Jurnal Tribologi 38 (2023) 19-28

MYTRIBOS Malaysian Tribology Society

Jurnal Tribologi

Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Utilization of Taguchi method in screening significant factors affecting spray droplets in minimum quantity lubricant using computational fluid dynamic

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KEYWORDS

MQL
CFD
Taguchi method
Spray droplets

ABSTRACT

Research is still in progress to study the effectiveness of Minimum quantity lubricant (MQL), as well as to improve the current MQL systems. This computational fluid dynamic (CFD) simulation study using Ansys Fluent focused on investigating the factors affecting the characteristic spray in the current MQL systems by employing Taguchi method. For analysis regarding the droplet size at the nozzle exit, the factors under investigation were delivery method, inner surface roughness of the nozzle, cutting fluid material, mass flow rate and air pressure using volume of fluid (VOF) model to discrete phase model (DPM). Then the droplet size is further analyzed at the cutting zone with the consideration of factors such as delivery method, number of nozzles, application angle, stand off distance and cutting fluid material using DPM. This study revealed that only delivery method was significant using VOF-to-DPM model affecting the diameter of the droplet produced within this range of levels of factors, while delivery method and cutting fluid materials were significant using DPM.

Received 27 July 2022; received in revised form 29 November 2022; accepted 3 March 2023.
To cite this article: Nor Hamran et al. (2023). Utilization of Taguchi method in screening significant factors affecting spray droplets in minimum quantity lubricant using computational fluid dynamic. Jurnal Tribologi 38, pp.19-28.

1.0 INTRODUCTION

Machining is one of the most important processes in manufacturing industries, especially in relation to the automotive and aerospace industries. Flood cooling is still traditionally and widely used to improve the machinability of metal cutting. However, this method consumes a large amount of cutting fluid, which needs to be treated, and has a negative effect on the environment (Khan and Dhar, 2006). As a result of this, minimum quantity lubricant (MQL) is one of the options to the machinist to create a better working environment. The advantages of MQL include being an environmentally friendly solution, the oil being nontoxic, is biodegradable and that it can be manufactured from renewable raw materials compared with flooding coolant technique (Ezugwu et. al, 2017). According to Hamran et al. (2020) the minimum quantity lubrication advancements outperform when machining in MQL conditions and will generate better surface quality, while lowering tool wear and cutting force. According to Ezugwu (2005), minimum quantity cutting fluid application is a viable alternative to improving the characteristics of the tribological processes present at the tool–workpiece interface in order to improve the machinability of materials and, at the same time, can eliminate environmental damage while minimizing some problems associated with the health and safety of operators. Furthermore, the MQL technique is considered a 'clean cutting process', since it consists of applying a small amount of the highly efficient coolant/lubricant which is pulverized in a compressed air stream to the cutting zone at a flow rate often below 200 mL h^{-1} compared with 120,000–720,000 mL h^{-1} (2–12 L min^{-1}) generally employed in conventional coolant flow.

In MQL, an improvement in machining performance can be achieved when a sufficient amount of cutting fluid accesses the chip–tool interface (Ezugwu, 2005; Yazid et.al, 2013). MQL cooling provides adequate lubrication at the cutting zone, which reduces the friction at the chip/tool and tool/workpiece interfaces, hence further reducing temperature at the cutting zone (Okafor, 2006). There are many factors which will affect the characteristics of the droplets in the current MQL system such as air pressure, flow rate of compressed air, liquid velocity, liquid mass-flow, nozzle surface roughness, nozzle angle, nozzle distance, etc. Shiva Sai et al. (2015) and Verma et al. (2017) conducted a numerical study and found that the average diameter of the outer droplet of the atomizing air and the median diameter of the droplet decrease significantly with the increase of the air pressure. Furthermore, it had also been reported that the air pressure is more important than the fluid flow rate, whereby higher flow rate or air pressure increases the wettability area, which helps to reduce the temperature of the cutting area.

The computational fluid dynamics (CFD) method has become a powerful tool to model the two-phase flow field such as the numerical model of paint atomization of air spraying using the volume-of-fluid method and large eddy simulation (Chen et. al 2021). CFD also is utilized in drug delivery (Fung et. al, 2012) and other areas (Liu et. al, 2011) using the methods available according to the purpose of the study.

In this study CFD simulation was conducted to investigate the factors affecting the characteristic spray in the current MQL systems using VOF-to-DPM model for analysis of the droplet size at the nozzle exit, and DPM model to analyze the droplet size at the cutting zone.

2.0 METHODOLOGY

CFD spray simulations using Ansys Fluent were carried out utilizing multiphase flow modelling of volume of fluid (VOF) model to discrete phase model (DPM) for analysis of the droplet size at nozzle exit and DPM at the cutting zone.

In this study the factors and levels used in the simulation were based on the previous work carried out. From the previous findings (Shiva Sai et al. 2015; Verma et al. 2017), it was decided that the eight factors which should be further studied affecting the droplet size were as shown in Table 1. Table 2 shows the randomized L18 ($2^1 \times 3^7$) simulation runs for all the combination of factors and levels. For each run, five factors, namely delivery method, inner surface roughness of the nozzle (SR), cutting fluid material, mass flow rate and air pressure, were investigated for VOF-to-DPM simulations, while for DPM simulations, another 5 factors were investigated, namely, delivery method, number of nozzles, application angle, stand off distance and cutting fluid material.

Table 1: Factors and levels used in the simulation study based on Taguchi method L18 ($2^1 \times 3^7$).

Factors	**Levels**		
	1	**2**	**3**
Delivery method	Conventional	Ejector	-
No. of Nozzles	1	2	3
SR (μm)	5.3	6.8	8.3
Application angle (degree)	35	45	55
Stand off distance (mm)	31	40	49
Cutting Fluid material	Water	Acculube LB2000	Canola Oil
Mass flow rate (ml/h)	120	150	180
Air pressure (MPa)	0.4	0.5	0.6

2.0 RESULTS AND DISCUSSION

Table 3 shows the results obtained for the particle diameter or the droplet size from the CFD simulation using Ansys Fluent using VOF-to-DPM and DPM. The diameter of the droplets at the nozzle exit were between 7.160e-5 m (71.6 μm) to 1.494e-4 m (149.4 μm) for VOF-to-DPM. The smallest droplet diameter was obtained using conventional delivery method, one nozzle, surface roughness of 5.3 μm, using water as cutting fluid, volume flow rate of 120 ml/hour and 0.4 MPa air pressure. Whereas for droplets at the cutting zone using DPM model, the diameter of the droplets obtained were in the range of 1.91e-6 m (1.91 μm) to 1.494e-4 m (149.4 μm). Smaller and wider ranges of diameters were obtained at the cutting zone, compared at the nozzle exit. According to Liu et a. (2011) use of the VOF method attenuates the influence of the pulsating interface and results in a more accurate representation of the experimental test case during study of three-dimensional (3-D) unsteady incompressible and non-cavitating flow in a radial flow pump during the rapid stopping period.

Figure 1 shows the SN ratios plot for “the smaller the better” of particle diameter from the VOF-to-DPM simulation results. It was shown that the delivery method was the most significant factor affecting the particle diameter. However, other factors were not significant, or the effect was negligible as supported by the analysis of variance (ANOVA) in Table 5.

From the SN ratios plot in Figure 1, the recommended factors and levels to obtain the smallest particle diameter were conventional delivery method, two nozzles, 5.3 µm surface roughness of the nozzle, using water as the cutting fluid, 120 ml/hour of volume flow rate and 0.4 MPa air pressure.

Table 2: Randomized runs with assigned levels for each factor.

Run	Delivery method	No. of Nozzles	SR (µm)	Application angle (degree)	Stand off distance (mm)	Cutting Fluid material	Volume flow rate (ml/h)	Air pressure (MPa)
1	Conventional	1	5.3	35	31	Water	120	0.4
2	Conventional	1	6.8	45	40	LB2000	150	0.5
3	Conventional	1	8.3	55	49	Canola Oil	180	0.6
4	Conventional	2	5.3	35	40	LB2000	180	0.6
5	Conventional	2	6.8	45	49	Canola Oil	120	0.4
6	Conventional	2	8.3	55	31	Water	150	0.5
7	Conventional	3	5.3	45	31	Canola Oil	150	0.6
8	Conventional	3	6.8	55	40	Water	180	0.4
9	Conventional	3	8.3	35	49	LB2000	120	0.5
10	Ejector	1	5.3	55	49	LB2000	150	0.4
11	Ejector	1	6.8	35	31	Canola Oil	180	0.5
12	Ejector	1	8.3	45	40	Water	120	0.6
13	Ejector	2	5.3	45	49	Water	180	0.5
14	Ejector	2	6.8	55	31	LB2000	120	0.6
15	Ejector	2	8.3	35	40	Canola Oil	150	0.4
16	Ejector	3	5.3	55	40	Canola Oil	120	0.5
17	Ejector	3	6.8	35	49	Water	150	0.6
18	Ejector	3	8.3	45	31	LB2000	180	0.4

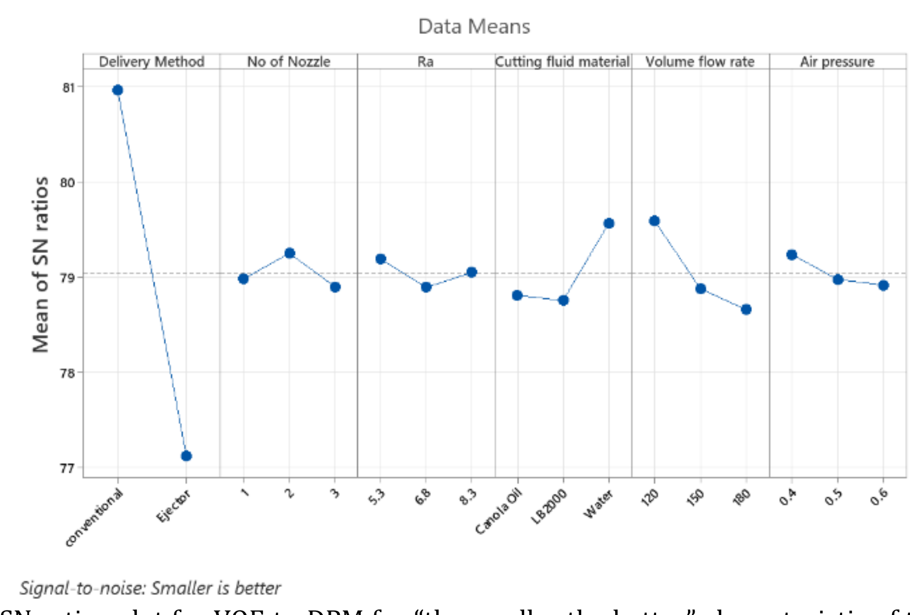


Figure 1 SN ratios plot for VOF-to-DPM for "the smaller the better" characteristic of the particle diameter.

Table 3: Results for the CFD simulation.

Run	Delivery method	No. of Nozzles	SR (µm)	Application angle (deg.)	Stand off dist. (mm)	Cutting Fluid mat.	Volume flow rate (ml/h)	Air press. (MPa)	VOF-to-DPM (nozzle exit)	DPM (cutting zone)
									Particle dia. (m)	Particle dia. (m)
1	Conventional	1	5.3	35	31	Water	120	0.4	7.160e-5	9.41e-6
2	Conventional	1	6.8	45	40	LB2000	150	0.5	1.063e-4	1.23e-5
3	Conventional	1	8.3	55	49	Canola Oil	180	0.6	9.865e-5	1.75e-5
4	Conventional	2	5.3	35	40	LB2000	180	0.6	9.100e-5	1.58e-5
5	Conventional	2	6.8	45	49	Canola Oil	120	0.4	9.028e-5	1.83e-5
6	Conventional	2	8.3	55	31	Water	150	0.5	7.593e-5	7.05e-6
7	Conventional	3	5.3	45	31	Canola Oil	150	0.6	9.806e-5	2.67e-5
8	Conventional	3	6.8	55	40	Water	180	0.4	8.877e-5	9.35e-6
9	Conventional	3	8.3	35	49	LB2000	120	0.5	9.084e-5	1.36e-5
10	Ejector	1	5.3	55	49	LB2000	150	0.4	1.405e-4	5.89e-6
11	Ejector	1	6.8	35	31	Canola Oil	180	0.5	1.419e-4	7.54e-6
12	Ejector	1	8.3	45	40	Water	120	0.6	1.350e-4	1.91e-6
13	Ejector	2	5.3	45	49	Water	180	0.5	1.494e-4	2.10e-6
14	Ejector	2	6.8	55	31	LB2000	120	0.6	1.282e-4	4.09e-6
15	Ejector	2	8.3	35	40	Canola Oil	150	0.4	1.406e-4	1.01e-5
16	Ejector	3	5.3	55	40	Canola Oil	120	0.5	1.306e-4	8.28e-6
17	Ejector	3	6.8	35	49	Water	150	0.6	1.387e-4	1.7e-6
18	Ejector	3	8.3	45	31	LB2000	180	0.4	1.494e-4	8.01e-6

Table 4 Response Table for Signal to Noise Ratios for VOF-to-DPM for “the smaller the better” characteristic of the particle diameter.

Level	Delivery Method	No. of Nozzles	Ra	Cutting fluid material	Volume flow rate	Air pressure
1	80.96	78.98	79.19	78.81	79.59	79.24
2	77.13	79.25	78.89	78.75	78.88	78.98
3		78.90	79.05	79.57	78.66	78.92
Delta	3.83	0.35	0.30	0.81	0.93	0.32
Rank	1	4	6	3	2	5

Table 4 shows the response table for Signal to Noise Ratios for VOF-to-DPM for “the smaller the better” characteristic of the particle diameter at the nozzle exit. The rank of the factors affecting the particle diameter were the delivery method, number of nozzles, surface roughness, cutting fluid material, volume flow rate and air pressure.

The ANOVA performed using Minitab software has been shown in Table 5 indicated that delivery method was the most significant factor affecting the particle diameter at the nozzle exit and the model was adequate with R-sq of 95%. The zero values for Adj SS and Adj MS indicate that these values are too small to be displayed. This result was consistent with the SN ratios plot.

Table 5 Analysis of Variance (ANOVA) of VOF-to-DPM for the particle diameter and model summary

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Delivery Method	1	0.000000	0.000000	106.58	0.000
No. of Nozzles	2	0.000000	0.000000	0.21	0.813
Ra	2	0.000000	0.000000	0.07	0.930
Cutting fluid material	2	0.000000	0.000000	1.06	0.405
Volume flow rate	2	0.000000	0.000000	2.31	0.180
Air pressure	2	0.000000	0.000000	0.08	0.925
Error	6	0.000000	0.000000		
Total	17	0.000000			

Model Summary

S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
0.0000101	95.00%	85.84%	55.02%

The factors affecting the particle diameter at the cutting zone using DPM was analyzed as shown in Figure 2. Figure 2 is the SN ratio for particle diameter using DPM at the cutting zone which revealed that the delivery method and cutting fluids material significantly affected the droplet size. Table 6 shows that the cutting fluid was ranked 1, followed by delivery method, air pressure, stand off distance, surface roughness, number of nozzles, volume flow rate and application angle. From Figure 2, it is recommended to obtain small particle diameter by utilizing ejector for delivery method, one nozzle, 6.8 µm surface roughness of the nozzle, 45-degree application angle, 49 mm stand off distance, water as cutting fluid, low volume flow rate of 120 ml/hour and high air pressure of 0.6 MPa.

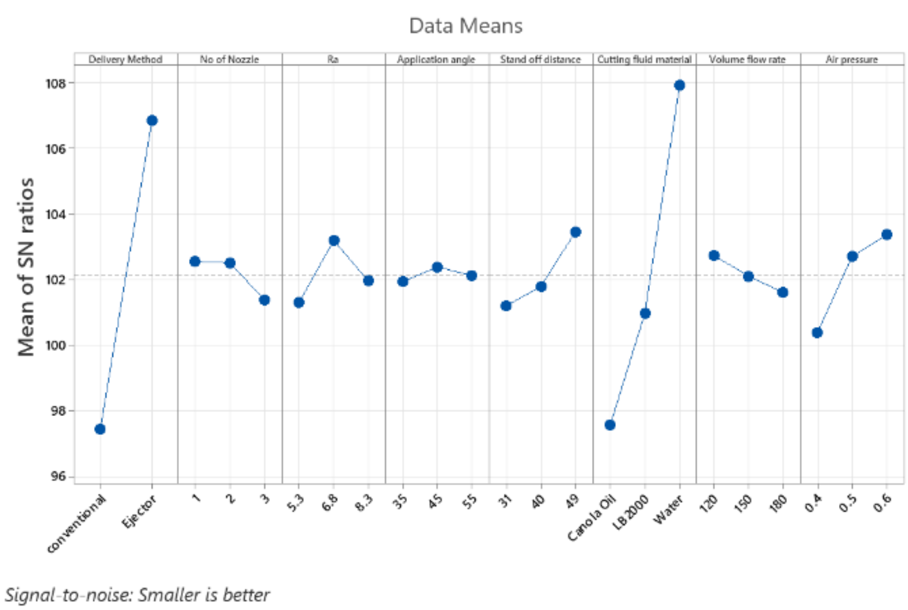


Figure 2: SN ratio for particle diameter at the cutting zone using DPM.

Table 6: Response Table for Signal to Noise Ratios for DPM.

Level	Delivery Method	No. of Nozzles	Ra	Application angle	Stand off distance	Cutting fluid material	Volume flow rate	Air pressure
1	97.45	102.55	101.30	101.94	101.20	97.56	102.73	100.38
2	106.85	102.51	103.19	102.38	101.79	100.97	102.10	102.70
3		101.39	101.95	102.13	103.46	107.91	101.61	103.36
Delta	9.40	1.16	1.89	0.44	2.26	10.35	1.12	2.98
Rank	2	6	5	8	4	1	7	3

ANOVA performed using a Minitab software as shown in Table 7 indicated that only delivery method and cutting fluid materials significantly affected the particle diameter at the cutting zone, where the model was adequate at R-sq. 99.18 %. ANOVA results were consistent with the SN ratios plot in Figure 2. The zero values for Adj SS and Adj MS indicate that these values are too small to be displayed.

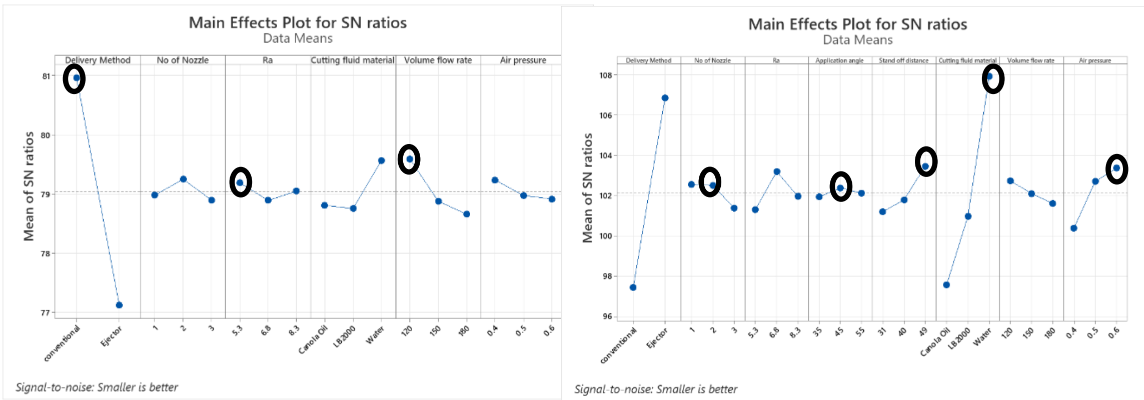
Simultaneous optimization was carried out, as shown in Figure 3, to select the optimum condition for obtaining small particle diameter at the nozzle exit and the cutting zone. In real situations, it is suggested to obtain small particle diameter at the nozzle exit and cutting zone using conventional delivery, one nozzle, 45-degree application angle, 49 mm stand off distance, water as cutting fluid, 120 ml/hr flow rate and air pressure 0.6 MPa. However, since air pressure is not significant, in order to save energy, one can choose to utilize 0.4 MPa.

Table 7: Analysis of Variance of particle diameter for DPM and model summary.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Delivery Method	1	0.000000	0.000000	119.78	0.008
No. of Nozzles	2	0.000000	0.000000	2.63	0.276
Ra	2	0.000000	0.000000	3.21	0.238
Application angle	2	0.000000	0.000000	4.22	0.192
Stand off distance	2	0.000000	0.000000	0.38	0.724
Cutting fluid material	2	0.000000	0.000000	45.01	0.022
Volume flow rate	2	0.000000	0.000000	0.93	0.518
Air pressure	2	0.000000	0.000000	4.00	0.200
Error	2	0.000000	0.000000		
Total	17	0.000000			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0000017	99.18%	92.99%	33.20%



(a) SN ratio for VOF to DPM (nozzle exit) (b) SN ratio for DPM (cutting zone)

Figure 3: (a) and (b) Simultaneous optimization to determine the optimum condition for particle diameter at the nozzle exit and the cutting zone.

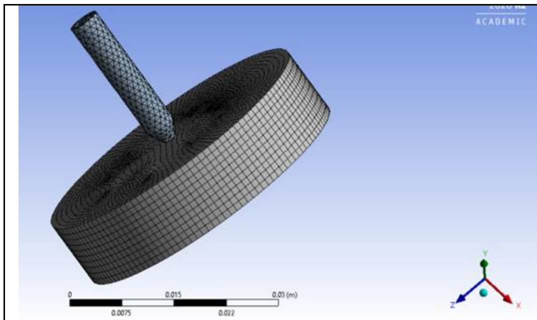
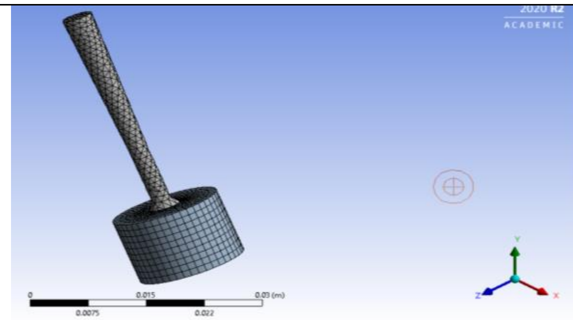
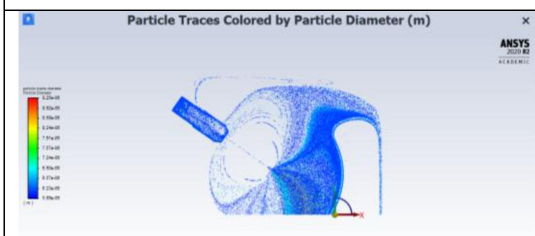
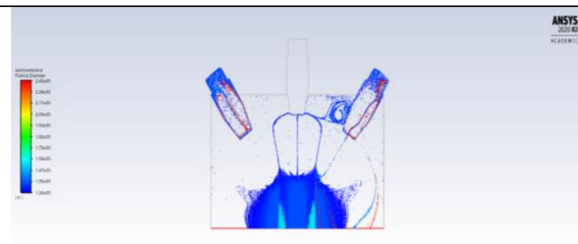
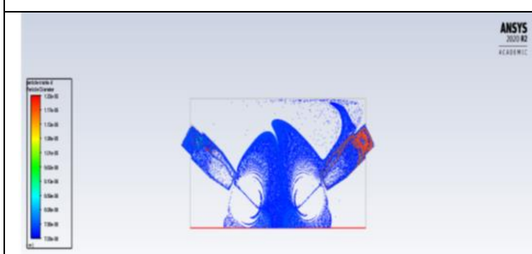
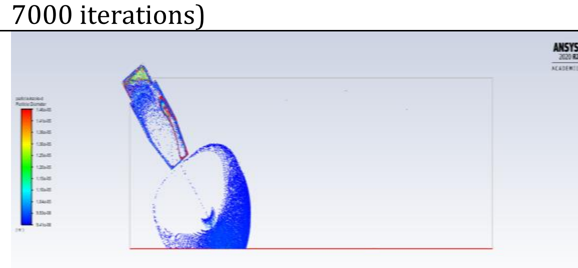
Table 8 shows the selected CFD simulation models and results obtained in the present study. It was clearly shown that dispersion of the droplets is strongly influenced by the number of nozzles applied. As shown, the droplets will less disperse with three nozzles as compared with the two and one nozzle. However, the size of the particle is not strongly influenced by the number of nozzles used.

CONCLUSIONS

The following can be concluded from the simulation analysis performed:

1. The SN ratios plot for “the smaller the better” of particle diameter from the VOF-to-DPM simulation results revealed that the delivery method was the most significant factor affecting the particle diameter at the nozzle exit. However, other factors were not significant.
2. The SN ratio for particle diameter using DPM at the cutting zone revealed that the delivery method and cutting fluids material significantly affected the droplet size.
3. Simultaneous optimization performed showed that it is possible to obtain smaller particle diameter at the nozzle exit and cutting zone by using conventional delivery, one nozzle, 45-degree application angle, 49 mm stand off distance, water as cutting fluid, 120 ml/hr flow rate and air pressure of 0.6 MPa.

Table 8: Selected CFD simulation models and results.

 Meshing for 3D ejector nozzle (Run 10)	 Meshing for 3D conventional nozzle (Run 9)
 Results for Run 10 ((2d, dpm) = pathline, v, x, d 2500 iterations)	 Results for Run 9 ((2d, dpm) = pathline, v, x, d 7000 iterations)
 Results for Run 6 ((2d, dpm) = pathline, v, x, d 3500 iterations)	 Results for Run 1 ((2d, dpm) = pathline, v, x, d 3000 iterations)

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support and facility from Universiti Kebangsaan Malaysia under grant GUP-2022-018.

REFERENCES

Chen, Y., Chen, S., Chen, W., Hu, J., & Jiang, J. (2021). An Atomization Model of Air Spraying Using the Volume-of-Fluid Method and Large Eddy Simulation. Coatings, 11, 1400. https://doi.org/10.3390/coatings11111400

Ezugwu, E.O., 2005. Key improvements in the machining of difficult-to-cut aerospace superalloys. International Journal of Machine Tools and Manufacture., 45(12-13): 1353-1367

Ezugwu, O.E., Da Silva, R.B., Sales, W.F., Machado, A.R. (2017). Overview of the Machining of Titanium Alloys. Encyclopedia of Sustainable Technologies, Elsevier: 487-506, ISBN 9780128047927.

Fung, M.C., Kiao, I., Yang, W., & Tu,J. (2012). CFD Modeling of Spray Atomization for a Nasal Spray Device. Aerosol Science and Technology, 46:1219–1226.

Hamran, N. N. N., Ghani, J. A., Ramli, R., & Haron, C. H. C. (2020). A review on recent development of minimum quantity lubrication for sustainable machining. Journal of Cleaner Production, 268, 122165. https://doi.org/10.1016/j.jclepro.2020.122165

Khan, M. M. A. & Dhar, N. R. (2006). Performance evaluation of minimum quantity lubrication by vegetable oil in terms of cutting force, cutting zone temperature, tool wear, job dimension and surface finish in turning AISI-1060 steel, J. Zhejiang Univ SCIENCE A, 7(11):1790-1799.

Liu, J., Li, Z., Wang, L., & Jiao, L. (2011). Numerical Simulation of the Transient Flow in a Radial Flow Pump during Stopping Period, Journal of Fluids Engineering 133(11):111101. DOI: 10.1115/

Okafor, A.C. (2020). Chapter 5 - Cooling and machining strategies for high speed milling of titanium and nickel super alloys, High Speed Machining, Academic Press: 127-161, ISBN 9780128150207

Shiva Sai, S., Manojkumar, K., & Ghosh, A. (2015). Assessment of spray quality from an external mix nozzle and its impact on SQL grinding performance. International Journal of Machine Tools and Manufacture, 89, 132–141. https://doi.org/10.1016/j.ijmachtools.2014.10.004

Verma, N., ManojKumar, K., & Ghosh, A. (2017). Characteristics of aerosol produced by an internal-mix nozzle and its influence on force, residual stress and surface finish in SQCL grinding. Journal of Materials Processing Technology, 240, 223–232. https://doi.org/10.1016/j.jmatprotec.2016.09.014

Yazid, M.Z.A., Che Haron, C.H., Ghani, J.A., Ibrahim, G.A., Said, A.Y.M. (2013). Tool Life Modeling of Inconel 718 under MQL with Coated Carbide Tool, Journal of Applied Sciences Research, 9(4): 2591-2597.