Enabling Production of Low-Carbon Emissions Steel Through CO_2 Capture from Blast Furnace Gases (BFGs)

primary project goal

Dastur International Inc. (Dastur) is designing and engineering a solution to maximize decarbonization of available blast furnace gas (BFG) at Cleveland-Cliffs' 5-million-tonne/year integrated steel plant in Burns Harbor, Indiana. The project aims to capture 2.8 million tonnes per annum (mtpa) of carbon dioxide (CO_2) emissions from the BFG by designing and integrating a BFG flow distribution system and an innovative BFG conditioning process, and by deploying a proven solvent-based carbon capture technology. The overall process will capture more than 75% of CO_2 emissions from the available BFG at the cost of capture of around $42 per tonne of CO_2.

technical goals

- Design and engineer a cost-competitive, techno-economically viable, industrial-scale carbon capture system for Cleveland-Cliffs' Burns Harbor steel plant.
- Design and engineer a water-gas shift (WGS) unit to maximize CO_2 capture from a single point source and increase the CO_2 concentration at the carbon capture unit.
- Optimize the WGS-based gas conditioning and reforming system to convert and extract hydrogen (H_2)-rich fuel and syngas from the BFG for use in existing combustion and conversion to pure H_2 in the future.
- Evaluate and validate the downstream combustion operations of converted H_2-rich fuel using computational fluid dynamics (CFD) and operating models.
- Evaluate the best possible strategy for sourcing the required steam and electricity and optimize the amount of sourced inputs for the lowest overall cost of capture, as well as the cost of CO_2 avoided ($/tonne CO_2).
- Conduct a series of environmental and safety studies related to the project, namely solvent and CO_2 disposal/disposition studies, a wastewater treatment study, a permitting study and review, a hazard and operability (HAZOP) review, a constructability review, and an environmental health and safety (EH&S) risk assessment.
- Develop a techno-economic assessment (TEA) to determine the CO_2 capture costs.

technical content

Dastur is undertaking the initial engineering design of a scalable carbon capture system for BFG at Burns Harbor, without impacting the competitiveness and techno-economics of the steelmaking process. The envisaged project will also extract low-carbon, H_2-rich fuels from the BFG for enhanced usage within the steel plant downstream operations. The goal is to engineer and design an industrial-scale CO_2 capture solution to capture 95% of the CO_2 in the BFG consisting of H_2,

program area:
Point Source Carbon Capture

ending scale:
Pre-FEED

application:
Post-Combustion Industrial PSC

key technology:
Solvents

project focus:
Steel Blast Furnace Gas Conditioning Process

participant:
Dastur International Inc.

project number:
FE0031937

predecessor projects:
N/A

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start date:
10.01.2020

percent complete:
40%

carbon monoxide (CO), and CO_2 before combustion, which equates to 75% of CO_2 emissions of the combusted BFG. This enables a competitive, environmentally friendly, and sustainable BFG-based process for producing low-carbon emissions steel.

The project proposes to capture 2.8 mtpa of CO_2 emissions from the available BFG at Burns Harbor by utilizing ION Clean Energy's solvent-based, state-of-the-art carbon capture technology, which has a proven carbon capture efficiency of more than 95%. To facilitate greater CO_2 capture, a compositional shift of the BFG is carried out using the WGS reactor. The initial engineering design system (Figure 1) uses a WGS compositional shift of the CO and water (H_2O) mixture in the BFG to raise the CO_2 concentration, resulting in better capture efficiency and maximizing the CO_2 at a single point source of carbon capture. The BFG is also enriched to an H_2-heavy fuel gas, with H_2 content of up to 36%.

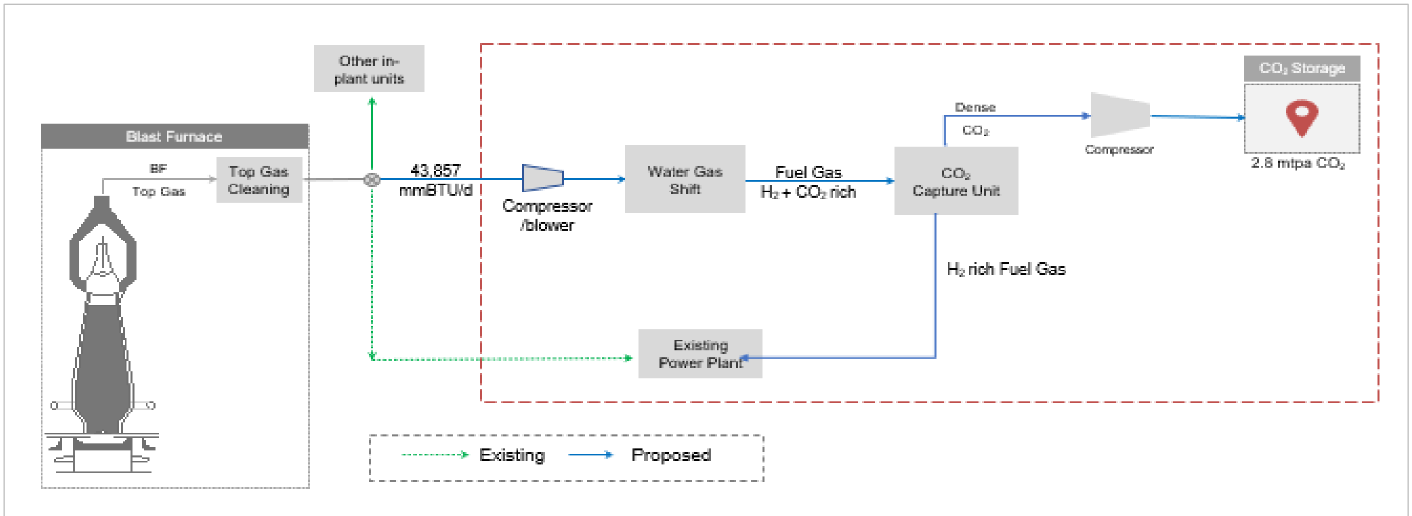

Figure 1: Flowchart of carbon capture system to be retrofitted to blast furnace.

Depending on the steam-to-dry-gas ratio required, external steam is added to perform the shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$). Thereafter, the shifted gas from the WGS reactor is passed through the carbon Capture unit (CCU), which has a similar configuration to typical post-combustion amine-based CO_2 capture systems. In the CCU, the gas enters the absorber and interfaces with the carbon capture solvent, which absorbs the CO_2, leaving an H_2-rich gas. The solvent is routed to a stripper column where it is heated, releasing the captured CO_2. The captured CO_2 is compressed to pipeline pressure for transportation to locations for storage and/or utilization. The process parameters of the solvent are shown in Table 1.

TABLE 1: SOLVENT PROCESS PARAMETERS

Pure Solvent	Units	Current R&D Value	Target R&D Value
Molecular Weight	mol^{-1}	80 – 150	100 – 150
Normal Boiling Point	°C	220 – 250	220 – 250
Normal Freezing Point	°C	< -15	< -20
Vapor Pressure @ 15°C	bar	<0.0001	<0.0001
Manufacturing Cost for Solvent	$/kg	-	-
Working Solution			
Concentration	kg/kg	0.65 – 0.80	0.65 – 0.80
Specific Gravity (15°C/15°C)	-	0.8 – 1.1	0.8 – 1.1
Specific Heat Capacity @ STP	kJ/kg-K	1.5 – 2.5	1.3 – 2.0
Viscosity @ STP	cP	<10	<10
Surface Tension @ STP	dyn/cm	<50	<50
Absorption			
Pressure	bar	1.0	1.0
Temperature	°C	40	40

Equilibrium CO_2 Loading	mol/mol	0.5 – 1.0	0.5 – 1.0
Heat of Absorption	kJ/mol CO_2	-1,600 to -1,750	-1,600 to -1,750
Solution Viscosity	cP	<20	<20
Desorption			
Pressure	bar	1.5 – 2.0	1.5 – 4.5
Temperature	°C	110 – 125	110 – 140
Equilibrium CO_2 Loading	mol/mol	0.05 – 0.20	0.05 – 0.20
Heat of Desorption	kJ/mol CO_2	<1,800	<1,800

Definitions:

STP – Standard temperature and pressure (15°C, 1 atmosphere [atm]).

Pure Solvent – Chemical agent(s), working alone or as a component of a working solution, responsible for enhanced CO_2 absorption (e.g., monoethanolamine [MEA] in an aqueous solution).

Manufacturing Cost for Solvent – "Current" is the market price of chemical, if applicable; "Target" is the estimated manufacturing cost for new solvents or the estimated cost of bulk manufacturing for existing solvents.

Working Solution – The solute-free (i.e., CO_2-free) liquid solution used as the working solvent in the absorption/desorption process (e.g., the liquid mixture of inorganic salt and water).

Absorption – The conditions of interest for absorption are those that prevail at maximum solvent loading, which typically occurs at the bottom of the absorption column. These may be assumed to be 1 atm total flue gas pressure (corresponding to a CO_2 partial pressure of 0.13 bar) and 40°C; however, measured data at other conditions are preferable to estimated data.

Desorption – The conditions of interest for desorption are those that prevail at minimum solvent loading, which typically occurs at the bottom of the desorption column. Operating pressure and temperature for the desorber/stripper are process-dependent (e.g., an MEA-based absorption system has a typical CO_2 partial pressure of 1.8 bar and a reboiler temperature of 120°C). Measured data at other conditions are preferable to estimated data.

Pressure – The pressure of CO_2 in equilibrium with the solution. If the vapor phase is pure CO_2, this is the total pressure; if it is a mixture of gases, this is the partial pressure of CO_2. Note that for a typical pulverized coal power plant, the total pressure of the flue gas is about 1 atm and the concentration of CO_2 is about 13.2%. Therefore, the partial pressure of CO_2 is roughly 0.132 atm or 0.130 bar.

Concentration – Mass fraction of pure solvent in working solution.

Loading – The basis for CO_2 loadings is moles of pure solvent.

Estimated Cost – Basis is kg/hr of CO_2 in CO_2-rich product gas; assuming targets are met.

Flue Gas Assumptions – BFG is considered as input. Unless noted, BFG pressure, temperature, and composition received at project area (dry basis) should be assumed as:

Pressure	Temperature	Composition							
		vol%						ppmv	
psia	°F	CH_4	CO_2	H_2	N_2	CO	Ar	SO_x	NO_x
16.7	86	0.5	22	9	45	23	0.5	-	-

Other Parameter Descriptions:

Chemical/Physical Solvent Mechanism – Chemical absorption/desorption of CO_2 to/from working solution.

Flue Gas Pretreatment Requirements – As for any stable amine-based solvent.

A number of power and steam-sourcing options are being investigated for this study. These include using a steam boiler, a combined heat and power system for supplementary power, and/or waste heat recovery (WHR) from coke-dry quenching at the coke oven plant. A summary of two such options being evaluated is provided in Figure 2.

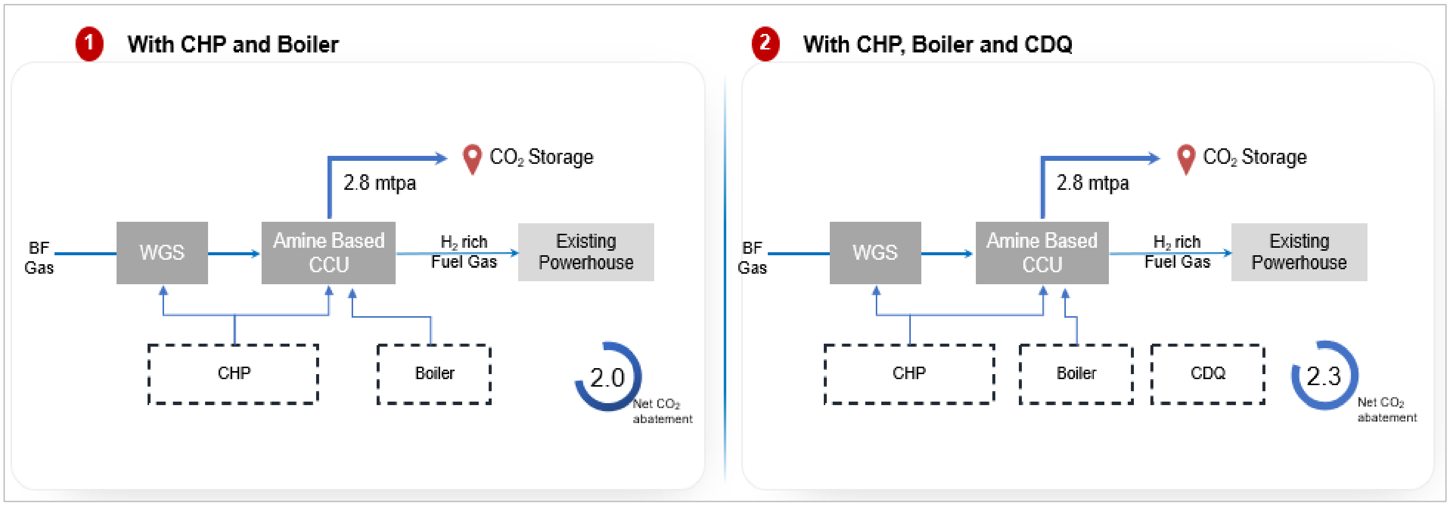

Figure 2: Steam and power-sourcing options.

The conditioned H_2-rich BFG has little to no CO_2. CFD models are being used to evaluate and validate the use of multiple H_2-rich combustion stream options in the firebox of the furnace under varying operating conditions and the performance in terms of temperature distribution, flame profiles, flashback, and nitrogen oxide (NO_X) formation. The performance of the conditioned H_2-rich BFG has been evaluated as a boiler fuel against the unconditioned BFG, using CFD modelling of combustion characteristics. The base case corresponds to the current boiler operations, wherein suitable amounts of BFG, coke oven gas, natural gas, and preheated air are injected into the boiler in a non-premixed fashion. The H_2-rich cases consist of H_2-rich gas replacing the BFG in the current fuel mix, with varying H_2 content, 32% and 36% by volume, corresponding to 77% and 100% CO shift in the WGS, respectively. The developed CFD model is validated against velocity, temperature, and gas composition data obtained during a typical boiler operation.

The simulation results for the base and the H_2-rich cases are compared for the degree of combustion from the exit gas composition, velocity and temperature profiles, wall heat flux profiles, and exit NO_X flow rate. It is observed that the H_2-rich gases behave largely similar to the BFG. This similarity stems from the proximity of the calorific value of these gases and is due to the fact that the H_2-rich gas has a moderate volume fraction of H_2 (32% and 36%). Moreover, the lack of pre-mixed combustion eliminates the possibility of flashbacks in all cases. Thus, it can be concluded that the H_2-rich gas can safely replace the BFG in the boiler without the need for any design modifications to the boiler. This also enables the shifting of BFG all the way up to 100% in the WGS and therefore maximizing the CO_2 capture volume, based on the requirements.

Finally, a TEA will be performed as a part of this study. Preliminary data at the onset of the project predicts an overall cost of capture of up to \$42/tonne of CO_2 captured. This cost of capture excludes the cost of transportation and storage (e.g., 10 \$/tonne).

technology advantages

- No oxidative degradation.
- Low volatile organic compound and nitrogen emissions.
- Increased maximum train size.
- Significantly smaller absorber and ducting.
- Outlet CO_2 is supercritical (possibility for high byproduct power production/energy recovery).

R&D challenges

- Implementation of heat-integration strategies.

- Verification of long-term solvent performance in the BFG environment.
- Selection of proper CO_2 storage location. More geological surveying is required.

status

The project has begun. The preliminary study has been performed and the plant location has been sited.

available reports/technical papers/presentations

Mukherjee, A. & Sarkar, A., 2021, "Enabling Production of Low Carbon Emissions Steel Through CO_2 Capture from Blast Furnace (BF) Gases (FE0031937)." Project Kickoff Meeting. Pittsburgh, PA. *https://netl.doe.gov/projects/plp-download.aspx?id=11014&filename=Enabling+Production+of+Low+Carbon+Emissions+Steel+through+CO2+Capture+from+Blast+Furnace+(BF)+Gases.pdf*.