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CO_2 Capture and Development of an Advanced Pilot-Scale Cryogenic Separation and Compression Unit

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Abstract

At present, the use of fossil fuels in the current energy mix represents the largest source of carbon dioxide (CO_2) emissions, an important greenhouse gas (GHG), which is largely blamed for global warming. It is estimated that roughly 26 to 30 percent of all CO_2 emissions due to human activities come from fossil fuels used for generating electricity. Moreover, a variety of other industrial processes such as oil refineries, fertilizer and cement plants also emit large amounts of CO_2. The opportunity therefore exists for a significant reduction of CO_2 from industrial processes and power plants through CO_2 Capture and Storage (CCS). Currently, there are three main pathways to capturing CO_2 from fossil fuel energy conversion processes, namely, pre-combustion capture, post-combustion capture, and oxy-fuel combustion with CO_2 capture. Among these approaches, pre-combustion and oxy-fuel combustion take advantage of the fact that CO_2 capture is further facilitated by increasing the concentration of CO_2 in the flue gas stream, or by increasing the flue gas pressure, or both.

There are several different processes available for CO_2 capture and compression from low-pressure flue gas streams rich in CO_2. These processes vary from simple straight or once through low-temperature separation and compression to more complex processes involving some form of recycle and/or auto-refrigeration. Given the economic constraints often placed on the cost of CO_2 capture, and based on energy demand of each process, the ultimate success of these processes hinges on further refining the existing ones or developing new processes that can lower the cost of CO_2 capture. The CANMET Energy Technology Centre in Ottawa is currently pursuing a leading research and development program in the field of near-zero emission fossil fuel technologies. This program includes the development of next generation oxy-fuel combustion technologies, as well as the design and development of efficient CO_2 capture and compression processes to recover CO_2 from oxy-fuel and other fossil fuel energy conversion systems. In this paper, we present and discuss the technical challenges, development stages and commissioning of the CANMET's pilot-scale CO_2 capture and compression unit (CO_2CCU). This pilot-scale CO_2 separation and compression unit provides an excellent test platform to study the impact of flue gas impurities on the CO_2 capture process. This advanced gas separation system is first-of-a-kind pilot-scale unit that represents an integrated approach to oxy-fuel combustion of coal and other fossil fuels with CO_2 capture for storage.

Keywords: **Greenhouse Gas Emission, CO_2 Capture, Low-temperature Gas Separation, CO_2CCU.**

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1. Introduction

Fundamentally, there are number of ways to reduce the level of CO_2 emissions from fossil fuel usage: 1) increasing the "fuel to end-use" energy conversion efficiency; 2) replacing high-carbon fuels with lower-carbon fuels; and, 3) capturing and storing, in suitable geological formations, the CO_2 emitted from fossil fuel energy conversion systems. While the first two are effective options, they alone cannot fully mitigate the global increase in CO_2 emissions. The third option de-couples the use of fossil fuels from CO_2 emissions, thus allowing for the continued use of fossil fuel in a sustainable way. Hence, there are immense opportunities exist for a significant reduction in greenhouse gas (GHG) emissions from industrial processes and power plants through the capture and storage of CO_2[1, 2].

Currently, there are three main approaches to capturing CO_2 from the fossil fuel energy conversion systems, namely, pre-combustion capture, post-combustion capture, and oxy-fuel combustion with CO_2 capture. Among these approaches, pre-combustion and oxy-fuel combustion take advantage of the fact that CO_2 capture is facilitated by increasing the concentration of CO_2 in the flue gas stream, or by increasing the flue gas pressure, or both[3, 4, 5, 6]. Pre-combustion processes through gasification remove pollutants and CO_2 from fossil fuels prior to their conversion into electric power, or hydrogen and chemicals[7, 8]. Oxy-fuel combustion, on the other hand, has a unique advantage over other approaches to CO_2 capture, in that it generates a flue gas stream that is mostly composed of CO_2 and H_2O. Hence, CO_2 capture from this flue gas stream is relatively straightforward, involving no solvents and requiring only compression and cooling[5]. Large industrial-scale oxy-fuel combustion has been used in glass, aluminum and steel furnaces for high temperature heating and glass or scrap metals melting. However, oxy-fuel combustion for power generation is an emerging technology and, to date, no commercial unit has been built; however, several large-scale pilot demonstrations for power generation are either planned or underway[9, 10].

There are several different processes cited in the literature for CO_2 capture and compression from flue gas streams that are rich in CO_2[11, 12, 13]. These processes vary from simple straight or once through compression to more complex processes involving some form of recycle and/or auto-refrigeration. Given the economic constraints often placed on carbon capture technologies and based on energy demand of each process, the ultimate success of these CO_2 compression processes hinges on further refining already available processes or on the development of new processes. In this paper, we present and discuss the development stages and commissioning results of the CANMET's pilot-scale CO_2 capture and compression unit (CO_2CCU). This pilot-scale CO_2 separation and compression unit provides an excellent test platform to study the impact of flue gas impurities on the CO_2 capture process. This advanced system is first-of-a-kind pilot-scale unit that represents an integrated approach to oxy-fuel combustion of coal and other fossil fuels with CO_2 capture for storage.

2. Design Considerations

Due to the fact that high gas temperature are intrinsically associated with gas compression and also based on materials safe operating limits, the compression of inlet gas generally occurs in a number of stages. Three or more compression stages are usually required to achieve near optimal separation pressures. Strict control of the water content in the CO_2 product stream is also essential to avoid ice formation and corrosion for safe and efficient operation of the compressors and heat exchangers. A dehydration unit is often installed, especially if a low-temperature, or commonly referred to as "cryogenic", separation process is employed. For smaller scale operation, the dehydration unit may be eliminated if the temperature of the gas stream at the intercooler stages can be controlled to cause the water to drop out. This technique is widely practiced in acid gas compression in Western Canada. When dehydration is included, the metallurgy of the piping and pressure vessels can be relaxed from a corrosion point of view. However, whether to switch back and forth between carbon steel and stainless steel, or whether to make all piping around the compressor out of stainless steel depends on the cost consideration. If the cost difference is small, it may be more practical to use stainless steel in all the piping, coolers, and suction scrubbers or vapor knock-down vessels. In addition, some petroleum based and synthetic lubricants can be harden and become ineffective in the presence of CO_2; therefore, specific sealing materials and gaskets are typically required for the CO_2 compressors and pipe fittings. Also, impurities in the feed gas stream, such as SO_2, NOx, and O_2 might have an impact on the materials and physical state of the rich CO_2 stream and operation of the compressors, pipelines and storage tanks or vessels. However, the impact of impurities in the flue gas streams from different fossil fuel energy conversion processes on the CO_2 compression unit is a topic of the current research.

3. Process Modeling and Analysis

The CO_2CCU process was modeled and simulated using Aspen HYSYS process and plant modeling software. For the pilot-scale unit, two different feed gases with significantly different concentrations of CO_2 were used to model and evaluate the performance of these processes. The compositions of these feed gas streams, henceforth referred to as "Feedgas-1" and "Feedgas-2", are given in Table 1. "Feedgas-1" is representative of an exhaust gas from an advanced supercritical oxy-coal fired boiler[5]. The CO_2 concentration of "Feedgas-1" (i.e., 75.6% on dry basis) is considerably higher than "Feedgas-2" (i.e., 51.6% on dry basis). "Feedgas-2" represents the flue gas from the same oxy-coal plant but, one where a lower purity of O_2 and some allowance for air leakage is used in the modeling of the oxy-coal combustion process. This is done in order to evaluate the performance of the CO_2CCU for a wide spectrum of possible feed gas compositions [15].

	Feedgas-1		**Feedgas-2**	
Flow (kg/hr)	120		120	
Temp (deg C)	25-45		25-45	
Press (bar)	1		1	
Composition	**[% vol]**	**[% vol]**	**[% vol]**	**[% vol]**
	Wet basis	Dry basis	Wet basis	Dry basis
CO_2	74.34	75.68	50	51.68
O_2	6.14	6.25	2.42	2.50
Argon	2.41	2.45	2.03	2.10
N_2	14.98	15.25	42.02	43.43
H_2O	1.77	0.00	3.25	0.00
SO_2	0.32	0.33	0.23	0.24
NO	0.042	0.04	0.05	0.05

Table 1: Compositions of "Feedgas-1" and "Feedgas-2"

4. Model Development for CO_2CCU

The detailed model development for the CO_2CCU process was carried out by using the Aspen HYSYS process simulation software. The main steps for the CO_2 capture and compression process include moisture separation, compression stages with separators and intercoolers, dryers and heat exchangers. The flow diagram for "CO_2CCU" is shown in Figure 1. The details of the CANMET's proposed CO_2 capture and compression process can be found elsewhere[11, 14]. In this process, the inlet feed gas stream is compressed, dried and then sent to Separator-1. The gas outlet from Separator-1 is split into two streams. One branch connects to Separator-2 via an exchanger, while the other branch goes to an Expander, and then passes through Separator-3 and an exchanger on its way to the 3rd stage of the compressor as a recycled stream. After the start up, as the process progresses further, the split ratio is adjusted to maintain near optimal process conditions. The proposed process does not require any external refrigeration. The expander also produces additional power that can reduce the energy demand due to CO_2 compression and thus enhances the overall energy balance of the process. The pressure of the liquid stream from Separator-3 is raised using a pump to match the pressure of the stream from Separator-1, before merging the two liquid streams.

In order to have a higher purity product stream, a variant of the CO_2CCU was also proposed. In this case, a combination of a new compressor and a separator is added into the process and the separated gas from the latter separator is recycled back to the process. This recycle stream is connected to the main dry gas stream flowing to the Separator-1. More details about the latter process can be found elsewhere [14].

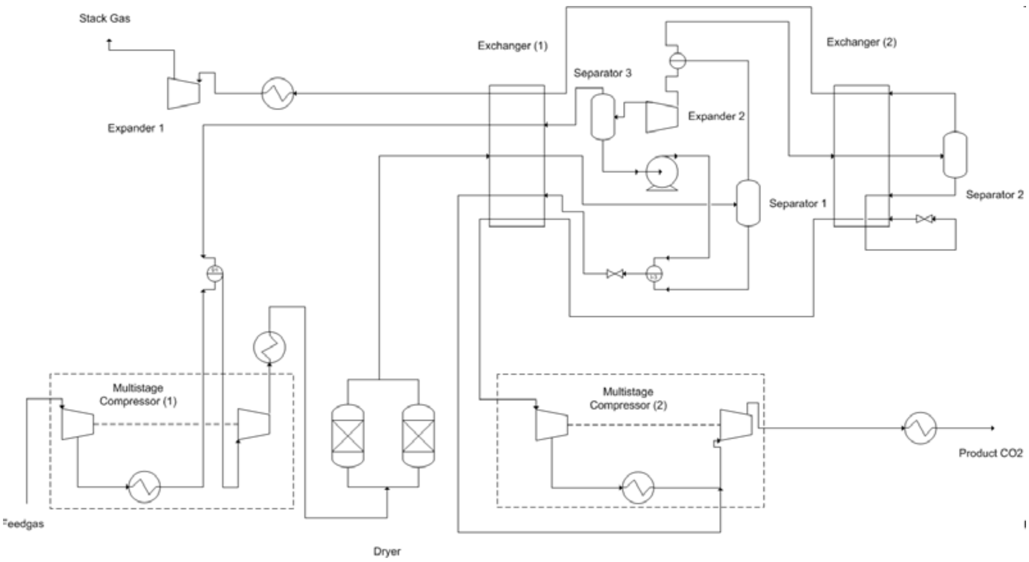

Figure 1: Flow sheet for the CO_2CCU

5. Pilot-Scale CO_2CCU Development

In order to verify the performance of the CANMET's proposed CO_2 capture and compression process, as shown in Figure 1, a proof-of-concept pilot-scale CO_2CCU was implemented. The work consisted of several major activities including system engineering, fabrication, installation, and commissioning. The CO_2CCU was designed for integration with the CANMET's 0.3 MW_{th} oxy-fuel combustion facility. Therefore, it was required for the unit to handle the flue gas stream from this facility with different concentrations of CO_2 and impurities (e.g., Ar, N_2, O_2, NOX, SO_2, H_2O), and to compress and dry the CO_2-rich feed gas stream to recover the maximum amount of CO_2, thus, rendering a high-purity CO_2 product stream. Some of the system requirements for the unit were defined as:

- The CO_2CCU must be housed in a container mounted on mobile trailer chassis in order to facilitate the transportation and relocation of the unit for filed demonstration using slip-stream feed gases from a large-scale commercial plant;
- The unit must be capable of operating both continuously and intermittently;
- A self-contained and independent control system, which can control all of the CO_2CCU functions, including provisions to control the unit from a remote location;
- Venting of the non-condensable gas stream to atmosphere is to be done in a manner that is consistent with standard compressed gas venting practices and at noise levels consistent with standard compressed gas venting practices; and,
- Sample points are required at selected process points.

The engineering design and fabrication of the unit took about one year. Figure 2 depicts the final product based on a trailer-mounted configuration. The fabrication of CO_2CCU was done through a public tender and the work was completed in summer 2008. Subsequently, the unit was integrated with the CANMET's oxy-fuel combustion facility in Ottawa. The overall system is currently undergoing commissioning with a range of input feed gas streams to assess and verify its performance and its underlying low-temperature CO_2 separation and compression process.

(a) (b)

Figure 2: The trailer-mounted CO_2CCU; (a) the drier unit; (b) the separator vessels

6. Commissioning of the Pilot-Scale Unit

The simulation results for the final product composition of the two sample feed gases and the overall mass balance of the process are given in Table 2. The purity of the product stream for both cases remains above 95%, while for “Feedgas-2” the CO_2 recovery rate drops relative to “Feedgas-1” due to the lower concentration of CO_2 in the feed gas stream. The first stage of commissioning is underway using synthetic flue gas stream to mimic closely the feed gas compositions, as given in Table 1. The advantage of this approach is the controlled environment under which the feed gases are introduced to the unit, which allows close comparison with the process simulation results. The initial results from commissioning of the unit with synthetic flue gases is encouraging and further testing has been planned to determine the range and accuracy of the CO_2CCU product and vent streams relative to the simulation results obtained from the process models.

Compositions of “Feedgas-1” outlet streams	**Product**	**Vent**	Compositions of “Feedgas-2” outlet streams	**Product**	**Vent**
Flow (kg/hr)	89.1	29.8	Flow (kg/hr)	51.4	66.6
Temp (deg C)	43	25	Temp (deg C)	43	25
Press (bar)	110	1	Press (bar)	110	1
Composition	**[% vol]**	**[% vol]**	Composition	**[% vol]**	**[% vol]**
CO_2	95.8	24.24	CO_2	95.51	29.17
O_2	1.13	19.35	O_2	0.26	3.65
Argon	0.6	7.19	Argon	0.32	3.01
N_2	2.01	49.11	N_2	3.2	64.1
H_2O	0	0	H_2O	0	0
SO_2	0.45	0	SO_2	0.69	0
NO	0.01	0.11	NO	0.01	0.06

Table 2: Compositions of “Feedgas-1” and “Feedgas-2” outlet streams

7. Conclusions

The CO_2CCU was implemented as the proof-of-concept for evaluating the performance of the CANMET's proposed process. The assessment will be done through comparison with simulation results, which cover the range between the two sample feed gas streams, representing the extreme operational conditions for a supercritical oxy-coal fired power plant. The commissioning of the unit and initial results with synthetic flue gases is encouraging; moreover, further testing has been planned to determine the range and overall performance of the pilot-scale unit. This pilot-scale CO_2 separation and compression unit, integrated with the CANMET's oxy-fuel combustion facility, provides an excellent test platform to study the oxy-fuel combustion and low-temperature CO_2 separation processes, as well as the impact of flue gas impurities on the CO_2 capture efficiency.

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