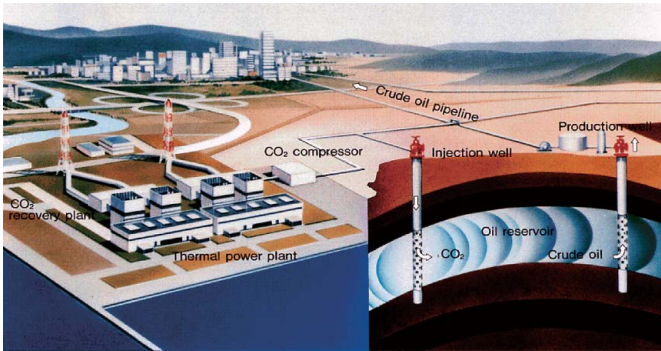


Flue Gas CO₂ Recovery Technology and Its Application to EOR: an Effective Strategy for Addressing the Issues of Global Warming and Peaking Oil Supply

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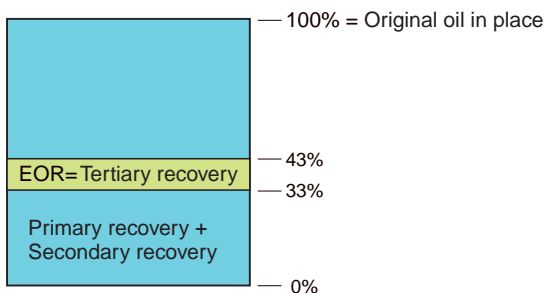


1. Introduction

The price of oil peaked at US\$78/barrel in mid 2006 and then edged downwards. The current market price, around US\$60/barrel, is considerably lower than the peak but still considered quite high (about triple the level in the 1990s [US\$15 to \$18/barrel]).

Energy consumption and demand, meanwhile, continue to rapidly increase, particularly in BRIC countries such as China and India. In parallel, CO₂ emission reductions have not been sufficiently addressed. Is it really possible to prevent global warming by reducing CO₂ emissions? In this paper we discuss CO₂ EOR (Enhanced Oil Recovery), a technology that significantly enhances the crude oil recovery rate^(Note 1) by capturing CO₂ from fossil-fuel-fired flue gas and injecting the recovered CO₂ into an oil field. We also discuss CO₂ recovery and disposal technology [Carbon Capture and Sequestration (CCS)] as another approach for combating global warming. Lastly, we summarize the background of the development of these technologies by Mitsubishi Heavy Industries, Ltd., present our ideas on the application of CCS technology in the future, and paint an image of the future as we foresee it.

Note 1: In general, crude oil production (primary and secondary recovery) leads to the production of around 33% of original oil in place. EOR can lead to an additional 10 % recovery. (See the figure below.)



Relations between original oil in place and oil production
 Original oil in place: oil reserves lying under the ground before oil production is commenced.

2. Worldwide energy consumption and the need for measures to prevent global warming

In 2004 we published a technical report entitled "The View of Oil Resources and CO₂ Emission Mitigation." In that report we summarized the basics of Peak Oil Theory^(Note 2) by Dr. C. J. Campbell and forecasted oil and natural gas production by the ASPO (Association for the Study of Peak Oil and Gas). It is particularly notable that the Peak Oil Theory, a concept generally only discussed in Europe when that report was published, is now discussed widely within the U.S. In the latter part of 2005 this issue was brought back into public debate by Matthew R. Simmons, Chairman of a U.S.-based energy investment banking firm. Nearly a year ago the U.S. Congress held a public hearing to discuss the related measures to be taken by the U.S in relation to this topic.

Note 2: Peak Oil theory: A theory that global oil production will peak in several years and decline thereafter.

Mr. Simmons insists that the Peak Oil crisis is looming and that we must take swift and comprehensive action⁽¹⁾. The Peak Oil Theory is based on a report by Dr. C. J. Campbell concluding that the amount of oil consumed had surpassed the reserves discovered on an annual basis from 1981. This trend has continued moving in the same direction for the last 25 years, and is reflected by the present stringent supply-demand situation. Simmons argues that the production from the world's major oil fields is now declining, as shown below⁽¹⁾.

Daily production now (Unit: Million barrels/day)

- * Ghawar Field (Saudi Arabia):
4.5 - Presumably declining
- * Cantarell Field (Mexico):
2.0 - Declining
- * Burgan Field (Kuwait):
1.7 - Presumably declining
- * Taquing Field (China):
1.0 - Presumably declining

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Several large fields that once produced very large amounts of oil are now producing considerably less. Please see the following examples:

- * Samotlor Field (Russia):
 - 3.0 in 1982
 - 0.3 in 2002
- * Romashkino Field (Russia):
 - 1.6 in 1973
 - 0.3 in 1997
- * Prudhoe Bay Field (Alaska, USA):
 - 1.5 in 1987
 - 0.4 in 2001

The North Sea Oil Field produced 6.0 million barrels a day in 1999. By the end of 2005 the yield had decreased to 4.8 million barrels a day.

Though the production from the major oil fields is declining, recent production from newly commissioned deep sea oil fields, off the coasts of West Africa and Brazil is making up the difference. By around 2010, however, ASPO estimates that global oil production will peak. Oil consumption in the BRIC countries, meanwhile, has been increasing, and their demand for energy will also increase as their standards of living improve. Simmons argues that without immediate action, the whole world will plunge into economic turmoil⁽¹⁾.

He maintains that if plan C is an "alternative energy to oil," then plan B is a "transit energy leading to plan C." And to succeed with plan B, he argues, it will be necessary to execute the following measures immediately⁽²⁾.

- (1) Countermeasures to reduce fuel consumption for transportation, the primary mode of oil consumption:
 - * Hybrid cars
 - * Improvements in gas mileage
 - * Use of rail and shipping for transportation instead of road vehicles (Hydrogen is made from fossil fuel and has very poor economical efficiency.)
- (2) Oil alternatives and technologies for maximizing recovery rates:
 - * Production of heavy crude oil including oil sand
 - * Enhanced Oil Recovery (EOR)
 - * Gas to Liquid
 - * Coal to Liquid
 - * Oil Shale

While the above measures may be available for plan B, the measures for plan C (energies to replace oil) are still unforeseeable.

The former U.S. Vice-President Al Gore has recently toured various countries to assert the importance of preventing global warming. Gore's recent film, "An Inconvenient Truth," has instilled a tremendous public response to the potential crisis of global warming. Gore asserts that political will is more important than anything else in addressing global warming.

The IPCC (Intergovernmental Panel on Climate Change) published a special report entitled "Carbon Dioxide Capture and Sequestration (CCS)" in late 2005. In response, the U.S. and many European countries highlighted the importance of CO₂ recovery and disposal. Without CSS, they maintain, the prevention of global warming may not be achieved. Among the CCS techniques, enhanced oil recovery (EOR) utilizing CO₂ leads to the effective use of CO₂ as a commodity and may serve as a powerful tool for relieving Peak Oil and securing domestic oil reserves. This is why we are most interested in EOR.

3. Requirements for CO₂ recovery technology

This section discusses the various requirements of CO₂ recovery technology for CCS, the prevention of global warming, and EOR.

According to the IPCC Special Report on CCS, 98% of CO₂ emitted to the atmosphere arises from the combustion of fossil fuels (oil, natural gas, and coal). If we are to use our existing energy infrastructures without modification, our top priority should therefore be to recover CO₂ from the flue gas produced from power plants and other large CO₂ sources. Further tasks will be to reduce the energy used to recover the CO₂ emitted to the atmosphere and to compress the CO₂ for disposal, sequestration or use. CO₂ recovery usually requires significant thermal energy, and CO₂ compression requires a great deal of power. For these reasons, the most important requirements in CCS will be to minimize the energy required for both CO₂ recovery and CO₂ compression and to make both processes more cost effective.

To reduce the cost of CO₂ recovery, the equipment cost must be further reduced along with the energy demand for CO₂ recovery. Soaring oil prices have increased the cost of CO₂ for EOR in the U.S. to around US\$50/Ton-CO₂. So the target price for CO₂ recovery and compression in CCS may reach US\$50/ton-CO₂.

CO₂ recovery technology is a technology to prevent global warming. As a matter of course, the technology is required to reduce the negative impacts on the environment. This is why it is essential to minimize the emissions and waste output from CO₂ recovery plants.

4. Background of the development of CO₂ recovery technology

In 1990, MHI started developing technologies to recover CO₂ from flue gas generated from power stations in cooperation with Kansai Electric Power Co., Inc. While the prevention of global warming was certainly one of our motives for developing these technologies, our main objective was to find potential commercial applications for chemicals, general use products already in demand, and CO₂ EOR, in anticipation of shortage of oil supplies in the future.

In the 1990s the need for CO₂ recovery for EOR was still not apparent, with the prices of crude oil stable at around US\$20/barrel or less. Even so, the need for CO₂ recovery technology for the prevention of global warming was expected in the distant future. This compelled us, in the early 1990s, to commence research on basic technology development and to begin acquiring property rights in our developed technologies through patent applications.

Our initial attempts to demonstrate the technology in research and development were performed with monoethanolamine (MEA), a solvent compound that has been conventionally used for CO₂ recovery over the last few decades as one of the most basic absorbents. The relatively small molecular weight of MEA (62) ensures that MEA naturally absorbs a large amount of CO₂ per kilogram of the gas. For this reason, it has been considered difficult to obtain a performance superior to MEA using any other substance within the range of low CO₂ partial pressures under atmospheric conditions. Our comprehensive experiments on CO₂ recovery from boiler flue gas using MEA absorbent liquid revealed the following problems;

- (1) Abundant energy is required for regenerating the absorbent.
- (2) Significant amine loss occurs.
- (3) The rapid and substantial degradation of amine requires frequent reclaiming operations and the discharge of large amounts of waste.

In addition to the problems of the absorbent itself, various issues related to the overall system have been identified.

To address these problems, we returned to the stages of basic research in order to develop a new absorbent, plant and system.

4.1 Development of absorbents

We selected a range of candidate substances for experimental research whilst considering the degree of steric hindrance of amine substances. The conventional absorbent MEA has a low steric hindrance. The amino group of MEA reacts rapidly with CO₂, but once it reacts it is the strong bond which limits the release of CO₂. The amino groups of substances with higher steric hindrance react more slowly with CO₂ but tend to release the CO₂ more readily. We commenced experiments using these substances to select those most suitable for CO₂ recovery from flue gas.

A succession of tests using available amine substances that met specific property and molecular weight requirements has helped us to clarify the characteristics of a wide range of amine substances.

We began by conducting basic experiments on the amounts of CO₂ absorption, reaction heats, reaction velocities, and corrosion behaviors of these substances. Next, the substances that demonstrated positive results

were subjected to continuous tests on absorption and regeneration processes using a bench-scaled test plant for assessment.

The absorbents selected by the bench test were examined by further experiments to assess the energy consumption, amine loss and other properties related to operation using a pilot plant installed at the Nanko Power Station operated by Kansai Electric Power Co., Inc. Three absorbents with high energy saving properties, KS-1, KS-2 and KS-3, were identified to be feasible for practical use. From a cost standpoint, we decided to commercialize the first of these three, KS-1.

4.2 Plant development

We also succeeded, while testing and developing the absorbent, in designing a plant capable of complementing the solvent. Initially we developed a heat exchanger and tried to optimize the packing materials for the absorption and regeneration beds, in order to ensure that the plant would be suitable for the absorbent. In most of the work we sought to extend conventional design work rather than develop new types. We developed low-pressure-loss packing materials KP-1 with significantly reduced pressure loss and demonstrated the low pressure loss and high CO₂ absorbability of the packing material using the pilot plant installed at the Nanko Power Station, Kansai Electric Power Co., Inc. As KP-1 is currently more expensive than commercially available packing materials, it has not yet been commercialized.

We also attempted to effectively utilize thermal energy in the overall system for electric power generation and CO₂ recovery. Through this effort, we established a system that simultaneously uses the heat transferred to the steam condenser in the CO₂ recovery system and the waste heat of the CO₂ recovery system for preheating the boiler feed-water.

Lastly, we established an energy-saving system that significantly reduces thermal energy requirements for regenerating absorbents by effectively using the surplus heat in the CO₂ recovery system. This system was demonstrated using the pilot plant at the Nanko Power Station.

5. Potential future of CO₂ recovery technology application

The CO₂ recovery technology from flue gas may be used in the following applications.

- * General use such as carbonated beverage and dry ice industrie
- * Chemical uses such as the urea, methanol, and oxo gas
- * EOR by way of CO₂
- * Enhanced Coal Bed Methane Recovery (ECBMR) by way of CO₂
- * Geological storage to aquifer, depleted oil and gas fields.

Among the above applications, methods capable of effectively using the recovered CO₂ are of course the most

desirable. According to general use and use for chemicals, CO₂ is re-released and does not serve to prevent global warming. Available approaches for the prevention of global warming include EOR, ECBMR, the storage-to-aquifer process, and injection into depleted, oil and gas fields. Among these, EOR and ECBMR enable the recovery of crude oil and natural gas during CO₂ disposal.

A special report on CO₂ recovery and sequestration from the IPCC⁽³⁾ and a report from the Engineering Advancement Association of Japan⁽⁴⁾ have reported the following values as the maximum CO₂ receptive capacities throughout the world.

- * EOR: 65 billion tons-CO₂
- * ECBMR: 15 - 200 billion tons-CO₂
- * Depleted, oil and gas fields: 675 - 900 billion tons-CO₂
- * Aquifer: 1,000 - 10,000 billion tons-CO₂

In calculating the EOR potential above, CO₂ is assumed to be injected with optimal efficiency (smallest amount of CO₂) according to the estimation of the Engineering Advancement Association of Japan.

The annual emission of CO₂ into the atmosphere worldwide is estimated at 23 billion tons. Thus, the maximum CO₂ receptive capacity shown above is sufficient for underground storage and processing. Where CO₂ is effectively used for EOR, an amount of CO₂ corresponding to a 3-year period of emission can be used for EOR. The problem is whether CO₂ can be recovered from adequate CO₂ emission sources in the Middle East or other areas, then transported to the oil fields (especially those in the Middle East, where EOR has the most potential). The original oil in place in the Middle East currently has a total expected is about 2 trillion barrels. Assuming that 15% of the original oil in place is recovered by CO₂ EOR, an additional 300 billion barrels of oil will be recovered. To accomplish this, an estimated 80 billion tons of CO₂ will be required. If this amount of CO₂ is to be supplied in the next 50 years, then 1.6 billion tons of CO₂ a year will be required. The amount of CO₂ currently emitted from power stations and large industrial sources in the Middle East is estimated at between 0.2 to 0.4 billion tons/year. So even if CO₂ emissions in the Middle East significantly increase in the future, the CO₂ capacity sufficient for EOR will not be realized. If CO₂ EOR is to be performed on a wide-scale in the Middle East, it will be necessary to recover CO₂ from other areas such as Japan, Asia, and Europe and transport it using pipelines and liquid CO₂ tankers.

According to an estimate by the Engineering Advancement Association of Japan, the cost of recovering CO₂ at power stations in Japan and transporting it to the Middle East would be US\$120/ton-CO₂.

If EOR is applied to the Middle East oil fields using the CO₂ thus transported, the cost of EOR is calculated to be about US\$30/barrel (CO₂ cost). Therefore, if the current oil price of around US\$60/barrel is maintained

in the future, EOR in the Middle East using CO₂ recovered and transported from Japan will become economically feasible.

Based on the foregoing, we conclude that if the CO₂ now emitted into the atmosphere is recovered, the recovered CO₂ could be effectively used not only as a means of preventing global warming, but also for commercial application in EOR worldwide. To accomplish this, a system for transporting the recovered CO₂ to oil fields would need to be established. Transportation of liquefied CO₂ is relatively easy compared with that of LNG in terms of temperature, and it involves no technical barriers. The important challenge will be to create a market mechanism to ensure that this system becomes economically feasible.

6. Conclusion

Global warming results from the combustion and use of fossil fuels such as oil, natural gas and coal. However, we have now developed technologies capable of further recovering oil and securing important energy reserves. When CCS is applied to prevent global warming, we can effectively use the recovered CO₂ in applications such as EOR for the stable supply of oil. This can help alleviate the tremendous problems we are expected to face in the near future.

However, this requires political initiative to promote CO₂ EOR as a measure for the prevention of global warming and energy security.

MHI will work towards the technological advancement and industrialization of CO₂ recovery technology, in an effort to address the issues outlined in this paper.

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