Spectrum of Mechanical Engineering and Operational Research, Volume 2, Issue 1 (2025) 93-103

SCIENTIFIC OASIS

Spectrum of Mechanical Engineering
and Operational Research

Journal homepage: www.smeor-journal.org
eISSN: 3042-0288

Disintegration of Bone Cement Using Pulsating Water Jet: A Comparative Study of Standard and Extended Nozzles

Akash Nag[1], Sergej Hloch[1,2*]

[1] Faculty of Mechanical Engineering, VŠB - Technical University of Ostrava, Ostrava, Czech Republic
[2] The Czech Academy of Sciences, Institute of Geonics, Ostrava, Czech Republic

ARTICLE INFO

Article history:
Received 20 June 2024
Received in revised form 9 December 2024
Accepted 19 January 2025
Available online 28 January 2025

Keywords:
Pulsating water jet; Erosion; PMMA; Bone cement.

ABSTRACT

The paper deals with erosion of bone cement using a pulsating water jet at a pressure of 15 MPa, comparing the effectiveness of standard and extended nozzle with the length of 100 mm and diameter d = 0,3 mm. The research addresses the problem of optimizing bone cement removal techniques, which is critical for various medical applications, including revision surgeries and bone cement removal. The study employs an design of experiments where bone cement samples are subjected to erosion using a pulsating water jet system equipped with both standard and specially designed extended nozzles. Key parameters such as maximal depth, groove width and volume rate were measured and analyzed. Findings indicate that the extended nozzle significantly enhances the erosion process, achieving higher material removal rates and smoother surface finishes compared to the standard nozzle. The results demonstrate the potential of the extended nozzle design in improving the efficiency and precision of bone cement removal, offering valuable insights for medical practitioners and researchers in the field of orthopedic surgery.

1. Introduction

The effective removal of bone cement is a critical challenge in orthopedic revision surgeries [1], where precision and safety are important [2]. Conventional methods, such as manual chiseling [3], mechanical drilling caused the damaging of surrounding bone and tissue. It leads to prolonged recovery times and increased patient discomfort. The need for a more efficient, precise, and minimally invasive technique has driven the exploration of advanced technologies[4,5].The ultrasonic pulsating water jet presents a promising solution [6] offering the potential to disintegrate bone cement with high precision while preserving the integrity of the cortical bone. This method leverages the synergistic effects of ultrasonic vibrations and pulsating water jets to achieve controlled erosion, reducing the risk of collateral damage.

---

[*] *Corresponding author.*
E-mail address: sergej.hloch@ugn.cz

https://doi.org/10.31181/smeor21202525

The research conducted by [7] has significantly advanced the field of bone cement removal using water jet technology. Their studies have demonstrated the efficacy of both continuous and pulsating water jets in achieving precise and controlled erosion of bone cement [8]. For instance, following works [9-11] on the utilization of ultrasonically forced pulsating water jets [12]has shown that this method can effectively and selectively disintegrate bone cement while possible preserving the integrity of the surrounding cortical bone. This is achieved through the high-frequency pulsations that enhance the erosion process, allowing for more precise control compared to traditional methods. Their research highlights the importance of parameter optimization [13] such as standoff distance and pulsation frequency, to maximize the efficiency and safety of the procedure. Furthermore, the integration of real-time monitoring systems, such as vibration analysis, has been a key focus in their work, enabling adaptive control of the water jet during surgery [14].

While the studies demonstrated the potential of using an ultrasound-induced water jet for controlled bone cement disintegration, they all employed a standard, commercially available nozzle. The limitation of this nozzle is its unsuitability for minimally invasive procedures to disintegrate bone cement without visual access. To overcome this research gah, the aim of the study is to test initial prototype of the extended nozzle was entirely metal, measuring 100 mm in length with a reinforced shaft in the middle. The internal recess, created using EDM drilling, having a diameter of 1 mm, while the hole at the nozzle's tip was 0.3 mm and compared with commercially available inserts at the same diameter.

2. Materials and Methods

2.1 Materials

As bone cement C-ment was used in the study, which was prepared following the strict requirements of the manufacturer. The preparation process involved mixing the cement components under vacuum conditions to minimize porosity and enhance mechanical strength. During the plastic phase, the bone cement was pressed into the metal bed and leveled with the matrix surface to eliminate any unevenness. Once the bone cement had hardened [15] and naturally cooled, the sample was subjected to a pulsating water jet, with the technological conditions described in the following chapter.

2.2 Experiments

The experiments were conducted at the Institute of Geonics, part of the Academy of Sciences of the Czech Republic, using patented equipment ultrasonic pulsating water jet (uPWJ). A pressure of 15 MPa was produced by a Hammelmann HDP 253 pump and directed into the acoustic chamber, where the ultrasonic stepped sonotrode oscillated at a frequency of 40 kHz. These oscillations were generated via the inverse piezoelectric effect using piezoceramics, connected to an Ecoson WJ-UG 630-40 acoustic generator with a maximum power output of 800 W. The positioning of the acoustic head was managed by an ABB IRB 6640-180 robot. In the experiment, commercially available Hammelmann nozzle with diameter d = 3 mm were compared with an extended nozzle with d = 3 mm featuring an extended shaft l = 100 mm, as detailed in the last paragraph of the introduction. For both nozzles, the standoff distance z (mm) was adjusted to achieve maximum erosion efficiency using a stair trajectory [16,17]. To fully utilize the erosion potential of each hydraulic pressure variation, it was essential to set optimal technological parameters, such as the acoustic chamber length lc (mm) and the standoff distance [18] z (mm) the distance between the jet exit and the workpiece surface. These optimal parameters were determined using a methodology described in [19, 20]. Further focus was concerned with examining how the speed of travers speed influences the disintegration of bone cement. The selected traverse speeds were (v = 0.5, 1.0, 1.5, 2.0, 2.5) m/s employes to determine erosion capability of the set technological conditions (Figure 1).

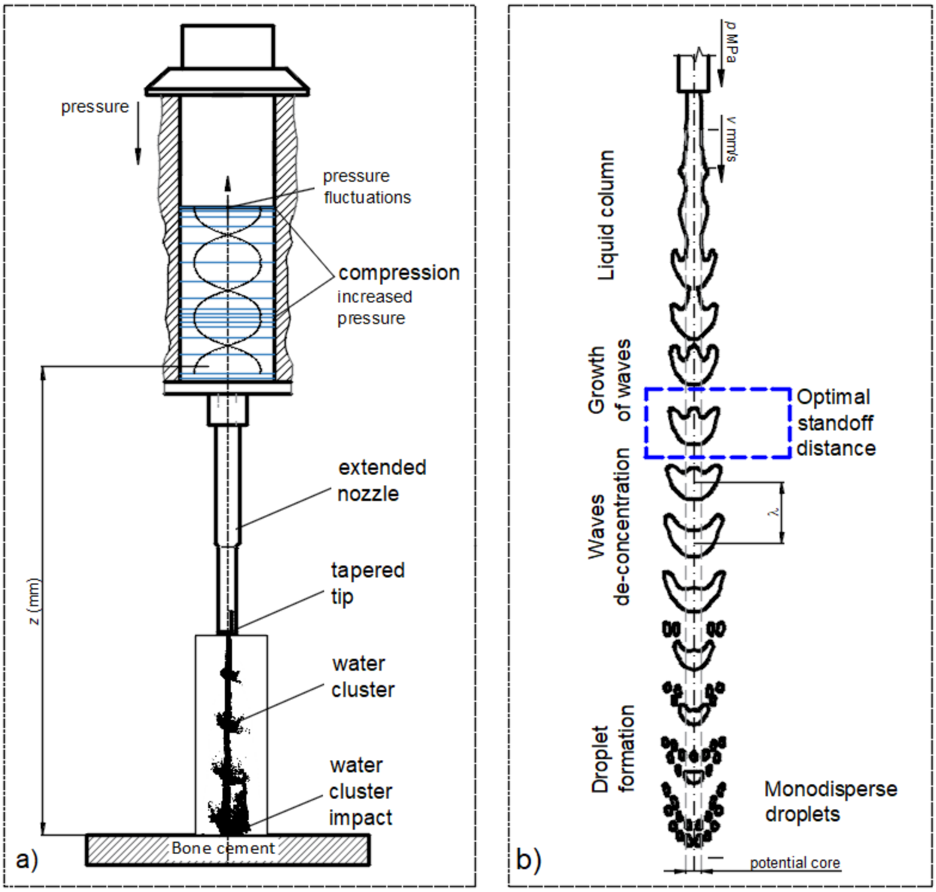

Fig. 1. Experimental setup for eroding bone cement at 15 MPa using an extended nozzle at an optimized standoff distance

2.3 Measurements

The measurement of the erosion grooves was performed using a contactless optical profilometer, MicroProf FRT. Each groove was scanned for its width and depth at five different locations along its length for each nozzle, supply pressure, and traverse speed. Since the experiments were repeated five times, this resulted in 25 repeated measurements of groove width and depth for each nozzle, pressure, and feed rate. Additionally, the total erosion, represented by the volume of material removed, was evaluated. Each groove was individually scanned over a length of 20 mm to determine the volume of material removed. All grooves from the five experimental replicates were also scanned. The measured data were processed using Mountains software, from which the data were extracted for statistical analysis. Subsequently, a statistical analysis of the measured data was conducted and presented graphically, including the standard deviations of specific measurements, to observe the effect of the input parameters on the erosion responses.

3. Results and discussion

Based on the measurements and obtained data, which are visualized in the graphs, we determined the influence of the exposure time of the ultrasonically excited water jet on the material's depth (Figure 2), groove width (Figure 4) and and bone cement volume removal (Figure 6) within a parametrically defined experiment (Figure 1, Chapter 2.2).

3.1 Disintegration depth

The following Figure 2 shows the development of depth penetration over time. With the increase in the traverse speed from v = 0.5 to 2.5 mm/s, the disintegration depth decreases from h = 764.88 ± 67.22 µm to 299.48 ± 52.78 µm and h = 899.44 ± 77.45 µm to 366.36 ± 69.65 µm for standard and extension tube nozzle, respectively. This decrease in the disintegration depth is due to a decrease in the interaction time of the PWJ with the workpiece material from 2s to 0.4 s per unit length of the material for v = 0.5 to 2.5 mm/s. Also, the number of impacts per unit length of the material decreases from 80,000 to 16,000 impacts/mm with the increase in the traverse speed from v = 0.5 to 2.5 mm/s. With larger impacts, the repetitive loading of the material leads to fatigue failure of the bone cement material in the form of cracks, which then propagate through the material. These interconnected cracks finally result in dislodging a large volume of material at a lower traverse speed as compared to a higher traverse speed. The disintegration depth *h* (µm) is influenced by the nozzle geometry. In this study, we compared a standard nozzle insert Hammelmann at the outlet of the PWJ head with a monolithic extension tube, 100 mm in length, fitted at the end of the PWJ head. The results indicated that changing the nozzle length configuration and type led to an increased disintegration depth for the extension tube nozzle compared to the standard nozzle while keeping all other technological parameters constant. It should be emphasized that attenuation was assumed to be more significant in PWJ with an extended shaft. Additionally, it is possible to assume that the internal structure could amplify and direct the standing waves, similar to the effect observed with the focusing nozzle in AWJ systems. For instance, at v = 0.5 mm/s, the disintegration depth obtained for the extension tube nozzle is 899.44 ± 77.45 µm compared to 764.88 ± 67.22 µm for the standard nozzle insert. This difference in the erosion efficiency is due to the proper propagation of the pressure fluctuations in the system before exiting. This increased magnitude of the pressure fluctuations also increases the velocity fluctuations responsible for the clustering of the PWJ, increasing its erosion efficiency. However, this increase in efficiency due to changes in the nozzle type is not as significant as changing the traverse speed levels.

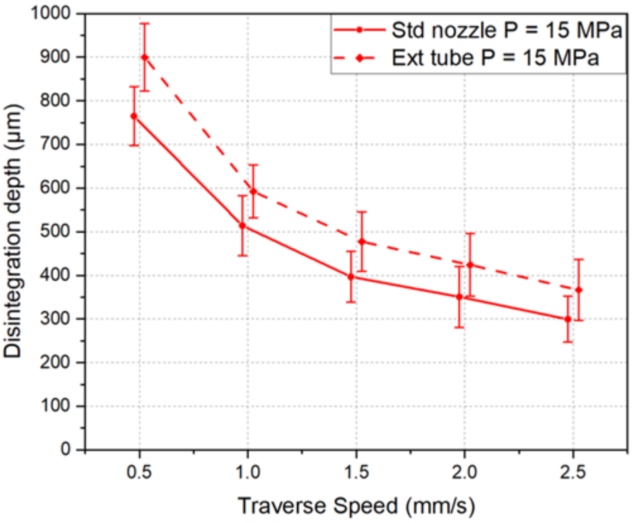

Fig. 2. Effect of traverse speed and nozzle type on the disintegration depth of bone cement sample

ANOVA analysis was carried out to understand which input parameter significantly affects the output response (Table 1). A full factorial design of the experiment was used with two input factors (nozzle type and traverse speed) having 2 (Standard and extension tube) and 5 (0.5, 1.0, 1.5, 2, 2.5) levels were conducted. The ANOVA results showed that both the input parameters, which is disintegration depth, statistically affect the output response significantly. However, the contribution of nozzle type is relatively lesser, accounting for 5.60% as compared to 93.95% for predicting the disintegration depth. This statistical observation also supports or complements the results shown in Figure 2.

Table 1
ANOVA table for disintegration depth

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	333486	99.55%	333486	66697.1	178.88	0.000
Linear	5	333486	99.55%	333486	66697.1	178.88	0.000
Nozzle type	1	18771	5.60%	18771	18771.4	50.34	0.002
Traverse speed	4	314714	93.95%	314714	78678.5	211.01	0.000
Error	4	1491	0.45%	1491	372.9		
Total	9	334977	100.00%				
S =19.3097, R-Sq = 99.55%, R-sq(adj) = 99.00%, R-sq(pred) = 97.22%							

Figure 3 presents the Pareto chart, which is used to determine the statistical significance of the input parameters on the output response, specifically the disintegration depth. The chart indicates that both input parameters—nozzle type and traverse speed—significantly influence the disintegration depth. Additionally, the main effect plot illustrates the impact of individual parameter levels on the responses. It can be observed that the extension tube nozzle consistently achieves greater depths across all traverse speed values compared to the standard Hammelmann nozzle insert. The reason for higher efficiency is already discussed in the above section. Similarly, it can also be observed that with an increase in traverse speed from v = 0.5 to 2.5 mm/s, the disintegration depth decreases exponentially for both the nozzle types. This is due to the distribution of the hydraulic energy over the entire erosion length. The figures also clearly indicate or correspond to the ANOVA results depicting a higher contribution of traverse speed than nozzle type for disintegration depth.

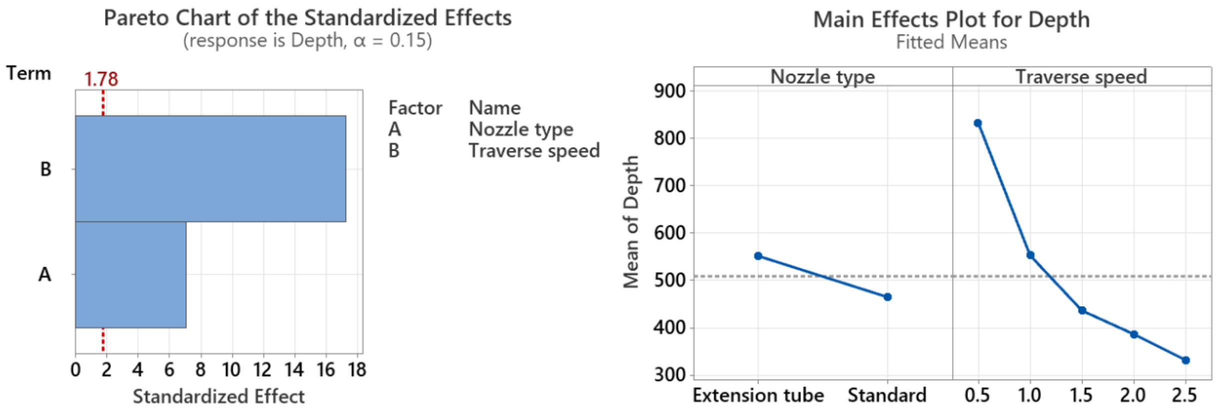

Fig. 3. Pareto chart of the standardized effects and the main effect plot for disintegration depth

3.2 Disintegration Width

Figure 4 shows the effect of input parameters on the disintegration width of the bone cement. The trend shows an inverse effect in the response with increasing traverse speed. The disintegration width decreases from w = 452.70 ± 33.61 µm to 283.94 ± 21.39 µm and w = 476.79 ± 33.73 µm to 307.49 ± 29.83 µm for the standard nozzle and extension tube nozzle, respectively, for an increase in traverse speed, v = 0.5 to 2.5 mm/s. This decrease in the width magnitude is due to the lower energy density of the jet with increasing speed as discussed in the previous section for disintegration depth. However, when comparing the width obtained by different configurations of the nozzle, the extended tube nozzle showed a slightly wider disintegration width as compared to the width obtained using a standard nozzle, keeping other input parameters the same. Moreover, the spread of the jet exiting the nozzle exit and interacting with the material surface depends much more on the standoff distance and exit diameter, both being the same in the current experiment doesn't generate significantly different disintegration widths.

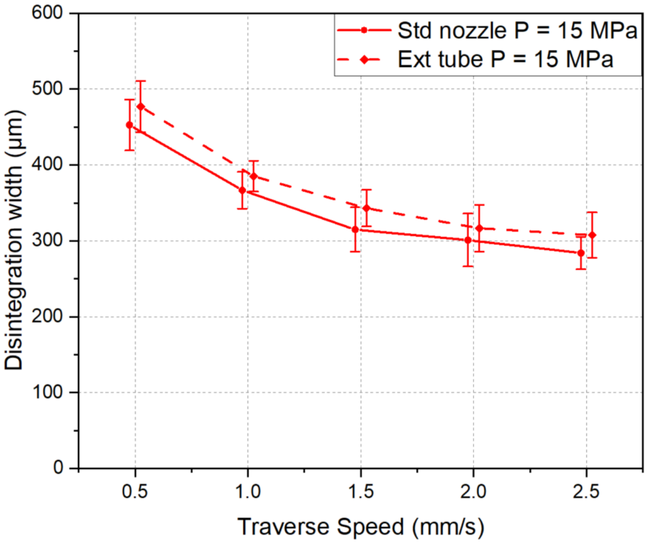

Fig. 4. Effect of traverse speed and nozzle type on the disintegration width of bone cement sample

Table 2
ANOVA table for disintegration width

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	58177.5	99.37%	58177.5	11635.5	126.34	0.000
Linear	5	58177.5	99.37%	58177.5	11635.5	126.34	0.000
Nozzle type	1	15088.0	25.77%	15088.0	15088.0	163.83	0.000
Traverse speed	4	43089.6	73.60%	43089.6	10772.4	116.97	0.000
Error	4	368.4	0.63%	368.4	92.1		
Total	9	58545.9	100.00%				

S =9.59673, R-Sq = 99.37%, R-sq(adj) = 98.58%, R-sq(pred) = 96.07%

Table 2 shows the ANOVA analysis for the disintegration width. The table shows that the model is statistically significant, along with both the input parameters statistically significant. Higher values of R-Sq(pred) correspond to the statistical significance of the model with the experimental values obtained within the selected experimental domain. Figure 5 shows the Pareto chart for the disintegration width. The chart shows that traverse speed and nozzle type are both equally statistically significant in affecting the disintegration width. The mean effect plot shows the trend of the individual input parameters on the disintegration width. The graph clearly shows the higher value of the width obtained with the extension tube nozzle, taking into consideration all the tested traverse speed levels as compared to the standard nozzle inserts. An increase of 18.62% was observed in the disintegration width when disintegrated using an extension tube nozzle as compared to a nozzle insert. Similarly, an increase of 149.96% in disintegration width was observed with an increase in traverse speed from v = 0.5 to 2.5 mm/s considering both the nozzle types.

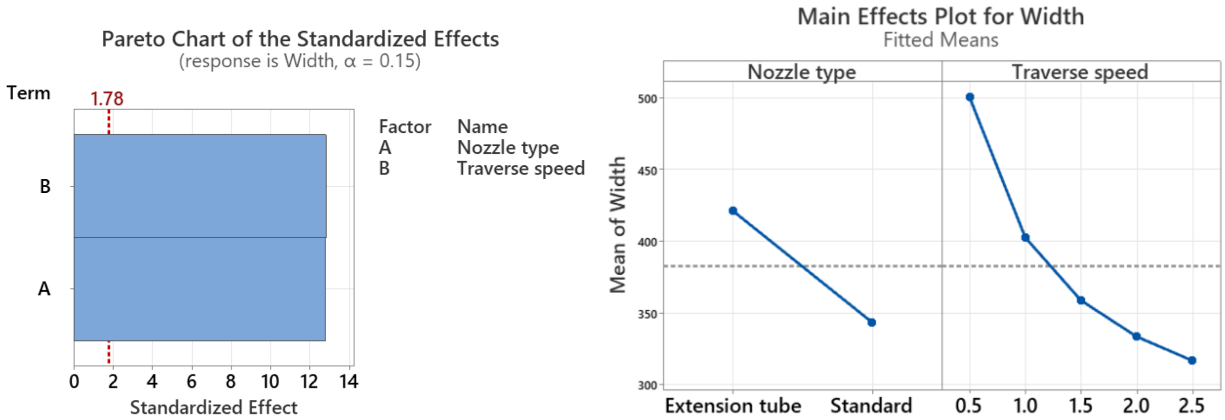

Fig. 5. Pareto chart of the standardized effects and the main effect plot for disintegration width.

3.3 Disintegration Volume

Figure 6 shows the effect of input parameters on the disintegration volume of the bone cement. The trend shows a decreasing trend in the volume values ranging from V = 6.92 ± 0.33 mm^3 to 1.70 ± 0.33 mm^3 and V = 8.58 ± 0.32 mm^3 to 2.18 ± 0.23 mm^3 for the standard nozzle and extension tube nozzle, respectively, for an increase in traverse speed, v = 0.5 to 2.5 mm/s. This trend also shows the combined effect of both depth and width taken together into account depending on all the input parameters and their levels. The decreasing trend of the disintegration volume is attributed to a similar reason responsible for both the disintegration depth and width. The bulk material removal depends on the brittle fracture of the bone cement occurring due to the repetitive impact of the water clusters overcoming the fatigue limit of the material even at lower input parameters. This observation corresponds to the increase in the disintegrated volume with a larger number of repetitive impacts (80,000) for lower traverse speed (v = 0.5 mm/s) as compared to the lower number of impacts (16,000) for higher traverse speed (v = 2.5 mm/s). With higher cumulative impacts, the material relaxation interval decreases significantly, and the disintegration volume increases exponentially, as seen in Figure 6. However, the magnitude of the disintegration volume also depends on the type of the nozzle output. As seen in Figure 6, with an extended tube nozzle, due to better propagation and amplification of the standing waves, the disintegration efficiency of the system increases as compared to standard nozzle inserts. The difference in the efficiency in the disintegration volume is larger for the lower traverse speeds and compared to the higher traverse speeds.

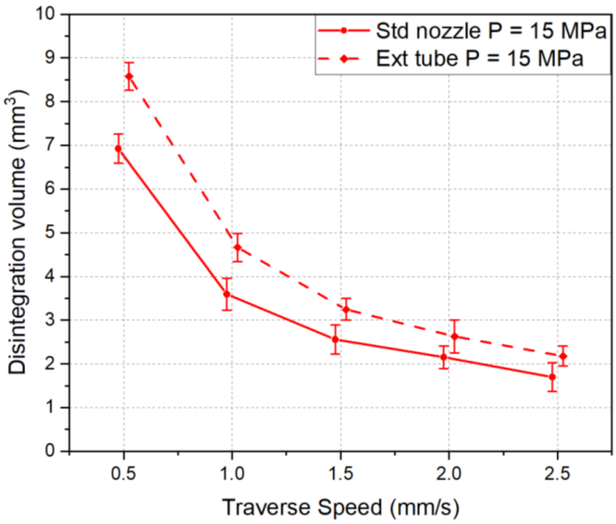

Fig. 6. Effect of traverse speed and nozzle type on the disintegration volume of bone cement sample

Table 3
ANOVA table for disintegration volume

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	45.8315	98.93%	45.8315	9.1663	74.05	0.000	45.8315
Linear	45.8315	98.93%	45.8315	9.1663	74.05	0.000	45.8315
Nozzle type	1.9011	4.10%	1.9011	1.9011	15.36	0.017	1.9011
Traverse speed	43.9305	94.83%	43.9305	10.9826	88.72	0.000	43.9305
Error	0.4951	1.07%	0.4951	0.1238			0.4951
Total	46.3267	100.00%					46.3267
S =0.351833, R-Sq = 99.93%, R-sq(adj) = 97.60%, R-sq(pred) = 93.32%							

Table 3 shows the ANOVA analysis of disintegration volume depending on the input parameters. The analysis showed that both the parameters are statistically significant for the determination of disintegration volume. However, the contribution of the effect of nozzle type is 4.10% as compared to 94.83% for traverse speed. Overall, the regression model is statistically significant in predicting the disintegration volume. Figure 7 shows the Pareto chart depicting the statistically significant input parameters selected for the present study affecting the disintegration volume. It clearly shows that both the input parameters selected statistically significantly affect the disintegration volume; however, the traverse speed significantly affects the results more than the nozzle type. This result also corresponds to the contribution level shown by the ANOVA table for both the input parameters. The mean effect plot shows the individual effect of both the input parameters on the disintegration volume. An increase of 25.66% is observed when using an extended tube nozzle for disintegration as compared to a standard nozzle, keeping all the other conditions the same. For traverse speed, the increase in the volume amounts to 299.48% for the decrease in the traverse speed from v = 2.5 to 0.5 mm/s. This significant increase in the volume is a product of the increase in the disintegration depth and width simultaneously with decreasing traverse speed. Therefore, an extension tube nozzle with a lower traverse speed can be used for better productive efficiency when removing or extracting bone cement from the femoral canal.

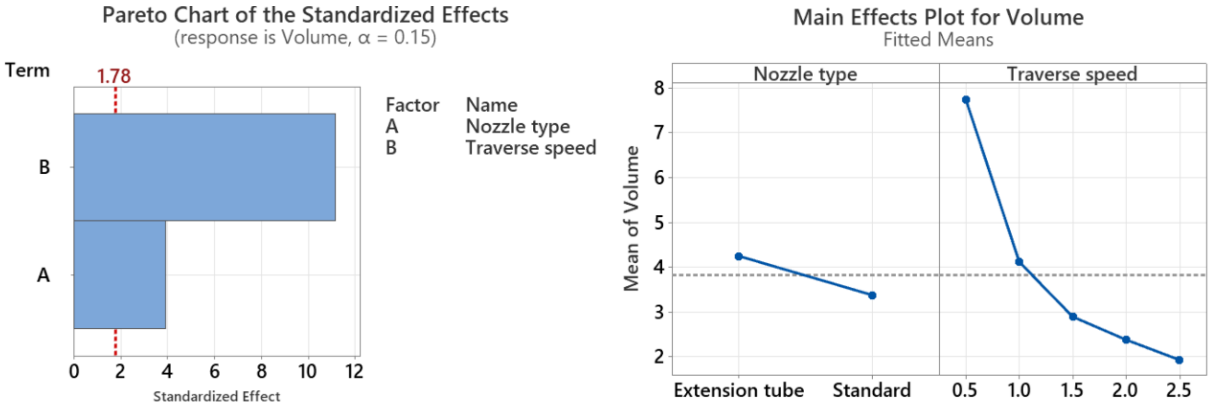

Fig. 7. Pareto chart of the standardized effects and the main effect plot for disintegration volume.

Based on above mentioned findings the next phase of research will focus on investigating the performance of the pulsating water jet in submerged conditions [21, 22]. This study aims to understand how the presence of a liquid medium influences the erosion characteristics of bone cement where hydrostatic pressure can influence the disintegration process. The insights gained from this research will be crucial for optimizing bone cement removal techniques in scenarios where the surgical environment involves fluids, thereby enhancing the applicability and effectiveness of pulsating water jet technology in potential orthopedic procedures. Additionally, further research will explore the use of self-resonating nozzles [22,23] or devices operating at different frequencies to minimize the size and complexity of handheld devices.

4. Conclusions

This study has demonstrated the enhanced effectiveness of an extended nozzle design in the erosion of bone cement using a pulsating water jet at a pressure of 15 MPa. By comparing the standard nozzle with a 100 mm extended nozzle both with diameter 3 mm, the research has addressed the critical need for optimizing bone cement removal techniques, which are essential for various medical applications, including revision surgeries. The design of experiments approach allowed for a thorough analysis of key parameters such as maximal depth, groove width, and volume rate. The following findings clearly indicate that the extended nozzle significantly improves the erosion process:

- The use of both nozzles shows a similar erosion development over time, with a noticeable offset for the nozzle with an extended shaft.
- The width of the cutting gap, along with variations in its values, indicates a concentrated removal of material, characterized by relatively sharp transitions, enabling precise guidance.
- It is still necessary to determine how the number of passes over the same area could affect the results.
- The next step is to verify whether the disintegration of the bone cement works in a submerged condition using different frequency in order to minimize the sonotrode and thus entire whole device, or to use self-excited nozzles.

Author Contributions

Conceptualization, A.N. and S.H.; methodology, A.N.; software, A.M.; validation, A.N., S.H.; formal analysis, A.N.; investigation, A.N.; resources, S.H.; data curation, A.N.; writing—original draft preparation, S.H.; writing—review and editing, A.N., S.H.; visualization, A.N., S.H.; supervision, S.H.;

project administration, S.H.; funding acquisition, S.H. All authors have read and agreed to the published version of the manuscript.

Funding

Please add: This study was supported by the Slovak Research and Development Agency under Contract No. APVV-22-0391 and Slovak Grant Agency 1/0377/22

Data Availability Statement

Data are available based on the request of the authors.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgement

The authors are grateful for the performance of the experiments at the Institute of Geonics of the CAS, v.v.i, Ostrava – Poruba, namely to Dr Josef Foldyna, for the permission to perform the experiments using Pulsating Water Jet Technology. The experiments were conducted at the Institute of Geonics of the Czech Academy of Sciences, Ostrava-Poruba, Czech Republic, with the support of the Institute of Clean Technologies for Mining and Utilisation of Raw Materials for Energy Use – Sustainability Program, Reg. No. LO1406 financed by Ministry of Education, Youth, and Sports, of the Czech Republic, and with the support for the long-term conceptual development of the research institution RVO: 68145535.

References

[1] den Dunnen, S., Dankelman, J., Kerkhoffs, G. M. M. J., & Tuijthof, G. J. M. (2016). How do jet time, pressure and bone volume fraction influence the drilling depth when waterjet drilling in porcine bone? Journal of the Mechanical Behavior of Biomedical Materials, 62, 495–503. https://doi.org/10.1016/j.jmbbm.2016.05.030

[2] Kavanagh, B. F., Ilstrup, D. M., & Fitzgerald, J. R. H. (1985). Revision total hip arthroplasty. The Journal of Bone and Joint Surgery. American Volume, 67(4), 517-526.

[3] Porsch, M., & Schmidt, J. (2001). Cement removal with an endoscopically controlled ballistically driven chiselling system. A new device for cement removal and preliminary clinical results. Archives of Orthopaedic and Trauma Surgery, 121(5), 274-277. https://doi.org/10.1007/s004020000233

[4] Sherk, H. H., Lane, G., Rhodes, A., Black, J., H.H., S., G., L., A., R., & J., B. (1995). Carbon dioxide laser removal of polymethylmethacrylate. Clinical Orthopaedics and Related Research, 310, 67-71.

[5] Zimmer, M., Klöbl, R., De Toma, G., Jansson, V., Refior, H. J., Heimkes, B., & Kühne, J. H. (1992). Bone-cement removal with the excimer laser in revision arthroplasty. Archives of Orthopaedic and Trauma Surgery, 112(1), 15-17. https://doi.org/10.1007/BF00431037

[6] Foldyna, J. (2011). Use of acoustic waves for pulsating water jet generation. Acoust. Waves-Microdevices Helioseismology, 14, 323-342. https://doi.org/10.5772/18862

[7] Honl, M., Rentzsch, R., Müller, G., Brandt, C., Bluhm, A., Hille, E., Louis, H., & Morlock, M. (2000). The use of water?jetting technology in prostheses revision surgery-First results of parameter studies on bone and bone cement. Journal of Biomedical Materials Research Part A, 53(6), 781-790. https://doi.org/10.1002/1097-4636(2000)53:6<781::AID-JBM20>3.0.CO;2-G

[8] Honl, M., Schwieger, K., Carrero, V., Rentzsch, R., Dierk, O., Dries, S., ... & Morlock, M. (2003). The pulsed water jet for selective removal of bone cement during revision arthroplasty. Biomedizinische Technik. Biomedical engineering, 48(10), 275-280. https://doi.org/10.1515/bmte.2003.48.10.275

[9] Hloch, S., Foldyna, J., Pude, F., Kloc, J., Zelenak, M., Hvizdos, P., ... & Mihalcinova, E. (2015). Experimental in-vitro bone cements disintegration with ultrasonic pulsating water jet for revision arthroplasty. Tehnički vjesnik, 22(6), 1609-1615. https://doi.org/10.17559/TV-20150822145550

[10] Saha, S., & Pal, S. (1984). Mechanical properties of bone cement: a review. Journal of biomedical materials research, 18(4), 435-462. https://doi.org/10.1002/jbm.820180411

[11] Hloch, S., Foldyna, J., Sitek, L., Zeleňák, M., Hlaváček, P., Hvizdoš, P., Kľoc, J., Monka, P., Monková, K., Kozak, D., Magurová, D., Kl'oc, J., Monka, P., Monková, K., Kozak, D., & Magurová, D. (2017). Disintegration of bone cement by continuous and pulsating water jet. Technical Gazette, 3651(4), 593-598.

[12] Hloch, S., Nag, A., Pude, F., Foldyna, J., & Zeleňák, M. (2019). On-line measurement and monitoring of pulsating saline and water jet disintegration of bone cement with frequency 20 kHz. Measurement, 147, 106828. https://doi.org/10.1016/j.measurement.2019.07.056

[13] Nag, A., Hloch, S., Dixit, A. R., & Pude, F. (2020). Utilization of ultrasonically forced pulsating water jet decaying for bone cement removal. International Journal of Advanced Manufacturing Technology. https://doi.org/10.1007/s00170-020-05892-9

[14] Nag, A., Dixit, A. R., Petrů, J., Váňová, P., Konečná, K., & Hloch, S. (2022). Maximization of wear rates through effective configuration of standoff distance and hydraulic parameters in ultrasonic pulsating water jet. Facta Universitatis, Series: Mechanical Engineering. https://doi.org/10.22190/FUME220523045N

[15] Hvizdoš, P., Jakubéczyová, D., Hloch, S., Kľoc, J., Balko, J., & Monka, P. (2014). Local mechanical properties of various bone cements. Key Engineering Materials, 592, 382-385. https://doi.org/10.4028/www.scientific.net/KEM.592-593.382

[16] Hloch, S., Srivastava, M., Nag, A., Muller, M., Hromasová, M., Svobodová, J., Kruml, T., & Chlupová, A. (2020). Effect of pressure of pulsating water jet moving along stair trajectory on erosion depth, surface morphology and microhardness. Wear, 452, 203278. https://doi.org/10.1016/j.wear.2020.203278

[17] Nag, A., Hloch, S., Dixit, A. R., & Pude, F. (2020). Utilization of ultrasonically forced pulsating water jet decaying for bone cement removal. The International Journal of Advanced Manufacturing Technology, 110, 829-840. https://doi.org/10.1007/s00170-020-05892-9

[18] Nag, A., Stolárik, G., Svehla, B., & Hloch, S. (2021). Effect of water flow rate on operating frequency and power during acoustic chamber tuning. In Advances in Manufacturing Engineering and Materials II: Proceedings of the International Conference on Manufacturing Engineering and Materials (ICMEM 2020), 21–25 June, 2021, Nový Smokovec, Slovakia (pp. 142-154). Springer International Publishing. https://doi.org/10.1007/978-3-030-71956-2_13

[19] Srivastava, M., Nag, A., Chattopadhyaya, S., & Hloch, S. (2020). Standoff distance in ultrasonic pulsating water jet. Materials, 14(1), 88. https://doi.org/10.3390/ma14010088

[20] Nag, A., Hvizdos, P., Dixit, A. R., Petrů, J., & Hloch, S. (2021). Influence of the frequency and flow rate of a pulsating water jet on the wear damage of tantalum. Wear, 477, 203893. https://doi.org/10.1016/j.wear.2021.203893

[21] Hloch, S., Svobodová, J., Srivastava, A. K., Srivastava, M., Poloprudský, J., & Nag, A. (2024). Submerged pulsating water jet erosion of ductile material. Wear, 538–539. https://doi.org/10.1016/j.wear.2024.205243

[22] Szada-Borzyszkowska, M., Kacalak, W., Banaszek, K., Borkowski, P. J., & Szada-Borzyszkowski, W. (2023). Analysis of the pulsating properties of a high-pressure water jet generated in a self-excited head for erosion processing. Archives of Civil and Mechanical Engineering, 23(4). https://doi.org/10.1007/s43452-023-00769-6

[23] Szada-Borzyszkowska, M., Kacalak, W., Banaszek, K., Pude, F., Perec, A., Wegener, K., & Królczyk, G. (2024). Assessment of the effectiveness of high-pressure water jet machining generated using self-excited pulsating heads. The International Journal of Advanced Manufacturing Technology, 133(9), 5029-5051. https://doi.org/10.1007/s00170-024-14040-6