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# A Study on the Scope for Improvement of the Operating Conditions at the Boundary Dam Unit 3 Carbon Capture and Storage Facility †

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**Abstract:** We will continue to rely on fossil fuel energy generation for at least this century. Reducing our carbon footprint is vital for the welfare of our environment and human health. The province we live in, Saskatchewan, is the second-highest emitter of $CO_2$ in Canada. This is primarily due to our reliance on coal-fired power plants for electricity. The Boundary Dam power plant in Estevan, SK, is the first-ever commercial power plant equipped with CCS technology. The current CCS process is highly efficient in capturing its carbon dioxide emissions and storing them underground. As with any first-of-its-kind project, numerous operational challenges have occurred that have affected the capture plant availability and, in turn, resulted in reduced efficiency of the plant. One of the major concerns is fly ash accumulation on plant equipment, which causes outages and the accumulation of fly ash in the amine-based absorbent that is utilized for capturing $CO_2$. This is primarily due to the transfer of PMs in the fly ash from pre-conditioning to downstream equipment. This study identified three alternatives to address PM accumulation and improve the operation of the capture facility: using a water and oil column, a hybrid electrostatic precipitator, and polytetrafluoroethylene (PTFE) membrane filters.

**Keywords:** CCS; boundary dam; fly ash; hybrid electrostatic precipitator; PTFE; carbon footprint

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## 1. Introduction

Boundary Dam Power Station Unit 3 is the world's first coal-fired power plant and capable of reducing its emissions of $CO_2$ by up to 90%. It has captured 5,376,837 tonnes of $CO_2$ since the beginning of its operation in 2014. However, since 2014, the CCS facility has experienced numerous operational challenges that affected the capture facility's availability [1]. Absorbers, strippers, and reboilers have been fouled overtime and required maintenance to restore the facility's capacity. Online and proactive maintenance, enhanced wash systems, and the addition of redundant equipment have increased the facility's availability and reliability. However, the accumulation of fly ash and heat-stable salts on the equipment and in the absorbent is still an issue. This results in higher regeneration temperature requirements, the transfer of heat-stable salts to the amine solvents, a loss of the solvents' capacity to absorb $CO_2$, and higher electricity requirements [1,2]. The aim of this study is to determine the scope of improvement of the operating conditions of the $CO_2$ capture facility at Boundary Dam Unit 3 and suggest alternatives to improve the fly ash removal process.

The pre-conditioning of flue gas removes more than 99.5% of fly gas before it is sent to the capture facility; however, the remaining 0.5 percent causes operational issues and results in unplanned outages of the facility [3]. The remaining particulate matter within

the fly ash accumulates on carbon capture equipment, which results in the fouling of equipment. Thus, periodic maintenance is required to remove PMs [4].

Fouling does not only occur on equipment that comes into direct contact with fly gas. Fly ash can dissolve in the amine solvents. Equipment that handles the solvent, such as the $SO_2$ reboiler, the $SO_2$ lean/rich heat exchanger, the $CO_2$ lean/rich heat exchangers, the lean amine cooler, and the wash water cooler also suffer from fouling and the buildup of scale [2,4]. Fouling in heat exchangers causes large differential pressures, limits the amine flow, and reduces the plant's availability. Buildup also creates an insulating layer between the plates, which reduces the heat transfer coefficients. This leads to reduced efficiency and higher energy requirements to maintain desired temperatures and, subsequently, leads to higher operational costs. Due to a lack of adequate isolations and redundancy in the original design, the plant had to be shut down for either chemical cleaning or pressure washing to remove the buildup in the heat exchangers [1,2].

## 2. Methodology and Approach

The methodology and approach used in this project included contacting the former Combustion Gas Clean Up Lead, SaskPower Clean Coal Project Wilf Olson, for feedback on operational issues. We also conducted a review and analysis of the existing CCS operation at Boundary Dam Unit 3. Additionally, we researched available technologies for fly ash removal from coal flue gas. Furthermore, a risk analysis was performed for identifying and mitigating risks. Lastly, a weighted decision matrix was developed to evaluate alternatives against several different criteria.

## 3. Design Alternatives to Address the Issue of Fly Ash Accumulation

The current particulate matter removal system at BD3 removes almost 99.5 percent of particulate matter from the combustion gas [4]. However, the remaining 0.5 percent of PM entrains the capture facility's equipment and has been a major cause of periodic planned and unplanned outages of the capture facility. Significant efforts have been made to address this issue, such as adding throat spray systems and spray curtains and performing periodic maintenance of equipment that is prone to clogging. The entraining particulate matter not only causes outages of the capture facility due to equipment clogging, it also degrades the quality of the absorbent that is used for absorbing particulate matter [5]. Thus, this results in a reduced carbon removal efficiency and requires a higher solvent regeneration heat. In order to minimize planned and unplanned outages due to equipment failures and solvent degradation, three alternatives are proposed. Below is a description of each alternative.

### *3.1. Removal of PMs and Some Gases Using Column of Oil and Water*

One of the methods for improving the efficiency of particulate matter removal is removal by mixing flue gas into a liquid. It is evident that mixing flue gas into water would result in a PM removal efficiency of 100 percent. The capturing of gaseous and particulate pollutants into a liquid phase using a water/oil column and microbubbles was reported in a study published in 2020, in which a PM capture efficiency of 100 percent was achieved [6]. The authors performed an experiment where gas containing PMs and some gaseous pollutants was bubbled into a liquid column. From the results of the experiment, it was confirmed that nano-sized particles that are hard to capture from gasses with conventional methods could be captured completely in water [7]. This oil and water column can be incorporated into existing PM removal systems, as depicted in Figure 1. It utilizes an existing ESP and flue gas cooler, which is then followed by the water and oil column, membrane filtration, and vacuum degasser.

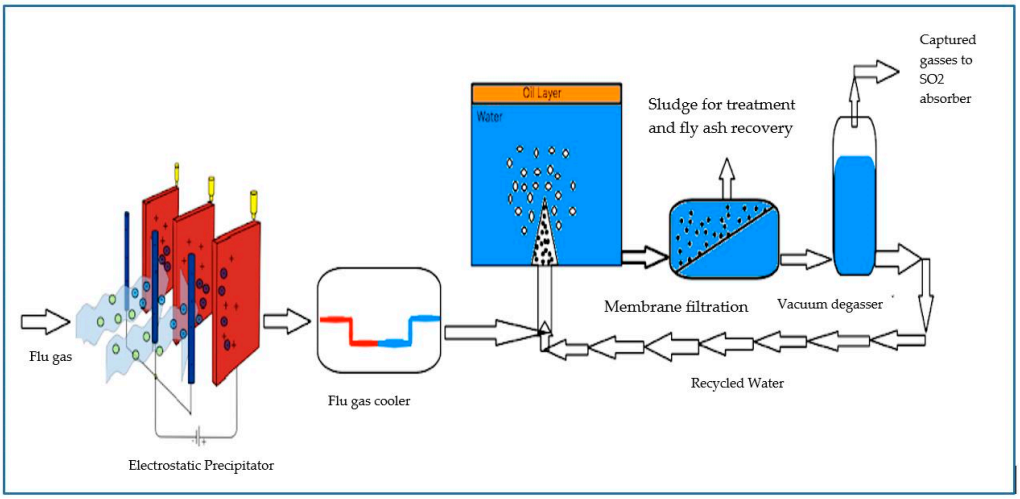



**Figure 1.** Particulate matter separation using water and oil column.

### *3.2. Hybrid Electrostatic Precipitator*

A hybrid electrostatic precipitator is a gas cleanup system that utilizes an electrostatic precipitator as the primary phase in the gas cleanup process and a baghouse filter as the subsequent stage. Figure 2 provides a schematic of a hybrid electrostatic precipitator. The electrostatic precipitator removes larger particles from the gas after charging, whereas the bag filter removes the remaining particles, which are usually smaller and pass through the electrostatic precipitator. In power plants, this type of technology is used to remove particulates of fly ash from exhaust gasses [8,9].

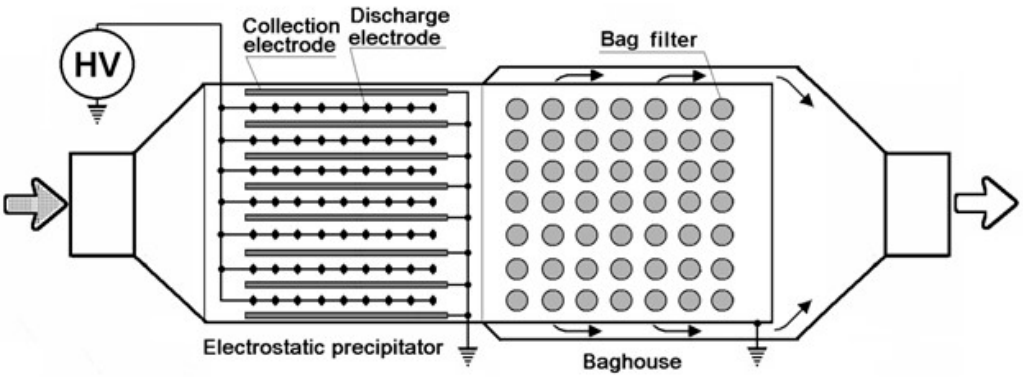



**Figure 2.** Diagram of a hybrid electrostatic precipitator and a bag filter from a top view: the gas flows into the bag from an outside source and exits through the upper opening of the bag [9].

To improve the collection performance of hybrid systems, the particle charging, precipitation, and bag filtering techniques have been integrated into a single device. Figure 3 provides an illustration of a hybrid electrostatic precipitator with a bag filter [9]. An electrostatic precipitator with perforated collection electrodes charges and precipitates the particles in this device. Particles of smaller sizes that are not precipitated go through the collection electrodes' openings and proceed straight into the parallel bag filters that are positioned between them. The gas in the bag filter moves from the exterior to the interior of each bag before escaping through the top opening [10].

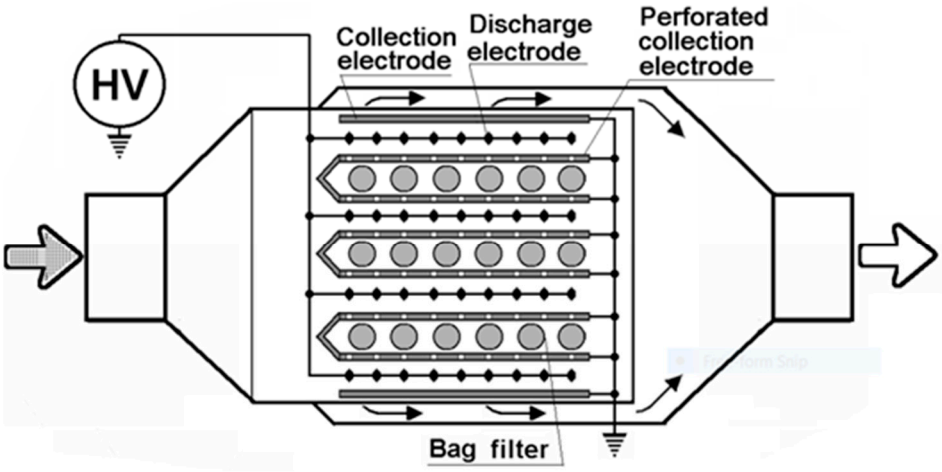



**Figure 3.** Illustration of a hybrid electrostatic precipitator using bag filters and electrodes with perforation from a top view: the gas enters the bag from the outside and exits using the outer opening of the bag [9].

### *3.3. Collection of PMs and Some Gases Using Poly Tetra Fluoroethylene (PTFE) Membrane Filters*

For extremely low PM emissions, filtration is still the most popular and efficient option, particularly membrane filtering technology [11]. The complicated composition of the incoming flue gas and the various operating conditions may, however, combine to adversely affect the system's filtering efficacy. In particular, humidity is the most crucial factor that significantly influences the effectiveness of filtration and resistance, as well as the service life of the filter media [12]. A process flow diagram utilizing the PTFE membrane filters has been illustrated in Figure 4.

Studies have shown that in the process of air filtration, the relative humidity (RH), dust characteristics (hygroscopic or non-hygroscopic), and filter medium surface hydrophobicity are highly related to one another. The filtration effectiveness of a filter is commonly assessed using hygroscopic NaCl and non-hygroscopic $Al_2O_3$ aerosols [13]. For non-hygroscopic aerosols or when the humidity is below the point at which hygroscopic aerosols deliquesce, the filtration resistance brought on by a particle cake typically decreases as the relative humidity rises.

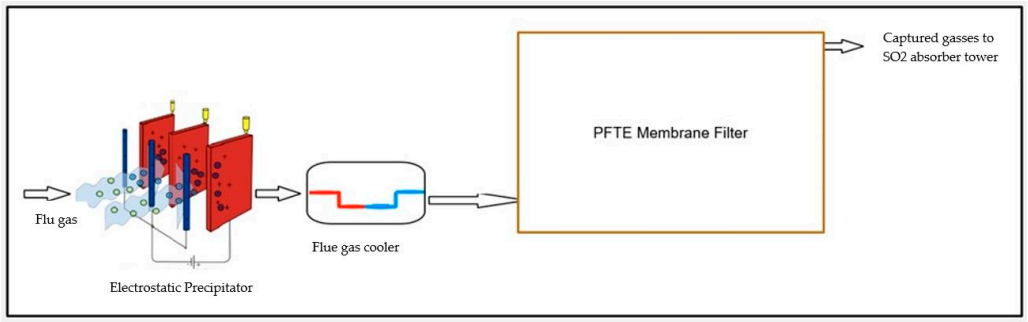



**Figure 4.** Schematic diagram of the PTFE membrane filter for the CCS project.

The membrane resistance brought on by the particulate cake grows more noticeably when the RH is over the hygroscopic aerosols' deliquescent points. In addition, aside from a liner relation to the filtration duration, the filtration resistance's rising tendency is more comparable to that of liquid aerosol [14]. The link between filtration efficiency, resistance, and filtration time is more complex in practical filtration operations than it is in simulated processes.

The hydrophobic property of membrane materials also has a significant impact on the filtration resistance in a system of humid filtration [12]. The impact of the filter hydrophilicity on filtration effectiveness was covered by Wang et al. When the RH is higher

than the hygroscopic aerosol's deliquescent point, hydrophilic filters initially exhibit a large increase in resistance, whereas hydrophobic filters continue to exhibit a higher rate of pressure decrease with time [15]. Hydrophobic filters exhibit a smaller pressure drop than hydrophilic filters when filtering non-hygroscopic particles at a high RH.

Filtration Tests

The filtering capabilities of PTFE membranes were evaluated using a filtration device [15], Aerosols were produced using the SAG 410 device and an air compressor. The vacuum pump was used to manage the subatmospheric pressure during the filtration experiment. Aerosols can be thoroughly combined in the vertical tube with a controlled concentration before being filtered by the membrane [16]. Continuous aerosol concentration measurements were taken using a laser particulate before and after the membrane module. With the use of a differential pressure transmitter, the pressure drop over the membrane was determined.

A mass flow controller was used to regulate the gas velocity. An autonomous monitoring and control system continuously recorded all the parameters. The environmental humidity was regulated using the steam humidification technique [12,16,17]. The dust inlet port on top of the vertical tube was connected to a humidity generator, which can produce regulated levels of moisture. Prior to the membrane module, the dust detector's placement was the first place where the relative humidity was gauged and noted [15].

## 4. Result Analysis and Discussion

All three alternatives—particulate matter separation using an oil and water column, a hybrid electrostatic precipitator, and poly tetra fluoroethylene (PTFE) membrane filters—are capable of achieving high PM removal efficiencies and result in reductions in the accumulation of PM on equipment. The current PM removal measures, such as the addition of mid-level wrapping, replacement of emitter wires, throat spray systems, spray headers, sprays at the top of the demister section, spray nozzles on the impellers of booster fans, and redundant equipment, result in improved operations of the capture facility and require less maintenance. However, very fine PMs remain in the flue gas, due to which fly ash issues remain. The three alternatives identified in this report all aim to improve the capture efficiency of PMs; however, risks associated with each alternative and criteria such as the capital cost, operation and maintenance cost, ease of implementation and use, energy requirement, etc., vary. In order to identify the most feasible solution, a risk assessment and weighted decision matrix are utilized.

### *4.1. Risk Assessment*

Every suggested treatment option carries an inherent possibility of risk. An evaluation of these risks was conducted to identify possible hazards and the corresponding precautionary measures. The potential risks linked with each individual alternative, along with their respective preventive actions, are detailed in Table 1. The identified risks were categorized and ranked as Very High, High, Medium, Low, or Very Low according to their likelihood. A risk with the greatest likelihood of occurrence was categorized as Very High, while a risk with the lowest likelihood received a rating of Very Low.

Each associated risk can be controlled by mitigating, transferring, avoiding, or accepting the risk. Most of the risks identified can be dealt with through mitigation measures presented in the table. However, the risk of environmental contamination from alternative sources remains high when using particulate separation using an oil and water column, even after mitigation measures. This is primarily because particles that are smaller than 0.01 um may still be present in the water after filtration, because the ultrafine membrane will only remove particles that are larger than 0.01 um.

**Table 1.** Risk assessment and potential mitigation measures.

| Alternative | Potential Risk | Pre-Response | Risk Response | Post-Response | Numerical Value | Total |
|---|---|---|---|---|---|---|
| Alternative 1 | Environmental contamination | VH | Water treatment prior to its release into the environment and performance of water quality test | H | 4 | 13 |
| | Noise pollution | M | Isolate and adequately seal equipment | L | 2 | |
| | Equipment failure | H | Monitor and inspect regularly | M | 3 | |
| | Particulate matter accumulation in downstream equipment | L | Continuously monitor and perform maintenance as required | VL | 1 | |
| | Health risk | H | Ensure equipment is sealed adequately to avoid exposure of toxic gasses to crew | L | 2 | |
| | Air quality | L | Perform air quality testing before emitting gas to the environment | VL | 1 | |
| Alternative 2 | Environmental contamination | L | Water treatment prior to its release into the environment and performance of water quality test | VL | 1 | 8 |
| | Noise pollution | M | Isolate and adequately seal equipment | L | 2 | |
| | Equipment failure | L | Monitor and inspect regularly | VL | 1 | |
| | Particulate matter accumulation in downstream equipment | M | Continuously monitor and perform maintenance as required | L | 2 | |
| | Health risk | L | Ensure equipment is sealed adequately to avoid exposure of toxic gasses to crew | VL | 1 | |
| | Air quality | L | Perform air quality testing before emitting gas to the environment | VL | 1 | |
| Alternative 3 | Environmental contamination (water) | M | Water treatment prior to its release into the environment and performance of water quality test | L | 2 | 10 |
| | Noise pollution | M | Isolate and adequately seal equipment | L | 2 | |
| | Equipment failure | H | Monitor and inspect regularly | L | 2 | |
| | Particulate matter accumulation in downstream equipment | M | Continuously monitor and perform maintenance as required | L | 2 | |
| | Health risk | L | Ensure equipment is sealed adequately to avoid exposure of toxic gasses to crew | VL | 1 | |
| | Air quality | L | Perform air quality testing before emitting gas to the environment | VL | 1 | |

### *4.2. Weighted Decision Matrix*

A weighted decision matrix illustrated in Table 2 was created to assess the three alternatives. Each alternative's performance across the designated criteria was assessed using a numerical ranking scale. This scale uses values ranging from one to five to indicate their respective performances, with five indicating the highest and one indicating the lowest. The matrix takes into consideration social, environmental, and economic factors.

Alternative 1 involving particle separation using a water and oil column has a score of 2.80. The main disadvantage of this alternative is its footprint in terms of the size, capital cost, time required to implement, and potential environmental contamination. However, one of the greatest advantages of this alternative is the particle removal efficiency. It has been proven that the water and oil column would result in a PM removal efficiency of 100 percent. Such an advanced water treatment system also involves a high capital cost, and this is also the main reason why this alternative has a relatively low score.

Alternative 2 consists of using a hybrid electrostatic precipitator for PM removal. It received the highest score of 4.18 in the weighted decision matrix. This is primarily because it has a high PM removal efficiency, is easier to operate and maintain, is easier to implement, and would have a high return in terms of investment.

**Table 2.** Weighted decision matrix.

| Parameters | | | Design | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Alterative 1 | | Alterative 2 | | Alterative 3 | |
| Criteria | Description | Weight | Rating | Score | Rating | Score | Rating | Score |
| 1 | Safety, health, and environmental impact | 0.08 | 3 | 0.25 | 4 | 0.34 | 4 | 0.34 |
| 2 | Capital cost | 0.10 | 2 | 0.19 | 4 | 0.39 | 5 | 0.48 |
| 3 | Operation and maintenance cost | 0.08 | 2 | 0.17 | 4 | 0.34 | 4 | 0.34 |
| 4 | Footprint of equipment in terms of size | 0.04 | 2 | 0.07 | 4 | 0.14 | 4 | 01.4 |
| 5 | Effectiveness in removing PM (efficiency) | 0.11 | 5 | 0.54 | 5 | 0.54 | 3 | 0.33 |
| 6 | Ease of use | 0.05 | 2 | 0.10 | 5 | 0.24 | 3 | 0.14 |
| 7 | Ease of implementation | 0.05 | 2 | 0.10 | 5 | 0.24 | 4 | 0.19 |
| 8 | Time required to implement | 0.04 | 2 | 0.07 | 4 | 0.14 | 4 | 0.14 |
| 9 | Time required to remove particulate matter | 0.05 | 3 | 0.14 | 4 | 0.19 | 4 | 0.19 |
| 10 | Feasibility (impact on other systems or equipment) | 0.06 | 3 | 0.18 | 4 | 0.24 | 4 | 0.24 |
| 11 | Support and enthusiasm (of team and of others) | 0.07 | 3 | 0.22 | 4 | 0.29 | 4 | 0.29 |
| 12 | Economical return on investment | 0.06 | 3 | 0.18 | 5 | 0.30 | 4 | 0.24 |
| 13 | Energy requirements | 0.08 | 3 | 0.25 | 3.5 | 0.30 | 3 | 0.25 |
| 14 | Reliability | 0.06 | 2 | 0.12 | 4.5 | 0.27 | 3 | 0.18 |
| 15 | Redundancy | 0.07 | 3 | 0.22 | 3 | 0.22 | 3 | 0.22 |
| **Total Score** | | | 2.8072 | | 4.1807 | | 3.7228 | |

Lastly, alternative 3, which utilizes poly tetra fluoroethylene (PTFE) membranes received a rating positioned between alternative 1 and alternative 2. The use of a poly tetra fluoroethylene (PTFE) membrane received a score of 3.72. The key advantages identified for this alternative were that it has a PM removal efficiency that will remain stable in terms of particle concentration and in terms of different pore sizes of the membrane. However, it also comes with disadvantages; for example, it would require humidity to be maintained to achieve maximum efficiency and would require the filtration velocity to be maintained well to achieve maximum efficiency.

## 5. Conclusions

The Boundary Dam Unit 3 CCS facility of Saskpower's coal-fired power plant is the world's first plant to capture and store carbon dioxide. It has demonstrated to the world that it is possible to capture and store carbon dioxide. Since the beginning of its operation, it has successfully captured and stored approximately 5,376,837 tonnes of $CO_2$ that could have been emitted into our environment. However, the road to achieving this number was not easy. There have been numerous unplanned outages since commissioning in 2014. Fly ash accumulation on facility equipment has resulted in numerous outages, such as fouling of absorbers, strippers, reboilers, booster fan, etc. Moreover, compressor failure is another

concern that has been occurring. In order to address fly ash issues, three alternatives were presented, which included capturing fly ash in a water and oil reservoir, a hybrid of ESP and baghouse filters, and poly tetra fluoroethylene (PTFE) membrane filters. Based on our risk analysis and weighted decision matrix, the hybrid of ESP and baghouse filter is the recommended alternative.

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## References

1. Pradoo, P.; Jacobs, B.; Hill, K.; Wilkes, S.; Ruffini, J.; Srisang, W.; Feng, Y.; Daverne, D.; Nelson, C. Improving the Operating Availability of the Boundary Dam Unit 3 Carbon Capture Facility. In Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16), Lyon, France, 23–27 October 2022. [CrossRef]
2. Giannaris, S.; Janowczyk, D.; Ruffini, J.; Hill, K.; Jacobs, B.; Bruce, C.; Feng, Y.; Srisang, W. SaskPower's Boundary Dam Unit 3 Carbon Capture Facility—The Journey to Achieving Reliability. In Proceedings of the 15th International Conference on Greenhouse Gas Control Technologies, GHGT-15, Abu Dhabi, United Arab Emirates, 15–18 March 2021. [CrossRef]
3. Yao, Q.; Li, S.-Q.; Xu, H.-W.; Zhuo, J.-K.; Song, Q. Studies on formation and control of combustion particulate matter in China: A review. *Energy* **2009**, *34*, 1296–1309. [CrossRef]
4. Stéphenne, K. Start-up of World's First Commercial Post-combustion Coal Fired CCS Project: Contribution of Shell Cansolv to SaskPower Boundary Dam ICCS Project. *Energy Procedia* **2014**, *63*, 6106–6110. [CrossRef]
5. Dindi, A.; Quang, D.V.; Vega, L.F.; Nashef, E.; Abu-Zahra, M.R.M. Applications of fly ash for $CO_2$ capture, utilization, and storage. *J. CO2 Util.* **2019**, *29*, 82–102. [CrossRef]
6. Sekiguchi, K.; Yasui, F.; Fujii, E. Capturing of gaseous and particulate pollutants into liquid phase by a water/oil column using microbubbles. *Chemosphere* **2020**, *256*, 126996. [CrossRef] [PubMed]
7. Payam, A.F.; Fathipour, M. A capillary force model for interactions between two spheres. *Particuology* **2011**, *9*, 381–386. [CrossRef]
8. Ortiz, F.G.; Navarrete, B.; Cañadas, L.; Salvador, L. A technical assessment of a particle hybrid collector in a pilot plant. *Chem. Eng. J.* **2007**, *127*, 131–142. [CrossRef]
9. Jaworek, A.; Sobczyk, A.; Krupa, A.; Marchewicz, A.; Czech, T.; Śliwiński, L. Hybrid electrostatic filtration systems for fly ash particles emission control. A review. *Sep. Purif. Technol.* **2019**, *213*, 283–302. [CrossRef]
10. Benson, S.A.; Pavlish, J.H.; Holmes, M.J.; Crocker, C.R.; Galbreath, K.C.; Zhaung, Y. Mercury control testing in a pulverized lignite-fired system. *Fuel Process. Technol.* **2009**, *90*, 1378–1387. [CrossRef]
11. Rao, C.; Gu, F.; Zhao, P.; Sharmin, N.; Gu, H.; Fu, J. Capturing PM2.5 Emissions from 3D Printing via Nanofiber-based Air Filter. *Sci. Rep.* **2017**, *7*, 10366. [CrossRef] [PubMed]
12. Huang, Y.; Huang, Q.-L.; Liu, H.; Zhang, C.-X.; You, Y.-W.; Li, N.-N.; Xiao, C.-F. Preparation, characterization, and applications of electrospun ultrafine fibrous PTFE porous membranes. *J. Membr. Sci.* **2017**, *523*, 317–326. [CrossRef]
13. Japuntich, D.; Stenhouse, J.; Liu, B. Experimental results of solid monodisperse particle clogging of fibrous filters. *J. Aerosol Sci.* **1994**, *25*, 385–393. [CrossRef]
14. Liu, X.; Xu, Y.; Fan, B.; Lv, C.; Xu, M.; Pan, S.; Zhang, K.; Li, L.; Gao, X. Field Measurements on the Emission and Removal of $PM_{2.5}$ from Coal-Fired Power Stations: 2. Studies on Two 135 MW Circulating Fluidized Bed Boilers Respectively Equipped with an Electrostatic Precipitator and a Hybrid Electrostatic Filter Precipitator. *Energy Fuels* **2016**, *30*, 5922–5929. [CrossRef]
15. Li, D.; Tang, X.; Feng, S. Humidity-control assists high-efficient coal fly ash removal by PTFE membrane. *Chin. J. Chem. Eng.* **2021**, *40*, 88–95. [CrossRef]

16. Hu, D.; Qiao, L.; Chen, J.; Ye, X.; Yang, X.; Cheng, T.; Fang, W. Hygroscopicity of Inorganic Aerosols: Size and Relative Humidity Effects on the Growth Factor. *Aerosol Air Qual. Res.* **2010**, *10*, 255–264. [CrossRef]
17. Kim, H.-J.; Park, S.J.; Kim, D.-I.; Lee, S.; Kwon, O.S.; Kim, I.K. Moisture Effect on Particulate Matter Filtration Performance using Electro-Spun Nanofibers including Density Functional Theory Analysis. *Sci. Rep.* **2019**, *9*, 7015. [CrossRef]

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