = 10 and 20 MPa, respectively. Furthermore, an exponential dependency is observed in the disintegration volume with respect to the traverse speed. It can be observed that the disintegration volume exponentially decreases with a linear increase in the traverse speed from v = 0.5 to 2.5 mm/s. An increase of 274.4% was measured for the disintegration volume generated with traverse speed v = 2.5 mm/s compared to 0.5 mm/s using an extension tube nozzle with supply pressure, p = 20 MPa.

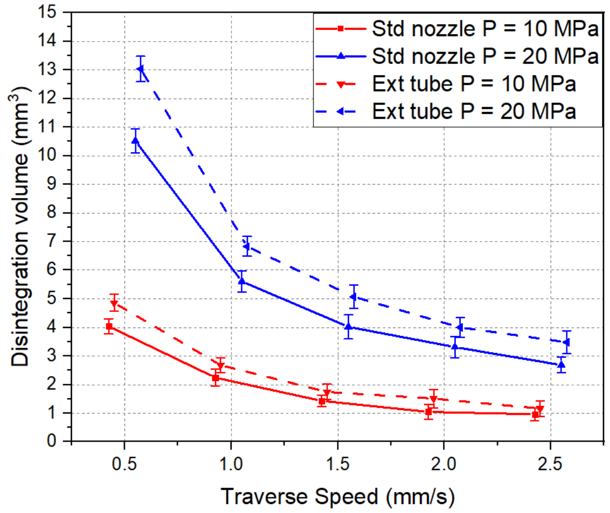

Fig. 5: Effect of traverse speed (v = 0.5 – 2.5 mm/s), supply pressure (p = 10 and 20 MPa) and nozzle type (standard nozzle and extension tube nozzle) on bone cement disintegration volume.

Statistical analysis of the responses was also carried out to determine which input parameter affected the erosion performance the most statistically. For statistical analysis, the mean value of the responses from each experimental condition was taken, and ANOVA analysis was conducted for each output response, i.e., disintegration depth, width and volume. The ANOVA table of the responses is shown in Tab. 2. The ANOVA results show that for disintegration depth, all the input parameters were statistically significant, with supply pressure as the most statistically significant, followed by traverse speed and then nozzle type. Not only was the linear model of the parameters significant, but the 2-way interaction of the parameters was also statistically significant and contributed to the erosion depth. Therefore, supply pressure plays a crucial role in controlling depth within the experimental domain shown. For disintegration width, the order of significant parameters remains the same as that of disintegration depth. However, the level of contribution of the nozzle type in the model decreases a bit as compared to depth, which also corresponds to the tighter trendline shown in Fig. 4. This may be due to the fact that the width of the generated groove largely depends on the nozzle exit diameter which is same for both the nozzle type as 0.3 mm and attributed to not so statistically significant effect compared to supply pressure and traverse speed. For disintegration volume also, supply pressure and traverse speed have higher statistical significance than nozzle type. Moreover, the interaction term also has higher significance, pointing to the importance of both the input parameters simultaneously.

Tab 2: ANOVA analysis of output responses: disintegration depth, width and volume.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Disintegration depth					
Model	15	1265127	84342	389.01	0.000
Linear	6	1203669	200611	925.29	0.000
Nozzle type	1	31433	31433	144.98	0.000
Supply pressure	1	526514	526514	2428.46	0.000
Traverse speed	4	645721	161430	744.57	0.000
2-Way Interactions	9	61459	6829	31.50	0.002
Nozzle type*Supply pressure	1	3831	3831	17.67	0.014
Nozzle type*Traverse speed	4	3846	962	4.43	0.089
Supply pressure*Traverse speed	4	53782	13445	62.01	0.001
Error	4	867	217		
Total	19	1265995			
S:14.7245, R-sq:99.93%, R-sq(adj):99.67%, R-sq(pred):98.29%					
Disintegration width					
Model	15	155805	10387.0	25945.58	0.000
Linear	6	154189	25698.1	64191.10	0.000
Nozzle type	1	1356	1356.1	3387.29	0.000
Supply pressure	1	76015	76015.5	189878.23	0.000
Traverse speed	4	76817	19204.3	47970.28	0.000
2-Way Interactions	9	1616	179.6	448.56	0.000
Nozzle type*Supply pressure	1	30	30.3	75.67	0.001
Nozzle type*Traverse speed	4	43	10.8	27.02	0.004
Supply pressure*Traverse speed	4	1543	385.7	963.32	0.000
Error	4	2	0.4		
Total	19	155807			
S: 0.632723, R-sq:100%, R-sq(adj):100%, R-sq(pred):99.97%					
Disintegration Volume					
Model	11	186.455	16.9505	114.44	0.000
Linear	6	167.331	27.8885	188.29	0.000
Nozzle type	1	3.618	3.6177	24.42	0.001
Supply pressure	1	67.911	67.9113	458.51	0.000
Traverse speed	4	95.802	23.9506	161.70	0.000
2-Way Interactions	5	19.124	3.8248	25.82	0.000
Nozzle type*Supply pressure	1	0.819	0.8193	5.53	0.047
Supply pressure*Traverse speed	4	18.305	4.5762	30.90	0.000
Error	8	1.185	0.1481		
Total	19	187.640			
S: 0.384856, R-sq:99.37%, R-sq(adj):98.50%, R-sq(pred):96.05%					

Pareto charts for each output response were also plotted to statistically determine the magnitude and importance of the effects for each input model term. The bars crossing the reference line are considered statistically significant input parameters that affect the output response. The Pareto chart for all the measured responses is shown in Fig. 6, 7 and 8. The visual representation of the parameters statistically affecting the output responses are at par with the results obtained numerically by ANOVA analysis depicting the importance of all the selected input parameters for output responses with the selected experimental domain.

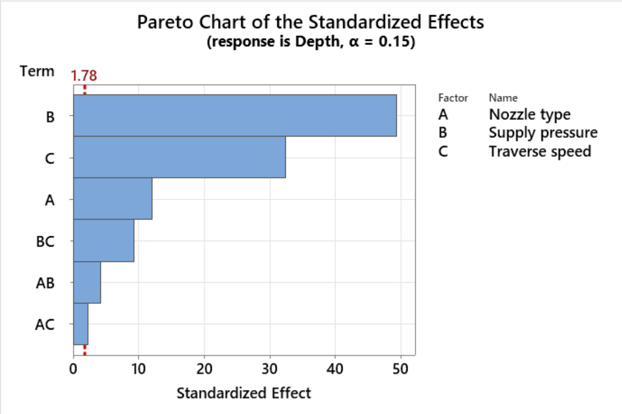

Fig. 5: Pareto chart for disintegration depth.

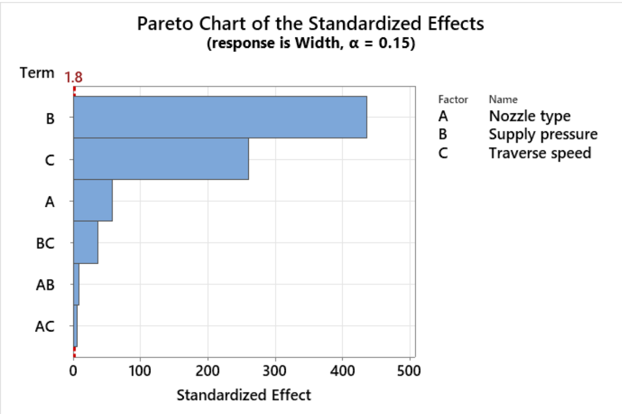

Fig. 6: Pareto chart for disintegration width.

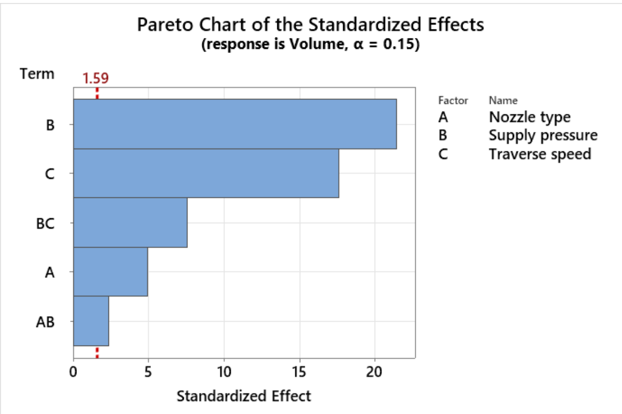

Fig. 7: Pareto chart for disintegration volume.

The regression equation obtained as a result of the ANOVA analysis for the explicit determination of disintegration depth, width and volume within the experimental domain when using a standard nozzle is given by equations 1, 2 and 3, respectively, and when using an extension tube nozzle, the regression equations are given by equation 4, 5 and 6.

For standard nozzle

$$Depth = 295.2 + 52.89\, Supply\ pressure - 483.7\, Traverse\ speed + 150.8\, Traverse\ speed * Traverse\ speed - 13.63\, Supply\ pressure * Traverse\ speed \quad (1)$$

$$Width = 311.6 + 15.785\, Supply\ pressure - 194.9\, Traverse\ speed + 49.05\, Traverse\ speed * Traverse\ speed - 2.303\, Supply\ pressure * Traverse\ speed \quad (2)$$

$$Volume = 0.56 + 0.7286\, Supply\ pressure - 5.56\, Traverse\ speed + 2.122\, Traverse\ speed * Traverse\ speed - 0.2400\, Supply\ pressure * Traverse\ speed \quad (3)$$

For extension tube nozzle

$$Depth = 374.5 + 52.89\, Supply\ pressure - 483.7\, Traverse\ speed + 150.8\, Traverse\ speed * Traverse\ speed - 13.63\, Supply\ pressure * Traverse\ speed \quad (4)$$

$$Width = 328.0 + 15.785\, Supply\ pressure - 194.9\, Traverse\ speed + 49.05\, Traverse\ speed * Traverse\ speed - 2.303\, Supply\ pressure * Traverse\ speed \quad (5)$$

$$Volume = 1.41 + 0.7286\, Supply\ pressure - 5.56\, Traverse\ speed + 2.122\, Traverse\ speed * Traverse\ speed - 0.2400\, Supply\ pressure * Traverse\ speed \quad (6)$$

Further, response surface plots were plotted for each response to understand the simultaneous effect of the input parameters on the output responses for both nozzle types. This was done due to the significant contribution of the 2-way interaction terms, mainly supply pressure and traverse speed, to the models predicting disintegration depth, width and volume. Therefore, the effect of supply pressure and traverse speed on the disintegration depth, width and volume is shown in Fig. 8, 9 and 10, respectively, for both standard and extension tube nozzle. The results showed that with a simultaneous increase in the supply pressure from p = 10 to 20 MPa and a decrease in traverse speed from v = 2.5 to 0.5 mm/s, all the output responses, such as disintegration depth, width and volume increases for both standard and extension tube nozzle. The trend of increase in the responses is largely similar for both nozzle types, with magnitude having higher values for the extension tubes, which can also be depicted in Fig. 3, Fig. 4 and Fig. 5. The slope of the surface is much steeper for depth and volume response as compared to width which aligns with the results and reasons described above. All the response plots support the importance of not only individual parameters but also the interaction between the input parameters on the output responses.

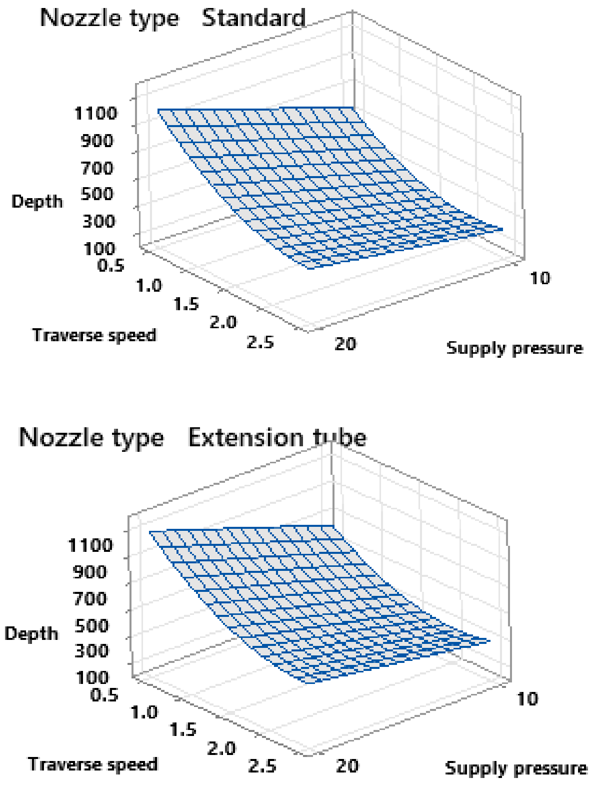

Fig. 8: Surface response plot of traverse speed and supply pressure on disintegration depth for standard and extension tube nozzle.

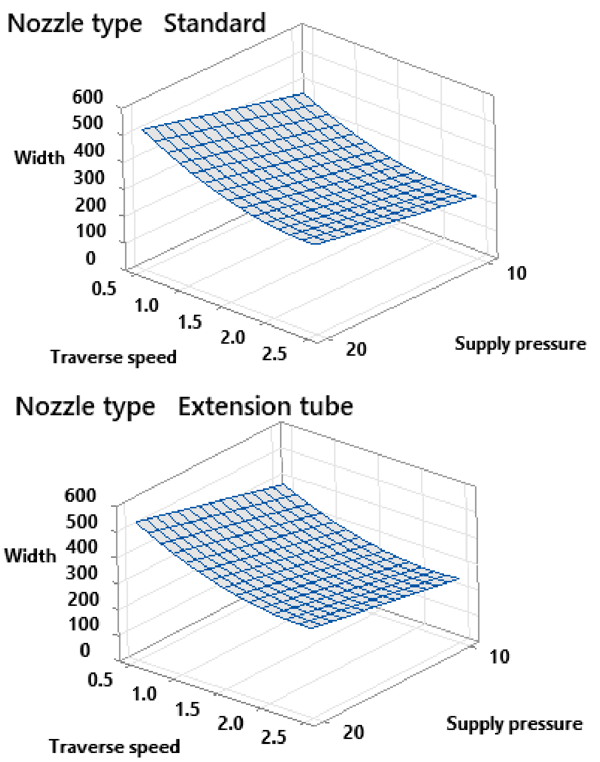

Fig. 9: Surface response plot of traverse speed and supply pressure on disintegration width for standard and extension tube nozzle.

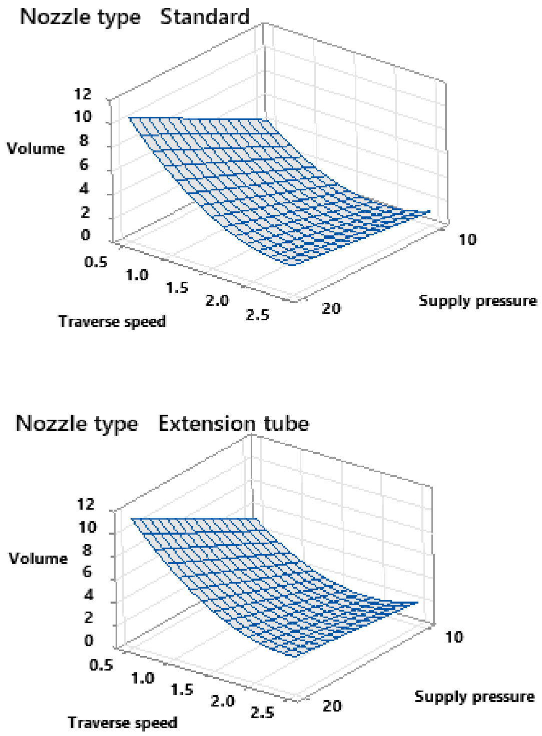

Fig. 10: Surface response plot of traverse speed and supply pressure on disintegration volume for standard and extension tube nozzle.

4 CONCLUSION

This study compared the disintegration efficiency of PWJ using two different nozzle designs, i.e., standard nozzle and extension tube fitted nozzle, along with its dependency on technological parameters such as supply pressure and traverse speed. The main findings of the study are as follows:

1) For all the experimental conditions, the extension tube-fitted nozzle outperformed the standard nozzle by approximately 25% in terms of disintegration responses, keeping other parameters constants.

2) Disintegration responses increased with a decrease in the traverse speed, attributing to the longer interaction time.

3) With an increase in the supply pressure, the disintegration responses also increased due to the increase in the impact pressure and speed induced by the jet.

4) Statistical analysis showed that all three selected input parameters significantly affected the output responses with the chosen experimental domain.

Overall, the current study illustrated the potential of PWJ for bone cement disintegration, which can be used to extract bone cement from the desired site minimally during revision surgeries. Also, it showed the importance of optimal selection of the technological parameters and the major effect of the nozzle design. In future work, further optimization of the nozzle design, along with different working fluids, such as physiological saline on the bone cement disintegration, can be investigated. Also, the nozzle wear as the long-term effect should be also explored. Moreover, the effect of the working conditions on bone cement disintegration can also be investigated, as done in these studies (Hloch et al., 2024; Stolarik et al., 2024).

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