Topical Report 1, 2 and 3: Technology Survey, Screening, and Final Selection

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DISCLAIMER

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EXECUTIVE SUMMARY

Under cooperative agreement DE-NE0005649 ADA-ES is working to assess the viability and accelerate development of solid sorbents for post-combustion CO_2 capture. This program is focused on retrofitting the existing fleet of coal-fired power plants, taking into consideration the DOE's goal for commercialization by 2020. To adequately assess the viability of solids for post-combustion capture, the costs associated with a commercial system must be considered. However, since this is not a commercial technology, processes and equipment that are currently used for other applications were evaluated to provide insights related to operating costs, footprint, etc.

ADA-ES is working closely with Stantec, an engineering firm with experience in the power sector as well as retrofit post-combustion CO_2 capture, to examine potential process and equipment options. The following key process steps were identified for inclusion in the process evaluation:

1. Adsorption
2. Heat transfer (heating and cooling)
3. Desorption
4. Conveying

A technology survey which encompassed a broad range of gas-solids contactor and thermal regeneration technologies (including fluid beds, entrained flow, gravitational cross flow, moving bed, radial flow fixed bed, etc.), from air pollution control (APC) as well as chemical process industry (CPI) and mineral processing industry was conducted as the first step in identifying applicable commercial technologies for a solid-based CO_2 capture process. The survey included both identifying commercial processes that performed one of the key process steps identified above, and completing a brief summary of each process to facilitate an evaluation of its applicability for post-combustion CO_2 capture in a subsequent task.

In order to analyze and screen the commercial process technologies, a list of scoring criteria were compiled for each key process step and each was given a weight according to the perceived importance of each item (Kepner, Tregoe 1997). The major scoring categories and their respective scoring weights were:

- Economic – 30%: The economic rating was based primarily on capital and operating costs.

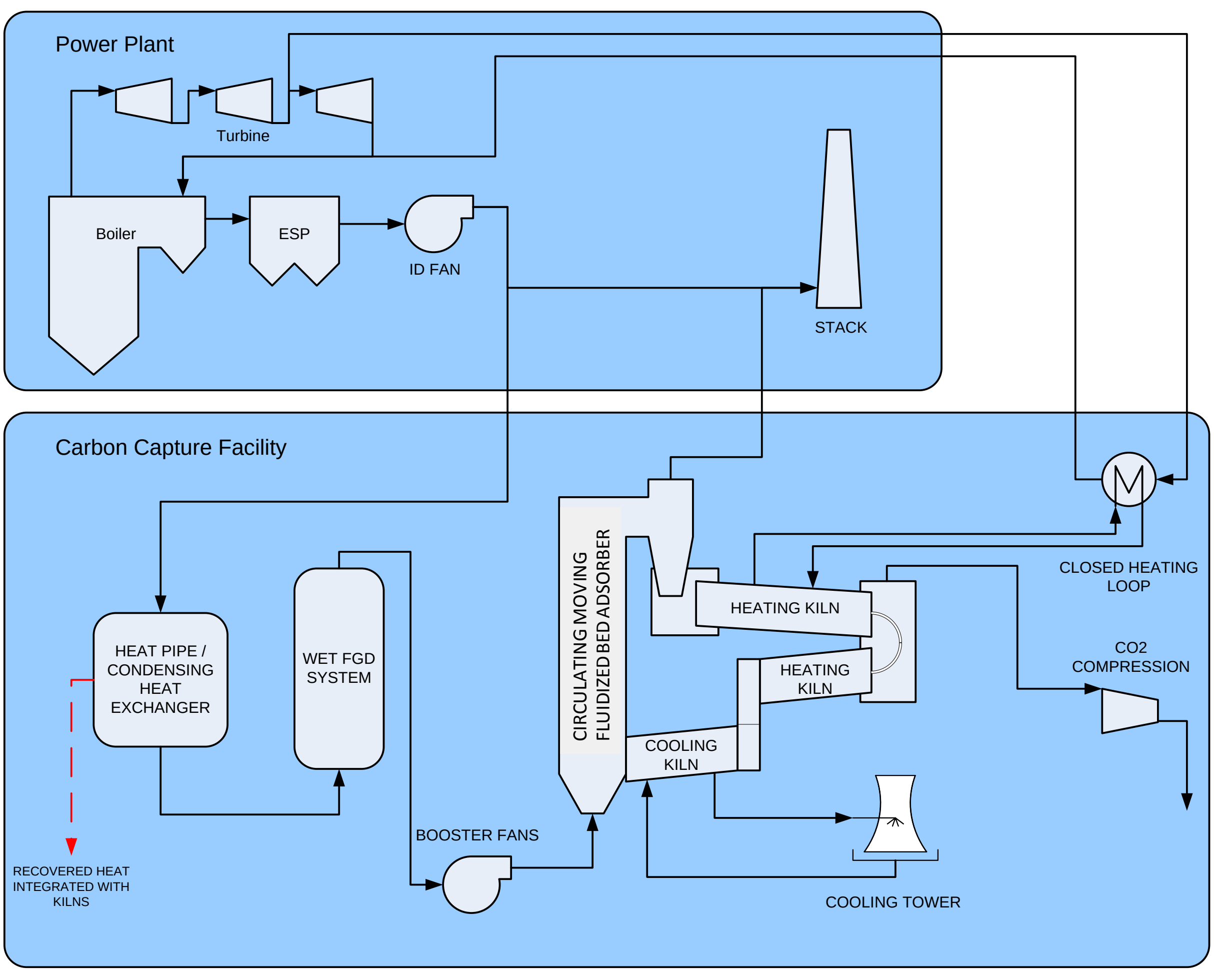
- Risk – 25%: The risk rating was based on different criteria for the different CO_2 capture steps, but included considerations such as reliability, scaling, safety, attrition, retrofit integration, etc.

- Performance – 35%: The performance rating was also based on different criteria for the different CO_2 capture steps, but included concerns such as residence time, pressure drop, footprint, and automation

- Environmental – 10%: The environmental rating included co-benefits (i.e. the ability to remove emissions other than CO_2), waste quantity, waste containment, and fugitive emissions

These criteria were developed by engineers at Stantec with feedback from ADA-ES and power producers. Each technology was scored accordingly and a single weighted score for each technology was established. This method allowed each technology to be compared against all others, and higher scoring technologies were then selected for further investigation. In many cases, a single process technology covered more than one of the key process steps under investigation. In such cases, the technology was rated separately for applicability in each category.

Although several technologies were interesting and promising, those selected as the process concept for the full-scale viability assessment were proven commercial technologies that were the most reliable, cost effective, and versatile options available. As an example, the fluidized bed and the rotary kiln in combination eliminate the need for an additional conveying system. A schematic of the final technology selection integrated into a power plant is shown in the following figure. This system will be used to complete a preliminary cost assessment for a 500 MW system.



INTRODUCTION

Solid sorbents used in a temperature-swing process have the potential to significantly reduce the energy penalty associated with post-combustion CO_2 capture. This can be attributed to the selection of materials with an excellent affinity for CO_2 (i.e. high CO_2 working capacity) that also exhibit a low specific heat, both of which will lead to a reduction of the parasitic energy requirements. Although certain attributes of solid sorbents prove to be promising, they still must be integrated into a viable process, which includes the implementation of equipment that can take full advantage of the sorbent properties. The US Department of Energy (DOE) has set a goal that CO_2 capture technologies will be commercially available by 2020. If a solid-based CO_2 capture technology is to meet the DOE's deadline, processes and equipment that are already commercially available for other applications must be evaluated and employed to the greatest extent possible. In addition, by evaluating similar commercial processes and equipment, the capital costs associated with solid-based CO_2 capture can be more accurately estimated.

Sorbents that can be utilized for post-combustion CO_2 capture can be divided into four categories:

- Supported amines
- Activated carbons
- Zeolites
- Carbonates

All four are capable of adsorbing carbon dioxide, but do so through different mechanisms. For the purposes of this study, it is assumed that:

- A successful sorbent can be produced in powdered or granular form. (Based on discussions with sorbent developers, there is there is some ability to customize the particle size of the sorbent, which is important because the process and equipment will not necessarily be limited by this sorbent characteristic.)
- The sorbent will be able to withstand multiple adsorption and desorption cycles
- The sorbent will be chemically resilient to deal with flue gas contaminants or additional treatment of flue gas will be employed upstream of the CO_2 capture system

The purpose of this report is to discuss different equipment and process options that can be employed regardless of the sorbent type. A basic process flow diagram relating the main components of CO_2 capture into a power plant is provided in Figure 1.

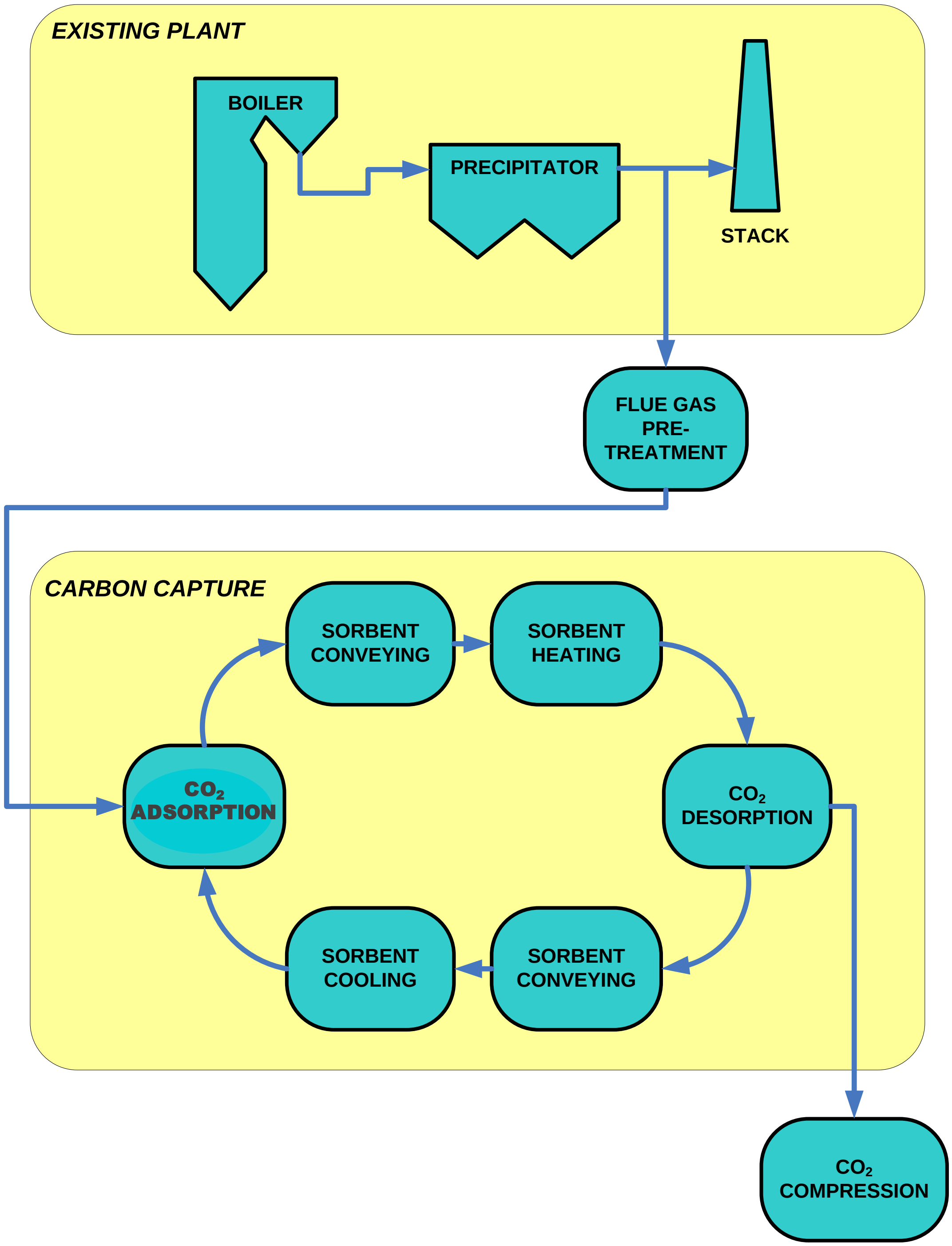


Figure 1: Solid-Based CO_2 Capture Process Flow Diagram

Flue gas is extracted from the existing plant after particulate removal in an electrostatic precipitator or other device. It then proceeds through flue gas pretreatment, which at this time is assumed to be high efficiency FGD, most likely wet limestone. Preliminary sorbent screening conducted by ADA-ES has indicated that at least for supported amines and carbonates, sulfur dioxide contamination is detrimental and must be avoided. Thus, for these materials, it is assumed that deep flue gas desulphurization (FGD) must be performed prior to carbon capture, targeting a near zero concentration of SO_2. The FGD process will also cool the flue gas. The flue gas then enters a gas / solids contactor where CO_2 is adsorbed from the flue gas. The gas temperature entering the contactor was assumed to be within the range of gas at the exit of a wet FGD system, approximately 55°C (130°F). The remaining CO_2 lean flue gas proceeds either up a new stack or back to the existing stack if the conditions are suitable. Further heat removal could be necessary during the adsorption process because the reaction is exothermic and an increase in temperature could significantly limit the CO_2 capacity of the sorbents. Preliminary estimates of the required reaction time are up to five seconds for sorption and up to 500 seconds for regeneration. While further experimentation and sorbent design may optimize these values, the technology review is based on projections drawn from laboratory-scale results to-date.

After the sorption step the sorbent, now loaded with CO_2, is separated from the flue gas. As the sorbent is heated, CO_2 is released, and desorption (i.e. regeneration) takes place in another gas / solid contactor, allowing the CO_2 to be removed in a highly concentrated form. The regenerator heat input includes both the sensible heat required to increase the temperature of the sorbent as well as the heat required to overcome the endothermic reaction responsible for disassociating the CO_2 from the sorbent. Conveying may also be necessary in the regenerator. The regenerated sorbent is cooled and returned to the adsorber to begin the cycle again. Clearly in a temperature-swing process heat transfer is an extremely important operation.

APPROACH

Currently, there is no commercial process to achieve post-combustion CO_2 capture using solids. However, to assess the viability of solids for this application, both the sorbents and the commercial-scale costs must be taken into account. ADA-ES is conducting an extensive study of the sorbents both on the laboratory-scale as well as the 1 kW scale. In a parallel effort, ADA-ES is also working with the engineering firm Stantec to study the equipment, process, and costs related to using these sorbents, preliminary results of this effort are discussed in this report. While realizing that a commercial CO_2 capture process must be designed specifically for this application, ADA-ES is looking to existing technologies to find those that may offer some applicability, as well as provide enough information to calculate high level estimates of capital and operating costs.

As the preliminary process flow diagram shown in Figure 1 was developed it was determined that the necessary technologies would be divided into the following categories (note that the commercial availability of both pretreatment and compression options are fairly advanced, and are not discussed in detail in this report):

1. Adsorption
2. Heating and cooling, or heat transfer
3. Conveying
4. Desorption

With the four main unit operations related to CO_2 capture in mind, a technology review was conducted. The review included collecting information from a wide variety of sources, including published papers, advertisements, web searches, and vendor interviews. The survey encompassed a broad range of gas-solids contactor and thermal regeneration technologies (including fluid beds, entrained flow, gravitational cross flow, moving bed, radial flow fixed bed, other), from air pollution control (APC) as well as chemical process industry (CPI) and mineral processing industry (MPI) that could be used for solid sorbent CO_2 capture will be performed. A technology survey sheet was generated for each technology; they are all provided in Appendix A. For each technology, key typical information collected (at least qualitatively) during the technology survey included:

- Brief process description, including configuration of gas solids contact and regeneration method
- Simple flow sheet
- Space requirement
- Experience record (number of units, application type, vendors, reliability, etc.)
- Date commercially available
- Chemicals used (physical properties in comparison with proposed CO_2 sorbents)
- Retention time
- Pressure drop
- Materials of construction
- Operating temperature range
- Attrition of sorbent
- Power requirements

- Water requirements
- Capital cost $/kW from published costs or quotes
- Operation cost $/MWh
- Compatibility with existing power plant equipment.

A weighted scoring system used to objectively analyze and screen the technologies. The process detailed in “The New Rational Manager” by Kepner and Tregoe was utilized in this analysis (Kepner, Tregoe 1997). A list of criteria was compiled, and each was given a weight according to the perceived importance of each item. When a technology was screened, it was given a score from 1 to 10 against each criterion, and the weighted score was the product of the weight and the score. A summation of the weighted scores provided a total score, which was then compared to all the other technologies. This method allowed each technology to be compared against others, and higher scoring technologies were then selected for further investigation. In many cases technologies were applicable to more than one of the four main categories (adsorption, heat transfer, convey, and desorption). In such cases, the technology was rated separately applicability in each category. An example of the screening criteria for adsorption is provided in Table 1.

Table 1: Adsorption Screening Criteria

Criteria Number		Criteria	Weight	Description of Criteria
1.0		**Economic - 30%**		**Analysis of System Economics**
	1.1	Capital Cost	15	Appraisal of apparent capital costs
	1.2	Operating Cost	15	Appraisal of apparent operating costs
		SUB-TOTAL	**30**	
2.0		**Risk - 25%**		**Analysis of Process Risk Items**
	2.1	Turndown	1	Ability to operate at reduced capacity
	2.2	Availability / Reliability	1	Dependability of equipment
	2.3	Erosion	1	Susceptibility to erosive wear
	2.4	Corrosion	1	Susceptibility to corrosion
	2.5	Plugging	1	Susceptibility to solids pluggage
	2.6	Scaling	1	Susceptibility to scaling
	2.7	Simplicity	4	Measure of system complexity
	2.8	Modularization	1	Ability to modularize equipment into parallel operations
	2.9	Technology Maturity	1	Measure of development of the equipment
	2.10	Commercial Scale	4	Suitability of equipment for a 500 MW sized unit
	2.11	Construction Schedule	0.5	Any impacts to schedule due to long lead times
	2.12	Retrofit Integration	1	Appraisal of difficulty of retrofit
	2.13	Safety	1	Measure of any safety concerns
	2.14	Attrition	3	Estimate of physical or chemical damage to solid sorbent
	2.15	Materials of Construction	0.5	Analysis of typical system metallurgy
	2.16	Maintenance	3	Estimate of maintenance requirements
		SUB-TOTAL	**25**	
3.0		**Performance - 35%**		**Efficiency and Performance of System**
	3.1	Residence Time	6	Ability to provide or modify reaction residence time
	3.2	ΔP	10	Pressure drop of the system
	3.3	Footprint	6	Measure of how much plan area is required to arrange equipment
	3.4	Energy Use	10	Parasitic power consumption
	3.5	Automation	3	Ability to automate system
		SUB-TOTAL	**35**	
4.0		**Environmental - 10%**		**Analysis of Environmental Impacts of Equipment**
	4.1	CO-benefits	2.5	Additional benefits provide for emissions control, or if equipment can simultaneously accomplish several steps of the process.
	4.2	Waste Quantity	2.5	Measure of any additional waste generated through use of the equipment
	4.3	Waste Containment	2.5	Ability of the system to contain any wastes
	4.4	Fugitive Emissions	2.5	Ability of the system to not produce any additional emissions
		SUB-TOTAL	**10**	

The technologies that scored the highest were carried forward to determine if and how they could be combined into a conceptual system. An ideal system would have both low capital and operating costs, while reaping synergistic benefits as technologies are combined. For example, it is preferable if certain parts of the same system accomplish multiple goals simultaneously (e.g. a transport reactor could be used for adsorption and conveying). The decision analysis flow chart used to select the preliminary conceptual design is provided in Figure 2.

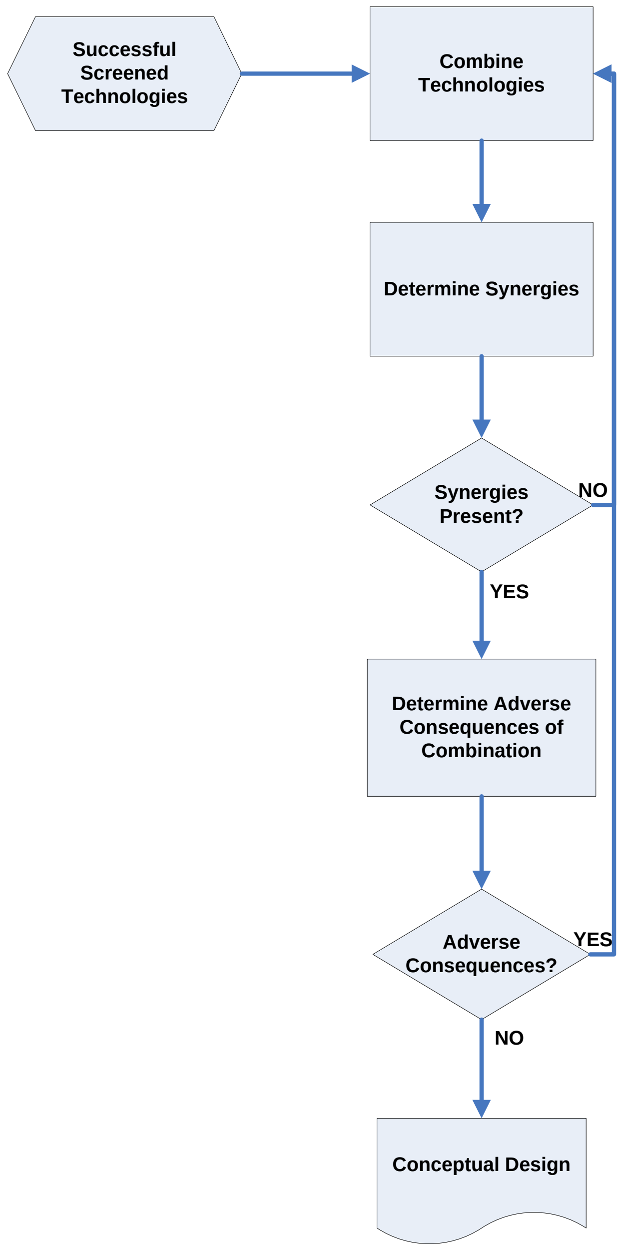


Figure 2: Technology Combination Decision Analysis

As an example, the kiln was analyzed using the flowchart shown in Figure 2. The kiln can achieve heat transfer, conveying, and desorption simultaneously. For this reason it proceeded to the conceptual design, while technologies like bucket conveyors were eliminated from further consideration. After all the technologies were reviewed and scored one equipment design was selected as the basis for the 500 MW preliminary conceptual design and costs analysis.

RESULTS AND DISCUSSION

Technology Survey

A technology survey was completed to identify both commercial and conceptual processes and equipment that could offer applicability for post-combustion CO_2 capture. During the technology survey, information was gathered on each technology related to the level of development, current vendors, and operation. As different technologies were evaluated they were grouped according to which unit operation they would be most applicable. In several cases technologies were appropriate for multiple operations. For example, a heated screw conveyor could be used for heat transfer, conveying and desorption. The following sections discuss the results of the technology survey. The equipment and processes are described according to the CO_2 capture step they are most applicable (i.e. adsorption, heat transfer, conveying, and desorption or regeneration). In several cases, commercial examples of a particular technology are provided.

Adsorption

Technologies considered viable for adsorption must include an effective means for gas/solids contacting. There are many different commercial options available today that include a contacting scheme that could be applicable to solid-based CO_2 capture.

Fixed Bed

A fixed bed, also referred to as a static bed, is the simplest type of reactor that can be used for adsorption. This type of system is often used in a process for molecular sieve dryers. In a CO_2 capture system, flue gas is introduced to an active bed of sorbent where CO_2 is adsorbed. When the bed is saturated, flue gas feed is ceased and a heated sweep gas, possibly CO_2 or steam is used as a purge gas during the release of CO_2. While the sorbent regeneration is occurring flue gas is routed to one or more previously regenerated beds. The typical process continues with beds in various states of activity or regeneration. Two fixed beds set up to operate in parallel are provided in Figure 3.

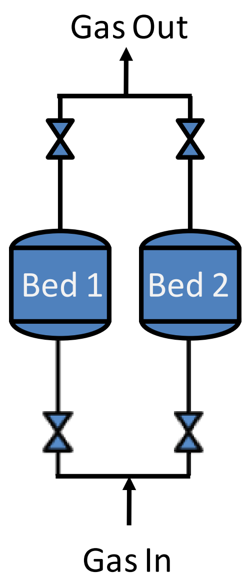


Figure 3: Two Fixed Beds in Parallel

Fixed beds have the potential to have low capital costs due to simplicity. However, for the case of CO_2 capture where an exothermic reaction is occurring during adsorption, it is important that heat of reaction is removed so that the sorbent does not increase in temperature, which quenches the desired adsorption reaction. Temperature control is much more difficult in a fixed bed compared to other types of systems. In addition, the pressure drop across a fixed bed is expected to be much greater than what would be observed in other types of systems. Thus, although fixed beds are commercially available and require few moving parts, they were not considered suitable for the application of post-combustion CO_2 capture.

Rotating Bed

A rotating bed is similar to a fixed bed, except that the actual bed itself rotates. The advantage of using a rotating bed is that the flue gas does not need to be diverted. Instead, in a rotating bed configuration it is likely that multiple zones would exist. For the application of CO_2 capture there would be an adsorption zone where flue gas is passed through the sorbent as well as a regeneration zone where the sorbent would be heated (likely with steam or regenerated CO_2 used to purge the sorbent) and the CO_2 would be released. A simple schematic of a rotating bed used for CO_2 capture is provided in Figure 4.

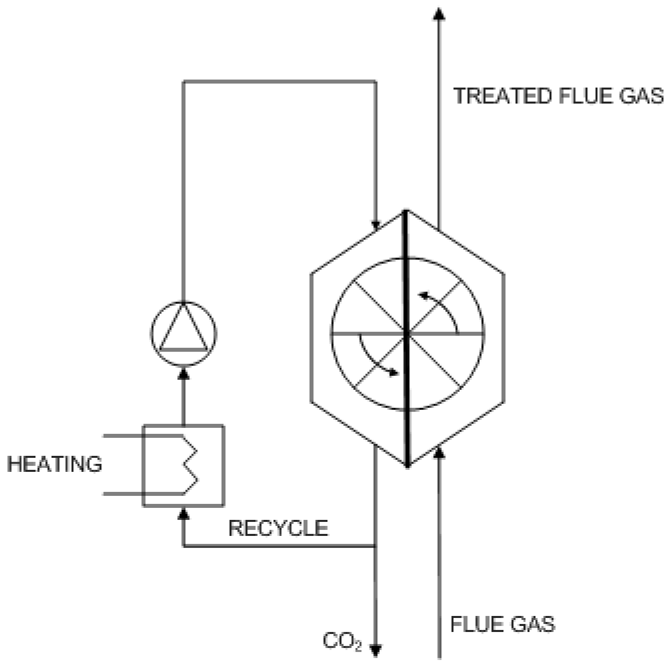


Figure 4: Rotating Bed

Although having a rotating reactor could present more challenges than a completely static bed, no valve switching to redirect the gas flow would be required. However, the pressure drop and heat transfer issues that were concerns for the fixed bed also are applicable to rotating beds. In addition, preliminary laboratory-scale data suggests that the adsorption time and regeneration time for a sorbent can be different; long regeneration times would lead to a slow rotation speed, possibly causing design concerns if the adsorption reaction occurs much more quickly.

Moving Bed

Moving beds are characterized by moving gas and solids flow. The sorbent is not entrained by the flue gas, and in many cases the gas and solids flow counter-currently to each other. Although a moving bed system can offer the ability to more closely control temperatures as well lower pressure drops compared to fixed or rotating beds, since the sorbent is moving during adsorption at least one conveying step will be required. Two examples of processes that utilize a moving bed (and their respective level of development) are:

- Dry Carbonate CO_2 Capture Process (bench-scale)
- ReACT – Regenerative Activated Coke Technology (commercially available and performance guaranteed)

The Dry Carbonate CO_2 Capture Process was developed by researchers at the Research Triangle Institute (RTI) specifically to remove CO_2 from flue gas using a sodium carbonate sorbent. The other aspects of this process are discussed in the conveying, desorption, and heat transfer sections. In the adsorption section the flue gas and sorbent flow co-currently (downward) and are then separated via gravity.

The ReACT process is currently marketed as a commercial system by J-Power EnTech Inc. This system uses activated carbon to remove SO_x, NO_x, mercury and particulate matter from flue gas. The adsorption step is carried out by a moving bed where the sorbent flows downward due to gravity while the gas flows across it. This system includes not only adsorption with a solid sorbent, but also includes methods for solids handling and regeneration (see respective sections for details). A schematic of the process is provided in Figure 5. To date there have been 10 commercial applications of the ReACT process, including two 600 MW coal flue gas clean up applications.

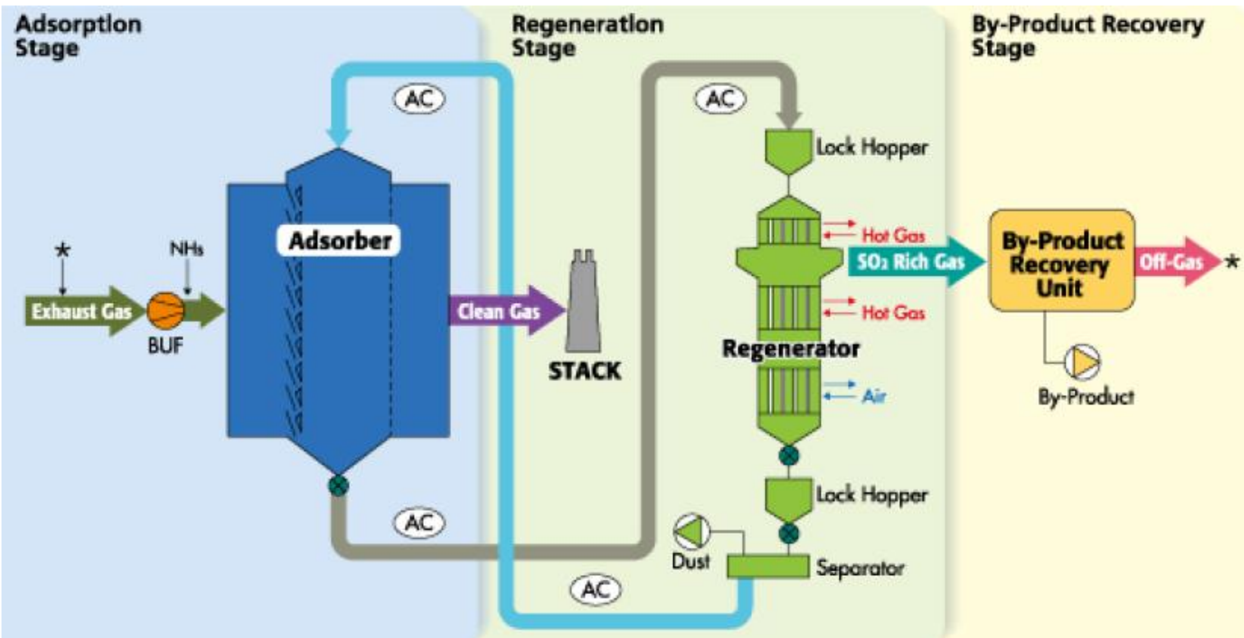


Figure 5: ReACT Technology

Note that the sorbent circulation requirements for removing SO_x, NO_x, and mercury are much lower than that for CO_2. Therefore, the ReACT system would either need to be modified or several systems would be used in parallel to treat the flue gas from a coal-fired power plant. One concern for the adsorption section of the ReACT system if applied to CO_2 capture is that the sorbent could be inadvertently entrained by the gas.

Fluid Bed

There are several applications of fluidized beds in the power industry and specifically the gas cleanup industry. In most fluid beds gas bubbles through a bed of solids; as the relative gas velocity increases the rate of bubbling will also increase. When a solid is bubbled in a fluidized bed, some amount of the solid can be entrained. If the solid is circulated back to the fluidized bed (often after a regeneration step) the system can be considered a circulating fluidized bed (CFB). Two examples of commercially available systems that utilize fluid beds are

- Gas Suspension Adsorber
- Semi-dry Flue Gas Purification

In the gas suspension adsorber, which is currently marketed by FLSmidth Airtech Inc., flue gas is fed through a venturi into the reactor where pollutants are removed by chemical reactions with injected lime. The venturi ensures the velocity of the flue gas is high enough to create a fluidized bed. As the solids are entrained and carried away with the flue gas they are taken to a cyclone where they are then separated from the gas. After the cyclone 99% of the particles are then transferred to a re-circulation box where some are recycled while a portion are removed from the system for disposal. The smaller particles which do not drop out in the cyclone are removed by a fabric filter then discarded. For the application of CO_2 capture, slurry injection may or may not be feasible given the final form of the sorbent; however, the application of a cyclone creates recirculation potential and reduces duty on the fabric filter. Depending on the particle size of the sorbent the cyclone could be effective for separation from the flue gas if necessary.

The semi-dry flue gas purification system, marketed by vonRolliNova, is similar to the gas suspension adsorber in that it also utilizes a circulating fluidized bed reactor with reagent circulation to decrease the reagent use. There are several variations of this technology offered by other vendors. A simple flow diagram for this process is provided in Figure 6.

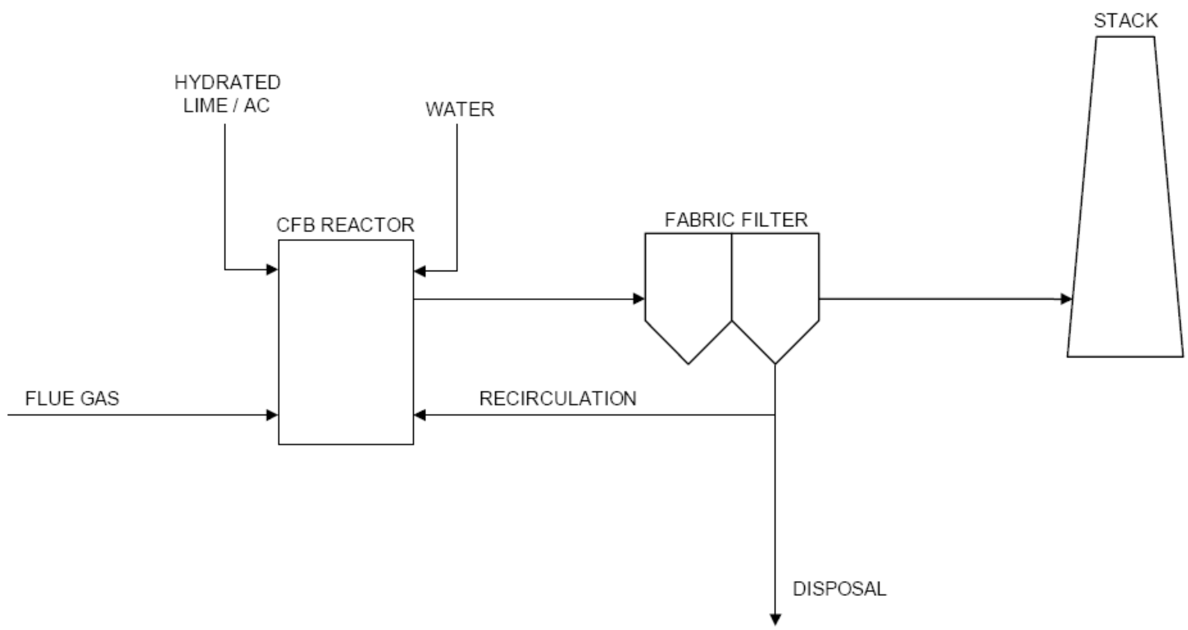


Figure 6: Semi-dry Flue Gas Purification Circulating Fluidized Bed

CFB reactors are simple and have been successfully demonstrated on large scales. They exhibit mixing characteristics superior to other technologies, which will aid heat removal during CO_2 adsorption. Potential concerns with CFB systems is that they have limited ability to turn down when the flue gas flow rate is decreased; a minimum fluidization velocity will be required to circulate the sorbent. It is possible that multiple systems could be used in parallel, which could address the requirement for many power plants to operate according to electricity demand.

Entrained Flow

An extreme case of a CFB is such that the gas velocity is high enough that the solid is completely entrained. This type of reactor can be referred to as a CFB or a transport reactor; they are common and have been successfully demonstrated on a commercial scale for multiple applications. Several technologies that utilize entrained flow were evaluated for potential synergies with CO_2 capture including:

- Alstom Best Available Recovery Technology
- Dry Flue Gas Scrubbing
- Dry Sorbent Injection
- NID System
- Spray Dry Adsorber (SDA)

Each of these commercial technologies is described in the respective technology survey sheet (provided in Appendix A). What all these technologies have in common is that they employ a sorbent that is entrained by the gas that is being treated. In most cases a fabric filter is used to separate the flue gas from the sorbent after the reaction has occurred. In addition, they are all currently used to remove constituents present in concentrations much lower than that of CO_2 at a conventional coal-fired power plant. Entrained systems are particularly interesting for the application of CO_2 capture because they are characterized by turbulent flow and thus superior mixing. This is important both to improve the kinetics of the reaction with CO_2 as well as to remove the heat generated by the adsorption reaction. One potential concern is the physical attrition of the sorbent. Because the volume of sorbent being used is so large, even a small amount of attrition could dramatically increase the costs associated with the CO_2 capture process. Therefore, if an entrained flow reactor is to be used the sorbent properties must be suitable so that attrition is limited.

Heat Transfer

Effective heat transfer will be extremely important in a temperature swing system. In addition to the temperature swing required for regeneration, there could be several opportunities to utilize and recover heat from the system, but the appropriate heat exchangers must be selected. If the CO_2 capture system is optimally integrated with the power plant, efficient heat exchangers could lead to a reduction in the CO_2 capture operating costs.

There are many different types of heat exchangers that could be used to transfer heat between the sorbents and an appropriate working fluid (flue gas, condensing steam, oil, etc.). Heat exchangers are not as easily classified as reactor types. Several heat exchanger options that may have applicability for CO_2 capture are described in this section.

Cooling or Heating Solids

Clearly in a solid-based temperature swing process heat transfer to and from the solids is critical. Fortunately, there are many heat transfer options that are well-understood and commercially available that could be applicable for the process under consideration. The only heat exchanging process discussed in this section that is not commercially available (although the components are commercially available) is that which is used in the Dry Carbonate CO_2 process. In this process, the sorbent is transported while it is heated for regeneration. The heat exchangers that are utilized are screw conveyors that are encompassed by a hollow jacket. While the sorbent is being transported in the screw conveyors steam is passed through the hollow jacket and allowed to condense. The liquid water is collected from the bottom of the screw conveyor. A similar screw conveyor is used after regeneration to cool the sorbent. This process is of interest because it allows for conveying and heat transfer to occur simultaneously. However, the uniformity of the heat transfer and the physical attrition to the sorbent caused by the screw conveyor are both areas of concern. The Holo-Scru is an example of a commercial system that is similar to the regeneration process in the Dry Carbonate Process. It also utilizes indirect heat exchange through a series of rotating helical ducts or hollow flights and can be used to convey materials simultaneously with the heat transfer process.

Indirect heaters are often used for effective heat transfer (this could be used for heating or cooling). One example of a commercially available option for indirect heat transfer to solids is the Solex heat exchanger shown in Figure 7. Note that the regeneration in the ReACT system operates similarly. These processes utilize a slow and controlled movement of the material through the heat exchanger, which is valuable to minimize the physical attrition of the sorbent. The inlet hopper and discharge feeder are used to ensure that the proper residence time is achieved. The plates inside the system are used for indirect heat transfer. This system is designed for bulk solids and could be easily applied to a dry CO_2 sorbent application. It would be important to ensure that the solids would be heated uniformly; partial regeneration of the materials would lead to a decrease of the sorbent working capacity, which would directly increase overall operation costs.

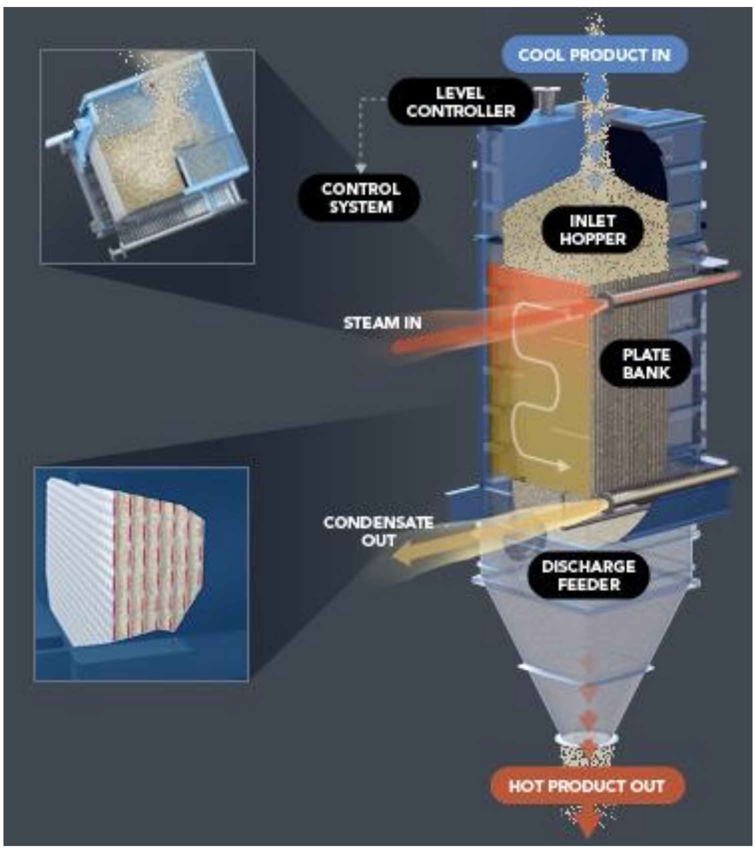


Figure 7: Solex Heat Exchanger

Another example of a commercially available option for indirect heat transfer of solids would be a rotary kiln. With an indirect fired rotary kiln the heating occurs in a furnace surrounding the outside of the kiln shell. This could also be used for cooling. This rotary kiln shown in Figure 8 already includes the ability to collect an exhaust gas. For the application of regenerating CO_2 sorbent, the exhaust gas would consist of CO_2 and possibly purge steam.

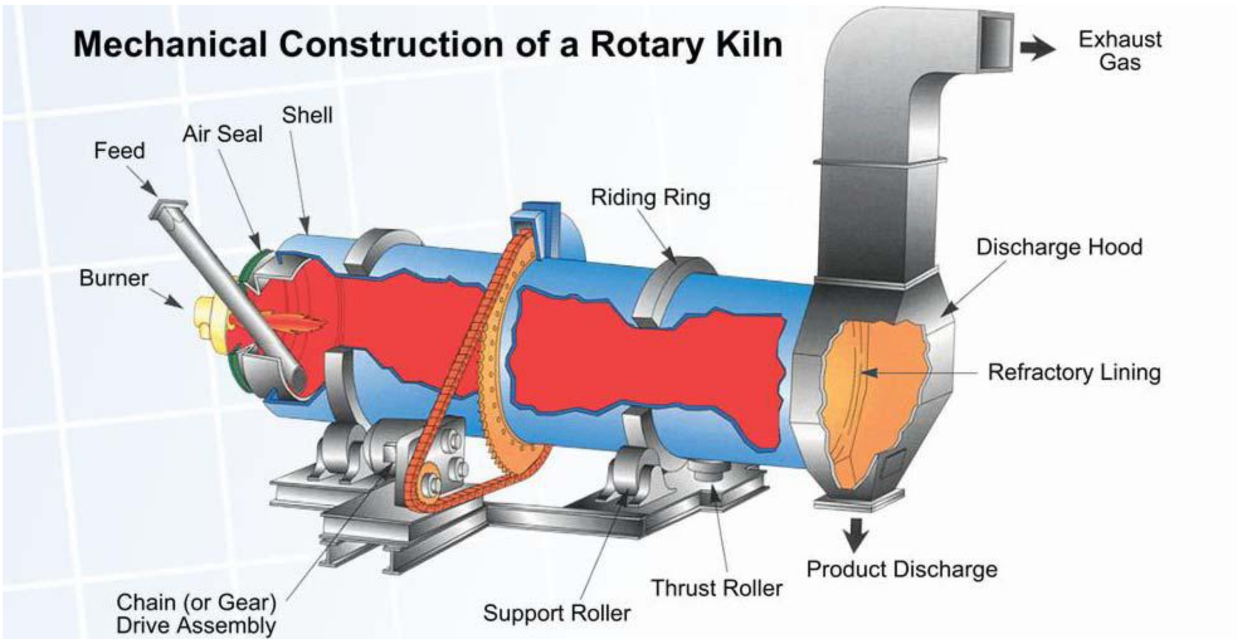


Figure 8: Schematic of a Rotary Kiln

Cooling or Heating Flue Gas

Some researchers have proposed using the flue gas as a potential source of heat for the temperature swing. If heat is removed from the flue gas, the temperature will be decreased. If the flue gas temperature was lowered, it is feasible that the sorbent regeneration could be conducted at a lower temperature, which would allow for some of the heat removed from the flue gas to be used to heat up the sorbent during regeneration. One option for such an operation could be to use a condensing heat exchanger (CHX), shown in Figure 9, marketed by Condensing Heat Exchanger Corp. This system uses a single pass to remove both sensible and latent heat from the flue gas. The flue gas enters the Teflon covered heat exchanger through a carbon steel inlet plenum at the top and flows downward across the horizontal banks of the heat exchanger tubes and exits through a fiberglass reinforced plastic plenum on the bottom of the exchanger while cold water flows through the tubing.

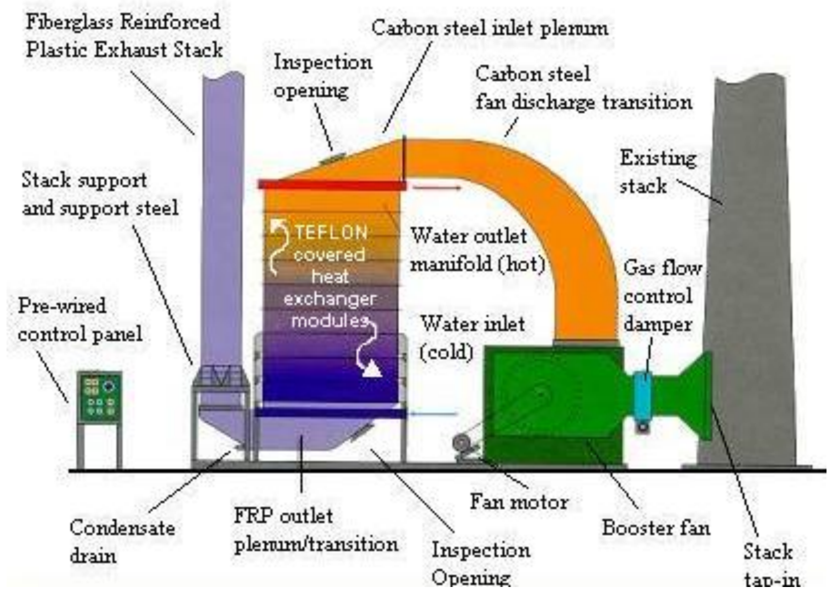


Figure 9: Condensing Heat Exchanger

Another interesting option to heat or cool gases in the CO_2 capture process is the Bry-Air heat pipe heat exchanger, a schematic of which is provided in Figure 10. This system contains several heat pipes, which are placed horizontally across the width of the exchanger and pass through a center seal partition to avoid cross contamination. The exchanger is installed across two side-by-side air ducts. The exhaust air and the supply air are discharged in counter flow direction across the exchanger through the ducts to facilitate the maximum energy transfer. The heat pipes pick up the thermal energy from the exhaust (evaporator region) and transfer it to supply air (condenser region). Such a system could not be readily adapted to heat or cool solids, but could be used to transfer heat between two fluids, such as the flue gas and the CO_2 rich stream, if necessary. As the detail in the level of design increases and system optimization and integration becomes more important heat such options may be necessary.

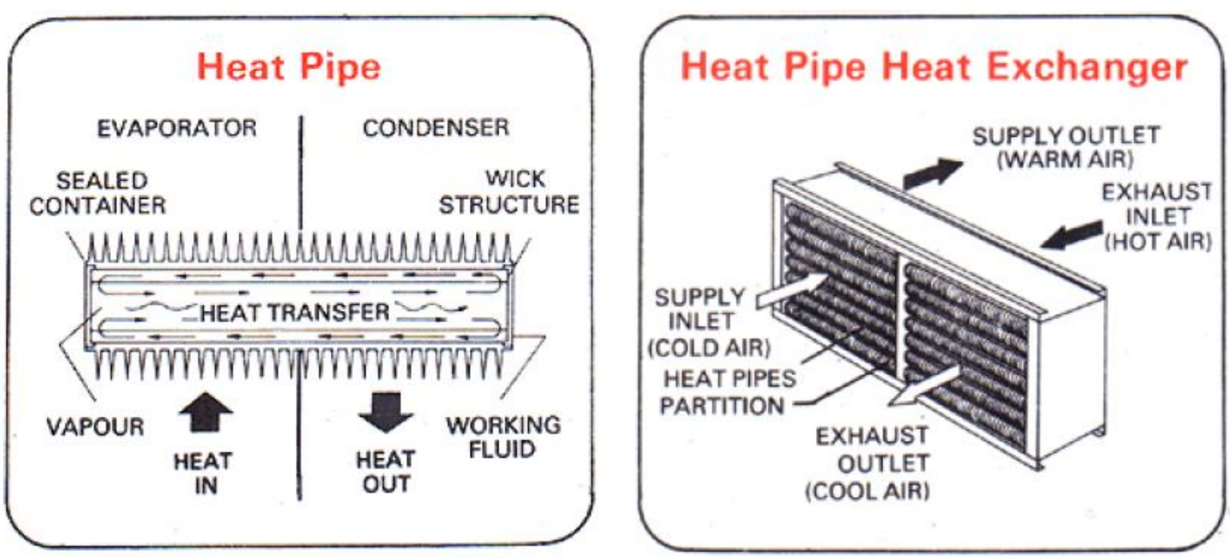


Figure 10: Schematic of Bry-Air Heat Pipe Heat Exchanger

Desorption

There are cases of dry, regenerable sorbents used in the power industry. For example, as described previously the ReACT process is an example of a commercial process that utilizes a moving bed for regeneration. The Dry Carbonate CO_2 Capture Process is not commercially available, but provides another potential conceptual design for the regeneration step (i.e. heated screw conveyor). Several of the technologies and processes described previously in other sections (e.g. heated screw conveyor, rotary kiln, etc) were also considered options for the regeneration step because effective heat transfer is one of the most important aspects of regeneration. Because CO_2 desorption is coupled with heat transfer, potential configurations for desorption are not discussed separately.

Conveying

Unless a fixed bed or a rotating bed system is used for both adsorption and regeneration some form of material conveying will be required. Ideally, conveying will be integrated into adsorption, regeneration, or sorbent cooling to maximize efficiency. There are several different options for materials conveying.

Bucket Conveyors

Bucket conveyors consist of a series of buckets attached to a chain drawn by rotors. Once a bucket reaches the end of the system it hits a tipping ramp and empties its load. The buckets can be spaced closely to allow for a nearly continuous flow of product. Bucket conveyors are commercially available for several different industries and are used in the ReACT process to move solid sorbents between the adsorption and regeneration vessels. Although bucket conveyors are not complex, they do consist of several moving parts, which could increase down time and/or operational and maintenance costs. In addition, bucket conveyors are less readily integrated to perform dual tasks because of a lack of heat transfer and mixing. One significant benefit of bucket conveyors is that their use would result in very low attrition.

Screw Conveyors

Screw conveyors are commercially available and are used in several industries; they come in many different sizes and shapes. Some screw conveyors are jacketed and are used for indirect heat transfer (see the discussion of the Holo-Scru and the Dry Carbonate Process in the Heat Transfer section). Because they can be used for indirect heat transfer, there is a significant opportunity to integrate the conveying step with either regeneration or cooling. One drawback for screw conveyors is that they can result in high levels of physical attrition.

Pneumatic Conveying

Gas flow can be induced by pressure or vacuum. If the driving force for the gas movement is sufficient the gas can also entrain solid particles, which is often referred to as pneumatic conveying. Typically the solids being conveyed are dilute relative to other conveying options described previously. The solid material can be separated from the gas via cyclones, fabric filters, or other options. A significant disadvantage for the application of pneumatic conveying to a regenerable CO_2 sorbent is the associated level of attrition. The concern caused by high attrition levels is sorbent dependent; for mechanically strong materials attrition levels may be low even after pneumatic conveying. One important advantage of pneumatic conveying is the high level of mixing, which is optimal for effective heat transfer.

Technology Scoring Results

After the survey was complete, each technology was scored. For each technology area a detailed scoring criteria sheet was developed. As an example, the scoring sheet for adsorption is provided in Table 1. For all steps in the CO_2 capture process the major categories of the scoring sheets and their respective scoring weights were:

- Economic – 30%: the economic rating was based primarily on capital and operating costs
- Risk – 25%: the risk rating was based on different criteria for the different CO_2 capture steps, but included considerations such as reliability, scaling, safety, attrition, retrofit integration, etc.
- Performance – 35%: the performance rating was also based on different criteria for the different CO_2 capture steps, but included concerns such as residence time, pressure drop, footprint, and automation
- Environmental – 10%: the environmental rating included co-benefits (i.e. the ability to remove emissions other than CO_2), waste quantity, waste containment, and fugitive emissions

After each technology was scored in all the listed areas, a final score was determined, which was used to compare the different technology options. The results of the technology screening are provided in Table 2. For the purposes of this review, the heat transfer technologies have been included in the desorption category. Also note that the highest possible score is 10.

Table 2: Technology Screening Results

Technology	Adsorption	Desorption	Conveying
Down Flow Reactor	7.3		
Moving Bed	5.6	5.8	
Static Fixed Bed	5.7		
Rotating Bed Reactor	5.2		
Circulating Fluidized Bed	7.2	5.5	✓
Rotary Kiln		7.3	✓
Heated Screw Conveyor		6.4	✓
Bucket/Belt Conveyor			7.3
Pneumatic Conveyor			4.1

Adsorption

After scoring all select adsorption technologies, the two highest scoring technologies were the down flow reactor (used in the Dry Carbonate CO_2 System) and the circulating fluidized bed (specifically a CFB characterized by entrained flow). The two technologies are very similar because they use a co-current flow pattern. The down flow reactor has not been manufactured at commercial scale and some assumptions were made for this assessment. However, both the down flow reactor and the circulating fluidized bed should be considered viable because the particle size of the solid sorbent has not been finalized. Should larger particles be suitable, then the down flow reactor may be preferable, as it uses simple gravity to separate the solids from the flue gas. If the particles are much smaller in size, then a circulating fluidized bed where the particles are entrained by the flue gas may be required, which would employ cyclones or fabric filters to separate the gas and solid particles. Since the two options are similar, the circulating fluidized bed, which is commercially available and thus has more readily available cost information, will be used to conduct the preliminary 500 MW conceptual design and cost analysis.

Desorption/Heat Transfer

Based on the scoring results provided in Table 2, the rotary kiln was selected as the model for the preliminary 500 MW conceptual design. One of the reasons that this technology was selected was because it can be used for simultaneous heat transfer and conveying, which makes it an ideal option for a regenerator.

Conveying

It is expected that conveying the solid materials will be required to reduce the overall energy input for CO_2 capture. If the sorbent is stationary during a temperature swing cycle, it is likely that the equipment as well as the sorbent will need to be heated to achieve the temperature swing. If this is the case, the advantage of using sorbents with a low specific heat has been diminished. If conveying is required, based on the screening results it is clear that a bucket conveyor would be a superior choice over pneumatics. However, for the preliminary 500 MW conceptual design the adsorption step includes entrained flow and the regenerator is a rotary kiln, both of which also include conveying. Therefore, no additional conveying will be required. If additional conveying must be taken into consideration in the future, the technology scoring will be taken into consideration.

Final Technology Selection

Using the circulating fluidized bed for adsorption and the rotary kiln (for both desorption and cooling) that were selected during the technology scoring; a complete conceptual CO_2 capture process can be pieced together. The conceptual flow sheet provided in Figure 11 shows how the selected equipment could be arranged in a power plant to capture carbon dioxide from flue gas.

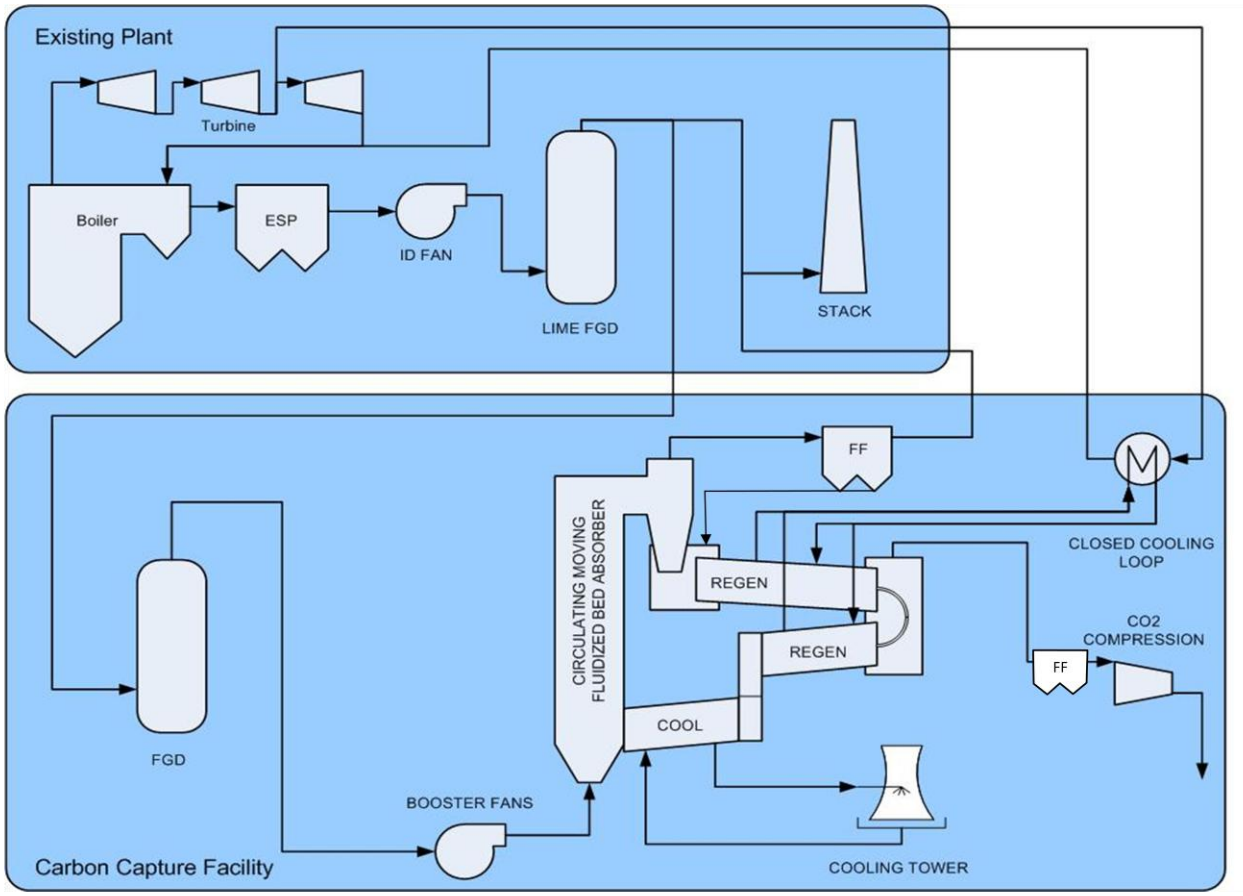


Figure 11: Conceptual Flow Sheet

In this conceptual arrangement, flue gas is sourced from the existing unit after particulate removal. It then proceeds through a heat recovery device, where the flue gas is cooled. The recovered heat is incorporated with the regeneration of the sorbent. The cooled flue gas then enters a wet FGD system for desulphurization and additional cooling. The pretreated gas then proceeds through a booster fan, then through a vertically arranged adsorber. Cooled solid sorbent is introduced to the bottom of the adsorber, and the flue gas carries it upwards in a circulating fluidized bed (i.e. transport reactor).

Carbon dioxide is adsorbed by the solid particles (either through a physical reaction, a chemical reaction, or a combination of the two), which are separated from the flue gas by a cyclone. The flue gas then proceeds back to stack, while the solids are directed towards regeneration. A rotary kiln, jacketed to provide heat, conveys the solids slowly away from the adsorber, and then back. The carbon dioxide is driven off as the adsorption reaction is reversed and is withdrawn for compression. A final kiln is jacketed for cooling, which prepares the sorbent for reintroduction to the adsorber. The process shown in Figure 11 will be used to evaluate the capital costs, operating costs, footprint, and other important criteria for a 500 MW power plant that is retrofit for CO_2 capture.

CONCLUSIONS

Many different technologies exist that may be applicable for post-combustion CO_2 capture using solids in a temperature-swing system. Background information has been collected on these technologies using a variety of sources. Working with power producers, scoring sheets were prepared and used to compare different technology options. Although several technologies were interesting and promising, those that were selected for the final conceptual design performed multiple steps simultaneously. For the adsorption step adsorption and conveying were both accomplished in a circulating fluidized bed. A rotary kiln was selected for desorption and cooling because it can simultaneously accomplish conveying and effective heat transfer. The final technology selection will be used to complete preliminary costs assessments for a conceptual 500 MW CO_2 capture process.

REFERENCES

Kepner, Charles, and Benjamin Tregoe. The Rational Manager. Princeton Research Press, 1997.

LIST OF ACRONYMS AND ABBREVIATIONS

APC	Air pollution control
CO_2	Carbon dioxide
CFB	Circulating fluidized bed
CPI	Chemical processing industry
DOE	Department of Energy
FGD	Flue gas desulfurization
MPI	Mineral processing industry
MWh	Megawatt hours
NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
SO_2	Sulfur dioxide
TSA	Temperature Swing Adsorption

APPENDIX A: TECHNOLOGY SURVEY SHEETS

Technology Survey

Technology: Alstom Best Available Recovery Technology - ABART

Date of Technology Assessment : March 9, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☒ Entrained Flow Bed

Company Name:	Alstom	Contact Name:	
Address:	1409 Centerpoint Boulevard	Telephone:	+1 865 693 7550
City, State, Zip:	Knoxville, TN, 37932	Email:	
Country:	U.S.A.	Website:	www.power.alstom.com

Equipment Summary:

Aluminum oxide (alumina) is injected into the gas as it enters the filter, the aluminum oxide is collected and sent to the fluoride reactor where it continues to remove fluoride gases and then is separated from the gas and either recycled or sent to reduction cells for the production of aluminum.

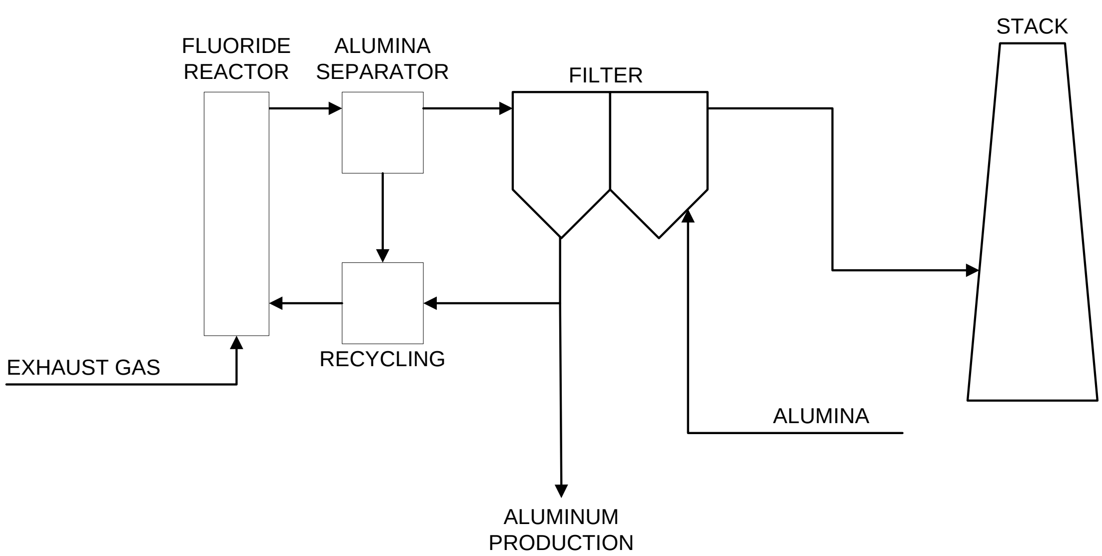
Detailed Description:

Aluminum oxide is used as a reagent for the fluoride compounds that escape the smelting process which are then recycled and used to turn aluminum oxide into liquid aluminum. Fresh aluminum oxide is injected into the filter, following the adsorption of fluoride gas. Aluminum oxide is separated from the gas using a cloth filter. The aluminum oxide is then collected in the bottom funnel, led upstream in the gas and injected into a reactor.

Potential for Use with Solid CO_2 Sorbents:

This system already involves the injection and removal of a dry reagent, whereas the aluminum oxide is used in the production of aluminum after it completes its scrubbing a CO_2 sorbent would need to be transported for regeneration.

Flowsheet:



Technology Survey

Technology: Bucket Solids Transport

Date of Technology Assessment : March 27, 2009

☐ Adsorption → ☒ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Ryson International, Inc.	Contact Name:	
Address:	300 Newsome Drive	Telephone:	(757) 898-1530
City, State, Zip:	Yorktown, VA 23692	Email:	sales@ryson.com
Country:	U.S.A.	Website:	www.ryson.com

Equipment Summary:

A series of buckets are attached to chain which is drawn by rotors. Once a bucket reaches the end of the system it hits a tipping ramp to empty its load. In the case of multiple outlets pneumatically activated tipping ramps are installed. This technology is offered by other vendors.

Detailed Description:

Bucket elevator conveyors move dry product or solid product to a high level. The conveyor takes the product at a low level and carries it to a high level in a bucket. At the top of the conveyor, the bucket rotates over and dumps the product out. The bucket then travels down the back side of the frame to be filled again. A bucket elevator has two chains which carry the buckets. The buckets are closely spaced together allowing for a nearly continuous flow of product.

Potential for Use with Solid CO_2 Sorbents:

A bucket conveyor could be used to transport a solid sorbent to and from the other process units in a solid sorbent system.

Flowsheet:

Technology Survey

Technology: CHX Condensing Heat Exchangers

Date of Technology Assessment : March 27, 2009

☐ Adsorption → ☐ Conveying → ☒ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Condensing Heat Exchanger Corp.	Contact Name:	
Address:	900 Commerce Drive	Telephone:	(518) 877-8805
City, State, Zip:	Clifton Park, NY 12065	Email:	sps@capital.net
Country:	U.S.A.	Website:	www.chxheat.com

Equipment Summary:

The condensing heat exchanger allows flue gas to be cooled below the water vapor dew point without being corroded due to their Teflon coating. This allows for flue gas to be cooled and heat to be recovered beyond conventional levels.

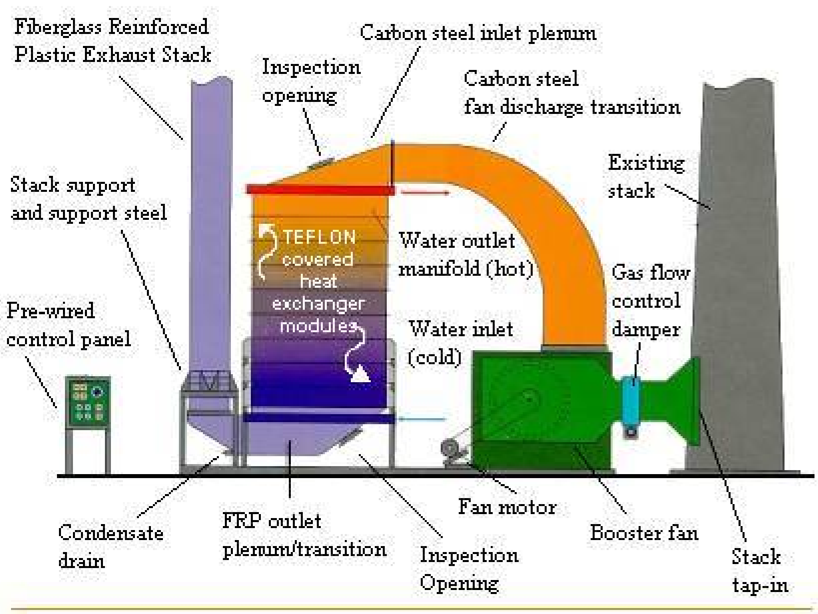
Detailed Description:

A CHX condensing heat exchanger uses a single gas pass to remove both sensible and latent heat from the flue gas. The flue gas enters the Teflon covered heat exchanger through a carbon steel inlet plenum at the top and flows downward across the horizontal banks of heat exchanger tubes and exits through and fiberglass reinforced plastic plenum on the bottom of the exchanger. The cold water flows through the tubing.

Potential for Use with Solid CO_2 Sorbents:

Could be used to transfer heat between hot flue gas to be cooled.

Flowsheet:



Technology Survey

Technology: Dry Carbonate CO_2 Capture Process

Date of Technology Assessment : March 27, 2009

☒ Adsorption → ☒ Conveying → ☒ Heat Transfer → ☒ Desorption

☐ Rotating Bed ☐ Fixed Bed ☒ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Research Triangle Institute	Contact Name:	Mr. Thomas Nelson
Address:	3040 Cornwallis Road	Telephone:	(713) 942-7864
City, State, Zip:	Research Triangle Park, NC, 27709	Email:	tnelson@rti.org
Country:	U.S.A.	Website:	www.rti.org

Equipment Summary:

This system involves a down flow contactor for absorption. Regeneration, cooling, and material handling are performed by two jacketed screw conveyors.

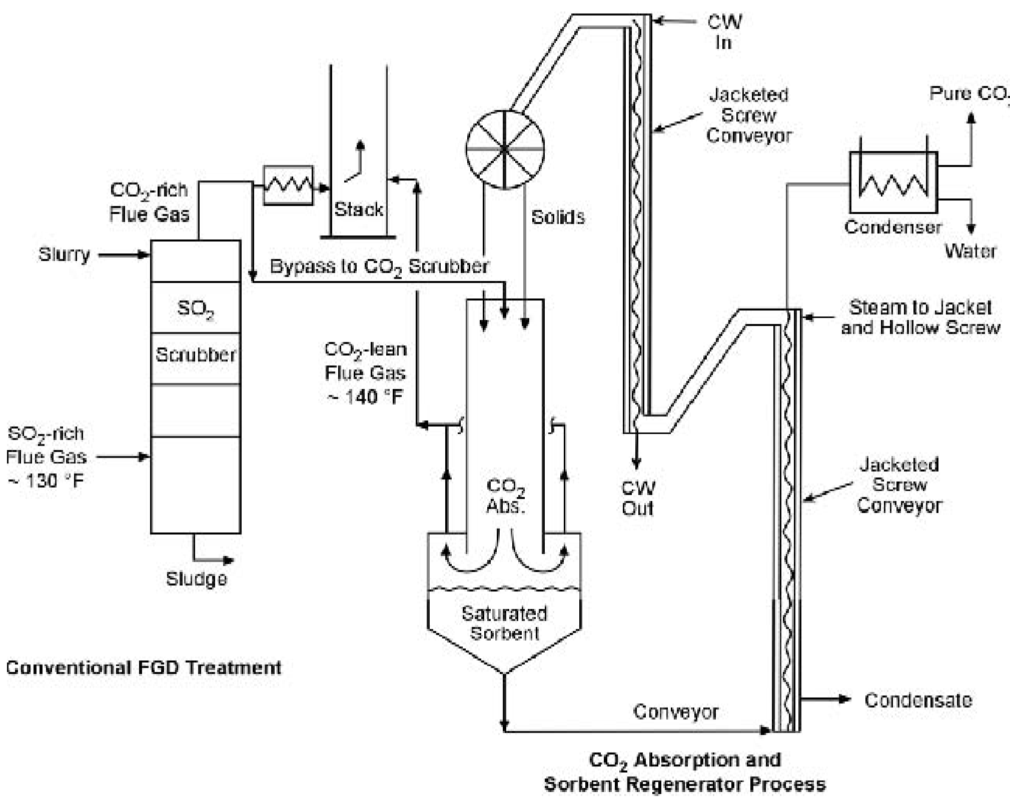
Detailed Description:

Sorbent to gas contact is performed in a down flow contactor. The sorbent is not entrained in the flue gas so as the sorbent collects at the bottom of the vessel the CO_2 lean flue gas exits to the stack. Regeneration is performed in a jacketed screw conveyor where steam is injected inside the jacket providing the thermal swing. The exiting gas is sent to a condenser while the lean sorbent is carried in another jacketed screw conveyor this time with cooling water in the jacket. These two screw conveyors have been arranged to carry the sorbent back to the top of the contactor.

Potential for Use with Solid CO_2 Sorbents:

This system uses a supported sorbent (Na_2CO_3 on a high surface area support material). This system has been specifically designed for solid sorbents so its application to other types of solid sorbents would be advantageous.

Flowsheet:



Technology Survey

Technology: Dry Flue Gas Scrubbing

Date of Technology Assessment : March 10, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☒ Entrained Flow Bed

Company Name:	GRAF-WULFF USA	Contact Name:	
Address:	5401 Weywood Drive	Telephone:	+1 443 / 745 5763
City, State, Zip:	Reisterstown, MD, 21136	Email:	j.toher@graff-wulff.de
Country:	USA	Website:	www.graf-wulff.de

Equipment Summary:

Hydrated lime is injected at the bottom of the absorber where it reacts with the sulphur compounds and is carried in the flue gas to the fabric filter. In the fabric filter the reacted lime is separated from the flue gas and recycled into the flue gas while a portion is disposed of as a byproduct. Variations of this technology are available from other vendors.

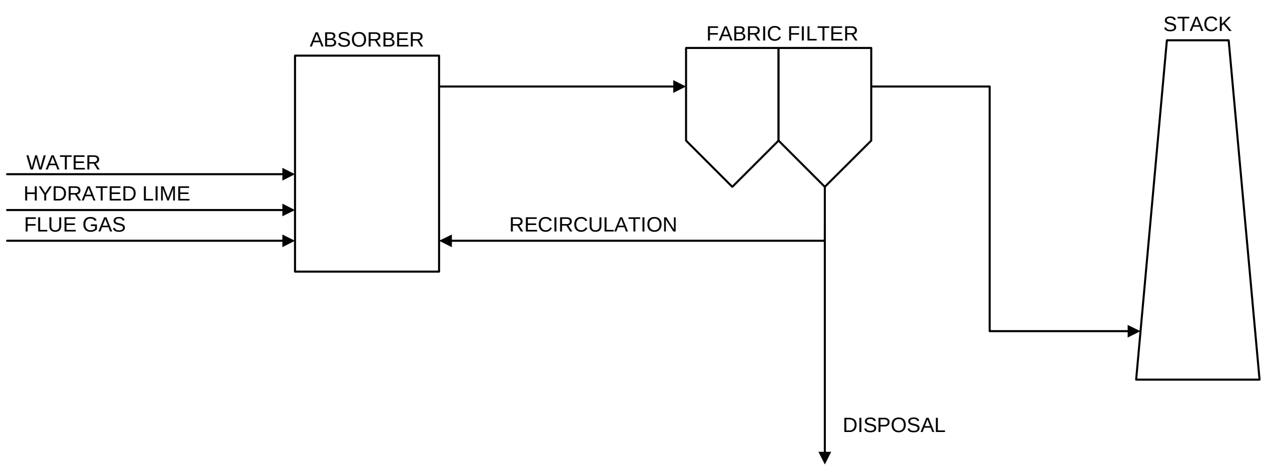
Detailed Description:

The flue gas enters the bottom of the absorber and comes into contact shortly after with the injected hydrated lime. As the lime reacts, water is injected into the absorber to control the exiting flue gas temperatures. The recirculation achieves optimal reagent usage.

Potential for Use with Solid CO_2 Sorbents:

This system uses a dry injection and separation scheme which could be used in a dry CO_2 sorbent application. The recirculation would help to ensure maximum sorbent loading is achieved before regeneration. Also the water injection to control flue gas temperature could be utilized as well to maintain optimal reaction temperatures.

Flowsheet:



Technology Survey

Technology: Airpol Dry Injection Scrubber System

Date of Technology Assessment : March 27, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☒ Entrained Flow Bed

Company Name:	Airpol Inc.	Contact Name:	
Address:	199 Pomeroy Road	Telephone:	(973) 599-4400
City, State, Zip:	Parsippany, New Jersey, 07054	Email:	Info@airpol.com
Country:	U.S.A.	Website:	www.airpol.com

Equipment Summary:

Typically used for waste incineration applications, the dry injection scrubber system consists of a dry injector followed by a particulate removal system. The injector is a proprietary design and is placed in the duct leading to the injector. The reagent is pneumatically conveyed to the injector where it is mixed into the flue gas. There are variations of this system supplied by other vendors.

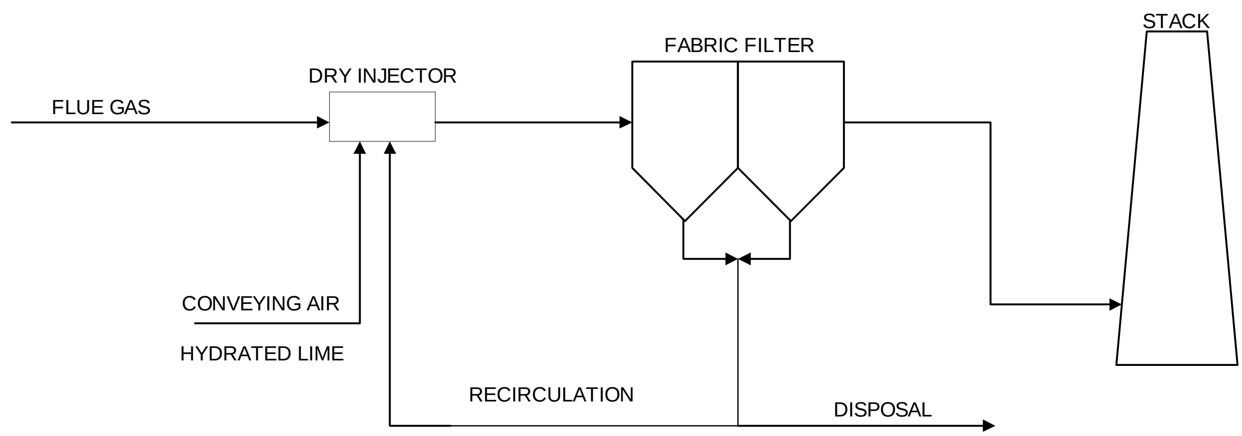
Detailed Description:

The dry injection scrubber system is installed in the ducts before the particulate removal section. The particulate and reaction product removal is typically performed by a fabric filter. The removed products are either recycled or disposed of.

Potential for Use with Solid CO_2 Sorbents:

Dry injection and removal would be suitable for the adsorption step in a solid sorbent process.

Flowsheet:



Technology Survey

Technology: Dry Sorbent Injection

Date of Technology Assessment : March 23, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☒ Entrained Flow Bed

Company Name:	Benetech USA	Contact Name:	
Address:	1851 Albright Road	Telephone:	1-630-844-1300 x214
City, State, Zip:	Montgomery, IL 60538	Email:	benetechusa@benetechusa.com
Country:	U.S.A.	Website:	www.benetechusa.com

Equipment Summary:

The sorbent is injected into the duct via an advanced nozzle design which optimizes the reaction surface by permitting the fluidized lime to be fed from a tubular injector surrounding the cylindrical humidification nozzle lance. The site of injection for the sorbent in upstream of the particulate removal equipment. Variations of this technology are supplied by other vendors.

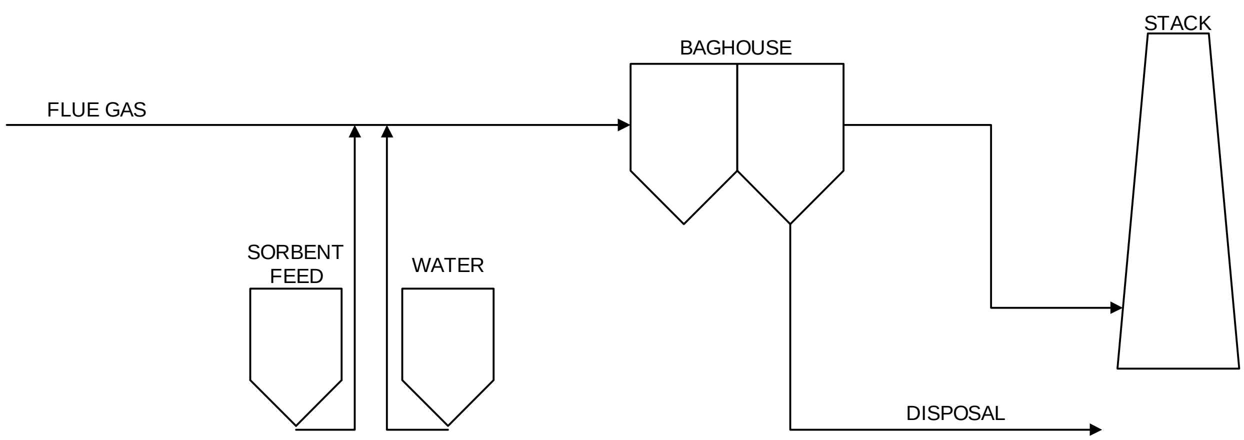
Detailed Description:

This technology injects the sorbents into the duct to react with the sulfur in the flue gas which was vaporized during the coal combustion. The flue gas emissions are humidified by fresh water in the air duct feeding the particulate collection device. An array of proprietary nozzles ensures even distribution of the water and the sorbent.

Potential for Use with Solid CO_2 Sorbents:

The dry sorbent injection could be applied for a CO_2 sorbent and the water injection may be used to help control temperatures as a result of the heat of reaction.

Flowsheet:



Technology Survey

Technology: Fluidized Bed

Date of Technology Assessment : January 29, 2010

☐ Adsorption ➔ ☐ Conveying ➔ ☐ Heat Transfer ➔ ☒ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☒ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name: Multiple Vendors	Contact Name:
Address:	Telephone:
City, State, Zip:	Email:
Country:	Website:

Equipment Summary:

In this device, a bed of solids is fluidized by the upward flow of a pressurized gas. This is an elemental piece of equipment as far as unit operations, and is available from numerous vendors.

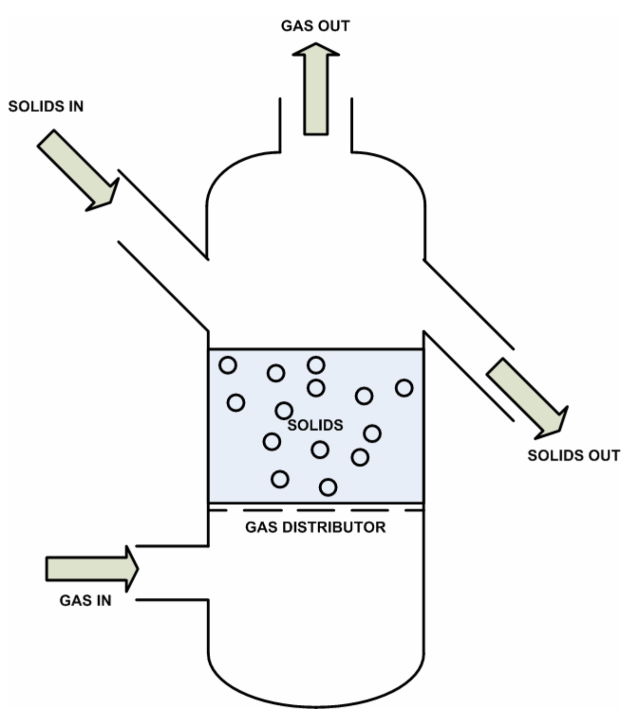
Detailed Description:

A bed of solid particles is made to behave like a fluid, as pressurized gas is forced upwards through it. The bed behaves hydrostatically like a liquid. Due to the intimate gas solid contact, fluidized beds exhibit excellent mass and heat transfer characteristics.

Potential for Use with Solid CO_2 Sorbents:

A fluidized bed has high solids to gas ratio, and thus would be suitable for the desorption reaction, as the bed could contain sufficient solids to allow for the longer regeneration times required as compared to absorption.

Flowsheet:



Technology Survey

Technology: Gas Suspension Absorber

Date of Technology Assessment : March 6, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☒ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	FLSmidth Airtech Inc	Contact Name:	
Address:	3231 Schoenersville Road	Telephone:	1 610 264 6000
City, State, Zip:	Bethlehem, PA, 18017	Email:	info-us@flsmidth.com
Country:	U.S.A	Website:	www.flsmidth.com

Equipment Summary:

The flue gas enters the reactor through a venturi where the lime slurry is also injected. The solid particles are lifted by the flue gas out of the reactor where the heavier ones are separated by a cyclone separator. The lighter particles are removed in a fabric filter. The heavy particles are recycled back to reactor while the rest are disposed of. Variations of this technology are available through other vendors.

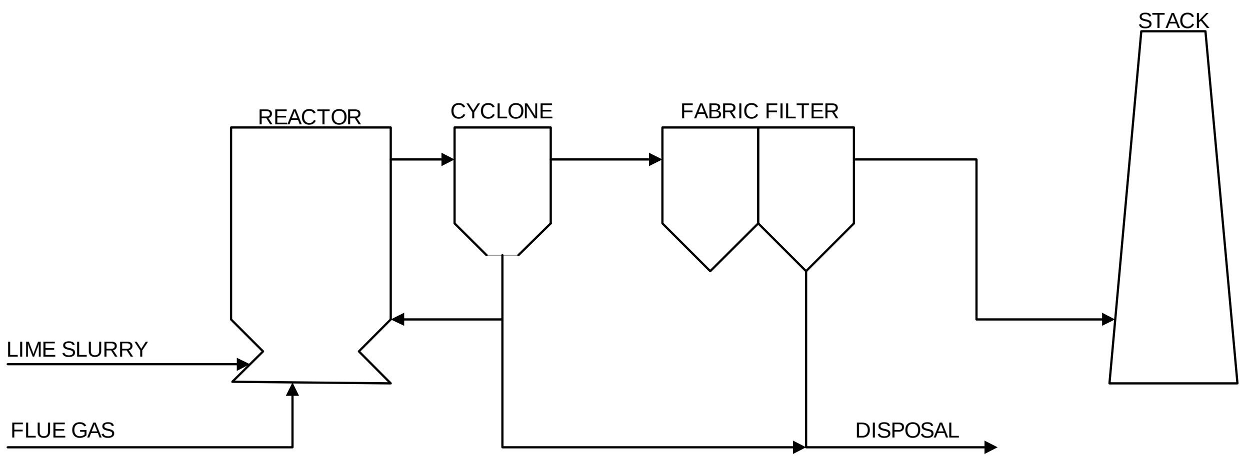
Detailed Description:

Flue gas is fed through the venturi into the reactor where the pollutants are removed by chemical reactions with the injected lime. The venturi ensures the velocity of the flue gas is high enough to create a fluidized bed. 99% of the entrained particles, which are separated from the flue gas by the cyclone, are then transferred to a re-circulation box where some are recycled while a portion is disposed of. The smaller particles which do not drop out in the cyclone are removed by a fabric filter and also disposed of.

Potential for Use with Solid CO_2 Sorbents:

Slurry injection may or may not be feasible given the final form of the sorbent, however the application of a cyclone creates recirculation potential and reduces duty on the fabric filter. Depending on the grain size of the sorbent the cyclone could be effective.

Flowsheet:



Technology Survey

Technology: Heat Pipe Heat Exchanger

Date of Technology Assessment : March 27, 2009

☐ Adsorption → ☐ Conveying → ☒ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Bry-Air	Contact Name:	
Address:	10793 St. Rt. 37W	Telephone:	(740) 965-2974
City, State, Zip:	Sunbury, Ohio 43074	Email:	info@bry-air.com
Country:	U.S.A.	Website:	www.bry-air.com

Equipment Summary:

Bry-Air heat pipe is a self-contained passive energy recovery device. Heat pipes have no moving parts and hence require minimum maintenance. They are silent and reversible in operation and require no external energy other than the thermal energy they transfer.

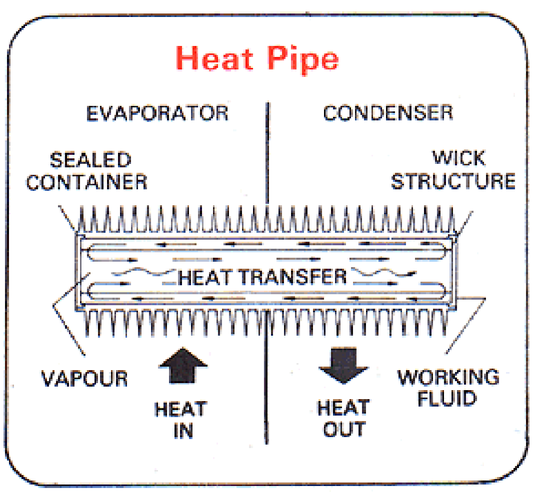
Detailed Description:

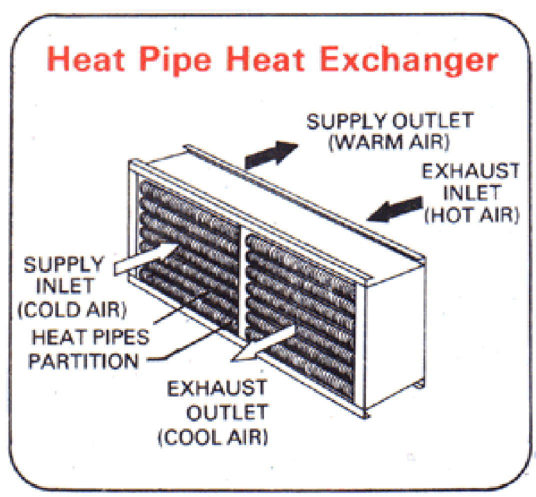
Bry-Air heat pipe heat exchanger contains a number of heat pipes. These heat pipes are placed horizontally across the width of the exchanger and pass through a center seal partition to avoid cross contamination. The exchanger is installed across two side-by-side air ducts. The exhaust air and the supply air are discharged in counter flow direction across the exchanger through the ducts to facilitate the maximum energy transfer. The heat pipes pick up the thermal energy from the exhaust (evaporator region) and transfer it to supply air (condenser region).

Potential for Use with Solid CO_2 Sorbents:

Could be used to transfer heat between hot flue gas to be cooled or cool CO_2 to be heated for regenerative purposes.

Flowsheet:





Technology Survey

Technology: Holo-Scru

Date of Technology Assessment : March 27, 2009

☐ Adsorption → ☒ Conveying → ☒ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Therma-Flite	Contact Name:	
Address:	849 Jackson St.	Telephone:	(707) 747-5949
City, State, Zip:	Benicia, CA, 94510	Email:	info@therma-flite.com
Country:	U.S.A.	Website:	www.therma-flite.com

Equipment Summary:

The "Holo-Scru" is widely used for cooling, heating, drying and other application where heat transfer is involved. Heat transfer agents such as refrigerants, water, steam or hot oil provide for wide range or processing temperature.

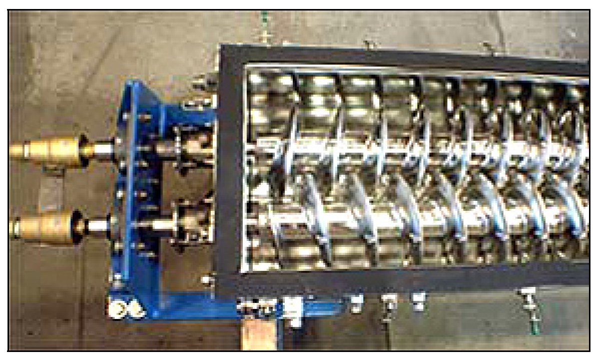
Detailed Description:

The 'Holo-Scru" processor is an indirect heat exchanger comprising of a series of rotating helical ducts or hollow flights. Heat is transferred via a heat exchange agent through the inner surfaces of the hollow flights and shaft. The continuous movement, provided by the helices, produces frequent and repeated contact with the surface containing the heat exchange agent. The slow rotation, conveying, interfolding and dispersing action increase the heat exchange with the product. The motion is however mild enough that there is no dusting or particle degradation.

Potential for Use with Solid CO_2 Sorbents:

This device would allow for both heat transfer and conveying in a CO_2 sorbent process.

Flowsheet:



Technology Survey

Technology: NID System

Date of Technology Assessment : March 9, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☒ Entrained Flow Bed

Company Name:	Alstom	Contact Name:	
Address:	1409 Centerpoint Boulevard	Telephone:	+1 865 693 7550
City, State, Zip:	Knoxville, TN, 37932	Email:	
Country:	U.S.A.	Website:	www.power.alstom.com

Equipment Summary:

This semi dry FGD system uses the inlet gas duct of the particulate collector as its absorber. Some of the solid particulate, once separated from the flue gas is disposed of while the rest is sent to an integrated mixer/humidifier/hydrator to be recycled. The first generation FGD system that Alstom developed was a Spray Dryer Absorber (SDA), where the NID system is second generation and more advanced. Variations of these technologies are available from other vendors.

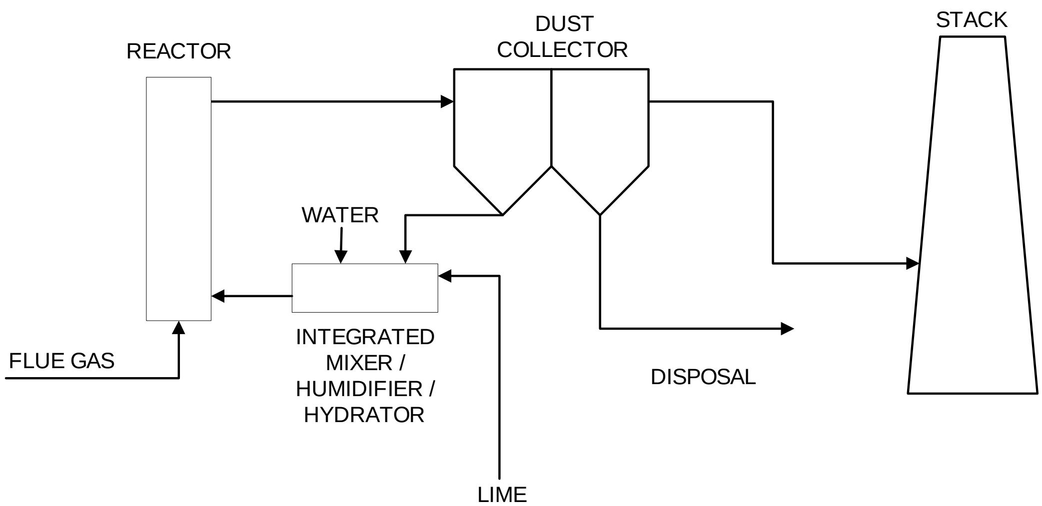
Detailed Description:

The reagent is injected into the inlet gas duct as a moistened free flowing dust, which avoids all aspects of slurry handling. The moist powder particles react with the acid flue gas components and simultaneously evaporate the excess moisture. The particulate matter is removed in a dust collector.

Potential for Use with Solid CO_2 Sorbents:

The injection of a powder, removal, and small reactor size could be useful in applying this system with a dry sorbent injection system.

Flowsheet:



Technology Survey

Technology: Pneumatic Conveying System

Date of Technology Assessment : March 27, 2009

☐ Adsorption → ☒ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Flexicon Corp.	Contact Name:	
Address:	2400 Emrick Blvd.	Telephone:	(610) 814-2400
City, State, Zip:	Bethlehem, PA 18020	Email:	sales@flexicon.com
Country:	U.S.A.	Website:	www.flexicon.com

Equipment Summary:

A pneumatic conveyor uses a pressure blower or vacuum pump to supply movement to the material being handled. Valves are used to direct and redirect where the material goes while silos are typically used for storage. This technology is provided by other vendors.

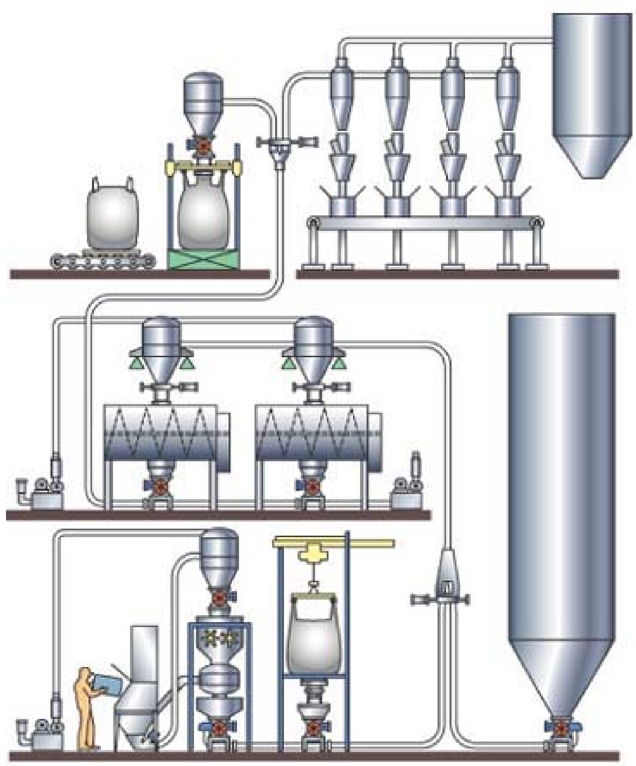
Detailed Description:

A typical dilute phase pneumatic conveying system moves bulk materials that are suspended in an air stream that is introduced by a positive pressure blower upstream of material intake points, or by a vacuum pump that removes air from the system downstream of material discharge points. Material is separated from the conveying air at the use point and then discharged on a batch basis via butterfly or slide gate valves, or continuously via rotary airlock valves.

Potential for Use with Solid CO_2 Sorbents:

This system could supply the conveying for a solid sorbent system. CO_2 could be used as the conveying gas.

Flowsheet:



Technology Survey

Technology: ReACT – Regenerative Activated Coke Technology

Date of Technology Assessment : March 27, 2009

☒ Adsorption → ☒ Conveying → ☒ Heat Transfer → ☒ Desorption

☐ Rotating Bed ☐ Fixed Bed ☒ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	J-Power EnTech Inc.	Contact Name:	Koutaro (Taro) Eguchi
Address:	1101 17th street NW Suite 609	Telephone:	(202) 429-0670
City, State, Zip:	Washington, DC, 20036	Email:	keguchi@epdc.com
Country:	U.S.A.	Website:	www.jpower.co.jp/entech_e/what

Equipment Summary:

Flue gas passes through a single stage adsorber which contains a bed of activated coke (AC). A bucket conveyor transports the saturated AC to a regenerator where the pollutants in the AC are decomposed. The AC then passes through a separator which removes the smaller particles and the larger AC particles are returned back to the adsorber.

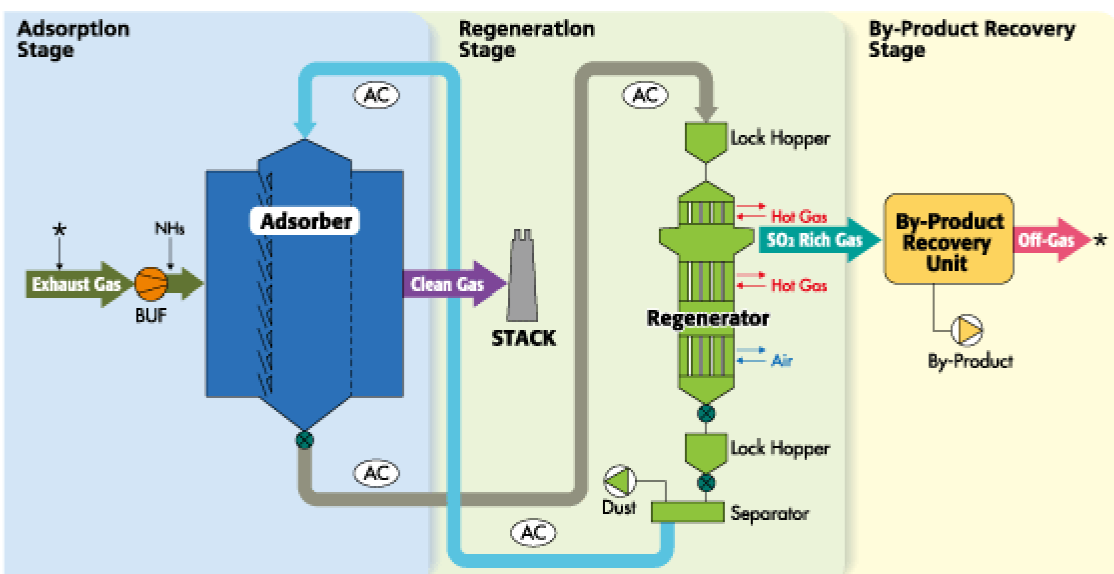
Detailed Description:

The AC bed moves slowly downward as the flue gas passes through it. None of the AC tablets are entrained in the flue gas. While in contact with the flue gas the AC removes SO_x, NO_x, mercury and particulate. In the regenerator, due to the addition of heat, the sulphuric acid or ammonium salts in the AC are decomposed to N_2, SO_2 and water. Mercury is retained in the AC and removed with it every few years depending on the concentrations.

Potential for Use with Solid CO_2 Sorbents:

This system involves not only an adsorption with a solid sorbent but also includes methods for solid material handling and regeneration.

Flowsheet:



Technology Survey

Technology: Rotary Kiln

Date of Technology Assessment : March 27, 2009

☐ Adsorption → ☐ Conveying → ☒ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Feeco International Inc.	Contact Name:	
Address:	3913 Algoma Rd.	Telephone:	(920) 468-1000
City, State, Zip:	Green Bay, WI 54311	Email:	sales@feeco.com
Country:	U.S.A.	Website:	www.feeco.com

Equipment Summary:

Rotary kilns are used to heat solids to the point where a required chemical reaction takes place. The rotary kiln is basically a rotating inclined cylinder. Solids retention time in the kiln is an important design factor and is set by proper selection of the diameter, length, speed, slope and internals design. They can be directly or indirectly fired. Other vendors provide similar technologies.

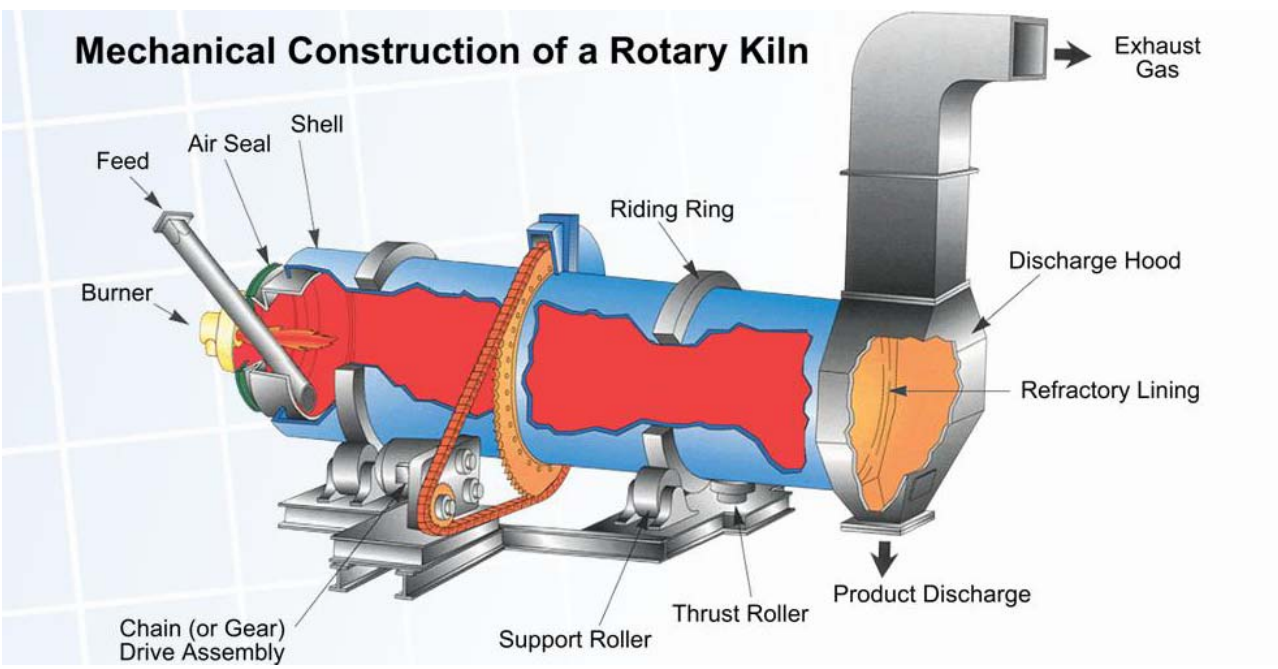
Detailed Description:

With an indirect fired rotary kiln heating occurs in a furnace surrounding the outside of the kiln shell. This way the material does not come in contact with the heating media. Similarly the kiln can be cooled in a later section with cooling water applied to the shell. Using an indirect rotary kiln the exhaust gas can be kept separate.

Potential for Use with Solid CO_2 Sorbents:

A rotary kiln would allow for indirect heat transfer in a solid sorbent process and the exhaust would contain the liberated CO_2. Proper sealing of the feed mechanism would be critical. It is unclear if indirect firing could be converted to steam heated.

Flowsheet:



Technology Survey

Technology: Rotating Bed

Date of Technology Assessment : March 27, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☒ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name: No Vendor

Address:

City, State, Zip:

Country:

Contact Name:

Telephone:

Email:

Website:

Equipment Summary:

An air heater-like rotating device that would swing sorbent impregnated surfaces into the gas path then swings them into a regeneration system. This system is conceptual.

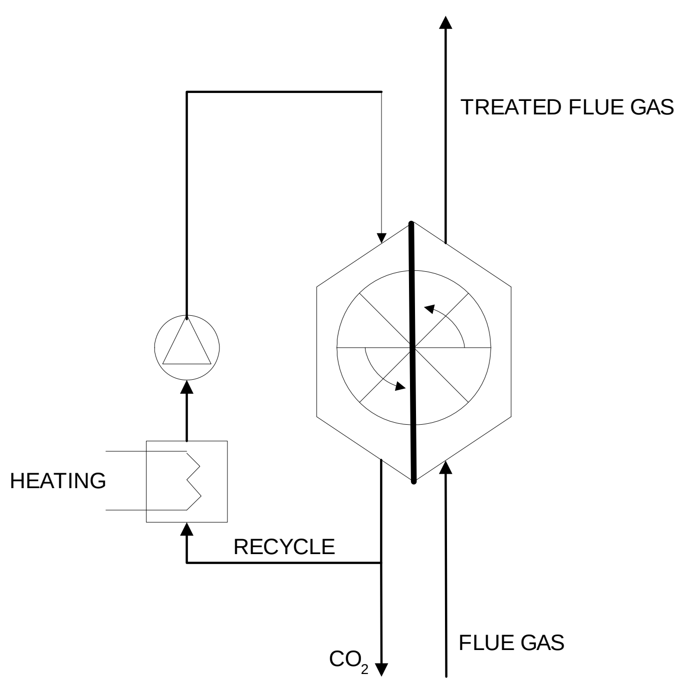
Detailed Description:

A rotating bed similar to a rotating air heater could have a sorbent impregnated surface composition. It could rotate into the flue gas path where it would absorb CO_2. It would then rotate over to the regenerator side where heat would be applied to liberate captured CO_2. Sectors of the rotating bed could be devoted to pre-heating and pre-cooling if required.

Potential for Use with Solid CO_2 Sorbents:

Direct application of the technology if the sorbent proves to be applicable to solid surface usage with reasonable reaction kinetics.

Flowsheet:



Technology Survey

Technology: Spray Dry Absorber (SDA)

Date of Technology Assessment : March 4, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☒ Entrained Flow Bed

Company Name:	Babcock & Wilcox	Contact Name:	
Address:	800 Main Street, 4th Floor	Telephone:	
City, State, Zip:	Lynchburg, VA, 24504	Email:	
Country:	U.S.A.	Website:	www.babcock.com

Equipment Summary:

A rotary atomizer is used to atomize a mixture of lime and recycle slurry into a fine spray. This spray reacts with the sulphur compounds and the water evaporates leaving an entrained solid in the flue gas. This solid is removed from the flue gas through some sort of particulate collector, typically a fabric filter. Variations of this technology are available from other vendors.

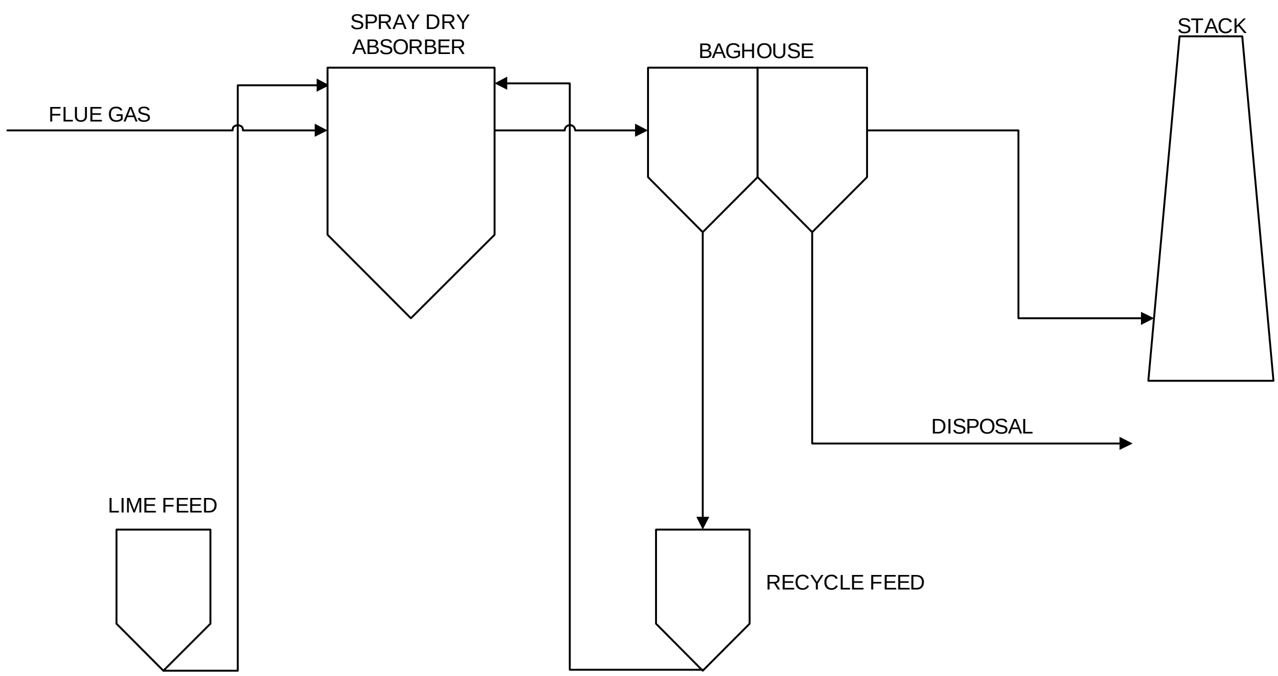
Detailed Description:

Hot untreated flue gas is brought into contact with the spray where a chemical reaction results in the removal of sulphur compounds and the evaporation of the water. The cooled and treated gas is directed to a fabric filter to remove solids, part of which can be used in a recycle slurry to reduce reagent consumption.

Potential for Use with Solid CO_2 Sorbents:

The rotary atomizer could be utilized depending if sorbent is to be injected as a slurry and the evaporation of the water could be used for cooling in the reaction.

Flowsheet:



Technology Survey

Technology: Semi-dry Flue Gas Purification

Date of Technology Assessment : March 5, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☒ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	vonRolliNova	Contact Name:	
Address:	Hardturmstrasse 127 Post office box 680	Telephone:	+41 44 277 11 11
City, State, Zip:	CH-8037 Zürich	Email:	info@aee-vonrollinova.ch
Country:	Switzerland	Website:	www.aee-vonrollinova.ch

Equipment Summary:

This system utilizes a circulating fluidized bed reactor with reagent recirculation to decrease reagent usage. The flue gas is then treated with a fabric filter which removes the solids, some of which are recirculated, the rest are disposed of. There are several variations of this technology offered by other vendors.

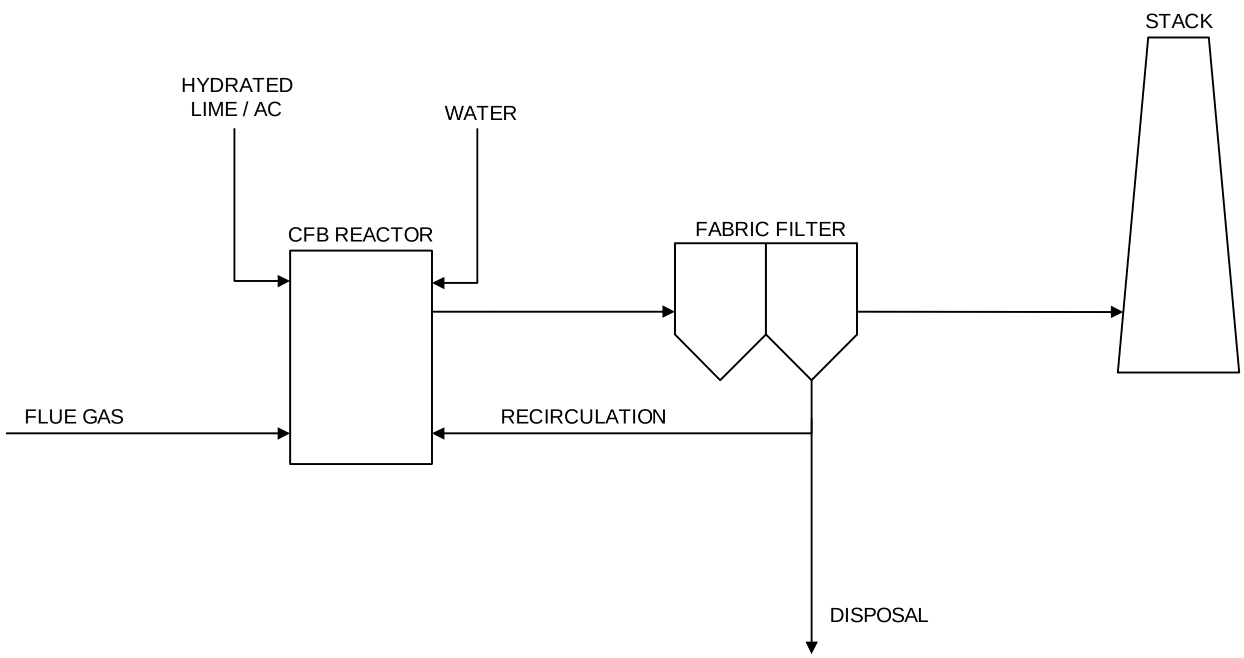
Detailed Description:

The flue gas enters the reactor from below and is conditioned with water. Both hydrated lime and activated carbon are fed into the flue gas. The hydrated lime chemically reacts with the contaminants to form salts. The activated carbon ensures effective separation of heavy metals and dioxin. The recirculation system maximizes the efficient use of the reagents.

Potential for Use with Solid CO_2 Sorbents:

A solid sorbent could be injected in the same way as the lime or activated carbon is, and also be removed by a fabric filter. The recirculation of the reagent could ensure the full working capacity of the sorbent is utilized.

Flowsheet:



Technology Survey

Technology: Solex Heat Exchanger

Date of Technology Assessment : March 27, 2009

☐ Adsorption ➔ ☐ Conveying ➔ ☒ Heat Transfer ➔ ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Solex Thermal Science Inc.	Contact Name:	
Address:	100, 3595 114 Ave SE	Telephone:	(403) 254-3500
City, State, Zip:	Calgary, AB, T2Z 3X2	Email:	info@solexthermal.com
Country:	Canada	Website:	www.solexthermal.com

Equipment Summary:

The Solex heat exchanger is designed for use with bulk solids. One of the main design features is the inlet hopper and discharge feeder which control the mass flow to achieve proper residence time. The exchanger plates allow for indirect heating, allowing for a wide variety of heating media and isolation from the solid.

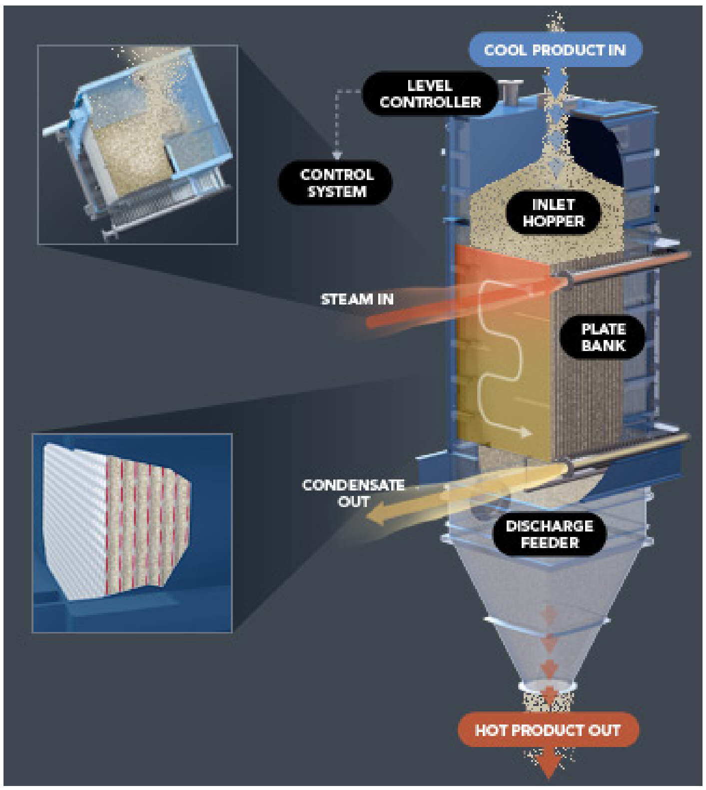
Detailed Description:

The slow and controlled movement of the material through the heat exchanger produces a product with less abrasion and degradation so there is minimal change in particle size and shape. Indirect heating through exchanger plates eliminates the use of air as a heating/cooling medium and creates accessibility for maintenance.

Potential for Use with Solid CO_2 Sorbents:

This heat exchanger is designed for bulk solids and could be easily applied to a dry sorbent application.

Flowsheet:



Technology Survey

Technology: Static Bed Temperature Swing Absorption

Date of Technology Assessment : March 27, 2009

☒ Adsorption → ☐ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☒ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name: Contact Name:

Address: Telephone:

City, State, Zip: Email:

Country: Website:

Equipment Summary:

This process is typical of such systems like molecular sieve dryers. An active bed of sorbent is exposed to flue gas then regenerated at high temperatures to release the absorbed CO_2.

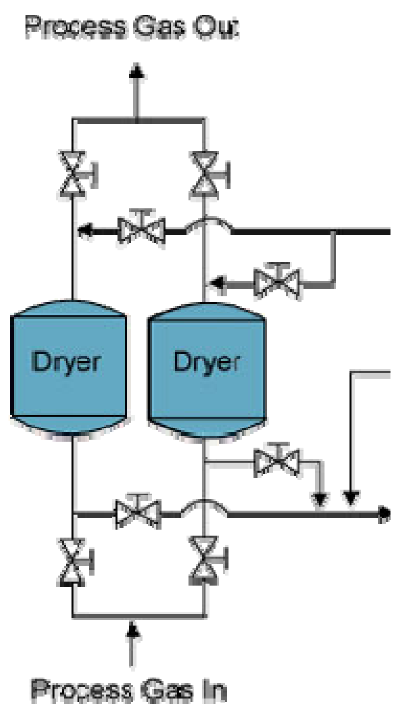
Detailed Description:

Flue gas is introduced to an active bed of sorbent where CO_2 is absorbed. When the bed is saturated, flue gas feed is ceased and a heated sweep gas, possibly CO_2 is used to desorb the sorbent. While regeneration is occurring flue gas is routed to one or more previously regenerated beds. The typical process continues with beds in various states of activity or regeneration.

Potential for Use with Solid CO_2 Sorbents:

Temperature swing absorption is a typical method of gas/solid contact absorption processes.

Flowsheet:



Technology Survey

Technology: Heat Pipe Heat Exchanger

Date of Technology Assessment : March 27, 2009

☐ Adsorption → ☐ Conveying → ☒ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Bry-Air	Contact Name:	
Address:	10793 St. Rt. 37W	Telephone:	(740) 965-2974
City, State, Zip:	Sunbury, Ohio 43074	Email:	info@bry-air.com
Country:	U.S.A.	Website:	www.bry-air.com

Equipment Summary:

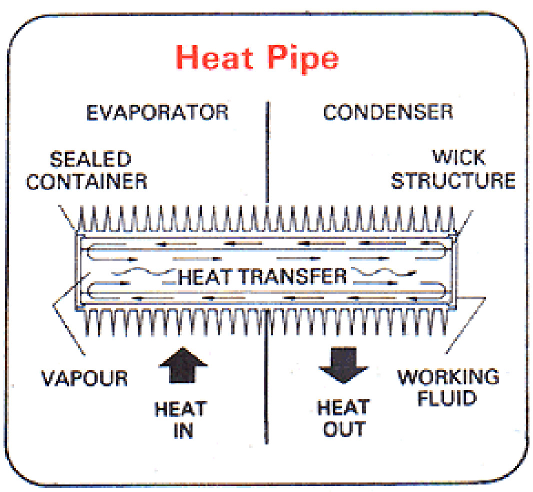
Bry-Air heat pipe is a self-contained passive energy recovery device. A heat pipe can transfer up to 1000 times more thermal energy, than copper, the best known conductor; that too with less than -17°C per foot temperature drop. Heat pipes have no moving parts and hence require minimum maintenance. They are completely silent and reversible in operation and require no external energy other than the thermal energy they transfer. Heat pipes are versatile and robust.

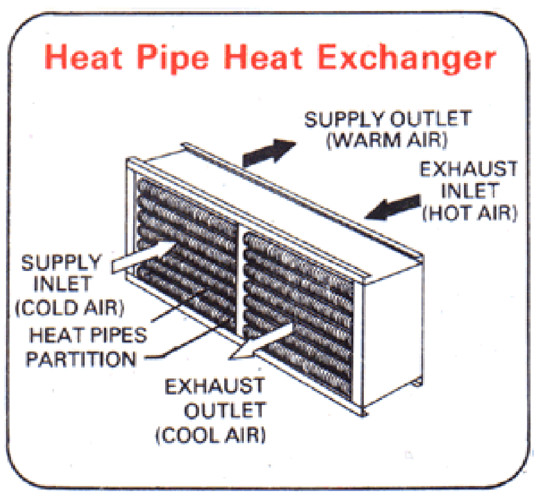
Detailed Description:

Bry-Air heat pipe heat exchanger contains a number of heat pipes. These heat pipes are placed horizontally across the width of the exchanger and pass through a center seal partition to avoid cross contamination. The exchanger is installed across two side-by-side air ducts. The exhaust air and the supply air are discharged in counter flow direction across the exchanger through the ducts to facilitate the maximum energy transfer. The heat pipes pick up the thermal energy from the exhaust (evaporator region) and transfer it to supply air (condenser region).

Potential for Use with Solid CO_2 Sorbents:

Flowsheet:





Technology Survey

Technology: Turbo-Dryer

Date of Technology Assessment : March 27, 2009

☐ Adsorption → ☐ Conveying → ☒ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☐ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Wyssmont Inc.	Contact Name:	
Address:	1470 Bergen Blvd.	Telephone:	(201) 947-4600
City, State, Zip:	Fort Lee, NJ 07024	Email:	sales@wyssmont.com
Country:	U.S.A.	Website:	www.wyssmont.com

Equipment Summary:

The Turbo-Dryer consists of a stack of slowly rotating circular trays. Material is fed onto the top tray. After one revolution the material is wiped onto the next lower tray where it is mixed, leveled and then after one revolution is wiped to the next tray and the operation is repeated. The trays are contained in an enclosure in which heated air or gas is circulated by internal fans.

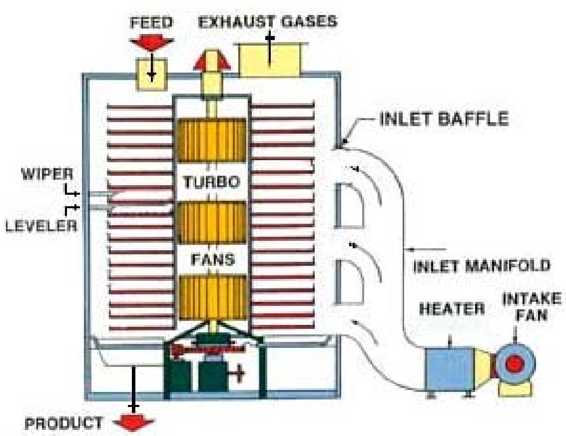
Detailed Description:

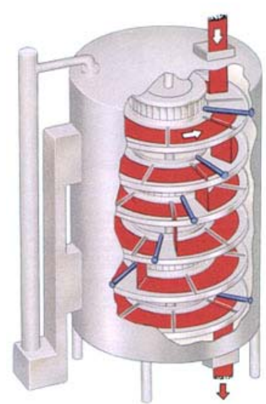
The Turbo-Dryer provides gentle handling of the material, reducing dust and product degradation. This dryer can handle temperatures up to 1200°F which can be precisely controlled along with residence time. Also a variety of heating mediums can be used such as steam, waste gas, electricity, etc.

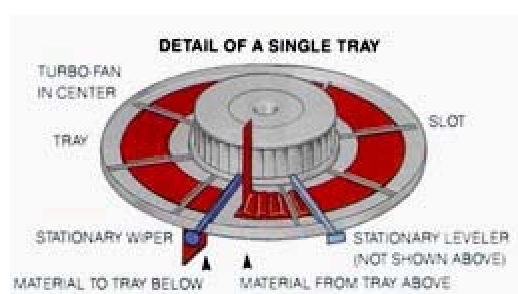
Potential for Use with Solid CO_2 Sorbents:

This product would provide the heat exchange portion of a CO_2 sorbent process.

Flowsheet:







Technology Survey

Technology: TURBOSORP®

Date of Technology Assessment : January 13, 2009

☒ Adsorption → ☒ Conveying → ☐ Heat Transfer → ☐ Desorption

☐ Rotating Bed ☐ Fixed Bed ☐ Moving Bed ☒ Fluid Bed ☐ Fixed Particle Bed ☐ Entrained Flow Bed

Company Name:	Babcock Environmental Inc.	Contact Name:	
Address:		Telephone:	
City, State, Zip:	Danvers, MA	Email:	info@babcockpower.com
Country:	U.S.A.	Website:	www.babcockpower.com

Equipment Summary:

Flue gas flows through a cylindrical apparatus (fluidized bed reactor) from the bottom (a Venturi nozzle) to the top. Active material is injected into the reactor and the solid reacted particles are carried by the flue gas to either an electrostatic precipitator or a fabric filter which removes them. The recirculation of the separated material is conveyed pneumatically or with a screw conveyor. There are several variations of this technology offered by other vendors.

Detailed Description:

This FGD technology uses fresh and active material, $Ca(OH)_2$ or CaO, injected into the reactor while solids that have already undergone several cycles are recirculated into the reactor. In order to lower the flue gas temperature for achieving increased desulphurization capacity, water is injected. The wetting of the recirculated sorbents also makes new and reactive surfaces available as some layers that are already formed become detached by this wetting. Activation of the material also occur do to the turbulent flow in the fluidized bed reactor.

Potential for Use with Solid CO_2 Sorbents:

CO_2 sorbent could be substituted for lime. Flue gas could convey the sorbent to a dust filter where it would be removed for further processing. Recirculation of solids could ensure the full working capacity of the sorbent is utilized.

Flowsheet: