# Experimental study of an innovative wet scrubber concept in regards to particle filtration and pressure loss

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## ABSTRACT

The risen awareness of improved indoor air quality has resulted in an increased energy demand for HVAC systems due to higher air exchange rates and the additional operation of air purifiers. Therefore, the need for energy-efficient methods to improve indoor air quality has grown. In this experimental study, we develop an innovative wet scrubber concept to remove solid particles from the airflow. In contrast to conventional wet scrubbers, this concept uses a perforated plate and the hydrostatic pressure to feed water droplets into the air stream. The absence of injectors reduces the energy demand compared to common wet scrubbers, as the required pressure to generate the water droplets is significantly lower. In addition, the larger droplet sizes enable the usage of a matching droplet separator with negligible pressure drop. Within the scope of this work, we investigate the particle removal efficiency and the pressure drop for a range of ambient conditions, which represent the different seasons: summer, winter and transition period. Furthermore, we analyze three different volume flow rates of water to cover a broad spectrum of droplet formation regimes. In the scenarios investigated, we measure a pressure drop of 4 – 7 Pa and a particle removal efficiency of up to 38 %. The results show that the ambient conditions have little influence on the particle removal efficiency. However, the presented wet scrubber concept displays the same behavior as common wet scrubbers, where the particle removal is less efficient for smaller particles. The investigated wet scrubber concept demonstrates a significant decrease in particle removal efficiency for droplets with a diameter below 4 µm. Higher water flow rates improve the particle removal efficiency but also increase the pressure drop across the wet scrubber.

## KEYWORDS

wet scrubber, removal efficiency, energy efficient, particle, pressure drop

## 1 INTRODUCTION

Air pollution is one of the greatest environmental risks to human health. Ambient air consists of many harmful substances, which originate from numerous natural and anthropogenic sources. Among the various pollutants, fine and coarse particulate matter is one major contributor. They can penetrate deeply into the respiratory tract and increase mortality and morbidity even at low concentrations (World Health Organization, 2016). Many studies have shown that particulate matter is positively associated with an increased risk for cardiovascular diseases and respiratory diseases that, as a result, lead to increased hospital admissions (Adar et al., 2014; Beelen et al., 2014; Lu et al., 2015; Hystad et al., 2020; Yee et al., 2021).
Therefore, the removal of fine and coarse particulate matter from the supply air of buildings is necessary to improve indoor air quality and reduce the risk to human health. Fabric filters and wet scrubbers are common and efficient technologies in practical applications. Fabric filters are easy to install and can filter up to 99.99 % of the particles contained in the air stream. However, they are only useable in dry conditions due to fouling and need to be replaced periodically due to clogging caused by particulate build-up over time. In comparison, wet scrubbers are less efficient at removing particulate matter, especially at small particle sizes. However, they have the advantage of filtering both solid and gaseous pollutants and can be used in high humidity conditions (Cheremisinoff, 2002).
There are different wet scrubber concepts, which differ in particle removal efficiency and pressure drop in the airflow. The simplest wet scrubbers are spray towers or spray columns.

They achieve particle removal efficiencies of 90 % or higher for particles that are larger than 5 µm. However, the efficiency drops to 50 % or less for particles that are smaller than 3 µm. Cyclonic wet scrubbers and venturi scrubbers achieve higher efficiencies due to higher relative velocities and higher turbulence at the expense of higher pressure drops. Venturi scrubbers can achieve up to 99 % particle removal efficiency for particles larger than 1 µm. For submicron particles, the efficiency drops to 50 %. The pressure drop across a venturi scrubber can vary between 2400 Pa and 37 000 Pa. Higher velocities in a venturi scrubber will result in higher efficiencies but also to increased pressure drops (Schifftner and Hesketh, 2017).

Table 1 shows the particle removal efficiencies, the pressure drops and the particle sizes investigated in previous particle removal studies of wet scrubbers. (Biswas et al., 2008) investigated the influence of various parameters on the hydrodynamics of a counter-flow spray column. They found that the pressure drop increases with rising gas flow rates, liquid flow rates and solid loading conditions in the inlet. The droplets were in the range of 80 – 200 µm. (Raj Mohan and Meikap, 2009) investigated a two-stage “spray-cum-bubble” column scrubber to remove particulate matter in the range of 1 – 200 µm. This concept consists of a bubble column mounted above a spray column with a twin fluid air-assist atomizer. They studied the particle removal efficiency for varying water heights, gas flow rates and spray liquid flow rates. The droplets were in the range of 80 – 200 µm. They found that the contribution of the spray section of the combined wet scrubber is prominent. However, the bubble section can remove very fine particles that escaped the spray section. (Zhao and Zheng, 2008) performed a numerical flow simulation analysis of a gravitational wet scrubber with electrostatically charged particles and droplets. They found that the electrostatic enhancement increases the removal efficiency. (Lee et al., 2013) developed a turbulent wet scrubber by using high-velocity supply gas to displace water in a water reservoir, which creates droplets and turbulence. They found that the particle removal efficiency and the pressure drop increased with increasing water levels and gas flow rates. (Hu et al., 2021) conducted an experimental study on the particle removal efficiency of a wet scrubber with a radial mixing impeller. The mixing impeller generates a fine mist with the supplied water and separates the water-dust mixture through centrifugal force. They varied the number of blades and the water intake. The mixing impeller with 16 blades and medium water intake achieved the highest particle removal efficiency. The pressure drop increased with increased water intake. However, the particle removal efficiency did not correlate linearly with the number of blades. (Qian et al., 2022) proposed a numerical model to consider particle aggregation and particulate removal with a cyclonic wet scrubber with swirling flow. The gas flow rate, spray flow rate and particle concentration were varied to investigate the particle removal efficiency. High turbulent kinetic energy facilitated the high particle removal efficiency because turbulence supports particle aggregation. Furthermore, a big contact area between droplets and particles due to higher water flow rates was also positively associated with particle removal efficiency.

Table 1: Literature overview of particle removal efficiency, pressure drop and particle sizes

| Author | Particle removal efficiency / % | Pressure drop / Pa | Particle sizes / µm | Wet scrubber |
|---|---|---|---|---|
| Biswas | | 100 – 327 | 2 – 200 | Counter-flow spray Columns |
| Raj Mohan | 57.5 – 99.3 | | 2 – 200 | Spray & bubble column scrubber |
| Zhao | 5 | | < 1 | Gravitational wet scrubber, no charge |
| | 99 | | < 1 | Gravitational wet scrubber, charged |
| Lee | 87 – 99 | 1176 – 2157 | > 0.95 | Turbulent wet scrubber |
| | 43 – 79 | 1176 – 2157 | < 0.95 | Turbulent wet scrubber |
| Hu | 96 | 170 | 0.8 – 75 | Radial mixing impeller, 16 blades |
| | 86 | 264 | 0.8 – 75 | Radial mixing impeller, 20 blades |
| Qian | 99.7 | | 1 – 12.1 | Cyclone water spray, swirling gas flow |

Previous studies on wet scrubbers regarding particle removal mainly focus on different approaches to improve the removal efficiency of particulate matter, especially fine particles. These modified wet scrubber concepts can remove even fine particles very well. However, the studies do not consider the energy demand required to remove the particulate matter. With increasing particle removal efficiencies, the need for energy efficient methods has grown. Wet scrubbers are rarely used in residential buildings. They are mostly part of industrial applications with high particle loads in the exhaust air, such as coal combustion (Qian et al., 2022).
In this study, we investigate a wet scrubber concept, which aims at reducing the operational energy demand by reducing the pressure drop across the wet scrubber and by modifying the droplet generation method. We replace the spray injection of water droplets that wet scrubbers commonly use with a perforated plate and the droplets are fed into the airstream by dripping through the perforated plate. This reduces the required power to feed water into the wet scrubber because spray injections usually require a substantial pump head. Furthermore, the generated droplets in this wet scrubber feature a bigger diameter than droplets generated by spray injection. Hence, a droplet separator for bigger droplets with less pressure drop can be used to remove excess water droplets from the supply air vent (Bürkholz and Muschelknautz, 1972).

## 2 EXPERIMENTAL SETUP

### 2.1 Ventilation test bench

In order to analyze the removal efficiency and pressure drop of this wet scrubber concept we develop a test bench. Figure 1 shows the developed wet scrubber test bench and the positions of the utilized sensors. The air duct features a 300 mm x 300 mm cross-section, which tapers into a 130 mm diameter pipe at the end. The first HEPA filter at the beginning of the air duct removes ambient particulate matter in the supply air. An aerosol generator feeds the particles into the airflow downstream of the first HEPA filter. The particle feed's nozzle is positioned in the center of six horizontal cylinders that are staggered vertically. Each cylinder has a diameter of 35 mm. This cylinder arrangement introduces additional turbulence and facilitates a homogenous distribution of the particles within the air duct. A calming section of 1000 mm between wet scrubber section and cylinders enables particle mixing into the airflow and a homogenous flow structure. At the end of the wet scrubber section, a honeycomb structure with a depth of 80 mm and at an angle of 13° to the vent acts as a droplet separator. Another honeycomb structure with a depth of 40 mm directly downstream of the first one acts as a flow straightener. The honeycomb structures in this study have a diameter of 9 mm. The second HEPA filter downstream of the wet scrubber section protects the fan at the end of the pipe from the remaining particulate matter in the airflow.

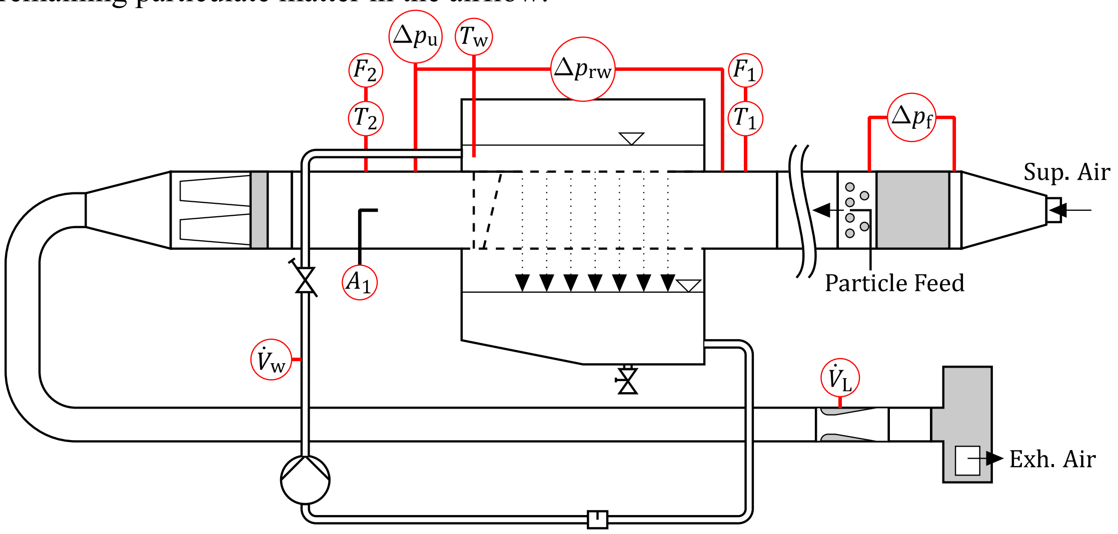


Figure 1: Schematic diagram of test bench

## 2.2 Wet scrubber section

The wet scrubber section consists of a water basin on top of the air duct, a perforated plate, a collection tank below the air duct, honeycomb structures, a pipe system and a pump. Figure 2 shows the perforated plate that separates the water basin from the air duct. The plate has a thickness of 1 mm.

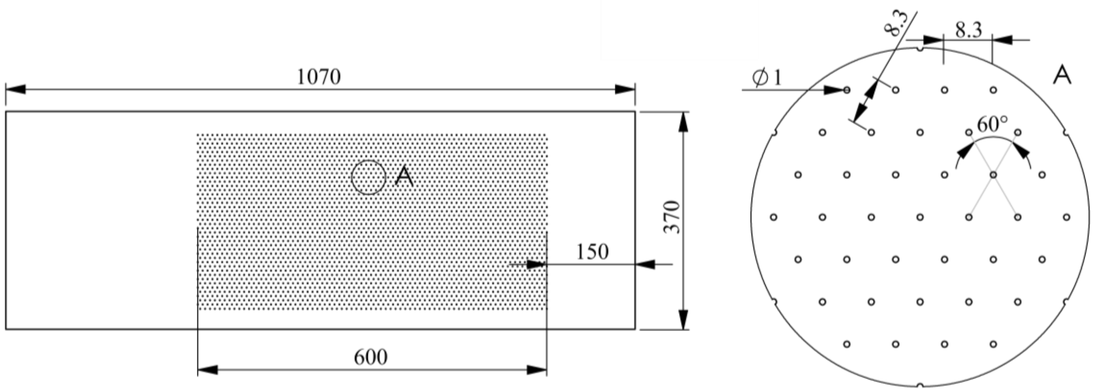


Figure 2: Perforated plate, dimensions in mm

Another horizontal honeycomb between the air duct and the collection tank prevents falling drops from bouncing back into the air duct after impinging on the water surface. A pipe system connects the water basin and the collection tank. It contains a pump, a line regulating valve and a filter. The pump circulates the water within the pipe system and controls the water mass flow. The line regulating valve supports pump control at low water flow rates by increasing the pressure drop and shifting the system's characteristic curve into the operating range of the pump. The filter has a 0.6 mm mesh and protects the pump from coarse particulate matter.

## 2.3 Sensors

A differential pressure sensor measures the pressure drop $\Delta p_{\mathrm{rw}}$ across the wet scrubber section. Another differential pressure sensor measures the pressure difference relative to the ambient air $\Delta p_{\mathrm{u}}$. This measurement allows the pressure in the duct to be monitored and adjusted in the case of overpressure. The pressure within the duct has a significant effect on the droplet shape due to the low pressures used to generate the droplets in this wet scrubber concept. A third differential pressure sensor measures the pressure drop $\Delta p_{\mathrm{f}}$ across the first HEPA filter to monitor the clogging of the filter. We use combination sensors to measure the temperature and the relative humidity before $(F_1, T_1)$ and after $(F_2, T_2)$ the wet scrubber section. A temperature sensor measures the water temperature $T_{\mathrm{w}}$ within the water basin. The water temperature is not controlled in this study. An optical particle sizer (OPS) measures the particle sizes and particle size distribution. The measurable particle sizes range from 0.3 – 10 µm. A 9 mm probe in the center of the air duct is installed 470 mm downstream of the wet scrubber area $(A_1)$. It is oriented parallel to the flow direction and guides the collected particles through a 90° elbow tube into the OPS. An external vacuum pump is connected to the probe to ensure isokinetic sampling. A venturi throttle in accordance to DIN 51678-1 measures the airflow rate $\dot{V}_L$. The fan of the test bench uses this measurement to adjust its fan speed according to the external air supply settings. An electromagnetic flowmeter measures the water volume rate $\dot{V}_{\mathrm{W}}$ in the pipe system. The programmable logic controller monitors the sensor values and adjusts the water and airflow rates. It measures the sensor data every 10 ms and averages the values.
An external air supply system provides the test bench with conditioned air via a tube. Figure 3 shows the setup of this external system. The air supply system consists of a sorption dryer, a fan, a cooler, a heater, a steam humidifier and various valves. The air supply system sucks in ambient air and conditions it according to the set boundary conditions. The different valves

regulate the airflow within the system and into the test bench. The supply system controls temperature and humidity using the sensor values of the wet scrubber test bench.

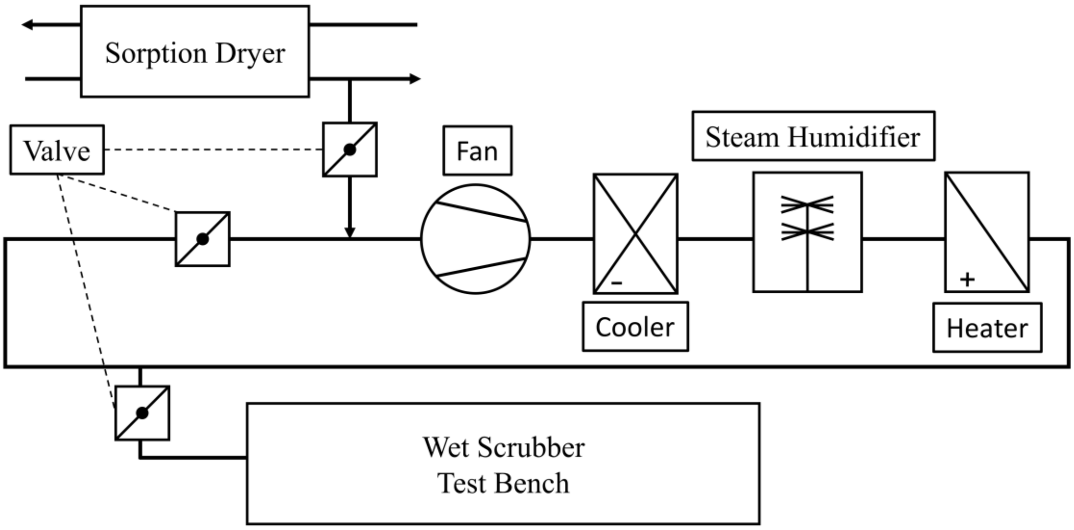


Figure 3: Schematic diagram of air supply system (Kremer and Mathis, 2020)

## 3 EXPERIMENTAL METHODS

During this study's experiments, the airflow rate is kept constant at $560\ \mathrm{m}^3/\mathrm{h}$. The aerosol mass flow rate is also kept constant throughout all experiments at 1.11 g/h. To evaluate the performance of the wet scrubber we define the particle removal efficiency $\eta$ as:

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

where $K_{\mathrm{wet}}$ and $K_{\mathrm{dry}}$ are the particle numbers per cubic meter with and without the wet scrubber running, respectively. The particle removal efficiency and the pressure drop are investigated for three different scenarios, which differ in temperature and humidity. Table 2 sums up the boundary conditions for each scenario.

Table 2: Boundary conditions of investigated scenarios

| Scenario | Temperature [°C] | Rel. Humidity [%] |
|---|---|---|
| Summer | 32 | 30 |
| Transition | 13 | 55 |
| Winter | 3 | 72 |

An experiment to determine the particle removal efficiency consists of two phases. In the first phase, the particle concentration is measured without the wet scrubber running. In the second phase, the measurement is performed under the same boundary conditions with an active wet scrubber. In each phase, the particle concentrations are measured for five minutes. These concentrations are used to calculate the particle removal efficiency. After each phase, a five-minute break is included to prepare for the next phase. The break after phase one ensures that there is sufficient time for the water in the water basin to reach a stationary level. The pause after phase two allows sufficient time for the water basin and the duct walls to dry.
The water flow rate is used to determine the critical Weber number. The critical Weber number defines the transition from dripping to jetting. (Clanet and Lascheras, 1999) experimentally determined the critical Weber number for the transition from dripping to jetting for needles. Although the present study does not investigate needle dripping, the findings from Clanet will be used to approximate the transition boundaries for our perforated plate. The critical Weber number for the transition from periodic dripping to chaotic dripping and from chaotic dripping

to jetting are approximately 1.07 and 3.16, respectively. Table 3 summarizes the regimes and the Weber number for the investigated water flow rates. The investigated water flow rates ($2\ m^3/h$, $4\ m^3/h$ and $6\ m^3/h$) cover three different regimes.

Table 3: Droplet Regime

| Water flow rate | Weber Number | Regime |
|---|---|---|
| $2\ m^3/h$ | 0.74 | Periodic dripping |
| $4\ m^3/h$ | 2.96 | Chaotic dripping |
| $6\ m^3/h$ | 6.65 | Jetting |

The OPS uses scattered light to determine the optical diameters of the particles. It divides the particle into 17 bins. From now on, unless otherwise noted, the diameter will always refer to the optical diameter. Table 4 shows the particle size ranges each bin covers. The OPS cannot size particles with a diameter greater than 10 µm and assigns them to bin 17.

Table 4: OPS bin particle size range

| **Bin** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Range [µm] | 0.3 - 0.374 | 0.374 – 0.465 | 0.465 – 0.579 | 0.579 – 0.721 | 0.721 – 0.801 |
| **Bin** | **6** | **7** | **8** | **9** | **10** |
| Range [µm] | 0.801 – 1.001 | 1.001 – 1.391 | 1.391 – 1.732 | 1.732 – 2.156 | 2.156 – 2.501 |
| **Bin** | **11** | **12** | **13** | **14** | **15** |
| Range [µm] | 2.501 - 3 | 3 – 4.162 | 4.162 – 5.182 | 5.182 – 6.451 | 6.451 – 8.031 |
| **Bin** | **16** | **17** | | | |
| Range [µm] | 8.031 - 10 | > 10 | | | |

For each of the investigated cases ten experiments are performed. The measurements are averaged in each case and the uncertainty of the measurement is determined according to (JCGM, 2008).

## 4 RESULTS

Figure 4 illustrates the particle count for each bin on a logarithmic y-scale for a case without active wet scrubber. The bin with the smallest particles (0.3 – 0.374 µm) has the highest number of particles with a count of approximately two million particles. The particle count decreases with larger particle sizes. Bin 6 and bin 9 show a slight deviation from the overall trend as their particle count is higher than both their neighboring bins. The bin with the largest particle sizes (> 10 µm) consists of approximately 370 particles.

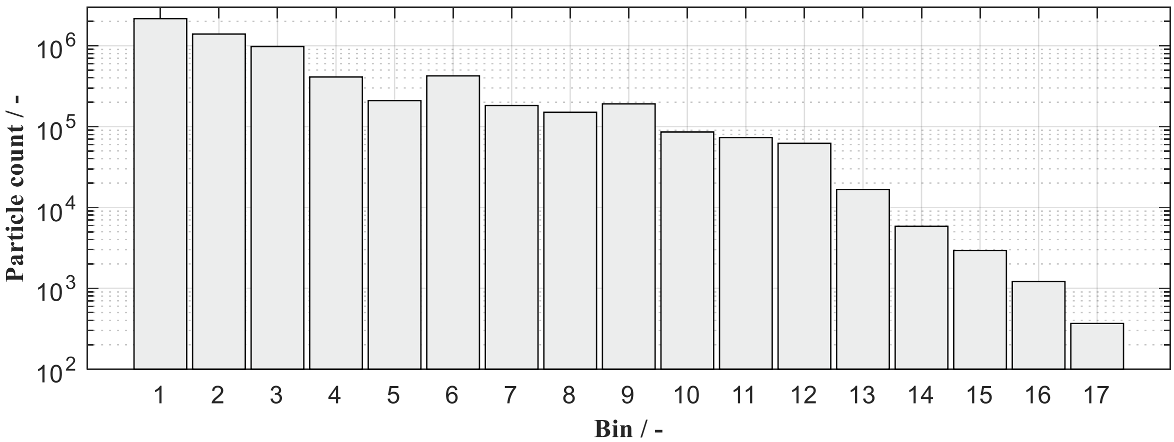


Figure 4: Particle count for one experiment without wet scrubber running

Figure 5 shows the pressure drop of the investigated wet scrubber over the water flow rate for all cases. The pressure drop increases with higher water flow rate. Depending on the water flow rate, the pressure drop ranges from 3.6 Pa to 6.9 Pa. The difference in pressure drop among the first three settings is 1 Pa on average. There is, however, a slight jump of approximately 2 Pa in the pressure drop at the highest water flow rate investigated.

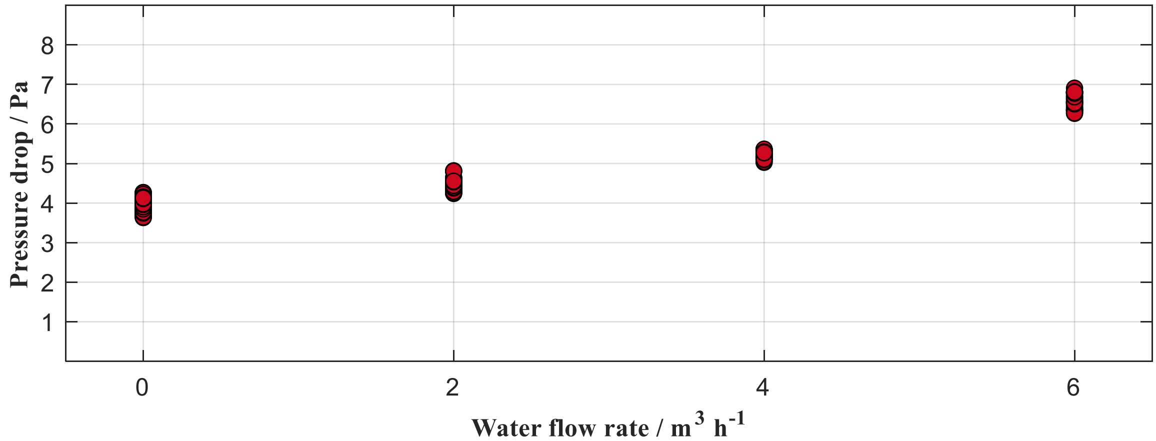


Figure 5: Pressure drop over water flow rate of all cases

Figure 6 displays the particle removal efficiency over the particle bins for the transition scenario at the three investigated water flow rates. The particle removal efficiency for bin 12 (3 – 4.162 µm) and lower bins is negative. This indicates that the particle count in the measurements with an active wet scrubber is higher than in the measurements with an inactive wet scrubber. In bin 13, the particle removal efficiency is positive for the highest water flow rate of 6 $m^3/h$ only. Starting from bin 14, the particle removal efficiencies are positive. In these bins, the particle removal efficiency increases with rising water flow rate and larger particle sizes. The efficiency rises up to 29 % for the largest particle sizes at the highest water flow rate. The uncertainty bars indicate a very good repeatability of the measurements at low bin numbers. The uncertainty increases with higher bin numbers to $\pm 3$ percentage points (pp). The negative particle removal efficiencies range from -1.2 % to -3 % with an uncertainty of approximately $\pm 0.23$ to $\pm 0.36$ pp. The most negative particle removal efficiency occurs in bin 6 for a water flow rate of 4 $m^3/h$. The described behavior can also be observed in the other scenarios.

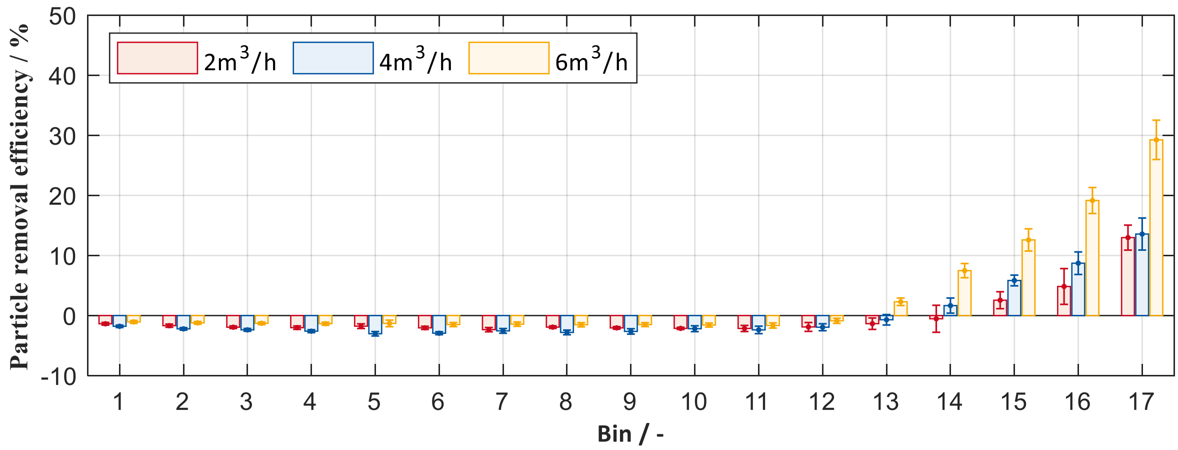


Figure 6: Particle removal efficiency for different water flow rates over the particle bins in the transition scenario

Figure 7 shows the particle removal efficiency for the various scenarios at a water flow rate of 2 $m^3/h$ (top), 4 $m^3/h$ (center) and 6 $m^3/h$ (bottom). At a water flow rate of 2 $m^3/h$, negative particle removal efficiencies occur in bins 14 and lower. The transition scenario shows the highest particle removal efficiency at approximately 14 % for particle sizes larger than 10 µm. Overall, all scenarios achieve similar efficiencies in all bins except in bin 17, where the transition scenario has an approximately 6 pp higher efficiency than the other scenarios. At a water flow rate of 4 $m^3/h$, the efficiencies behave similarly to the cases with a water flow rate of 2 $m^3/h$. However, in the higher bins, the positive particle removal efficiencies of the different scenarios are in the same range. At a water flow rate of 6 $m^3/h$, the particle removal efficiency in the summer scenario is about 8 – 10 pp higher than in other two scenarios, which show similar efficiencies. Across all water flow rates similar negative particle removal efficiencies are detected in the lower particle bins. In analogy to Figure 6 the particle removal efficiency increases for higher water flow rates in all scenarios.

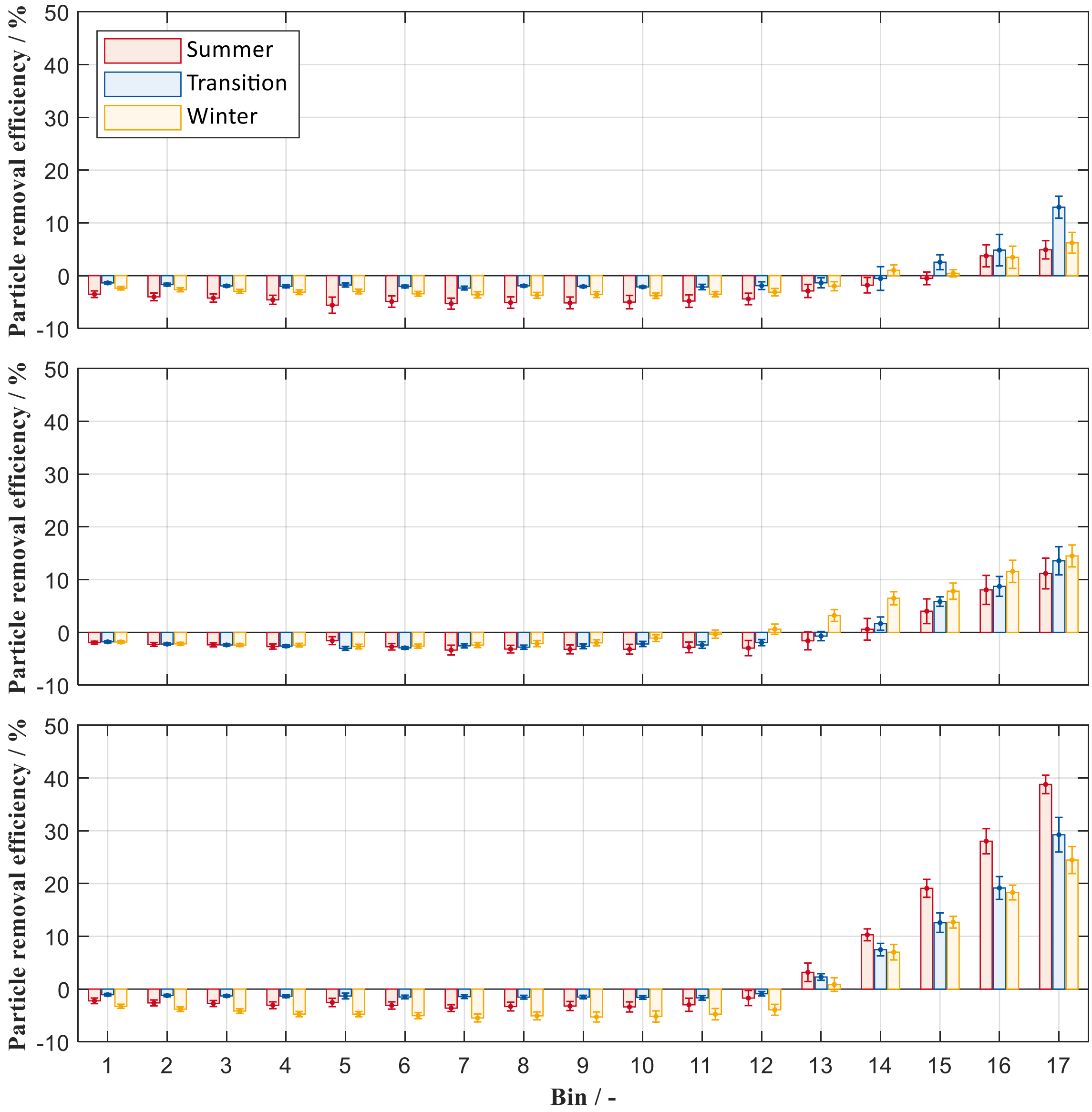


Figure 7: Particle removal efficiency for all scenarios at 2 $m^3/h$ (top), 4 $m^3/h$ (center) and 6 $m^3/h$ (bottom) for all particle bins

## 5 DISCUSSION

The high particle count in the lower bins allows for a better repeatability among the measurements because stochastic deviations are less significant compared to the total count. The pressure drop across the investigated wet scrubber is 1 – 2 orders of magnitudes less than in already existing wet scrubbers. This wet scrubber concept achieves a particle removal efficiency of up to 38 % depending on water flow rate and particle size. However, the particle removal efficiency of the investigated wet scrubber is significantly lower than for existing wet scrubbers due to the relatively low number of droplets in this concept. The water is not atomized due to the low pressures applied. Therefore, the droplet sizes for the investigated concept are larger than those for existing wet scrubber concepts. The investigated wet scrubber concept has a smaller water surface area as it produces less droplets and droplets with larger diameters. This results in a lower particle removal efficiency because particle removal via interception is less likely with less contact area between the water and the particles. The generated droplets are also significantly larger than the hole diameter of the perforated plate because the water wets the plate surface and coalesces into larger droplets before falling. At a water flow rate of $6\ \mathrm{m^3/h}$, the water forms ligaments through the plate holes without wetting the plate surface. These ligaments break into small droplets due to the relative velocity between the airflow and the water. The increase in particle removal efficiency at higher water flow rates is a result of the increased water surface area due to an increase in the number of droplets. The negative particle removal efficiencies may indicate an agglomeration of particles outside of the measureable range. However, the current OPS does not allow further investigation of particles smaller than 0.3 µm in diameter. Furthermore, the OPS detected an insignificant amount of particles in experiments with an active wet scrubber and an inactive particle feed. Hence, small water droplets that passed the droplet separator are not the cause of the significant increase in measured particles in the active wet scrubber measurements. Overall, the particle removal efficiency of each bin is approximately the same for the different scenarios. Therefore, temperature and humidity appear to have little influence on the particle removal efficiency. On the other hand, the particle removal efficiency increases with higher water flow rates.

## 6 CONCLUSION

We have developed a test bench to investigate our new wet scrubber concept. This wet scrubber concept reduces the energy demand by not using sprays to generate droplets and by having low pressure drops across the wet scrubber. The experimental results show, that the particle removal efficiency for coarse particles increases with higher water flow rates. A plate with a shorter perforated section may result in better droplet generation because the hydrostatic pressure is higher for the same water flow rate. Hence, the length of the perforated section shall be investigated in future studies. There is no particle removal detected for fine particles. However, if particle agglomeration occurs and increases particle sizes to larger diameters, this wet scrubber concept can be used as a pre-filter to another method that removes fine particles.

Further investigations could also address the adhesion of water to the plate surface. The adjustment of the adhesion between plate surface and droplet can result in better dripping behavior and smaller droplets, which increase the water surface area. An increased water surface area facilitates the particle removal efficiency for fine and coarse particles. The adhesion can be influenced by altering the roughness of the plate surface or by applying a waterproof coating to the plate surface. Wet scrubbers can remove particulate and gaseous pollutant. Therefore, the removal of gaseous pollutant needs to be investigated in future studies to facilitate a holistic evaluation of this wet scrubber concept.

## 7 ACKNOWLEDGEMENTS

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