Investigating submicron particle generation in machining: The role of coolants and operational conditions

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Abstract. Submicron particles in industrial environments pose significant health risks due to their ability to penetrate deep into the lungs, leading to respiratory and long-term health effects. The novelty of this study lies in its focus on submicron (< 1 µm) particle generation in machining environments, an area that has received little attention compared to measuring larger particle sizes (2.5 to 10 µm). Particle emissions were analysed under different cooling/lubrication methods, spindle speeds, and mist extraction conditions. Conventional emulsions were compared with alternative coolants using liquid carbon dioxide (LCO_2) and LCO_2+MQL under varying operational parameters. Results indicate that LCO_2+MQL produces the highest particle concentrations, particularly at high spindle speeds, whereas LCO_2 achieves near-background air quality. Mist extraction significantly reduces exposure, emphasizing the need for proper coolant selection and ventilation.

Introduction

In machining processes, airborne particles are generated from various sources, including chips or swarf from the machined material, cooling/lubricating fluids, and compressed air. Among these, submicron particles, those smaller than 1 micron in diameter, pose significant health risks. These particles remain suspended in the air for prolonged periods and are easily inhaled, making them a critical concern in machining environments [1]. Once inhaled, submicron particles can penetrate deep into the lungs and even enter the bloodstream, leading to various health issues such as respiratory and cardiovascular diseases [2]. Studies have linked exposure to fine particulate matter with increased mortality rates, nonfatal heart attacks, aggravated asthma, and decreased lung function [3]. The small size of submicron particles makes them particularly challenging to filter from the air, necessitating effective control measures to protect workers' health [4].

Coolants play a crucial role in machining operations by enhancing tool life, part quality, and overall process efficiency. However, they are also one of the main contributors to airborne particle generation in machining [5]. During machining, the high-speed interaction between the cutting tool and workpiece generates heat, causing the coolant to vaporize and form mist [6]. Additionally, the mechanical action of the rotating tool or workpiece can aerosolize the coolant droplets, further increasing airborne particle concentrations in the workshop. The mist generated by coolants can create several respiratory and skin problems, motivating health organizations to establish occupational exposure limits (OELs) for these substances [7]. These limits typically focus on particle matter (PM) in mass concentration, distinguishing coarse particles (PM10, <10 µm) from fine particles (PM2.5, <2.5 µm), Thresholds vary by country, with the strictest set by the American NIOSH at 0.5 mg/m³. Compliance with these limits can increase machining costs, requiring mist collection systems to purify workshop air or extending cycle times and costs due to the standby time needed for particle extraction before opening the machine-tool doors, as demonstrated by [8]. Incidences have been reported even when particle concentrations were below the occupational exposure limit [9], highlighting the need to study and mitigate smaller particles, particularly those in the submicron range.

Efforts have been made to develop coolants and lubricants that reduce the environmental footprint and improve operator safety compared to conventional emulsions. For instance, minimum quantity lubrication (MQL) uses a very small amount of coolant, atomised at the tool-chip interface, to provide effective lubrication [10]. Similarly, cooling without cutting fluids has been achieved using liquefied gases, such as liquid nitrogen (LN_2) and liquid carbon dioxide (LCO_2). While these techniques eliminate oils, they introduce new health concerns, such as oxygen depletion in the workplace [11].

Machining process parameters influence airborne particle concentrations and worker exposure. Variables such as coolant type and machining parameters, or process dependent outputs such as the cutting temperature, affect the generation and dispersion of particles in the workshop [12]. For example, Iwasaki et al. [13] demonstrated that machining processes which usually employ flood cooling, like turning, generate higher ultrafine particle concentrations (PM1, <1 µm) than processes using neat oils, like gear grinding. Djebara et al. [14] investigated the effects of cutting speed and tool coating on PM2.5 particle emissions during metal cutting, emphasizing the importance of optimizing these parameters to reduce particle emissions. Similarly, Khettabi et al. [15] modelled particle emissions during dry orthogonal cutting and showed that cutting speed and tool rake angle significantly impact particle concentration. These studies highlight the importance of understanding how process parameters influence airborne particle generation to develop effective control strategies.

Despite ongoing research on airborne particle generation in machining environments, significant gaps remain, particularly regarding submicron particles. Most studies have focused on fine (PM2.5) and coarse (PM10) particles, with limited attention given to particles smaller than 1 µm (PM1). Additionally, while the effects of individual factors such as cutting speed, tool geometry, and coolant type on particle emissions have been examined, their combined effects under varying operational conditions are not well understood.

The novelty of this study lies in its focus on submicron particle generation and the influence of machining parameters under different cooling and lubrication conditions. By varying spindle speed, airflow extraction, and three cooling/lubrication methods, namely conventional emulsion, pure LCO_2 cooling, and LCO_2+MQL cooling/lubrication, this research aims to identify conditions that minimize emissions and reduce air quality impact. To achieve this, each parameter was varied individually, and the concentration and size distribution of particles to which a worker might be exposed upon opening the machine-tool doors were characterized. The findings will contribute to the development of guidelines for selecting appropriate coolants, optimizing machining parameters, and implementing effective ventilation strategies to protect worker health and enhance sustainability in machining operations.

Methodology

The following section outlines the experimental plan and procedure used to assess the impact of machining parameters on airborne particle concentrations, including the conditions tested and the methods for measuring particle size distributions and concentrations.

Experimental plan and procedure

The experimental plan aimed to evaluate the influence of process parameters, including cutting conditions, coolants, and airflow extraction, on the exposure of machine-tool workers to airborne particles (Fig. 1a). The variable experimental parameters included spindle speed (2,500 rpm and 5,000 rpm), coolant and lubricant type (Blaser B-Cool 9665 emulsion coolant at 6% concentration, straight LCO_2, and LCO_2 combined with MQL), and the state of airflow extraction (ON or OFF, being the airflow of the extractor 1,200 m^3/h when activated). Fixed parameters, all specific to the Scanning Mobility Particle Sizer (SMPS), included a scanning time of 120 seconds, an aerosol flow rate of 1 litre/min, and a detectable particle size range from 14.3 nm to 673 nm, as seen in Fig. 1b. Each experimental condition was repeated three times to ensure consistency and repeatability of results.

Two key outputs were derived from the measured particle concentrations. First, the total particle count and the size distribution of particles in the sampled air were analysed (dark green line in Fig. 1c). Second, the particle concentration, expressed as particle count per unit volume [#/cm^3], was calculated by integrating the area under the particle size distribution curve (light green area in Fig. 1c). The experimental procedure, detailed in Fig. 1d, followed a systematic approach for consistent data collection. Initially, the doors of the machine-tool were closed, and the spindle, coolant, and airflow extraction systems were activated as specified by the experimental condition. A background measurement of airborne particles was conducted during the operation, with the doors closed, to evaluate the impact of the selected experimental parameters on ambient particle concentrations.

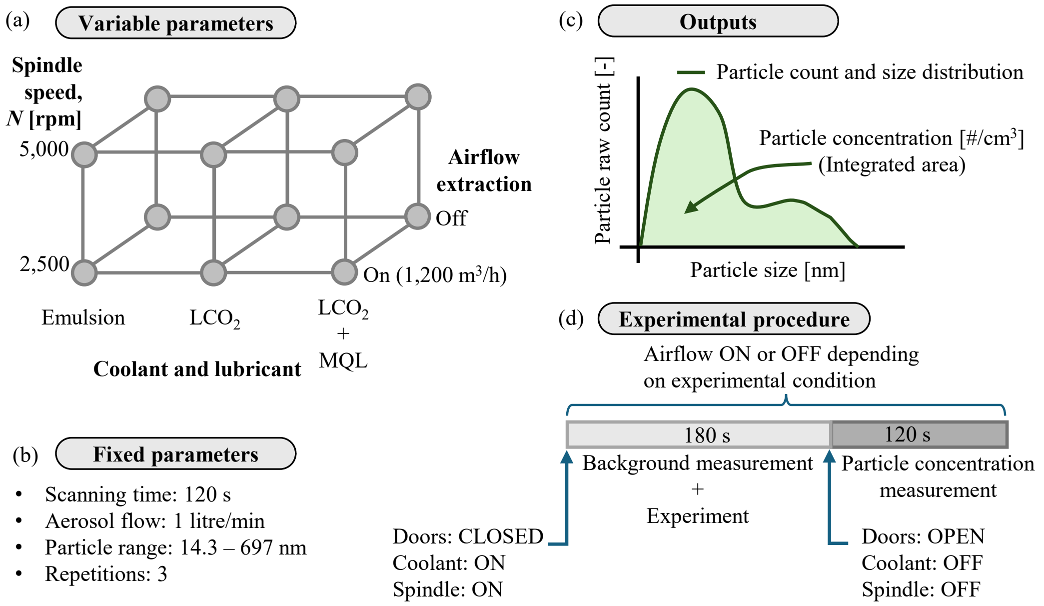

Figure 1 – (a) variable parameters tested in the experimental plan; (b) fixed experimental parameters; (c) outputs analysed; (d) experimental procedure followed in the tests

After three minutes (180 seconds) of operation, the spindle and coolant systems were stopped, and the doors of the machine-tool were opened. If the airflow extraction was set to ON, it remained active after the doors were opened. At this point, a second measurement of airborne particle concentration was taken to determine the particle exposure level in the air immediately following the machining operation, as a worker might experience when opening the machine-tool.

Experimental setup

For submicron particle measurement, a TSI Scanning Mobility Particle Sizer (SMPS) was utilized (Fig. 2), comprising an aerosol neutraliser (TSI Model 3087), an electrostatic classifier (TSI Model

3080), and a water-based condensation particle counter (TSI Model 3785). The process for particle counting begins with the neutralizer, which ensures particles are electrically charged appropriately for their size. This step is critical, as the electrostatic classifier relies on electrical mobility, directly related to particle size, to separate the particles. Finally, the water-based condensation particle counter enlarges the classified particles using them as nuclei for condensation of water vapour, and making them detectable for counting by light scattering [16]. This setup enables measurement of particles ranging from 5 nm to over 3,000 nm, with an uncertainty of 10%.

The sampling point for the aerosol measurements was located at the front of the machine-tool doors and at a height of 160 cm from the ground, simulating the position where the respiratory tract of the operator would be when opening the doors of the machine-tool after a machining operation. The LCO_2 and LCO_2+MQL coolants were supplied through a 10 mm endmill with four 0.5 mm internal cooling holes, while the emulsion was supplied externally. The emulsion cooling was supplied at 12 bar and a flow rate of 25 litre/min, while the flow rates for the LCO_2 were 150 g/min and for the MQL 12 ml/min. For extracting the particles from the machine-tool cavity, a LOSMA Darwin extractor was employed with an airflow of 1,200 m^3/h.

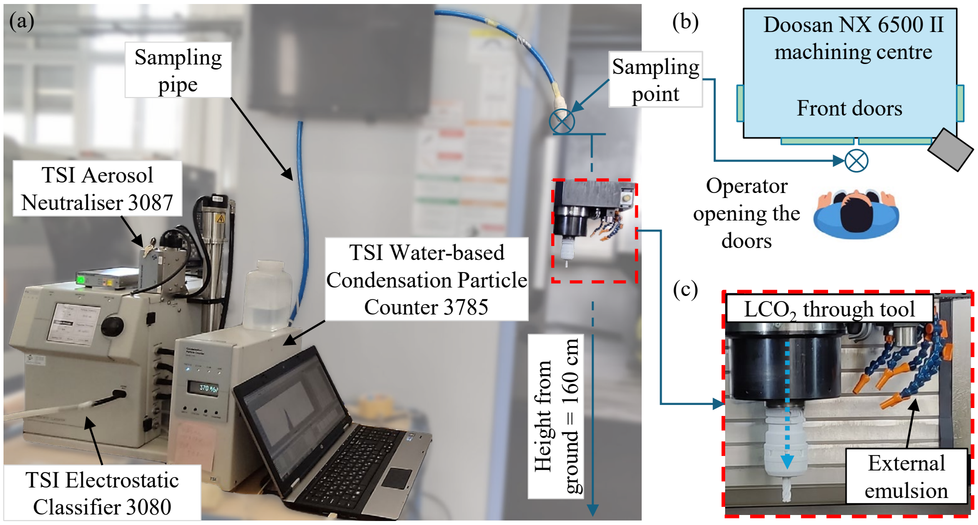

Figure 2 – (a) overview of the experimental setup and the devices comprising the Scanning Mobility Particle Sizer (SMPS); (b) top view detail of the location of the sampling point; c) detailed view of the coolant delivery

Results and discussion

To evaluate the baseline airborne particle concentration in the workshop, measurements were taken every 15 minutes overnight, starting at the end of the work shift (16:00) and continuing until the start of the next morning's shift (6:00). A 3D surface plot of the particle size distributions recorded during this period is shown in Fig. 3a, illustrating the changes in particle count and size distribution over time. It is worth noting that the particle diameter axis is evenly spaced for each bin measured by the SMPS. This adjustment simplifies data visualization, as the lower size range contains a greater number of bins.

The raw particle count and overall particle concentration at different times are shown in Fig. 3b. During work hours, the particle concentration was approximately 10,000 #/cm^3, gradually decreasing to about 6,000 #/cm^3 overnight as particles settled and no new emissions occurred.

Fig. 3c shows the changes in particle size distribution over time. As the particle concentration decreased during the night, the dominant particle size also shifted. Coarser particles, around 50 nm in diameter, were more present during working hours when concentrations were higher. Smaller particles, about 28 nm in diameter, became dominant as concentrations decreased overnight. This indicates that smaller particles stay airborne longer, while larger particles settle more quickly [2].

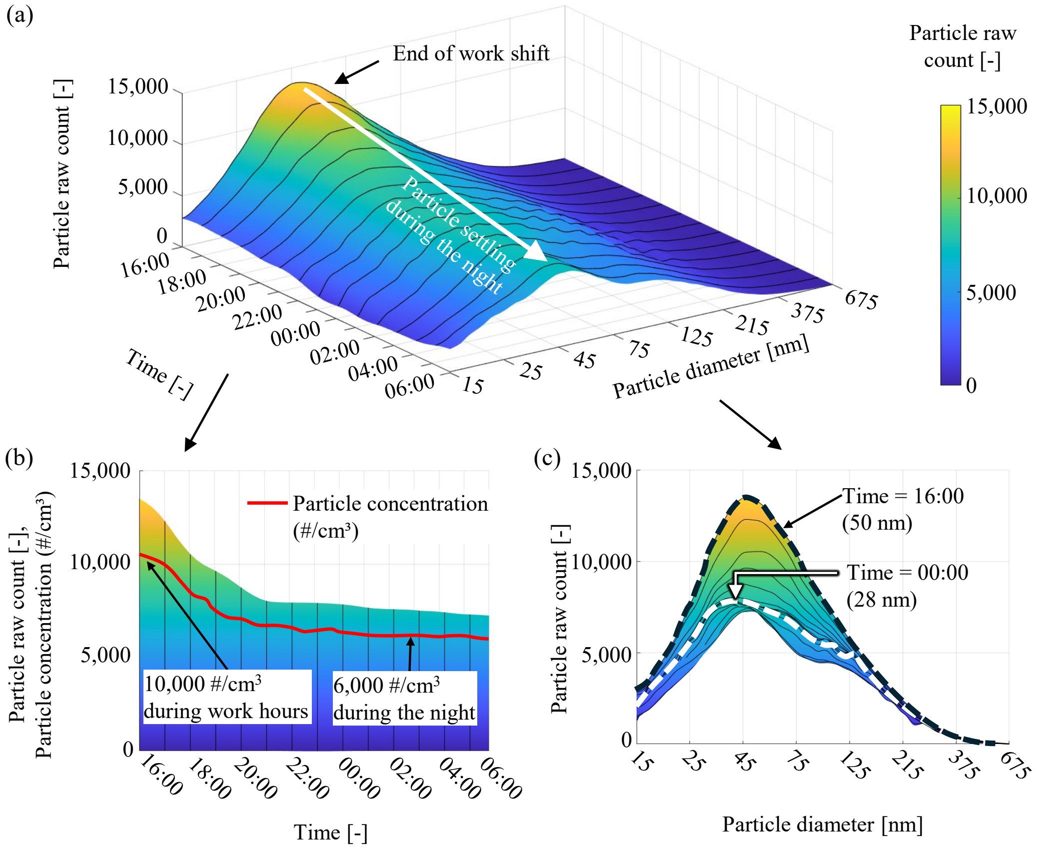

Figure 3 – (a) evolution of the particle size distribution during non-working hours; (b) evolution of the particle concentration; (c) change in dominant particle size

The particle size distributions presented in Fig. 4 show a subset of all the background measurements taken across the experimental conditions detailed in the experimental procedure (Fig. 1a). Specifically, this figure focuses on measurements obtained during operation at a spindle speed of 5,000 rpm, with the airflow extraction turned off, and under various coolant conditions, including emulsion, LCO_2, LCO_2+MQL, and no coolant (just the spindle spinning).

These measurements confirm that the baseline airborne particle concentration outside the machine-tool, with doors closed, is not significantly affected by the type of coolant used. As shown in Fig. 4, the background particle concentrations under these conditions closely align with those recorded at the end of the work shift (16:00) in Fig. 3b, remaining around 10,000 #/cm³. Slightly elevated concentrations were observed with LCO_2+MQL and emulsion coolants, which could be attributed to the escape of fine particles through the machine-tool doors during operation. Nevertheless, these measurements are inside the 10% uncertainty of the equipment employed.

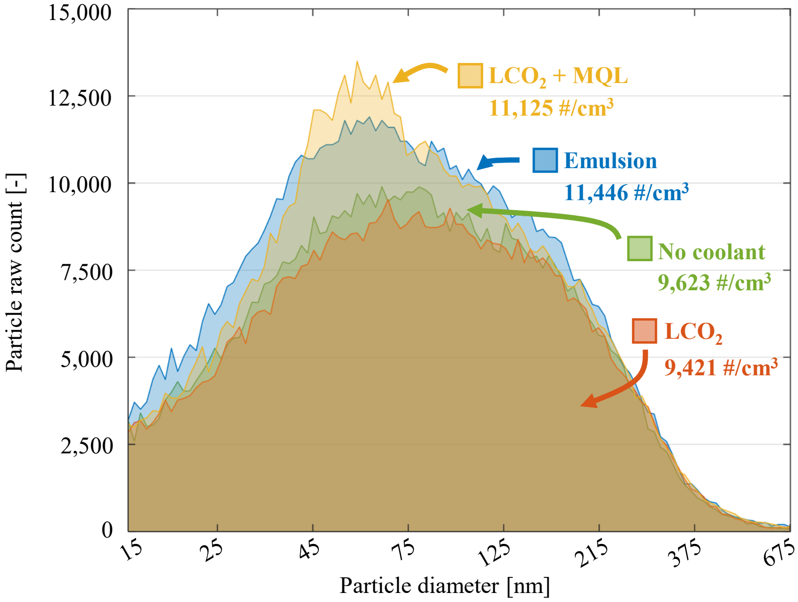

Figure 4 – Particle concentrations measured outside of the machine-tool enclosure when using different coolants

After evaluating the background particle concentration, the maximum particle concentrations achieved after opening the machine-tool doors, following the procedure outlined in Fig. 1d, are presented in Fig. 5.

The results show that under the LCO_2 cooling conditions, the particle concentration remained similar to the background concentrations, regardless of spindle speed or airflow extraction settings. This indicates that pure LCO_2 cooling generates minimal airborne particles. However, there are other concerns, such as the potential pollution from CO_2 and CO gases released when liquid CO_2 converts to gas, which could lead to oxygen depletion and pose risks to operators. LCO_2+MQL produced the highest particle concentrations, followed by emulsion. Although MQL uses less oil than emulsion, the submicron particle concentration was higher due to the increased atomisation in MQL. This occurs because the MQL is mixed with LCO_2, which is a liquid at 57 bar pressure, creating finer atomisation compared to the emulsion, which is supplied as a continuous flood at 15 bar pressure.

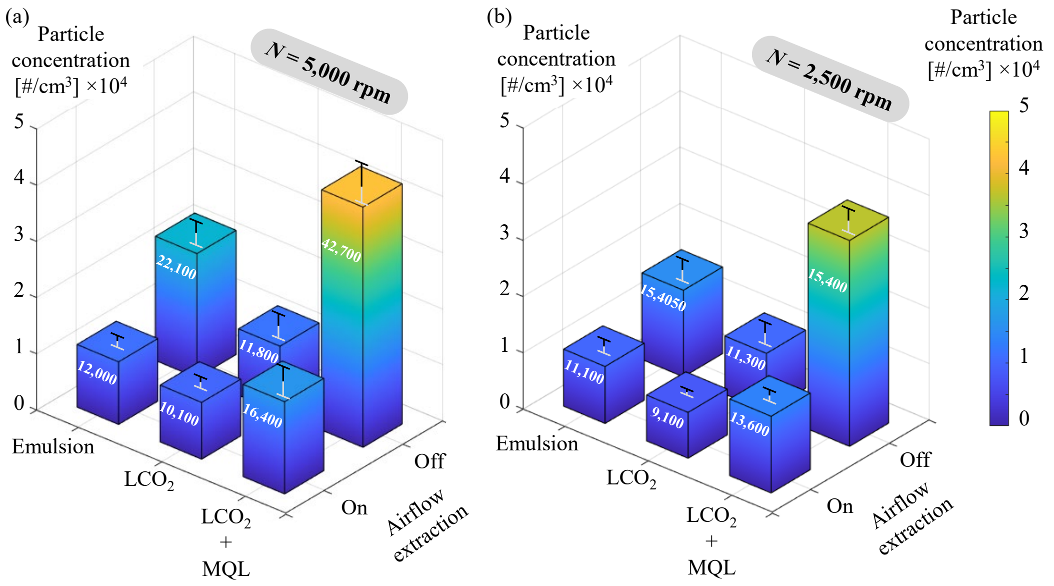

Figure 5 – Maximum particle concentrations achieved when using different coolants and airflow extraction conditions for a spindle speed of: (a) 5000 rpm and (b) 2500 rpm

Activating the airflow extraction significantly reduced particle concentration, cutting it by half for emulsion and by 65% for LCO_2+MQL. The impact of airflow extraction was less noticeable with pure LCO_2, as its particle concentration was already close to the baseline concentration observed in the workshop during work hours. Increasing the spindle speed from 2,500 rpm to 5,000 rpm resulted in higher particle concentrations. This effect on particle concentration aligns with the findings of Wang et al. [12], who demonstrated that higher centrifugal forces, due to increased spindle speed, enhance the atomisation of a coolant sprayed onto the rotating tool or workpiece. The relation between spindle speed and particle emission rate is linear as proven by [12] with their predictive model, also showing that increased atomisation, raises the particle concentration.

Fig. 6 provides a detailed comparison of the particle size distributions observed under the various tested conditions. The data reveals a difference in the dominant particle sizes depending on the cooling and lubrication method used. For LCO_2+MQL, the dominant particle size is approximately 25 nm, whereas for the emulsion coolant, it is around 50 nm. This indicates that the higher atomisation achieved with MQL, due to the elevated pressure of LCO_2 (57 bar), not only generates a higher overall particle concentration but also produces smaller particles. These smaller particles are more likely to remain suspended in the air for extended periods, increasing their potential to contribute to airborne exposure risks [4].

Similar to the results seen in Fig. 5, Fig. 6 shows that lower spindle speeds produce a smaller amount of particles detected when opening the doors of the machine-tool. Likewise, activating the airflow extraction system significantly reduces the particle concentration by removing the dominant particle fraction from the distribution. This reduction is particularly evident in conditions where higher particle concentrations were initially observed, such as with LCO_2+MQL and emulsion coolants. It can also be observed that the airflow extraction is more effective removing smaller diameter particles. This shows the relevance of choosing the adequate ventilation system depending on the machining application and the size of airborne particles that are generated, as also reported by airflow extraction system manufacturers [2].

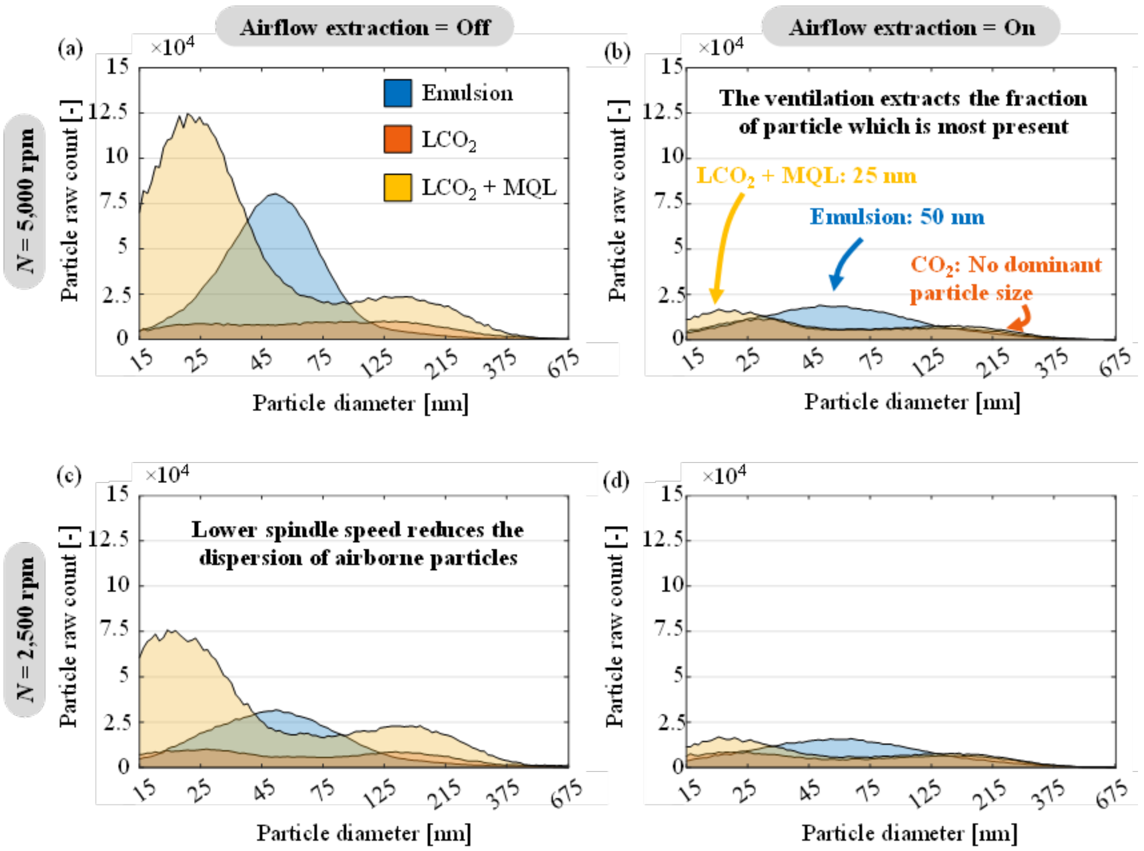

Figure 6 – Particle size distributions obtained for different coolants, spindle speeds and airflow extraction conditions

Conclusions

This study highlights the influence of coolant type, spindle speed, and airflow extraction on airborne particle emissions and distribution in machining environments. The main conclusions are as follows:

- Pure LCO_2 cooling resulted in particle concentrations near baseline levels, making it the least polluting option. In contrast, LCO_2+MQL produced the highest particle concentrations, dominated by finer particles (~25 nm). The high delivery pressure of LCO_2+MQL (57 bar) enhanced atomisation, resulting in smaller particles and higher concentrations compared to emulsion cooling, which operates at a lower pressure (15 bar) and produced coarser particles (~50 nm).
- Increasing the spindle speed from 2,500 rpm to 5,000 rpm raised particle emissions. The enhanced atomisation caused by higher centrifugal forces at elevated speeds underscores the need to optimise spindle speed to manage particle generation effectively, while still ensuring adequate cutting conditions.
- Activating airflow extraction reduced particle concentrations by up to 50% for emulsion and 65% for LCO_2+MQL. This demonstrates the importance of ventilation in capturing airborne particles, particularly finer ones that pose greater health risks.

Acknowledgements

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