SAVONIA

THESIS - **MASTER'S DEGREE PROGRAMME**
TECHNOLOGY, COMMUNICATION AND TRANSPORT

CREATING DRY SORBENT INJECTION 3D MODEL WITH SYSTEM PARAMETER CALCULATION

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SAVONIA UNIVERSITY OF APPLIED SCIENCES THESIS
Abstract

Field of Study Technology, Communication and Transport			
Degree Programme Master’s Degree Programme in Energy Engineering			
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Title of Thesis Creating Dry Sorbent Injection 3D model with system parameter calculation			
Date	17 January 2022	Pages/Appendices	80/4
Supervisor(s) Teija Honkanen, Harri Heikura			
Client Organisation /Partners Sumitomo SHI FW Energia Oy			

Abstract

Speed, efficiency and competitiveness are major factors for any business to become a winning company. To gain that companies need tools such as Plant Design Management Systems (PDMS), and design solutions for a cost-effective flue gas cleaning technologies such as Dry Sorbent Injection (DSI). DSI is a pollution control technology of injecting a dry alkaline mineral into a flue gas stream to reduce acid gas emissions (i.e SO_2, SO_3, H_2SO_4, HCl, HF, Hg, dioxins and furans). The use of this technology is expanding rapidly as a low capital cost solution for compliance with environmental control requirements.

The purpose of this thesis was to create DSI Model using PDMS software by importing a calculation result value from another system and to explore the science behind all calculation. A literature review on dry sorbent was conducted. There are some variations of DSI so with these tools a designer can modify and take Material Take Off (MTO) quickly which is important in the bidding phase and the design phase.

The output of this thesis is DLL, a Library that contains the lines of code of the programming language and consists of functions, classes, variables, and user interfaces. PDMS customization is needed to create an interface between PDMS and .Net Framework, which is software developed by Microsoft. Source code compilation creates DLL needed in the PDMS environment. In this thesis, the phrase "DLL" is referred to as a "Tool" instead. Then this tool can be accessed from a pulldown menu.

Keywords
PDMS, 3D Model, Baghouse, Flue Gas Cleaning, DSI, Dry Sorbent Injection, Pulse Jet, Cost

PREFACE

First of all, I want to thank God for giving us health in this pandemic, therefore I can do thesis work and thanks to my family for their support.

I would like to thank Teija Honkanen for her big effort to supervise me in this thesis. She came to my office to conduct a thesis meeting with Sumitomo Supervisor Pasi Liimatainen and Ari Ojala. Thank you very much, Pasi and Ari, for your time, precious guidance, and giving me the opportunity to take this subject as my master's thesis topic plan.

Varkaus 17 January 2022
Achmad Yusuf

CONTENTS

Abbreviations and definitions

API = Application Programming Interface
APTI = Air Pollution Training Institute
ASTM = American Society for Testing and Materials
BBR = Bottom Bag Removal
BET = Brunauer Emmet Teller
BFB = Bubbling Fluidized Bed
B-PAC = Brominated- Powdered Activated Carbon
CAF = Common Application Framework
CCR = Coal Combustion Residue
CFB = Circulating Fluidized Bed
CFM = Cubic Feet Per Min
CO = Carbon monoxide
CO = Cotton
CS-ESP =Cold Side Electrostatic Precipitators
DLL = Dynamic Link Library
DSI = Dry Sorbent Injection
EPA = Environmental Protection Agency
ESP = Electrostatic Precipitators
FF = Fabric Filter
FG = Fiberglass
FGC = Flue Gas Condensers
GCA = Gross Cloth Area
GUI = Graphical User Interface
HA = Homopolymer Acrylic
HCl = Hydrogen Chloride
HF = Hydrogen Fluoride
HS-ESP = Hod Side Electrostatic Precipitators
LEL = Lower Explosive Limit
MCR = Maximum Continuous Rating
MMACF = Million Actual Cubic Feet
MTO = Material Take Off
NA = Not Applicable
NO = Nomex
NOx = Nitric oxide
NSR = Normal Stoichiometric Ratio
NX = Nextel
P8 = P84
PAC = Powdered Activated Carbon
PDMS = Plant Design Management System
PE = Polyester
PJFF = Pulse Jet Fabric Filter

PML = Programming Macro Language

PP = Polypropylene

PRB = Powder River Basin

RH = Re Heater

RT = Ryton

SBC = Sodium Bicarbonate

SCR = Selective Catalytic Reduction

SD = Spray Dryer

SDA = Spray Dryer Absorber

SH = Super Heater

SHI = Sumitomo Heavy Industry

SNCR = Selective Non Catalytic Reduction

SO_2 = Sulphur dioxide

SO_3 = Sulphur trioxide

SPLP = Synthetic Precipitation Leaching Procedure

TF = Teflon Felt

TR = Top bag Removal (Snap in)

1 INTRODUCTION

Sumitomo SHI – Foster Wheeler has been using PDMS for more than 20 years. They started by using first version PDMS 11.0, 12.0 and 12.1. So many PDMS development projects have been done. One of PDMS development projects is relating to this thesis that creating 3D model for dry sorbent injection.

The purpose of this thesis was to create DSI Model using PDMS software by importing calculation result value from another system and getting more understanding the science behind all calculation including Dry sorbent literature study. There are some variations of DSI thus with this tools designer can modified and can take Material Take Off (MTO) quickly which is important in bidding Phase and design Phase.

This thesis consists of three parts. The first of main components was PDMS Setting environment, PDMS customization, Piping Catalog and specification which can be setup on admin and paragon module.

The second one is user interface and code behind creation. All coding is done with C# by using AVEVA API which built by Visual studio 2017.

The last one is Dry sorbent injection literature Study, the main focuses were in dry flue gas cleaning process and reducing of the acid gases hydrogen chloride (HCl) and sulphur dioxide (SO_2), and absorbent. Type of absorbent is important variable which influences flue gas emissions.

Nobody can deny the value of a digital 3D model in the modern era. Every business will eventually migrate to digitalization. AVEVA PDMS software significantly simplifies the process of creating a digital 3D model. A digital 3D model of the DSI baghouse was created using the PDMS software.

A water boiler is designed to operate at pressures greater than 160 psi (1.1 MPa) and/or temperatures in excess of 250°F (120°C). (ASME BPVC, 2015)

2 PLANT DESIGN MANAGEMENT SYSTEM

CAD Center was founded in 1967 and changed its name to Aveva in 2001 from UK Head Quarter at Cambridge. First version of PDMS (Plant Design Management System) was published in in 1976 and used in SHI FW since 1997. Last version is PDMS 12.1 SP4 currently in use. 3D modeling is the process of creating a mathematical representation of any surface of an object in three dimensions using specialized software in 3D computer graphics. The product is referred to as a 3D model. A 3D artist or a 3D modeler are terms used to describe someone who works with 3D models. One company which produced this specialized software is CAD Centre (Computer Aided Design Center). PDMS is AVEVA's 3D Plant Design Software which is Capable to provide Full Range of solutions for Project Life Cycle, customizable, multiuser, and multi-discipline. PDMS can be applicable on design and construction project in Offshore, onshore, Boiler powerplant and nuclear powerplant.

2.1 Benefits of PDMS

There are some benefits of using PDMS, these are consistent and reliable component data, manageable specification, manageable component connection, and avoid component interferences. In the following paragraph there are some explanations from PDMS how all of them can be achieved.

PDMS Ensures that component data is consistent and reliable. All piping component sizes and geometries are predefined and saved in a catalogue by PDMS, and the designer cannot change them. This ensures that all objects are accurate in size and are consistent across the design, regardless of how many people are working on the project. Usually each fitting's size must be determined before it can be drawn In a design environment that exclusively uses 2D drawing techniques. This is a time-consuming and error-prone operation, with design flaws frequently discovered only during the erection stage of the project. (Aveva 1, 2013)

PDMS refers to engineering specifications that can be defined. Specifications are used in design applications for Piping, Hangers and Supports, HVAC, Cable trays and Steelwork to assist component selection. All specifications store in paragon Module and specify the exact components to be used. (Aveva 1, 2013)

PDMS Ensures that the geometry and connectivity are correct. PDMS can check all of design errors using built in data consistency procedures to check all or individual parts of the design model. Design errors can occur in a variety of ways, such as incorrect fitting lengths, incompatible flange ratings, or simple alignment errors. (Aveva 1, 2013)

PDMS prevents Component interferences. Traditional drawing office techniques are still prone to human error, despite a wealth of skill and experience in plant design. When utilizing conventional 2D methods to lay out complex pipe runs and general arrangements in tight areas, clashes between elements attempting to share the same physical space unavoidably occur. (Aveva 1, 2013)

PDMS allows us to avoid such issues in two ways, the first is that, by viewing the design interactively during the design process, visual checks on the model from various viewpoints are possible. Potential issues can thus be resolved as they arise. (Aveva 1, 2013)

Second, by utilizing PDMS's powerful clash checking facility, which will detect clashes anywhere in the plant. This can be done both interactively and selectively. (Aveva 1, 2013)

All dimensions and annotations were obtained directly from the design database.
Extracted information from the PDMS database, such as arrangement drawings, piping isometrics and reports, will always be the most recent available because it is only stored in one source. Throughout the course of a project, information changes and drawings must be reissued. When this occurs, drawings, reports, and other documents can be easily updated and reissued. (Aveva 1, 2013)

2.2 Database Driven PDMS

Database Driven means that all information is stored in database format, does not save graphics, only references from catalog projects. PDMS is database driven, all 3D model information including position, size, part numbers, and geometric relationships, are saved in databases. It becomes a single source of engineering data for all different output channels, from which information can be passed on as illustrated on figure 1. This allows complex reports, automated drawing production, back tracking, and history data. (Aveva 1, 2013)

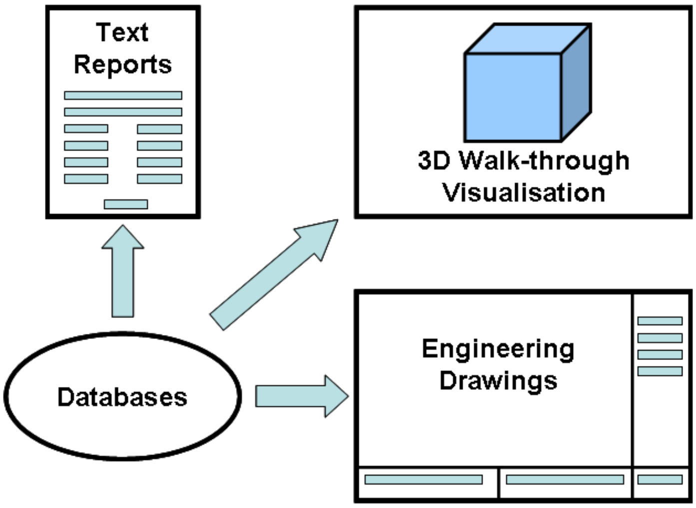


FIGURE 1. Database relational in PDMS (Aveva 1, 2013)

2.3 Database types

A PDMS project is the complete collection of information pertaining to a single design project. The project is identified by a name, which is assigned by the Project Administrator when the project is first started. When a user wants to work on a project using PDMS, the project name is used to identify the project to the system. This enables the monitoring and control of access rights and the use of system resources. (Aveva 1, 2013)

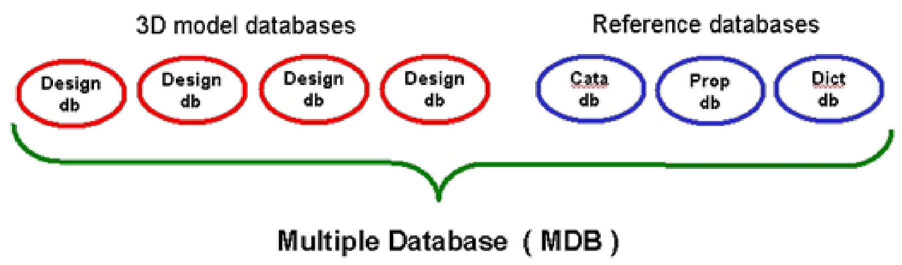


FIGURE 2. PDMS MDB system (Sumitomo-1, 2020)

Figure 2 shows multiple Database, there are 12 different types of database which can be used to make up a complete Project: DESIGN, PADD (DRAFT), ISOD (Spooler) database are type of design and drawing Databases. SCHEMATIC and ENGINEERING databa0s e are two types of 2D Design Databases. CATALOGUE, LEXICON (Dictionary), PROPERTIES databas e are types of Reference Databases, and SYSTEM, COMMS, MISC, TRANSACTION database are types of Administration Databases. (Aveva 1, 2013)

The DESIGN databases contain all of the information required to create a full-scale three-dimensional model of the plant. Each user is usually allowed to modify the DESIGN databases that are relevant to his role in the plant design team, and he is frequently allowed to look at other DESIGN databases to ensure that his work is compatible with that of other designers. (Aveva 1, 2013)

The Production of Annotated and Dimensioned Drawings (PADD) database stores information about drawings' pictorial content as well as annotation and dimensional information. As a result, it contains a complete specification of the contents of a drawing. Its application is limited to the interactive drawing module DRAFT. (Aveva 1, 2013)

2.4 Multi discipline PDMS

All disciplines like piping, mechanical, structure, electrical and HVAC can access database simultaneously in the same time with certain PDMS hierarchy. All layouts on PDMS are saved via the user interfaces of the design module. The design module is used for creating piping lay out (the pipes that connect the various pieces of equipment), equipment (heat exchangers, pumps, storage vessels, process vessels, and other components), structures (beams, columns, stairways, walls, and so on that support and provide access to operational equipment and pipework) and Pipe Supports. All information in PDMS are saved to objects in the hierarchy which is described on figure below. (Aveva 1, 2013)

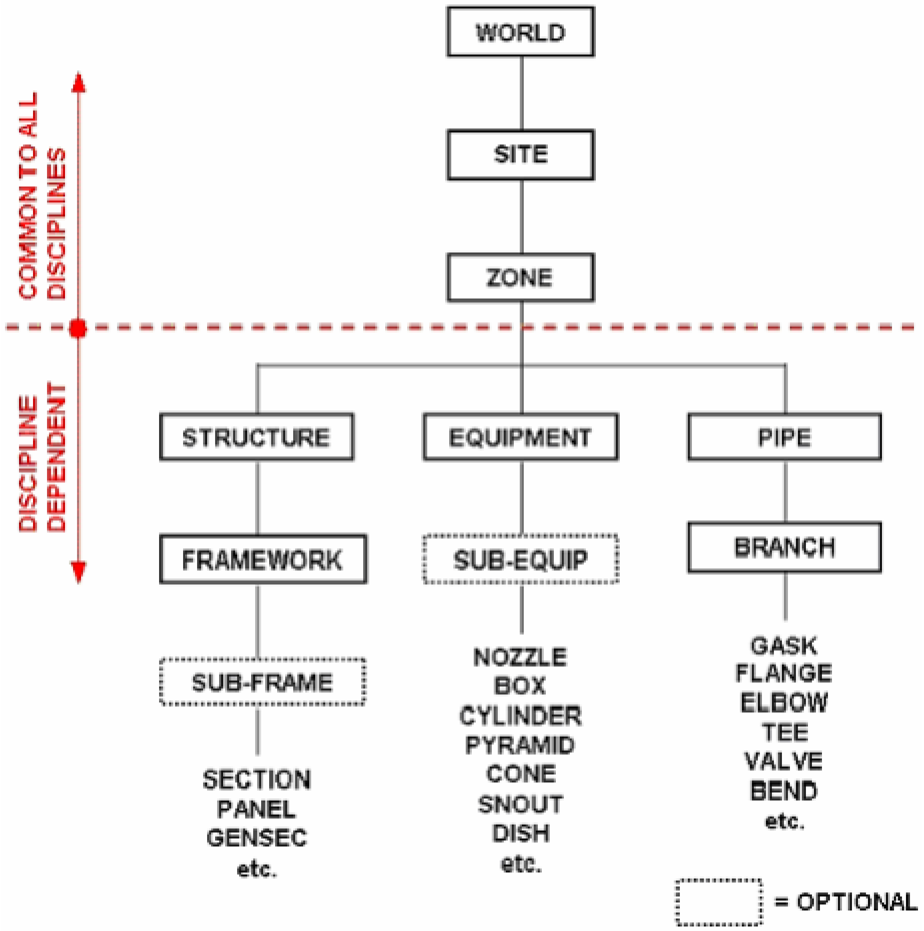


FIGURE 3. The PDMS Design database hierarchy (Aveva 1, 2013)

With the exception of the WORLD, all database elements in this hierarchical structure are owned by other elements. Elements that are owned by another element, such as a ZONE and a SITE, are referred to as members of the owning element. The ZONE is a member of the SITE. If Piping discipline wants to create Flange or valve model they have to create Site, Zone, Pipe and Branch. The way How to save element looks like Windows explorer on Windows operating system. (Aveva 1, 2013)

2.5 Global Workshare

Global workshare means all PDMS databases can be shared with each of the branch office locations, as illustrated in the figure below. Database projects are distributed by PDMS to the entire remote location server. For headquarter location PDMS server, it is called a Hub, and a Satelite is for remote location server or branch office. When a user designs or works with a satellite version, it will be updated to the Hub or central location. Data is available for users at other locations to read. + means full right access on the current location as shown on picture below (Aveva 1, 2013)

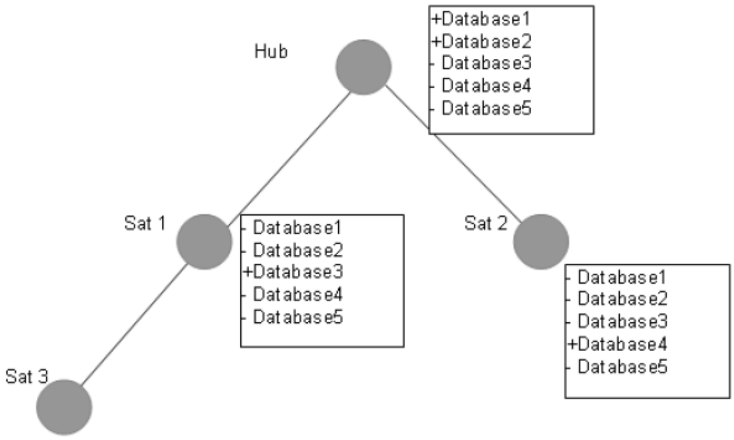


FIGURE 4. Global user guide (Aveva 2, 2013)

3 BOILER TYPE

The boiler is an equipment used to make steam. Steam can be used to drive turbines in power plants and function as a temperature guard in the petroleum distillation. In another words, a boiler is used to turn energy from a combustion process into heat or power. ASME 2015 section I classified boiler become six boilers: miniature boilers, power boilers, electric boilers, solar receiver steam generators, heat recovery steam generators, and high-temperature water boilers. This thesis focuses on power boilers. (ASME BPVC, 2015)

A power boiler is a boiler that produces steam or other vapor at a pressure greater than 15 psi (100 kPa) for use elsewhere. An electric boiler is a power boiler or a high-temperature water boiler that uses electricity as its heat source. A solar receiver steam generator is a boiler system that converts water to steam by utilizing solar energy as the primary source of thermal energy. Solar energy is typically concentrated onto the solar receiver using a mirror array that focuses solar radiation on the heat transfer surface. A heat recovery steam generator (HRSG) is a boiler that uses a hot gas stream with high ramp rates and temperatures, such as the exhaust of a gas turbine, as its primary source of thermal energy. (ASME BPVC, 2015)

3.1 CFB Boiler Technology

CFB is an abbreviation and it comes from Circulating Fluidized Bed. CFB technology is an ideal Technology to be used for large scale power generation with broad range of solid biomass fuels. CFB technology with pure biomass firing is available up to 600 MWe scale and with coal co-firing up to 800MWe scale. Fuel flexibility has an important role in reducing the costs and environmental effects of energy production both in pure biomass plants and in coal and biomass co-combustion. (Sumitomo-2, 2021)

3.1.1 CFB Combustion Concept

Combustion is defined as the complete exothermic oxidation of a fuel with sufficient oxygen or air to produce heat, steam, and/or electricity. The final gaseous product of combustion is then referred to as a flue gas. The fuels used for this purpose are primarily hydrocarbons (natural gas, coal, fuel oil, wood, and so on), which are converted to CO_2 and H_2O. Other fuel components may produce by-products such as ash and gaseous pollutants, requiring the use of emission control equipment. Solid fuels such as coal, peat, or biomass are typically fired at air factors 1.1 - 1.5, or 110-150 percent of the oxygen required for complete oxidation of the fuel's hydrocarbon fraction to CO_2 and H_2O. (Zevenhoven and Kilpinen, 2005)

Figure five below explains the CFB Combustion Concept. Bed material exiting furnace is separated in solids separator and returned back to furnace(a). Unburnt Fuel / coal particles are recycled back with help of separator (steam cooled cyclone). Moderate combustion temperature (800-900 C) enables: SOx removal in furnace with limestone injection and low thermal NOx formation(b). Part of heat surfaces can be located to solids return flow enabling effective heat transfer In corrosion-free environment INTREX SH/RH (c). Bed material (sand, fuel ash, limestone) in furnace is fluidized with primary air. Fuel is fed to bed in lower part of furnace(d). (Sumitomo-3, 2020)

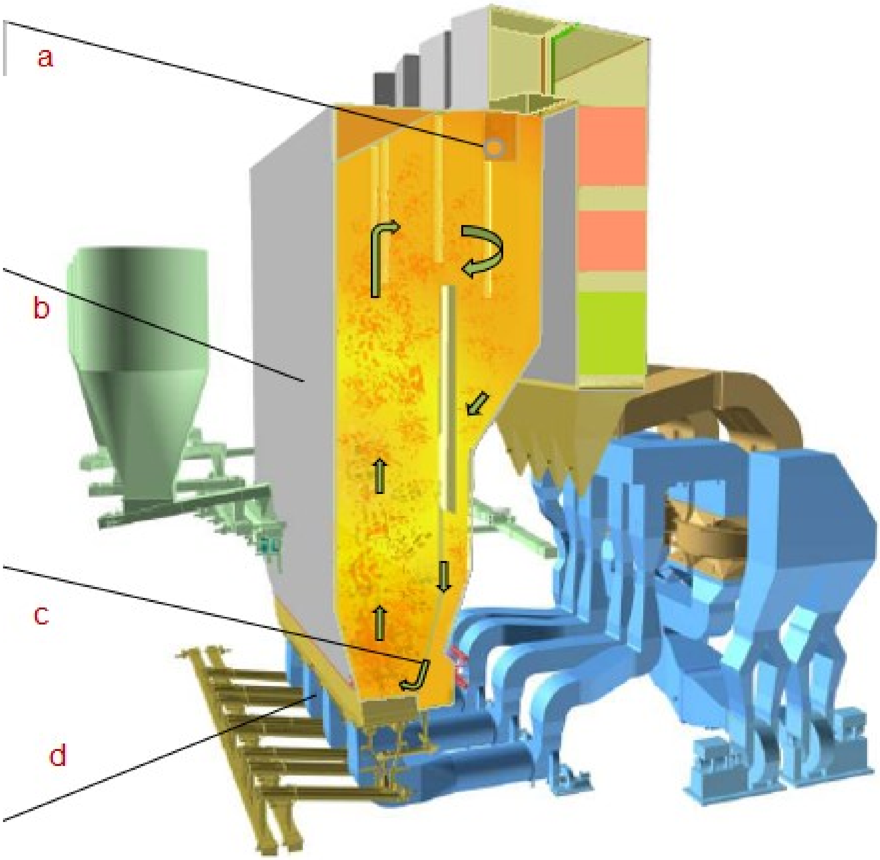


FIGURE 5. CFB Combustion Concept (Sumitomo-3, 2020)

in part b when lime is injected to the furnace there is two-stage process. First calcination can take place as illustrated by the following chemical equation.

$$CaCO_3 \rightarrow CaO + CO_2 \qquad 1$$

and second is Desulfurization reaction @ 700 °C to 850 °C temperature

$$CaO + SO_2 + \frac{1}{2} O_2 \rightarrow CaSO_4 \qquad 2$$

3.1.2 Key Advantages of CFB Combustion Technology

Here are presented some key advantages of CFB Combustion Technology. Fuel adaptability means that circulating solids provide high thermal inertia for stable combustion over wide range of fuels such as coal, lignite, peat, wood chips, pellets, pet.coke, and oil shale. Another benefits are simple emission control, very low NO_x, low CO and sulfur capture in the furnace. CFB combustion technology offers high reliability, low maintenance, and no ash slagging, which minimizes furnace corrosion and fouling. (Sumitomo-3, 2020)

3.1.3 Flue Gas Cleaning Process in CFB

The fuel is burned in a bed material of mostly sand, which is fluidized by combustion air supplied from below. The advantages of this technology include the ability to use low-grade fuels such as wet sludges or waste-derived fuels, relatively low NOx emissions due to the low combustion temperature, and the ability to trap sulfur by adding limestone or lime to the bed. (Zevenhoven and Kilpinen, 2005)

Nitric oxide formation from fuel nitrogen could be significantly reduced. By arranging local zones in the furnace with a reducing atmosphere. This can also be accomplished by rearranging the combustion air supply, a process known as air staging. (Zevenhoven and Kilpinen, 2005)

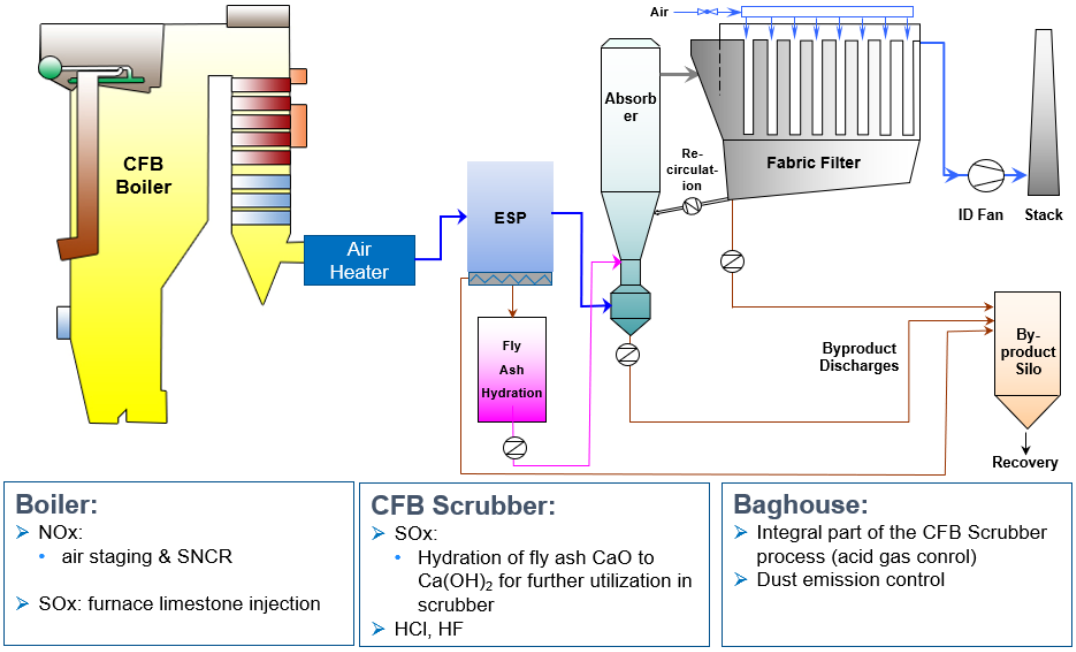
It is also possible to reduce nitric oxide to molecular nitrogen by adding ammonia to the flue gases at around 900 °C. As a byproduct, water is formed. This is known as the Selective Non-Catalytic Reduction (SNCR) process. (Zevenhoven and Kilpinen, 2005)

The SNCR method requires the presence of oxygen in order to function. Ammonia decomposes to amino radicals (NH_i) due to the presence of OH radicals and oxygen atoms (O), which react with nitric oxide:

$$NH_3 + OH + O \rightarrow NH_i + NO \rightarrow N_2 \qquad 3$$

The method is only effective at temperatures ranging from 850 to 1000 °C. When the temperature rises, NH_3 begins to react with nitric oxide instead. If the temperature is lower, the NH_3 decomposes slowly, resulting in a significant NH_3 slip. (Zevenhoven and Kilpinen, 2005)

Circular Scrubber Technology’s sulfur capture exceeds 95%(<200 mg/Nm^3 SOx), Scrubber uses 40% less water than wet FGD, and capital cost is 50% less than in wet FGD. There are two stages in the CFB scrubber technology, first is emission capture such as HCl, HF, and SOx in absorber, and the second one is particulate control in fabric filter, as illustrated in the figure below. (Sumitomo-4, 2021)



Boiler:

- NOx:
  - air staging & SNCR
- SOx: furnace limestone injection

CFB Scrubber:

- SOx:
  - Hydration of fly ash CaO to $Ca(OH)_2$ for further utilization in scrubber
- HCl, HF

Baghouse:

- Integral part of the CFB Scrubber process (acid gas conrol)
- Dust emission control

FIGURE 6. Scrubber technology in CFB Combustion (Sumitomo-4, 2021)

Flue gas with fly ash enters the bottom of the absorber, flowing upward through venturi to accelerate the gas causing turbulence flow. The gas and solids enter the baghouse where solids are captured and recycled back to the absorber to capture more pollutants. Pollutant SO_2 can be reduced by at least 85% and up to 99%, SO_3 can be reduced by at least 90% and up to 99%, HCl can be reduced by at least 95% and up to 99%, HF can be reduced by at least 95% and up to 99%, and Hg can be reduced by at least 60% and up to 99%. (Sumitomo-5, 2020)

3.2 BFB Boiler technology

BFB is abbreviation for Bubbling Fluidized Bed Boiler. Sumitomo Bubbling Fluid Bed steam generators have a history of reliable operation and have brought value to many clients due to their ability to burn high moisture and high ash fuels. Sumitomo has progressively advanced the state of BFB technology by incorporating design improvements like our rugged step grid, staged air mixing and gas recirculation systems. (Sumitomo-6, 2020)

3.2.1 BFB Combustion Concept

The fuel is burned inside furnace above a fluidized bed consisting of natural sand. The fluidizing air is blown at a lower velocity, and the bed materials behave like a boiling fluid but remain in the bed. When air velocity is getting higher the bed becomes turbulent with rapid mixing of the particles, bubbling of sand bed is similar with a boiling liquid. A lower density object will float, while a higher density object will sink. A fluidized combustion bed temperature is 850-900ºC. It is recommended for low flammable, low grade fuels and high moisture fuels. The below picture is Sumitomo BFB boiler technology. (Sumitomo-6, 2020)

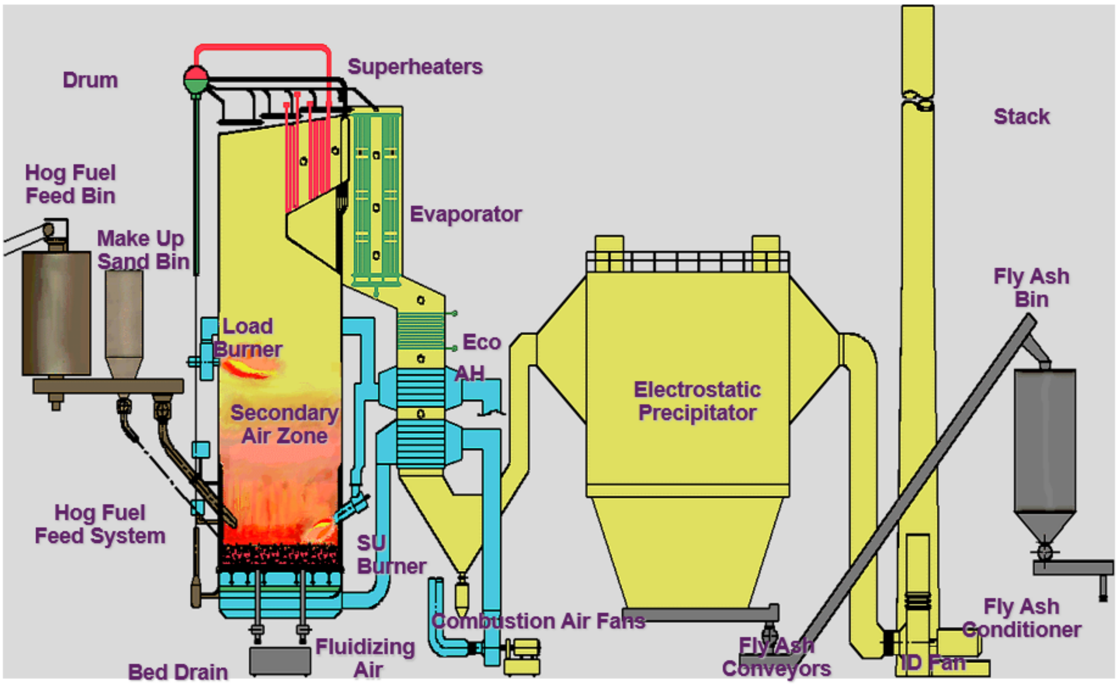


FIGURE 7. Flue Gas conventional technology on BFB Combustion (Sumitomo-6, 2020)

3.2.2 Key Advantages of BFB Combustion Technology

Sumitomo BFB combustion technology has some benefits. The first is the Stepped Grid, which has been designed for the most difficult fuels. The second benefit is high gas residence time to ensure dioxin, CO, and fly ash carbon decomposition. The third benefit is wide superheater, evaporator, and economizer tube bank spacing and retractable soot blowing to maintain high boiler efficiency and long tube life. The last benefit is low gas velocity for minimum heat transfer surface erosion. (Sumitomo-6, 2020)

3.2.3 Flue Gas Cleaning Process in BFB

Multiple levels of secondary air (air staging) and SNCR or SCR technology can be used to minimize NOx formation. SO_2 control can be achieved with calcium carbonate injection or with flue gas scrubber technique. Flue gas flow is conducted to electro static precipitator where the dust components are captured before flue gas enters the stack. After flue gas treatment, cleaned flue gas is released to the atmosphere. (Sumitomo-6, 2020)

4 PARTICULATE COLLECTION DEVICES AND TYPICAL FLUE GAS CLEANING

There are two common Particulate Collection Devices more frequently used, the First is ESP (Electrostatic precipitators) and second one is FF (Fabric Filter). The difference between ESP and FF comes down to the Basic Idea of Cleaning Method. (APTI Course, 2021-04-05)

4.1 Electrostatic Precipitators

The basic idea of an ESP is charging, collecting, and removing particle on flue gas stream, as illustrated in the picture 8 below. Precipitation of flue gas stream can be done by giving a charge positive or negative to all particles in a gas stream. (APTI Course, 2021-04-05)

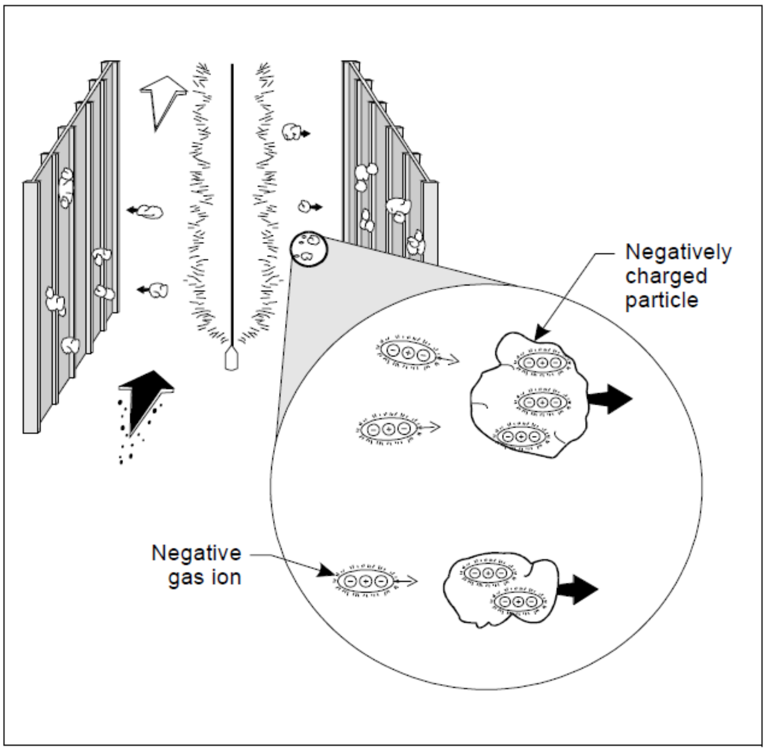


FIGURE 8. Particle charging (APTI Course, 2021-04-05)

Small particles (less than 1 μm diameter) can absorb “tens” of ions. Large particles (greater than 10 μm) can absorb "tens of thousands" of ions (Turner, 1992)

The negatively charged particle will then migrate to the positively grounded collection plate, where it will be captured. The particles would quickly clump together on the plate, forming a dust layer. The dust layer would build up until we removed it by rapping the plate or spraying it with a liquid, as illustrated in the figure below. (APTI Course, 2021-04-05)

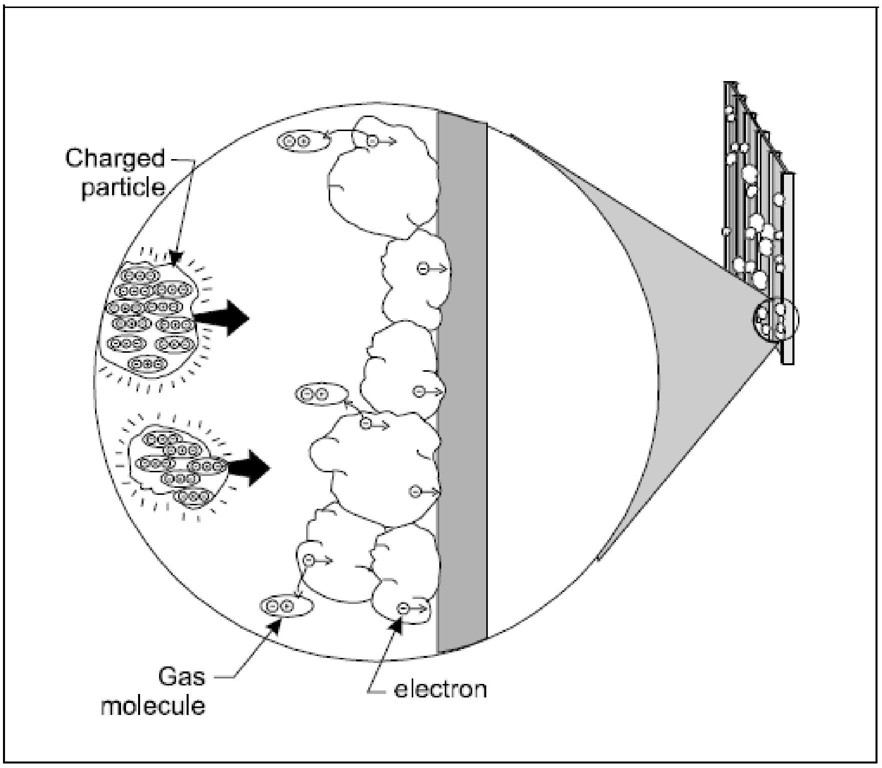


FIGURE 9. Particle collection at collection electrode (APTI Course, 2021-04-05)

Figure below shows thin wires called discharge electrodes which are placed between large plates called collection electrodes, which are grounded. Discharge electrodes create a strong electrical field that ionizes flue gas, and this ionization charges particles in the gas. Collection electrodes collect charged particles. Rappers remove dust that has accumulated on both collection electrodes and discharge electrodes by vibration, shock, or water spray. (APTI Course, 2021-04-05)

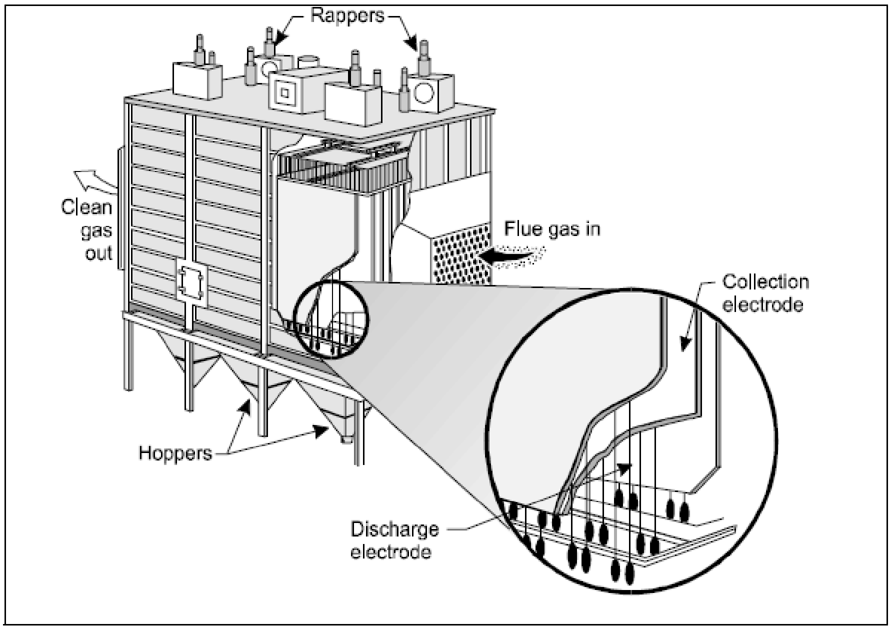


FIGURE 10. Typical dry electrostatic precipitator (APTI Course, 2021-04-05)

4.2 Fabric Filter

The fabric filter's basic concept is to empower particle behaviors such as impaction, interception, and diffusion. Particles can be captured by using cylindrical bags with felted or woven fabric as the filtering medium. Baghouses are another name for fabric filters. Particles from industrial sources float in the gas stream in general. Larger particles cannot turn around the fiber and must continue straight ahead until they impact on the fiber surface, as shown in the figure below. This is referred to as impaction behavior. (Beachler, 1995)

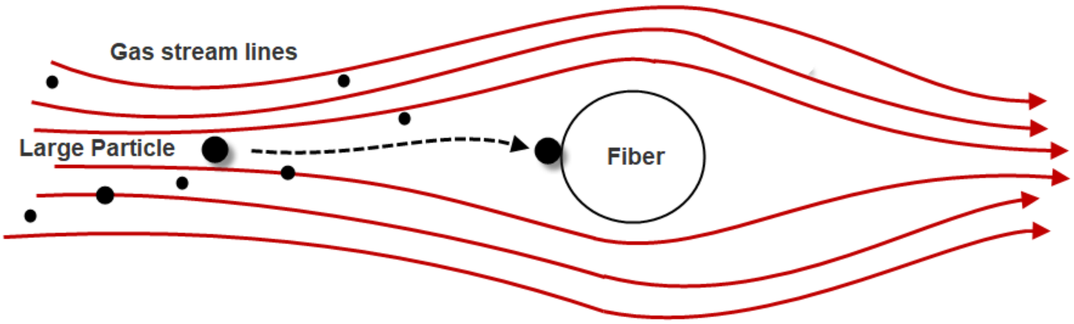


FIGURE 11. Impaction (Beachler, 1995)

The figure below shows that medium-sized particles have less inertia. They usually begin by grazing the fiber on the side or being "intercepted" by the gas stream. This is referred to as interception. (Beachler, 1995)

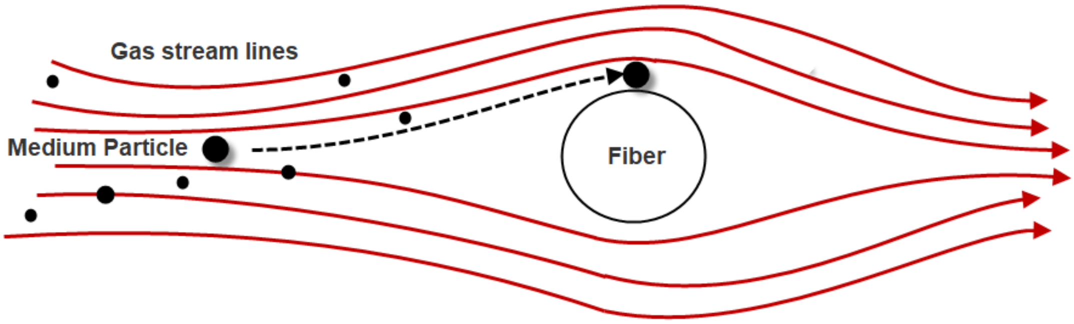


FIGURE 12. Interception (Beachler, 1995)

Impaction and direct interception account for almost 99% collection of the particles greater than 1 micrometer (µm) in aerodynamic diameter in fabric filter systems (Bethea, 1978).

A fabric filter can also collect very small particles with a diameter of less than 1 µm. Figure 13 Shows Small Size Particles. When particles collide with gas molecules, they simply bounce around and deflect slightly. The particles may have a different velocity than the gas stream and may come into contact with the fiber and be collected at some point. Individual or random motion distributes them throughout the fluid (gas), and it is known as Brownian motion or Brownian "diffusion." (Beachler, 1995)

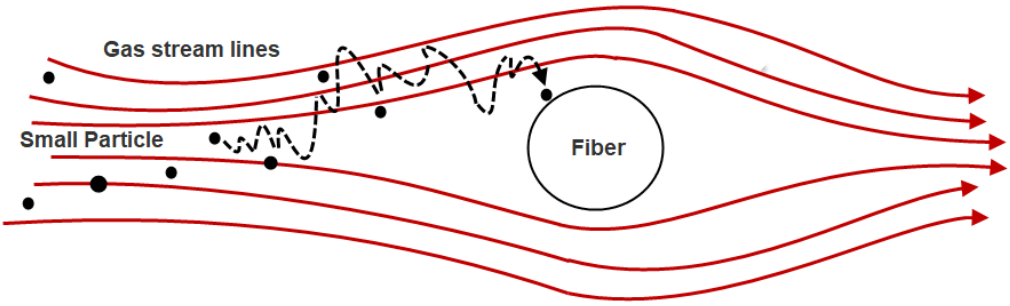


FIGURE 13. Diffusion (Beachler, 1995)

Fabric filters have been used on the majority of acid gas control systems, due to their ability to obtain slightly higher residual acid gas removal than ESPs. (Beachler, 1995)

4.2.1 Fabric Filter Systems

Fabric filters are typically made up of many cylindrical bags that hang vertically, as shown in the figure below. The quantity of bags may vary. The bag is cleaned once the dust layers have accumulated to a sufficient thickness resulting in dust particles falling into a collection hopper. Bag cleaning can be accomplished in a variety of ways. (Beachler, 1995)

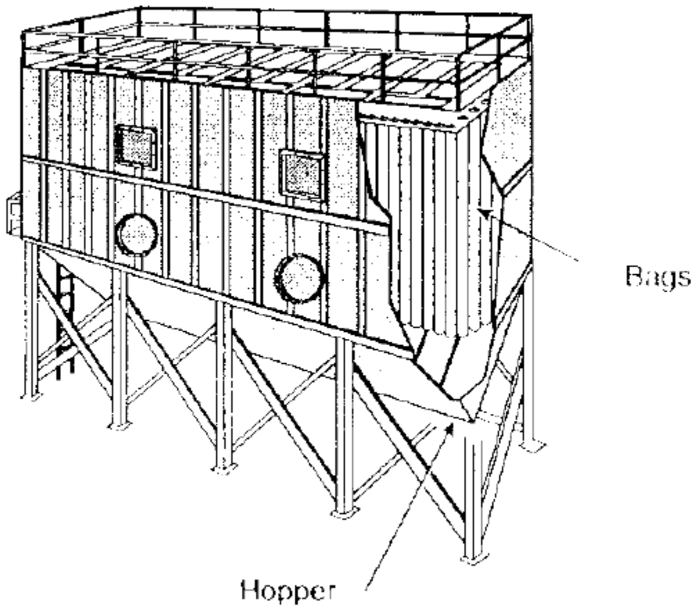


FIGURE 14. Typical baghouse (Beachler, 1995)

Cartridge systems work similarly to baghouses that use bag tubes, and are typically used on smaller industrial processes with exhaust flow rates less than 50,000 cfm, as illustrated in the figure below. (Beachler, 1995)

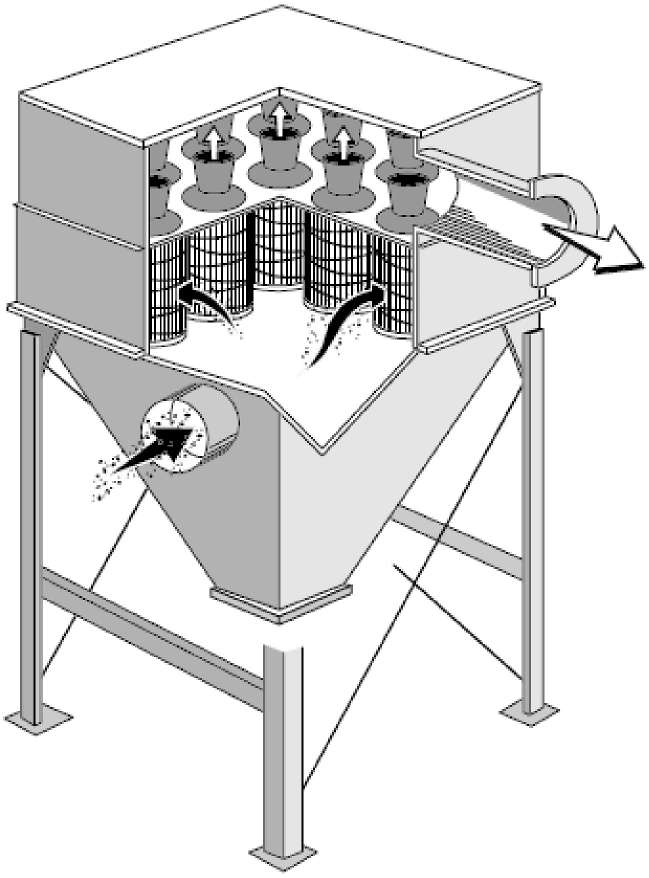


FIGURE 15. Cartridge baghouse (Beachler, 1995)

Cartridge filters are constructed from cylindrical pleated filter media. Clean air flows through the center of the cartridge, after dust has accumulated on the outside surface of the pleated filter of the cartridge. The cartridge filter's accumulated dust is cleaned on a regular basis. It is called pulse jet cartridge cleaning because it uses a blast of air into the center of the cartridge, as shown in the figure below. (Beachler, 1995)

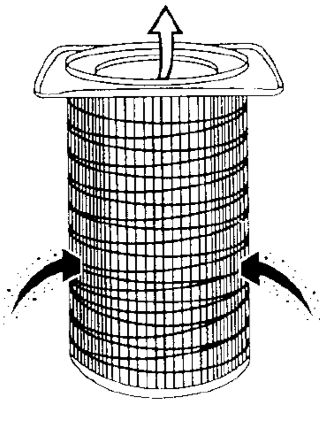


FIGURE 16. Cartridge filter (Beachler, 1995)

4.2.2 Bag Cleaning

There are four types of bag cleaning: shaking, reverse air, pulse jet, and sonic. The shaking method uses mechanical shaking to move a rod connected to the bags. Therefore, it gently shakes the bags to remove deposited particles. The shaking motion is generally in the horizontal direction, as shown on figure below. (Beachler, 1995)

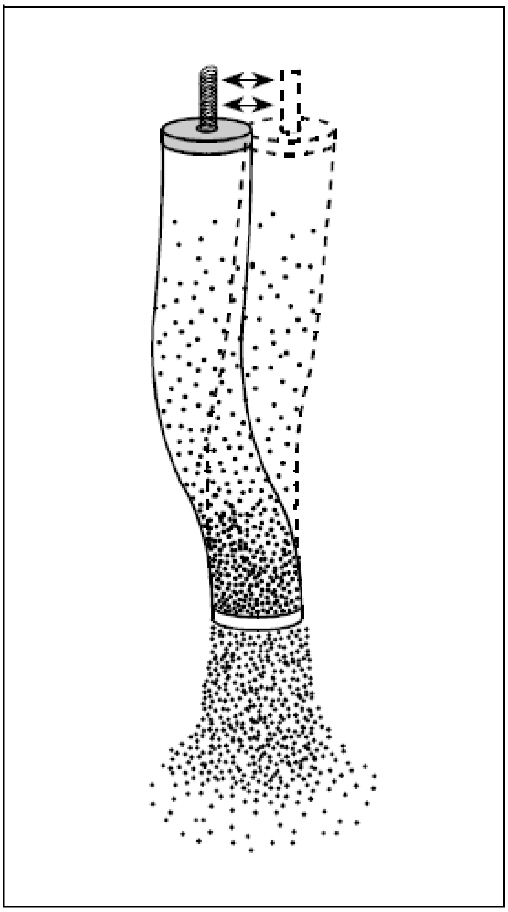


FIGURE 17. Shaking (Beachler, 1995)

Reverse air method uses clean air as the result of filtration then reversed air back to clean bag on off-line compartment. The compartment’s outlet gas damper and inlet gas damper are both open during the filtering mode. When bag cleaning begins, the outlet damper is closed to prevent gas flow. After allowing the bags to rest for a few moments, the reverse air damper located at the top of the compartment is opened to allow reverse air for bag cleaning into the compartment. The reverse air flow usually lasts between 30 seconds and several minutes. During this time, dust falls in the hopper, as illustrated in Figure 18.

Pulse jet is the most commonly used cleaning method. To remove dust from the bag, the pulse-jet cleaning mechanism uses a high-pressure air jet. A blast of compressed air is injected into the top of bag tube. As shown in figure 19 below, it generates a shock wave that travels down and back up the tube in about 0.5 seconds.

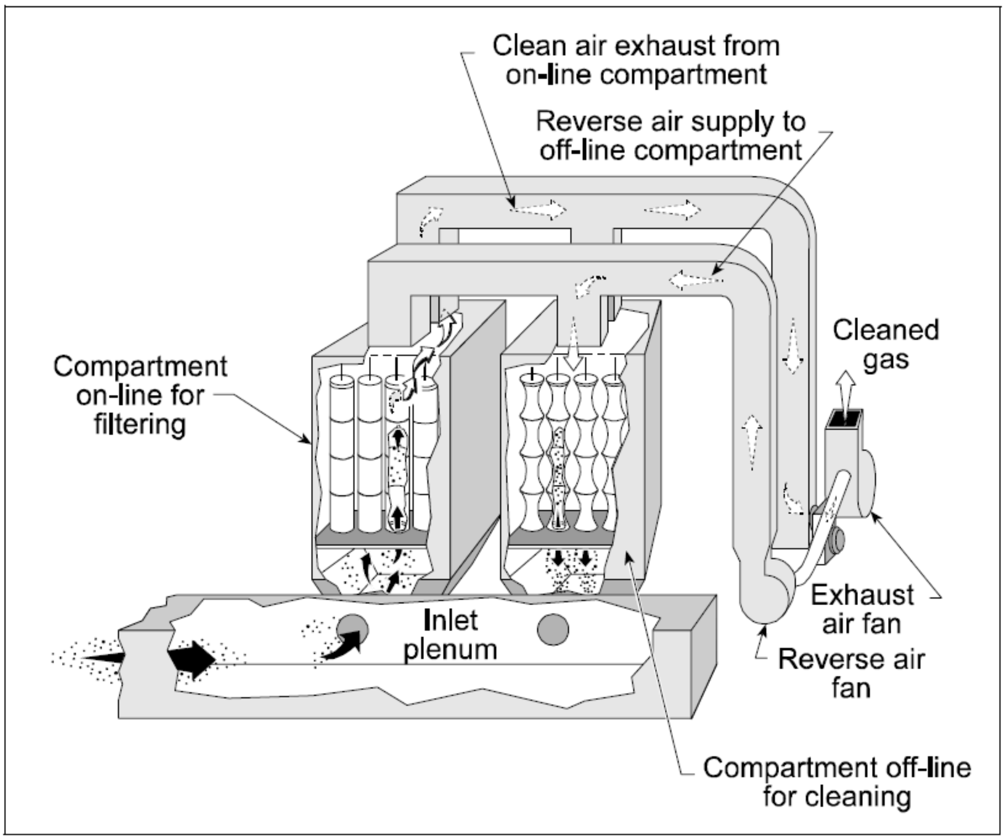


FIGURE 18 Typical reverse air baghouse (Beachler, 1995)

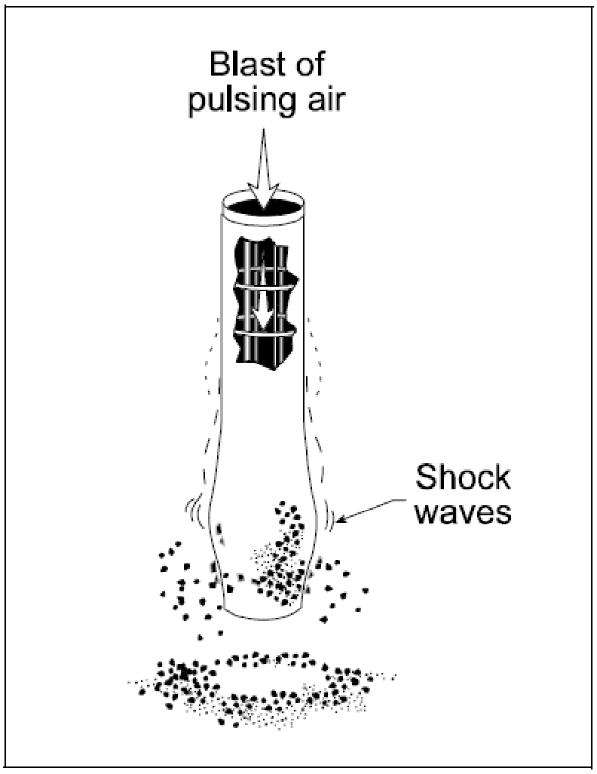


FIGURE 19 Pulse jet cleaning (Beachler, 1995)

As shown in the figure below, the sonic cleaning mechanism uses a sound generator to generate a low frequency sound that causes the bags to vibrate. (Beachler, 1995)

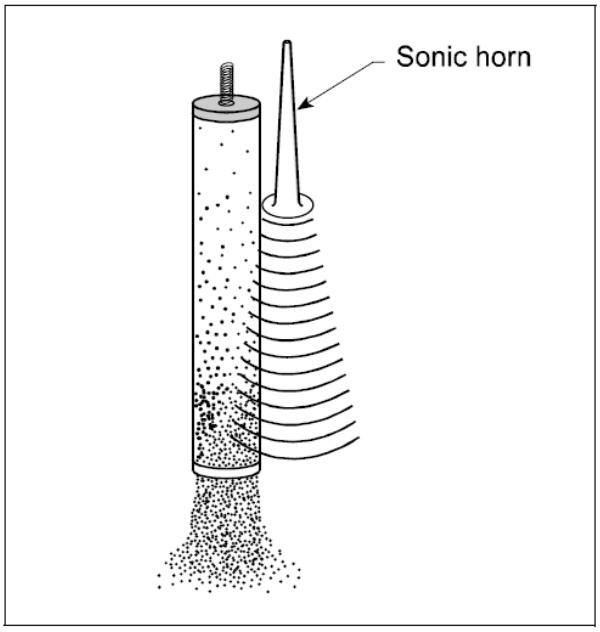


FIGURE 20. Sonic cleaning (Beachler, 1995)

4.3 Flue Gas Cleaning

Most of flue gas cleaning technology adopt scrubber systems. Scrubber systems are a type of air pollution control device that can remove particles and/or gases from industrial exhaust streams. Scrubbers are pollution control devices that "scrub" unwanted pollutants from a gas stream using liquid. Scrubbers are now also used to describe systems that inject a dry reagent or slurry into a dirty exhaust stream in order to "scrub out" acid gases. Scrubbers are one of the most important devices for controlling gaseous emissions, particularly acid gases. The scrubber classification can be divided into two main types as shown in the below picture. (Joseph , Beachler, 1998)

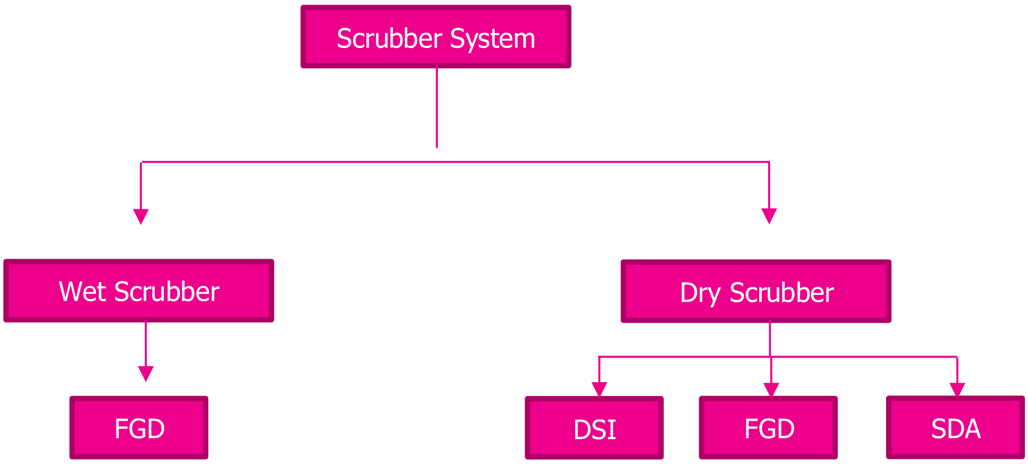


FIGURE 21. Scrubbing system (Joseph , Beachler, 1998)

4.3.1 Wet Scrubber

A wet scrubber is a term that refers to a diversity of devices that remove pollutants using liquid. In a wet scrubber, the dirty gas stream is sprayed with the scrubbing liquid, forced through a pool of liquid, or otherwise brought into contact with the scrubbing liquid. (Joseph , Beachler, 1998)

The scrubbing liquid in wet FGD scrubbing systems contains an alkali reagent to improve SO_2 and other acid gas absorption. It occurs inside a scrubber vessel, and produces wet waste or gypsum. Dry FGD, on the other hand, eliminates SO_2 with a spray dryer that evaporates the water before the vessel exits. Produces a dry byproduct. (Joseph , Beachler, 1998)

4.3.2 Dry Scrubber

Dry scrubber is a term used to describe a variety of devices that use reagent and do not use liquid to remove pollutants therefore does not have wastewater handling or disposal requirements. Dry Sorbent Injection (DSI) utilize a powder sorbent material, either calcium (lime) or sodium based to react with the acid gases in the flue gas and produce a solid salt that must be removed in a particulate control device. Spray Dryer Absorber is an enhancement of DSI, the alkaline sorbent is mixed with water and injected into a reaction vessel. the water cools and humidifies the gas stream, increasing the efficiency of reaction, the acid gases are absorbed into liquid droplet where they react with sorbent. (Joseph , Beachler, 1998)

5 DSI FLUE GAS CLEANING

The Dry Sorbent Injection (DSI) is a sulfur dioxide (SO_2), sulfur trioxide (SO_3), hydrogen chloride (HCl) and hydrogen fluoride (HF) reduction that uses an alkali sorbent as the injection material. The alkali sorbent is injected into ductwork/reaction chamber to react with pollutants and then is removed by a particulate removal device such as an electrostatic precipitator or a fabric filter. (Joseph , Beachler, 1998)

5.1 DSI system Configuration

Prior to the air pollution control device, the sorbent can be injected into the furnace during the combustion process, the boiler area, or the ductwork/ reaction chamber. A schematic of a typical dry injection system is shown in Figure 22. (Joseph , Beachler, 1998)

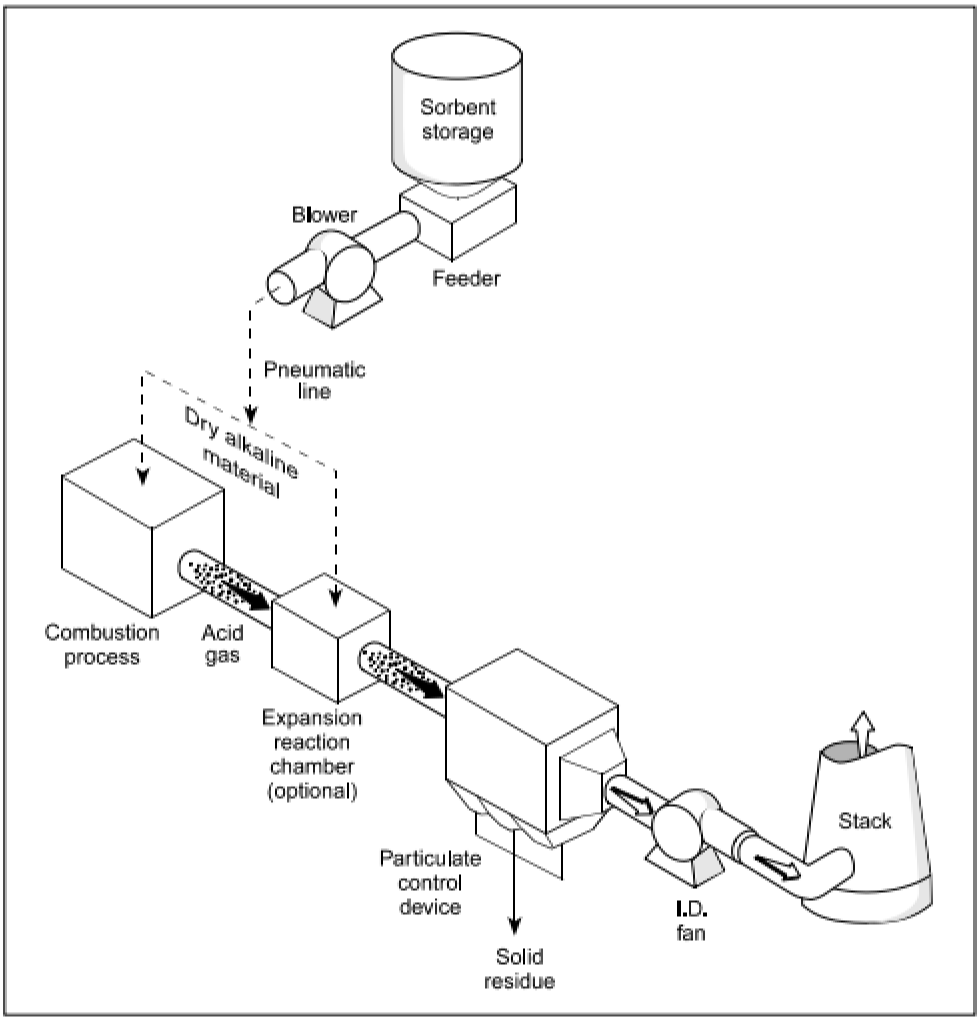


FIGURE 22. Component of dry injection system (Joseph , Beachler, 1998)

A dry sorbent injection system comprises of a dry sorbent storage tank, a weight feeder to meter the required amount of sorbent, a blower and transfer line, and an injecting equipment like a venturi. The dry sorbent material is blown through a pneumatic line to the injection point, where the sorbent material is continuously fed by the pneumatic line. To increase turbulence and enhance mixing, injections into the duct are usually done in the opposite direction of the gas flow. To give the acid gases more time to react with the sorbent, an expansion/reaction chamber may be provided. (Joseph , Beachler, 1998)

To achieve moderate acid gas control, for example, 50% SO2 removal and 90% HCl removal on municipal and medical waste combustion, the basic dry injector procedure described above can be used. Cooling and/or humidifying the flue gas stream can improve the efficiency of acid gas removal. Between 204ºC to 315ºC, the exhaust gases from industrial boilers or waste combustors. A heat exchanger or dry quench chamber can be used to cool the flue gases before they reach the injection point. As the flue gas temperature is cooled, the sorbent and acid gases react faster. In order to ensure that all the water droplets used to quench are evaporated, the temperature must be maintained at 148-176ºC.

Another way to boost the overall effectiveness of dry scrubbing systems is to recycle some of the collected particles and unreacted sorbent. Additional sorbent (beyond the stoichiometric amount) must be injected since it is difficult to blend a dry solid and a gas stream. As a result, the baghouse or electrostatic precipitator collects unreacted sorbent. Recycled material can sometimes be returned to the injection point.

To obtain high removal efficiencies while utilizing relatively affordable calcium sorbents, the majority of dry injection systems must run at greater stoichiometric ratios than a spray drier. To ensure moderate acid gas control, for example, stoichiometric ratios of 2.0 to 4.0 are utilized in municipal waste combustors. This increased use of sorbents limitations their use to smaller sources such as medical waste incinerators.

5.2 Mass and Energy Balance

In this thesis we use Polish coal for detail information. Please see Fuel Analysis Table Below

TABLE 1. Coal content analysis (moisture 9 %) (Savonia Moodle, 2020)

Coal Ultimate Analysis	
Compound	Content percent
Carbon (C)	73,2%
Hydrogen (H)	4,7%
Oxygen (O)	9.1%
Sulfur (S)	1%
Nitrogen (N)	1%
Ash	11%
Total	100%

Here below is amount of air flow rate and flue gas rate calculation based on coal content analysis.

TABLE 2. Oxygen Calculation (Savonia Moodle, 2020)

Material (A)	Composition in % (B)	input weight kg/kg_{pa} (C)	Molecular Weight Kg/Kmol (D)	consumed Kmol/Kg_{pa} C/D (E)	Amount of O2 needed Kmol/Kg_{pa} C/D (F)	Molecular Weight O2 Kg/Kmol (G)	Amount of O2 needed Kg/Kg_{pa} FXG (H)	Combustion Reaction
C	73.2%	0.732	12.01	0.0609	0.0609	32	1.95	$C+O_2->CO_2$
H_2	4.7%	0.047	2.016	0.0233	0.0117	32	0.37	$2H_2+O_2->2H_2O$
O_2	9.1%	0.091	32	0.0028	-0.0028	32	-0.09	
S	1%	0.01	32	0.0003	0.0003	32	0.01	$S+O_2->SO_2$
N_2	1%	0.01						
ASH	11%	0.11						
total	100%	1			0.0701	32	2.24	

Amount of oxygen consumed for coal combustion is 0.0701 kmol/kg fuel. The composition of air 79% N_2 and 21% O_2 leads to total N_2 needed 0,0701 X (79%/21%)=0.2635 kmol/kgpa. N_2 needed in kg/kgpa is 0.2635 X molecular weight of N_2 (0.2635 X 28 =7.386) .Thus total Air needed is O_2+N_2 (2.24+7.386=9.63 kg/kgpa).

TABLE 3. Flue Gas Composition

Material	Amount of Material in Kmol/Kg_{pa}	Reaction Product	Amount of Flue Gas Produced Kmol/Kg_{pa}	Proportion in dry Flue Gas	Proportion in Wet Flue Gas
C	0.0609	CO_2	0.0609	0.188	0.1751
H_2	0.0233	H_2O	0.0233	0	0.0670
S	0.0003	SO_2	0.0003	0.001	0.0009
N_2			0.2635	0.8114	0.7570
		total (dry)	0.3247	1.0000	
		total (wet)	0.3481		1.000

As shown in table 3, the total amount of flue gas produced in dry conditions is $CO_2+ SO_2+ N_2$ (0.0609 + 0.0003 + 0.2635 = 0,3247 Kmol/Kgpa). In wet conditions, the total amount of flue gas produced is $CO_2+ H_2O+SO_2+ N_2$ (0.0609 +0.0233+0.0003 +0.2635=0.3481 Kmol/Kgpa).

TABLE 4. Amount of Flue Gas Calculation

Material (A)	Amount of Flue Gas in Kmol/Kg_{pa} (B)	Molecular Weight Kg/Kmol (C)	Amount of Flue Gas in Kg/Kg_{pa} (B) X (C) (D)
CO_2	0.0609	44.01	2.68
H_2O	0.0233	18.016	0.42
SO_2	0.0003	64	0.02
N_2	0.2635	28.02	7.38
		total (dry)	10.09
		total (Wet)	10.51

Table above shows that the amount of flue gas in coal combustion is 10.51 kg per kg of coal burned.

5.3 DSI Chemistry

The reaction between acid gas and the alkaline material takes place on the surface of these solid sorbent particles. It is called adsorption mechanism as the primary removal mechanism. The alkaline materials are generally calcium hydroxide or sodium – based reagents that have large surface areas to aid adsorbing the acid gas as shown in figure below. Adsorption occurs when the acid gas molecules adhere to the surface of the solid sorbent. Absorption occurs when the acid gases dissolve in the liquid droplets. (Joseph , Beachler, 1998)

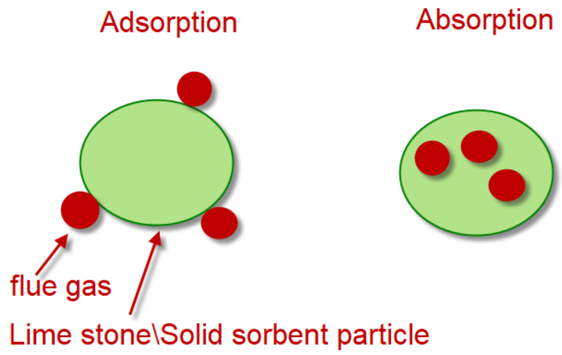


FIGURE 23. The mechanism of acid gas removal adapted from Jose and Beachler (Joseph , Beachler, 1998)

Due to the need for humidity, absorption mechanism is used to reduce acid gases whereas adsorption mechanism is used to reduce metal emissions. (Teija, 2022)

A particle size of less than 74 micrometers, with an average of about 40 micrometers, is typical for commercial $Ca(OH)_2$ and can be expected to yield efficiencies in excess of 95% in the CFB. $Ca(OH)_2$ is composed of soft hexagonal crystals. As displayed in figure below, the surface morphology of the adsorbent was examined using a JEOL JSM7800F field emission scanning electron microscope (FESEM). (Yimin Deng, Renaud Ansart, Jan Baeyens and Huili Zhang, 2019)

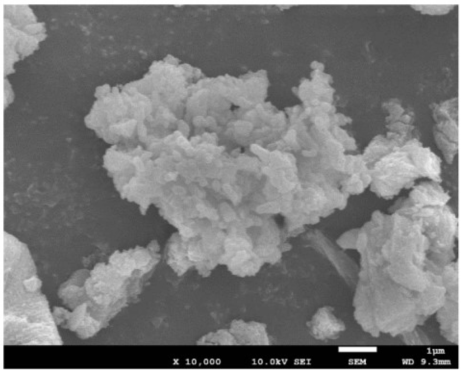


FIGURE 24. SEM Imaging of $Ca(OH)_2$ particles. (Yimin Deng, Renaud Ansart, Jan Baeyens and Huili Zhang, 2019)

The primary calcium reagent being widely utilized is hydrated lime or calcium hydroxide ($Ca(OH)_2$), and as sodium base is sodium bicarbonate. The important reactions that result in the capture of the primary acid gases present in industrial flue gas streams are outlined below. (Joseph , Beachler, 1998)

5.3.1 Hydrated Lime

Hydrated lime is a low-cost chemical that has a high elimination capacity for HCl and HF in most cases. Because sulfur dioxide has a lower reactivity than HCl and HF, the SO_2 removal efficiency with hydrated lime injection is lower than the HCl and HF removal efficiency. However, with hydrated lime injection, it is possible to achieve significant SO_2 elimination in the majority of cases. Whenever HCl or HF removal is the primary goal, the presence of SO_2 in the flue gas will have a negative impact on the HCl/HF removal rate. (Joseph , Beachler, 1998)

Specifically, the contribution of pollutant species, particularly SO_2 and HCl, should be taken into consideration when developing this removal process (contents of these two compounds in flue gas have to be specified). Because of variations in the reactivity of acid compounds, it is necessary to maintain the following sequence of removal reactions:

$$SO_3 > HF > HCl >> SO_2 \tag{4}$$

Most of the sulfur in coal is converted to SO_2 when it is burned as a combustion source. As a result, about 1% of the sulfur is converted to SO_3. When coal contains more sulfur, flue gas SO_3 levels tend to rise as well. (APTI Course, 2021-04-05)
Hydrated lime reacts with flue gas pollutants as follows:

$$\mathrm{Ca(OH)_2(s) + SO_3(g) \rightarrow CaSO_4(s) + H_2O(g)} \tag{5}$$

$$\mathrm{Ca(OH)_2(s) + SO_2(g) \rightarrow CaSO_3(s) + H_2O(g)} \tag{6}$$

$$\mathrm{Ca(OH)_2(s) + 2HCl(g) \rightarrow CaCl_2(s) + 2H_2O(g)} \tag{7}$$

$$\mathrm{Ca(OH)_2(s) + 2HF(g) \rightarrow CaF_2(s) + 2H_2O(g)} \tag{8}$$

Calcium hydroxide [$Ca(OH)_2$] neutralizes one mole of SO_2, while two moles of HCl or Fluoride HF can be neutralized by one mole of calcium hydroxide in the reactions described above. The molecular weight of each component must be taken into account when calculating how many kilograms of calcium hydroxide are needed to neutralize a given weight of SO_2 or HCl. For example, SO_2, HCl, and [$Ca(OH)_2$] have the following molecular weights:

TABLE 5. Molecular Weight

Compound	Molecular Weight (kg/kg-mole)
Calcium (Ca)	40
Oxygen (O_2)	32
Sulfur (S)	32
Carbon (C)	12
SO_2	64
HCl	36
HF	20
$NaHCO_3$	84
$Ca(OH)_2$	74

Thus, one kilogram of calcium hydroxide is capable of neutralizing 0.86 kilograms of SO_2 (64 divided by 74) or 0.97 kilograms of hydrochloric acid (36 times 2 divided by 74).

To determine a system's stoichiometric ratio, all acid components in the waste stream must be considered. Additionally, the previous formula (5,6,7, and 8) are for the stoichiometric amounts of sorbent. Actual sorbent consumption will exceed these figures due to inherent inefficiencies in operation; interaction between sorbent and acid gases is seldom optimum, and acid gas distribution in the flue gas is frequently not uniform (especially in incineration systems). Actual stoichiometric ratios can range from 1.5 to 4.0, depending on the design of the system and the needed removal efficiency.

5.3.1.1 SO_2 Emission

Sulphur in fuel will eventually be oxidized in combustion facilities, resulting in sulphur dioxide SO_2 and some sulphur trioxide SO_3 being produced. While at the same time, there has been a long history of capturing SO_2 with limestone, which has been performed at relatively modest costs due to the abundance of these materials in nature. (Zevenhoven and Kilpinen, 2005)

Reasons for controlling SO_2 emissions are related to its contribution to acid rain, and more recently it was recognized that sulphate-containing aerosols form a health hazard as well, causing problems to the respiratory and cardio-vascular systems. (US EPA2, 2021)

The entire amount of sulfur dioxide released can be calculated. If a 150MW CFB plant consumes 70 T/h of coal with an average energy content of roughly 20.000 kJ/kg and a sulfur concentration of 1%, as indicated in Table 1, Assume that 95 percent of the sulfur in fuel interacts via Reaction 9 below.

$$S + O_2 \rightarrow SO_2 \qquad 9$$

Percentage of sulfur in the coal that converts to SO_2: 95 percent conversion factor came from an Environmental Protection Agency (EPA) document in the 1980s.

Mass of Fuel sulfur = Amount of Fuel X Content of Sulfur in Fuel % 10

$$70.000\,\frac{kg}{h} * \frac{1}{100} = 700\,\frac{kg}{h} \qquad 11$$

Total amount of sulfur in the coal is 700 kg /hr. Total amount of Sulfur quantity can be converted to kilomoles per hour. Amount of kilomoles of sulfur per hour is 21,87 kmol /h, as shown here below.

$$700\,\frac{kg}{h} * \frac{kg\ mole\ S}{32\ kg\ S} = 21{,}87\,\frac{kmol\ S}{h} \qquad 12$$

$$Stoichiometric\ SO_2 = 1 * (k\ mol\ S) \qquad 13$$

$$21{,}87\frac{kmol\ S}{h} * \frac{0.95 * kg\ S\ converted}{kg * \ S\ total} * \frac{1 * kmol\ SO_2}{1 * kmol\ S} = 20.78\,\frac{kmol\ SO_2}{h} \qquad 14$$

According to equation 9, 95% mole S converted to SO_2 is 20,78 kmol SO_2/h.

$$20.78\,\frac{kmol\ SO_2}{h} * 64\frac{kg}{kmol\ SO_2} = 1330\frac{kg}{h} \qquad 15$$

Thus, the total mass of SO_2 emitted per hour is 1330 kg/h. 1330 kg/hr of SO_2 is formed in Furnace and it will react with limestone.

The remaining 3 to 5.5 percent of sulfur in a pulverized coal-burning boiler that is not oxidized to sulfur dioxide or sulfur trioxide exits the boiler as bottom ash, as shown in Figure 25, depending on the sulfur content of the fuel. Five strategies can be used to reduce sulfur dioxide emissions from fossil-fuel-fired combustion sources. Low-sulfur fuel burning, Flue gas desulfurization, Dry scrubbing, fluidized bed combustion, and fuel treatment are all examples of these methods. (John, 1995)

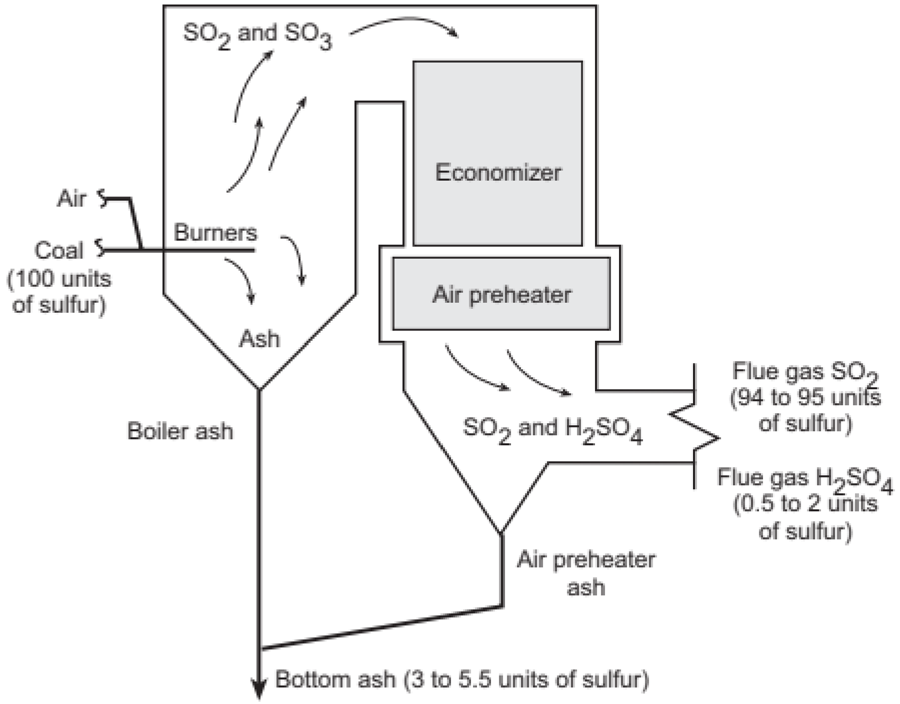


FIGURE 25. Conversion of fuel sulfur (John, 1995)

Figure 26 illustrates the furnace sorbent injection principle. As with in-duct sorbent injection at lower temperatures, this method has a low capital cost and achieves sulphur removal efficiencies of 60–75 percent by utilized sorbent recycling. Assuming 70% removal efficiencies, the theoretical limestone takes 931 kg/h of SO_2 out of the flue gas.

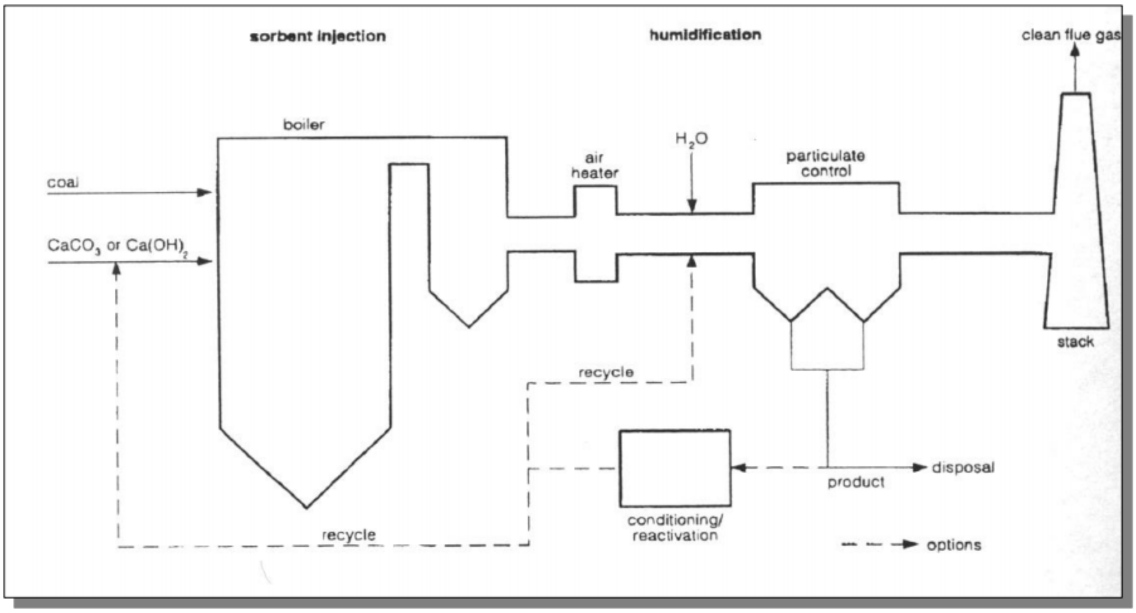


FIGURE 26. Furnace Sorbent injection (Zevenhoven and Kilpinen, 2005)

$$\frac{70}{100} * 1330\,\frac{kg}{h} SO_2 = 931\frac{kg}{h} SO_2 \qquad 16$$

Total amount of limestone can be calculated by utilitized equation 17 and 18 below. Equation 17 represents the calcination reaction at temperatures ranging from 600°C to 750°C and Equation 18 represents the desulfurization reaction at temperatures ranging from 700 °C to 850°C.

$$100\ \mathrm{CaCO_3(s)\ Heat} \rightarrow 56\ \mathrm{CaO(s)} + 44\ \mathrm{CO_2(g)} \tag{17}$$

$$56\ \mathrm{CaO(s)}\ +\ 64\ \mathrm{SO^2} +\ 16\ ½\ \mathrm{O^2 Heat} \rightarrow 136\ \mathrm{CaSO_4(s)} \tag{18}$$

Molecular weight ratios can be used to calculate theoretical limestone usage. If molecular weight of SO_2 = 64 and molecular weight Of $CaCO_3$ = 100 then total amount of limestone is 1454 kg/h.

$$931\ \frac{kg}{h} * \frac{100}{64} = 1454 \frac{kg}{h}\ CaCO_3 \tag{19}$$

1454 kg/h limestones are injected on furnace to remove 70% of SO_2. 399 kg/h of SO_2 release to inlet plenum or duct.

$$\frac{30}{100} * 1330\ \frac{kg}{h} SO_2 = 399 \frac{kg}{h} SO_2 \tag{20}$$

TABLE 6. DSI Removal rate (Zevenhoven and Kilpinen, 2005)

DSI + FF	**SO_2 removal rate**	**HCl removal rate**	**HF removal rate**
Hydrated Lime $Ca(OH)_2$	from 65% to 85%	from 50% to 80%;	from 50% to 98%;
Sodium Bicarbonate $NaHCO_3$	from 10% to 90%	from 50% to 99%;	90%;

Table 6 shows that DSI technology utilized hydrate lime has improved greatly up to 85% for SO_2 removal rate. Assuming 65% removal, the theoretical dsi takes 259.35 kg/hr of SO_2 out of the flue gas.

$$\frac{65}{100} * 399\ \frac{kg}{h} SO_2 = 259.35 \frac{kg}{h} SO_2 \tag{21}$$

Molecular weight ratios on equation 6 can be used to calculate theoretical hydrated lime usage. If molecular weight ratios of SO_2 = 64 and molecular weight of $Ca(OH)_2$ = 74 then total amount of hydrated lime is 449.81 kg/hr. 499.81 kg/h hydrated lime is needed to remove 259.35 kg/h SO_2 emission. SO_2 emission on duct is 139,65 kg /hr.

$$Stoichiometric\ Ca(OH)_2 = 1{,}5 * (k\,mol\ SO_2) \qquad 22$$

$$259.35\frac{kg}{h}SO_2 * \frac{74}{64} * \frac{1\ {,}5kmol\ Ca(OH)_2}{1\ kmol\ SO_2} = 449.81\frac{kg}{h}Ca(OH)_2 \qquad 23$$

$$\frac{35}{100} * 399\ \frac{kg}{h}SO_2 = 139.65\frac{kg}{h}SO_2 \qquad 24$$

$$Mass\ Emission = Volume\ Flow\,rate * Concentration\ of\ substance \qquad 25$$

From table 4 above shows that the amount of flue gas in coal combustion is 10.09 (dry) kg per kg of coal burned (Kg/kg$_{Pa}$). If coal was burned 70000kg/h (19.44 Kg/s) will produce 196,15 kg/s flue gas, but Excess air is needed to calculate the real amount of flue gas in combustion.

$$Theoritical\ amount\ of\ Flue\ Gas = amount\ of\ flue\ gas\ combustion\ x\ amount\ of\ fuel \qquad 26$$

$$Theoritical\ amount\ of\ Flue\ Gas = 10.09\ \frac{kg}{kg_{pa}} * 19.44\frac{kg}{s} = 196.15\frac{kg}{s} \qquad 26$$

The real total flue gas is theoretical flue gas calculation add by excess air rate. It can be calculated by formula below.

$$\dot{V}_{sk} = \left[\frac{V_{sk(teor)}}{m_{pa}} + (\lambda - 1)\cdot\frac{V_{i(teor)}}{m_{pa}}\right]\cdot \dot{m}_{pa} \qquad 27$$

where λ is burning air coefficient see table below

TABLE 7. Typical air coefficients for power plant chambers (Savonia Moodle, 2020)

Boiler fuel	Burning air factor λ
Coal	1.15-1.35
Gas	1.02-1.10
Heavy Oil	1.03-1.10
Black Liquor	1.10-1.25

On table 2, the total amount of air needed is 0,0701 + 0,2635 = 0,3336 kmol/kgpa, equal to 9,63 kg/kgpa. In table 4, the total amount of flue gas in dry condition is 0,3247 kmol/kgpa, equal to 10,09 kg/kgpa. The volume of 1 mole of a gas at Standard Temperature and Pressure (STP, 1 atm 0°C) is equal 22,4 L.

$$V = \frac{nRT}{P} \qquad 29$$

where P = 1 atm, n=1 mole, R=0,0821 atm L/mol K, K = 273K

$$V = \frac{1\,\cancel{mol}\,\frac{0{,}0821(\cancel{atm}\;L)}{\cancel{mol\;K}} * 273\cancel{K}}{1\;\cancel{atm}} = 22{,}4\mathrm{L} \qquad 30$$

Assume for this coal combustion $\lambda = 1.2$

$$\dot{V}_{sk} = \left[0{,}3247\,\frac{kmol}{kgpa} * 22{,}4\frac{L}{mol} + (1{,}2-1) * 0{,}3336\,\frac{kmol}{kgpa} * 22{,}4\frac{L}{mol}\right] * 19{,}44\frac{kg}{s} \qquad 31$$

$$\dot{V}_{sk} = \left[7{,}273\,\frac{kL}{kgpa} + (1{,}2-1) * 7{,}47\frac{kL}{kgpa}\right] * 19{,}44\frac{kg}{s} \qquad 32$$

$$\dot{V}_{sk} = \left[7{,}273\,\frac{k * 0{,}001m^3}{kgpa} + (1{,}2-1) * 7{,}47\frac{k * 0{,}001m^3}{kgpa}\right] * 19{,}44\frac{kg}{s} \qquad 33$$

$$\dot{V}_{sk} = [7{,}273 + 1{,}494]\frac{m^3(n)}{kgpa} * 19{,}44\,\frac{kg}{s} \qquad 34$$

$$\dot{V}_{sk} = [8{,}76] \cdot 19{,}44\frac{M^3(n)}{s} = 170{,}43\frac{M^3(n)}{s} = 613.549\,\frac{M^3(n)}{h} \qquad 35$$

The real total flue gas is 613.549m^3(n)/h therefore the concentration of substance SO_2 is 227,50 SO_2 mg/(N)m^3 (O_2 content 3.5 %). it is calculated by utilizing equation 25, we can determine concentration of SO_2 in dry flue gas.

$$Concentration\;of\;subtance\;\;(SO_2) = \frac{139{,}65\frac{kg}{h}}{613.549\frac{m^3(n)}{h}} = \frac{139.650.000\frac{mg}{h}}{613.549\;\frac{m^3(n)}{h}} \qquad 36$$

$$Concentration\;of\;subtance\;\;(SO_2) = 227{,}50\;\;\frac{mg}{(N)m^3}\quad (\mathrm{O2\;content\;3.5\;\%}) \qquad 37$$

The Amount of O2 Content of the Flue Gas is 3.5%

$$\lambda = \frac{21}{21 - X_{O2(mit)}} \qquad 38$$

$$1{,}2 = \frac{21}{21 - X_{O2(mit)}} \qquad 39$$

$$X_{O2(mit)} = 3{,}5 \qquad 40$$

Refer to DIRECTIVE 2001/80/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL (O_2 content 6 %), Oxygen (O_2) content 0% should be interpolated to Oxygen (O_2) content 6% by below equation

$$Oxygen\ correction\ factor = \frac{(21 - reference\ oxygen)}{(21 - measured\ oxygen)} \quad 41$$

$$Oxygen\ correction\ factor = \frac{(21 - 6)}{(21 - 3.5)} = 0{,}8 \quad 42$$

$$Concentrtion\ at\ reference\ conditions = Concentration\ as\ measured\ x\ Correction\ factor\ for\ oxygen \quad 43$$

$$Concentration\ at\ reference\ conditions = 227{,}50 \frac{mg}{(N)m^3} * 0{,}8 = 182{,}11 \frac{mg}{(N)m^3} \quad 44$$

The concentration of substance SO_2 is 182,11 SO_2 mg/(N)m^3 (O_2 content 6%)(dry). As shown figure below if thermal efficiency is 50 MWth the SO_2 emission should be less than or equal 2000 mg/Nm^3. In case if thermal efficiency is 500 MWth it should be 400 mg/Nm3. (European Council, 2001).

For plant size 100-500 can use formula as shown on table 8 below.

$$Emission\ standard = 2000 - 4\ (P - 100) \quad 45$$

where P = Plant size in MW $_{\text{thermal}}$

$$Emission\ standard = 2000 - 4\ (150 - 100) = 1800 \quad 46$$

The concentration of substance SO_2 is 182,11 SO2 mg/(N) m^3 (O_2 content 6%) (dry), which is less than 1800 mg/(N) m^3 (O_2 content 6%) (dry). DSI technology complies with Emission standard for EU.

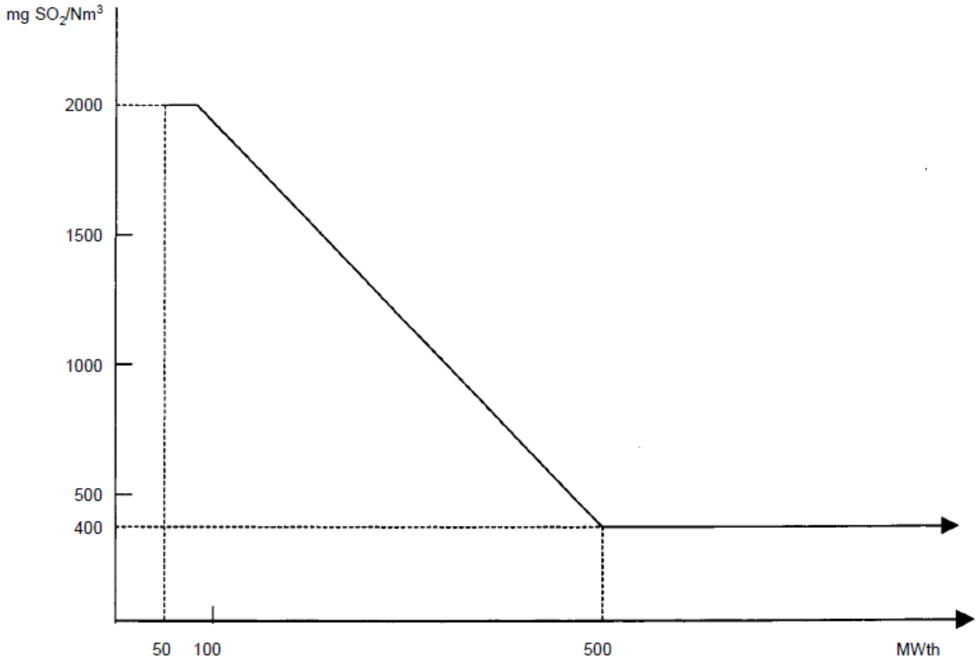


FIGURE 27. Emission limit value for SO_2 (O_2 content 6 %) Solid Fuel (European Council, 2001)

TABEL 8. SO_2 Emission standard for EU – Solids Fuel (Zevenhoven and Kilpinen, 2005)

Fuel	**Plant size (MW $_{th}$)**	**Emission standard (mg/m^3 $_{STP}$,dry)**	**Comments**
Solid	50-100	2000@6% O_2	If problem then removal 60%
Solid	100-500	2000 -4 (P-100) @6% O_2	If problem then removal 100-300 MWth>75% 300-500 MWth>90%
Solid	>500	400@6% O_2	If problem then removal 92% or 95%

5.3.1.2 HCl Emission

Hydrochloric acid (HCl) is usually formed when chlorine atoms are present in the organic compound being burned. Almost all of the chloride atoms in the fuel or waste being burned convert to HCl as long as there are sufficient hydrogen atoms present in the gas stream from hydrocarbons or water vapor. Chloride and fluoride ions are found in trace amounts in combustion ash. All chlorides and fluorides are released during the early stages of combustion and eventually combine with a hydrogen atom to form hydrogen chloride or hydrogen fluoride. Hydrogen chloride emissions are produced when coal, plastics, and paper are burned. (John, 1995)

HCl has a high acute toxic effect on all forms of life, irritates the membrane of the eye and upper respiratory tract. When released into the atmosphere (as a gas), it will undergo wet and dry deposition, and will be readily incorporated into cloud, rain, and fog water, thus forming a component of acid rain. Emissions Factors for HCl formed during the combustion of coal are shown on below table. (EPA 745-B-19-017, 2019)

TABLE 9. HCl emission factor of coal (EPA 745-B-19-017, 2019)

Source	**Emissions Factor (Kg/ton coal)**
Anthracite Coal	0.41
Bituminous Coal	0.86
Subbituminous Coal	0.86
Lignite	0.0045

Removing hydrogen chloride emissions is very much similar to approaches to SO_2 emission control. The methods used are often based on injection of (EPA AP-42, 1998)sorbent into gas at low temperatures (dry, wet or semi – dry duct injection) or at high temperatures (furnace injection, limestone in fluidized furnaces). The HCl reacts with CaO after calcination of the $Ca(OH)_2$. (Zevenhoven and Kilpinen, 2005)

$$\mathrm{Ca(OH)_2(s) \rightarrow CaO(s) + H_2O(g)} \tag{47}$$

$$\mathrm{CaO(s) + 2HCl(g) \rightarrow CaCl_2(s) + H_2O(g)} \tag{48}$$

If a facility combusts 70 tons of bituminous coal the amount of HCl formed can be calculated:

$$Amount\ of HCl\ emission = Emission\ factor\ X\ amount\ of\ Fuel \tag{49}$$

$$Amount\ of HCl\ emission = 0{,}86\ HCl \frac{Kg}{ton} * 70 \frac{ton}{hr} Coal = 60{,}2 \frac{Kg}{hr} \tag{50}$$

The amount of HCl aerosols released to air from the stack will be the amount formed minus amount removed by air control devices and will depend on the efficiency of the device for removing HCl. (EPA 745-B-19-017, 2019)

Furnace Sorbent injection technology can remove HCl Emission 63- 86% (Zevenhoven and Kilpinen, 2005). Assuming 80% removal of HCl, the unreacted HCl is 12.04 kg/hr (20% X 60,2 kg/hr). Referring to the removal rate on table 6, DSI technology can remove 50% - 80% of HCl. The unreacted HCl is 3.6 kg/hr(30% X 12.04 kg/hr). Formula 25 can be used to calculate the concentration of HCl.

$$Concentration\ of\ subtance\ (HCl) = \frac{3{,}6 \frac{kg}{h}}{613.549 \frac{m^3(n)}{h}} = \frac{3.600.000 \frac{mg}{h}}{613.549 \frac{m^3(n)}{h}} \tag{51}$$

$$Concentration\ of\ subtance\ (HCl) = 5{,}8\ \frac{mg}{(N)m^3} \quad (\text{O2 content } 3.5\ \%) \tag{52}$$

Formula 41 can be used to calculate oxygen correction factor by using reference oxygen 11% (European Council, 2010).

$$Oxygen\ correction\ factor = \frac{(21-11)}{(21-3.5)} = 0{,}57 \tag{53}$$

The result of oxygen correction factor (0,57) on formula 50 can be used to determine the concentration of HCl at reference conditions (O2 content 11 %). Thus, the concentration of HCl is 3,36 mg/N m^3 (dry) (O2 content 11 %).

$$Concentration\ at\ reference\ conditions = 5{,}8 \frac{mg}{(N)m^3} * 0{,}57 = 3{,}36 \frac{mg}{(N)m^3} \tag{54}$$

Thus, DSI technology complies with EU standard for combustion plants firing solid fuels, with HCl emission levels expected to be less than 10 mg/Nm³ (European Council, 2010)

5.3.1.3 HF Emission

If fluorine atoms are present in the organic compound being burned, hydrofluoric acid (HF) will usually be formed. Hydrogen Fluoride is a strong acid which contributes to acid rain and can heavily impact the flora around an emission point, as well as human health. Irritation to skin, eye, nose, throat, and breathing passage (Environmental Healt & Engineering inc, 2011). EPA reports an emission factor of 0.068 kg/ton for coal combustion under a variety of firing conditions as shown table below. (EPA AP-42, 1998)

TABLE 10. HF emission factor (EPA AP-42, 1998)

Firing Configuration	**Emissions Factor (kg/ton coal)**
PC-Fired	0.068
FBC ,Circulating Bed	0.068

Removing hydrogen Fluoride emissions is very much similar to approaches to SO_2 emission control. The methods used are often based on injection of sorbent into gas at low temperatures (dry, wet or semi – dry duct injection) and can reduce 98% of HF or at high temperatures (furnace injection, limestone in fluidized furnaces) can reduce 94 - 99% of HF. The HF reacts with CaO after calcination of the $Ca(OH)_2$. (Zevenhoven and Kilpinen, 2005)

$$\mathrm{Ca(OH)_2(s)Heat \rightarrow CaO(s) + H_2O(g)} \qquad 55$$

$$\mathrm{CaO(s) + 2HF(g) \rightarrow CaF_2(s) + H_2O(g)} \qquad 56$$

If a facility combusts 70 tons of bituminous coal the amount of HF manufactured can be calculated:

$$Amount\ of HF\ emission = Emission\ factor\ X\ amount\ of\ Fuel \qquad 57$$

$$Amount\ of HF\ emission = 0{,}068\ HF \frac{Kg}{ton} * 70 \frac{ton}{hr} Coal\ = 4{,}76 \frac{Kg}{hr} \qquad 58$$

When assuming 98% removal of HF the unreacted HF is 0.095 kg/hr (2% X 4,76 kg/hr) . DSI technology can remove 98% of HF. When assuming 98% removal of HF the unreacted HF is 0,0019 kg/hr (2% X 0.095 kg/hr). Formula 25 can be used to calculate the concentration of HF.

$$Concentration\ of\ subtance\ (HF) = \frac{0{,}0019\frac{kg}{h}}{613.549\frac{m^3(n)}{h}} = \frac{1.900\frac{mg}{h}}{613.549\ \frac{m^3(n)}{h}} \quad 59$$

$$Concentration\ of\ subtance\ (HF) = 0{,}00309\ \frac{mg}{(N)m^3} \quad (\text{O2 content } 3.5\ \%) \quad 60$$

Formula 43 can be used to calculate oxygen correction factor by using reference oxygen 11% and oxygen correction factor is 0,57. (European Council, 2010).

$$Concentration\ at\ 11\%O_2(dry) = 0{,}00309\frac{mg}{(N)m^3} * 0{,}57 = 0{,}00177\frac{mg}{(N)m^3} \quad 61$$

Thus, DSI technology complies with the EU standard for combustion plants firing solid fuels, with HF hydrogen fluoride emission levels expected to be less than 1 mg/Nm³ (European Council, 2010)

5.3.2 Sodium Bicarbonate

Another often used sorbent is sodium bicarbonate, which is quite effective against HCl and SO_2. High amounts of acid gas elimination are possible at lower feed rates than with hydrated lime. This sorbent, however, is more expensive than hydrated lime. Solvay's recent pilot plant experiments at an independent site prove that dry injection of sodium bicarbonate can achieve more than 99% removal rates for HCl. The studies successfully illustrate sodium sorbents' selectivity for removing HCl in a medium to high sulfur environment. A sodium DSI system injects a sorbent straight into the hot flue gas duct, where it rapidly reacts with HCl, SO_2, SO_3, and HF, reducing NO_x in some cases. Field testing has demonstrated that this method is capable of removing almost all SO_3 and HCl, as well as well over 90% of SO_2. Many waste incinerators in Europe and coal-fired power plants in the United States have already implemented this technology. (Yougen Kong, Michael Wood, 2012)

Sodium bicarbonate in its natural state is too coarse to be injected directly. As a result, milling is necessary. This milling is performed by vendors or by the end user at the point of usage. When milled on-site, the particle size target is 90% less than 20 microns. (Yougen Kong, Michael Wood, 2012)

The minimum temperature of flue gas at the sorbent injection point should be 135 °C. Generally, higher temperatures result in improved performance. The maximum temperature that is recommended is 815 °C. Sodium bicarbonate ($NaHCO_3$) is calcined into sodium carbonate (Na_2CO_3) after being injected into hot flue gas (> 135 °C), as shown in the following equation:

$$2\ \mathrm{NaHCO_3(s)} \xrightarrow{\sigma > 135°\mathrm{C}} \mathrm{Na_2CO_3(s) + CO_2(g) + H_2O(g)} \quad 62$$

The release of water vapor and CO_2 during calcination results in the formation of many micropores inside the sorbent, a phenomenon called the "pop-corn" effect. Calcined sorbent has a BET specific area of approximately 10 m²/g as shown on figure below. Due to the relatively large surface area, sodium carbonate reacts rapidly with acid gases such as SO_2, SO_3, HCl, and HF. (Yougen Kong, Michael Wood, 2012)

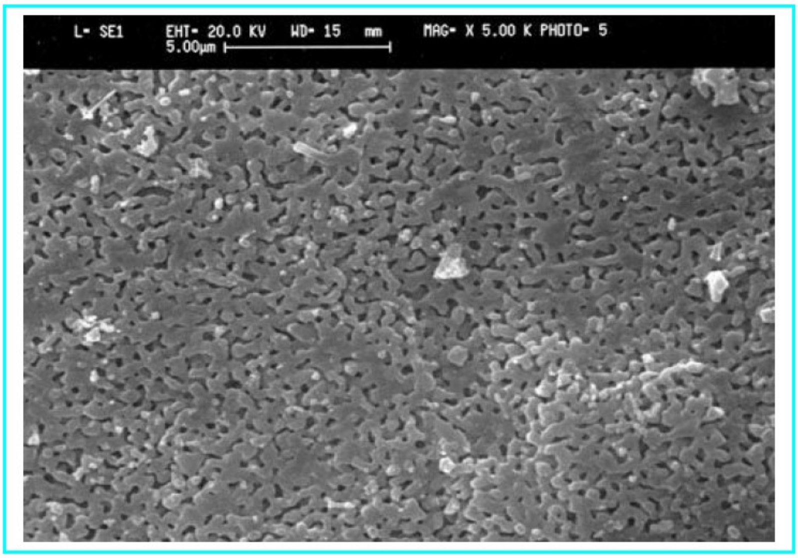


FIGURE 28. Calcined Sodium Bicarbonate Under Microscope (Yougen Kong, Michael Wood, 2012)

The calcined Sodium bicarbonate reacts with flue gas pollutants as follows:

$$\mathrm{Na_2CO_3(s) + SO_2(g) + \frac{1}{2}O_2(g) \rightarrow Na_2SO_4(s) + CO_2(g)} \qquad 63$$

$$\mathrm{Na_2CO_3(s) + 2HCl(g) \rightarrow 2NaCl(s) + CO_2(g) + H_2O(g)} \qquad 64$$

$$\mathrm{Na_2CO_3(s) + 2HF(g) \rightarrow 2NaF(s) + CO_2(g) + H_2O(g)} \qquad 65$$

The calcination leads to a greater specific surface area (BET). The greater the available reaction surface, the more efficient the reduction performance of the sodium carbonate. The removal process also generally increases in line with a rise in temperature. (Yougen Kong, Michael Wood, 2012)

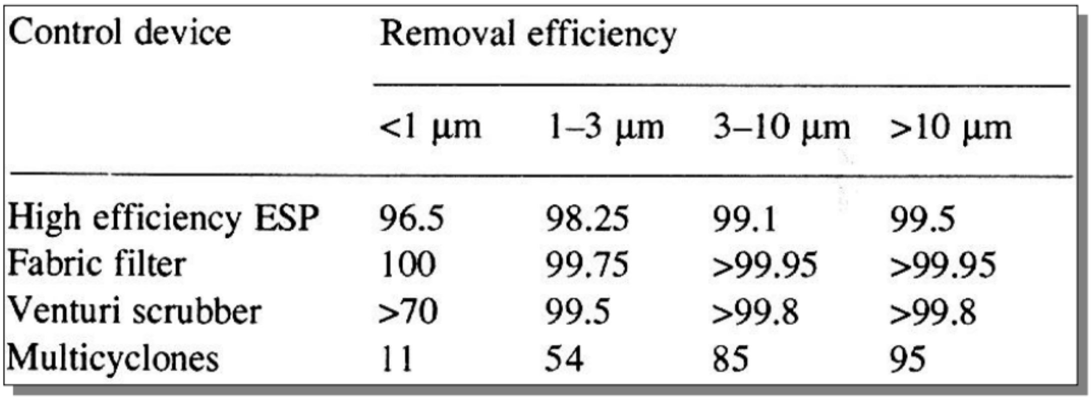
5.4 Particulate Matter Control Impacts

Particulate Matter (PM) is One of the major pollutants from bituminous and subbituminous coal combustion. Uncontrolled PM emission from coal fired boiler include the ash from combustion of the fuel as well as unburnt carbon resulting from incomplete combustion. Coal ash may either settle out in the boiler (bottom ash) or entrain in the flue gas (fly ash). PM emission rate is affected by the distribution of ash between the bottom ash and fly ash. Boiler load also affects the PM emission. (EPA AP-42, 1998). Table below shows dust emission limit values expressed in mg/N m^3 (O_2 content 6 % for solid fuels, 3 % for liquid and gaseous fuels).

TABLE 11. Dust emission standard for EU Large Combustion plants (European Council, 2001)

Type of Fuel	Rated thermal input (MW)	Emission limit values (mg /Nm^3)
Solid	≥500	50
Solid	<500	100
liquid	all plants	50

Particulate matter entrained in the gas stream along with the gaseous contaminants can have a significant effect on the collector's efficiency and reliability. Particulate matter can accumulate in these areas, obstructing normal gas flow. Particulate matter has a particularly negative impact if it is relatively large (i.e., > 3 micrometers) or sticky. If the gaseous contaminant control system is prone to failures caused by particulate matter, a pre-collector may be required. Extremely small particles (less than 1 µm in diameter) can be efficiently collected in a baghouse or fabric filter. (John, 1995)



Control device	Removal efficiency			
	<1 µm	1–3 µm	3–10 µm	>10 µm
High efficiency ESP	96.5	98.25	99.1	99.5
Fabric filter	100	99.75	>99.95	>99.95
Venturi scrubber	>70	99.5	>99.8	>99.8
Multicyclones	11	54	85	95

FIGURE 29. Collection Efficiencies (in%) of several particulate control devices (Zevenhoven and Kilpinen, 2005)

Figure above illustrates the removal efficiencies of a few different types of particulate control devices over four particle size ranges. Gravity and centrifugal forces can be effective for larger particles (> 10 µm), while electrostatic forces can be used in conjunction with particle charging for smaller particles (< 2 µm). Venturi scrubbers operate at a few micrometer resolution, whereas Fabric filters have extremely high efficiencies across a wide size range. This comparison demonstrates the enormous potential of Fabric filter systems: they provide high removal efficiencies over a wide size range and are more adaptable to the particle properties and process conditions than other methods. (Zevenhoven and Kilpinen, 2005)

Information concerning the oxygen, carbon monoxide, ammonia, and hydrogen sulfide concentration is needed to determine the allowable contaminant concentrations. If contaminant concentrations, oxygen concentrations, and gas temperatures are in the hazardous range, many of the organic and inorganic chemicals collected can be ignited. These potentially explosive circumstances must be anticipated and carefully avoided during the control system's design. (John, 1995)

Modifications to the combustion process (applicable to small fired boilers) and postcombustion treatments are the two most important PM control strategies (applicable to most boiler type and sizes). The use of a fabric filter or a baghouse to limit particulate matter emissions from coal-fired combustion sources can be achieved after the combustion process. (EPA AP-42, 1998). More contact between the gas and the injected sorbent is achieved with fabric filters or baghouses than with electrostatic precipitators (ESPs), resulting in improved removal at any given reagent treatment rate. (NESCAUM, 2011)

Dry sorbent injection will increase the quantity of particulate and the composition of particulate collected in the particulate control device will change from just fly ash to sorbents and reaction products. It also increases dust loading and may impact operation of the baghouse.
(Michael,Joshua,Curt and friend, 2016)

5.4.1 Potential Baghouse Impacts

The baghouse collects the particulate matter (including metals, acid gas reaction products (mainly calcium chloride and calcium sulfate), unused sorbent, material, and fly ash) from a flue gas stream. A pulse jet fabric filter collects filterable material on the outside of the filter bags after the flue gas flows through the filter bags as shown in the figure below. (Beachler, 1995)

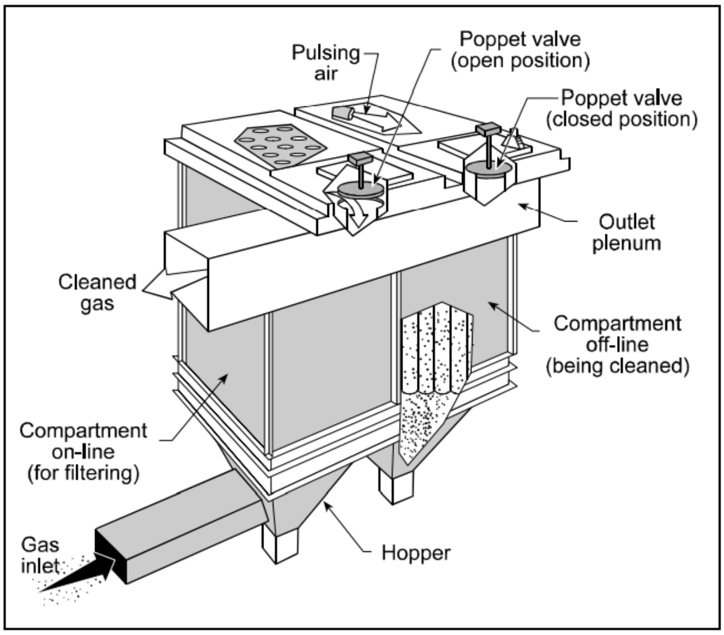


FIGURE 30. Compartmentalized pulse jet baghouse (Beachler, 1995)

Potential impacts for baghouses are cleaning frequency, corrosion, and filter cake formation.

With the additional PM loading from DSI, the baghouse pressure drop or cleaning frequency will increase. It is possible that the pressure drop will increase if the bag cleaning controls are configured to run on a timer. If pressure drop control is used to manage cleaning events, the frequency of cleaning will rise. The plant will determine which technique of control is the most appropriate for actual baghouse operation. (Michael,Joshua,Curt and friend, 2016)

Corrosion in the system's backend and baghouse is often minimized when calcium and sodium-based sorbents are injected for acid gas mitigation. This is also true when using halogenated activated carbon in conjunction with a calcium or sodium-based sorbent and/or a high calcium oxide fly ash. (Michael,Joshua,Curt and friend, 2016)

The figure below illustrates how gases (and also liquids) are separated from dispersed particles by passing them through a large surface area fabric or ceramic filter "medium." Particles that are unable to penetrate the medium will remain on its surface, forming what is referred to as the "filter cake." In general, the filter cake is almost as critical to the filtration process as the medium. Filter systems achieve extremely high collection efficiencies, typically greater than 99 percent, over a relatively wide size range. Operating temperature range is between (120 -200^{0}C). (Zevenhoven and Kilpinen, 2005)

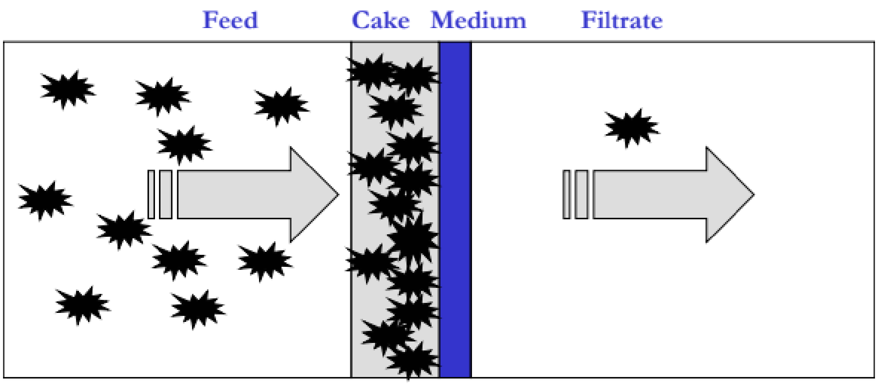


FIGURE 31. Principle of filtration (Zevenhoven and Kilpinen, 2005)

The formation of filter cakes on the bags will vary according to the concentration of DSI sorbents and reaction products in relation to the existing fly ash. Collecting and testing samples during a DSI trial will assist in determining whether the filter bags experience properties that may affect their long-term performance. According to studies, baghouse optimizations can reduce sorbent consumption by up to 33% (Michael,Joshua,Curt and friend, 2016). The presence of filter cake on the bags allows for a longer reaction period between the sorbent solids and the flue gas, resulting in higher SO_2 removal efficiency for baghouses than ESP.

5.5 Potential Impact on Process Byproducts

When hydrated lime is utilized as DSI reagent, the reaction compounds present dry solid of $CaSO_4$, $CaCl_2$ and CaF_2. These are byproducts of Acid Removal Process that has been outlined on chapter 5.3.1. These impacts must be considered regardless of whether these materials can be marketed or disposed of. Solubility and metal leaching potential are the two primary properties that are impacted by the addition of unreacted DSI reagent and reaction products. These altered properties may have an effect on the way the resulting byproduct material can be used or disposed of responsibly. A facility's impact on any byproduct material it produces should be evaluated. (Michael,Joshua,Curt and friend, 2016)

The following table summarizes the reaction products as defined in the CRC Handbook of Chemistry and Physics. Solubility of byproduct impacted by sodium DSI reagents would be expected to be much higher than the byproducts impacted by calcium DSI reagent products if sulfur is present in the flue gas stream. since Na_2SO_4 is 28.1 more soluble than Ca_2SO_4 only 0.21. In another Case if there is Chlorides in flue gas stream, the use of sodium would result in slightly less soluble byproduct materials as the solubility of NaCl is lower than that of $CaCl_2$.

TABLE 12. Solubility of selected compounds in water (David R. Lide, 2005)

Reaction Compound	**25⁰C H_2O Solubility (Grams per 100 g H_2O)**
Na_2SO_4	28.1
$CaSO_4$	0.21
NaCl	36
$CaCl_2$	81.3
NaF	4.13
CaF_2	0.0016

American Society for Testing and Materials (ASTM) classifies coal combustion products (C and F) based on the relative concentration of silica, aluminum, and iron oxide in the fly ash. Class F ash is pozzolanic in nature, with more than 70% $SiO_2 + Al_2O_3 + Fe_2O_3$ and low lime content. The combustion of older, harder anthracite and bituminous coal produces this fly ash. Some self-cementing properties can also be found in the Class C ash produced by the combustion of younger lignite or subbituminous coal. For Class C fly ash, the typical composition is 50–70 wt% Si_2O_3, Al_2O_3, Fe_2O_3, and a significant amount of lime. (Zhang, 2014)

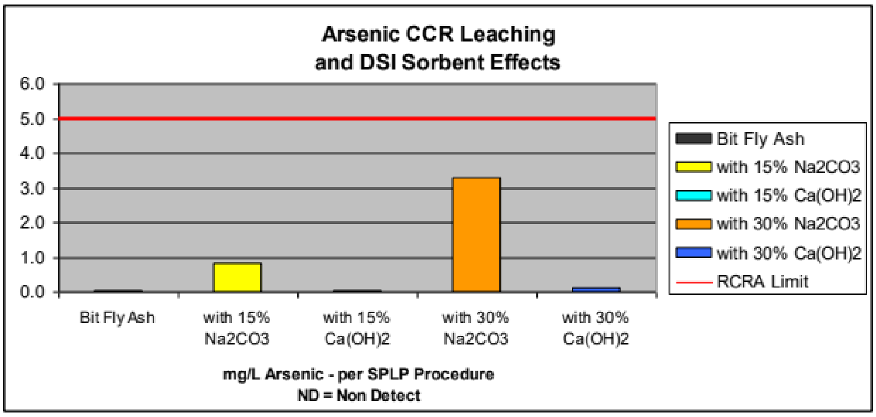


FIGURE 32. Arsenic leaching from bituminous fly ash combined with DSI Reagents (Michael, Schantz, and Melissa, 2013)

As a result, when calcium hydroxide is used as a DSI reagent, part of the reagent that does not react with the acid gases in the flue gas stream reacts with the pozzolan, resulting in the encapsulation of some metals. In some situations, this cementing mechanism can mitigate the effect of the DSI material's elevated pH and minimize the metals leaching potential of certain byproduct materials. A demonstration of this phenomenon is shown in Figure above, where the addition of 15% $Ca(OH)_2$ does not result in an increase in arsenic leaching despite the increase in alkalinity. Due to the fact that sodium lacks the ability to drive this cementitious mechanism, the leaching potential of metals is always increased when sodium DSI reagents are used. (Michael, Schantz, and Melissa, 2013)

5.6 Potential Impact on Capture of Mercury

Mercury is a highly volatile metal and therefore, the majority of the mass of mercury in the coal tends to be emitted from the boiler in the flue gas and not in the bottom ash or in the fly ash. Mercury removal efficiency from combustion gas is significantly impacted by the presence of halide gases like hydrogen chloride (HCl) and hydrogen bromide (HBr). The halogen component of these acid gases promotes the oxidation of elemental mercury (Hg0) to its divalent state (Hg2+), which can then be easily removed using powdered activated carbon (PAC) injection into the flue gas stream. (Michael,Joshua,Curt and friend, 2016)

Both calcium or sodium-based sorbents can remove out or neutralize the halogens, thereby degrading or eliminating mercury oxidation. This can have a negative impact on mercury control by particulate collectors, scrubbers, or activated carbon where no oxidation capability has been designed (non-halogenated (PAC) Powdered Activated Carbon). PAC can also be impregnated with halides as part of its formulation, achieving the similar result of oxidizing and then securely trapping the mercury and collected with the fly ash in the bag house. (Michael,Joshua,Curt and friend, 2016)

Figure below shows data, taken from St. Clair Unit 3, on stack mercury emissions. Nonbrominated PAC was injected downstream of the air preheater, while sodium sorbent was injected upstream of the air preheater. Bromine was also added to the coal in these tests. When either trona or SBC was injected, mercury stack emissions increased significantly.

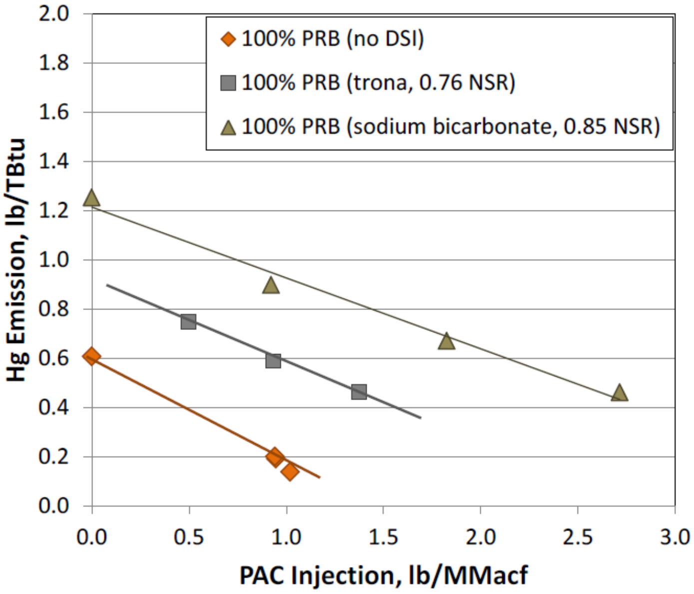
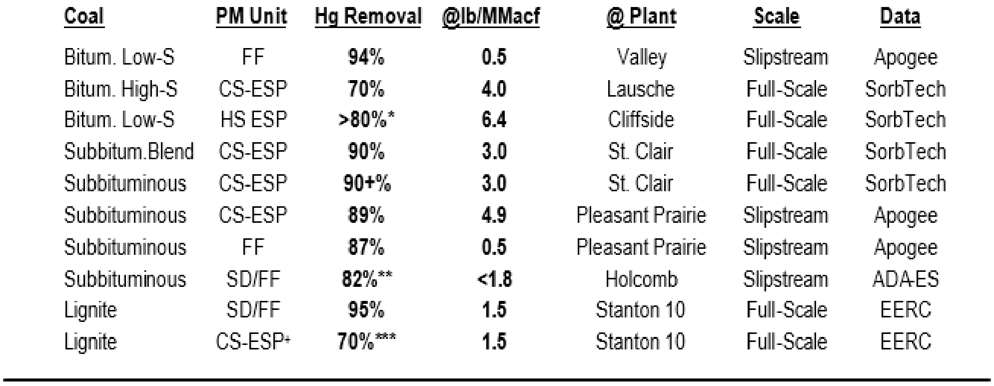


FIGURE 33. Mercury emissions as a function of non-brominated PAC injection rate with and without sodium DSI sorbents (Michael,Joshua,Curt and friend, 2016)

For plants that require both DSI and PAC injection, the injection location of the alkaline sorbent and PAC is determined by the plant's architecture and fuel type. Several factors to consider include the type of DSI sorbent employed; the uncontrolled SO_3 content in the flue gas; the temperature of the flue gas at the particulate control device; and the amount of available residence time before the particulate control device. To determine the optimal injection locations for specific sorbents, manufacturers of sorbents and sorbent injection equipment should be consulted. (Michael,Joshua,Curt and friend, 2016)

The performance of powdered activated carbons (PAC) and iodine-impregnated PAC at power plants can be very different, depending on the type of coal that is used and the plant's existing air pollution control equipment. However, Sorbent Technologies Corporation's brominated mercury sorbents (B-PAC^{TM}) have shown that they can remove a lot of mercury at low injection levels with a wide range of coals and configurations. Mercury levels have been reduced by over 90 percent. This is shown on Figure here below. (Sid Nelson Jr., Ronald Landreth, Ph.D., Qunhui Zhou, Ph.D., and Jon Miller, 2004)



Coal	PM Unit	Hg Removal	@lb/MMacf	@ Plant	Scale	Data
Bitum. Low-S	FF	**94%**	**0.5**	Valley	Slipstream	Apogee
Bitum. High-S	CS-ESP	**70%**	**4.0**	Lausche	Full-Scale	SorbTech
Bitum. Low-S	HS ESP	**>80%***	**6.4**	Cliffside	Full-Scale	SorbTech
Subbitum.Blend	CS-ESP	**90%**	**3.0**	St. Clair	Full-Scale	SorbTech
Subbituminous	CS-ESP	**90+%**	**3.0**	St. Clair	Full-Scale	SorbTech
Subbituminous	CS-ESP	**89%**	**4.9**	Pleasant Prairie	Slipstream	Apogee
Subbituminous	FF	**87%**	**0.5**	Pleasant Prairie	Slipstream	Apogee
Subbituminous	SD/FF	**82%****	**<1.8**	Holcomb	Slipstream	ADA-ES
Lignite	SD/FF	**95%**	**1.5**	Stanton 10	Full-Scale	EERC
Lignite	CS-ESP+	**70%*****	**1.5**	Stanton 10	Full-Scale	EERC

FIGURE 34. B-PAC result to date indicate applicability across all coals and plant configuration

The use of brominated powdered activated carbon (B-PAC^{TM}) to remove mercury from power plant flue gas has been tested at seven different power plants. These plants have burned bituminous, subbituminous, lignite, and blends of coals. They have also done tests with PM unit Such as cold-side ESP(CS-ESP), hot-side ESP(HS ESP), spray dryer (SD), and fabric filters(FF). The consumption rate of B-PAC sorbent injection may vary from 8 to 102.5 kg/MMacm (million actual cubic meter of flue gas). Mercury-removal performance at these sites has ranged from 70% to 95% at a cost of about $4,410 to $44,100 per kg of mercury removed, which is a lot less than previous technologies. (Sid Nelson Jr., Ronald Landreth, Ph.D., Qunhui Zhou, Ph.D., and Jon Miller, 2004)

5.7 Potential Impact on another metal

Numerous investigations, including those by Meij and others (Meij,1989), demonstrated that trace elements can be classified into three classes, as seen in figure below Class I components do not volatilize during combustion or gasification and are distributed fairly evenly between bottom and fly ashes. Class II elements are vaporized but are primarily present in fly ashes as a result of condensation on particulates and nucleation mechanisms caused by a decrease in temperature in a flue gas duct, for example. A considerable proportion of these small particles are sub-micron in size, making some dust control systems ineffective. Within the installation, Class III elements are vaporised and condense partially (Kema, 1997, Couch,1995). Additionally, figure below includes the boiling points of several compounds. When combined with data on toxicity and adverse effects on process equipment, this categorization provides an early indicator of which trace elements require extra attention.

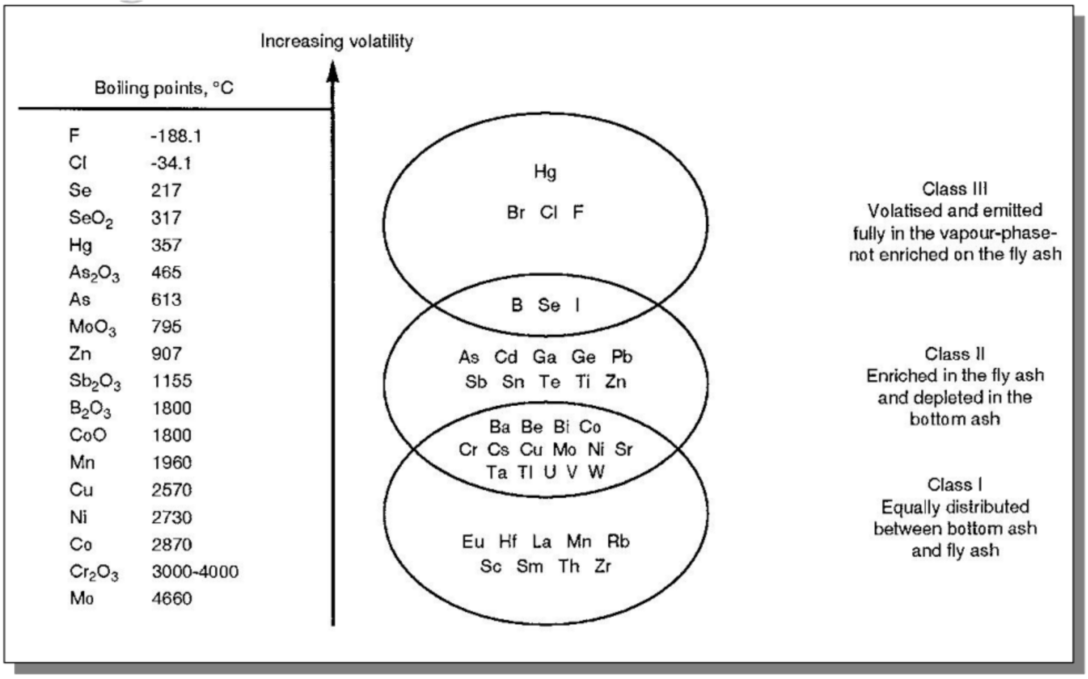


FIGURE 35. Classification of trace elements present in the coal feed by their behavior during combustion and gasification (Couch, 1995).

As, Be, Co, Cd, Cr, Mn, Ni, Pb and Sb as fly ash will be captured in particulate control device. Halides (Br, Cl and F) will be depleted by DSI.

5.8 Potential Impact of acidic particulate matter

Acid gases are present in the gas stream and may damage the sensor to malfunction and fail to read the LEL (Lower Explosive Limit) Measuring in the presence of corrosive gases and vapors in the sample gas stream can damage the LEL meter's sensor and cause the measurement results to be biased. Sulfuric acid, hydrogen chloride, and hydrogen fluoride are all examples of corrosive gases and vapors. LEL monitors are not aimed to measure the concentration or ignition potential of particulate matter or fibers. The following are examples of ignitable particulate matter and fibers: Coal dust, wood sander dust, flour and grain dusts, metal dusts such as aluminum, carbonaceous dusts, and organic. (John, 1995)

These materials' ignitability is highly dependent on their particle size. These materials are most dangerous when they have a small distribution size, as this creates a large surface area for oxidation reactions. Regrettably, LEL monitors are incapable of detecting the presence of these substances in the gas stream entering a gaseous contaminant control system.

6 PDMS IMPLEMENTATION

PDMS has provided user interface customization via dot Net Framework and PDMS Macro. All code can be written via dot Net C# and programming macro language. While PML is a powerful language within PDMS, it suffers from a lack of fundamental resources such as a debug tool, a graphical interface for creating forms, and the ability to communicate with third-party software in a practical manner. The new.NET APIs address these PML deficiencies while also opening up a whole new world of possibilities for developing new interfaces with other software or just for customizing existing software. Microsoft began developing the.NET framework in the early 1990's, but the first beta version was not published for almost ten years. It is currently at version 4.0, however PDMS only supports version 3.5, .NET programming is built on DLL, which means that the code is compiled to a.dll file instead of an.exe file. When PDMS is opened, it calls this.dll file. in this way, an external application that connects to and interacts with PDMS could be developed. (Rbasniak, 2013)

6.1 PDMS .NET Customization Architecture

.NET is not an abbreviation; it is a Microsoft product that integrates all platforms, including desktop apps, mobile apps, and cloud, into a single framework. The .NET APIs provided access to a variety of features of the product, including the Graphical User Interface, the database, and geometry. As part of AVEVA's 'continual progression' strategy, the.NET customization capability has been provided in a way that it may be utilized in conjunction with the existing PML-based customization. By utilizing PML.NET, a PML upgrade that enables the PML programmer to call.NET code, customization that takes advantage of the characteristics of both.NET generated code and PML can be accomplished. (Aveva 3, 2012)

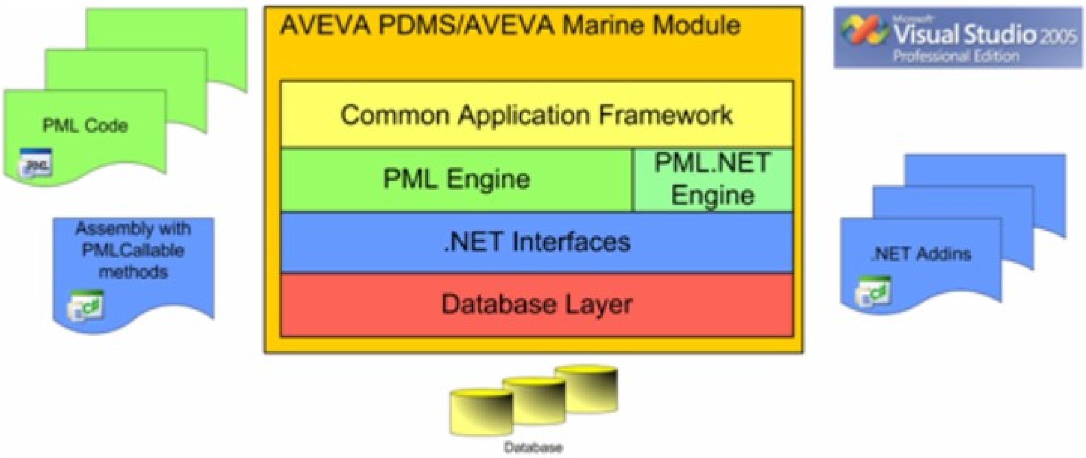


FIGURE 36..Net customization Architecture

The diagram above displays two new approaches of customisation that utilize technology. The first is accomplished through the use of a.NET Addin, while the second is accomplished through the use of PML.NET. Both approaches enable dynamic loading of a.NET assembly (DLL) into a module at runtime. in this thesis .Net Addins is used. The Common Application Framework (CAF) is an extensible framework that provides.NET programmers with access to a variety of services that support in the development and customization of applications. The two interface assemblies Aveva.Application-Framework.dll and Aveva.ApplicationFramework.Presentation.dll provide as the CAF's foundations. (Aveva 3, 2012)

6.2 PDMS Process Flow Diagram and Code

After getting all the values needed from mass energy balance calculation software, including flow rate, pressure, temperature, and velocity of flue gas. user or designer opens the user interface on PDMS and inserts all the values needed. PDMS will validate all these values and produce the baghouse dimension and amount of needed bags. After generating a DSI model on the design module, material take off can be exported to excel format as a final result as shown on figure below. (Sumitomo-5, 2020)

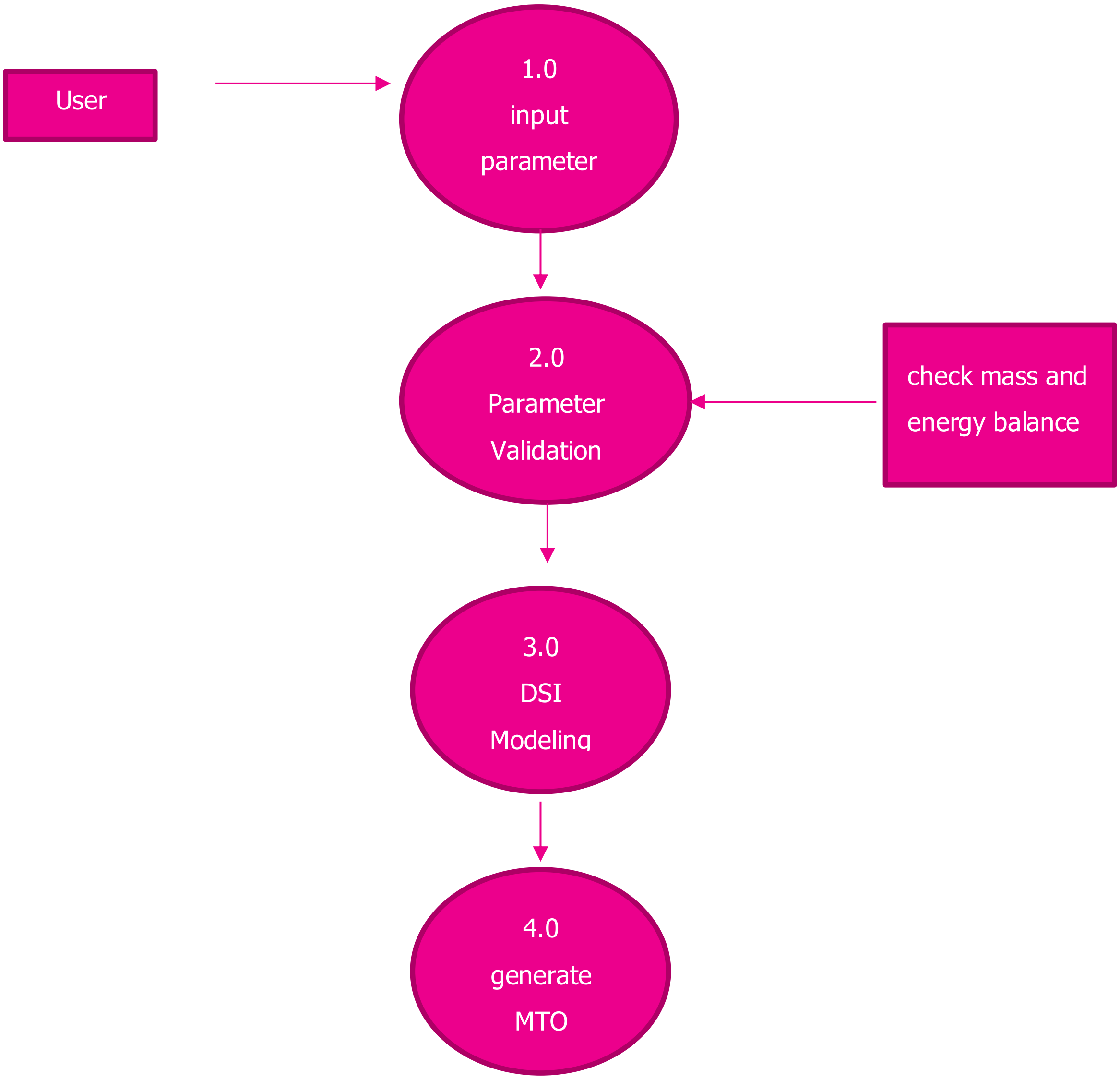
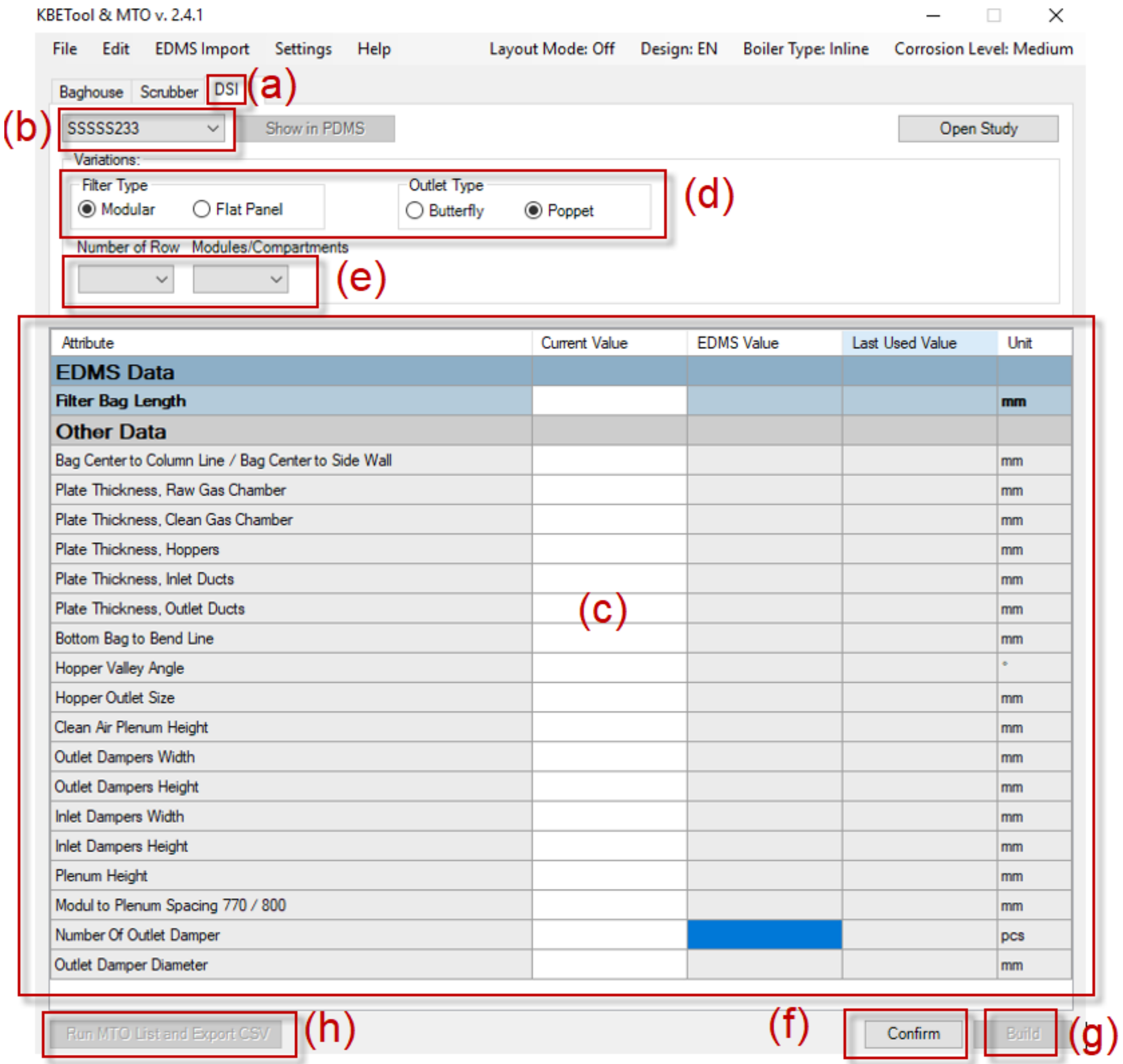


FIGURE 37. Process Flow Diagram

6.2.1 Graphical User interface

Graphical user interface is illustrated here below. user selects the used component from tablist "DSI" (a) for dry sorbent injection model and creates DSI name on combobox (b). GUI shows component attributes in Datagridview (c). User selects wanted variations for the component by checking option value on filter type and outlet type (d). Number of row bag and Modules/ compartments can be determinated by checking combobox (e).



Layout Mode: Off Design: EN Boiler Type: Inline Corrosion Level: Medium

SSSSS233

Filter Type: ● Modular ○ Flat Panel

Outlet Type: ○ Butterfly ● Poppet

Attribute	Current Value	EDMS Value	Last Used Value	Unit
EDMS Data				
Filter Bag Length				**mm**
Other Data				
Bag Center to Column Line / Bag Center to Side Wall				mm
Plate Thickness, Raw Gas Chamber				mm
Plate Thickness, Clean Gas Chamber				mm
Plate Thickness, Hoppers				mm
Plate Thickness, Inlet Ducts				mm
Plate Thickness, Outlet Ducts				mm
Bottom Bag to Bend Line				mm
Hopper Valley Angle				°
Hopper Outlet Size				mm
Clean Air Plenum Height				mm
Outlet Dampers Width				mm
Outlet Dampers Height				mm
Inlet Dampers Width				mm
Inlet Dampers Height				mm
Plenum Height				mm
Modul to Plenum Spacing 770 / 800				mm
Number Of Outlet Damper				pcs
Outlet Damper Diameter				mm

FIGURE 38.The GUI of Program

When user press confirm button (f), program checks that dimension values are available and if values appear to be invalid the program will leave background of cells with suspicious values red. Background of the cells with a confirmed value will turn green and "Build" button(g) will be activated. If "Build" button is pressed the 3D model will be shown on PDMS design layout and Button Run MTO list and export csv will be activated(h). Thereby MTO will be exported to excel file.

The number of bags can be calculated by formula below. (Beachler, 1995)

$$Ac = \frac{Q}{Vf} \tag{66}$$

where Q = Process exhaust rate,M^3/min

Vf = Filtration Velocity,M/min

from previous calculation on sub topic $S0_2$ emission we got flue gas rate 613.549 m^3/(n)h. By using the filtering surface Formula below to get Cloth Area values.

$$V = 2{,}878\, A\, B\, T^{-0{,}2335}\, L^{-0{,}06021}(0{,}7471 + 0{,}0853 \ln D\,) \tag{67}$$

where

V = gas-to-cloth ratio (ft/min)

A = material factor, from table 14

B = application factor, from table 13

T = temperature (°F, between 50 and 275)

L = inlet dust loading (gr/ft^3, between 0.05 and 100)

D = mass mean diameter of particle (μm, between 3 and 100)

For temperatures below 10 °C, use T= 50 and for temperatures above 275 °C use T= 275. For dust loading less than 1,76 gr/m^3 use L = 0.05 and for dust loading above 3531 gr/m^3 use L =100. For particle mass mean diameter less than 3 μm use use the value of D = 0,8 and for diameter greater than 100 μm D= 1,2. (James H, 1998)

CFB fly ash particle sizes (20–30 μm) and these had a prismatic shape. The uniformity coefficient is similar to Class C and F fly ash. However, the FBC bottom ash was much coarser in size (70–80 μm) (Zhang, 2014)

TABLE 13. Factor for Pulse Jet Gas To Cloth Ratios (James H, 1998)

Application Factor	
Nuisance Venting Relief of transfer points,conveyors, packing stations, etc.	1.0
Producct Collection Air conveying-venting, mills, flash driers, classifiers, etc.	0.9
Process Gas Filtration, Spray driers, kilns, etc.	0.8

Ash content is 11% according to table 1. Therefore, the total amount of ash produced when 70 tons/h of coal is burned is 7700 kg/h.

$$70.000\, \frac{kg}{h} * \frac{11}{100} = 7700\, \frac{kg}{h} \tag{68}$$

70% of the ash goes through to bottom ash and 20 - 30% leaves the furnace as fly ash in the flue gas (FHWA, 2016). Therefore, the total amount of fly ash is 2310 kg/h.

$$7700\,\frac{kg}{h} * \frac{30}{100} = 2310\,\frac{kg}{h} \tag{69}$$

$$Concentration\ of\ subtance\ \ (Ash) = \frac{2310000\frac{g}{h}}{613.549\frac{m^3(n)}{h}} = 3{,}764\,\frac{g}{(N)m^3} \tag{70}$$

TABLE 14. Factor for Pulse Jet Gas To Cloth Ratios (James H, 1998)

Material Factor				
15	12	10	9	6
Cake mix	Asbestos	Alumina	Ammonium	Activated carbon
Cardboar dust	Buffing dust	Aspirin	Dyes	Carbon Black
Cocoa	Fiborous and	Cement	Fly ash	Detergens
Feeds	cellulosic material	Ceramic	Metal Powder	Fumes and other
Flour	Gypsum	Clay dust	Metal Oxides	dispersed
Grain	Lime (hydrated)	Coal	Plastics	Product direct
Leather dust	Perlite	Limestone	Resins	from reactions
Sawdust	Rubber chemichals	Silica	Starch	Powder milk
Tobacco	Salt	Sorbic acid	Stearates	Soap
	Sand	Sugar	Tannic acid	
	Sandblast dust			
	Soda ash			
	Talc			

$$Concentration\ of\ subtance\ \ (Ash) = 3{,}764\,\frac{g}{(N)m^3} = \frac{3{,}764g}{(N)35{,}3ft^3} = 0{,}1066\frac{g}{ft^3} \tag{71}$$

by u sing equation 67 gas-to-cloth ratio can be calculated therefore a gas-to-cloth ratio is 2.01 m/min.

$$V = 2{,}878\,X\,9\,X\,0{,}8\,X\,275^{-0{,}2335}\,0{,}1^{-0{,}06021}(0{,}7471 + 0{,}0853\ln 30\,) \tag{72}$$

$$V = 6.6\frac{ft}{min}{=}2.01\frac{m}{min} \tag{73}$$

613.549 m^3/hr of flue gas equal to $10225{,}81\ m^3$/min therefore the fabric required is $5087M^2$.

$$Ac = \frac{10225{,}81\frac{m^3(n)}{min}}{2.01\frac{m}{min}} = 5087m^2 \qquad 74$$

$$Number\ of\ bags = \frac{Ac}{Ab} \qquad 75$$

where Ac=Cloth area, m^2 and Ab=Area of Bag, m^2 (Beachler, 1995)

$$Ab = \pi dt + \pi r^2 \qquad 76$$

where d=Diameter of the Bags in m (common usage 0,18m see Table 23 Bag Prices)

t=length of the Bags in m (common usage 10 m, the length of bag can be customized to reduce plant size)

π =3,14

$$Ab = 3{,}14x\ 0{,}18x10 + 3{,}14x0{,}09^2 = 5{,}68m^2 \qquad 77$$

$$Number\ of\ bags = \frac{5087m^2}{5{,}68m^2} = 896 \qquad 78$$

Area of bag equal 5,68 m^2 thus number of bags 5087 m^2 divide by 5,68 M^2 =896 of bags required the bags will be distributed into 4 compartments so each compartment will have 224 bags.

$$Vf = \frac{Q}{Ac} \qquad 79$$

$$Vf = \left[\frac{10225{,}81\ \frac{m^3}{min}}{5087\ m^2}\right] = 2{,}01\frac{m}{min} \qquad 80$$

Filtration velocity is equal to 2,01 m/min(3,35cm/sec). Air to cloth ratios (filtration velocity) for the various cleaning methods are given in table here below.

TABLE 15. typical air-to-cloth ratio (filtration velocity) comparisons for three cleaning mechanisms (Beachler, 1995)

	Air-to-cloth ratio(Q/Ac)		Filtration Velocity (Vf)	
	$(m^3/min)/\ m^2$	$(ft^3/min)/ft^2$	m/min	ft/min
Shaking	0.6 to 1.8	2 to 6	0.6 to 1.8	2 to 6
Reverse-air	0.3 to 1.2	1 to 4	0.3 to 1.2	1 to 4
Pulse -jet	0.6 to 4.5	2 to 15	0.6 to 4.5	2 to 15

Typical air-to-cloth ratios for baghouses used in industrial processes are listed in table here below as reference. Actual design values may need to be reduced if the dust loading is high. when Compartmental baghouses are used, the design A/C ratio must be based upon having enough filter cloth available for filtering while one or two compartments are off-stream for cleaning. (Beachler, 1995)

TABLE 16. typical A/C ratios for selected industries (Beachler, 1995)

Typical A/C ratios [$(ft^3/min)/ft^2$] For Selected Industries			
Industry	Fabric Filter air-to-cloth ratio		
	Reverse air	Pulse jet	Mechanical shaker
Basic oxygen furnaces	1.5-2	6-8	2.5-3
Brick Manufacturing	1.5-2	9-10	2.5-3.2
Castable refractories	1.5-2	8-10	2.5-3
Clay refractories	1.5-2	8-10	2.5-3.2
Coal-fired boilers	1-1.5	3-5	-
Detergent Manufacturing	1.2-1.5	5-6	2-2.5
Glass Manufacturing	1.5	-	-
iron and steel (sintering)	1.5-2	7-8	2.5-3
Lime Kilns	1.5-2	8-9	2.5-3
Municipal and medical waste incinerators	1-2	2.5-4	-
Phosphate fertilizer	1.8-2	8-9	3-3.5
Phosphate rock crushing	-	5-10	3-3.5
Polyvinyl chloride production	-	7	-
Portland cement	1.2-1.5	7-10	2-3
Secondary aluminum smelters	-	6-8	2
Secondary Copper smelters	-	6-9	-

6.2.2 PDMS interface

Some API's need to be added to source code as interface between PDMS and Dotnet Framework, the most needed API are Aveva PDMS database, Geometry, graphics, shared and utilities DLL. Aveva PDMS database DLL are more and less related to Database services such as open project, element creation or deletion, copy element, and allow retrieval of metadata such as size, name, pseudo attribute, and etc. (Aveva 3, 2012)

The interface assembly (Aveva.PDMS.geometry.dll) provides the geometry-related interfaces. All basic properties that needed by primitive component such as position, orientation, and direction. The interface assembly (Aveva.Pdms.Graphics.dll) includes interfaces for accessing the drawlist and colors. The interface assembly (Aveva.PDMS.shared.dll) provides Some general shared interfaces. This offers access to the currently selected element, selection changed events, and data listing functionality. The interface assembly (Aveva.PDMS.utilities.dll) provides some utility interfaces, including messaging, string utilities, tracing, undo, and units. (Aveva 3, 2012)

6.2.2.1 DbElement operation

The DbElement class is the most frequently used class, as it encompasses the majority of database functionality that is used in practice, including navigation, querying of attributes. Many PDMS element operation including creating and handling PDMS elements are using C#. Please see here below a sample of programme code to create objects as pdms element(site and zone). (Aveva 3, 2012)

```
using Aveva.Pdms.Database.DbElement;
DbElement Site;DbElement Zone;
```

6.2.2.1.1 Getting element for Object created

There is a way to get element by name by using a static GetElement() and find element method that returns a DbElement. This name should contain the slash on the first character "/". Please see here below a sample of programme code to get element by name. (Aveva 3, 2012)

```
using Aveva.Pdms.Database.DbElement;
DbElement Site;
DbElement Zone;
site=MDB.CurrentMDB.FindElement(Aveva.Pdms.Database.DbType.Design,
"/DSI_DEMO_MODEL");
DbElement vess1 = DbElement.GetElement("/VESS1");
```

6.2.2.1.2 Getting the owner PDMS-element and creating a new ZONE under it

Here, there is any combination between getting an element and creating an element in one way. For finding elements, use Findelement syntax, and for creating elements, use Create syntax. (Aveva 3, 2012)

When using the create method "Create (int, DbElementType)", two parameters are needed, where int is the position in list(0= first) and DbElementType is Element type to be created, such as SITE, ZONE, EQUI, PIPE, CYLINDER, etc. Here below is a sample of the programme code to get the owner element by sitename and create a new zone.

```
DbElement newZone = MDB.CurrentMDB.FindElement(Aveva.Pdms.Database.
DbType.Design, siteName).Create(0, DbElementType.GetElementType("ZONE"));
```

6.2.2.1.3 Getting attribute values from PDMS-element

DbAttributes is a single class for all attributes such as type, name, length, etc. In the DbAttributeInstance class, each attribute has a globally declared instance. This is the standard way to specify an attribute.there are more than 1000 instances attributes Here below a sample of programme code to get tail position attribute of element by “TPOS”. (Aveva 3, 2012)

```
using ATT=Aveva.Pdms.Database.DbAttributeInstance;
double length = newbran.GetDouble(ATT.TPOS);
```

6.2.2.1.4 Setting attribute values for PDMS-elements

The opposite of getting an attribute is setting an attribute using “Setattribute” syntax. Here is below a sample of the program code to set the zone name attribute of an element by "SetAttribute". (Aveva 3, 2012)

```
using ATT=Aveva.Pdms.Database.DbAttributeInstance;
newZone.SetAttribute(ATT.NAME, "/" + ecoName);
```

6.2.2.1.5 Element Navigation

There are basic methods for navigating the primary hierarchy. Firstmember, lastmember, previous, and owner can be used for navigation. Here is below is a sample of the program code to navigate and element. (Aveva 3, 2012)

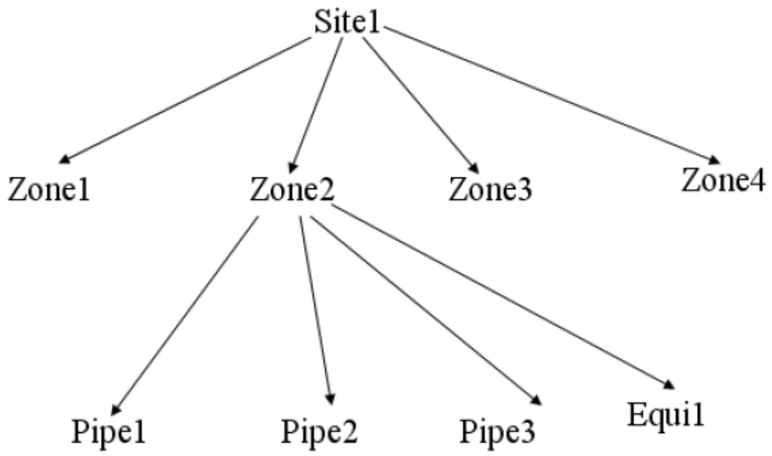


FIGURE 39. Example of PDMS Hierarchy

```
using NOUN=Aveva.Pdms.Database.DbElementTypeInstance;
DbElement zone = DbElement.GetElement("/Zone1")
DbElement temp=zone2.Next(); // temp is now Zone3
temp=zone2->Previous(); // temp is now Zone1
temp=zone2->Owner(); // temp is now Site1
temp=zone2->FirstMember(); // temp is now Pipe1
DbElement pipe1=temp;
temp=zone2->LastMember(); // temp is now Equi1
DbElement temp=pipe1.Next(NOUN.EQUIPMENT); // temp is Equi1
DbElement temp=pipe1.Previous(); // temp is ‘null’ as there is no
previous element. This can only be tested using the ‘IsNull’ method
zone = site.FirstMember(); Getting the first member of site for the zone-object
```

6.2.2.2 Creating Pipework Element

The tubes in PDMS are made up of BENDS that are connected by straight tubes. Tube is constructed of the following ELEMENTS:1. PIPE (Under SITE), 2. Specifies the type of pipe (Specs) that is being used. 3. BRANCH (Under PIPE),4. The pipe's starting and ending points. 5. BEND(S) (Under

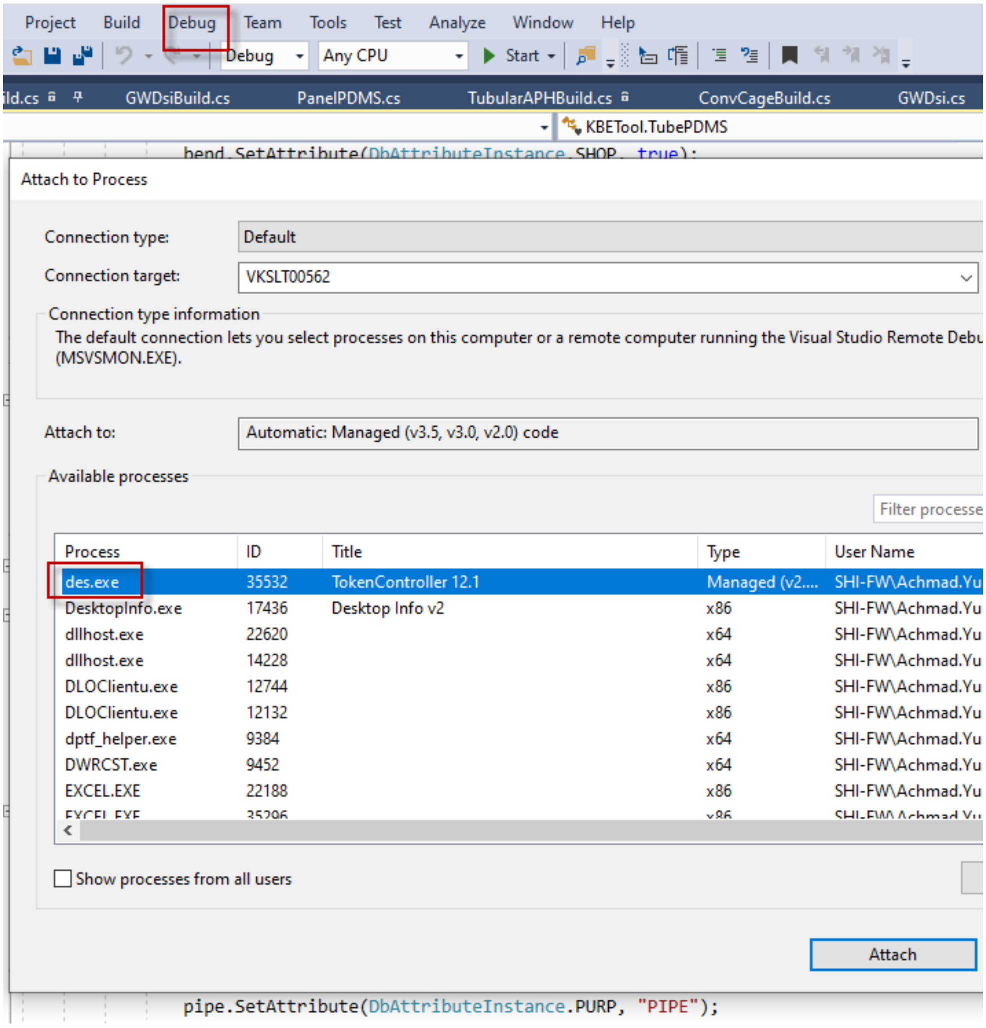
BRANCH),6. Bends automatically connect the tube's straight section. Here is below, an implementation of these steps in the program code. (Aveva 4, 2013)

```
zone = MDB.CurrentMDB.FindElement(Aveva.Pdms.Database.DbType.Design, "/" + zoneName);
pipe = zone.CreateLast(DbElementType.GetElementType("PIPE"));
pipe.SetAttribute(DbAttributeInstance.NAME, "/" + pipeName);
pipe.SetAttribute(DbAttributeInstance.PSPE, pipeSpec);
bran = pipe.Create(branCounter, DbElementType.GetElementType("BRANCH"));
bran.SetAttribute(DbAttributeInstance.NAME, branch_name+ branCounter);
bran.SetAttribute(DbAttributeInstance.HPOS, Position.Create(headXpos, headYpos, headZpos));
bran.SetAttribute(DbAttributeInstance.TPOS, Position.Create(tailXpos, tailYpos, tailZpos));
bend = bran.Create(bendCounter, DbElementType.GetElementType("BEND"));
bend.SetAttribute(DbAttributeInstance.LSTU, tubeSpc);
```

FIGURE 40. Creating BEND as Pipe work element

6.2.3 Code Debugging

Debugging is one of the good features of Microsoft visual studio. Go to debug pulldown menu and choose attach to process menu and below picture will appear. PDMS design Application Running in des.exe can be chosen to debug. Yellow line will appear on each line when tracing for code. It's possible to observe what the code is doing in real time using the debugger. (Microsoft, 2021)



```
bend.SetAttribute(DbAttributeInstance.SHOP, true);
```

Attach to Process

Connection type: Default

Connection target: VKSLT00562

Connection type information
The default connection lets you select processes on this computer or a remote computer running the Visual Studio Remote Debu
(MSVSMON.EXE).

Attach to: Automatic: Managed (v3.5, v3.0, v2.0) code

Available processes

Process	ID	Title	Type	User Name
des.exe	35532	TokenController 12.1	Managed (v2....	SHI-FW\Achmad.Yu
DesktopInfo.exe	17436	Desktop Info v2	x86	SHI-FW\Achmad.Yu
dllhost.exe	22620		x64	SHI-FW\Achmad.Yu
dllhost.exe	14228		x64	SHI-FW\Achmad.Yu
DLOClientu.exe	12744		x86	SHI-FW\Achmad.Yu
DLOClientu.exe	12132		x86	SHI-FW\Achmad.Yu
dptf_helper.exe	9384		x64	SHI-FW\Achmad.Yu
DWRCST.exe	9452		x64	SHI-FW\Achmad.Yu
EXCEL.EXE	22188		x86	SHI-FW\Achmad.Yu
EXCEL.EXE	35296		x86	SHI-FW\Achmad.Yu

☐ Show processes from all users

```
pipe.SetAttribute(DbAttributeInstance.PURP, "PIPE");
```

FIGURE 41. Debugging programme code

7 RESULTS

Here are presented some comparisons between PDMS MTO and Actual MTO for DSI System, and Cost of MTO comparison between DSI and CFB Scrubber.

7.1 PDMS MTO comparison with actual MTO

PDMS MTO means all components that have been modeled or built can be extracted to report or list of materials with quantity and type. The width and depth of compartment can be calculated by multiplying number of columns and diameter of bag and by adding space between bags. From previous calculation total of 224 bags are needed for each compartment and can be arranged to columns of 16 bags and rows of 14 bags.

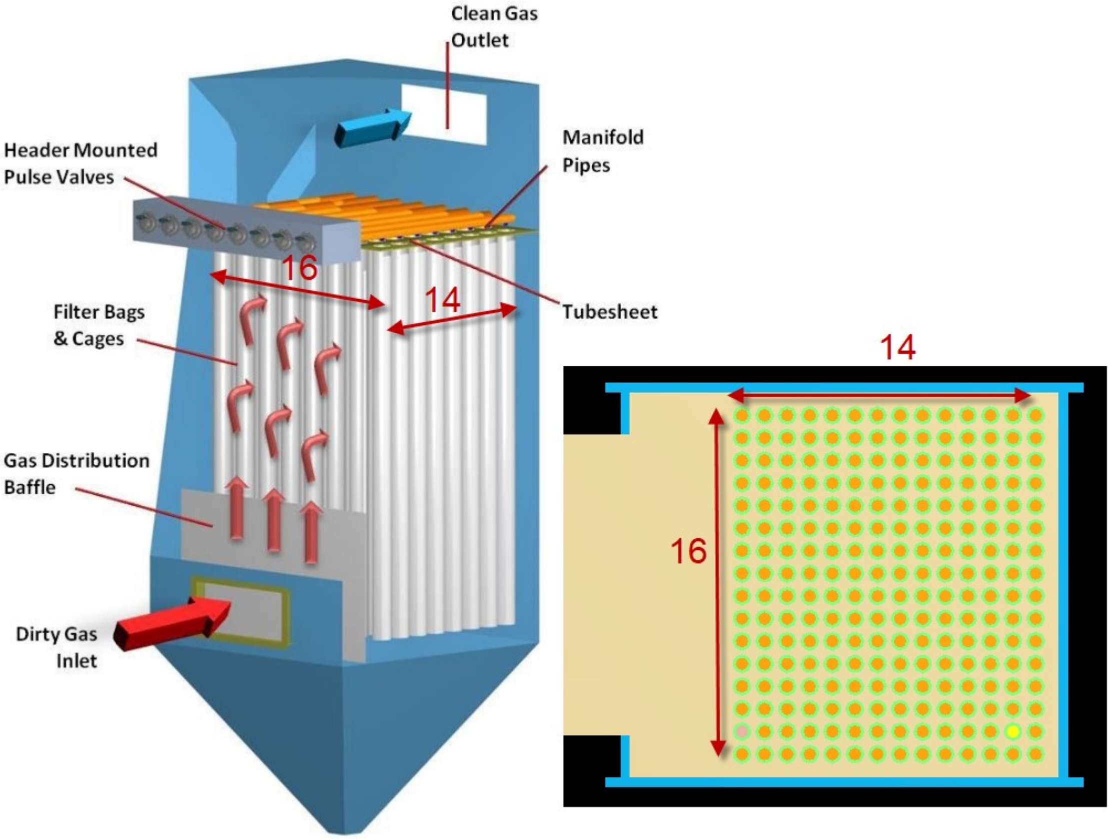


FIGURE 42. Plan and side view of bag on Pulse-jet cleaning system (Filsonfilters, 2021)

The table below shows the PDMS MTO summary of pipe consumption. The detailed MTO can be seen in Appendix 1.

TABLE 17. PDMS MTO for Piping pipeline

Size	Description	Dimension standard	Pipeline	Spec	Quantity (m)
88.9	Pipe	DIN 2448 OD	tes2222_tubes	FURNACE_OD	249.057
88.9	**Pipe**	**DIN 2448 OD**	**Total**		249.057

The table below shows the PDMS MTO Summary of panel consumption. The height of panel is 3250 mm. It comes from 16 bags, multiplied by 180 and added by the distance of bag center to the Side wall. The detailed MTO can be seen in Appendix 2.

TABLE 18. PDMS MTO for Panel

FRMW	PANEL/FLOOR	Height(mm)	Volume(m3)	Surface Area(m2)	Total Surface Area(m2)
DSI01_Distribution1	=16386/96820	5	0.22	0.06	2.45
DSI01_Distribution0	=16386/96584	5	0.22	0.06	2.45
DSI01_OutletDucts	=16386/96246	5	0.07	14.87	79.22
DSI01_InletDucts	=16386/96062	5	0.07	14.24	89.98
DSI01_RoofTOPTOP	=16386/96034	5	0.05	9.02	30.01
DSI01_ROOFhatch	=16386/95961	5	0	0.25	1.2
DSI01_Roof	=16386/95912	5	0.06	12.34	84.21
DSI01_RoofTOP	=16386/95887	5	0.05	10.14	34.18
DSI01_CleanGasRSW2	=16386/95862	5	0	0.51	2.02
DSI01_CleanGasLSW2	=16386/95837	5	0	0.51	2.02
DSI01_CleanGasRSW3	=16386/95812	5	0	0.45	1.8
DSI01_CleanGasLSW3	=16386/95787	5	0	0.45	1.8
DSI01_CleanGasRW3	=16386/95762	5	0	0.34	1.62
DSI01_CleanGasFW3	=16386/95737	5	0	0.34	1.62
DSI01_CleanGasFW2	=16386/95712	5	0	0.39	1.26
DSI01_CleanGasRW2	=16386/95687	5	0	0.39	1.26
DSI01_CleanGasRW	=16386/95662	5	0.02	3.12	1.47
DSI01_RawGasRW	=16386/95637	5	0.18	35.32	1.47
DSI01_CleanGasFW	=16386/95612	5	0.02	3.12	11.84
DSI01_RawGasFW	=16386/95587	5	0.18	35.32	133.94
DSI01_SeparWallRaw	=16386/95562	5	0.19	37.27	134.3
DSI01_CleanGasRSW	=16386/95537	5	0.02	3.3	11.88
DSI01_RawGasRSW	=16386/95524	5	0.19	37.27	67.15
DSI01_CleanGasLSW	=16386/95499	5	0.02	3.3	11.8
DSI01_RawGasLSW	=16386/95486	5	0.19	37.27	67.15
				Total	920.05

The table below shows the PDMS MTO Summary of type U Steel Consumption.

TABLE 19. PDMS MTO for Type U Steel

Description	Height	Width	Length(mm)	Weight(kg)	Total Weight(kg)
UNP200	200	75	3639	92	
UNP200	200	75	3639	92	
UNP200	200	75	3250	82.2	
UNP200	200	75	3250	82.2	
UNP200	200	75	3639	92	
UNP200	200	75	3639	92	
UNP200	200	75	3250	82.2	
UNP200	200	75	3250	82.2	
UNP200	200	75	3639	92	
UNP200	200	75	3639	92	
UNP200	200	75	3250	82.2	
UNP200	200	75	3250	82.2	
UNP200	200	75	3639	92	
UNP200	200	75	3639	92	
UNP200	200	75	3250	82.2	
UNP200	200	75	3250	82.2	1393.46
Description	**Height**	**Width**	**Total Length(m)**	**Total Weight(kg)**	**Pieces**
UNP200	200	75	55.112	1393.46	16

Actual MTO is a Report or list of materials with quantity and type that have been extracted by using Combination Excel including macros and model including all components and parts. The table below shows the Actual MTO Summary of Panel consumption, the detailed MTO can be seen on Appendix 2.

TABLE 20. Actual MTO For Detail Plates, Panels and beams

DesignArea	PartDesc	Type	Quantity	Unit	MaterialStandard	Length
Bag house	Main Columns	HEA	24750	mm	EN 10025-2	4125
Bag house	Front & Rear Wall Columns	IPE	19200	mm	EN 10025-2	4800
Bag house	Side Wall Bracings	CHS	20800	mm	EN 10219-1	5200
Bag house	Main Beams	HEA	30900	mm	EN 10025-2	5150
Bag house	Purlin beams	RHS	63200	mm	EN 10219-1	7900
Bag house	Hoist Beams	HEB	15800	mm	EN 10025-2	7900
Bag house	Internal Main Columns	HEB	23320	mm	EN 10025-2	5830
Bag house	SS Wall - Vertical X Bracings	CHS	26640	mm	EN 10219-1	4440
Bag house	SS Platform - Horizontal X Bracings	CHS	19000	mm	EN 10219-1	4750
Bag house	Platform Beam	HEB	40000	mm	EN 10025-2	4000
Bag house	Horizontal Beams X	HEA	29754	mm	EN 10025-2	3306
Bag house	Extreme main beams	IPE	5200	mm	EN 10025-2	2600
Bag house	Module Plates	Plate	14.4	m2	EN 10025-2	1000
Bag house	Internal beam / Tubesheet	UNP	14400	mm	EN 10025-2	3600
Bag house	Round beam / Roofdoors	UNP	43200	mm	EN 10025-2	10800
Bag house	Compartment Inlet Duct, Plate	Plate	1.564	m2	EN 10025-2	
Bag house	Compartment Outlet Duct, Plate	Plate	1.564	m2	EN 10025-2	
Bag house	Tubesheet	Plate	39.71056	m2	EN 10025-2	3508
Bag house	Baffle Plates	Plate	116.9356	m2	EN 10025-2	10330

There is a difference between PDMS MTO and actual MTO (Macros) due to not all auxiliaries being modeled on PDMS, only primary beams. The actual MTO is calculated by combining the PDMS model and the excel macro.

7.2 Cost of MTO related DSI and CFB Scrubber

The difference between DSI and CFB Scrubbing flue gas Cleaning Technology comes down to Scrubber. DSI system does not need a separate Scrubber Vessel and therefore it is cost effective flue gas Cleaning Technology. CFB Scrubbing Technology has scrubber vessel as absorber. Flue Gas with fly ash enters from the bottom of absorber, flowing upward through venturi to accelerate the gas and causing turbulence flow. (Sumitomo-2, 2021)

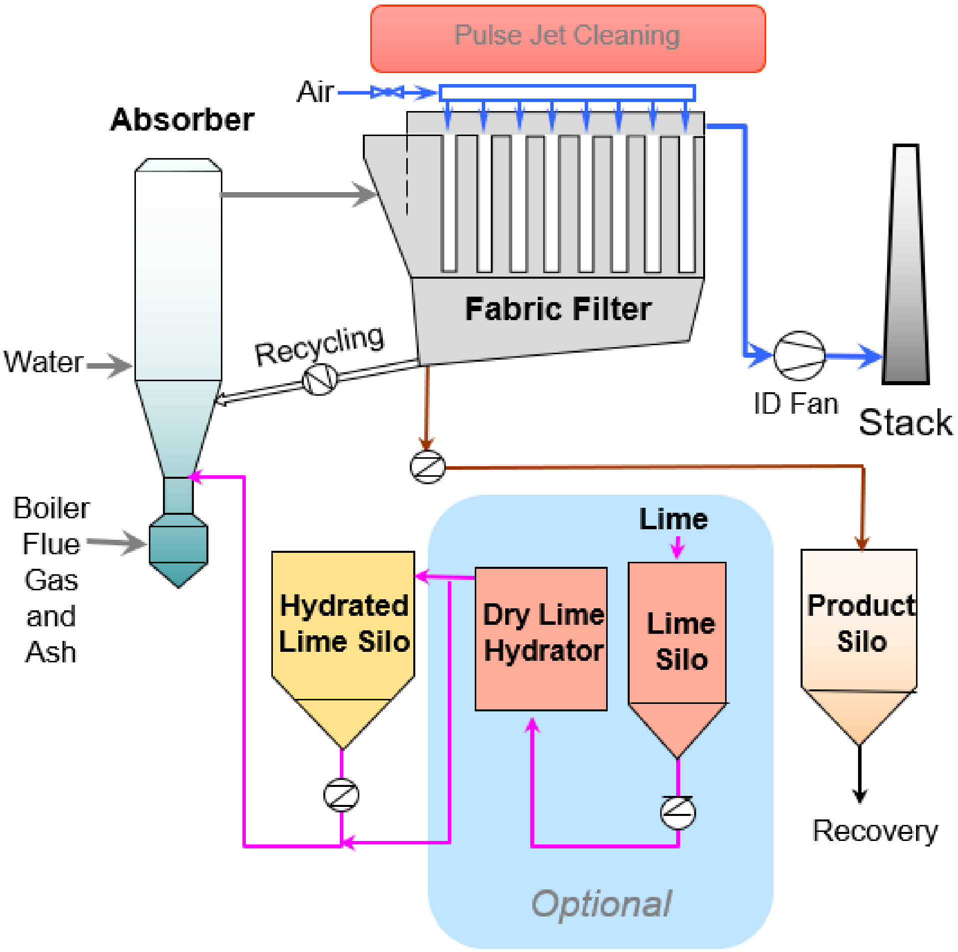


FIGURE 43. CFB Scrubbing Technology Scrubber (Sumitomo-2, 2021)

Recycled solids, reagents and water are mixed with the turbulent flue gas providing gas cooling, reactivation of ash and capture of pollutants. The gas and solids enter the baghouse where solids are captured and recycled back to the absorber to capture more pollutants. Reactive absorbents like sodium bicarbonate, hydrated lime, activated carbon or others can be added to target specific pollutants. Optional dry lime hydrator produces hydrated lime on-site from lower cost quick lime.

CFB-scrubber (semi-dry technology) and DSI are very often not competing against each other. That is because of the magnitude of desulfurization needed. CFBS technology is usually connected to coal or petcoke firing, so the markets for new units are nowadays mostly outside EU. DSI is used for biomass and waste fuels and in many different size classes, so it’s use is expanding strongly. (Pasi, 2022)

CFBS has bigger investment cost – it’s very clear and self-evident. It comes from the reactor, associated water injection system, and relatively larger baghouse due to high-ash environment that requires lower air to cloth ratios. Regarding operating costs, CFBS has somewhat higher power consumption than DSI due to higher pressure drop of flue gas ID fan (CFBS fluidized bed’s additional dp).CFBS benefits of the circulation of the product material and of much lower stoichiometric ratio especially with high reduction-%, so reagent costs are much lower than DSI in the same process. (Pasi, 2022)

CFBS also benefits of the possibility to use limestone in the boiler (in coal firing, for example) and then some of the calcium in fly ash is reactivated in the presence of water spray, thereby enabling deSOx in the scrubber without any FGD reagent. The in-furnace limestone is the cheapest of the available deSOx sorbents, so this way calcium hydroxide $Ca(OH)_2$ can even be avoided in certain cases. The combination of CFB boiler and CFB scrubber is a concept used by SWF in certain cases. This was not mentioned in the thesis. (Pasi, 2022)

CFBS shall not require 5-8 additional operating persons. One (max two, case by case) dedicated operator is enough in regular operation (per shift), to operate whole FGC area. This does not include stand-by maintenance crew who is and organized by the plant according to their own staffing plan. CFBS can reach bigger deSOx rates and this is important for high sulphur fuels (especially coal) to reach the emission limits. DSI is good for modest SO2 reductions and removing HCl and HF, very suitable for moderate sulphur fuels. Activated carbon can be used together with both systems if needed. (Pasi, 2022)

The table 21 below compares the cost of FGD to that of DSI. The DSI Cost is the least costly only takes 10% of FGD Cost. The fixed operating and maintenance costs are determined by the additional operation staff, maintenance labor and materials, and administrative labor required to install the FGD or DSI. The cost of bags and cages is included in the fixed O&M cost on the assumption that bags are replaced every three years and cages are replaced every nine years. (Sargent and Lundy, 2017)

The variable operation and maintenance costs are determined by the amount of reagent used, the amount of waste generated (cost per unit disposal), and the additional power required (unit power Cost). The capital cost is the base installed cost that includes equipment, installation, buildings, foundations, and electrical. The total cost is established as the sum of fixed operation and maintenance costs, variable operation and maintenance costs, and capital costs.

TABLE 21. FGD and DSI Cost Estimate based on 2016 Dollars (Sargent and Lundy, 2017)

Plant Size MW	S (%)	Flue Gas Process	SO_2 removal	Reagent	Fixed O&M	Variable O&M	Capital Cost	Total Cost
500	1.8	Wet Limestone Scrubber	95%	Limestone	4,385,000	1,650,000	281,395,000	287,430,000
500	1.8	Spray dry Scrubber + Baghouse	95%	Lime	3,550,000	1,820,000	249,282,000	254,652,000

500	1.8	DSI + Baghouse	70%	Trona	415,000	4,580,000	19,489,000	24,484,000
500	1.8	DSI + Baghouse	70%	Hydrated Lime	385,000	2,455,000	15,860,000	18,700,000

DSI systems are quite different with FGD. The major cost for the DSI system is the sorbent itself. The sorbent feed rate is proportional to sulfur generation rate, particulate collection device, and removal efficiency. While a DSI project can be completed in less than a year from contract award to commercial operation, A FGD project requires three years. A DSI system requires two additional operators, but a FGD system requires eight additional operators and required water treatment. Capital cost calculation includes Equipment, installation, building, Foundations, and Electrical. DSI capital costs are calculated at 10% of the cost of FGD, as shown in the table above indicates. There is a significant cost difference between DSI and FGD, a full cost comparison may be seen in Appendix 3 and 4. Below picture is Lhoist's DSI super-sack test skid system.

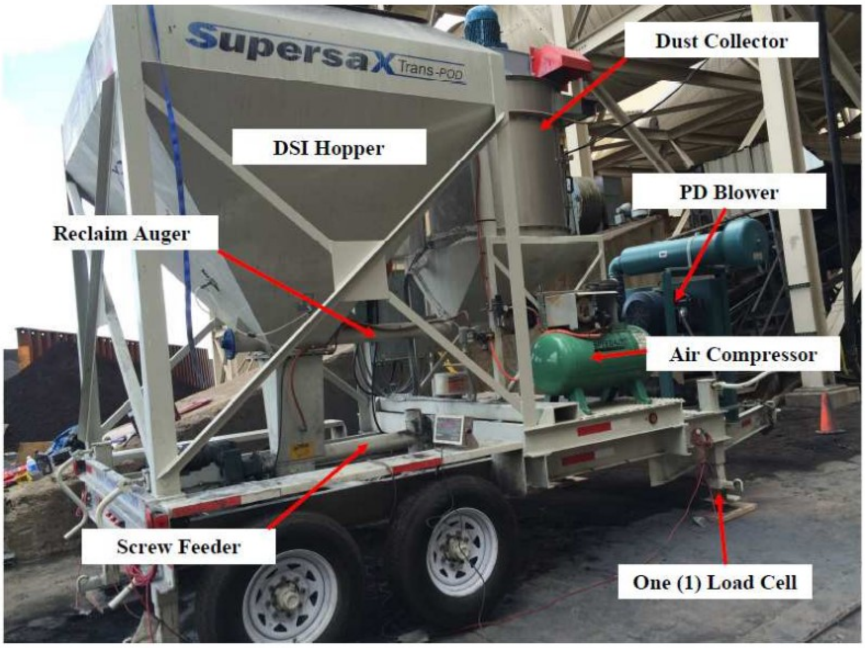


FIGURE 44. Lhoist's DSI super-sack test skid system (Gerald Hunt and Melissa Sewell, 2015)

It is consisted of a DSI Hopper capable of holding approximately 1500 kilograms of hydrated lime. Another component, a Screw Feeder with Variable Frequency Drive (VFD) is used to meter sorbent into the eductor and control the sorbent injection rate between approximately 13,6 and 450 kg/hr. A positive displacement blower that pressurizes ambient air to be used as motive air for transporting sorbent from the pick-up point to the exhaust gas. A desiccant-filled air compressor to provide dry air to fluidize the bottom of the hopper and clean the dust collector filter bags. A dust collector and vent fan are used to mitigate the emission of fugitive dust. A reclaim auger is used to return fugitive dust collected by the dust collector to the hopper. Four load cells (one for each trailer leg), a summation box, and a scale read-out are included to keep track of the trailer's weight. (Gerald Hunt and Melissa Sewell, 2015)

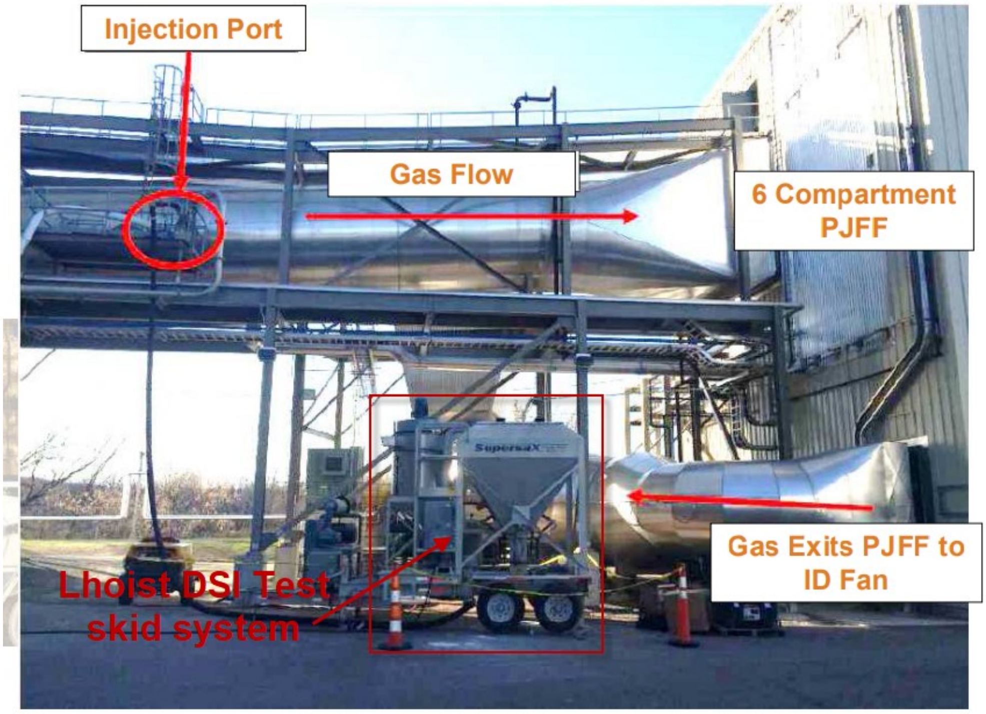


FIGURE 45. Lhoist's DSI Injection Port (Jim Dickerman and Jerry Hunt, 2015)

Retrofitting a majority of facilities is relatively simple (only injection lances are in contact with exhaust gas). The system has a high degree of process flexibility for various sorbents and the ability to easily modulate the process based on the unit load and/or the fuel type. Equipment with a small footprint (typically footprint of one or two silos and blower building).

7.2.1 Bare Baghouse Cost

Figure 46 and 47 show cost for common housing units and modular pulse jet baghouses, Common housing units have all bags within one housing, modular units are constructed from separate modules that should be arranged for off-line cleaning. (James H, 1998)

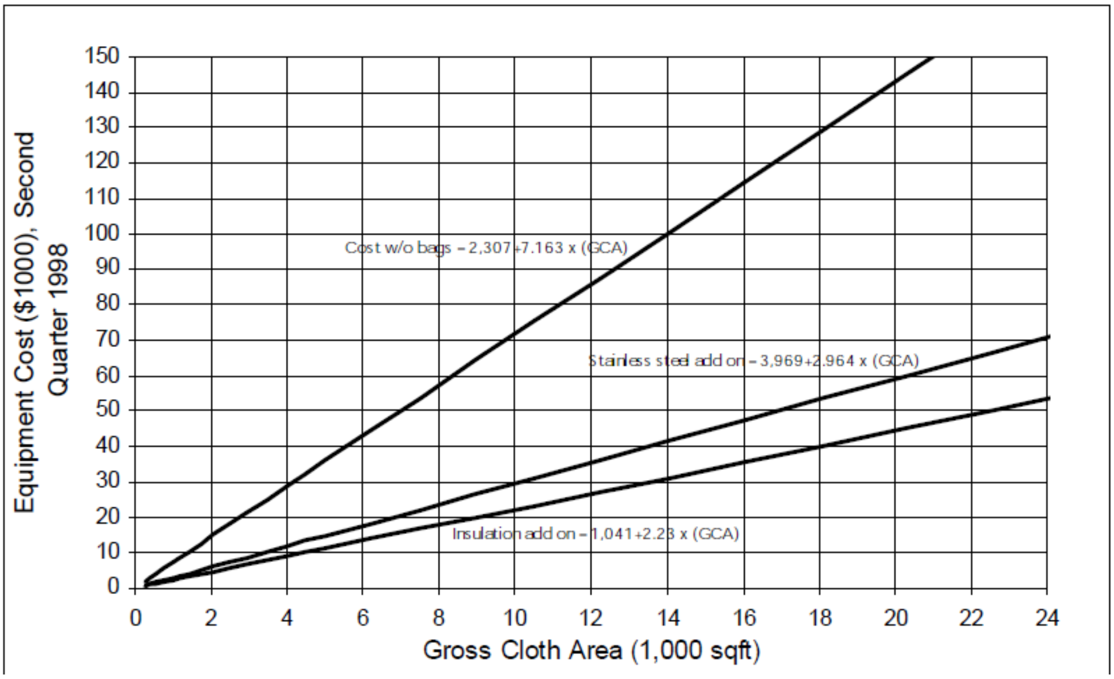


FIGURE 46. Equipment Cost for Pulse-Jet Filters-Common housing (James H, 1998)

Particularly, in the single-unit (common-housing) pulse jet, the height and width of the unit remain constant while the length increases; thus, unlike the modular units discussed previously, the cost increases linearly with size. Due to the low cost of the Common housing, the stainless steel option is proportionately more expensive than for modular units. The majority of the additional expense is due to the increased material costs, setup, and labor charges associated with the less workable stainless steel.

All curves are calculated using vendor quotations. The quotes have been fitted with a regression line and the equation for the regression line is provided. Generally, these lines should not be extrapolated beyond the indicated limits. If the reader obtains vendor quotes, they may deviate by up to 25% from these curves. All estimates take into account the supports for the inlet and exhaust manifolds, platforms, handrails, and hopper discharge devices. Prices are flange to flange. The reader should note that the scale of each figure varies to reflect the various gas flow ranges that the various types of baghouses operate within.

The 304 stainless steel construction option is used when it is necessary to prevent the exhaust gas stream from corroding the baghouse interior. All metal surfaces in contact with the exhaust gas stream are replaced with stainless steel.

Insulation costs are based on three inches of shop-installed glass fiber encased in a metal skin, with the exception of custom baghouses, which have insulation installed in the field. Insulation costs are based on the flange-to-flange structure of the baghouse on the exterior of all areas in contact with the exhaust gas stream.

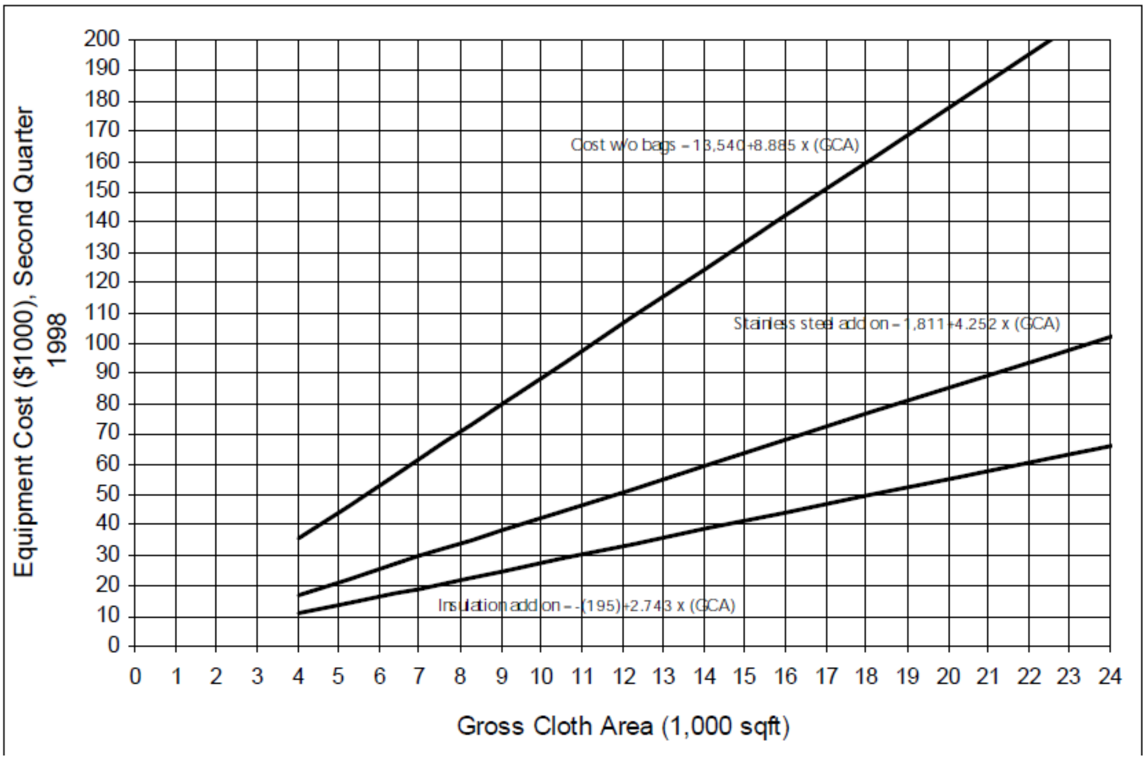


FIGURE 47. Equipment Cost for Pulse-Jet Filters-Modular (James H, 1998)

Here below is reference table for estimating Gross Cloth Area.

TABLE 22. Approximate Guide TO Estimate Gross Cloth Area From Net Cloth Area (James H, 1998)

Net Cloth Area (ft^2)	Multiplier To Obtain Gross Cloth Area(ft^2)
1-4.000	Multiply by 2
4.001 - 12.000	Multiply by 1.5
12.001 - 24.000	Multiply by 1.25
24.001 - 36.000	Multiply by 1.17
36.001 – 48.000	Multiply by 1.125
48.001 – 60.000	Multiply by 1.11
60.001 – 72.000	Multiply by 1.10
72.001 – 84.000	Multiply by 1.09
84.001 – 96.000	Multiply by 1.08
96.001 – 108.000	Multiply by 1.07
108.001 – 132.000	Multiply by 1.06
132.001 – 180.000	Multiply by 1.05
above 180,001	Multiply by 1.04

7.2.2 Bag Costs

The price per square foot of bags in 1998 is listed in Table 23 by fabric type and cleaning system. Actual quoted prices may vary by 10% from the table values. When estimating bag costs for an entire baghouse, use the gross cloth area determined in Table 22. The cost of a membrane PTFE fabric is a combination of the cost of the base fabric and a premium for the PTFE laminate and application. As fiber market conditions change, so too do the costs of fabrics in comparison to one another. Prices are based on average fabric weights in ounces per square yard. While sewn-in snap rings are included in the price, additional mounting hardware such as clamps or cages may be required depending on the baghouse type. (James H, 1998)

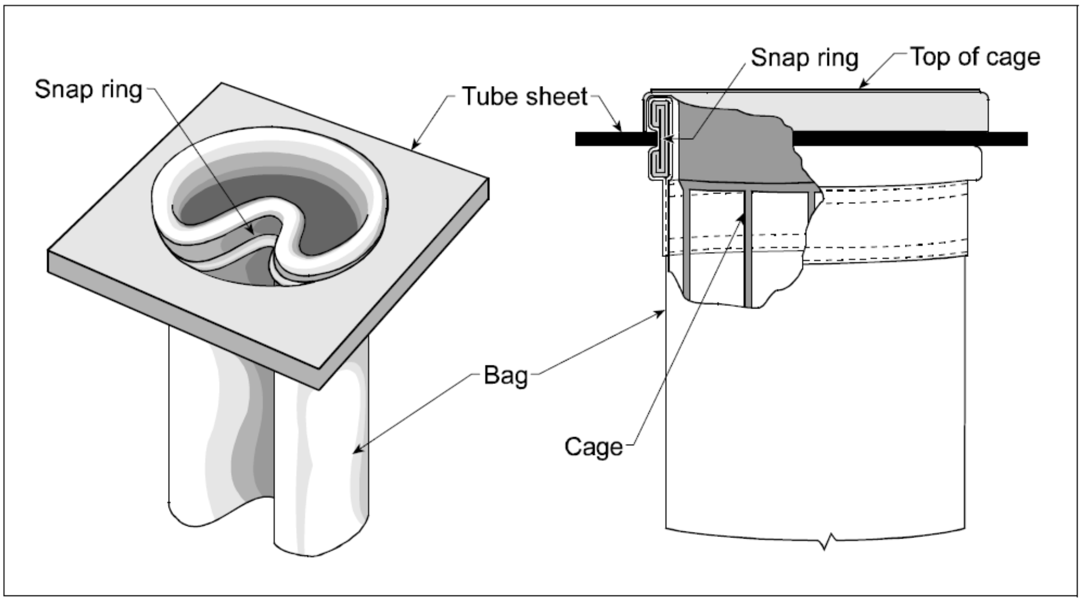


FIGURE 48. Snap-ring bag design for pulse-jet systems (Beachler, 1995 pp. 2-8)

Bag costs range between less than 15% and more than 100% of the cost of the bare baghouse (baghouse without bags or auxiliaries), depending on the fabric type required. This situation makes it inadvisable to estimate total purchased costs without also estimating baghouse and bag costs separately, and discourages the use of a single factor to estimate the combined baghouse and bag costs.

TABLE 23. Bag Prices ,2nd quarter 1998 \$/m^2 (James H, 1998)

		Type of Material									
Type of Cleaning	Bag Diameter(mm)	PE	PP	NO	HA	FG	CO	TF	P8	RT	NX
Pulse Jet,TR	114.3 to 130.2	8.3	9	24	13.7	21.3	NA	135.7	45.1	31.8	230
	152.4 to 203.2	7.4	8	21.7	12.8	17.8	NA	108	42.8	29.1	NA
Pulse Jet, BBR	114.3 to 130.2	5.9	5.9	20.4	10.5	18.7	NA	143.5	40	26.9	185.2
	152.4 To 203.2	5.9	6.6	19.6	10.8	17.2	NA	100.00	39	25.5	NA
Pulse Jet,Cartridge	120.7	32.8	NA	68	NA	NA	NA	NA	NA	NA	NA
	155.6	17	NA	51.9	NA	NA	NA	NA	NA	NA	NA

Shaker, Strap Top	127	7	8.8	17.8	11.4	NA	7.7	NA	NA	NA	NA
Shaker, Loop Top	127	6.7	11.2	17	11.5	NA	6.5	NA	NA	NA	NA
Reverse Air with Rings	203.2	7	16.8	15	NA	12.6	NA	NA	NA	NA	NA
	292.1	6.8	NA	15.8	NA	11.2	NA	NA	NA	NA	NA
Reverse Air w/o rings	203.2	4.8	NA	15.4	NA	10.5	NA	NA	NA	NA	NA
	292.1	4.8	NA	13	NA	8.3	NA	NA	NA	NA	NA

8 CONCLUSIONS

The sorbents most frequently used for acid gas control with DSI (trona, SBC, and hydrated lime) remove a variety of acid gases from the flue gas (SO_2, SO_3, HCl, HF). Understanding all of the flue gases acid gas constituents, not just the targeted acid gases, is critical for determining a DSI application's effectiveness.

Particle size of the sorbent: Finer particles result in improved performance. Due to the fact that sorbents can accumulate on the fabric filters of the bag house, forming a layer of sorbent for following reactions with acid gases, baghouse filters have a higher efficiency. When hydrated lime is utilized as DSI reagent, the reaction compounds present dry solid of $CaSO_4$, $CaCl_2$ and CaF_2. These are byproducts of Acid Removal Process. These impacts must be considered regardless of whether these materials can be marketed or disposed of.

The DSI Process requires PAC Injection Combination in order for the use of DSI to be possible. Several factors to consider include the type of DSI sorbent employed; the uncontrolled SO_3 content in the flue gas; the temperature of the flue gas at the particulate control device; and the amount of available residence time before the particulate control device. To determine the optimal injection locations for specific sorbents, manufacturers of sorbents and sorbent injection equipment should be consulted.

The cost comparison between FGD and DSI has been shown in table 21. It shows that the capital cost for DSI technology is only take 10 % of FGD Scrubber Technology. There is a significant cost difference between DSI and FGD. DSI systems are quite different from FGD in that way that the major cost for the DSI system is the sorbent itself. The capital cost calculation includes Equipment, installation, building, Foundations, and Electrical. The DSI system does not need a separate scrubber vessel and water treatment and therefore will reduce Equipment Cost and variable cost. While a DSI project can be completed in less than a year from contract award to commercial operation, a FGD project requires two years. A DSI system requires two additional operators, but a FGD system requires five additional operators.

Retrofitting a majority of facilities is relatively simple (only injection lances are in contact with exhaust gas). The DSI system has a high degree of process flexibility for various sorbents and the ability to easily modulate the process based on the unit load and/or the fuel type. The DSI Equipment has a small footprint (typically footprint of one or two silos and blower building). The DSI system has Ability to provide fuel flexibility in order to use high sulfur fuel while maintaining current SO_2 removal efficiency and/or SO_2 emissions without requiring significant retrofit to the existing FGD system.

There is a difference between PDMS MTO and actual MTO (Macros) due to not all auxiliaries or peripherals being modeled on PDMS, only primary beams. More details in PDMS modeling will result in a more accurate MTO. The main purpose of PDMS is for layout modelling and reservation space, therefore there is no need for detailed modeling. The actual MTO is calculated by combining the PDMS model and the Excel macro.

Nobody can deny the importance of a digital 3D model nowadays. AVEVA PDMS software facilitates the creation of a digital 3D model with numerous advantages. Using the PDMS software, a digital 3D model of the DSI baghouse was created. All parameter values that have been created on 3D model and the theory behind it have been explained in this thesis including Dry Sorbent Injection Theory and Baghouse Calculation. DSI as Cost Effective Technology Can be Proven. As Recommendation, All Parameter values that have been used in this DLL do not connect directly to Material energy balance calculation. In the next development phase, the data from material energy balance calculation should be received directly to the DLL so it would make parameter validation more accurate. It is understandable given that energy balance calculation software was not available at the time this thesis was written.

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APPENDIX 1: PIPING MTO DETAIL

Pipeline Prefabrication Report

KKS -CODE	DESCRIPTION	DN (mm)	Length (mm)
TESTREAL111_tubes/BR1	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR2	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR3	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR4	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR5	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR6	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR7	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR8	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR9	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR10	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR11	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR12	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR13	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR14	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR15	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR16	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR17	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR18	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR19	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR20	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR21	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR22	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR23	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR24	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR25	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR26	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR27	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR28	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR29	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR30	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR31	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR32	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR33	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR34	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR35	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR36	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR37	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR38	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR39	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR40	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR41	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR42	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR43	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR44	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR45	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR46	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR47	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR48	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR49	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR50	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR51	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR52	88.9 Pipe DIN 2448 OD	88.9	3662.6

TESTREAL111_tubes/BR53	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR54	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR55	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR56	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR57	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR58	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR59	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR60	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR61	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR62	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR63	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR64	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR65	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR66	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR67	88.9 Pipe DIN 2448 OD	88.9	3662.6
TESTREAL111_tubes/BR0	88.9 Pipe DIN 2448 OD	88.9	3662.6
		TOTAL	249056.8

APPENDIX 2: PANEL MTO DETAIL

Panel Report

FRMW	PANEL/FLOOR	Height(mm)	Volume(m3)	Surface Area(m2)	Total Surface Area(m2)
TESTREAL111_Distribution1	=16386/34690	6	0.01	1.16	
	=16386/34680	3250	0.2	0.06	
	=16386/34674	6	0.01	1.16	
	=16386/34664	3250	0.2	0.06	2.45
TESTREAL111_Distribution0	=16386/34474	6	0.01	1.16	
	=16386/34464	3250	0.2	0.06	
	=16386/34458	6	0.01	1.16	
	=16386/34448	3250	0.2	0.06	2.45
TESTREAL111_OutletDucts	=16386/34258	5	0.01	1.8	
	=16386/34252	5	0.01	1.8	
	=16386/34246	5	0.01	1.8	
	=16386/34240	5	0	0.92	
	=16386/34234	5	0	0.92	
	=16386/34228	5	0.01	1.16	
	=16386/34222	5	0.01	1.16	
	=16386/34216	5	0	0.92	
	=16386/34210	5	0	0.92	
	=16386/34204	5	0.01	1.16	
	=16386/34198	5	0.01	1.16	
	=16386/34187	5	0.01	1.8	
	=16386/34181	5	0.01	1.8	
	=16386/34175	5	0.01	1.8	
	=16386/34169	5	0	0.92	
	=16386/34163	5	0	0.92	
	=16386/34157	5	0.01	1.16	
	=16386/34151	5	0.01	1.16	
	=16386/34145	5	0	0.92	
	=16386/34139	5	0	0.92	

	=16386/34133	5	0.01	1.16	
	=16386/34127	5	0.01	1.16	
	=16386/34116	5	0.02	3.19	
	=16386/34110	5	0.06	11.87	
	=16386/34104	5	0.04	8.86	
	=16386/34097	5	0.07	13.93	
	=16386/34090	5	0.07	13.93	79.22
TESTREAL111_InletDucts	=16386/34082	5	0.01	2.93	
	=16386/34076	5	0.01	2.93	
	=16386/34070	5	0.01	2.93	
	=16386/34064	5	0	0.23	
	=16386/34058	5	0	0.23	
	=16386/34052	5	0	0.55	
	=16386/34046	5	0	0.55	
	=16386/34040	5	0	0.77	
	=16386/34034	5	0	0.77	
	=16386/34028	5	0.01	1.85	
	=16386/34022	5	0.01	1.85	
	=16386/34016	5	0	0.77	
	=16386/34010	5	0	0.77	
	=16386/34004	5	0.01	1.85	
	=16386/33998	5	0.01	1.85	
	=16386/33987	5	0.01	1.79	
	=16386/33981	5	0.01	1.79	
	=16386/33975	5	0.01	1.79	
	=16386/33969	5	0	0.23	
	=16386/33963	5	0	0.23	
	=16386/33957	5	0	0.55	
	=16386/33951	5	0	0.55	
	=16386/33945	5	0	0.77	
	=16386/33939	5	0	0.77	
	=16386/33933	5	0.01	1.85	

	=16386/33927	5	0.01	1.85	
	=16386/33921	5	0	0.77	
	=16386/33915	5	0	0.77	
	=16386/33909	5	0.01	1.85	
	=16386/33903	5	0.01	1.85	
	=16386/33892	5	0.02	3.19	
	=16386/33886	5	0.06	11.87	
	=16386/33880	5	0.04	8.86	
	=16386/33873	5	0.07	13.93	
	=16386/33866	5	0.07	13.93	89.98
TESTREAL111_RoofTOPTOP	=16386/33856	5	0.04	7.53	
	=16386/33850	5	0.04	7.53	
	=16386/33844	5	0.04	7.53	
	=16386/33838	5	0.04	7.53	30.1
TESTREAL111_ROOFhatch	=16386/33831	5	0	0.03	
	=16386/33825	5	0	0.03	
	=16386/33819	5	0	0.03	
	=16386/33813	5	0	0.03	
	=16386/33807	5	0	0.03	
	=16386/33801	5	0	0.03	
	=16386/33795	5	0	0.03	
	=16386/33789	5	0	0.03	
	=16386/33783	5	0	0.25	
	=16386/33777	5	0	0.25	
	=16386/33771	5	0	0.25	
	=16386/33765	5	0	0.25	1.2
TESTREAL111_Roof	=16386/33758	5	0.05	10.53	
	=16386/33752	5	0.05	10.53	
	=16386/33746	5	0.05	10.53	
	=16386/33740	5	0.05	10.53	
	=16386/33734	5	0.05	10.53	
	=16386/33728	5	0.05	10.53	

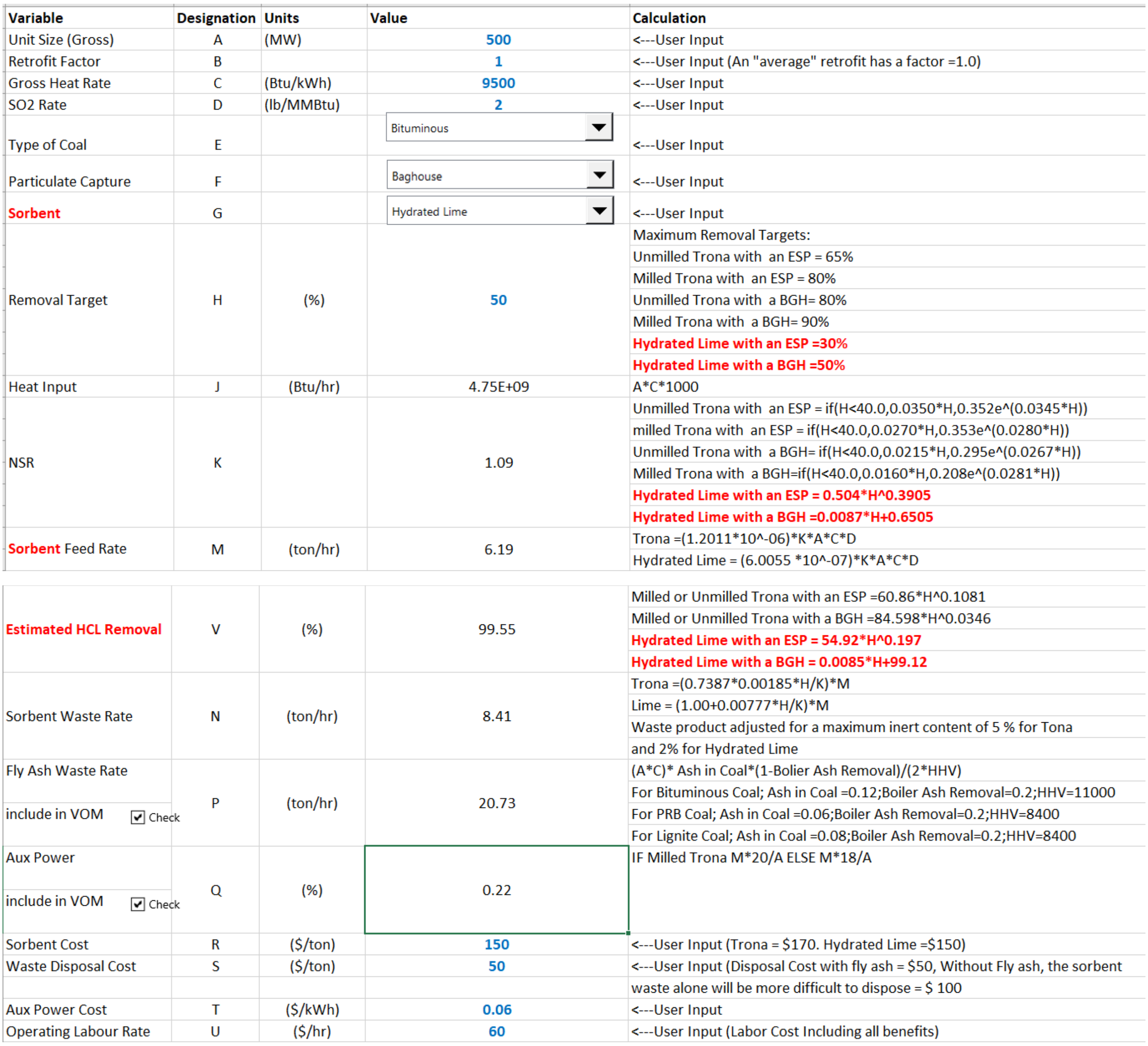
	=16386/33722	5	0.05	10.53	
	=16386/33716	5	0.05	10.53	84.21
TESTREAL111_RoofTOP	=16386/33709	5	0.04	8.54	
	=16386/33703	5	0.04	8.54	
	=16386/33697	5	0.04	8.54	
	=16386/33691	5	0.04	8.54	34.18
TESTREAL111_CleanGasRSW2	=16386/33684	5	0	0.46	
	=16386/33678	5	0	0.46	
	=16386/33672	5	0	0.46	
	=16386/33666	5	0	0.46	1.82
TESTREAL111_CleanGasLSW2	=16386/33659	5	0	0.46	
	=16386/33653	5	0	0.46	
	=16386/33647	5	0	0.46	
	=16386/33641	5	0	0.46	1.82
TESTREAL111_CleanGasRSW3	=16386/33634	5	0	0.4	
	=16386/33628	5	0	0.4	
	=16386/33622	5	0	0.4	
	=16386/33616	5	0	0.4	1.62
TESTREAL111_CleanGasLSW3	=16386/33609	5	0	0.4	
	=16386/33603	5	0	0.4	
	=16386/33597	5	0	0.4	
	=16386/33591	5	0	0.4	1.62
TESTREAL111_CleanGasRW3	=16386/33584	5	0	0.31	
	=16386/33578	5	0	0.31	
	=16386/33572	5	0	0.31	
	=16386/33566	5	0	0.31	1.26
TESTREAL111_CleanGasFW3	=16386/33559	5	0	0.31	
	=16386/33553	5	0	0.31	
	=16386/33547	5	0	0.31	
	=16386/33541	5	0	0.31	1.26
TESTREAL111_CleanGasFW2	=16386/33534	5	0	0.37	
	=16386/33528	5	0	0.37	

	=16386/33522	5	0	0.37	
	=16386/33516	5	0	0.37	1.47
TESTREAL111_CleanGasRW2	=16386/33509	5	0	0.37	
	=16386/33503	5	0	0.37	
	=16386/33497	5	0	0.37	
	=16386/33491	5	0	0.37	1.47
TESTREAL111_CleanGasRW	=16386/33484	5	0.01	2.96	
	=16386/33478	5	0.01	2.96	
	=16386/33472	5	0.01	2.96	
	=16386/33466	5	0.01	2.96	11.84
TESTREAL111_RawGasRW	=16386/33459	5	0.17	33.48	
	=16386/33453	5	0.17	33.48	
	=16386/33447	5	0.17	33.48	
	=16386/33441	5	0.17	33.48	133.94
TESTREAL111_CleanGasFW	=16386/33434	5	0.01	2.96	
	=16386/33428	5	0.01	2.96	
	=16386/33422	5	0.01	2.96	
	=16386/33416	5	0.01	2.96	11.84
TESTREAL111_RawGasFW	=16386/33409	5	0.17	33.48	
	=16386/33403	5	0.17	33.48	
	=16386/33397	5	0.17	33.48	
	=16386/33391	5	0.17	33.48	133.94
TESTREAL111_SeparWallRaw	=16386/33384	5	0.17	33.58	
	=16386/33378	5	0.17	33.58	
	=16386/33372	5	0.17	33.58	
	=16386/33366	5	0.17	33.58	134.3
TESTREAL111_CleanGasRSW	=16386/33359	5	0.01	2.97	
	=16386/33353	5	0.01	2.97	
	=16386/33347	5	0.01	2.97	
	=16386/33341	5	0.01	2.97	11.88
TESTREAL111_RawGasRSW	=16386/33334	5	0.17	33.58	
	=16386/33328	5	0.17	33.58	67.15

TESTREAL111_CleanGasLSW	=16386/33321	5	0.01	2.97	
	=16386/33315	5	0.01	2.97	
	=16386/33309	5	0.01	2.97	
	=16386/33303	5	0.01	2.97	11.88
TESTREAL111_RawGasLSW	=16386/33296	5	0.17	33.58	
	=16386/33290	5	0.17	33.58	67.15

920.05

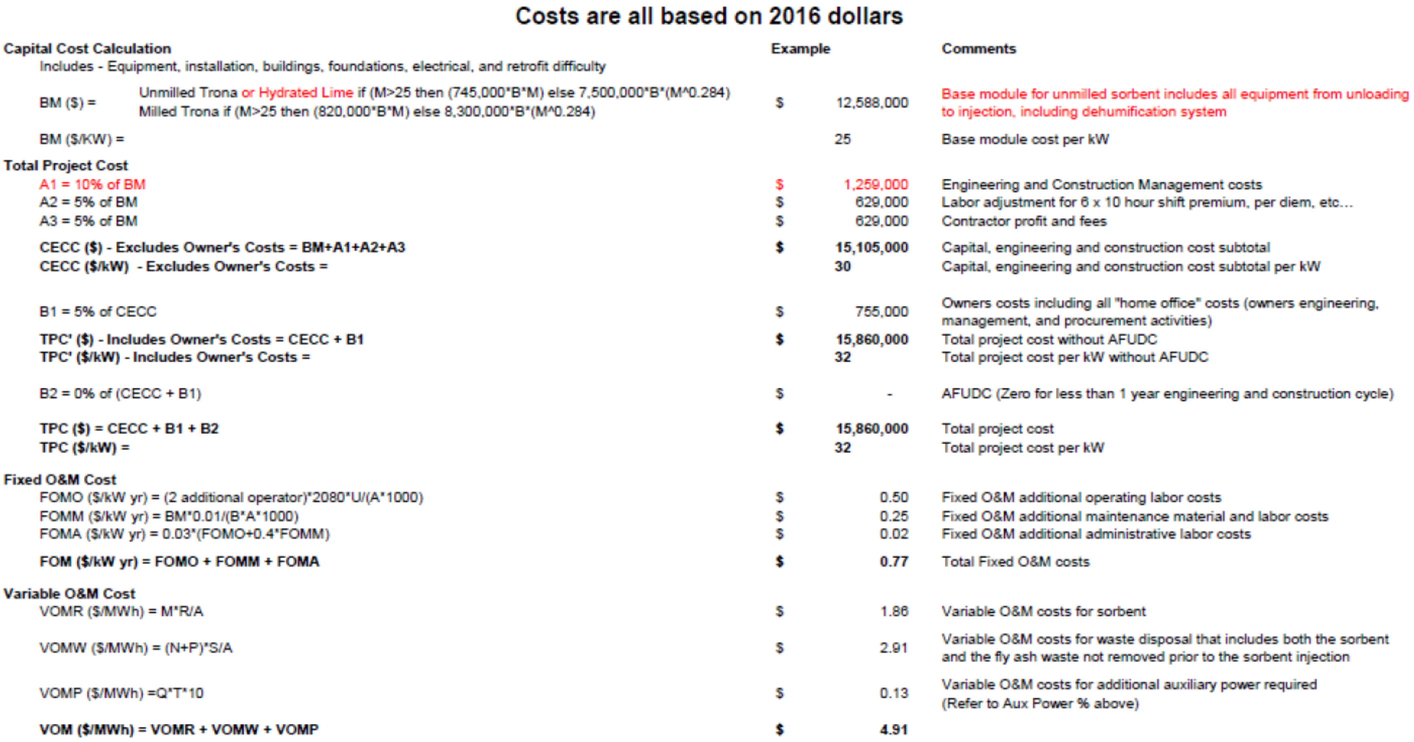
APPENDIX 3: COST ESTIMATE FOR A HYDRATED LIME DSI SYSTEM WITH A BAGHOUSE



Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<---User Input
Retrofit Factor	B		1	<---User Input (An "average" retrofit has a factor =1.0)
Gross Heat Rate	C	(Btu/kWh)	9500	<---User Input
SO2 Rate	D	(lb/MMBtu)	2	<---User Input
Type of Coal	E		Bituminous	<---User Input
Particulate Capture	F		Baghouse	<---User Input
Sorbent	G		Hydrated Lime	<---User Input
Removal Target	H	(%)	50	Maximum Removal Targets:
				Unmilled Trona with an ESP = 65%
				Milled Trona with an ESP = 80%
				Unmilled Trona with a BGH= 80%
				Milled Trona with a BGH= 90%
				Hydrated Lime with an ESP =30%
				Hydrated Lime with a BGH =50%
Heat Input	J	(Btu/hr)	4.75E+09	A*C*1000
NSR	K		1.09	Unmilled Trona with an ESP = if(H<40.0,0.0350*H,0.352e^(0.0345*H))
				milled Trona with an ESP = if(H<40.0,0.0270*H,0.353e^(0.0280*H))
				Unmilled Trona with a BGH= if(H<40.0,0.0215*H,0.295e^(0.0267*H))
				Milled Trona with a BGH=if(H<40.0,0.0160*H,0.208e^(0.0281*H))
				Hydrated Lime with an ESP = 0.504*H^0.3905
				Hydrated Lime with a BGH =0.0087*H+0.6505
Sorbent Feed Rate	M	(ton/hr)	6.19	Trona =(1.2011*10^-06)*K*A*C*D
				Hydrated Lime = (6.0055 *10^-07)*K*A*C*D
Estimated HCL Removal	V	(%)	99.55	Milled or Unmilled Trona with an ESP =60.86*H^0.1081
				Milled or Unmilled Trona with a BGH =84.598*H^0.0346
				Hydrated Lime with an ESP = 54.92*H^0.197
				Hydrated Lime with a BGH = 0.0085*H+99.12
Sorbent Waste Rate	N	(ton/hr)	8.41	Trona =(0.7387*0.00185*H/K)*M
				Lime = (1.00+0.00777*H/K)*M
				Waste product adjusted for a maximum inert content of 5 % for Tona and 2% for Hydrated Lime
Fly Ash Waste Rate include in VOM ☑ Check	P	(ton/hr)	20.73	(A*C)* Ash in Coal*(1-Bolier Ash Removal)/(2*HHV)
				For Bituminous Coal; Ash in Coal =0.12;Boiler Ash Removal=0.2;HHV=11000
				For PRB Coal; Ash in Coal =0.06;Boiler Ash Removal=0.2;HHV=8400
				For Lignite Coal; Ash in Coal =0.08;Boiler Ash Removal=0.2;HHV=8400
Aux Power include in VOM ☑ Check	Q	(%)	0.22	IF Milled Trona M*20/A ELSE M*18/A
Sorbent Cost	R	($/ton)	150	<---User Input (Trona = $170. Hydrated Lime =$150)
Waste Disposal Cost	S	($/ton)	50	<---User Input (Disposal Cost with fly ash = $50, Without Fly ash, the sorbent waste alone will be more difficult to dispose = $ 100
Aux Power Cost	T	($/kWh)	0.06	<---User Input
Operating Labour Rate	U	($/hr)	60	<---User Input (Labor Cost Including all benefits)

Note : VOM : Variable Operation And Maintenance

BGH : Bag House



Costs are all based on 2016 dollars

Capital Cost Calculation	**Example**		**Comments**
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty			
BM ($) = Unmilled Trona or Hydrated Lime if (M>25 then (745,000*B*M) else 7,500,000*B*(M^0.284) Milled Trona if (M>25 then (820,000*B*M) else 8,300,000*B*(M^0.284)	$	12,588,000	Base module for unmilled sorbent includes all equipment from unloading to injection, including dehumification system
BM ($/KW) =		25	Base module cost per kW
Total Project Cost			
A1 = 10% of BM	$	1,259,000	Engineering and Construction Management costs
A2 = 5% of BM	$	629,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc...
A3 = 5% of BM	$	629,000	Contractor profit and fees
CECC ($) - Excludes Owner's Costs = BM+A1+A2+A3	**$**	**15,105,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) - Excludes Owner's Costs =		**30**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC	$	755,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
TPC' ($) - Includes Owner's Costs = CECC + B1	**$**	**15,860,000**	Total project cost without AFUDC
TPC' ($/kW) - Includes Owner's Costs =		**32**	Total project cost per kW without AFUDC
B2 = 0% of (CECC + B1)	$	-	AFUDC (Zero for less than 1 year engineering and construction cycle)
TPC ($) = CECC + B1 + B2	**$**	**15,860,000**	Total project cost
TPC ($/kW) =		**32**	Total project cost per kW
Fixed O&M Cost			
FOMO ($/kW yr) = (2 additional operator)*2080*U/(A*1000)	$	0.50	Fixed O&M additional operating labor costs
FOMM ($/kW yr) = BM*0.01/(B*A*1000)	$	0.25	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW yr) = 0.03*(FOMO+0.4*FOMM)	$	0.02	Fixed O&M additional administrative labor costs
FOM ($/kW yr) = FOMO + FOMM + FOMA	**$**	**0.77**	Total Fixed O&M costs
Variable O&M Cost			
VOMR ($/MWh) = M*R/A	$	1.86	Variable O&M costs for sorbent
VOMW ($/MWh) = (N+P)*S/A	$	2.91	Variable O&M costs for waste disposal that includes both the sorbent and the fly ash waste not removed prior to the sorbent injection
VOMP ($/MWh) =Q*T*10	$	0.13	Variable O&M costs for additional auxiliary power required (Refer to Aux Power % above)
VOM ($/MWh) = VOMR + VOMW + VOMP	**$**	**4.91**	

Note: BM = Base Module Cost

CECC =Capital Engineering and Construction Cost

TPC = Total Project Cost

FOM = Fixed Operation and Maintenance

FOMO = Fixed Operation and Maintenance additional Operation Staff

FOMM = Fixed Operation and Maintenance labor and Materials

FOMA = Fixed Operation and Maintenance Administrative labor

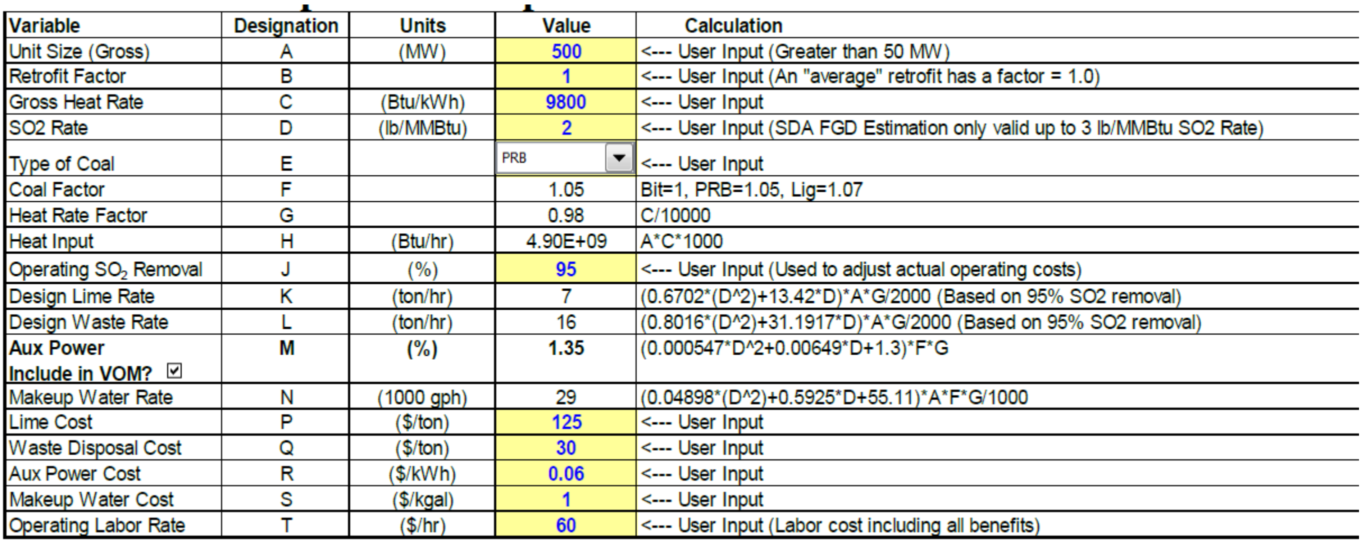
VOMR = Variable Operation and Maintenance for Reagent

VOMW = Variable Operation and Maintenance for Waste disposal

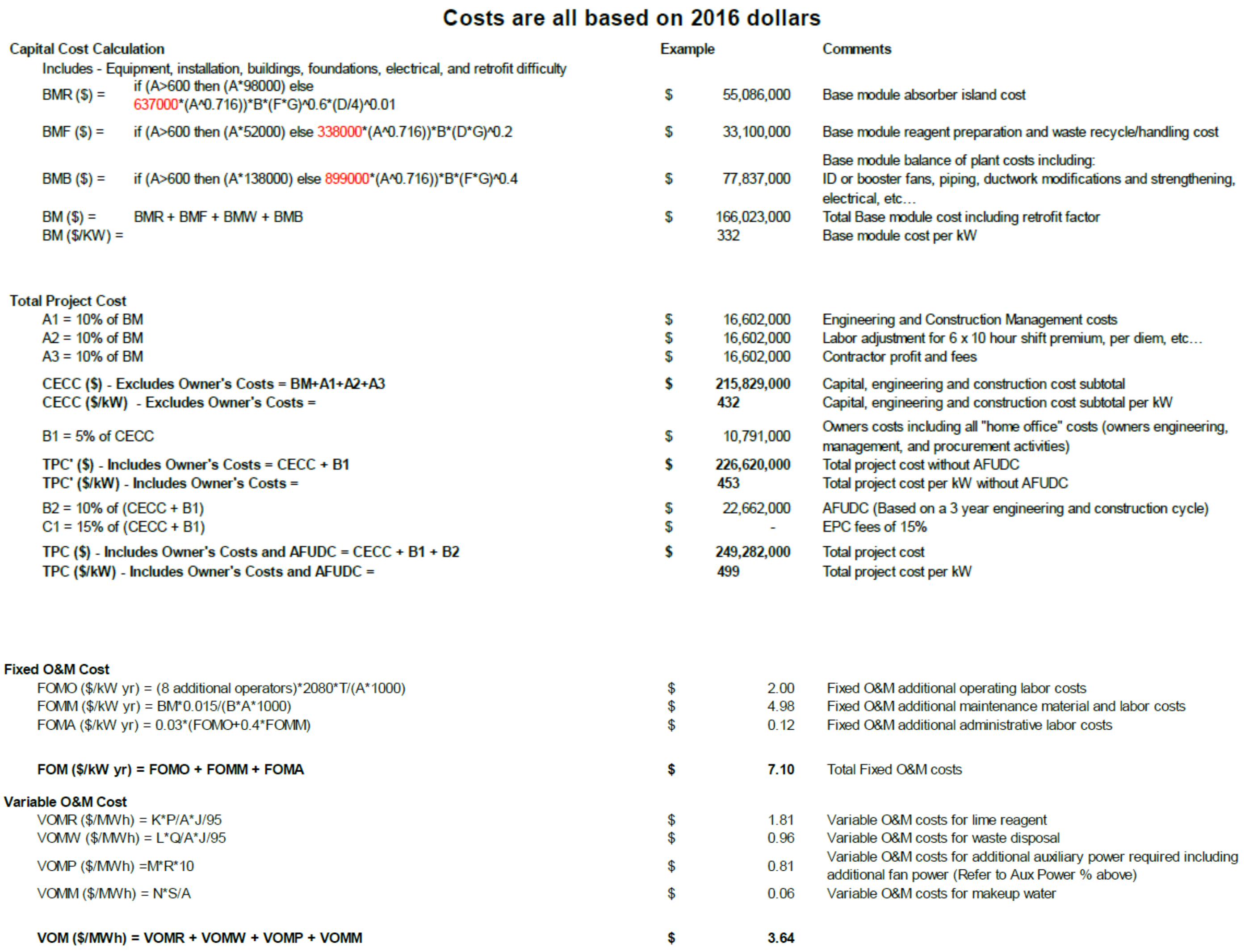
VOMP = Variable Operation and Maintenance for Auxiliary Power

AFUDC = Allowance For Fund Used During Construction

APPENDIX 4: COST ESTIMATE FOR A SDA FGD SYSTEM WITH A BAGHOUSE



Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input (Greater than 50 MW)
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	9800	<--- User Input
SO2 Rate	D	(lb/MMBtu)	2	<--- User Input (SDA FGD Estimation only valid up to 3 lb/MMBtu SO2 Rate)
Type of Coal	E		PRB ▼	<--- User Input
Coal Factor	F		1.05	Bit=1, PRB=1.05, Lig=1.07
Heat Rate Factor	G		0.98	C/10000
Heat Input	H	(Btu/hr)	4.90E+09	A*C*1000
Operating SO_2 Removal	J	(%)	95	<--- User Input (Used to adjust actual operating costs)
Design Lime Rate	K	(ton/hr)	7	(0.6702*(D^2)+13.42*D)*A*G/2000 (Based on 95% SO2 removal)
Design Waste Rate	L	(ton/hr)	16	(0.8016*(D^2)+31.1917*D)*A*G/2000 (Based on 95% SO2 removal)
Aux Power **Include in VOM?** ☑	**M**	**(%)**	**1.35**	(0.000547*D^2+0.00649*D+1.3)*F*G
Makeup Water Rate	N	(1000 gph)	29	(0.04898*(D^2)+0.5925*D+55.11)*A*F*G/1000
Lime Cost	P	($/ton)	125	<--- User Input
Waste Disposal Cost	Q	($/ton)	30	<--- User Input
Aux Power Cost	R	($/kWh)	0.06	<--- User Input
Makeup Water Cost	S	($/kgal)	1	<--- User Input
Operating Labor Rate	T	($/hr)	60	<--- User Input (Labor cost including all benefits)



Costs are all based on 2016 dollars

Capital Cost Calculation		Example	Comments
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty			
BMR ($) = if (A>600 then (A*98000) else 637000*(A^0.716))*B*(F*G)^0.6*(D/4)^0.01	$	55,086,000	Base module absorber island cost
BMF ($) = if (A>600 then (A*52000) else 338000*(A^0.716))*B*(D*G)^0.2	$	33,100,000	Base module reagent preparation and waste recycle/handling cost
BMB ($) = if (A>600 then (A*138000) else 899000*(A^0.716))*B*(F*G)^0.4	$	77,837,000	Base module balance of plant costs including: ID or booster fans, piping, ductwork modifications and strengthening, electrical, etc…
BM ($) = BMR + BMF + BMW + BMB	$	166,023,000	Total Base module cost including retrofit factor
BM ($/KW) =		332	Base module cost per kW
Total Project Cost			
A1 = 10% of BM	$	16,602,000	Engineering and Construction Management costs
A2 = 10% of BM	$	16,602,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 10% of BM	$	16,602,000	Contractor profit and fees
CECC ($) - Excludes Owner's Costs = BM+A1+A2+A3	**$**	**215,829,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) - Excludes Owner's Costs =		**432**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC	$	10,791,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
TPC' ($) - Includes Owner's Costs = CECC + B1	**$**	**226,620,000**	Total project cost without AFUDC
TPC' ($/kW) - Includes Owner's Costs =		**453**	Total project cost per kW without AFUDC
B2 = 10% of (CECC + B1)	$	22,662,000	AFUDC (Based on a 3 year engineering and construction cycle)
C1 = 15% of (CECC + B1)	$	-	EPC fees of 15%
TPC ($) - Includes Owner's Costs and AFUDC = CECC + B1 + B2	**$**	**249,282,000**	Total project cost
TPC ($/kW) - Includes Owner's Costs and AFUDC =		**499**	Total project cost per kW
Fixed O&M Cost			
FOMO ($/kW yr) = (8 additional operators)*2080*T/(A*1000)	$	2.00	Fixed O&M additional operating labor costs
FOMM ($/kW yr) = BM*0.015/(B*A*1000)	$	4.98	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW yr) = 0.03*(FOMO+0.4*FOMM)	$	0.12	Fixed O&M additional administrative labor costs
FOM ($/kW yr) = FOMO + FOMM + FOMA	**$**	**7.10**	Total Fixed O&M costs
Variable O&M Cost			
VOMR ($/MWh) = K*P/A*J/95	$	1.81	Variable O&M costs for lime reagent
VOMW ($/MWh) = L*Q/A*J/95	$	0.96	Variable O&M costs for waste disposal
VOMP ($/MWh) =M*R*10	$	0.81	Variable O&M costs for additional auxiliary power required including additional fan power (Refer to Aux Power % above)
VOMM ($/MWh) = N*S/A	$	0.06	Variable O&M costs for makeup water
VOM ($/MWh) = VOMR + VOMW + VOMP + VOMM	**$**	**3.64**	