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CO_2 removal optimisation for the BR-E membrane system by data analysis and modelling

Nguyen Hai An
Petrovietnam Exploration and Production Corporation
Email: annh1@pvep.com.vn

Summary

Development of offshore high carbon dioxide (CO_2) gas fields will indisputably pose significant new challenges for all E&P companies in the world. Acid gas removal from natural gas is an indispensable treatment process that is required to boost the produced gas quality prior to its utilisation. The use of membrane units has increased in natural gas treatment plants, particularly for acid gas removal. Such technology shows tremendous advantages over other conventional methods in terms of removal efficiency, compactness, and environmental friendliness.

BR-E CO_2 removal facility using membrane technology has been utilised for more than 10 years. As new acid gas fields require increasingly high gas volumes (more than 700 MMscfd production) and have very high CO_2 content (above 50%), existing membrane performance is no longer economical for such new field development.

In this paper, a data analysis model for membrane separation has been incorporated with HYSYS as a user defined unit operation in order to optimise performance and redesign the membrane system for CO_2 separation from natural gas. Parameter sensitivities have been studied for different crude gas flow and CO_2 contained in gas.

Key words: Petroleum system modelling, a prospect, drainage area, hydrocarbon migration and accumulation, Block 09-3/12.

1. Introduction

Membrane systems are modular and can easily cope with the increase of feed flow rate. An increase in feed flow rate requires a proportional increase in membrane area requirements. If the membrane area is fixed, an increase in feed flow will result in an increase of CO_2 in the produced gas.

Next to the changes in feed-gas conditions (flow and composition), normal membrane aging can result in a CO_2 concentration increase in the sales gas. Membranes are subjected to a lifetime that varies with feed-gas conditions, membrane pre-treatment design, and operator skills. The BR-E gas plant has shown excellent performance with the membrane lifetime of more than 10 years.

The design of a membrane system takes into account the natural performance decline (membrane aging) by sizing the system for end-of-life conditions so that the system will always reach the required specifications. During the lifetime of the membrane, the system will require minor operational adjustments as the membrane properties (selectivity and permeability) vary.

The research will further describe how the BR-E gas plant has been optimised as feed-gas conditions changed and as membranes aged, the objectives of producing gas with acceptable CO_2 content while minimising hydrocarbon losses that transpose directly in sales gas volume and revenue.

2. Removal of CO_2 with membranes

2.1 Membrane general

The most common membranes for gas sweetening processes are cellulose acetate (CA) membranes [1]. Recently, fixed site carrier membranes showed a great potential for removal of CO_2. A simple membrane process can be schematically represented as shown in Figure 1.

Membrane based gas separation process depends on the gas components, membrane material and the process

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conditions. The governing flux equation (Equation 1) is given by Fick's law of diffusion where the driving force is the partial pressure difference over the membrane.

$$\frac{q_{p,i}}{A_m} = \frac{q_p y_{p,i}}{A_m} = J_i = \frac{P_i}{l}(p_h x_i - p_l y_i) \quad (1)$$

Where J (m^3(STP)/m^2 h) is the flux of gas component i, q_p is the volume of the permeating gas (i) (m^3(STP)/h), P_i is the permeability of gas component i ((m^3(STP)/m^2 h bar), p_h and p_l are feed and permeate side pressures (bar), x_i and y_i are the fractions of component i on the feed and permeate sides and A_m (m^2) is the membrane area required for the permeation. The permeability (P) can be expressed as

$$P = D_{AB} \times S \quad (2)$$

Where D_{AB} (m^2/s) is the diffusivity and S (m^3(STP)/m^3 bar) is the solubility coefficient for the gas in the membrane. The ratio of pure gas permeabilities (P_A, P_B) gives the separation factor or membrane selectivity, $\alpha = P_A/P_B$.

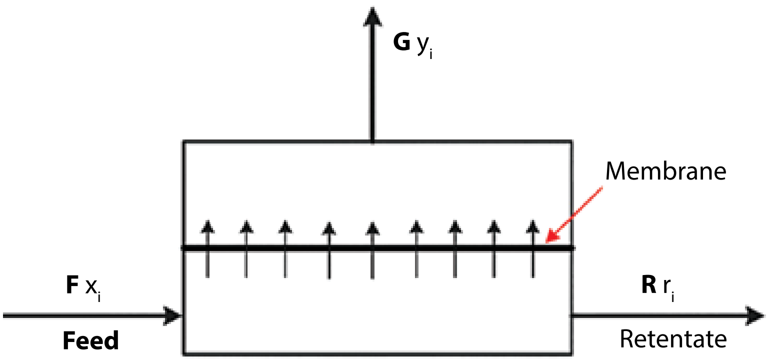


Figure 1. *Schematic illustration of membrane separation process.*

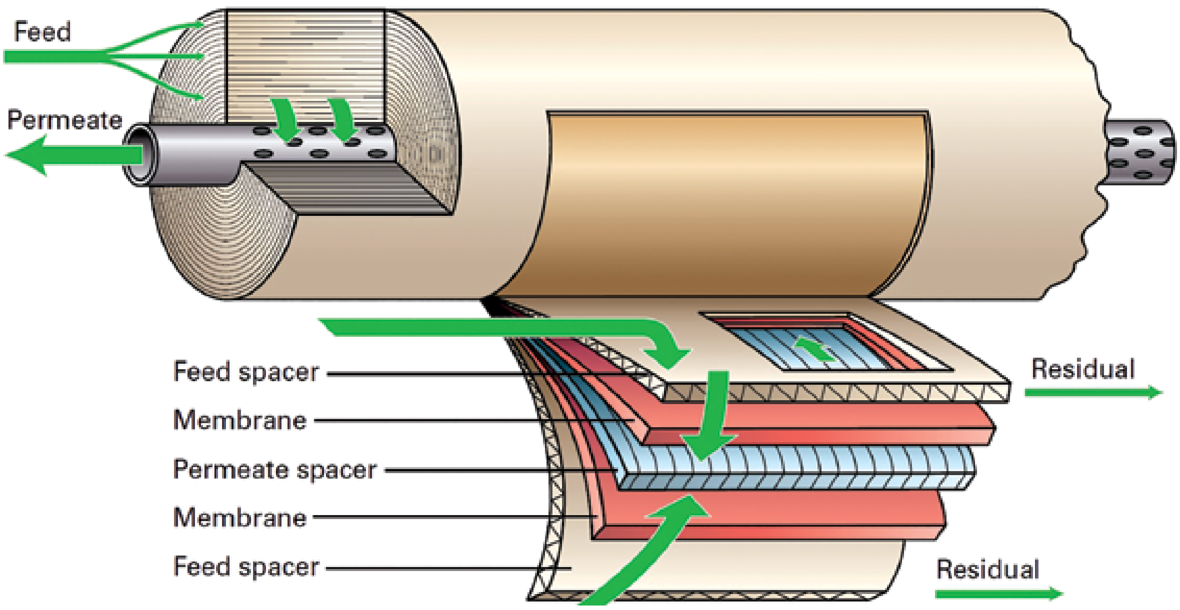
It is important to mention here that Equation 1 can be used to accurately and predictably rationalise the properties of gas permeation membranes.

2.2. Membrane modules

In order to make a membrane module for industrial application [2, 3] that consists of cellulose acetate membrane sheets that are bound onto a woven cloth support. A membrane sheet has two layers: a relatively thick microporous layer that is in contact with the cloth support and a thin active layer on top of the microporous layer.

A membrane element is a spiral wound assembly with a perforated permeate tube at its centre (Figure 2). One or more membrane leaves are wrapped around the permeate tube. Each leaf contains two membrane-cloth composite layers that are separated by a rigid, porous, fluid-conductive permeate channel spacer. These leaves are separated from each other by a high-pressure channel spacer. The membrane leaves are sealed with an adhesive on three sides; the fourth side is open to the permeate tube.

As the feed gas passes through the membrane tubes, the gas is separated into a



*Two membrane sheets with permeate spacer between: leaves are separated by feed spacers and wrapped around a permeate tube facing it with three open ends.

Figure 2. *Spiral-wound membrane elements [3].*

high-pressure methane rich gas (residual), and a low-pressure gas stream concentrated in carbon dioxide (permeate).

The first membrane stage is designed to produce a residual gas (sales gas) with low CO_2 concentration, which is supplied to the export compressors for gas metering. The permeate gas containing high CO_2 %mol is compressed through the permeate compressor and then directed to the second stage membrane package.

The second membrane stage is designed to recover most of the hydrocarbons from the first-stage permeate gas. The second membrane stage residual gas is recycled back to the first membrane stage. The second stage permeate gas containing the high concentration of CO_2 is flared.

2.3. Membrane system configurations

A single-stage membrane configuration consists of one permeation unit or more than one unit, but all are arranged in a barrel setup and have the same feed composition.

This configuration is the simplest and corresponds to the lowest capital investment. The single-stage configuration is schematically shown in Figure 3. The crude natural gas flows over the feed side of the membrane. Along the way, CO_2 permeates through the membrane to the permeate side. The retentate leaves the membrane with nearly the same pressure as the feed. On the permeate side, a permeate stream enriched with CO_2 leaves the membrane.

As seen in many industrial applications [3], the single-stage membrane separation has limitation in achieving high quality permeate or retentate while typically the objective of separation is either of these. As such, more stages are required in order to accomplish the desired product quality and recovery ratio. Figure 4 illustrates a simplified flow scheme of a two-stage cascade membrane system. A multistage configuration reduces the hydrocarbon losses to a minimum, however, those plants have higher investment costs than single stage configurations. The permeate stream of the first membrane serves as feed for the second membrane. Therefore, the permeate stream needs to be recompressed and cooled. The retentate stream of the second membrane stage is recompressed, cooled and recycled as feed to the first stage. The retentate stream from the first stage is collected as the product gas.

3. BR-E CO_2 removal facility

The BR-E CO_2 removal facility is 370km from Ca Mau terminal. The platform processes gas condensate from northern fields complex, and associated gas from the southern oil fields. The project produces about 350MMscfd (max) of export gas at an export pressure of 101 bars and 3,700stb of stabilised condensate. The BR-E platform has been in operation since in Q1, 2007 with the main function to process high CO_2 production gas to meet the sale gas specification of 8% mol CO_2

The flow diagram of the BR-E gas facility (Figure 5) shows gas flowing from the complexes into the system. First it enters a two-phase feed gas separator where the main condensate-gas separation takes place. Gas from the separator goes to the Coalescing Unit for liquid and mist elimination to reduce overall plant pressure drop. Then it flows to the Membranes System, which consists of a temperature swing adsorption (TSA) regenerable beds for the simultaneous removal of aromatics, water and other contaminants (e.g., mercury).

The retentate stream of the second membrane stage is recycled as feed to the first stage. This combined stream has a design CO_2 content of 40 - 45% mol and is the feed gas to the first-stage membrane skids. The retentate stream from the first stage is collected as product gas. Condensate collected from the various processing steps moves to stabilisation before

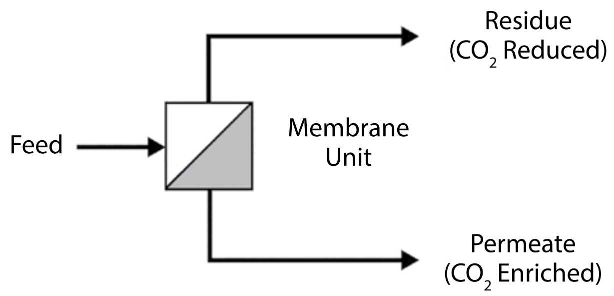


Figure 3. *Single-stage flow scheme*

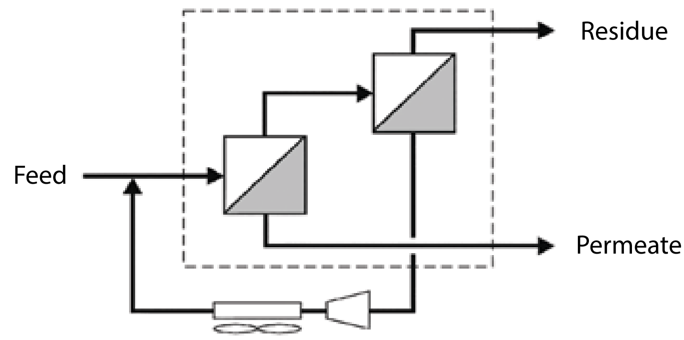


Figure 4. *Dual-stage flow scheme.*

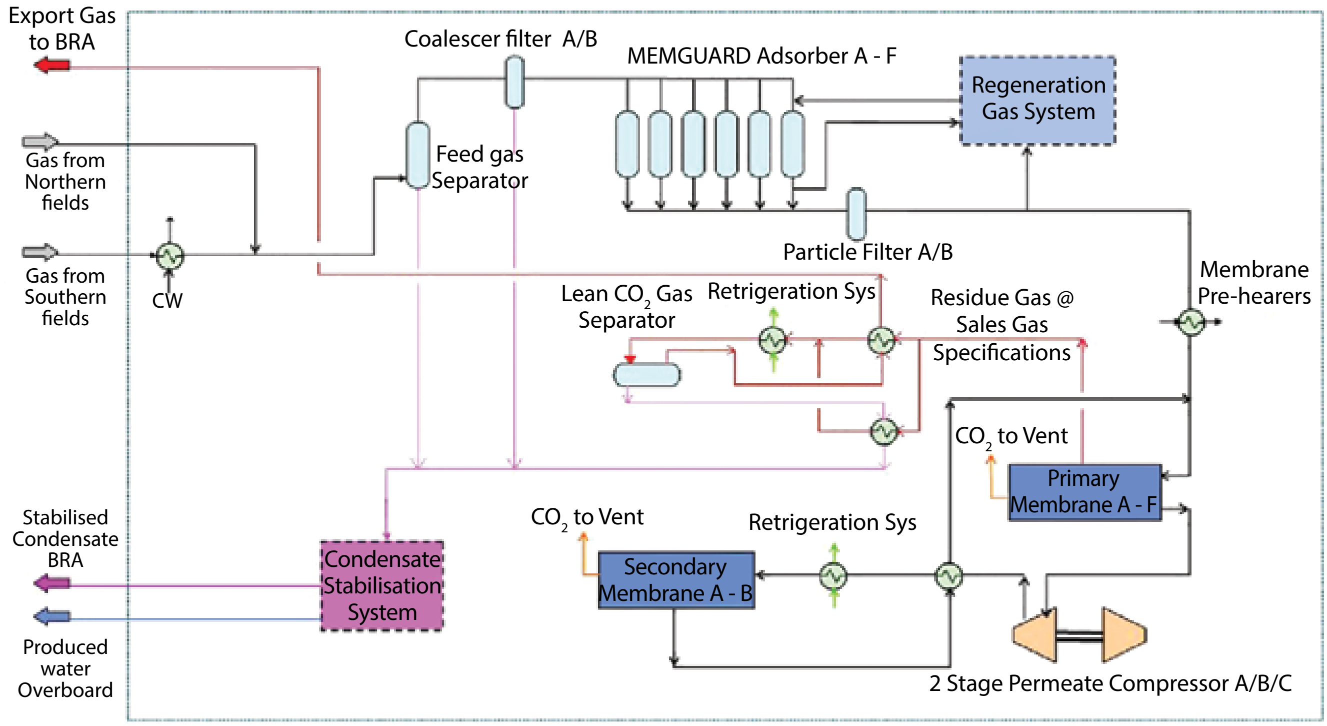


***Figure 5.** Flow diagram for CO_2 removal on BR-E platform [4].*

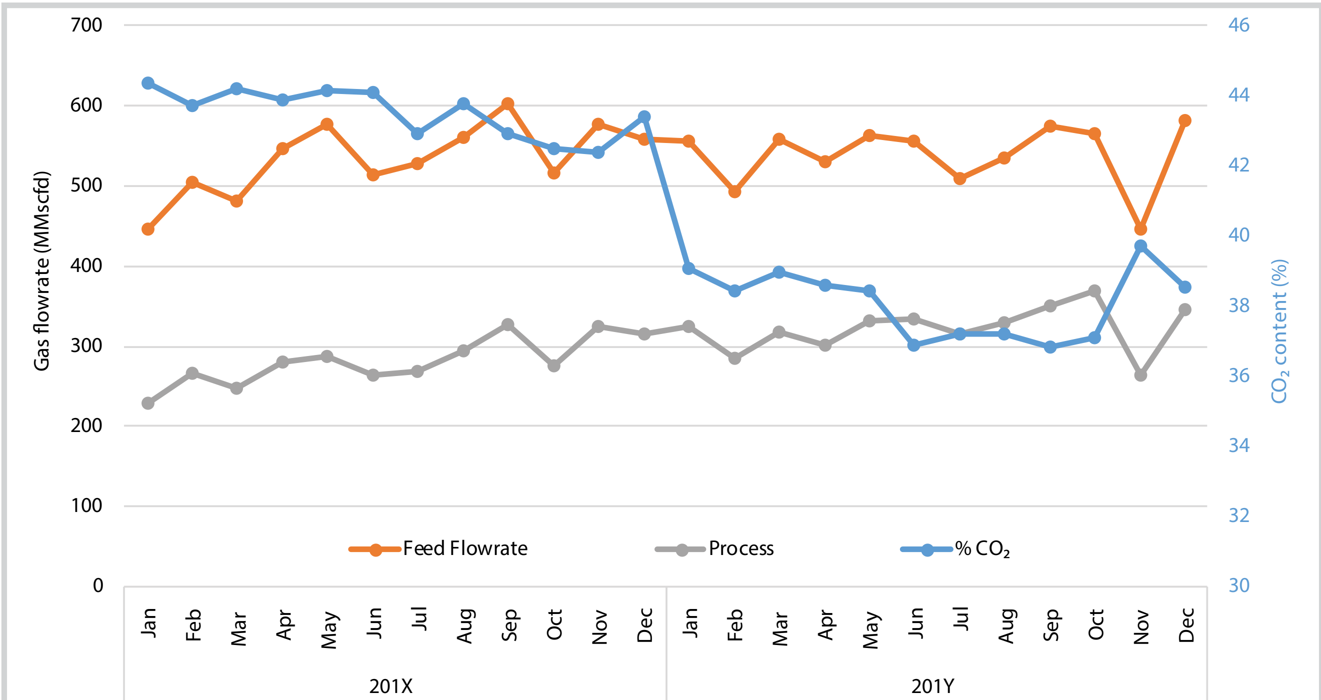


***Figure 6.** Gas process behaviour.*

being stored in the three storage tanks. The stabiliser tower removes the light hydrocarbons to avoid release in the tanks and to achieve the rvp specification.

After heating to required temperature, the gas enters the gas-sweetening system (dual-stage membrane package) to reduce CO_2 in the export gas. The final step is to export the gas via the export compressors.

3.1. Operation performance

Throughout the operating period of two years, changes were daily made in the feed gas rate and the CO_2 concentration. Figure 6 gives information about the behavior of feed gas flowrate, retentate ("process gas"), for two different levels of CO_2 concentration in the feed gas. In fact, the CO_2 concentration in the retentate product

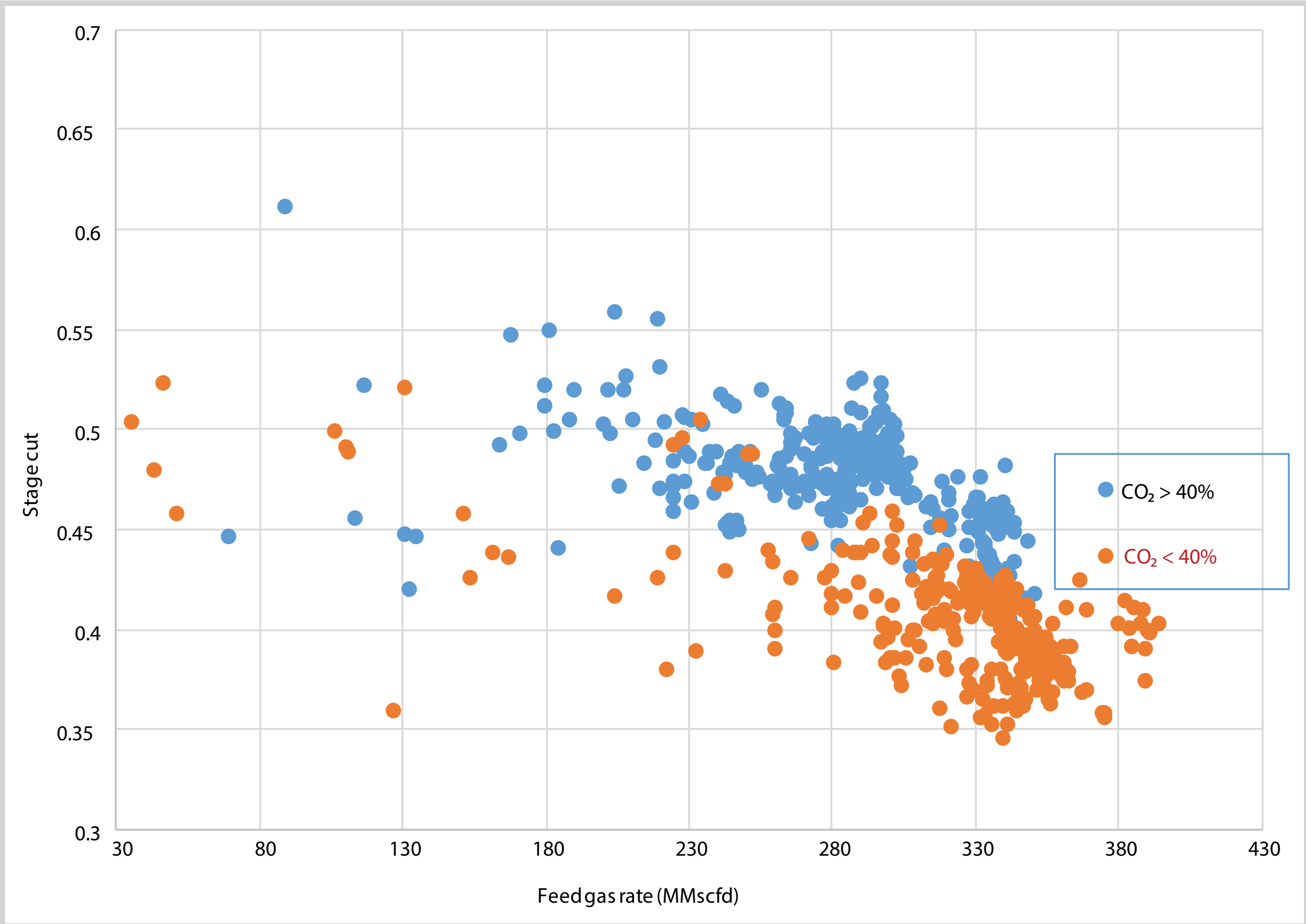


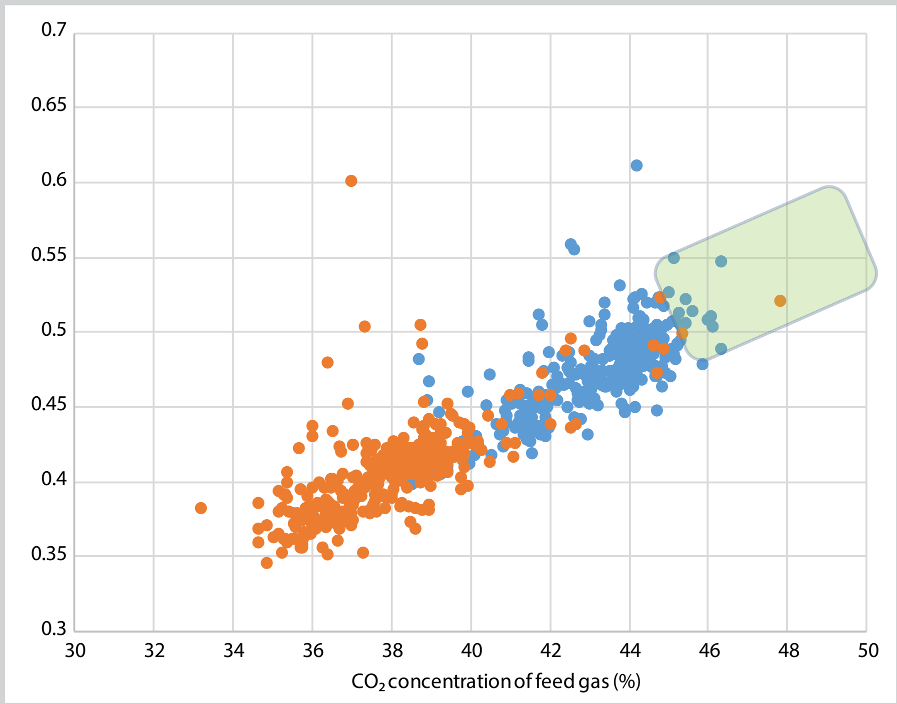
Figure 7. *Total gas stage cut for BR-E membranes system.*

remained below the pipeline specification throughout the measurement. These results show that, even with a CO_2 concentration of over 40% mol in the feed, it was possible to meet the pipeline specification of 8% mol CO_2.

Figure 7 shows the "total gas stage cut" for different CO_2 components of natural gas as a function of feed gas rate for membranes. The "stage cut" is generally defined as the fraction of the feed stream allowed to permeate through the membrane, i.e. the permeate/feed ratio. In the measurement period, it was found necessary to "force" the CO_2 balances for some surveys to obtain a good data fit, especially the data for high CO_2 concentrations in the feed. The field staff observed that the CO_2 concentration in the "sour" gas from the well typically varied by about 5% mol out of an average concentration of about 40% mol. This meant that the CO_2 stage cut for feed gases with high CO_2 content could vary by as much as 10%. For consistency, the CH_4 balances were also forced as necessary, but there was much less variability in these data because of the relatively high concentration of CH_4 in all streams.

The parameters of feed flow rate and CO_2 concentration in the feed are arbitrarily grouped in Figure 8 into ranges denoted as "CO_2 < 40%" and "CO_2 > 40%". As can be seen from this figure, the data are generally consistent in that the stage cuts decrease with increasing feed flow rate. The scatter in the data is not unusual for field test conditions. It was not possible to obtain data at higher feed flow rates with medium-to-high CO_2 concentrations in the feed without exceeding the pipeline-specified limit of 8% mol CO_2 in the retentate. Therefore, the data are generally limited to lower feed flow rates and lower CO_2 concentrations. There was no indication of membrane deterioration with time, based on the field test data.

In general, the stage cuts for the membrane system followed the same general dependence on feed flow rate and CO_2 concentration in the feed. High CO_2 stage cuts were necessary to reduce the CO_2 concentration in the retentate product to the pipeline specification of 8% mol, however the outlet gas rate was decreased accordingly. While this results in a better CO_2 removal, it also increases the losses of CH_4 and higher hydrocarbons in the permeate



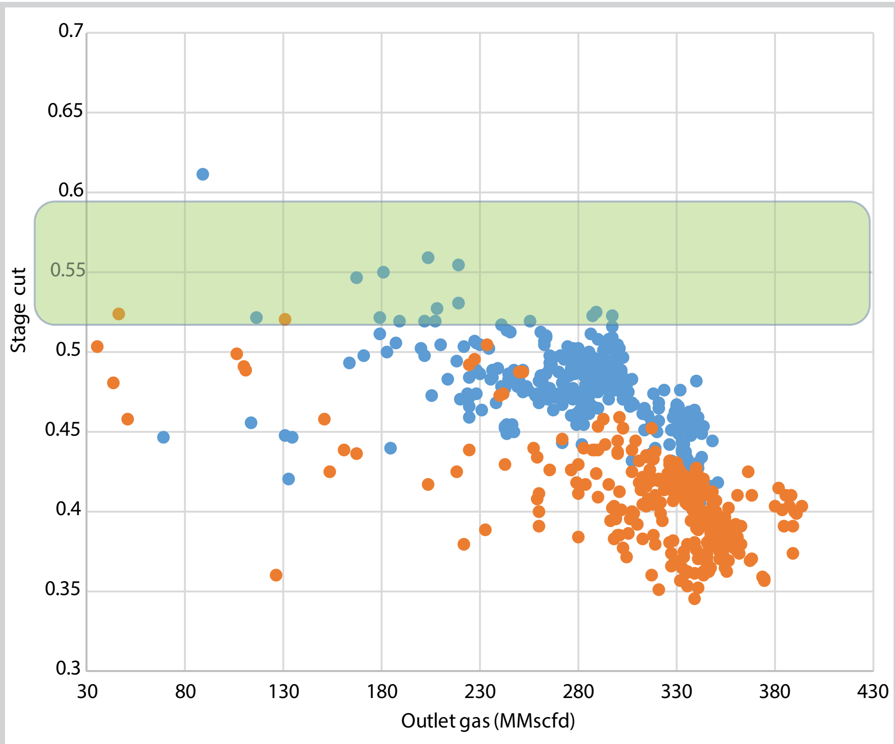


Figure 8. *Depends of outlet gas on CO_2 concentration of feed gas.*

(vent) stream. The component stage cuts also increase, as expected, with increasing pressure, because the partial pressures of the components increase.

It should be pointed out that the actual field surveyed flow rates were generally much lower than the design rate since the purpose of the tests was to obtain operating data over a wide range of conditions. Therefore, back-diffusion and perfect mixing were possible, and the methane loss in the permeate was generally higher than desired in commercial operation.

3.2. Process simulation

The numerous material balances that need to be resolved simultaneously within a multistage membrane unit make the prediction of unit's performance using conventional mathematical solvers (e.g. spreadsheet) challenging. Further, the struggle to solve the indicated balances obstructs any intended process optimisation. Hence, the development of a flexible, efficient, and user-friendly model is crucial to simulate, evaluate and optimise such processes.

The membrane separation process is modelled based on the solution-diffusion mechanism, which is governed by the following mass transfer equation. Detailed modelling of the CO_2 removal BR-E facility was performed with the confirmation of the capability of this equipment to process the design cases. Stream data for the boundaries of the model were provided, for the high and low CO_2 cases. The new process configuration and updated production data were incorporated into the HYSYS model, which has been further amended to align with the two design cases for CO_2 concentration.

In order to align with the models of design cases, it was necessary to match streams at the interface with the boundary stream data provided. As these design cases represent different production rates for modelling, it was necessary to adjust flows from wellhead platforms to the processing facilities.

The HYSYS models were consolidated and amended to match the facility processing configuration following the upcoming shutdown. The consolidation process was performed at the request incorporating the production data into a whole field model. This was achieved through the substitution of the fields models with streams specified to match forecast production rates. Other amendments included both recent changes to facilities and the work planned for the shutdown.

To investigate the accuracy of the mathematical model and the proposed solution algorithm, simulation predictions were validated against observed data reported by operator in two years. The feed enters the skid at a pressure of 4000kPag, while the permeate stream is collected from the fibre side at a pressure of 210kPa. These experimental conditions were used to investigate the membrane performance at high feed composition, pressure ratio, and target component selectivity. The model results are

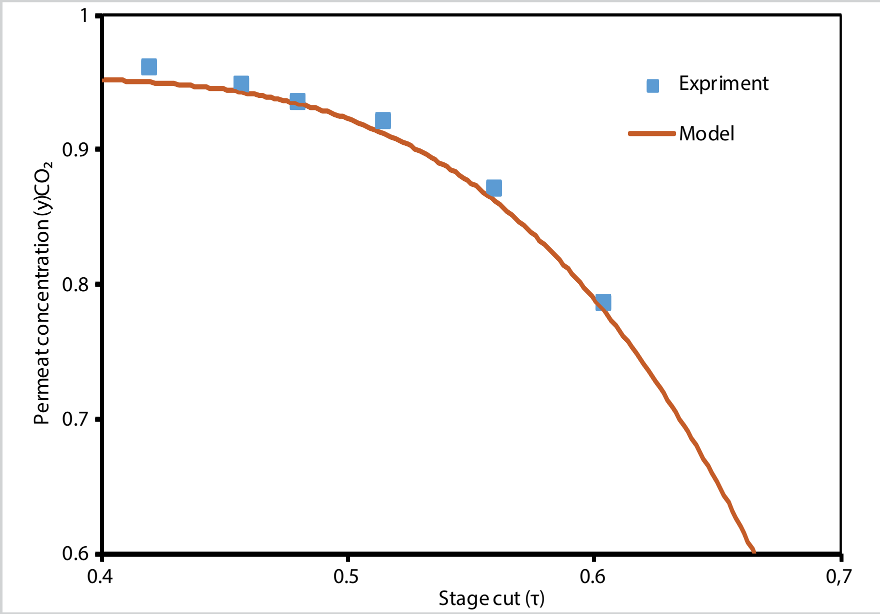


Figure 9. *Model validation against experimental data.*

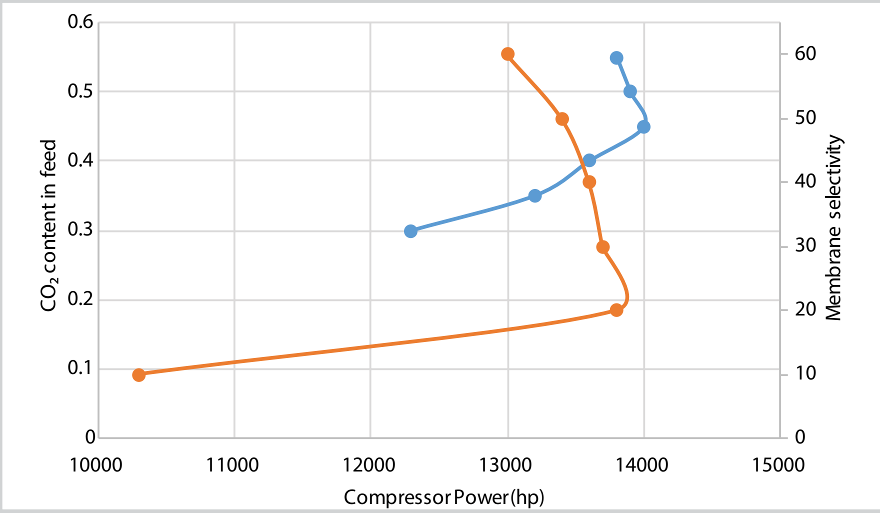


Figure 10. *Power requirement analysis.*

Table 1. *Factors for model*

Description	Unit	Actual	High CO_2	Low CO_2
Feed gas				
Flow rate	MMscfd	650	750	630
Pressure	kPag	4000	4000	4000
Temperature	C deg	30	30	30
CO_2 concentration	% mol	38 - 44	50	35
Outlet gas				
Flow rate	MMscfd	400	360	450
Pressure (expected)	kPag	3200	3000	3000
Temperature (max)	C deg	35	35	35
CO_2 concentration	% mol	7.8 - 8	8	8
Vent (CO_2 rich) gas				
Flow rate	MMscfd	350	350	210
Pressure (min)	kPag	250	250	250
Allowable skid dP	kPa	800	800	800
Hydrocarbon recovery	%	87 - 92	90 - 95	93 - 98

plotted against the experimental results in Figure 9 showing good agreement with experimental data over the tested range of stage cut.

4. Results and discussion

The research will determine the ability of the existing facilities to meet the new required capacities for between 35% and 50% CO_2 in the feed, identify bottlenecks and estimate work required to increase gas export volume. Hence, the maximum potential flow rate through the CO_2 removal equipment on BR-E has been analysed by considering two operating cases: high CO_2 case (a feed gas of 50% CO_2), and low CO_2 case (a feed gas of 35% CO_2).

To relieve some bottlenecks and produce maximum capacities, some processing reconfigurations and additional equipment have been studied. These design cases only consider the CO_2 removal equipment without considering the ability of the remainder of the processing facilities to either supply sufficient feed gas or export the subsequent sales gas.

The composition, flow rates, pressures and temperature of crude natural gas depend mainly on the

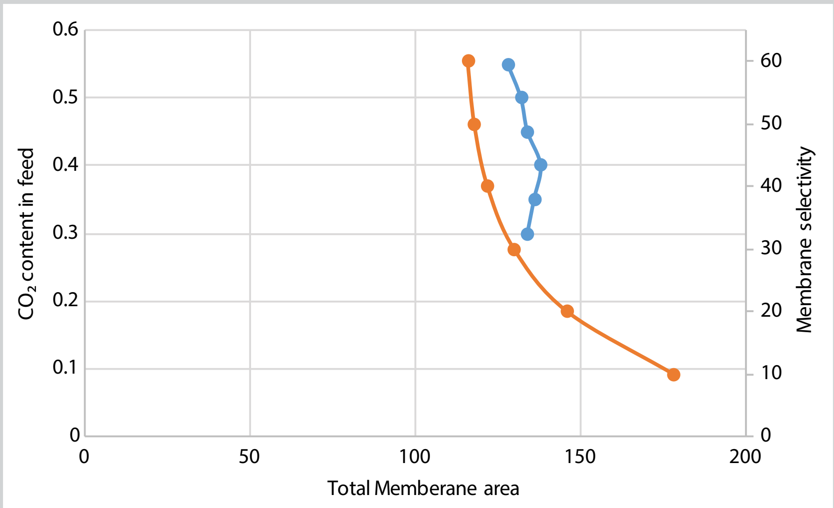


Figure 11. *Total membranes requirement analysis.*

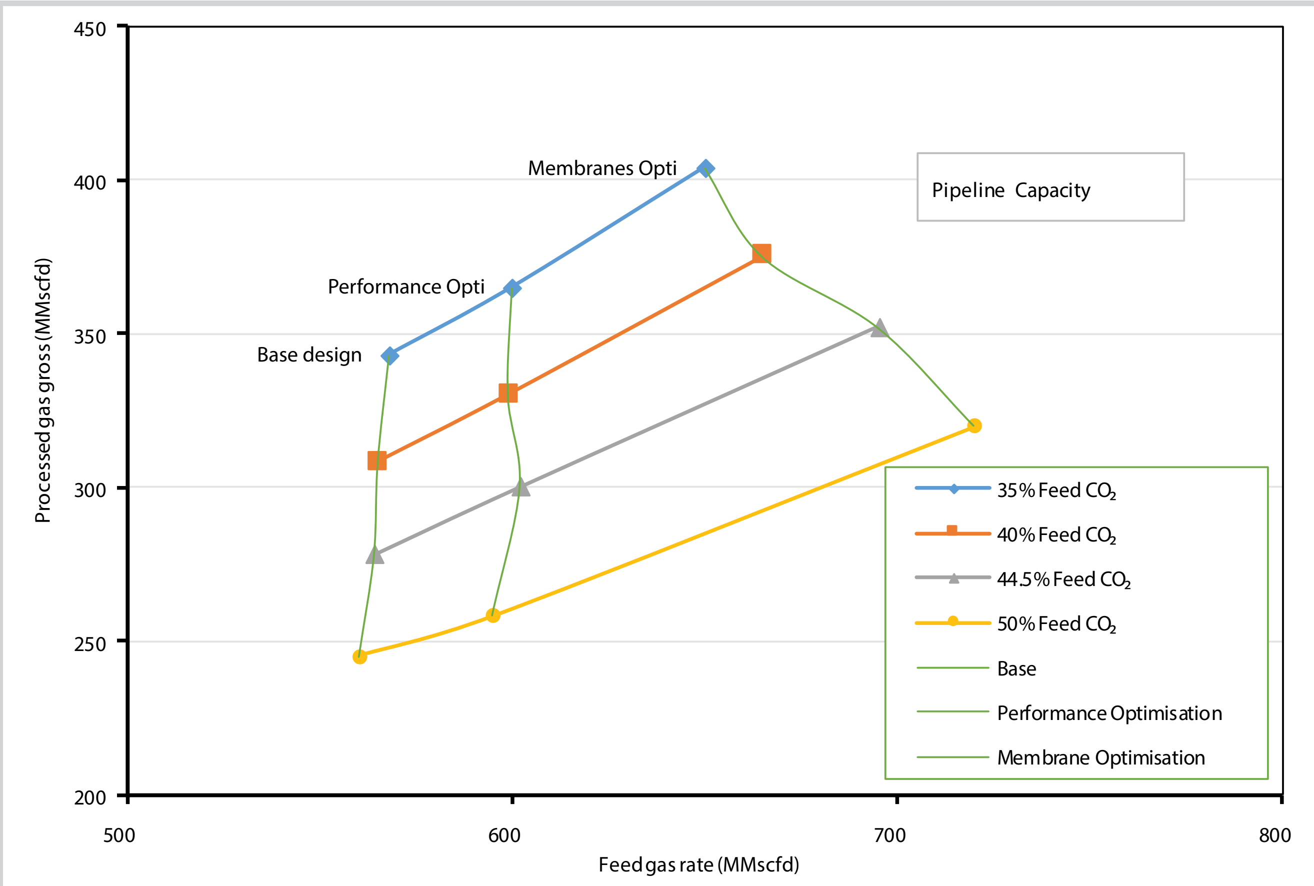


Figure 12. *Impact of performance optimisation and membranes enhancement.*

source therefore feed conditions that are typical for offshore natural gas treatment skid are selected. As a result, the mentioned factors of the feed, as well as the export gas, are given in Table 1.

On the other hand, a wide range of feed pressures (10 - 100 bar) and membrane selectivity (5 - 80) has been investigated. The outlet residue CO_2 concentration is set to 8% while the outlet permeate pressure for each stage is not greater than 32 bar. The thickness of membrane is considered to be 1000A˚ (3.937×10^{-6} in.). In addition, it is assumed that maximum outlet temperatures in the compressors are limited to 35°C giving the compression ratio of 20 over each compressor stage. The temperature of feed stream is decreased to 25°C before introducing into the membrane using cooler.

4.1. Compressor power

The effect of feed composition, feed pressure and membrane selectivity on the compressor power requirement has been investigated for the proposed design configurations. The compressor power is given by the expression

Figure 6 shows that the compressor power requirement increases with the increase in CO_2 composition of the feed until it reaches its maximum point. A further increase can lead to the decrease in the compressor power requirement. The reason for this behaviour is the characteristics of chosen selectivity of the membrane. The effect of membrane selectivity on the compressor power requirement for different design configurations has also been studied as shown in Figure 8. It shows that there is a sudden increase in power requirement by increasing membrane selectivity between 5 and 20, but if we keep increasing the selectivity, there is a slight decrease in compressor power requirement. It is due to the characteristics of specific feed and operating conditions for the investigation.

4.2. Total membrane area

The CO_2 rich crudes demand a larger separation area to achieve the targeted gas quality, which in turn increases the likelihood of methane slip, and subsequently amplifies the gas treatment cost. Besides, due to the significant and irrecoverable methane losses, that contribute most to the total treatment cost, the adoption of the parallel single-stage design is not recommended.

The effect of feed composition on the total membrane area required for the effective separation is studied for proposed design configurations as shown in Figure 11. It is observed that the total membrane area increases with the increase in CO_2 composition of the feed until it reaches its maximum point. After that, a further increase can lead to the decrease in the membrane area requirement. It is due to the characteristics of chosen selectivity of the membrane. It can also be observed that recycling the retentate stream in the multiple stage configurations can lead to large requirements of area, while in the single stage system, recycling has minimal effect. Figure 11 also shows the effect of membrane selectivity on the total membrane area for different design configurations. Increasing selectivity decreases the membrane area requirements, which is more pronounced in the multiple stage configurations, followed by single stage configuration with recycle and single stage configuration without recycle.

Because the feed CO_2 content and feed gas flow rate were well below design basis values during the performance measurement, the observed data were extrapolated to determine the performance optimisation at expected values. With new wells being added, the feed CO_2 increased to near design value of 44.5% and additional feed gas quantities were available for processing. The system parameters where then adjusted to increase the feed CO_2 to optimal value of 44.5%, and increased feed flow to the rate required to deliver the 400 MMscfd of sales gas gross (Export pipeline capacity). Adjustments were made by increasing the operating temperature at the membranes. While this improves the CO_2 removal performance, it also decreases hydrocarbon recovery.

The final step was modelled with the design amount of primary and secondary membrane area on-line. This extrapolation demonstrated that the unit met system design requirements and will achieve better hydrocarbon recovery by producing 400MMscfd of sales gas gross with less than the 750MMscfd feed rate used as the design basis.

5. Conclusions

Large offshore gas processing projects are complex and expensive to operate. The BR-E CO_2 removal facility, with membrane process system, meets the specific CO_2 concentration requirements of export pipeline. The system has been operated for more than 10 years meeting specifications and without significant membrane replacement.

Data analysis and mathematic model allow process engineers to simulate, optimise and evaluate the performance of complex dual-stage membrane processes. In this research, HYSYS module was utilised to simulate and subsequently evaluate the efficiency of the CO_2 removal process, where the crude gas CO_2 content was dropped from 35 - 50% mol down to 8% mol. The result showed that with the right temperature, pressure, and membranes configuration, the sale gas specification were met and the operational challenges, such as high feed flow rate, or bottlenecks were mitigated. Furthermore, the HYSYS user defined unit operation has the potential to be applied for complex membrane system design and optimisation study.

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