

Evaluation of various improvements to an innovative wet scrubber concept to increase particle removal efficiency

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Abstract. With increasing filter efficiency, the need for energy-efficient methods to improve indoor air quality has grown. The investigated wet scrubber concept has lower pressure losses across the device compared to conventional wet scrubbers. The produced droplets in this wet scrubber are significantly larger than those produced in conventional wet scrubbers that use injectors to atomize the water. Larger droplets result in a reduced interface between water and particles. Therefore, while the new wet scrubber concept is more energy-efficient, it achieves lower particle removal efficiencies than conventional wet scrubber methods. Hence, various adaptations such as additives or surface modifications are used to increase the particle removal efficiency. Additives containing silicone and a rougher surface improve the particle removal efficiency by a factor of 3. However, combining the two does not improve the particle removal efficiency much more than the additives alone. Increasing the hydrostatic pressure on the perforated plate facilitates the water dripping and reduces the average droplet diameter, thereby increasing the water-particle interface. At twice the Weber number, the particle removal efficiency increases by a factor of 2.5 resulting in a particle removal efficiency of 67 % for larger particle diameters.

1 Introduction

The awareness of indoor air quality has risen in recent times, and the demand for a healthy indoor environment has come to focus. Indoor air contains solid and liquid pollutants that can lead to increased mortality and morbidity. Wet scrubbers remove both simultaneously and are already used in industrial applications such as particle removal in flue gas from coal combustion.

There are several wet scrubber concepts. The most common ones are spray towers, cyclonic wet scrubbers, and venturi wet scrubbers. Cyclonic wet scrubbers and venturi wet scrubbers operate at high relative velocities, resulting in high pressure drops across the unit compared to spray towers. In spray towers, the polluted gas flows upwards in a vertical vessel, while a fine liquid spray is injected downwards. The falling droplets collect the pollutants, and the contaminated droplets are removed at the bottom of the vessel. Spray towers have a particle removal efficiency of 90 % for particles larger than 5 μm in diameter. The efficiency drops to 50 % for particles smaller than 3 μm in diameter [1]. Raj Mohan and Meikap attached a bubble column to the top of the spray tower to increase the particle removal efficiency at small particle diameters [2]. They investigated the influence of various parameters such as gas flow rate and particle load on the particle removal efficiency for particles in the range of 1 to 500 μm . They measured a particle removal efficiency of 75 – 99 % depending on the configuration of their investigated parameters. Kim et. al. overcame the problem of low particle removal efficiencies for small particle sizes by

introducing an electrospray system that applies a high voltage [3]. With the additional electrostatic attraction and an increased liquid-to-gas flow ratio, particle removal efficiencies increased from 41 % to 84 % for 0.3 μm particles.

There is a vast number of publications on increasing the particle removal efficiency of wet scrubbers. This includes the removal in the submicron range of particulate matter. However, with increasing particle removal efficiencies, the research needs to focus on discovering energy-efficient particle removal methods. For this purpose, we developed a low-pressure wet scrubber concept utilizing large droplets in a previous study [4]. The concept works like a spray tower since the pollutants are removed by falling water droplets. We investigated particle removal efficiency and pressure drop for different scenarios covering a wide range of temperatures and humidities. The pressure drop across the studied wet scrubber is 4 to 7 Pa, depending on the scenario. However, due to the use of large water droplets, the new wet scrubber concept does not remove particles smaller than 4 μm in diameter and the particle removal efficiency for larger particles ranges from 10 to 38 % depending on the investigated scenario.

Kim et. al. studied the particle removal mechanisms of gravitational wet scrubbers and discovered that the particle removal efficiency of wet scrubbers depends on the terminal velocity, droplet size, and liquid-to-gas flow ratio [5]. The terminal velocity determines the droplet residence time, and a longer residence time increases the particle removal efficiency. An increase in residence time can also be achieved by decreasing the

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average flow velocity, increasing the channel length, or increasing the number of water droplets [6]. A higher number of droplets facilitates particle removal by increasing the active surface area between the water droplet and the particles. On the other hand, larger droplets can reduce the removal efficiency because of droplet oscillations, which also increase eddy shedding downstream of the droplet [7]. The oscillations result in a reduced droplet cross-section, while the shed eddies hinder the droplet from collecting the particles.

In this study, we will enhance our previous study [4] and analyze various modifications to the wet scrubber concept to improve particle removal efficiency in ventilation air.

2 Test bench and conditions

The investigated wet scrubber concept reduces the operating energy demand due to its low pressure drop across the unit. Fig. 1 shows the developed test bench, including the wet scrubber used for the experiments. The water droplets are injected crosswise into the airflow. A water basin is installed on top of the air duct, and water drips through a perforated plate located between the water basin and the air duct. The droplets are created by the hydrostatic pressure that the water exerts on the perforated plate. The dripping velocity and droplet size depend on the water mass flow rate. The droplets produced by this concept are significantly larger in diameter than those produced by conventional wet scrubbers that atomize the water. The larger droplets allow the use of droplet separators with lower pressure drops. Particle counts are measured downstream of the wet scrubber using a TSI 3330 portable Optical Particle Spectrometer (OPS). The measurable particle sizes range from 0.3 – 10 μm . Further information about the wet scrubber, the sensors, the droplet separator, the test bench, and the air supply are described in our previous study [4].

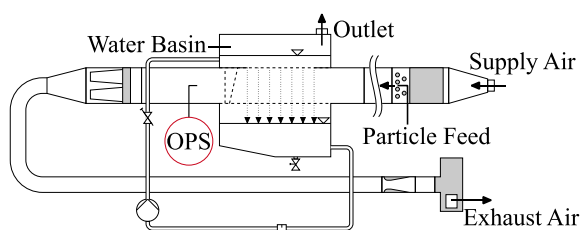


Fig. 1. Schematic diagram of test bench with wet scrubber

The developed test bench measures the number of particles at only one point. Therefore, the particle removal efficiency η , is defined as the relative difference in particle counts between consecutive test runs:

$$\eta = 1 - \frac{N_{\text{wet}}}{N_{\text{dry}}} \quad (1)$$

where N_{wet} and N_{dry} are the particle counts of a measurement with an active wet scrubber and a measurement with an inactive wet scrubber, respectively. We use A2 fine test dust according to ISO 12103 standards with a particle size distribution of

up to 176 μm . We can characterize the dripping regime with the Weber number We , which contains the density ρ , the droplet injection velocity v , the droplet diameter D , and the fluid surface tension σ :

$$We = \frac{\rho v^2 D}{\sigma} \quad (2)$$

We use empirical findings for needle dripping to approximate the transition We_i for the different dripping regimes of our perforated plate [8]. Therefore, the transition from periodic dripping (PD) to chaotic dripping (CD) and from chaotic dripping to jetting occurs at $We_1 = 1.07$ and $We_2 = 3.16$, respectively. Table 1 shows the test run conditions for the experiments. We repeat the experiments five times and average the results for the evaluation.

Table 1. Test run conditions of supply air

Parameter	Value
Air flow rate	560 m^3/h
Particle feed	1.11 g/h
Temperature	13 $^\circ\text{C}$
Relative Humidity	55 %

3 Experimental methodology

3.1 Influence of the wet scrubber operation on the particle count

Our previous study demonstrates that the investigated wet scrubber does not remove particles smaller than 4 μm in the studied scenarios. Furthermore, the results indicate negative particle removal efficiencies for small particle sizes. A measurement error is considered unlikely considering the calculated uncertainties.

In this study, we examine experiments with an active wet scrubber and no particle feed to determine if the increase in particle count is caused by small water droplets that pass the droplet separator. Moreover, we measure the particle removal efficiency for different horizontal OPS probe positions to investigate a possible shift of particles within the air duct during experiments with an active wet scrubber.

3.2 Dripping region length

The low-pressure wet scrubber concept relies on the hydrostatic pressure on the perforated plate to produce water droplets. We reduce the length of the perforated surface along the flow directions to investigate the effect of a shorter dripping region. However, by reducing the perforated area we achieve a higher hydrostatic pressure on the plate and a higher Weber number for the same water flow rate. This results in a higher water-to-gas flow ratio, which can increase the particle removal efficiency [5]. The experiments consist of perforated plates with a porosity of 1.3 % and a dripping region length of 200 mm, 400 mm, and 600 mm. The perforated plates have 1 mm diameter holes. Table 2 shows the volume flow rate at which the transition to the next dripping regime occurs for the different dripping region lengths.

Table 2. Volume flow rate for the dripping regime transitions

Plate	PD → CD	CD → Jetting
200 mm	0.81 m ³ /h	1.40 m ³ /h
400 mm	1.61 m ³ /h	2.77 m ³ /h
600 mm	2.41 m ³ /h	4.14 m ³ /h

3.3 Wetting of perforated plate

In the previous study, we discovered that the water does not drip cleanly from the holes of the perforated plate at low water flow rates. Fig. 2 shows the water adhesion to the underside of the 600 mm perforated plate at 4 m³/h. The falling droplets have a larger diameter than the hole diameter of the perforated plate due to wetting. Because of the wetting, the water from adjacent plate holes coalesces before falling as a large droplet or a ligament. The wetting of a solid surface is dependent on its roughness [9]. The roughness is defined as the ratio of the actual surface area to the geometric surface area. Increasing the roughness enhances the hydrophobicity or the hydrophilicity of a surface. Whether the roughness increases or decreases the wetting depends on the properties of the surface before modification. Usually, a hydrophilic surface becomes even more hydrophilic, and vice versa [10]. On hydrophobic surfaces, the roughness allows air to be trapped between the solid surface and the liquid droplet, while on hydrophilic surfaces, the roughness increases the contact surface area [11].

In this study, the surface roughness is modified using a random orbital sander with a coarse 24 grit attachment to reduce wetting. By decreasing the amount of water spread on the plate surface, the diameter of the falling droplets decreases because the water coalesces less on the underside of the plate before dripping.

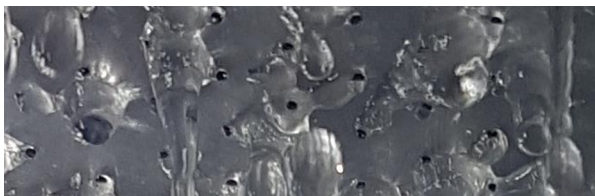


Fig. 2. Water behavior on the underside of the perforated plate

3.4 Water surface tension

Enhancing the particle removal efficiency can be achieved by increasing the number of water droplets [6]. This can be accomplished by either increasing the water flow rate or by reducing the surface tension of the water droplets with additives. The droplet size distribution depends on the surface tension of the liquid, and the average droplet size can be changed by adding additives to lower the surface tension [12].

The ability of water to spread on the perforated plate is defined by the spreading coefficient S , which is calculated with the surface energy of the plate γ_s , the surface energy of the water γ_w , and the energy of the solid-liquid interface γ_{sl} [13]:

$$S = \gamma_s - (\gamma_w + \gamma_{sl}) \quad (3)$$

A positive S means that the liquid spreads well on the solid surface. Additives can affect both the water surface

tension and the interfacial energy. Therefore, the effect on wetting depends on the degree of influence on the different parameters. In this study, defoamers with lower surface tension than water are used to investigate their impact on the wet scrubber's particle removal efficiency. A mineral oil-based defoamer, a silicon-based defoamer, and a polyether-based defoamer are investigated.

4 Results

4.1 Influence of the wet scrubber operation on the particle count

Fig. 3 shows the comparison between two different setups for the 600 mm perforated plate at a water flow rate of 4 m³/h. The first setup (red) displays the absolute difference in particle counts of consecutive experiments. In the consecutive experiments, we perform both experiments with an active particle feed. However, the first experiment is carried out with an inactive wet scrubber, while the subsequent experiment is performed with an active wet scrubber. The second setup (blue) shows the number of measured particles in an active wet scrubber experiment with an inactive particle feed. The measured particles in an active wet scrubber experiment with inactive particle feed are presumably water droplets. The OPS is expected to have a particle count of nearly zero in an inactive wet scrubber experiment with inactive particle feed because the supply air is filtered with a HEPA filter. The number of particles and droplets are plotted over the mean particle diameter of each OPS measurement channel on a logarithmic y-scale. The OPS bin with a mean particle diameter of 0.34 μm counts approximately 40,000 more particles in the active wet scrubber measurement than in the inactive wet scrubber measurement. For the same bin, the OPS counts approximately 50 water droplets that pass through the droplet separator. Overall, the number of additional particles in the active wet scrubber experiments is one to three orders of magnitude greater than the number of water droplets. The absolute particle count difference decreases as the mean particle diameter

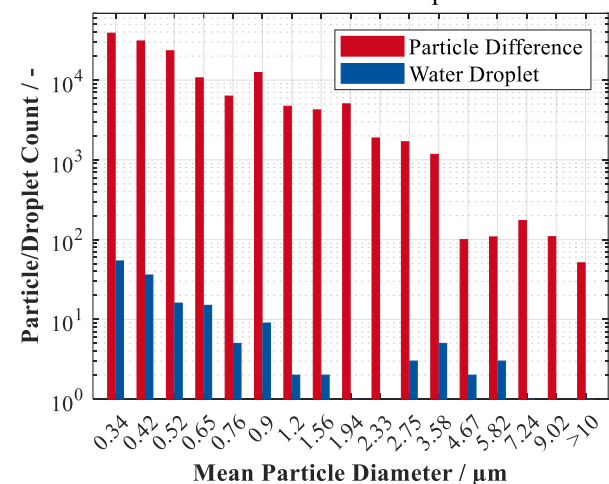


Fig. 3. Absolute difference of particle count of consecutive experiments (active particle feed, red) and particle count of active wet scrubber experiments (inactive particle feed, blue)

increases. The particle count differences at the mean particle diameters of 0.9 μm , 1.94 μm and 7.24 μm are higher than the counts in the adjacent bins.

Fig. 4 shows the particle removal efficiency over the mean particle diameter for a 600 mm plate at a water flow rate of 4 m^3/h . The different colored bars indicate the different positions of the particle probe. The results for the initial center position of the particle probe are shown in red. The blue and green bars represent the experimental results obtained when the probe is displaced horizontally by 6.25 cm (“Offset”) and 12 cm (“Far”) from the central position, respectively. The particle removal efficiencies for the “Center” and “Offset” experiments are negative for particle sizes smaller than 4.67 μm . Negative particle removal efficiencies indicate a higher particle count in the experiments with an active wet scrubber compared to the corresponding experiments with an inactive wet scrubber. The negative particle removal efficiencies for the “Center” experiments range from 0.7 % to 2.5 %, while the negative particle removal efficiencies for the “Offset” position range from 2.5 % to 3.5 %. The “Far” experiments with the probe closest to the wall show positive particle removal efficiencies for all particle sizes. The particle removal efficiencies for the “Far” experiments range from 3.7 % to 6.5 % for particle sizes smaller than 4.67 μm . The particle removal efficiencies for the “Center” and “Offset” experiments are in the same range, except for particle sizes larger than 10 μm . Here, the particle removal efficiency of the “Offset” experiment is the highest out of all three investigated scenarios at 22 %.

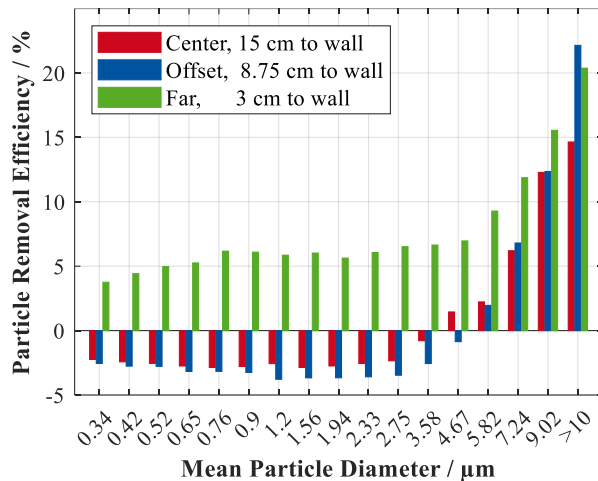


Fig. 4. Removal efficiency for different probe positions

4.2 Dripping Region Length

Fig. 5 shows the particle removal efficiency over the mean particle diameter for different dripping region lengths in the chaotic dripping regime. The Weber number for the investigated scenarios is $We \approx 1.6$. This results in the following volume flow rates for each plate: $\dot{V}_{200\text{ mm}} = 1\text{ m}^3/\text{h}$ (red), $\dot{V}_{400\text{ mm}} = 2\text{ m}^3/\text{h}$ (blue) and $\dot{V}_{600\text{ mm}} = 3\text{ m}^3/\text{h}$ (green). The particle removal efficiency of the 600 mm plate is higher than that of the 200 mm and 400 mm plates for particles larger than 5.82 μm . The 400 mm and 600 mm plates have similar

negative particle removal efficiencies for particles smaller than 2.33 μm in diameter. The positive particle removal efficiencies of the 400 mm plate are higher than the positive particle removal efficiencies of the 200 mm plate except for particles with a mean diameter of 9.02 μm . Furthermore, the 200 mm plate has a positive particle removal efficiency at 1.2 μm particles, while the particle removal efficiencies for all other scenarios below 2.75 μm are negative. At 0.76 μm , the removal efficiency of the 200 mm plate is about twice that of the other two investigated scenarios, while it has similar removal efficiencies at particle sizes smaller than 0.65 μm in diameter and at 0.9 μm particles. Based on our current knowledge, we are unable to identify a cause for the outliers at 0.76 μm and 1.2 μm particles for the 200 mm plate, but we do not consider these outliers to be plausible.

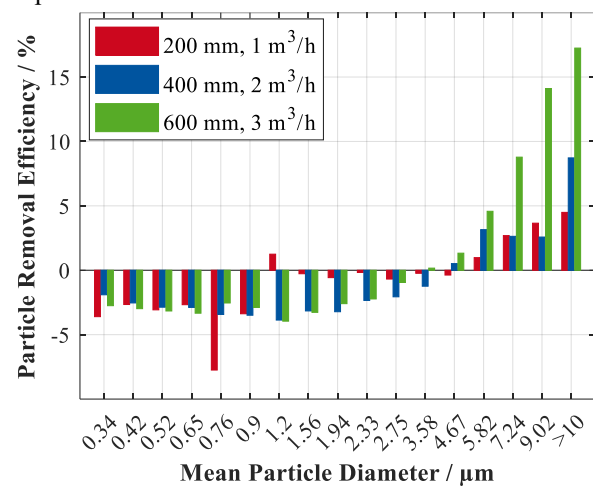


Fig. 5. Removal efficiency: Chaotic dripping for various plates

Fig. 6 shows the dripping behavior on the underside of the investigated perforated plates for a water flow rate of 4 m^3/h . The 600 mm plate displays chaotic dripping. The water exits the plate holes, spreads out on the underside of the plate, and coalesces with the water exiting the adjacent holes to form larger droplets before the droplets begin to fall. The 200 mm and 400 mm plates are in the jetting regime. Hence, the water exits the holes of the 200 mm and 400 mm plates as ligaments. The exit velocity is higher in the former, therefore, the water ligaments are stable for a longer time before breaking down into small droplets. With the 400 mm plate, the water does not form water ligaments as stable as with the 200 mm plate, and a small spread on the plate around the exit hole is seen.

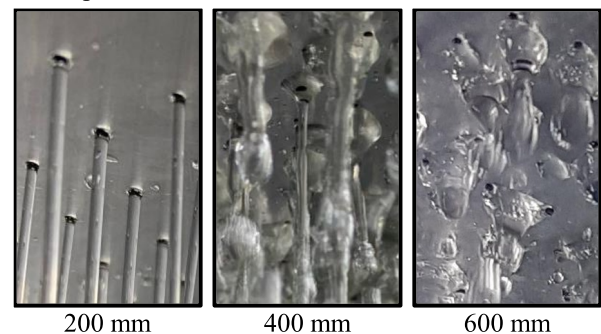


Fig. 6. Dripping behavior on the underside of perforated plate

Fig. 7 shows the particle removal efficiency over the mean particle diameter for different perforated plates at a water flow rate of $4 \text{ m}^3/\text{h}$. The various dripping region lengths have a different number of holes in the perforated plate, hence, at the same water flow rate, the velocity of each hole will vary between the plates. This results in the following Weber numbers: $We_{200 \text{ mm}} = 25.89$ (red), $We_{400 \text{ mm}} = 6.61$ (blue), $We_{600 \text{ mm}} = 2.96$ (green). In consequence, the dripping regimes for the plates differ. According to Table 2, the 200 mm and 400 mm plates are in the jetting regime, while the 600 mm plate is in the chaotic dripping regime. The 600 mm plate has negative particle removal efficiencies for particles below $5.82 \mu\text{m}$ in diameter and the 400 mm plate has negative particle removal efficiencies below $0.65 \mu\text{m}$ particles. The particle removal efficiencies for the 200 mm plate are positive for all the measured particle sizes. In general, for all particle sizes, the particle removal efficiency decreases with increasing dripping region length. The 200 mm plate has the highest particle removal efficiency of 55 % for particles larger than $10 \mu\text{m}$ in diameter.

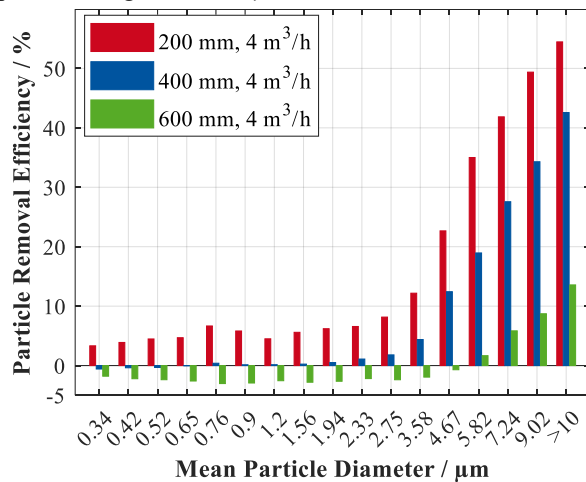


Fig. 7. Removal efficiency for different plates at $4 \text{ m}^3/\text{h}$

Fig. 8 shows the particle removal efficiency of the 400 mm (blue) and the 600 mm (green) perforated plates at a volume flow rate of $6 \text{ m}^3/\text{h}$. The particle removal efficiency is positive for all particle sizes with the 400 mm plate. The particle removal efficiency increases with particle size and ranges from 7.5 % to 67 %. The 600 mm plate has negative particle removal efficiencies for particles smaller than $4.67 \mu\text{m}$ in diameter. For particles exceeding $10 \mu\text{m}$ in diameter, the 600 mm plate exhibits a particle removal efficiency of 29%. The increase in the particle removal efficiency from $3.58 \mu\text{m}$ to $> 10 \mu\text{m}$ particles is steeper than the increase from $0.34 \mu\text{m}$ to $3.58 \mu\text{m}$ particles for both plates.

Fig. 9 shows the pressure drops over the water flow rate for all the investigated scenarios. A differential pressure sensor gauges the pressure drop in the air vent, measuring between a point slightly upstream and another slightly downstream of the water basin. The developed wet scrubber concept has a pressure drop of 4 Pa with an inactive wet scrubber. The pressure drops across the wet scrubber increase parabolically with increasing water flow rates. Depending on the flow rate

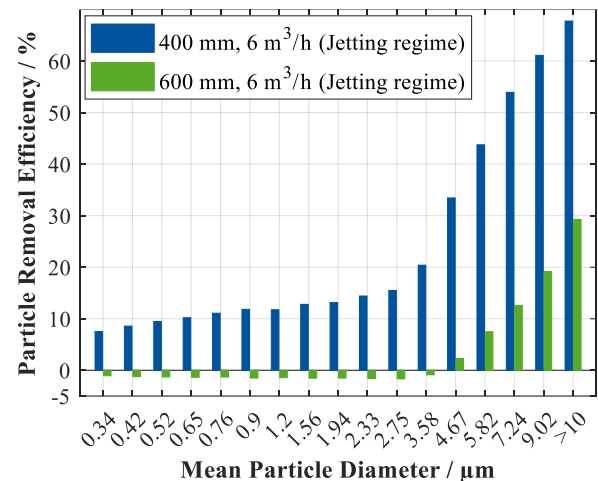


Fig. 8. Removal efficiency at $6 \text{ m}^3/\text{h}$ for different plates

the pressure drops range from 4 Pa to 8.5 Pa. For the same water flow rate, a shorter dripping region length results in an increased pressure drop across the wet scrubber. The 400 mm plate (blue) with a water flow rate of $6 \text{ m}^3/\text{h}$ displays the highest pressure drop among the investigated scenarios with 8.5 Pa. This is 1.9 Pa higher than with the 600 mm plate at the same water flow rate.

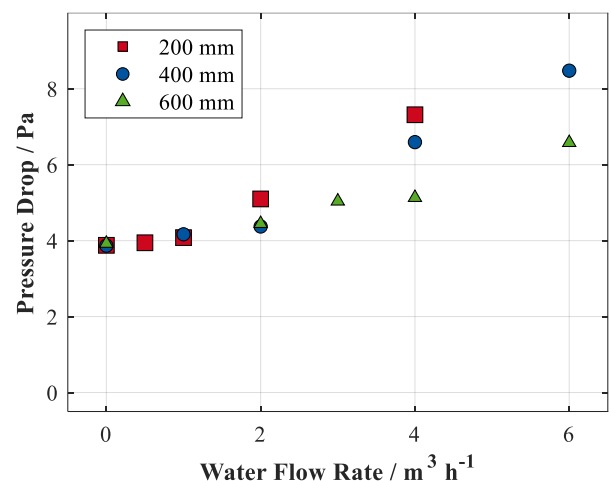


Fig. 9. Pressure drops for all experiments

4.3 Wetting of perforated plate and water surface tension

Fig. 10 shows the water spread on the underside of the perforated plate for different modifications to the wet scrubber setup and the unmodified setup. The various modifications are applied to a scenario with a dripping region length of 600 mm and a water flow rate of $4 \text{ m}^3/\text{h}$. Fig. 10 A shows the initial wet scrubber setup without any modifications to the perforated plate or additives in the water. Fig. 10 B – D are the wetting results for different defoamers added to the water while the perforated plate remains unchanged compared to the unmodified scenario. Fig. 10 E shows the water spread after changing the roughness of the plate surface and without additives in the water. Fig. 10 F shows the wetting of a perforated plate with a rough surface and a silicone-based defoamer added to the water. In the initial wet scrubber setup (A), water coalescence from adjacent

plate holes results in large droplets and wide water ligaments. The mineral oil-based defoamer (B) increases the wetting of the perforated plate. Therefore, the water coalescence involves more adjacent holes than in scenario A. With the silicone- and polyether-based defoamers (C, D) the water exits each hole as a ligament and the water coalesces less on the underside of the perforated plates. There is a small water spread around the holes where the water ligaments exit and some water ligaments exit the perforated plate holes with a slight offset from the vertical axis of the holes. In scenario E, the water exits the perforated plate holes in a straight vertical line. There is no coalescence of water from adjacent holes, and the water spread is barely visible compared to the scenarios with additives. Fig. 10 F shows a dripping behavior with no water coalescence on the underside of the perforated plate. However, the water ligaments do not exit the holes as orderly as in scenario E. Furthermore, some of the water ligaments appear to fall with a slight offset to the vertical axis of the holes, similar to the dripping behavior of the scenarios with silicon- and polyether-based defoamers. There is also a slight water spread around the holes of the perforated plate.

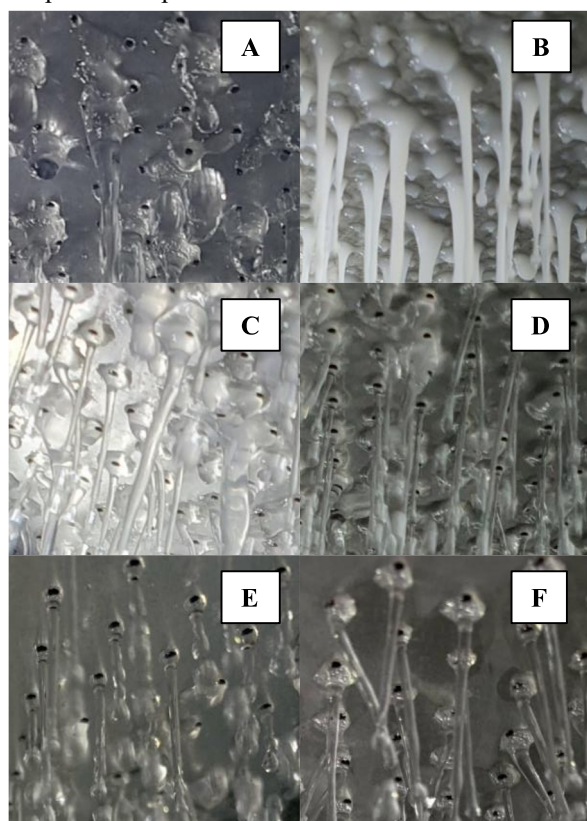


Fig. 10. Picture of the water spread on the underside of the perforated plate; A: unmodified, B: mineral oil-based defoamer, C: silicone-based defoamer, D: polyether-based defoamer, E: rough surface, F: rough surface + silicone-based defoamer

Fig. 11 shows the particle removal efficiency over the mean particle diameter for the initial wet scrubber setup without modifications (black) and the wet scrubber setups with different defoamers added to the water. The experiments with defoamers achieve higher positive particle removal efficiencies. Moreover,

silicon-based (blue) and polyether-based (green) defoamers have a positive particle removal efficiency at $4.67\ \mu\text{m}$, whereas the initial setup and the mineral oil-based (orange) defoamers display negative particle efficiencies at this particle size. The silicon-based and polyether-based defoamers show comparable positive particle removal efficiencies. The experiments with the mineral oil-based defoamer show higher negative particle efficiencies compared to the initial setup. The mineral oil-based defoamer scenario shows negative particle removal efficiencies between 3.5 % and 5.2 %, while the negative particle removal efficiencies of the initial setup are around 2 % to 3 %. The silicon- and polyether-based defoamers show comparable negative particle removal efficiencies to the initial setup. The mineral oil-based defoamer achieves 1 to 7 %-points higher particle removal efficiencies, while the other two defoamers achieve increases in particle removal efficiencies of about 5 to 27 %-points, depending on the particle size. For particles larger than $10\ \mu\text{m}$ in diameter, the silicon- and polyether-based defoamers achieve particle removal efficiencies of 40 %.

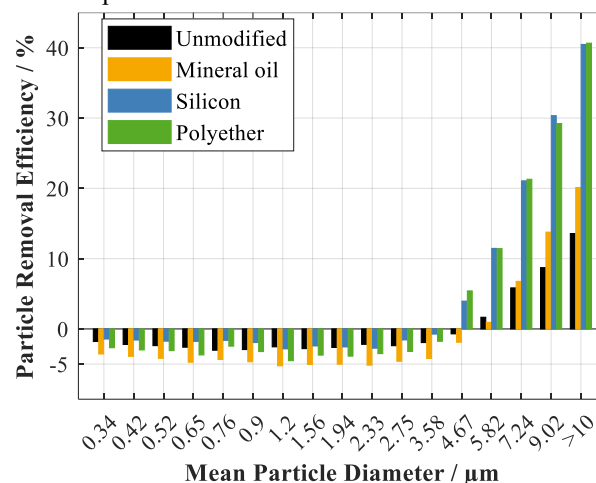


Fig. 11. Removal efficiency of various defoamer scenarios

Fig. 12 shows the particle removal efficiency over the mean particle diameter for different modification scenarios. The initial setup (black) is compared to the silicon-based defoamer scenario (red), a scenario with a rough plate surface (blue), and a scenario with both a rough surface and a silicon-based defoamer added to the water (purple). The rough surface scenario shows increased positive particle removal efficiencies compared to the initial setup. Moreover, the experiments with a rough plate surface display positive particle removal efficiencies for particles larger than $2.75\ \mu\text{m}$ in diameter, while the initial scenario and the defoamer scenario have negative particle removal efficiencies at $2.75\ \mu\text{m}$ and $3.58\ \mu\text{m}$ particles. The negative particle removal efficiencies of all scenarios are comparable. The increase in particle removal efficiency for a rough surface experiment compared to an unmodified setup ranges from 3 to 12 %. The rough surface experiment achieves its highest particle removal efficiency of 25 % for particles larger than $10\ \mu\text{m}$ in diameter. The combined modification scenario achieves particle removal efficiencies 2 to 16 %-points higher than the experiment with just a rough surface, and

3 to 27 %-points higher than the initial wet scrubber setup. However, the particle removal efficiencies of the combined scenario and the experiment with a silicon-based defoamer alone are comparable. In fact, the silicon-based defoamer achieves higher particle removal efficiencies at 7.24 μm and 9.02 μm particles.

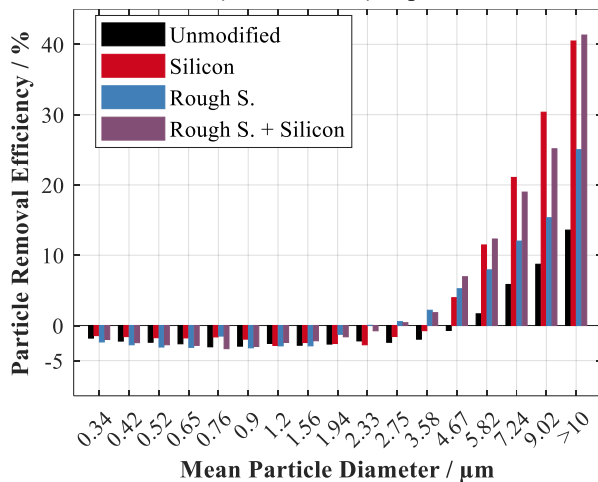


Fig. 12. Removal efficiency of different modifications

5 Discussion

The number of water droplets passing through the droplet separator is one to three orders of magnitude less than the number of additional particles counted in the active wet scrubber experiment. Hence, the number of water droplets passing the droplet separator may not be relevant to the negative particle removal efficiencies because the number is within the measurement uncertainties. The experiments with the offset OPS probe close to the wall display positive particle removal efficiencies for all particle sizes, while the experiments with the other probe positions showed negative particle removal efficiencies for particles smaller than 4.67 μm in diameter. The positive particle removal efficiencies may represent a particle removal by the wet air duct wall or a shift of particles towards the center of the air duct. The second reason would result in a higher particle count for active wet scrubber experiments with an OPS probe closer to the center position. The particle displacement near the wall may also occur with larger droplets ($> 4.67 \mu\text{m}$). However, this effect is difficult to quantify in this study due to the positive particle removal efficiencies at larger particle sizes. An agglomeration of small particles outside of the measuring range is not excluded and could also contribute to the negative particle removal efficiencies at small particle sizes.

A longer dripping region length results in higher particle removal efficiencies if the water flow rate is adjusted so that each plate has a similar Weber number. For the same Weber number, each plate has the same dripping regime and hence, the same terminal velocity and droplet shape. Therefore, a longer dripping region length facilitates particle removal due to the increased residence time of the particles within the dripping region. In the chaotic dripping regime, the particle removal efficiency of the plate with a larger dripping region is 13 %-points higher. However, for the same

water flow rate a perforated plate with a shorter dripping region results in a higher particle removal efficiency. A smaller perforated area creates a higher water column on the plate, resulting in an increased hydrostatic pressure that the water exerts on the perforated plate. A higher hydrostatic pressure increases the droplet terminal velocity and therefore the Weber number. At 4 m^3/h , the 600 mm plate is in the chaotic dripping regime, while the other two plates are in the jetting regime. In the jetting regime, the water exits the plate holes as ligaments that break up into smaller droplets as they fall. Furthermore, in the chaotic dripping regime, the water spreading on the bottom of the perforated plate is higher than in the jetting regime. The increased wetting causes water to coalesce on the underside of the perforated plate, resulting in larger droplets. Hence, a higher Weber number and therefore a higher droplet terminal velocity facilitates the particle removal efficiency because of the increased number of water droplets. A higher number of water droplets results in a larger interface between the water and the particles. For particles larger than 10 μm in diameter the particle removal efficiency increases by approximately 41 %-points with a 200 mm plate compared to the 600 mm plate. Moreover, the wet scrubber has positive particle removal efficiencies at small particle sizes for the same water flow rate with a smaller dripping region. The increased number of water droplets facilitates the removal of small particles possibly due to the increased interception of small particles. For the same water flow rate, a shorter dripping region results in a higher pressure drop across the wet scrubber because of the increased number of water droplets. With a 400 mm perforated plate and a water flow rate of 6 m^3/h , positive particle removal efficiencies are achieved across the entire investigated particle size range. At a water flow rate of 6 m^3/h , the particle removal efficiency of the 400 mm plate is about 39 %-points higher than that of the 600 mm plate. However, the pressure drop with the 400 mm plate is only 1.9 Pa higher than with the 600 mm plate in this scenario. With increasing water flow rates, the particle removal efficiency rises significantly while the pressure drop across the wet scrubber increases only slightly. In the scenario with the 400 mm dripping region, when the water flow rate is increased from 4 m^3/h to 6 m^3/h , the particle removal efficiency for particles larger than 10 μm increases by 25 %, while the pressure drop rises by 0.9 Pa.

Defoamers reduce the surface tension of the water. This can affect both the wetting of the plate and the average drop size. The mineral oil-based defoamer increases the wetting of the water and the water coalescence on the bottom of the perforated plate involves a higher number of adjacent plate holes compared to the unmodified case. However, the positive particle removal efficiencies are increased compared to the unmodified case, possibly due to the increased number of droplets within the air duct due to the lower water surface tension. The silicon-based and polyether-based defoamers reduce the wetting of the perforated plate. Hence, the average droplet size in the air duct is smaller than in the unmodified case due to the decrease in water surface tension and the decrease in water

coalescence on the underside of the perforated plate. The particle removal efficiency for both defoamers is similar and for particles larger than 10 μm in diameter, the defoamers increase the particle removal efficiency by a factor of 3, from 13 % to 40 %. The increase in the number of water droplets does not appear to be sufficient to enable particle removal at all small particle sizes, such as with a shorter dripping region. However, a similar effect can be observed with additives at 4.67 μm particles. Here, the silicon-based and polyether-based defoamers have positive particle removal efficiencies, while the unmodified scenario shows a negative particle removal efficiency at this particle size.

A rough surface can either enhance hydrophilicity or hydrophobicity. With the rougher perforated plate surface, we achieve a decrease in wetting. Without the water spread on the perforated plate, the water drips out of each hole in an orderly manner. This increases particle removal efficiency by up to 12 %-points over the unmodified scenario. A scenario with both a rough surface and a silicon-based defoamer does not result in higher particle removal efficiencies compared to the scenario with an unmodified surface and the silicon-based defoamer alone. The particle removal efficiency is similar for both scenarios.

Based on the results presented in this study, the investigated low-pressure wet scrubber concept cannot remove fine particles alone. However, it shows potential to be used as a pre-filter for coarse particles. Furthermore, wet scrubbers can additionally remove gaseous pollutants like volatile organic components and by varying the water temperature the wet scrubber can be used to condition the air temperature and humidity.

6 Conclusion

We applied modifications to the low-pressure wet scrubber concept and successfully increased the particle removal efficiency at the same water flow rate by either modifying the plate surface or adding an additive to the water. The rougher plate surface significantly improves the dripping behavior of this wet scrubber concept. However, defoamers that lower the water surface tension achieve higher particle removal efficiencies. Defoamers can both reduce the wetting on the bottom of the perforated plate and decrease the average drop size. A decrease in average drop size results in a greater number of water droplets for the same water flow rate. Furthermore, the particle removal efficiency can also be increased with the jetting regime of the water dripping. The jetting regime can either be achieved with an increase in the water flow rate or a shorter dripping region at the same water flow rate. Additionally, the low-pressure wet scrubber concept can remove particles with a diameter of 0.3 μm in the jetting regime. As the water flow rate increases both the particle removal efficiency and the pressure drop rise. Future work should investigate the agglomeration of particles smaller than 0.3 μm and quantify the contribution to the negative particle removal efficiencies. Moreover, it is necessary to investigate the vertical particle distribution, as this could contribute to the negative particle removal

efficiencies. The removal of gaseous pollutants, the conditioning, the additives' impact on the environment and the scalability of the concept need to be investigated for a holistic evaluation of the investigated low-pressure wet scrubber concept.

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