DESIGN AND ENGINEERING FACTORS AFFECTING CO_2 CAPTURE AND EOR APPLICATIONS

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Introduction

HTC Purenergy conducted a conceptual design study for CO_2 capture from 420-MW natural gas fired combined cycle (NGCC) power plant. The HTC designer solvent was utilized in this chemical absorption process to achieve CO_2 cleanup targets from 80 to 93%. The captured and conditioned CO_2, with more than 99 mol% purity, was compressed to 300 bar g and sent out for enhanced oil recovery (EOR) applications. The main design and engineering factors affecting the CO_2 capture process and its utilization for EOR have been highlighted in this paper. The study provides a feasible engineering design and acceptable production cost taking into consideration all the technical, economic, and location constraints. The study shows that it is advantageous to use HTC designer solvent over the conventional monoethanolamine (MEA) solvent mainly due to its lower steam consumption, circulation rate, and cooling water requirements. The use of a two-train configuration instead of one train leads to better plant availability and operating flexibility to treat all the flue gas capacity. Based on the constraints of the scope of work and the outcome of this engineering study, the production cost is estimated to be US$ 54/ ton CO_2 for the 90% CO_2 recovery of 3.8 mol% CO_2 content in the flue gas. Simulated cases for higher CO_2 contents in the flue gas showed a substantial reduction in the production cost. For a 14 mol% CO_2 content in flue gas of a coal fired power plant, the production cost is about US$ 20/ ton CO_2 using the same capture plant designed in this study and taking into consideration the changes in the main parameters and related additional investments, such as the additional compression facility required to handle the production capacity increase.

Once the CO_2 is captured in large quantities from any point source, the first step of any successful realization of CO_2 flooding in oil fields requires screening the available reservoirs for their suitability for CO_2 flooding. This initial screening requires information on reservoir pressure and temperature, composition of the oil in the reservoir, and composition of CO_2 stream available. These types of information are used to determine the minimum miscibility pressure (MMP) between the oil in the reservoir and available CO_2 stream. Laboratory and field tests have indicated that even under very favorable conditions, the injection of 5-20 MSCF of CO_2 is required to recover an additional barrel of oil [1]. Additionally, the injection and production schemes have a great effect on the performance of CO_2 flooding [2].

Inputs and Constraints

The design of the CO_2 capture facility is based on flue gas conditions, CO_2 product specifications, and constraints. The flue gas conditions are represented in Table 1, which shows less than 4 mol% CO_2 content in the flue gas stream of the NGCC Power plant.

Table 1. Flue Gas Composition

Oxygen, mol%	12
Nitrogen, mol%	75
CO_2, mol%	3.8
NOx, ppm	< 5
NH_3, ppm	< 5
SO_2, ppm	< 1
Argon, mol%	1
Water, mol%	8

The proposed location of the plant has a maximum allowable module dimension of 2000 metric ton, 12m width, and 45m length with no height restriction for the route through sea terminal to the CO_2 Capture Plant plot. Therefore, the equipment must either be limited in size to meet these constraints or be constructed on-site. The facility is designed based on a CO_2 capture efficiency ranging from 80% to 90% of the total flue gas from the 420-MW power plant. The main design and operation constraints can be presented as follows:

- Flow rate of the flue gas to design the plant is 725 kg/s at 105 ^oC and atmospheric pressure.
- CO_2 product discharge pressure is 300 bar g with CO_2 purity ≥ 99 mol% and water dew point of -16 ^oC.
- Low-pressure steam available ≤ 365,000 kg/h at 270 ^oC and 3.0 bar g. The return pressure of the condensates = 25 bar g.
- Low-pressure steam for reclaimer use only available at 200 ^oC and 6.0 bar g. The return condensates can be routed to a low-pressure condensate collection system.
- Seawater for process cooling available ≤ 23,000 m^3/h at 8 ^oC and maximum allowable temperature rise = 10 ^oC. A more expensive seawater cost will be developed for the incremental cooling requirement.
- Raw water is available at delivery pressure of 8 bara and a temperature varying with ambient temperature (above zero, assume from 5 to 20 ^oC)
- Minimize harmful emissions to air.
- Minimize liquid and solid discharge.
- Minimize or eliminate the need for water export.

All the CO_2 Capture equipment units are designed for 93% CO_2 recovery using HTC formulated solvent with additional capacity in the pumps and heat exchanger areas. This design provides excess capacity in order to accommodate any future utilization of new solvents, new packing, new operating conditions, change in the CO_2 content, new cleanup targets, and/or any new optimization parameters [3, 4].

Selected Chemical Solvents Technology

To demonstrate the advantage of using the HTC formulated solvent in this project, a direct comparison between 5 molar MEA (generally used for CO_2 absorption from flue gas streams) and the HTC formulated solvent has been investigated under the same constraints and in the same equipment size for this Project. The superior performance of HTC solvent relative to 5M MEA in the main performance areas can be presented in Figure 1. An environmental advantage offered by HTC solvent is that a lower solvent circulation rate and a lower vapour pressure combine to reduce emission rates, which is a significant environmental benefit. All these factors lead to a lower energy consumption rate, thus making the plant more energy efficient.

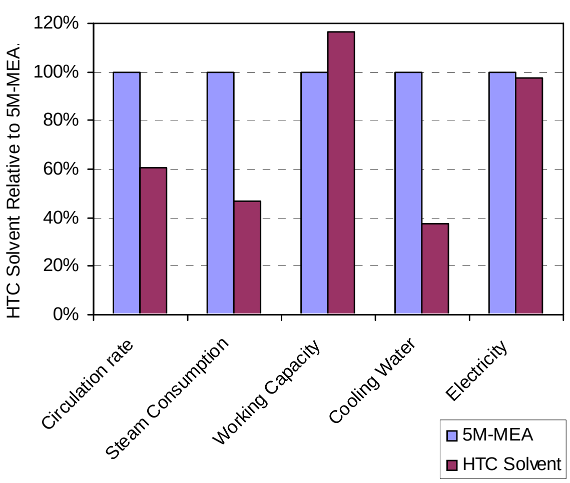

Figure 1. Comparison of HTC formulated solvent with 5 M MEA

Economic Analysis

Based on the HTC design, Bechtel estimated the capital cost of the plant based on a turnkey Engineering, Procurement and Construction (EPC) contract. The indicative estimated costs are priced based on 3rd Quarter, 2006, with an accuracy range of +/- 30%. The majority of the estimated operating costs are based on the consumption of utilities including steam, electricity, and cooling water. Other costs include chemical consumption, insurance and taxes, and labour associated with the operation and maintenance along with overhead. Based on the capitol and operating cost data, the production costs as function of the CO_2 recovery is presented in Figures 2 for straight-line depreciation. From this figure, the most optimum scenario is the 85% CO_2 recovery rate, which amounts to US\$ 52/ ton CO_2. This production cost is reasonable mainly because of the low concentration of the CO_2 in the flue gas stream, which is less than 4 mol%. The production cost will be much less than this in the case of CO_2 capture from coal fired power plant in which the CO_2 concentration is from 9 to 14 mol%. Simulated cases for higher CO_2 contents in the flue gas are presented in Figure 3. A substantial reduction in the production cost can be seen as the amount of CO_2 content is increased in the flue gas. For 14 mol% CO_2 content in flue gas of a coal fired power plant, the production cost is about US\$ 20/ ton CO_2. This cost is based on using the same plant design and taking into consideration the changes in the main parameters and related additional investments such as the production capacity and the additional compression facility required.

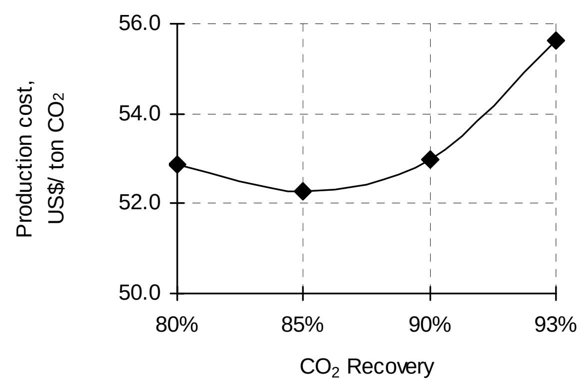

Figure 2. Production cost versus operating range based on straight-line depreciation.

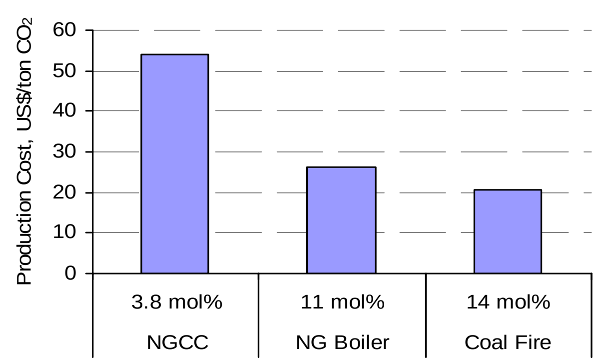

Figure 3. Simulated production cost for NG Boiler and coal fired power in comparison with the actual production cost of this study for NGCC Power Plant.

Engineering of CO_2 Flood in Oil Reservoirs

The first step of any successful realization of CO_2 flooding in oil fields requires screening the available reservoirs for their suitability for CO_2 flooding. This initial screening requires information on reservoir pressure and temperature, composition of the oil in the reservoir, and composition of CO_2 stream available. These types of information are used to determine the minimum miscibility pressure (MMP) between the oil in the reservoir and available CO_2 stream. Once a candidate reservoir passes the screening test, detailed geological and reservoir simulation models of the reservoir have to be constructed to quantify the increased oil recovery from the injection of CO_2 into the oil-bearing rock. These models predict increased recovery as a result of CO_2 injection into various production patterns. In North America, the implementation of CO_2 flooding has led to an incremental increase in oil recovery equal to 15 to 25% of the original oil in place, OOIP.

The viability of a CO_2 flood in areas of any oil field is dependent on the following general conditions:

- The reservoir is continuous and is well sealed to prevent excessive solvent loss to other zones.
- The reservoir pressure is greater than minimum miscibility pressure.
- The spacing between wells are optimized to allow efficient use of the CO_2 and to maintain effective flood control.
- The CO_2 flood should be designed to optimize the volumes of CO_2 required to produce the oil, since CO_2 represents a large operating cost component of the project.

In this part, the above-mentioned methodology for implementing CO_2 flooding in oil fields is presented through an example of a study conducted on Zama Keg River F pool located in northern Alberta, Canada. Zama Keg River F pool is a heterogeneous reef composed of two main dolomite formations separated by anhydrite layer. It is under-saturated and has a thick oil column spanning over only a small area. Production performance history and a material balance analysis indicated the maximum OOIP of 4.7 MMSTB with a weak water support, and no evidence of physical communication with any of other pinnacles in the same depositional basin. Total oil production is 1.107 MMSTB from two wells and the reservoir has produced under the bubble point pressure of 1276 psi for most of its life. The Zama basin contains a significant number of Keg River pinnacles with over-laying Zama carbonates. Most of these pinnacles are almost the same size with some exceptions. Thus, the CO_2 flooding plan can be extended to more than 670 pinnacles in the Zama basin. Evaluation of CO_2 flooding for this field was conducted in four stages as follows:

Stage 1. Fluid Characterization and Determination of MMP. Recent PVT study using new oil samples collected from one of the wells in the oil field has indicated that the data for the reservoir fluids obtained from this well compare very well with previous measurements. The oil gravity and saturation pressure were 34 API and 1276 psig respectively compared to 33.9 API and 1275 Psig measured in 1967. The minimum miscibility pressure measurement was carried out using the rising bubble apparatus. Two injection gases were used, pure CO_2 and 20% H_2S in CO_2 stream. The minimum miscibility pressure for the pure CO_2 was 2886 psi compared to 2407 psi for the 20% H_2S in CO_2 stream. This information along with geological model was used for predicting the performance of CO_2 flooding in this field.

Stage 2. Reservoir Characterization and the Geological Model. Zama Keg River F pool is composed of two distinct dolomite formations separated by anhydrite barriers. The upper formation's thickness is 80 ft and it has a porosity of 0.08 and high permeability in the range of 100 md except the first 18 ft zone that has 1000 md permeability. The lower formation is more heterogeneous with an average thickness of 85 ft, average porosity of 0.09, and average permeability of 300 md. The average reservoir depth is 3700 ft, 2100 psi initial pressure at 160 °F. Characterization and geological modeling of this reservoir was conducted through utilizing 3-D seismic, well-interpreted logs, and core data from wells. Composite porosity data from core and log data was assigned to the model grid blocks. Porosity-permeability cloud transform was used to assign the horizontal permeability to each grid block in the model. The model contained a total of 49,950 grid blocks (30 X 37 X 45) from which 15763 were active grid blocks. The average size of the grid blocks is 50 x 50 x 6 ft in I, J and K directions, respectively. The final model was exported to the numerical simulator "CMG-GEM" that was used for the dynamic model as shown in Figure 4.

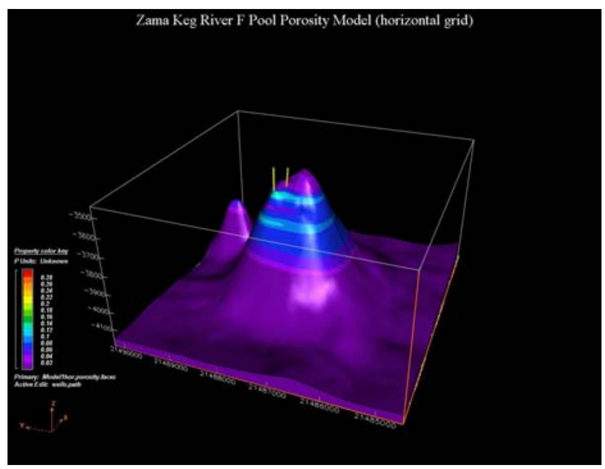

Figure 4. Geological model of Zama Keg River.

Stage 3. Reservoir Simulation and History Matching. An 8-components Peng-Robinson Equation of State was tuned based on PVT Lab data and used to simulate the reservoir fluid properties, which could provide more reliable prediction of CO_2/Oil phase behavior. A history match was achieved through some modifications to the soft and the hard data. The main adjustments in the model include: vertical permeability of the non-flow barriers, porosity and permeability of the attic and the main reef, saturation functions and aquifer strength. The quality of match was judged from how well simulated oil, water, and gas production and reservoir pressure tracked actual data.

Stage 4. Predicting the Performance of CO_2 EOR. Upon completion of history match, a series of predictive scenarios for implementing and optimizing CO_2 flooding in this filed was conducted and presented. Over fifteen scenarios for maximizing oil recovery due to CO_2 injection, as well as amount of CO_2 stored in reservoir, were studied and outcomes were presented to the oil company. Based on our positive findings and recommendations, the oil company started the CO_2 flooding in this reservoir since early 2006.

Findings and Recommendations

The formulation of absorption solvents provides better efficiency in terms of parameters such as energy consumption, solvent circulation rate and cooling water requirements, as well as flexibility, turn down capacity and in expanding the range of clean up targets.

Significant advantages are also derived from the two-train configuration in terms of plant availability and flexibility relating to turndown and start capabilities without losing plant efficiency. By using a process technology that combines the HTC formulated solvent with the optimum plant design configuration (two trains), additional benefits, including lower emissions, as well as an increased level of advantages accrue on top of those available individually from HTC solvent and the optimum plant configuration because of the synergy that exists between these two approaches. Based on the CO_2 recovery range in the scope of work, random packing is more appropriate for design than structured packing based primarily on cost relating to installation. Based on these findings, the following main recommendation can be seen:

Use of a Designer Solvent. The HTC formulated solvent is recommended because of its inherent advantage that it can be customized to meet the specific needs of a specific application, thus allowing for optimal design and operation of the CO_2 capture plant leading to a reduction in unit CO_2 capture cost.

Use Of Two Capture Trains. The concept of utilizing two process trains is recommended for the size of plant under study. This allows for the construction of smaller vessels that can be shop fabricated and delivered via the coastal accessible site rather than on-site fabrication for larger diameter columns in a single process train. Other advantages include higher flexibility with higher turndown capacity and the ability to turn off one train if this is required by electrical demands. Also, smaller size equipment such as orifice flow measuring devices, pumps, exchangers, etc is typically more readily available and at a much lower cost as compared to custom designed equipment. In addition, column sizes bigger than the one offered in this study could have problems in uniform liquid distribution over the large packing material. Furthermore, equipment start-up of smaller blowers, pumps and compressors in the two-train configuration puts less power demand on the NGCC power plant. Also as the compressor size becomes larger, very few compressor manufacturers are able to offer such a unit, and its economy of scale becomes less certain due to the lack of competition.

Use Circular Columns Versus Rectangular Columns. A circular column is recommended because it offers the benefits of a free standing design without the need of additional structure steel which is required to hold the rectangular box in place. The circular column is also more blast resistant, as well as more tolerant to wind load. Circular columns provide strength from the curvature of the steel, which also allows for a thinner wall construction. Liquid distribution is much more understood with circular columns and can be modelled with a great deal of accuracy. Although models can be developed for rectangular column performance, the engineering properties of a circular column is much more advanced, has been historically utilized and as such the modelling and simulation of the column has been proven over many years [5,6].

Use Random Packing Versus Structured Packing. Based on the CO_2 recovery range in the scope of work, random packing is recommended as being more appropriate for design. This decision is based primarily on cost relating to installation. Random packing can be delivered in bulk tote bags and basically poured into the column through the upper manhole by chutes. Structured packing must be pre-cut to the specific dimension and installed layer by layer manually in a size suitable for human maneuverability. The structured packing must also be crated for shipping to prevent damage. Other advantage random packing has over structured packing is its resistance to corrosion. The reason random packing has greater resistance to corrosion is due to the thickness of metal. Structured packing has about half the thickness of random. Additionally, plastic packing material can be used in the absorber and wash section, which is another possible solution to potential corrosion problems.

Considerations for CO_2 EOR. A successful implementation of CO_2 flooding in any oil field requires a detailed engineering approach that addresses not only the technical issues, but also undertakes a thorough optimization study. A detailed and comprehensive understanding of real field is required for conducting winning CO_2 flooding projects. As part of our all-inclusive approach to successful field implementation of CO_2 flooding, the following technical challenges will be addressed in order to optimize the field operations:

- Improving performance of CO_2 flooding
- Early breakthrough of injected CO_2
- Viscous fingering and low volumetric sweep efficiency
- Asphaltene and solid particles precipitation
- Injectivity loss
- Wettability and relative permeability alteration
- Potential corrosion issues
- Achieving and maintaining miscibility
- Effect of temperature of injected CO_2 on reservoir

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