Study of nozzle distance and oil flow rate effects on the droplets size of minimum quantity lubrication

K L J Kiat¹, N I K Ismail¹, N Rosli¹* and E A Alias²
¹Faculty of Manufacturing & Mechatronics Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
²Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

*Email: nurrinarosli@ump.edu.my

Abstract. Minimum Quantity Lubrication (MQL) machining process has been widely applied to replace the traditional lubrication and cooling method that brings various drawbacks involving environment, human’s health and manufacturing cost. Although the amount of oil being used in the MQL machining process is extremely little, oil mist formed in the cutting zone still can successfully prolong the cutting tool life and improve the surface quality of workpiece. However, the size of lubricant oil droplets must be fundamentally investigated to clarify the lubricating mechanism in the cutting zone. This paper is aimed to study the droplets size of lubricant oil delivered by a commercial MQL generator. Experiments were conducted to study the effects of vertical nozzle distance and lubricant oil flow rate to the droplets count and size. As a result, the smallest diameter of droplets were found to range in between 10 µm - 22 µm. With increasing vertical nozzle distance, the diameter became larger due to the increasing dominancy of air flow that influences the movement of droplets. With increasing oil flow rate, the droplets tend to merge together, forming multiple larger size of droplets. The size of lubricant oil droplets did not significantly change when varying the vertical nozzle distance starting from 35 mm and oil flow rate starting from 18 mL/h. Finally, the control dial to adjust oil flow rate when using an MQL generator with internal feeding system application must be handled properly to ensure precise amount of oil mist successfully being delivered to the cutting zone.

Keywords: nozzle, minimum quantity lubrication, machining

1. Introduction
Machining process is the most important operation in developing manufacturing industry across the globe. Monitoring the cutting process is a crucial one to ensure the manufactured products are made in desired size and shape. During the cutting process, the resistance to relative motion between cutting tool and workpiece which is commonly called as friction raise the temperature around the cutting zone due to the kinetic-to-heat energy conversion. Thus, the sharpness of cutting tool is declining. In turn, the usage of excessive cutting power increases while the surface of the workpiece becomes less smooth. Here, the usage of cutting fluids is vitally in demand to sustain the manufacturing performance. Since then, cutting fluids has been widely utilized in manufacturing operation to enhance the tribological properties of workpiece and cutting tool. The fluid is mainly functioned to lubricate and cool the cutting
zone where temperature rise occurs as a result of the frictional effects arises in the workpiece and cutting tool interfaces. Cutting fluids such as petroleum-based oils are non-biodegradable [1] and hence inappropriate disposal of this oils has leads to environmental issues such as water and soil pollution [2]. Moreover, this oils are also being reported to be harmful and jeopardize the health of workers as they experienced skin and breathing problems due to continuous exposure in high volume [3]. The cancer breeding has also become the major concern if the oils being used were not well-refined beforehand. Alternatively, vegetable oils are increasingly being used and even reportedly can produce a better performance [4].

Apart from all the issues being raised, inevitable matters to date are the rising of manufacturing cost resulted from the increasing demand of the cutting fluids especially the neat oils as lubricant. It has been reported that 20 % out of total production cost is merely sourced from the usage of lubricant oils [2]. The cost increment can be attributed to the cost of storage system, labour cost for oils monitoring and maintenance procedure, purchase cost as biodegradable oils are much more expensive, water purifying cost [5] and drying cost of wet chips for recycling process [6].

Therefore, the effort to reduce the usage of lubricant oils in manufacturing operation has been frequently debated despite the requirement to enhance the quality of manufacturing products as well as cut down the cost of manufacturing operation is continuously in demand. In order to replace the traditional lubrication and cooling method due to the problem mentioned above, Near-Dry Machining (NDM) or better known as Minimum Quantity Lubrication (MQL) has been introduced. According to Boswell et al. [7], the word “Minimum Quantity Lubrication” has been initially used by Weck and Koch [8] decades ago through their study of bearings lubrication. Since then, greater attention has been addressed to explore the implementation of MQL in the machining operation.

MQL became popular by the usage of extremely little amount of lubricant oil, typically in 50 to 500 mL/h [9]. With this amount of oil being used, additional cost of disposal is needless [10] and thus the manufacturing cost can be cut down. Moreover, MQL is also considered as green manufacturing approach since it is human and environmental friendly [11]. The great performance of MQL in machining process has been strongly proven in various machining condition including drilling, milling, turning, grinding, tapping, reaming and grooving. Despite the limited amount of oil being used, oil mist formed in the cutting zone still can successfully prolong the cutting tool life and improve the surface quality of workpiece [12]. In drilling process, the implementation of MQL produced better quality of holes compared to flood cooling method [13]. Built-up edge formation at the cutting edge and adhesion of workpiece to the cutting tool have been also reduced in MQL drilling [14]. Crucial improvement has been observed to the surface roughness, cutting power and specific cutting force when MQL was utilized [15]. In milling process, tool wear and surface finish improvement has been achieved by the application of pulsed-jet MQL [16]. On the other hand, better cutting temperature, chip reduction coefficient, cutting forces, tool wear, surface finish, and dimensional deviation has been obtained in MQL turning process compared to the dry turning operation [17].

The lubricant oil from MQL generator basically delivered from the nozzle in tiny droplets of oil mist. This is where the volume of lubricant oil being consumed are always in little amount. In order to produce these tiny droplets, the atomization process between the oil and air supply of MQL generator plays an important role [18]. However, the atomization process taking place in the MQL generator presents in different mechanisms, depending on the type of feeding system.

Basiclly, there are two feeding systems i.e., external and internal. External feeding system employs lubricant storage tank where several tubes equipped with their own nozzles are attached to the tank. This external MQL system can be installed anywhere around the machine to facilitate the nozzle position for better penetration of lubricant oil to the cutting zone. This system also utilizes self-contained convertible air and lubricant flow to ensure steady oil supply throughout the operation. Moreover, the external feeding system is also more economical, convenient and practically suitable for all machining process such as sawing, milling, broaching, shaping, drilling and threading operations [19].

On the other hand, the oil mist in internal feeding system can be administered directly into the cutting zone. Spindle, tool revolver and tools internal cooling passage are used to deliver the lubricant oil.
Compared to external feeding system, dispersion for internal feeding system is unlikely to occur and feed nozzles are also needless for adjustment. In addition, proportion of oil and air can be calibrated by the control system of the MQL generator [20].

Although the MQL generator usually allows users to adjust the oil flow rate and air pressure for spray output manipulation, the configuration may be difficult for inexperienced users. Thus, excessive lubricant will adversely affect the chip formation and be wasted, whereas inadequate lubricant oils reduce the tool life. Moreover, although the oil mist of MQL has been proven to enhance the machining quality, the tiny droplets of oil mist also easily evaporates thus can weaken the lubrication effects during the machining process. Former studies have found that smaller diameter size of oil droplets will evaporate faster than that of larger diameter size [16]. Recent report [17] has revealed that oil mist was found to hardly penetrate the cutting zone due to the chip accumulation in between the cutting zone and inappropriate droplet size of oil. An appropriate combination of nozzle distance, pressurized air and oil mist flow rate were also reported to help reducing the chip accumulation [18], [19].

Moreover, appropriate droplets size of oil was also proven to increase the penetration ability of the oil mist through the cutting zone. Since the surface roughness in between tool chip and tool work interfaces are relatively high, only oil with smaller droplets size can successfully passing through the cutting zone [11]. Hence, the size of lubricant oil droplets under MQL machining system must be fundamentally investigated to clarify the lubricating mechanism in the cutting zone. Nozzle angle, nozzle distance, oil flow rate and air pressure are examples of factors affecting the droplets size of lubricant oil [20]. A study of parametric optimization of MQL in turning of AISI 4340 using nano fluids [21] has been reported to observe the surface roughness by varying the pressure, flow rate and coolant type factors using the method of Taguchi and ANOVA analysis. From the ANOVA results, the flow rate of coolant was found to be the 2nd most contributing factor coming after the factor of cutting nano fluid coolant which gave the highest contribution to the results. Furthermore, another study using Taguchi optimization, S/N ratio and Anova analysis on machining under MQL with different variable [22] has found out that the flow rate operated in MQL generator appeared to be the 2nd most influencing parameter after the cutting speed.

Moreover, comparing different MQL conditions of the flow rate, speed and feed rate on the turning nickel based Nimonic 90 alloy, it was found that specific cutting energy decreased with pressure and flow rate increment [23]. Furthermore, the shear flow stress was found to reduce when a high pressure was applied during the MQL application. This is due to the number of droplets entering the contact zone at high pressure increases which in results in a better lubrication ability. Moreover, the frictional energy is observed to be halved when the flow rate increased from 50 ml/hour to 250 ml/hour as the wetting area increased when the volume of fluid increased in high flow rate. Furthermore, another study conducted for MQL drilling process [24] noticed that the attaching workpiece material on insert for MQL at the flow rate 15 ml/hour and 23 ml/hour can cause two little hills while there was only one little hill and whiter area which shows a higher wear on the substrate for air and MQL at the flow rate of 5 ml/hour. The whiter area was the results of higher temperature caused by the friction of the chip and inserts. This indicates that the higher flow rate conditions have a lower temperature as well as lower friction compared to the lower flow rate and air conditions.

Although there are quite a number of researcher exploring the investigation of MQL machining process, fundamental study merely focusing on the behaviour of lubricant oil droplets driven by the MQL generator are still need to be highlighted. This is of great importance area to discover the relationship between the machining performance and the behaviour of lubricant oil droplets behaviour. Moreover, since the operation mechanism of the MQL generator is comparatively complicated than that of conventional lubrication method, a proper handling of MQL generator also must be taken into account. Here, this paper is aimed to fundamentally investigate the effects of vertical nozzle distance and lubricant oil flow rate to the droplets counts and size of lubricant oil delivered by a MQL generator. The experiments were conducted to study the effects of vertical nozzle distance and lubricant oil flow rate to the droplets count and size. The images of lubricant oil droplets were captured by using a microscope and the droplets size were quantified by using ImageJ software.
2. Methodology

2.1 MQL Generator

Coolubricator™ from Unist Coolube® was used as the MQL generator to provide the MQL oil mist. This generator utilizes the internal feeding system with separated air and fluid control. It is equipped with a magnetic mount for it to be flexibly mounted anywhere on the machine. There are three adjustable knobs, i.e. cycle rate, pump stroke and air flow knobs. From the combination of these knobs adjustment, the form of oil mist spray can be customized based on the suitable lubrication urgency. It uses a standard 1-drop pump that provides a pump output of 0.03 mL lubricant oil per stroke. Table 1 shows the MQL generator specification.

| Specification                  | Value       |
|-------------------------------|-------------|
| Supply air pressure (bar)     | 4 – 7       |
| Air flow rate (ft.3/minute)   | 0 – 4       |
| Pulse generator frequency (pulses/minute) | 5 – 50   |
| Operating temperature range (˚C) | 0 – 50     |
| Storage temperature range (˚C) | -16 – 70   |
| Fluid reservoir capacity (mL) | 473 – 1893 |

The desired pump stroke for the experiment was firstly set from the configuration system of the MQL generator. The pump piston will then deliver a narrow conical spray pattern of lubricant oil mist through the nozzle tip. Atomization process to generate the lubricant oil mist occurs when the air surrounds the lubrication oil to disperse it to the cutting zone. The air supply can be adjusted to control the size of lubricant oil droplets. In this study, the amount of air supply was roughly adjusted as long as it can satisfactorily produce oil mist form of lubricant spray. The lubricant oil being employed was from Unist Coolube® 2210 which is a vegetable-based oil with dynamic viscosity of 18.5 cSt.

2.2 Experimental Setup and Procedure

The experimental setup in this study is illustrated in Figure 1. As a preliminary experiment, it is important to obtain a filter plate with suitable size of hole that able to produce a single lubricant oil droplet. Here, a filter plate with diameter of hole, d at 0.7 mm, 0.8 mm, 0.9 mm and 1.0 mm, respectively were fabricated by using PCB print circuit board carbide micro drill bits. The filter plate was attached on a holding tray mounted to the cutting tool of a milling machine. Thus, the filter plate can be move along with the cutting tool in the feed direction during the lubricant oil is being sprayed on it.

![Figure 1. Illustration of experimental setup.](image)
Upon experiment, the oil droplets from the nozzle passed through the filter plate and dropped onto a petri dish located on the machine worktable. Therefore, the overlap of multiple oil droplets at same location can be prevented. The images of lubricant oil droplets were then visualized by using a microscope connected to a personal computer. The images were then captured to quantify the droplets size by using ImageJ software. The droplets count categorized by its diameter was also obtained. A scale according to the microscope must be set beforehand to produce the scale bar for the image. Since there were no specification on the scale in the microscope, a ruler was used to determine the scale manually. The ruler was placed on the stage of the microscope under 4X magnification and the image of the ruler showing 1mm was captured simultaneously. The image was then measured on the Paint software to determine the length of the 1 mm in pixel unit.

The filter plate found to produce the smallest size of lubricant oil droplets was then selected for further analysis of oil droplets size affected by the parameters, i.e. vertical nozzle distance, L and lubricant oil flow rate, Q. Vertical nozzle distance, L is referred to the distance between nozzle tip to the petri dish. The smallest nozzle distance was manually set up in the beginning of the experiment by using a scale. The cutting tool mounted with the holding tray was then moved downward in z-axis to set the larger nozzle distance. Moreover, the distance between the nozzle tip and the filter plate was fixed at approximately 10 mm throughout the experiments.

On the other hand, the lubricant oil flow rate, Q can be controlled by adjusting the control dial of cycle rate. Specifically, air flow and pump stroke knobs were initially adjusted beforehand in order to obtain lubricant oil in mist form. After lubricant oil mist was successfully being produced, air flow and pump stroke knobs were fixed. Then, cycle rate knob was adjusted to the desired value of oil flow rate. Equation (1) shows the calculation of the lubricant oil flow rate based on the adjustment of cycle rate. Table 2 shows the experimental conditions set in this study. The experiments were conducted in 4 sets for each parameter.

\[ \text{Oil flow rate, } Q = \frac{60 \times 60}{60 \times \text{pumpstroke}} \times \text{pump output} \]  

Table 2. Experimental conditions.

| Machining Condition          | Value          |
|-----------------------------|----------------|
| Feed rate, \( V_f \) (mm/min) | 520            |
| Nozzle inner diameter (mm)  | 2              |
| Diameter of filter hole, \( d \) (mm) | 0.7, 0.8, 0.9, 1.0 |
| Oil flow rate, \( Q \) (mL/h)   | 9, 18, 27, 54  |
| Vertical nozzle distance, \( L \) (mm) | 30, 35, 40, 55 |

3. Results and Discussion

3.1 Preliminary Results – Selection of Filter Plate

Figure 2 shows the sample images of lubricant oil droplets visualized by the microscope under various cases of vertical nozzle distance and oil flow rate. As can be seen from the figure, multiple size of droplets were observed. For analysis, only the droplets with proper round shape were selected for the diameter measurement. Figure 3 shows the results of smallest diameter of lubricant oil droplets passing through various types of filter holes under 30 mm, 35 mm, 40 mm and 55 mm of vertical nozzle distance. The oil flow rate was fixed to 9 mL/h. For 35 mm, 40 mm and 55 mm of vertical nozzle distance, it is evident from the figure that the smallest diameter of lubricant oil was found to increase between 0.7 mm to 0.8 mm of filter hole but significantly decrease at 0.9 mm of filter hole before bouncing back upon
1.0 mm of filter hole. Meanwhile, for 30 mm of vertical nozzle distance, a weak increase of the smallest diameter of lubricant oil droplets was found between 0.7 mm and 0.9 mm of filter hole. The diameter size was then discovered to increase similarly back to its previous value upon 1.0 mm of filter hole. Since all considered vertical nozzle distance exhibit smallest diameter of lubricant oil droplets at 0.9 mm of filter hole, this size of filter hole was selected to study the lubricant oil droplets count affected by the vertical nozzle distance.

| Vertical nozzle distance, L | Oil flow rate, Q = 9 mL/h | Oil flow rate, Q = 18 mL/h | Oil flow rate, Q = 27 mL/h | Oil flow rate, Q = 54 mL/h |
|-----------------------------|--------------------------|---------------------------|--------------------------|--------------------------|
| 30 mm                       | ![Image](0.1 mm)         | ![Image](0.1 mm)         | ![Image](0.1 mm)         | ![Image](0.1 mm)         |
| 35 mm                       | ![Image](0.1 mm)         | ![Image](0.1 mm)         | ![Image](0.1 mm)         | ![Image](0.1 mm)         |
| 40 mm                       | ![Image](0.1 mm)         | ![Image](0.1 mm)         | ![Image](0.1 mm)         | ![Image](0.1 mm)         |
| 55 mm                       | ![Image](0.1 mm)         | ![Image](0.1 mm)         | ![Image](0.1 mm)         | ![Image](0.1 mm)         |

**Figure 2.** Images of lubricant oil droplets visualized by microscope.

**Figure 3.** Smallest diameter of lubricant oil droplet passing through filter hole at different vertical nozzle distance.
Figure 4 shows the results of smallest diameter of lubricant oil droplets passing through various types of filter holes under 9 mL/h, 18 mL/h, 27 mL/h and 54 mL/h of oil flow rate. The diameter of lubricant oil droplets was found to significantly fall between 0.7 mm to 0.9 mm of filter hole. However, the smallest diameter of lubricant oil droplets between the same filter hole for lower oil flow rate, i.e. 9 mL/h and 18 mL/h was found to similarly present a weak decreasing trend. For filter with 1.0 mm of hole, the smallest diameter of lubricant oil droplets for all cases were found to bounce back nearly to its initial value when using the filter with 0.7 mm of hole. Since all considered flow rates show smallest diameter of lubricant oil droplets at 0.9 mm of filter hole, this size of filter hole was selected to study the lubricant oil droplets count affected by the oil flow rate.

For the cases of different vertical nozzle distance and lubricant oil flow rate as shown in Figure 3 and 4, the filter plate whose diameter of hole larger than 0.9 mm was not suitable for analysis of droplets count since it produced larger size of smallest diameter of lubricant oil droplets. This may be resulted from multiple flying droplets that has combined together and successfully passed through the hole. At 0.9 mm of filter hole, the smallest size of droplets appeared. These kinds of droplets were believed to be the genuinely single droplets that was delivered from the nozzle of MQL generator and passed through the filter hole. However, when the filter plate whose diameter of hole smaller than 0.9 mm was being used, the smallest diameter of lubricant oil droplets were found in inconsistent value for cases of different vertical nozzle distance in Figure 3. This can be attributed to the collision of multiple droplets attempt to fit themselves inside the filter hole.

Upon entrainment through the filter hole, the pieces of each droplet have combined together and overlayed as a larger single droplet of lubricant oil on the petri dish. Hence, these kinds of droplets were not valid for further analysis. This phenomenon was strongly supported when looking through the results of shortest vertical nozzle distance, i.e. 30 mm where the diameter of lubricant oil droplets were found as the smallest of all other distances. This implies that the number of droplets collided before passing through the filter hole was much lesser than that of longer vertical nozzle distance. Similar occurrence can also be considered for filter plate whose diameter of hole is smaller than 0.9 mm for the cases of difference oil flow rate in Figure 4. As can be seen, the smallest diameter of lubricant oil droplets were found to increase with increasing oil flow rate. This suggests that with much higher flow rate, the number of droplets collided before passing through the filter hole became higher and hence larger diameter of lubricant oil droplets were formed.
3.2 Lubricant Oil Droplets Count and Size

Overall, the diameter size of lubricant oil droplets as shown in Figure 5 and 6 was found to range in between 10 µm - 100 µm. This range of diameter size was supported by the previous work of Park et al. [25], which agreed that the diameter of lubricant oil droplets in this range is not involved in major concerns of the human’s health.

3.2.1 Effects of Vertical Nozzle Distance

Figure 5 shows the results of number of droplets categorized by the diameter size at 30 mm, 35 mm, 40 mm and 55 mm of vertical nozzle distance. The oil flow rate was fixed at 9 mL/h.

![Figure 5. Number of droplets at different vertical nozzle distance.](image)

For the case under 30 mm of vertical nozzle distance, the highest number of droplets were found at smallest range of diameter i.e., 10 µm - 22 µm. However, for the cases at 35 mm, 40 mm and 55 mm of longer vertical nozzle distance revealed the highest number of droplets in larger range of diameter, i.e 23 µm - 35 µm. The reason why larger diameter of droplets appeared the highest at this range can be attributed to the inertia of the droplets. As stated by Duchosal et al. [26], small diameter of droplets carrying less inertia at longer vertical nozzle distance could be easily driven by the air flow to fly off from the test surface. Therefore, only large diameter of droplets successfully reached the test surface without majorly conquered by the air flow.

Furthermore, the highest number of droplets at 35 mm, 40 mm and 55 mm of vertical nozzle distance were also found to decrease almost half than that of 30 mm of vertical nozzle distance. This can be attributed to the evaporation of some droplets when the vertical nozzle distance was set at this range, as reported by Rahim et al. [21]. Park et al [27] also have stated that increasing the vertical nozzle distance increases the chances of droplets being exposed to the surrounding temperature and hence the oil
droplets can be easily evaporated. Therefore, lengthening the vertical nozzle distance may result in inadequate tiny oil droplets to penetrate the cutting zone. Najiha et al. [28] also agreed that adequate distance of oil channeled through the nozzle is crucial in order to generate ideal dispersion of oil mist to ensure effective lubrication.

Moreover, less than 200 number of droplets with diameter more than 36 µm were found for all considered vertical nozzle distance. A significant difference in number of droplets according to their diameter size can also be seen only for 30 mm of vertical nozzle distance. This suggests that changing the vertical nozzle distance between 35 mm, 40 mm and 55 mm does not significantly contribute to the change of droplets size for the case under 9 mL/h of oil flow rate.

3.2.2 Effects of Oil Flow rate

Figure 6 shows the results of number of droplets categorized by the diameter size at 9 mL/h, 18 mL/h, 27 mL/h and 54 mL/h of oil flow rate. The vertical nozzle distance was fixed at 30 mm.

![Figure 6. Number of droplets at different oil flow rate.](image)

For the case under 9 mL/h oil flow rate, the highest number of droplets was found at smallest range of diameter i.e., 10 µm - 22 µm. However, the higher oil flow rate, i.e.18 mL/h, 27 mL/h and 54 mL/h gave the highest number of droplets in larger range of diameter. This outcome is corresponded to the past study conducted by Emami et al. [29]. They discovered that the large number of droplets gained from increasing oil flow rate tend to combine themselves to form another multiple huge droplets. Therefore, increasing oil flow rate probably less effective to enhance the lubricating effects since the oil droplets size become larger. Najiha et al. [30] had already stated that unsuitable oil flow rate will affect the infiltration of oil into the cutting zone.
Thoroughly looking into the trending exhibited for the results at 18 mL/h, 27 mL/h and 54 mL/h shows that the highest number of droplets for 18 mL/h of oil flow rate was found at third range of diameter, i.e. 36 µm - 48 µm. However, the highest number of droplets for 27 mL/h and 54 mL/h of oil flow rate were found to drop to smaller range of diameter, i.e. 23 µm - 35 µm. This inconsistency is likely to be affected by the human errors when controlling over the pump stroke in determining the amount of oil delivered from the nozzle. The scale in the control dial is too narrow that it probably caused the adjustment to become uncertainty for every experiment.

Moreover, less than 200 number of droplets with diameter more than 49 µm were also found for all considered oil flow rate. A significant difference in number of droplets according to their diameter size was found significantly for 9 mL/h of oil flow rate. This suggests that changing the oil flow rate between 18 mL/h, 27 mL/h and 54 mL/h is less important in changing the lubricant oil droplets size for the case under 30 mm of vertical nozzle distance.

4. Conclusion

The droplets size of lubricant oil delivered by a commercial MQL generator was fundamentally investigated under different vertical nozzle distance and lubricant oil flow rate. Several conclusion remarks have been made as follows:

i. Under the shortest vertical nozzle distance and lowest operated oil flow rate, the smallest diameter of droplets were found to range in between 10 µm - 22 µm.

ii. With increasing distance, the air flow increasingly influences the movement of the droplets. Hence, the diameter became larger by ranging in between 23 µm - 35 µm. With increasing oil flow rate, the droplets tend to merge together, forming multiple larger size of droplets that range in between 23 µm - 48 µm.

iii. The size of lubricant oil droplets did not significantly change when varying the vertical nozzle distance starting from 35 mm and more at fixed 9 mL/h of oil flow rate and varying the oil flow rate starting from 18 mL/h and more at fixed 30 mm of vertical nozzle distance.

iv. Lengthening the vertical nozzle distance and increasing oil flow rate probably less effective to enhance the lubricating effects since the oil droplets size become larger.

v. When using an MQL generator with internal feeding system application, the control dial to adjust oil flow rate must be handled properly to ensure precise amount of oil mist successfully being delivered to the cutting zone.

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