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Ultrasonic MQL System for Generating Size-controlled Droplets

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ABSTRACT

We present an ultrasonic MQL system for generating size-controlled droplets, engaging the requirement of variations in MQL droplet size depending on the used machining process and material. The proposed system architecture features four series chambers with a different vibrating mesh actuator; it demonstrates that a wide range of material- and machining process-specific lubrication requirements can be achieved by varying the mist atomization rate and droplet diameter. The vibrating-mesh outlet pore sizes were differentiated between 2 to 20 μm and driven by a 100 V peak-to-peak bipolar sinusoidal voltage. The oil with a kinematic viscosity of 8.9 cSt contacted the atomizing surface using an FLDC-configuration. Four-size mists were generated with mean volumetric droplet diameters of 19.1, 21.7, 39.0 and 48.3 μm; their atomization rates vary between 1.3 to 39.4 ml/h. The droplet size control must provide more flexibility for emerging ultrasonic MQL systems with improved lubrication and optimized machine-working performance.

1. Introduction

Metal workpieces and their machining tools can be cooled and lubricated through a variety of ways, such as flood or minimum quantity (MQL) lubrication. Flood lubrication lets large quantities of coolant (up to 1,200 litres per hour [1]) flow over the workpiece, whereas in specific cases [2], similar performance can be achieved through MQL, where oil is sprayed in the form of a mist with oil consumptions as little as 50 ml/hour [3]. Benefits for MQL are summarized in terms of three target groups: business, people, and environment [4]. Due to the significantly reduced amount of used oil, costs are cut in terms of metal-working fluids and chip post-processing as no additional cleaning is required before the latter are sent off for recycling [4]. Additionally, thanks to the use of biodegradable oil, operators face less risks inhaling dangerous chemicals, while the environment also favours from the reduced oil sourcing energy and lack of waste treatment [5].

Current MQL devices use a dual-liquid air-assist nozzle, exposing small quantities of oil to rapid flows of air, allowing the atomization into droplets which vary around a mean diameter of 1 - 10 μm [4]. Our research group recently succeeded in the ultrasonic atomization of non-diluted oils with kinematic viscosities up to 37 cSt [6], accelerating the development of a purely ultrasonic MQL system. The implementation of such ultrasonic technology brings additional assets to the lubrication tuning, enhancing the performance for different machining processes and workpiece materials. The traditional MQL system often suffered here from the coupling between oil flow rate and droplet size [7]. Ultrasonic atomization is also known

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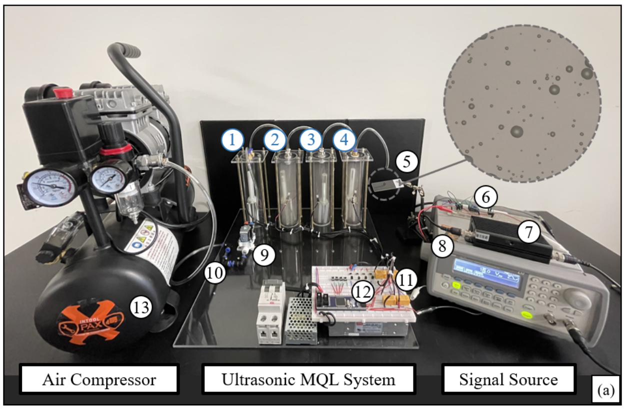
for its narrow droplet size spread [8], aiding in a more uniform cooling of the workpiece [9]. Lastly, the number of issues with conventional MQL systems, such as in-chamber liquefaction, or difficulties with the manufacture of the atomizing-nozzle, are cut down thanks to the removal of redundant components [10]. This research will demonstrate the design, specification, and performance of such a purely ultrasonic MQL system, enabling the generation of four differently sized droplets from a single biodegradable MQL oil (Accu-Lube LB-6000) [11]. This feature is of great importance as droplet diameter was shown to have significant effects on the lubrication performance of different workpieces [6,12-15].

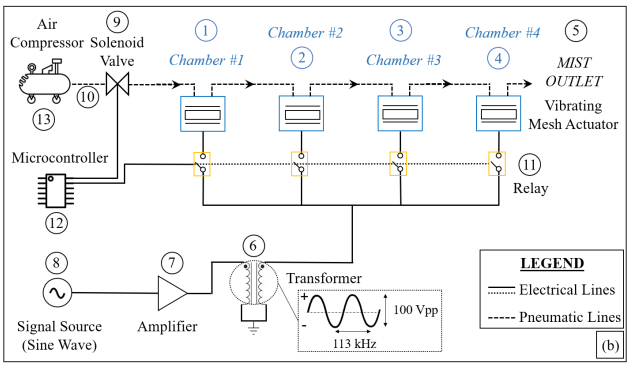
2. Design and specification

2.1 System architecture

The photo and architecture of the ultrasonic MQL system generating multi-size oil mists, are seen on Fig. 1(a)-(b). The system is built up out of four cascaded acrylic chambers (① - ④), each fitted with an atomization module and having differentiations in their vibrating mesh actuator characteristics, as later described in Section 2.2. The modules are loaded with Accu-Lube's LB-6000, a biodegradable MQL oil with a density of 0.93 g/ml, surface tension of 29.6 dyne/cm and a 40°C-kinematic viscosity of 8.9 cSt [11]. An air compressor (PAX ECO 10L, ⑬) produces a steady airflow picking up the mist from the atomization chambers, allowing it to pass through the outlet (⑤) and be followingly sprayed onto a microscopic glass plate for performance analysis. The microcontroller (ATmega 128, ⑫) further controls a solenoid valve (⑨), which regulates the possibility of air flowing through the chambers, entering from the assembly inlet (⑩). Additionally, the actuator driving signal, generated by an assembly of a sine-wave signal source (Keysight 33210A, ⑧), amplifier (FYA2030S, ⑦) and transformer (VTX-110-006, ⑥), is followingly regulated and sent to the appropriate atomization chamber using four relays (⑪), individually controlled by the microcontroller (⑫). Only a single relay can be operational at any point in time, preventing different mists from combining.



(a) Ultrasonic MQL system architecture



(b) Schematic of used components and relations within architecture

Fig. 1 Ultrasonic MQL system for generating size-controlled droplets

2.2 Atomization workings

The atomization of the biodegradable MQL oil is achieved in the same manner as presented earlier by our research group and shown on Fig. 2(a), using a vibrating mesh piezoelectric ring actuator [6]. Solid disk piezoelectric actuators are often used for the same purpose, but pose limits in that only driving signal characteristics, such as voltage and frequency, are dominant in changing the atomization performance [8]. Droplet sizes in a vibrating mesh piezoelectric ring actuator depend on the pore size, contrarily, having various size droplets generated without changes in driving frequency or voltage [16]. Solid disk actuators were also found in our investigation to produce too small atomization rates for the highly viscous MQL oil [6]. Oil is loaded on a Fibre Liquid Delivery Column (FLDC) [17] and followingly, using a 0.5 N-force spring, brought into contact with a piezoelectric vibrating mesh actuator. The actuator consists of a piezoelectric ring mounted below a thin meshed steel plate. The 113 kHz 100 Vpp sinusoidal-driving voltage is generated by the signal source, amplifier, transformer-assembly (⑥-⑧) and induces a resonant up-and-downwards vibration of the mesh actuator, causing a differential volume change of the mesh pores as described by Yan et al [18]. The volume change accordingly allows oil,

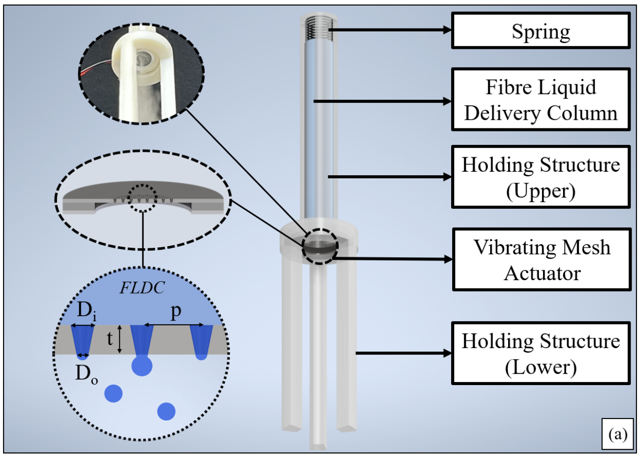
Table 1 Vibrating mesh actuator characteristics

	Chamber #1	Chamber #2	Chamber #3	Chamber #4
Frequency (kHz)	115	113	113	114
Mesh thickness, t (μm)	51	60	51	51
Pore pitch, p (μm)	125	100	135	128
Inlet pore diameter, D_i (μm)	28	19	18	40
Outlet pore diameter, D_o (μm)	2	3	8	20
Outlet pore bottom view				

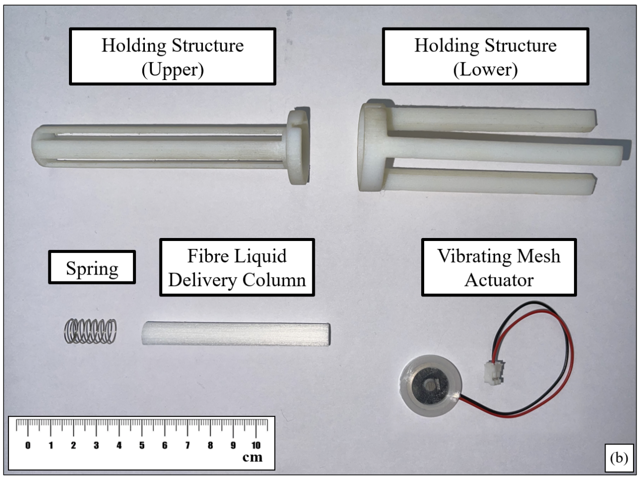
sucked in by capillary action from the FLDC, to enter the mesh through inlet pores with diameter, D_i, and are ejected through outlet pores with diameter, D_o, the latter being the deciding characteristic for mist droplet diameter as investigated by Lang et al[12]. Four vibrating mesh actuators, varying in D_o, were individually fitted to a single atomization chamber, with a summary overview of their specific actuator characteristics seen on Table 1[6]. All components are held together by 3D-printed holding structures, consisting of an upper and lower part seen on Fig. 2(b), allowing for the easy assembly and possible replacement of FLDC and mesh actuator. The FLDC and mesh actuator are specifically arranged within the holding structure in a top-to-bottom configuration, where oil is flowing downwards from the upper-located FLDC. Contrary to conventional water humidifiers, where an FLDC is placed below the mesh actuator (bottom-to-top configuration) in contact with a water reservoir[19]. The bottom-to-top configuration proved to be ineffective in our study as the increased oil viscosity and reverse gravitational influence did not enable a stable capillary suction action, resulting in the mesh contact-region of the column to dry up within seconds of operation. This bottom-to-top configuration makes it however challenging to install an oil reservoir providing the FLDC's with a continuous supply of oil, so further investigation is suggested to improve this shortcoming.

2.3 Mist flow and chamber connection

The four atomization chambers are connected in series with



(a) Structure of the atomization module



(b) Components of the atomization module

Fig. 2 Atomization module of the ultrasonic MQL system

each other, completing a full system assembly as seen on Fig. 3. Compressed air from the compressor (⑬), controlled in flow by the solenoid valve (⑨), enters chamber #1 (①) through its inlet. The flow exits through the outlet and followingly enters chamber #2 (②), so forth until eventually leaving chamber #4 (④) through the assembly outlet (⑤). Depending on the desired atomization performance for different machining operations[6,12-15], the appropriate vibrating mesh in the specific-related chamber, according to Table 1, can be actuated. The airflow then picks up the mist throughout the chamber assembly and guides it to the machining workpiece, located at the assembly outlet (⑤). This working is clearly demonstrated on Fig. 3 where mist is only generated in chamber #3 (③) and delivered through the chamber outlet to the inactive chamber #4 (④) and followingly sent to the assembly outlet (⑤). The microcontroller (⑫) and relays (⑪) ensure that at any given moment in time, only a single chamber

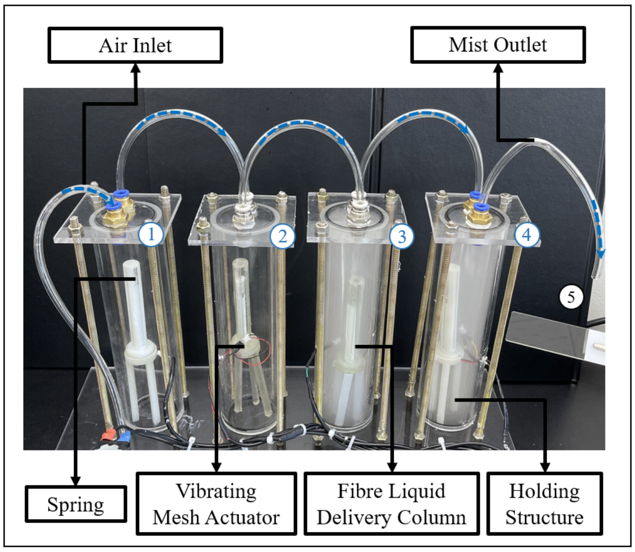


Fig. 3 Atomization chambers and their connections

can atomize oil, preventing differently sized droplet mists from mixing.

3. Measurement procedures

3.1 Atomization rate measurement

The atomization performance can be quantified in terms of both the atomized volume, also defined as the atomization rate and the size of the produced droplets, termed the mist volumetric mean diameter. The atomization rate is measured according to the same procedure as presented earlier by our research group[6]. The FLDC[18] inside the atomization module is loaded with oil to which the whole module then has its weight measured before and after an atomization period of one minute using a microbalance, Meddler Toledo ME204. The weight difference accordingly leads to a calculation of the atomization rate, expressed in ml/h.

3.2 Volumetric mean diameter measurement

The droplet size is measured according to a method presented by Park et al[20]. Droplets are caught on a glass plate at the assembly outlet (⑤) and followingly have their contact surface diameter, the diameter of the half ellipsoid in contact with the glass plate, Ds, measured using a digital microscope, Keyence VHX-7000. These values are followingly converted to a volumetric droplet diameter, the diameter of a perfect spherical droplet in flight, Dv, using a Confocal Laser Scanning Microscope (CLSM - Zeiss LSM 800) and followingly established Ds-Dv-relationships, as presented in earlier work[6]. The results presented are D50-values, calculated through a Rosin-Rammler distribution, an identical approach as laid out in our group's previous work[6]. This value known as the volumetric mean droplet diameter, indicates that 50% of the total atomized mist volume lies in droplets with diameters either smaller or larger than the given D50-value[8].

4. Measurements results

4.1 Atomization rate results

Fig. 4 shows the performance of the ultrasonic MQL system in terms of its atomization rate and vibrating mesh outlet pore size. Smaller pore sizes clearly show lower atomization rates for the simple reasoning that smaller pore volumes can hold, and followingly, eject less oil per up-and-downwards motion cycle. The atomization rate can be seen moving from 1.30

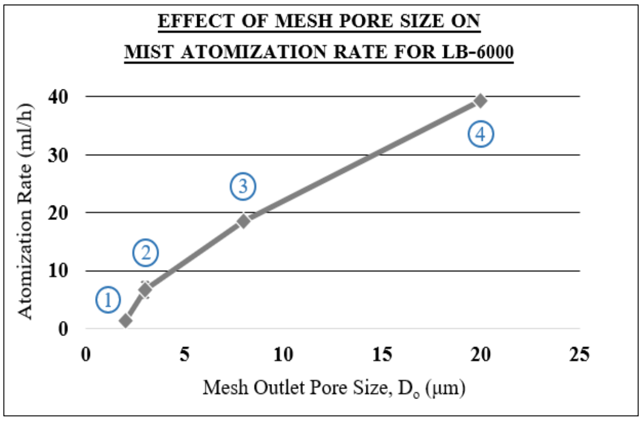


Fig. 4 Effect of mesh pore size on the mist atomization rate for LB-6000

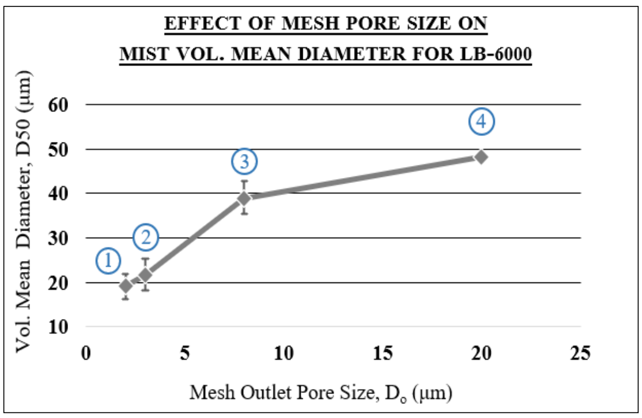


Fig. 5 Effect of mesh pore size on the mist volumetric mean diameter for LB-6000

ml/h for chamber #1, to 39.4 ml/h for chamber #4, or an increase by a factor of 40 for a 10 times larger outlet pore size, D_o.

4.2 Volumetric mean diameter results

The mean volumetric diameter for the different mists generated in chambers #1 - 4 is displayed on Fig. 5. Like the atomization rate, an increase in outlet pore size, Do, increased the mean droplet diameter, D50. The observed mean diameters for each respective chamber are 19.1, 21.7, 39.0 and 48.3 μm, indicating that the droplet diameter grows by a factor of 2.5 if the outlet size was increased 10 times. This result clearly implies the dominance of D_o on the droplet size, as investigated by Lang et al[16].

4.3 Discussions

The ultrasonic MQL system showed clear feasibility in terms of both mist atomization rate and mean diameter. Considering that the number of vibrating mesh actuators can be expanded and that the oil consumption rates are frequently found to be lower than the 50 ml/h-mark, the proposed system matched the desired atomization rate of traditional MQL systems[3-4]. Furthermore, the system successfully demonstrated the generation of size-controlled droplets based on solely actuator geometry-related characteristics.

This is of great value for the optimization of lubrication performance as different machining processes and workpiece materials desire alterations in the oil mist droplet size[6,12-15].

Further system improvements could be made to replace the assembly of four chambers by a single chamber, decreasing issues related to droplet collision and in-chamber mist liquefaction. The current top-to-bottom FLDC configuration additionally hinders a continuous operation of the system as it only operates for as long as there is oil present in the column. A re-design with a bottom-to-top configuration was however not possible as capillary suction issues arose due to reverse gravitational effects and increased oil viscosity.

5. Conclusions

This paper proposed an ultrasonic MQL system for the generation of size-controlled droplets. A commonly used MQL oil with a kinematic viscosity of 8.9 cSt was loaded onto an FLDC-configuration and brought into contact with the atomizing surface of a vibrating mesh actuator. Based on differentiations in the actuator characteristics, four mists were generated having a respective mean volumetric droplet diameter of 19.1, 21.7, 39.0 and 48.3 μm with atomization rates ranging from 1.3 to 39.4 ml/h.

The controllability in the droplet size should provide more flexibility for emerging ultrasonic MQL systems in terms of lubrication improvement and optimization of the machine-working performance.

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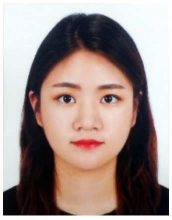

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