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Dynamic Micro-granular Adsorptive Filtration (DmGAF): A Fouling-Resistant, Low-Cost Pretreatment for Zero Liquid Discharge in FGD Wastewater

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ABSTRACT

Zero liquid discharge (ZLD) for flue gas desulfurization (FGD) wastewater is often cost-prohibitive due to severe scaling/fouling. This study introduces Dynamic Micro-granular Adsorptive Filtration (DmGAF), a novel pretreatment technology with a self-renewing filtration mechanism that can handle high solids loadings without fouling. Pilot testing with high-solids influent (turbidity: 11.6–7,830 NTU) showed stable effluent quality (average 0.2 NTU) with operating pressure consistently <16 psi and no sign of fouling, highlighting DmGAF's potential to enhance ZLD system feasibility.

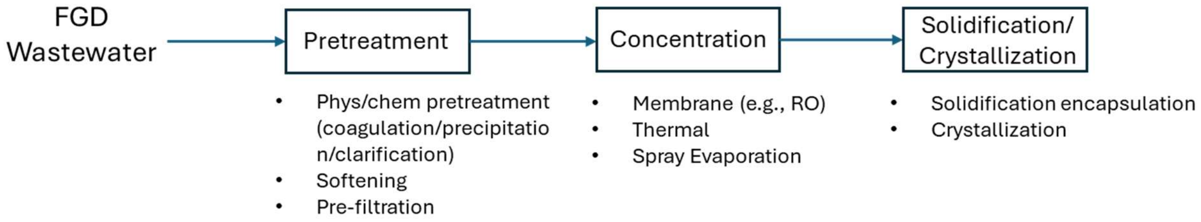
INTRODUCTION

BACKGROUND - Coal-fired power plants use flue gas desulfurization (FGD) systems, most commonly limestone-gypsum wet scrubbers, to control the sulfur dioxide emissions from coal combustion (Cordoba, 2015). FGD systems typically generate a wastewater stream that is super-saturated with respect to precipitation of gypsum (calcium sulfate) and contains high concentrations of suspended solids and dissolved solids, as well as trace levels of heavy metals (Koralegedara, 2019). The latest Steam Electric Power Generating Effluent Guidelines (ELGs), published by the Environmental Protection Agency (EPA) in May 2024 (EPA, 2024), require coal-fired power plants to achieve zero liquid discharge (ZLD) for all pollutants in multiple sources including FGD wastewater. Both the EU and China have their own regulatory drives for cleaner coal-fired energy, focusing on achieving ZLD of power plant waste. Many ZLD projects have been implemented, reflecting a global shift toward more sustainable waste management in the power sector.

Figure 1 presents a few examples of ZLD treatment processes for FGD wastewater. The overall process train can be categorized into three stages: pretreatment, concentration, and solidification/crystallization. The pretreatment processes remove components in the wastewater, such as suspended solids and hardness, that could affect later processes. The concentration stage, central to ZLD, significantly reduces wastewater volume using membrane (e.g., reverse osmosis) and/or thermal methods (e.g., mechanical vapor compression and multi-effect distillation). Often, multiple concentration steps are required. The resulting brine is then solidified through crystallization, in which water is evaporated to produce salts, or by encapsulation, in which the brine is stabilized with additives such as fly ash, lime, and cement to prevent leachate release (Zhang et al., 2020). Although it does not directly concentrate or reduce the volume of the wastewater, pretreatment is crucial to the overall ZLD process because it prevents scaling and fouling, which can lower efficiency and increase costs in both membrane and thermal systems.

Figure 1:

Treatment Process Example for ZLD of FGD Wastewater



Estimates for the operation and maintenance (O&M) costs to achieve ZLD vary widely, depending on the processes and parameters used for the estimate, the availability of resources (e.g., fly ash), and specific site conditions; recent estimates range from \$0.02 to \$0.24 per gallon (EPA, 2024; EPRI, 2023). Energy costs (electricity and heat) typically account for 25% to 34% of the O&M (Han et al, 2020), and maintenance, including cleaning and replacing core components (e.g., membranes), account for about 10%. These costs highlight the importance of the pretreatment steps in the ZLD, as energy costs and maintenance/replacement frequencies are impacted greatly by influent water quality and scaling.

As noted above, pretreatment removes suspended solids and, in some cases, hardness, from FGD wastewater. The total suspended solids (TSS) in the water ranges from several hundred to a few thousand mg/L and is mostly precipitated gypsum. Hydrocyclones are often used to remove the solids, but their performance can be uneven due to the large variability in water quality and flow rate. In other plants, solids removal is accomplished by settling in large impoundment ponds, but this approach might not be an option if land is unavailable or expensive. In yet other plants, large clarifiers and multiple stages of filtration (rapid sand filters and/or ultrafiltration) are used to remove the solids, in which case the pretreatment process becomes more complex and costly.

Chemical softening is sometimes included in the pretreatment stage to remove calcium and magnesium from FGD wastewater and thereby reduce the formation of gypsum scale on the treatment system surfaces. This is achieved by adding bases, typically calcium hydroxide or sodium hydroxide, and soda ash (sodium carbonate) to raise the pH of the water and precipitate calcium carbonate and magnesium hydroxide. However, chemical softening itself generates a large amount of suspended solids that need to be removed before the concentration steps. Depending on water quality, the TSS after softening can be as high as 30,000 mg/L. Chemical softening is usually followed by polymer flocculant addition and settling in large clarification tanks, and sometimes by sand filtration and/or ultrafiltration as well. If polymer flocculant addition is not carefully managed, the carried over flocculants can interfere with the subsequent filters. All of these steps increase the complexity and cost of the treatment.

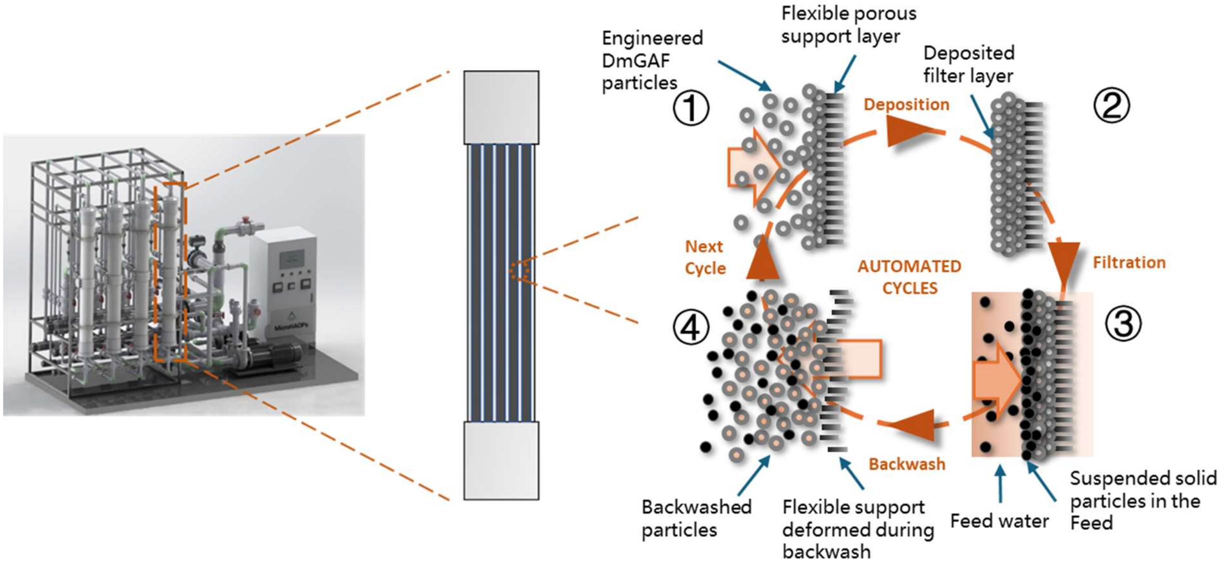
Here, we present case studies of the pretreatment of FGD wastewater with a novel high efficiency and anti-fouling filtration technology: Dynamic micro-Granular Adsorptive Filtration (DmGAF). This process can effectively replace multiple conventional treatment stages (clarification/sedimentation, pre-filtration and ultrafiltration) and eliminate the use of polymer flocculant. The process can help power plants achieve stable operation of their ZLD treatment systems while lowering overall costs.

TECHNOLOGY INTRODUCTION – In the DmGAF process, a layer of engineered micro- or nano- particles is first deposited on a flexible, polymeric mesh with micron-sized pores. Deposition is achieved by passing a slurry of the engineered particles through the mesh under carefully controlled hydraulic conditions. The water to be treated is then passed through the deposited layer, which serves as a filtration barrier that can achieve particle removal efficiencies comparable to those of ultrafiltration. The DmGAF filter can withstand high and variable solids loading, making the process ideal for FGD wastewater. At the end of a filtration step, usually triggered by a specified increase in the feed pressure, the filter is backwashed in an automated sequence during which the polymeric mesh undergoes elastic deformation that effectively sheds the deposited layer of engineered particles together with the retained solids from the FGD wastewater. After backwashing, a new active layer is deposited, and a new filtration cycle begins.

In summary, the DmGAF process circumvents the fouling issues that frequently plague conventional micro- and ultra-filters by utilizing a dynamic, temporary filter layer that can be easily, quickly and automatically deposited on and later removed from the surface of a flexible porous support. As will be shown, the process enables continuous operation over many deposition - filtration - backwash cycles and is applicable to high solids, high fouling source waters with variable flow rates and compositions. Figure 2 illustrates a DmGAF system and its operation cycles.

Figure 2:

System illustration and operation cycles of the DmGAF process



EXPERIMENTAL

CASE STUDY – In the Case Study, FGD wastewater from a coal-fired power plant in East China was treated onsite at a flow rate of 53 GPH (200 L/h). A two-stage, four-element DmGAF system was installed, but only one stage containing two elements with a total effective filter area of 1 m^2 (10.8 ft^2) was used during the test. The existing system at the plant treating the FGD purge includes a series of rapid sedimentation tanks (primary and secondary) followed by a tubular ultrafiltration system, with no chemical softening. Due to the high variability of the flow rate, the sedimentation tanks were ineffective, causing periodic carry-over of solids which frequently clogged the ultrafiltration system. Moreover, after prolonged fouling, the ultrafiltration effluent turbidity would gradually rise, sometimes to double-digit NTUs, posing a serious risk of damaging the downstream membrane concentration processes.

The DmGAF system was tested as a pretreatment alternative to the existing sedimentation and ultrafiltration system. The performance goals were to (1) consistently produce low turbidity effluent while (2) operating with consistently low feed pressures (i.e., low fouling) and (3) withstanding large fluctuations in influent water quality. The influent for the onsite testing was effluent from one of the primary sedimentation tanks. Some relevant water quality parameters from a sample of this feed water taken prior to the onsite testing are presented in Table 1. The turbidity and TSS of the FGD wastewater were highly variable during the testing , as will be shown in Figure 7 in the later chapter

DmGAF System – Figure 3 illustrates the DmGAF operational conditions used during the test. Silicon dioxide-based particles with an average diameter of approximately 23 microns were used to form the filtration layer. The particles, in the form of a dry powder, were added to a slurry storage tank at the beginning of each day. During operation, a predetermined volume of slurry was injected into the system with a metering pump, and the slurry was recirculated internally until essentially all the particles had been coated on the surface of the mesh substrate (as indicated by low turbidity of the circulating water). The duration of the deposition step can vary for different applications; in the Case Study, the duration was 30 min.

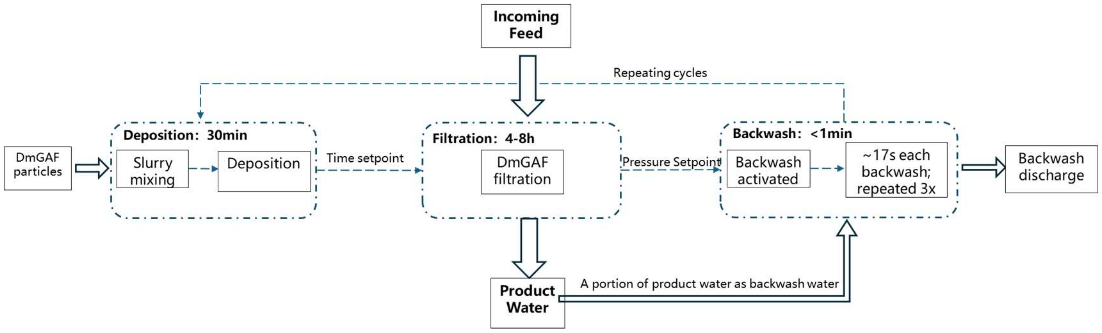
Table 1:

Feed FGD Wastewater Qualities

Parameters	Unit	Results
TDS	mg/L	34,800
TSS	mg/L	4,437
Turbidity	NTU	3,925
Hardness	mg/L-CaCO$_3$	18,600
Ca	mg/L	5,120
Mg	mg/L	1,232
Alkalinity	mg/L-CaCO$_3$	889

Figure 3:

Operational Conditions during the onsite DmGAF test



After the deposition step, water from one of the rapid sedimentation tanks was passed through the filtration element in dead-end filtration mode, and the effluent was collected. The filtration step continued either for four hours or until the feed pressure reached a setpoint of 16 psi (110 KPa).

Once the feed pressure setpoint was reached, the feed pump was turned off and the backwash pump was turned on. During backwash, permeate was pumped back into the filter elements in three pulses lasting approximately 17 seconds each. The volume of water used for backwashing was approximately 17.5 gallons (66 liters) per cycle. The backwash effluent slurry was discharged back to the sedimentation tank. The overall cycle lasted 4.5 to 8.5 h.

Some of the DmGAF system specifications are presented in Table 2, and Figure 4 shows images of the system at the project site.

Table 2:

DmGAF System Specifications

	System Specs
Power Loading	6.5kW
Effective Filter Area	0.5m^{2}x2 (5.4ft^2 x 2)
Operating Flux	50 - 250 LMH
Treatment Capacity	250L/h （1 GPM）
Footprint	4m x 1.5m x 2.2m （13ft x 5ft x 7.2ft）

Figure 4:

DmGAF System at the project site

Data Collection and Measurement – During operation, the feed flow rate, feed pressure, and effluent pressure were continuously monitored by an inline electromagnetic flowmeter and inline pressure sensors at the inlet and outlet of the filter element. Data was logged in the HMI system.

Feed and effluent samples were taken once or twice per hour and analyzed for turbidity using a Hach 2100Q portable multimeter and method DOC022.53.80041.

Turbidity and TSS Correlation – During the onsite testing, turbidity was used as the primary indicator of solids concentration. Both turbidity and TSS were analyzed for selected samples covering a wide range of turbidities. These data are presented in Table 3, and the Turbidity-TSS correlation is displayed in Figure 5. The two parameters were highly correlated (R^2=0.99) within the turbidity range tested. This correlation is used to estimate the TSS of the onsite samples based on turbidity data.

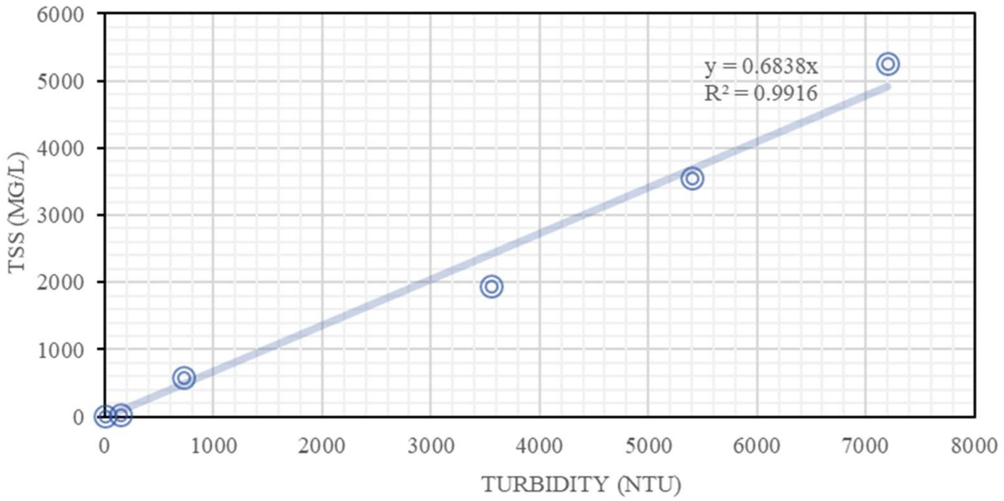
Table 3:

TSS and Turbidity of a few samples

No.	Turbidity (NTU)	TSS (mg/L)	Sample Source
1	0.99	4	Effluent
2	144	40	Influent
3	728	580	Influent
4	3,555	1,944	Influent
5	5,395	3,562	Influent
6	7,200	5,252	Influent

Figure 5:

Correlation between turbidity and TSS of the FGD samples



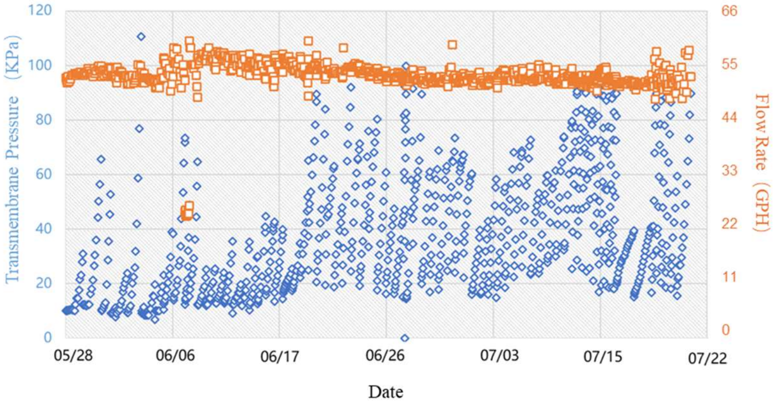
RESULTS AND DISCUSSION

INFLUENT FLOW RATE AND PRESSURE –The system operated continuously and stably with an average flow rate of 54.0±0.2 GPH (201.3 ± 6.7 L/h) during 80 treatment cycles over the two-month test period (May to July 2024) (Figure 6). (On June 7, one of the two DmGAF filter elements was offline for maintenance, so the total flow rate was one-half of that at all other times.)

In each filtration cycle, the pressure drop across the unit gradually increased during the filtration step. This pressure drop is analogous to the transmembrane pressure in a membrane system and is identified as such in the figures and subsequent discussion. In most cases, backwashing was triggered by the time filtration limit (four hours) rather than the transmembrane pressure (16 psi, or 110 KPa). Regardless of the trigger that ended the filtration step and initiated backwashing, the transmembrane pressure at the beginning of the next filtration cycle was in the range 2.9±1.5 psi (20±10 KPa), indicating the complete absence of irreversible fouling during the entire test period.

Figure 6:

System flowrate and transmembrane pressure during the test period



TURBIDITY REMOVAL – Figure 7 displays the influent and effluent turbidity during the test. The influent turbidity averaged 799 NTU but varied tremendously, from a minimum of 10.3 NTU to a maximum of 9,470 NTU. Based on the correlation in Figure 5, the corresponding estimated average influent TSS was 546 mg/L and the range was 7.0-6,475 mg/L. The influent turbidity was particularly high starting June 19, averaging 1,135 NTU (~776 mg/L TSS) from that date forward. During this latter stage of testing, the turbidity was >500 NTU (~342 mg/L TSS) in 61% of the samples, >1,000 NTU (~684 mg/L TSS) in 36%, and >2,000 NTU (~1,368 mg/L TSS) in 16%.

Figure 7:

Influent and effluent turbidity during the test period

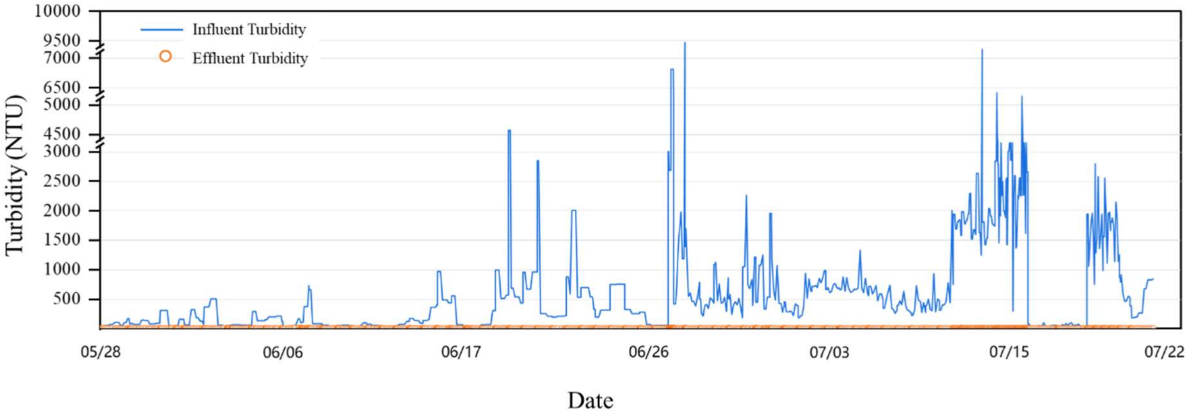
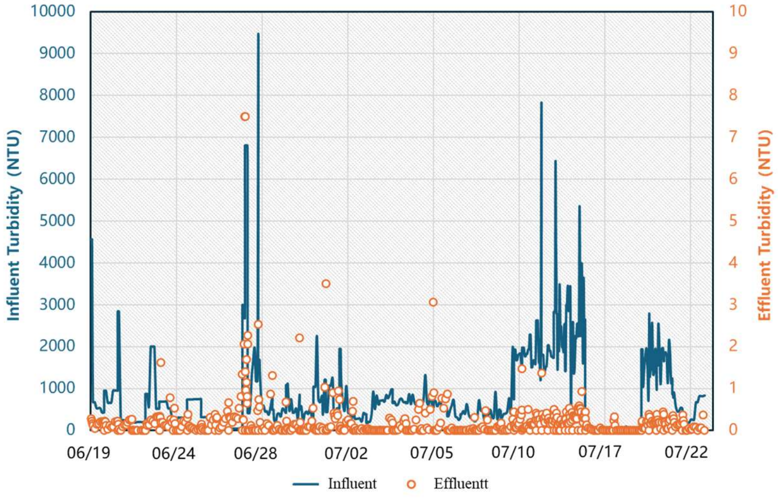


Figure 8 displays the influent and effluent turbidity during a portion of the period when the influent turbidity was especially high (June 19-22). During this period, 556 effluent samples were collected, and effluent turbidity averaged only 0.18 NTU. Of these samples, 98.2% had turbidities <1 NTU, and 93.2% had turbidities<0.5 NTU. The effluent turbidity exceeded the target of <1 NTU in occasional samples when the influent turbidity was extremely high. However, overall the system maintained very stable effluent quality, even in the face of high and fluctuating influent turbidity.

Figure 8:

Influent and effluent turbidity during periods of high influent turbidity

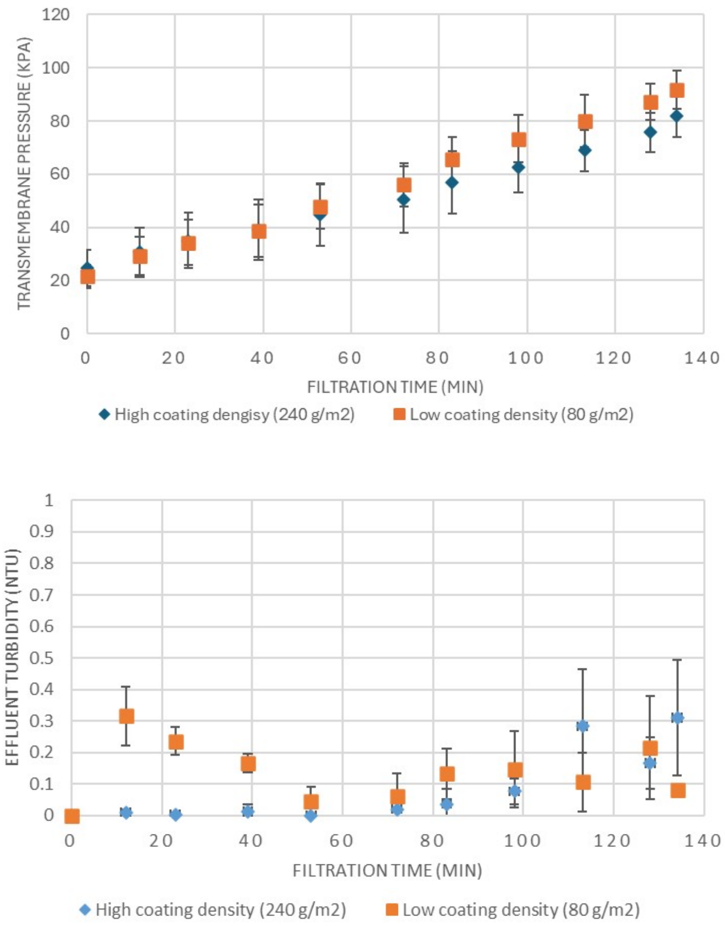


IMPACT OF COATING DENSITY – Coating density refers to the mass of DmGAF particles deposited per unit surface area of the porous substrate. Two coating densities were evaluated during the test period. Prior to July 10, the coating density was 240 g/m², and from that date onward the coating density was 80 g/m².

To reduce the impact of influent solids concentration when assessing coating density, seven data cycles with similar influent turbidity were chosen from both high (240 g/m²) and low (80 g/m²) coating density runs. The average influent turbidity during the selected high-coating-density cycles was 1,131 NTU, and that during the selected low-coating density cycles was 1,598 NTU. Figure 9 shows the average pressure and effluent turbidity for both these two groups of cycles. Despite the difference in coating density, both the transmembrane pressure increase and the effluent turbidity were very similar for the two groups. suggesting that the coating density for a full-scale application could be 80 g/m^2 or even less, thereby lowering the operational cost.

Figure 9:

Influent and effluent turbidity during high and low coating density period



The effective dose of filtration media (expressed in g/L or kg/t) is defined as the ratio of the mass of DmGAF particles used to the volume of water treated in a cycle. During the test period, the average effective DmGAF particle dose was 0.28 ± 0.09 g/L (range: 0.05-0.52 g/L). Since the operating time and thus the treated volume for a cycle is influenced by influent turbidity, the effective dose required for each cycle is also affected by influent turbidity. This relationship is discussed in the next Section.

IMPACT OF FEED TURBIDITY - Feed turbidity had notable impacts on the effluent turbidity and the duration of the filtration cycles, as discussed below.

Impact on Effluent Turbidity - Figure 10 shows that the impact of influent turbidity on the turbidity of the treated water is generally small up to influent turbidities of ~4000 NTU but is more pronounced at higher influent turbidities. Specifically, approximately 2% of effluent samples had turbidities exceeding 1 NTU when the influent turbidity was <4,000 NTU, compared to 42% when the influent turbidity was higher than that.

Impact on Water Recovery Rate - The single-pass permeate recovery rate is defined as the volume of permeate produced per cycle, after accounting for backwash water usage, divided by the volume of influent water fed to the system. During the stable operation phase, the average single-pass permeate recovery rate was 87% ± 8.4%, with a maximum of 96% and a minimum of 57%. During the onsite testing, the backwash water was pumped back to the sedimentation tank onsite.

The sludge from the sedimentation tank was managed by the plant and was not a part of the scope of the testing. Since the operating time (and thus the treated volume) per cycle is influenced by influent turbidity, the permeate recovery rate per cycle is also affected by influent turbidity. Because a high influent turbidity can shorten an operating cycle, it can reduce the volume of water processed and the permeate recovery rate and increase the effective dose. Figure 11 illustrates these effects for the period July 10-22. As anticipated, higher influent turbidity correlates with a more rapid increase in filtration pressure, shorter cycle times, lower permeate recovery rates, and higher effective doses.

EXAMPLE DmGAF TREATMENT PROCESS TRAIN - A treatment process train for DmGAF pretreatment of FGD wastewater is shown in Figure 12. A rapid sedimentation tank is recommended upstream of DmGAF to control the influent turbidity to below 2,000 NTU (estimated TSS 1,000 to 1,500 mg/L) to assure acceptable and stable effluent quality and a single-pass water recovery rate of at least 80%. As in the Test Case, the backwash from the DmGAF will be diverted to the sedimentation tank for further recycling and treatment. The sludge from the sedimentation tank can be treated by a filter press for dewatering. The treatment process can achieve zero liquid discharge while all FGD wastewater proceeds to the downstream concentration process.

Figure 10:

Impact of influent turbidity on effluent turbidity

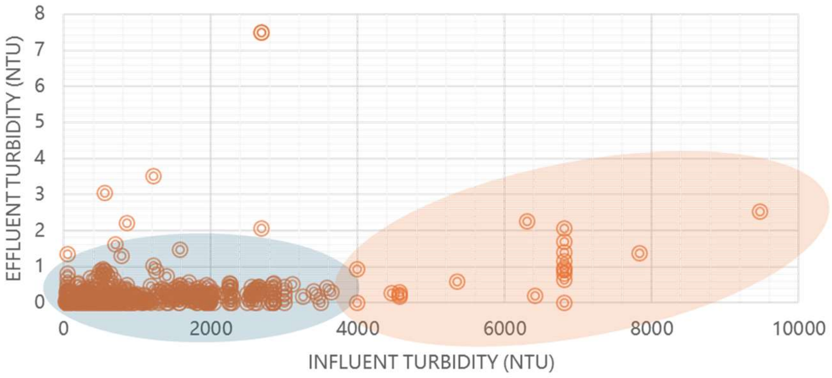


Figure 11:

Influence of influent turbidity on filtration duration, effective dose, and single-pass recovery

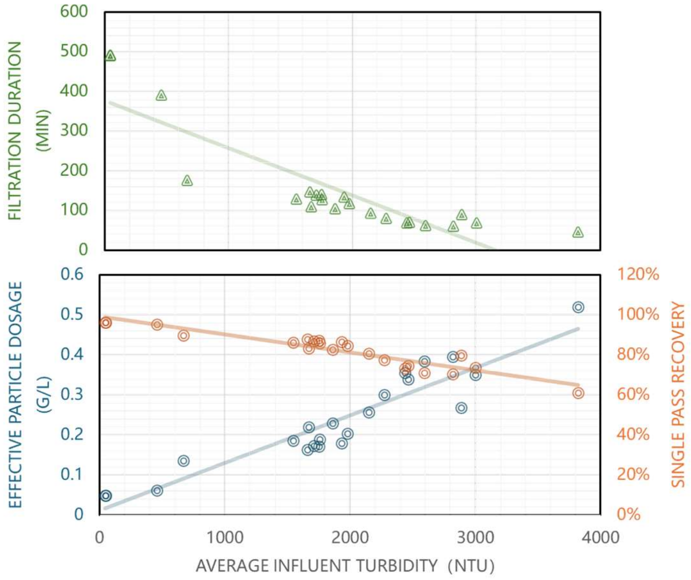
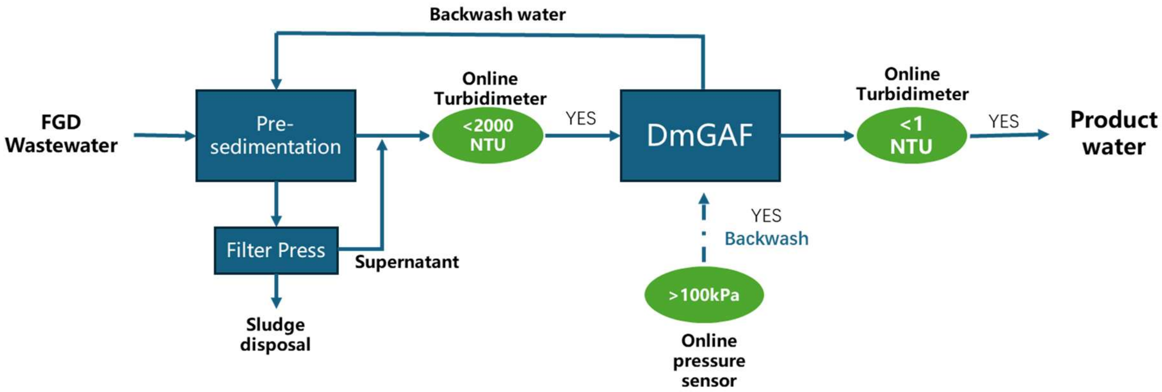


Figure 12:

Proposed DmGAF FGD pretreatment process for the water tested



CONCLUSION

A two-month test of the DmGAF integrated treatment system was conducted onsite at a coal-fired power plant. Based on operational and sampling data, the following conclusions were drawn:

The DmGAF process can effectively remove turbidity and suspended solids from FGD wastewater at coal-fired power plants, even when the feed water quality is highly variable. During two months of continuous testing, the process treated wastewater with turbidities ranging from 10 to more than 9,000 NTU (~7.0-6,475 mg /L TSS), with an average of 1,135 NTU (~776 mg/L TSS). The effluent turbidity averaged 0.18 NTU (~0.1 mg TSS/L), with 98.2% of the effluent samples having turbidity <1 NTU (<0.7 mg TSS/L).

For the entire test period, the effective filter media dose was 0.28 g/L, and the average single-pass permeate recovery rate was 87%.

Although the process can be successfully deployed for waters with a wide range of turbidities, higher feed turbidity does lead to shorter treatment cycles and reduced permeate recovery, and to a requirement for higher effective media doses. In a proposed treatment train, a sedimentation tank is placed upstream of the DmGAF process to control the influent turbidity/TSS and to further recycle the backwash water. This arrangement can improve the effective dosage and single-pass recovery rate in high influent turbidity/TSS scenarios.

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