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REDUCTION OF FINE AND ULTRAFINE PARTICLES BY WATER: APPLICATION TO THE MACHINING OF DUSTY MATERIALS

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Abstract— Machining of dusty materials such as granite generates fine and ultrafine silica-rich particles, sources of serious respiratory and cardiovascular problems among workers. Although conventional capturing methods such as filtration and ventilation exist, they remain insufficiently effective in capturing ultrafine particles. Thus, water usage appears as a promising alternative due to its natural mechanisms of absorption and deposition. However, its efficiency in industrial machining contexts remains uncertain due to the specific conditions involved in the process. Therefore, this study analyzes the physical and chemical mechanisms of particle capture by water to identify technological pathways and optimize their performance in capturing ultrafine particles.

Keywords: machining, dusty materials, natural or artificial stones, fine and ultrafine particles, water-based reduction.

I. INTRODUCTION

Machining of dusty materials, particularly granite polishing, is a widespread activity in the construction and natural stone processing industry (Songmene and al., 2018). However, this process generates significant emissions of fine (PM2.5) and ultrafine particles (PM0.1), primarily composed of crystalline silica (Bahri and al., 2021). Due to their low density and nanometric size, these particles remain airborne for prolonged periods and can penetrate deeply into workers' respiratory tracts. Consequently, they are directly implicated in severe pulmonary diseases such as silicosis and certain lung cancers (Ramkissoon and al., 2024; Bahloul and al., 2019; Saïdi and al., 2018). Furthermore, several recent studies indicate a worrying increase in silicosis cases linked to dust exposure from machining artificial and natural stones (Ramkissoon and al., 2024). Given these well-established health risks, stricter regulations have been implemented to limit worker exposure. In the United States, the Occupational Safety and Health Administration (OSHA) has set a permissible occupational exposure limit (PEL) to crystalline silica at 50 µg/m³ (OSHA, 2025). It was followed by Quebec (Canada) where granite processing companies must ensure that workers' exposure to quartz does not exceed the above PEL. Despite these regulations, managing ultrafine particle emissions remains a significant challenge for public health and occupational safety.

In this context, traditional capture methods, such as local exhaust ventilation and filtration, play an essential role in reducing exposure to fine particles. However, these solutions quickly show limitations when capturing ultrafine particles. Due to their low inertia and high dispersion, ultrafine particles frequently escape conventional devices and remain suspended in the ambient air (Zhang and al., 2022). Therefore, exploring more advanced technological solutions becomes necessary to optimize their capture and elimination. Among these alternatives, using water as a capture agent has been proposed due to its proven effectiveness against fine particles and because it represents a non-polluting solution for workers and the environment. Nonetheless, although water is effective for micrometric dust (PM2.5), several studies have demonstrated its significant inefficiency regarding ultrafine particles in machining contexts. Indeed, Bahloul and al. (2019) and Songmene and al. (2018) showed that water usage is highly effective in reducing fine particles, which become heavier and settle quickly, but is less effective against ultrafine particles. This inefficiency is attributed to the low mass and high mobility of ultrafine particles, allowing them to escape hydrodynamic impaction by droplets (Kim and al., 2021). Moreover, the complex dynamics of the cutting process and specific particle-water interactions further diminish capture efficiency (Moreno-Ríos and al., 2022).

These limitations underscore the necessity of optimizing water application parameters and exploring combined solutions. Among these, incorporating electrostatic charges or nanofluids appears promising for enhancing ultrafine particle capture in industrial environments (Abellán-Nebot and al., 2024). Thus, this study aims to examine various wet-capture techniques for ultrafine particles tailored to industrial environments. It will then analyze the involved physical and chemical mechanisms, provide an in-depth reflection on optimizing water application parameters, and explore combined solutions likely to significantly enhance the efficiency of these processes.

II. MATERIALS AND METHODS

The use of water in capturing fine and ultrafine particles relies on several physical and chemical mechanisms. Due to their extremely small size and low inertia, ultrafine particles (UFPs) require specific capture techniques. Various approaches have been developed to improve capture efficiency, including optimizing droplet properties, using electrostatic forces, or combining multiple methods. Table 1 summarizes the most widely used mechanisms and capture methods.

A. Hydrodynamic capture with microdroplets

The study conducted by Kim and al. (2024) highlighted that hydrodynamic capture with microdroplets, enhanced by a photothermal membrane, figure 1, significantly improves the capture efficiency of fine particles. This technology notably increases the deposition rates of PM1.0 (0.458 h^{-1}) and PM2.5 (0.472 h^{-1}), while also reducing water consumption. System performance also depends on solar intensity: after one hour, capture rates under 1 sun are 26.6% (PM1.0), 26.7% (PM2.5), and 26.8% (PM10), and reach 36.7%, 37.6%, and 38.4% respectively under 4 suns. This process primarily relies on two mechanisms: inertial impaction and Brownian diffusion. Additionally, Kim and al. (2021) previously noted that using submicron droplets (~800 nm) significantly enhances the capture of ultrafine particles due to their large specific surface area and strong Brownian agitation. However, Zhang and al. (2022) emphasized the importance of controlling the suspension time of droplets in the air to optimize capture.

Table 1: Summary of ultrafine particle capture mechanisms

Mechanism	***Description***	***References***
Inertial impaction	Particles with sufficient inertia collide directly with water droplets, increasing capture.	Dépée (2019)
Adsorption and particle adhesion	Ultrafine particles adhere to liquid surfaces via capillary and van der Waals forces.	Zhang and al. (2022)
Coalescence and agglomeration	Captured particles form larger clusters, facilitating gravitational or filter-based removal.	Zhang and al. (2022)
Brownian diffusion	Ultrafine particles follow erratic paths, increasing chances of collision with droplets.	Dépée (2019)
Condensation capture	Water vapor condenses on particles, turning them into larger, easily removable droplets.	Moreno-Ríos and al. (2022) ; Dépée (2019)
Electrostatic attraction	Electrostatic attraction between particles and charged droplets enhances capture and retention.	Zhang and al. (2022); Dépée (2019)
Gas solubilization and absorption	Soluble gases and some hydrophilic particles dissolve in water, aiding their removal.	Ramaswamy and al. (2022); Zhang and al. (2022)
Water-particle interfacial adsorption	Physicochemical interactions between particles and droplet surfaces promote adsorption capture.	Kim and al. (2021); Moreno-Ríos and al. (2022)
Chemical reactions	Chemical reactions with water or oxidants transform UFPs into less toxic or more soluble forms.	Krishnaraj and al. (2022); Saïdi and al. (2018)

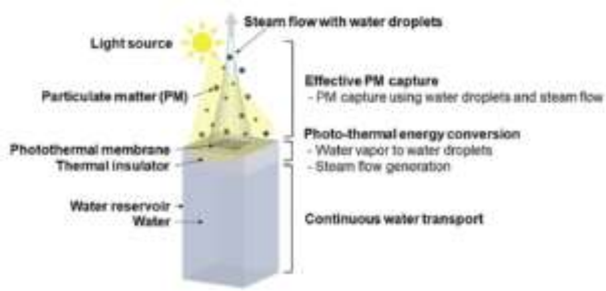

Figure 1: Diagram of solar steam generation and particle capture using evaporated water droplets and a vapor flow. Kim and al. (2024)

B. Electrostatic capture (charged droplets)

This technique involves charging water droplets electrostatically to improve the capture of ultrafine particles through direct Coulombic attraction. According to Zhang and al. (2022), applying an electrostatic charge to micrometric water droplets significantly enhances their efficiency in capturing negatively charged particles present in the air. The effectiveness of this method depends on several interrelated factors. First, relative humidity (RH) influences particle collection by altering their hygroscopic properties. High RH reduces collection efficiency by weakening thermophoretic and diffusiophoretic effects, while lower RH (<72%) amplifies them, thereby improving capture (Depée, 2019). Second, droplet size plays a crucial role. Droplets ranging from 40 to 60 µm are more effective in collecting particles between 100 and 500 nm. In contrast, particles smaller than 100 nm are harder to capture due to their high Brownian motion (Depée, 2019). Third, the applied electric charge on droplets significantly influences collection efficiency. Optimal charge coupling can raise the capture rate up to 85% for particles ranging from 200 to 400 nm (Zhang et al., 2022). Finally, the interaction between Image-Attractive-Short-Distance (IASD) and Coulombic-Long-Distance (CLD) forces modulates the process. IASD favors the capture of larger particles, while CLD may repel smaller ones (Depée, 2019).

Figure 2 illustrates the experimental setup used to capture ultrafine particles with electrically charged water droplets. The system includes an aerosol charger, a humidifier, a filtration system, and an ultrasonic atomizer to generate controlled water droplets.

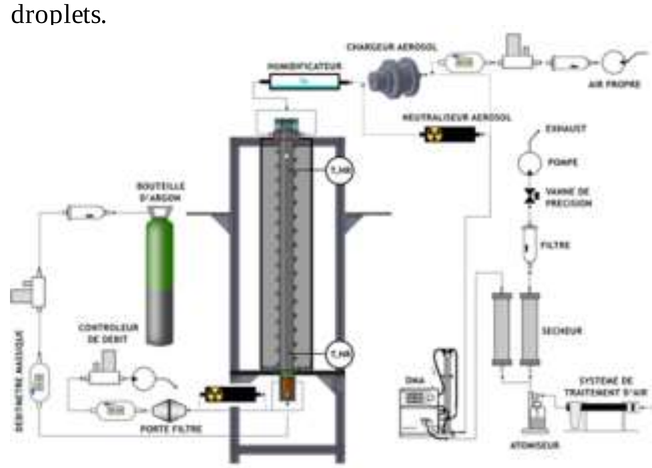

Figure 2 : Diagram of the Experimental Setup Dépée (2019)

C. *Wet crubbers (gas washers)*

Wet scrubbers are industrial devices used to capture airborne particles by intensifying the contact between water droplets and polluted air. Ramaswamy and al. (2022) demonstrated that these systems are particularly effective in removing fine particles and certain water-soluble gaseous pollutants (SO_2, NOx, HCl). However, their efficiency drops significantly for ultrafine particles, necessitating the addition of chemical reagents or an increased water recirculation rate. Figure 3 below illustrates the performance of the wet scrubber, which relies on the mechanism of particle capture via droplet collision and subsequent precipitation driven by gravity and fluid drag forces. Image (a) shows a concentration of particles mainly localized in the lower part, suggesting inefficient accumulation and possible residual dispersion. In contrast, image (b) highlights improved airflow and water distribution, resulting in more effective particle capture.

D. *Ultrasonic atomization and spraying systems*

Unlike conventional nozzles, ultrasonic atomization systems produce smaller and more uniformly dispersed microdroplets. Kim and al. (2021) showed that high-frequency atomization (2 MHz) produces droplets in the range of 1 to 5 µm, thereby optimizing the capture of ultrafine particles through Brownian diffusion and surface adsorption. The frequency of ultrasound directly affects droplet size and suspension time. Smaller droplets exhibit stronger random motion and remain airborne longer, increasing the likelihood of contact with particles. Figure 4 presents the schematic diagram of the experimental setup used to monitor particle concentration in the test chamber.

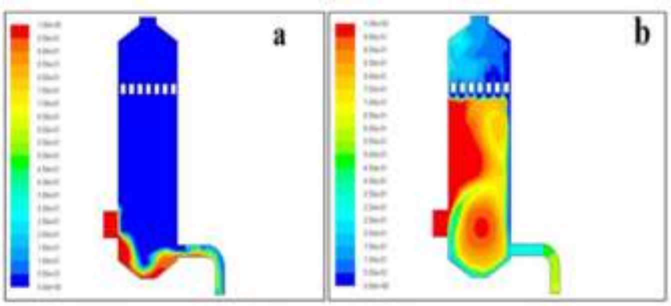

Figure 3 : (a) Dust volume fraction, (b) Combustion gas volume fraction Ramaswamy and al. (2022)

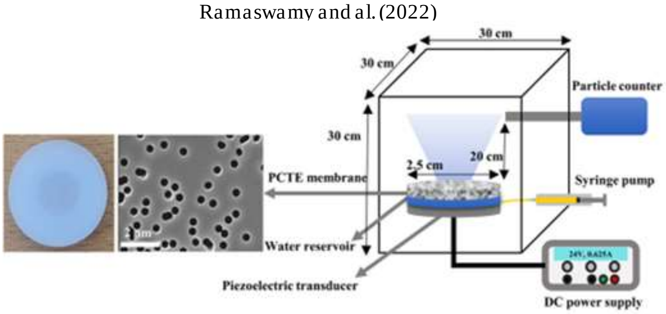

Figure 4: Diagram of the experimental setup for monitoring PM concentration inside the test chamber Kim and al. (2021).

E. *Minimum Quantity Lubrication (MQL) or micropulverization*

In machining and polishing of dusty materials, Minimum Quantity Lubrication (MQL) using water-based fluids represents an alternative to traditional lubricants. This approach not only reduces cutting fluid consumption but also minimizes fine and ultrafine particle emissions. However, its effectiveness strongly depends on several influential parameters, including fluid flow rate, tool rotational speed, feed rate, and the particle capture method employed.

First, the MQL flow rate plays a key role in reducing fine particles. An experimental study by Songmene and al. (2018) showed that flow rates of 20 ml/min result in reductions of 24% to 54% in fine particles, while increasing the flow to 40 ml/min achieves a reduction of 56% to 75%. At 80 ml/min, reductions can reach up to 90%, although the effect on ultrafine particles remains limited. Moreover, the tool's rotational speed directly influences the generation and dispersion of ultrafine particles. At 1500 rpm, effective capture is achievable with a 40 ml/min flow rate, whereas at 2500 rpm, where nanoparticle production increases, optimal capture requires 80 ml/min (Songmene and al., 2018). Feed rate also affects particle formation: low feed rates promote ultrafine generation, while higher feed rates produce larger chips, reducing particle emissions (Zaghbani and al., 2019). Additionally, the composition of the machined material is critical. According to Kouam and al. (2022), white granite containing 50% silica produces more fine particles than black granite, which contains only 10%. Thus, aqueous MQL is more effective on white granite due to the greater presence of larger, more easily captured particles. Figure 5 shows the schematic representation of the machining and dust sampling systems.

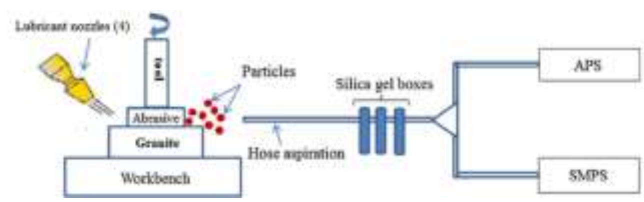

Figure 5: Schematic representation of the machining and dust sampling systems (Songmene and al., 2018).

Table 2: Influence of MQL flow rates and spindle speed on particle reduction (PM2.5 and UFPs). Songmene and al. (2018)

Parameter	***Value***	***PM2.5 Reduction (%)***	***UFP Reduction (%)***
MQL flow rate (ml/min)	20	24 - 54 %	10 - 25 %
	40	56 - 75 %	15 - 35 %
	80	80 - 90 %	20 - 40 %
Spindle speed (rpm)	1500	50 - 75 %	20 - 30 %
	2500	40 - 65 %	10 - 20 %

F. *Machining parameters and emission of ultrafine particles(UFPs)*

Analysis of Tables 3 and 4 highlights two essential and complementary aspects in reducing ultrafine particles (UFPs) during machining: on one hand, the control of operating conditions responsible for their emission, and on the other, the optimization of parameters that promote their wet capture.

Table 3 clearly shows that cutting speed and feed rate are key factors in UFP generation. High cutting speeds (>2500 rpm) significantly increase the concentration of airborne UFPs due to enhanced dispersion from tool rotation-induced turbulence (Bahloul and al., 2019). These findings are supported by studies on wet machining (Songmene and al., 2018; Bahri and al., 2021; Kouam and al., 2022), which also reveal combined mechanisms of fine abrasion, friction, and potentially increased material fragmentation. Regarding feed rate, results show that excessively low values intensify friction and abrasion phenomena, while excessively high values reduce tool-material contact time, thereby limiting UFP formation. These observations suggest the existence of an optimal range that must be determined experimentally to minimize emissions without compromising machining quality.

In contrast, Table 4 highlights how UFP reduction through water spraying depends on precise physicochemical and operating parameters. Water droplets with diameters between 800 nm and 2 µm offer maximum capture efficiency through the combined effects of inertial impaction and Brownian diffusion (Kim and al., 2021). Moreover, water flow rate and droplet velocity—particularly when using ultrasonic or electrostatic atomization—strongly influence droplet distribution and dynamics (Zhang and al., 2022). For example, a flow rate above 80 ml/min significantly increases the probability of particle capture (Songmene and al., 2018). Additionally, reducing the distance between the spray nozzle and emission source is recommended to maximize direct interception (Kim and al., 2020). Other factors, such as the electrostatic charge applied to droplets, the hydrophilic or hydrophobic nature of emitted particles, and ambient relative humidity, also affect capture efficiency (Sygusch & Rudolph, 2021; Moreno-Ríos and al., 2022). Ultimately, joint analysis of both tables supports an integrated approach to effectively reduce UFP emissions. This strategy would combine strict regulation of machining conditions with fine-tuned optimization of water spraying systems. While machining parameters directly influence UFP generation, spraying parameters determine their effective capture.

Table 3: Influence of machining parameters on UFP generation

Parameter	***Description***	***References***
Cutting speed	High cutting speed (>2500 rpm) increases material fragmentation and UFP concentration in air.	Songmene and al. (2018); Bahri and al. (2021); Bahloul and al. (2019); Kouam and al. (2022)
Feed rate	Low feed rate increases friction and UFP production; high feed rate reduces contact time and UFP formation.	Songmene and al. (2018) [1]; Bahri and al. (2021) [2]; Kouam and al. (2022) [16]

Table 4: Parameters influencing UFP reduction optimization by water

Parameter	***Description***	***References***
Droplet size	Droplets between 800 nm and 2 µm provide optimal capture efficiency via inertial impaction and Brownian motion.	Kim and al. (2021)
Water flow rate and droplet speed	(a) Low flow (<20 ml/min) reduces fine particles; high flow (>80 ml/min) enhances UFP capture. (b) Ultrasonic/electrostatic atomization affects droplet speed and dispersion.	(a) Songmene and al. (2018); Bahri and al. (2021); Kouam and al. (2022) (b) Zhang and al. (2022)
Spray distance	Short distance between nozzle and source improves particle interception.	Kim and al. (2020)
Electrostatic charge	Charging droplets improves UFP capture through electrostatic attraction.	Zhang and al. (2022)
Particle nature (hydrophilic/hydrophobic)	Hydrophilic particles are more easily captured; hydrophobic particles may require surfactants.	Sygusch, and Rudolph. (2021)
Ambient relative humidity	Humidity affects particle properties and enhances condensation-based capture.	Moreno-Ríos and al., (2022)
Spray pressure	High pressure improves droplet dispersion and contact with UFPs.	Kim and al., (2024)
Wettability	Spherical, hydrophilic particles are easier to capture than fibrous, hydrophobic ones.	Sygusch and Rudolph (2021)

III. Discussion

Reducing ultrafine particles (UFPs) in machining remains a major challenge due to their high dispersion in the work environment and their harmful effects on workers' health. Numerous strategies have been explored to limit their emission and improve their capture. However, each of these approaches has its advantages and limitations, requiring careful consideration of the most effective solutions.

First, conventional UFP capture methods, such as local exhaust ventilation, often prove ineffective. As shown by Bahri et al. (2021), UFPs' low inertia allows them to follow airflow paths and escape extraction systems, limiting ventilation efficiency. In response, Moreno-Ríos and al. (2022) proposed exploring more effective alternatives, particularly water-based capture.

According to Kim and al. (2021), water-based techniques rely on several physical mechanisms, including inertial impaction, adsorption, coalescence, and Brownian diffusion. While Songmene and al. (2018) demonstrated water's effectiveness in capturing fine particles (PM2.5) due to their greater mass, Moreno-Ríos and al. (2022) found a significant drop in efficiency when targeting UFPs (<0.1 µm). This is largely due to UFPs' high mobility, which allows them to evade droplet contact, making capture more complex.

To improve performance, Bahri and al. (2021) analyzed the influence of water flow rate and velocity on UFP capture. Their results indicate that too low a flow rate (<20 ml/min) fails to capture particles effectively, while too high a flow rate (80 ml/min) may favor re-dispersion. An optimal range of 40–60 ml/min was recommended for effective reduction.

Furthermore, Kim and al. (2021) showed that reducing droplet size significantly enhances UFP capture. Specifically, ultrasonic atomization, which generates submicron droplets (~0.8 µm), doubles the PM1.0 capture efficiency compared to standard spraying methods. Nevertheless, these techniques alone are often insufficient to achieve optimal levels.

Zhang and al. (2022) highlighted that adding surfactants or applying an electrostatic charge to droplets significantly improves adhesion of hydrophobic UFPs, thereby optimizing their capture. Given the limitations of conventional methods, they advocated for hybrid strategies combining wet capture and electrostatic forces.

Electrostatic spraying, which leverages attraction between positively charged droplets and negatively charged particles, improves UFP capture by 30–50% compared to traditional spraying. In addition, Abellán-Nebot and al. (2024) demonstrated that MQL enriched with nanofluids offers another promising solution. Adding metallic nanoparticles (Al_2O_3, TiO_2) to cutting fluids improves UFP wettability and can reduce emissions by up to 80% under specific industrial conditions.

These findings reinforce Moreno-Ríos and al. (2022), who emphasized the importance of combining approaches to maximize capture efficiency and reduce worker exposure. Still, capture alone is not enough; source reduction is equally critical.

According to Songmene and al. (2018), optimizing machining parameters is key to limiting UFP generation. Bahri et al. (2021) observed that excessive cutting speeds (>2500 rpm) promote material fragmentation and nanoparticle formation. They also found that low feed rates increase friction and UFP production. An intermediate setting could reduce generation while preserving machining quality.

Moreover, the machined material itself affects UFP emission. Kouam and al. (2022) noted that granite with high silica content generates more UFPs than low-quartz materials. Adjusting cutting parameters and selecting suitable materials could reduce emissions at the source and ease the burden on capture systems.

In conclusion, Zhang and al. (2022) affirmed that effective UFP management requires an integrated approach: optimize machining conditions to reduce emissions, improve capture methods, and explore hybrid solutions such as electrostatic spraying and nanofluids. Bahri and al. (2021) confirmed that filtration and ventilation alone are insufficient. Likewise, Kim and al. (2021) stressed that while water is a viable option, its success depends on precisely controlled spraying conditions. Abellán-Nebot and al. (2024) supported the idea that combined approaches, including electrostatic spraying and nanofluid use, offer the best UFP capture performance. Moreno-Ríos and al. (2022) concluded that the future of UFP reduction lies in intelligently integrating technologies and continuously adapting to industrial and health constraints.

IV. Conclusion

In conclusion, the management of ultrafine particles (UFPs) in machining requires a comprehensive and integrated approach. On one hand, conventional methods such as local exhaust ventilation are insufficient, highlighting the need to explore alternative solutions such as water-based and hybrid capture techniques. On the other hand, while water appears promising, its effectiveness strongly depends on precisely controlled parameters such as flow rate, droplet size, and the application of electrostatic charges.

Furthermore, Minimum Quantity Lubrication (MQL) enhanced with nanofluids represents a major advancement, as it improves UFP wettability and reduces their dispersion into the air. However, source reduction remains essential, particularly by optimizing machining parameters and selecting appropriate materials.

Finally, the treatment of water loaded with ultrafine particles emerges as a crucial consideration to ensure reuse and minimize the environmental impact of industrial processes. Therefore, intelligent integration of these strategies and ongoing adaptation to industrial and health constraints are essential to sustainably improve air quality in the workplace.

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