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Lower energy penalty CO2 capture system

CEFCO (Clean Energy and Fuel Company) has developed a process with a total energy penalty of less than 15% for capture of CO2 and other pollutants including NOX and SO2 from coal fired boilers. It also has a lower capital cost and a smaller footprint than some other comparable technologies.

By Robert E. Tang, President, CEFCO Global Clean Energy and Dr. Anupam Sanyal, President, International Environmental & Energy Consultants

Look out for part two of this article featuring recent results from the CEFCO process pilot plant in the next issue

Coal-fired power plants are the largest contributor to U.S. greenhouse gas ("GHG") emissions, and coal combustion accounts for 40% of global man-made carbon dioxide ("CO2") emissions.

U.S. DOE and EPA plan to overcome the barriers to the deployment of Carbon Capture and Sequestration ("CCS") within ten years with a goal of bringing five to ten commercial demonstration projects online by 2016.

Capture of CO2 from industrial gas streams has occurred since the 1930s. The history of transporting CO2 via pipelines in the United States spans nearly 40 years. Approximately 50 million tonnes of CO2 are transported each year in the United States through 3,600 miles of existing CO2 pipelines.

Though CCS technologies exist historically, "scaling up" these existing processes and integrating them with coal-based power generation poses technical, economic, and regulatory challenges. Of the 74 large-scale integrated CCS projects around the world, 14 projects are either coming into operation recently or under construction. In the electricity sector, estimates of the incremental costs of new coal-fired plants with CCS relative to new conventional coal-fired plants typically range from $60 to $95 per tonne of CO2 avoided. Approximately 50–90% of that substantial energy cost is associated with capture and compression of CO2.

The major cost for CCS alone is the energy penalty or "parasitic load" ranging from 20% to over 30% in applying the technologies. The current major emphasis is in pre-, post- and oxyfuel combustion capture applied to power stations (and other industrial applications). There are several research activities into reducing this cost. For example, U.S. DOE, through its National Energy Technology Laboratories ("NETL"), is promoting multiple projects to minimise energy penalty.

However in contrast to the uneconomic prospects, an EPA-recognised Hazardous Waste Combustion Maximum Achievable Control Technology (HWC MACT) is available and ready at demonstration stage which is designed for CO2 Capture and Multi-Pollutant Capture ("MPC") — all at under 15% total energy penalty together with the co-production of multiple saleable end-products, thus making this technology a "Profit Center" process.

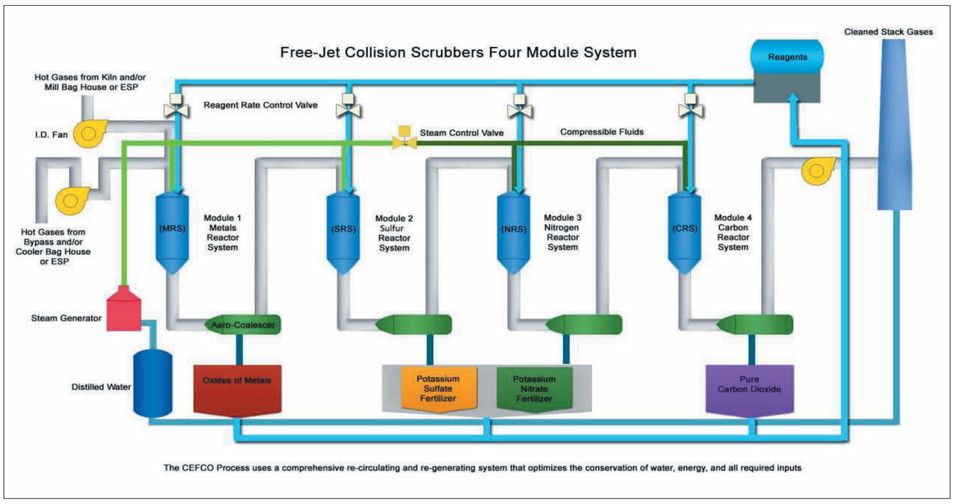

Figure 1 - flow diagram of the modularized CEFCO Process

It is designed to remove 90% of the CO2 as well as 99+% of SO2, NOX and particulates (including metallic solids) from coal and oil fired boilers, cement kilns and petro-chemical plants, and has both a significantly lower capital cost and O&M cost, in addition to having a smaller footprint than those employing conventional technologies. It is suitable for "greenfield" and "retrofitting/upgrading" application.

CEFCO Process Introducing a New Technology

The CEFCO (Clean Energy and Fuel Company) Process is a major improvement in Air Quality Control System ("AQCS") efficiency and CO2 capture levels compared to the currently available conventional technologies. It uses and embodies the slogan: "Physics first, Then Chemistry".

The traditional processes currently on the market use conventional thermo-chemistry based reactions for capturing CO2 and acid rain gases. They require substantial addition of expensive heat, pressure and catalyst that are referred as their "energy penalty".

On the other hand, the CEFCO Process is based on using shockwaves generated by "spent" or "post-power-production" steam in aerodynamic reactors as a low-cost substitute, thereby not only minimising energy penalty but also ultimately producing valuable end-products, making the CEFCO Process a "Profit Center" instead of a "Cost Center".

This article aims at citing the history of the technology, its acceptance by U.S. EPA, DOE and DOD as the Maximum Achievable Control Technology ("MACT"), its case histories and finally its recent extension to coal/oil fired boilers, cement and petro-chemical industries.

The Process Essentials

The CEFCO Process consists of two components: The capture of the pollutants and their conversion into saleable end-products.

The first component of the CEFCO Technology was invented by Thomas K. Ewan (a co-inventor of the CEFCO Process) and his team of aerophysicists. It applies a sequence of reactors and aero-coalescers, designed on aerodynamic principles that strips emissions of all metals, fine particulates, SOX, NOX and CO2 and captures them using a remarkable capture mechanism. Ewan's shockwave "free-jet collision scrubbing" has been duly tested, recognized and put into use at various U.S. Nuclear Waste Incineration facilities by the U.S. DOE and its Nuclear Regulatory Commission for years. The technology was adopted by the U.S. EPA as a component of its Haz-

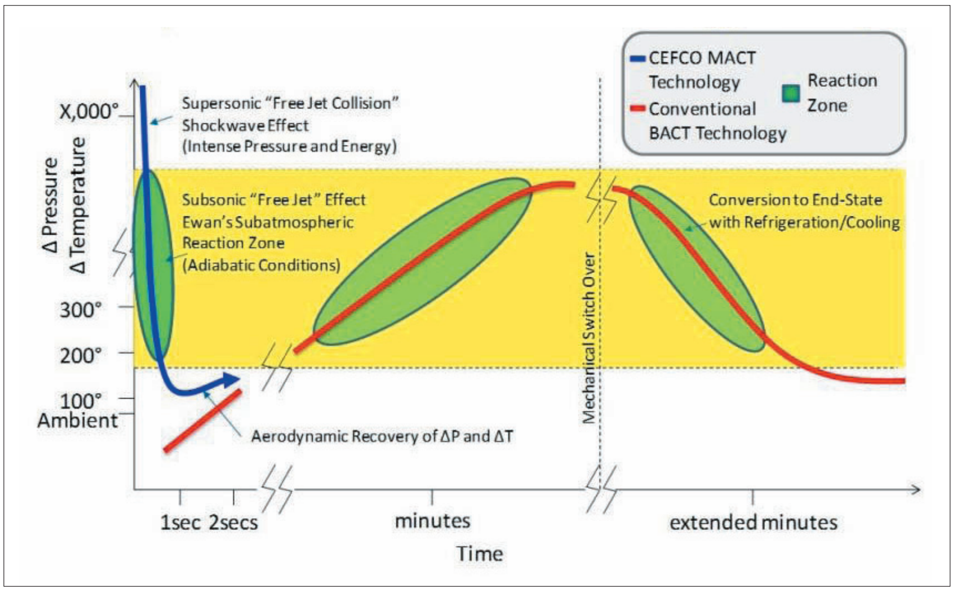

Figure 2 - comparison of parasitic load or energy penalty

ardous Waste Combustors ("HWC") MACT, which was codified and published by the EPA on May 22, 2002[1].

The operating principle of the capture mechanism is best described by the U.S. EPA as stated in its review, analysis and selection of the "Free-Jet" Technology in Section 3.4.2.2 of the "Technical Support Document for HWC MACT Standards", Vol. I: Description of Source Categories" (dated February 1996), as follows:

". . . When a gas stream is saturated with water and then cooled, a portion of the moisture will condense, and the fine particles in the gas stream serve as condensation nuclei. As moisture condenses on the particles, they grow in mass and are more easily collected by conventional impaction. Therefore, the condensation enhances the scrubbing system's collection of fine particles, acid gases and metals.. . . . "(emphasis added)

The second component of the CEFCO Process is a series of chemical processes invented and patented by Hal B.H. Cooper (a co-inventor of the CEFCO Process) which use chemical reagents for the selective conversion of each targeted compound in succession, resulting in captured and converted forms of recovered metals, potassium sulfate and potassium nitrate fertilizers, and pure CO_2 from a bicarbonate solution.

CEFCO Process Patent

CEFCO Global Clean Energy ("CEFCO") was formed for the purpose of providing air emissions capture technology and capabilities for all fossil fuels, especially targeting the high pollutant coal-fired power industry, the cement industry and the petro-chemical industry. CEFCO applied for a patent titled: "Process and apparatus for carbon capture and elimination of multi-pollutants in the flue gas from hydrocarbon fuel sources and recovery of multiple by-products" in 2008. On 30 November 2010 the U.S. Patent and Trademark Office issued a patent certificate covering the CEFCO Process to the company (U.S. 7842264B2).

Process Details

Under the CEFCO Process, the targets for capture are trace metals (including Mercury), fine particulates (including sizes as low as 2.5 microns), SOX, NOX and CO_2. The CEFCO Process is a comprehensive CO_2 Capture and MPC control technology that is designed to meet or exceed compliance with the ensuing MACT, NESHAPs[2] and CSAPR ("Cross-State Transport Rule")[3]. When future GHG6 or Carbon Rules are established in the U.S. by the EPA, the CEFCO Process will also offer compliance for carbon control.

The Process comprises multiple aerodynamically-shaped reactors and aerodynamic coalescers (gas/liquid separators) in series for sequential pollutant separation and removal. Each reactor system is designed to remove one of the targeted groups of pollutants, and the steps are repeated in sequence for the remaining pollutants. CEFCO believes that its Process will remove virtually all (99+%) of the pollutants and at least 90% of the CO_2.

The invention is based on highly efficient "molecular surface chemistry" that is achieved with proprietary aerodynamic reactor technology. The flue gas being treated is kept moving, with short residence time in each reactor system. A key concept of the CEFCO Process is that, by using the technology and injecting steam or air through aerodynamic nozzles exiting at Mach speeds (referred to in the EPA and the Department of Energy literature as well as in the MACT Standards as "hydro-sonic", or "free-jet collision", or "collision scrubber", or "supersonic collision"), supersonic shockwaves are generated resulting in the formation of a sub-atmospheric and adiabatic reaction zone in each reactor module.

Under this condition, each targeted group of the pollutants of the flue gas intimately collides with and mixes with very fine, fast moving liquid droplets of the appropriate absorbing or adsorbing reagent(s). The pollutants are captured and encapsulated by the liquid droplets (and reacted with the reagent).

The droplets then are "grown" to a physical size sufficiently large to permit separation by a flow separating aero-coalescer. (The capture and mass transfer mechanisms are detailed in the published patent). Consequently, the sub-atmospheric and adiabatic reaction zone enables the occurrence of endothermic-then-exothermic chemical reactions that capture the pollutant and then form the desired end-product almost instantaneously[4]. The CEFCO Process is thus based on the reactions being completed extremely rapidly in contrast to the traditional bulk chemistry reactions in other conventional processes, which rely on much longer residence time for proper contact with absorbents, catalysts and adsorbents, as dictated by Newtonian thermodynamics.

CEFCO describes this mechanism as "molecular surface chemistry" because the fine droplets have a large "ratio of surface area to mass" which makes it possible for the rapid chemical reactions to take place. There is no addition of a chemical or complex catalyst which serves to simplify the chemistry as well as to significantly reduce overall capital and operating costs. The shockwave performs all the requisite functions for energy, pressure and catalyst.

Overview of the CEFCO Process Equipment System

The complete CEFCO Process comprises a series of four reactor modules, for the sequential capture of all four groups of air emissions: the Trace Metals and Particulates are captured in the Metals Reactor System ("MRS"), the SOX are captured in the Sulfur Reactor System ("SRS"), the NOX are captured in the Nitrogen Reactor System ("NRS"), and the CO_2 is captured in the Carbon Reactor System

1. Ewan's Technology was recognized and codified in US Federal Legislation under 40 CFR §63.109 et al. on May 22, 2002.

2. NESHAPs is the acronym for New Emissions Standards for Hazardous Air Pollutants as promulgated by the U.S. EPA.

3. CSAPR is the acronym for Cross-State Air Pollution Rule promulgated by the U.S. EPA that severely limits air pollutants from being transported across state-borders to adversely affect the health and well-being of the victims in states downwind from the polluter.

4. Readers are welcome to contact the authors to discuss the application of Hess's Law and its effect.

("CRS").

Each of the systems includes subsequent processing of the captured pollutants into marketable end-products. Since the CEFCO Process is designed to be installed in modules, the users among the diversified groups of power producers (who may already have various conventional technologies, such as FGD, SCR, or baghouses installed with Activated Carbon Injection for significant Mercury removal) may want to retain their sunken investments, but to install some of the modules of the CEFCO Process in conjunction with or to augment their other recently installed processes, in order to meet compliance of the new regulations. The CEFCO technology is flexible and capable of accommodating such situations.

CEFCO Global Clean Energy designed the system for CO_2 Capture and MPC to work below 15%[5] total energy penalty or parasitic load. Moreover, the CEFCO Process uses post-power-generation "waste steam"[6] that is returning via the Return-Loop to be condensed for re-boil, etc. The shockwave is generated by channeling the low-quality or spent steam (through aerodynamically designed supersonic nozzles) that exits into a sub-atmospheric and adiabatic zone of the reactor at such energy and pressure that no other heat, pressure or catalyst are needed.

This will enable endothermic, then exothermic, reactions to capture the intended-target and make a product. Thus, the CEFCO Process creates the most economical energy and reactive condition where all reactions take place within seconds, so the equipment footprint and spatial volume are very small in comparison to other technologies. Furthermore, the source of heat applied to liberate the purified CO_2 from the bicarbonate-carbonate is a slipstream of the same spent steam (from the Return-Loop of the steam on its way to be condensed).

This heat as directed into the captured-product tank will cause the $KHCO_3$ contained inside to release the CO_2 to be sent to other uses[7]. By releasing the CO_2, the $KHCO_3$ is re-generated into K_2CO_3 and returned to be reused in the process, as shown in relevant equations later.

Figure 4 - CEFCO's 1 to 3 MW thermal equivalent pilot plant at Peerless Manufacturing Company's premises in Wichita Falls, Texas

The mass-transfer, capture mechanism and chemical reagents[8] injected applicable in each module of the CEFCO Process, and the co-production of Potassium Sulfate and Potassium Nitrate Fertilizer end-products have been described in great detail in the published patent. The CEFCO Process uses alkaline reagents[9] that are used for capturing the SOX, NOX, as well as the CO_2, and converting each of them into useful end-products. The use of K_2CO_3 and KOH combination injected into the shockwave reactor modules is the proposed complete replacement for all the current chilled amine, ammonia and designer-amines, and any other conventional technological methods, for CO_2 Capture at the exit of the system.

The CEFCO Process is able to maintain the selectivity of capturing each group of pollutants in sequential order for Metals and Fine Particulates in the MRS, and in series SOX in the SRS, NOX in the NRS and CO_2 in the CRS by manipulating the five parameters of the Process: residence time, velocity, temperature, pressure and pH in each reactor module. These parameters represent the intersection of physics and chemistry with the concept of reaction kinetics.

The CEFCO Process' final exit stack gas would be cleaned of metals, particulates, sulfur, NOX and carbon, leaving only pure O_2, N_2, Noble Gases, and water vapor. The next step is to harvest and separate such industrial gases. The final exit stack would only have to be normal industrial building-code height. No more tall stacks would be required in the future for power plants complex.

The following graphic will compare the time-and-energy saving features of using the aerodynamic principles in the CEFCO MACT Technology versus the time-and-energy consuming conventional thermodynamics used in the BACT technologies commonly available in the market place. The contrast is immediately apparent and the results are dramatically in favor of the CEFCO Process.

CEFCO's Pilot Plant

In the spring of 2011, CEFCO Global Clean Energy and Peerless Manufacturing Co. (the licensed manufacturer of the CEFCO Process equipment in the USA) have established a variable control size ranging from 1 to 3 MW thermal equivalent pilot plant at a Peerless factory in Wichita Falls, Texas. In the recent months, systematic parametric testing has been in progress and certain operational and performance steps are being developed at the request of several power producers and cement producers.

Energy Penalty Comparison of Post Combustion Carbon Capture Processes

In general the post-combustion CO_2 Capture technologies using conventional chemistry are reported to be in more advanced stages of commercialization compared to the Pre and Oxy-combustion processes. CO_2 absorption

5. Fifteen Percent (15%) is the maximum total energy penalty and parasitic load targeted by the Department of Energy, NETL, and many power producers as a reasonably acceptable commercial cost for pollution control and regulatory compliance.

6. This is the saturated steam that departs and exits from the fourth or last turbine in typical legacy power-generation on its way to the condenser, and the CEFCO Process will divert a slipstream of it for use to generate the shockwaves in the CEFCO Process. CEFCO uses between 3% to 6% in weight of such low-quality "spent" steam relative to the total mass (weight of 100%) of the polluted flue gas to generate shockwaves for the attack in each of the reactor module. Therefore, the CEFCO Process should not be regarded as "parasitic" on the energy to run electric power generation as a commercial consideration. It is to be considered as "borrowed water" which could be returned to the plant later (to be described).

7. The CEFCO system is an energy-saving technology. Carbon Capture can be turned into an economic process for producing alternative fuels in conjunction with other alternative fuel-technologies, such as via combination with introducing water or hydrogen in the modern Syngas (CTL) or in the Methane (GTL) process, or with algae production using the Potassium Sulfate and Potassium Nitrate Fertilizers end-products for making bio-diesel, etc.

8. Using a Hydroxide Solution (such as KOH) and/or a Carbonate Solution (such as K_2CO_3) in different respective modules for capturing each group of the SOx, the NOx and CO_2 respectively and converting each group of them into useful and sellable end-products. By using such a combination of reagents, the CEFCO Process anticipated the capability of some CO_2 being captured in the SRS, as well as some more CO_2 being captured in the NRS, thus lessening the overall load for 90% plus Carbon Capture in the CRS.

9. The co-inventors of CEFCO have studied and worked with NaOH + Na_2CO_3, as well as with KOH + K_2CO_3, for the past 30 years, and have specified them in the published patent. The CEFCO preference is for the Potassium-based reagents because they can make much more valuable end-products and will react faster with the targeted pollutant than Sodium-based reagents.

in solvents such as amines is a technology (which has been in use in petro-chemical industries for almost 50 years) and offers a costly solution for capturing CO2. However, while it is a proven technology with predictable performance, it has the disadvantage of high energy consumption for solvent regeneration, equipment corrosion, high solvent losses due to fast evaporation and degradation by oxygen, and the slippage of the solvent into the captured CO2.

Conventional CO2 Capture technologies significantly affect the plant design, thermal efficiency and turbo-machinery of a coal-fired power plant. The plant design must account for the CO2 Capture system components from the exit of AQCS to the CO2 scrubber and low pressure ("LP") steam has to be brought from the turbine to the scrubber. The "Balance of Plant" equipment needs to be enhanced to meet the CO2 Capture system. The electrical system capacity may also be required to be upgraded for retrofits.

Moreover, a large quantity of steam is required to regenerate the solvent of an amine-based process. That steam requirement is estimated to be at 44 psi and 518°F and may range from 2.9 to 3.5 lbs to remove 2.2 lb of CO2 from the flue gas. This would represent more than 50% of LP steam turbine's flow for a 90% CO2 capture.

Consideration must be given for the turbine design to be able to change the configuration that allows the LP module to operate under zero-extraction conditions. There are four options available for extracting steam from the system: throttle LP, floating pressure LP, LP spool with clutched LP turbine, and backpressure turbine. The power losses for these steam extraction systems range from 7.0% for backpressure turbine to 12.3% for Throttle LP, the figures for floating pressure LP and LP spool with clutched LP turbine are 11.2% and 10.5%, respectively.

Additionally, the capacity of the condenser and the cooling tower must be able to accommodate the extra steam required when the capture system is not in operation. The overall impact of adopting a conventional amine CO2 Capture system needs a detailed review of its complication.

Table 1 provides an example of the negative impacts of an Amine-based CO2 Capture system on the overall performance of an 800 MW (net) power plant.

The above figures are of course dependent on a specific design and the type of technology used. As each steam turbine vendor uses a different cycle design with dissimilar IP module exhaust pressures, the output power of the non-condensing turbine varies accordingly.

PARAMETER	WITHOUT CCS	WITH CCS	PERFORMANCE PENALTY (%)
Plant Gross Power (MW)	865	702	19.0
Plant Net Power (MW)	800	542	**32.3**
Steam Turbine Gross Power (MW)	865	662	23.5
Auxiliary Loads (MW)	65	160	145
Auxiliary Load (%) on net power sent out	7.5	22.7	
Non-condensing Turbine Output(MW)	NA	40	NA
Crossover steam extraction	0	62% of IP Exhaust flow	NA

Table 1 - impacts of an Amine-based CO2 Capture system on the overall performance of an 800 MW (net) power plant. (Table from POWER Magazine, June, 2008. Justin Zachary, "Options for Reducing a Coal-fired Plant's Carbon Footprint: Part 1".)

CEFCO Process Energy Penalty Analysis

Methodology

The preliminary design specifications, provided by CEFCO, for the 1 to 3 variable MWe pilot plant were the primary source of data used to calculate the total parasitic load for the CEFCO system, which can be divided into three main categories:

1. Injection Steam – the loss of usable steam from the power plant required by the CEFCO system
2. Electrical – all pumps and motors required to move reagent and other liquids through the CEFCO regenerating/recirculating system; including heat recovery and re-injection and miscellaneous lighting
3. Thermal – heat required for the decarbonation of CO2 and fertilizer-product drying

The sum of these loads results in an overall parasitic loss value for the CEFCO System.

Basis

1. Net output of the pilot plant to be 900 kW
2. 65% efficiency for turbine equivalency, pumps including motors
3. Steam taken from power cycle at an appropriate extraction point in the turbine
4. Steam requirement to be 4% of the flue gas mass flow for each stage of cleaning (conservative)
5. Thermal loads are satisfied via the utilization of waste heat from the pilot plant; i.e. thermal loads do not contribute to the parasitic load calculation.

Other minor assumptions were made based on the typical performance characteristics of industrial and auxiliary electrical and mechanical equipment and basic thermodynamic properties.

Based on the preliminary information available and general engineering calculations for all four MPC and Carbon Capture Modules, the CEFCO Process' original total system energy penalty calculation of ≤ 15.0% (which does not include CO2 transmission) is supported. The co-authors believe that CEFCO's estimated total system-wide energy penalty is advantageous relative to other experimental and conventional carbon capture technologies which typically range from 20% - over 30% for Carbon Capture alone, respectively.

Plant Output (Design: 1 MW gross)	Net 900 KW
66 psia Low-Quality Steam:	36 KW
Electrical Loads:	
• Pumps & Motors	25 KW
• Lights & Misc.	1 KW
• Heat Rejection & Recovery	5 KW
Parasitic Load — Total System:	**67 KW (7.45%)**
Aux Loads (outside of CEFCO Process):	
• CO_2 Compression[13] (conventional method)	62.7 KW (conventional)
• Material Handling	N/A
Parasitic Load (CEFCO + Aux) Total	**129.7 (14.41%)**
Thermal Loads**	
Decarbonator	178.9 KW
Product Drying	91.6 KW

Table 2 - Calculated Energy Penalty of the CEFCO Process:

More information

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