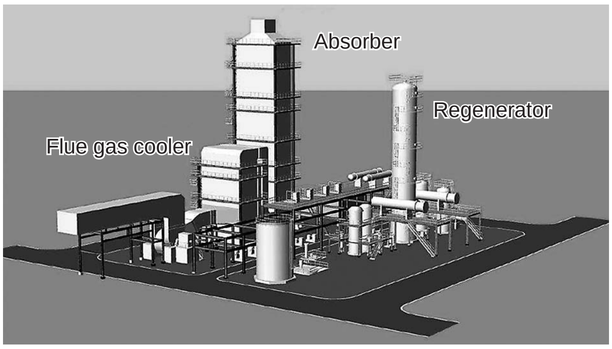

Large Scale Flue Gas CO_2 Recovering/CO_2 Cost and Total System for CO_2 Enhanced Oil Recovery

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Enhanced oil recovery (EOR) in which CO_2 is injected into reservoirs in order to increase crude oil production has been commercialized mainly in the US. By utilizing flue gas CO_2 recovery technologies, CO_2 recovered from the flue gas of power generation plants can be applied to EOR. When a flue gas CO_2 recovery plant is used as a source of CO_2 for CO_2 EOR, the plant comprises a large part of the total investment, and CO_2 recovery costs greatly affect oil recovery cost. The comprehensive economic studies are made for CO_2 recovery plant in application of EOR projects based on various parameters which include capacity of CO_2 recovery plant, utility cost, pipeline cost and any other operational requirements. This paper focuses on some of these economic study results to identify which parameters impact on CO_2 recovery cost. Consideration is also given to the selection of flue gas sources and plant locations with the aim of further minimizing recovery costs.

1. Introduction

CO_2 EOR(NOTE 1) is well known as an enhanced recovery method used in reservoirs that can theoretically lead to an increase ultimate oil recovery. The method was commercialized in the U.S. during the 1970s, and has since contributed to increasing oil production by approximately 200 000 barrels per day. The CO_2 EOR is also established in Canada, Turkey, and Hungary.

Almost all of the CO_2 used for EOR in the U.S. is generally supplied from gas fields through the CO_2 transport pipelines. Even in those areas where there is no large-scale CO_2 source, CO_2 can be recovered from flue gas discharged from the stacks of various plants by utilizing flue gas CO_2 recovery plants. CO_2 EOR can then be carried out by supplying the CO_2 thus recovered to neighboring reservoirs. The application of CO_2 recovery from flue gas for EOR also has an added beneficial environmental effect of reducing the discharge of CO_2 as a result of the CO_2 sequestration in the reservoir.

NOTE 1:
Although a secondary crude oil production such as water flooding is used, typically 60 to 70% of oil cannot be recovered from reservoirs with this method. EOR belongs to a tertiary crude oil production capable of further recovering oil. In the CO_2 EOR, a miscibility condition (state in which CO_2 is freely mixed in oil under supercritical pressure) is formed in a reservoir to remarkably increase an crude oil production.

The first commercial plant for recovering CO_2 from flue gas in the world was constructed about 20 years ago based on technology developed by Dow Chemical Company. At that time, there was already an idea to apply a flue gas CO_2 recovery plant to EOR. In fact, a 1000 t/d (19 MMSCFD(NOTE2)) flue gas CO_2 recovery plant was constructed in 1983 in Lubbock, Texas for the purpose of EOR. However, the plant was dismantled in 1985 for economic reasons.

The technology developed by Dow Chemical Company used monoethanolamine solvent, which had long been used for the absorption of acid gas. This method consumes much energy and leads to the violent deterioration of the solvent. In addition, it still has many technical problems such that it requires a metal-based corrosion inhibitor to protect against and prevent corrosion. Since then, Fluor Daniel Inc. acquired its license from Dow Chemical Company for the chemical absorption process. However, only limited technical improvement could be realized in the process.

NOTE 2:
MMSCFD = 10^6 standard cubic feet per day
MMSCF CO_2 = 10^6 standard cubic feet of CO_2
feet of CO_2 = 52.6 metric ton of CO_2

During the first part of the 1990s, MHI, working in joint cooperation with the Kansai Electricity Co., Inc., began to develop a new flue gas CO_2 recovery process for the large-scale CO_2 recovering discharged from power generation plants, and in 1998 delivered a first commercial plant with a maximum recovery rate of 210 t/d (4 MMSCFD) to Malaysia.

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The technology developed by MHI has several excellent features, including lower energy consumption and easy maintenance of the solvent. In addition, the process can also be used to recover a large amount of CO_2 at low cost for the purpose of EOR and is an effective countermeasure against global warming. MHI has also been actively taking part in many projects in order to achieve CO_2 EOR using the flue gas CO_2 recovery plant in the Middle East and South East Asia in the near future.

Needless to say, in CO_2 EOR, the cost of CO_2 has a major impact on the cost of oil production. When the flue gas CO_2 recovery plant is constructed for EOR, feasibility of EOR depends upon whether or not a large amount of CO_2 can be recovered and supplied to the reservoir at low cost.

In this study, factors affecting CO_2 recovery cost were quantitatively examined assuming that CO_2 is recovered from the large capacity flue gas sources of boilers and gas turbines and that CO_2 EOR is performed using an MHI flue gas CO_2 recovery plant.

2. Outline of overall CO_2 EOR system

Figure 1 shows a schematic view of the overall CO_2 EOR system with the flue gas CO_2 recovery plant. The basic configuration of the equipment used to separate oil from the associated gas and water does not differ from that used in normal oil production facilities. The points where the equipment in this system differ from typical oil production equipment include the incorporation of the flue gas CO_2 recovery plant, CO_2 compression/dehydration unit, CO_2 pipelines, CO_2 injection wells for injecting CO_2 into the reservoirs, and a facility for separating CO_2 from associated gas.

To prevent wet carbonate corrosion, recovered CO_2 from the flue gas is dehydrated until its dew point is lowered to less than 0°C. In order to transport and inject the CO_2 into underground reservoirs, the CO_2 gas needs to be compressed up to a critical pressure of 74 kg/cm^{2}G or higher, and fed to the reservoirs through a CO_2 pipeline.

Oil production is stimulated by the presence of CO_2. Concurrent with oil production rate increases, CO_2 is also produced since it is present in the crude oil and "CO_2 breakthrough" occurs. The associated gas requires processing in order to recover the valuable CO_2 for recycle usage for EOR as well as to eliminate CO_2 from the residue hydrocarbon product such as gas product or natural gas liquid.

The CO_2 recovered in the CO_2 separating plant is mixed with the CO_2 supplied from the flue gas CO_2 recovery plant and re-injected into the reservoirs. The CO_2 of the associated gas is in high partial pressure and, therefore, can be separated easily with less energy than that required when recovering CO_2 from the flue gas. In short, operation costs can be reduced by effectively utilizing the CO_2 separated from the associated gas.

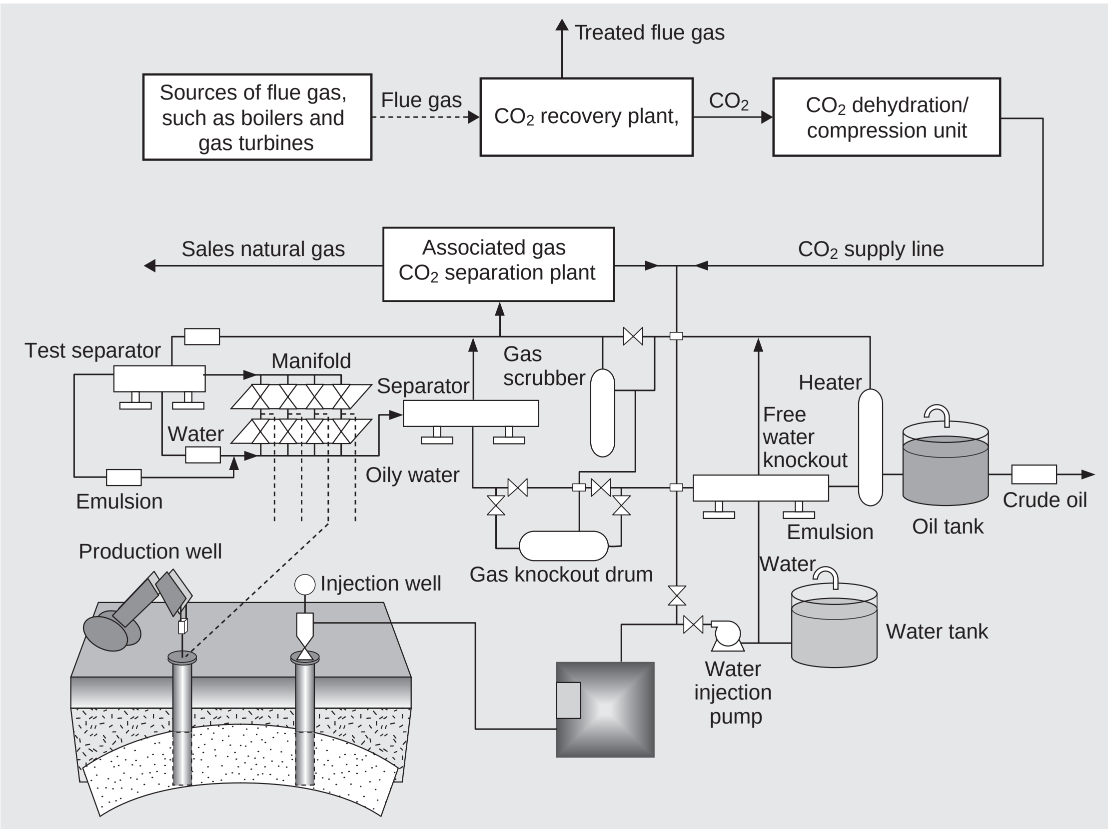

Fig. 1 Concept of overall system for CO_2 EOR

Various facilities are available for use in separating CO_2 from associated gas (CO_2 recycle plant). Some of these facilities only consist of the compression unit while others use various systems such as the membrane method, absorption method, or distillation method. These methods each have their respective merits and demerits, and an optimum method is selected at each site according to the concentration of CO_2 in the associated gas and the product specifications of hydrocarbons.

Typically, CO_2 EOR involves injecting CO_2 and water alternately. CO_2 gives a highly carbonate corrosive environment if it contains moisture. Corrosion-resistant steels or coated materials are used, or a corrosion inhibitor is used for the production equipment such as CO_2 injection wells and oil gas separators because the equipment has portions that are easily prone to corrosion.

When CO_2 EOR is performed in a reservoir that is currently under normal production, investment costs for the flue gas CO2 recovery plant and the CO_2 compression/dehydration unit comprise about half of the total investment cost involved, though it differs much depending upon the conditions.

Accordingly, this study focuses on the recovery cost of CO_2 produced using the flue gas CO_2 recovery plant and CO_2 compression/dehydration unit in the following.

3. Requirements for CO_2 used in EOR

3.1 Purity of CO_2 gas

CO_2 forms a miscibility condition in a reservoir, i.e., a state in which CO_2 is freely mixed in oil under supercritical pressure to remarkably lower the viscosity of the oil. This leads to significantly increasing the ultimate oil recovery. Impurities in CO_2 affects the phase boundaries and raises the CO_2 minimum miscible pressure (pressure achieving miscibility condition) of the reservoir, which becomes the cause of severe corrosion of the oil production equipment.

Accordingly, the CO_2 specification must be controlled so that any impurities mixed in the CO_2 are within allowable contents. The allowable contents of the impurities are dependent on the reservoir formation and the injection method. For example, in CO_2 EOR that is now performed mainly in the Western Texas in the US, impurities such as methane (CH_4), ethane (C_2H_6), nitrogen, and hydrogen sulfide are controlled so that the purity of CO_2 is 94 vol.% or higher. Since methane and ethane contained in CO_2 raises the miscible pressure of reservoir, these substances are limited to less than 4 vol.%. Since nitrogen also raises minimum miscible pressure, it is limited to a maximum of less than 5 vol.%. Although hydrogen sulfide is somewhat beneficial to increase miscibility condition, it is limited to less than 100 ppmv only for safety reason.

Since the MHI's flue gas CO_2 recovery plant utilizes a chemical absorption process, the purity of the recovered CO_2 is as high as 99 vol.% or higher. The major impurities include nitrogen and oxygen and, therefore, no significant problems occur when they are applied to EOR.

3.2 Required amount

The amount of additionally recovered crude oil when CO_2 is injected, that is, the effect of CO_2 EOR varies according to the subject reservoir. In general, the amount of crude oil further produced by the CO_2 supplied is reported to be 3 to 20 MMSCF/bbl. When the required amount of CO_2 is 3 to 8 MMSCF/bbl, the effect of CO_2 EOR is said to be high.

3.3 Gas pressure

CO_2 is typically transported in a supercritical state than critical pressure (74.3 kg/cm^{2}G) to prevent the CO_2 from separating into gas-liquid two phase in the pipelines, which would result in an increased pressure loss and hammering for pipelines. Thus, Usually, a CO_2 delivery pressure of 2 000 psig is used at the inlet of the CO_2 pipeline.

Once the CO_2 has been transported to the reservoir, it is further compressed for injection to suit the well head pressure into the reservoir. A special pump is typically used to compress the CO_2 in the EOR site.

4. Study conditions

4.1 Study cases

MHI flue gas CO_2 recovering process was chosen as appropriate CO_2 capture technology for performing CO_2 EOR. Consideration was given to the four cases outlined in **Table 1** as examples of recovering CO_2 from the boilers and gas turbines of power generating plants and industrial plants.

Natural gas is used as fuel in each of the cases of the boilers and gas turbines noted above. In addition, the flue gas do not contain any SOx, as it must undergo desulfurization treatment on the upstream side of the flue gas CO_2 recovery plant. In all cases, a dedicated auxiliary boiler is installed to supply the steam required to operate the CO_2 recovery plant and CO_2 compressor.

Table 1 Study basis

Study cases	CO_2 concentration (vol%)	CO_2 recovering capacity (t/d) (MMSCFD)
Boiler case 1	8.5	5 260 (100)
Boiler case 2	8.5	3 160 (60)
Gas turbine case 1	3.0	4 730 (90)
Gas turbine case 2	3.0	2 630 (50)

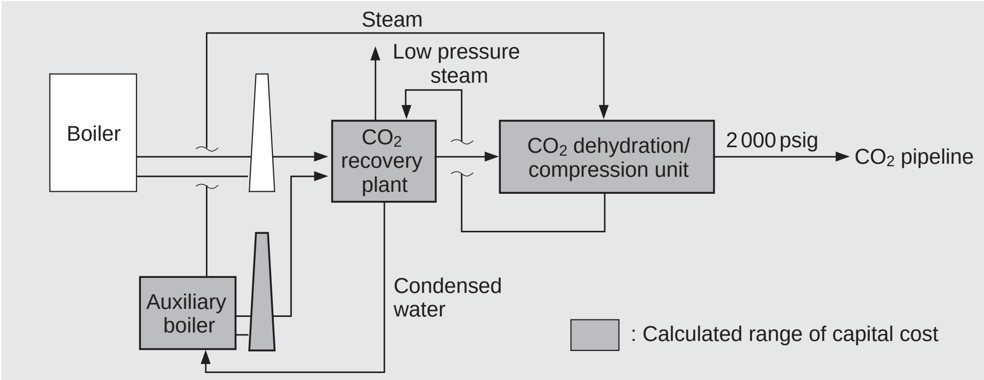

Fig. 2 Boiler case

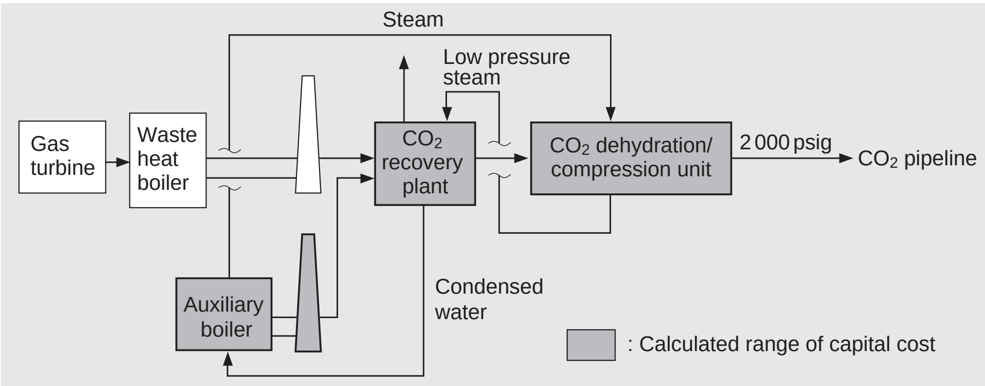

Fig. 3 Gas turbine case

Figures 2 and 3 show the system configurations of the flue gas CO_2 recovery plant and the CO_2 compression/dehydration unit. The CO_2 recovered from the flue gas of the boilers and gas turbines is compressed and dehydrated, and fed into the CO_2 pipeline. The conditions under which the CO_2 is supplied are estimated to be 2 000 psig in pressure and 45°C in temperature. The CO_2 compressor is of single train at the four-stage.

4.2 Basis for calculating capital cost

The capital cost (CAPEX) consists of the total of the initial investment cost to construct the flue gas CO_2 recovery plant, the CO_2 compression/dehydration unit, and auxiliary boiler for flue gas CO_2 recovery plant. The plant cost was calculated based on the results of delivering commercial plants by MHI in the Middle East countries. The depreciation of the capital costs were assumed to be 10% based on the fixed amount method.

Table 2 Basis for operating cost

	Cost of Utilities		
Fuel gas (US$/MMBtu)	0.5	1.0 (Base)	1.5
Cooling water (US ¢/t)	1.0	1.5 (Base)	2.0
Electricity (US¢/kWh)	2.0	3.0 (Base)	4.0
Operators (US$/Y)	0.25	→	→
Maintenance (US$/Y)	*	→	→

NOTE: Operator includes analyzer and engineer.
Maintenance includes consumable items and spare parts.
Maintenance costs are set at 1% (annually) of the capital cost.

4.3 Basis for operation cost

To obtain the operation cost (OPEX), expenses associated with the operation of the flue gas CO_2 recovery plant, that is, expenses for utilities, operators, maintenance, consumable items, and spare parts, as well as general plant and administrative expenses were totaled.

The unit price of the utilities was varied in the area described below. The values of the unit prices of fuel gases in areas in the Middle East where the fuel gas cost is inexpensive were taken as typical examples.

The ratio of the expenses for operators, maintenance, consumable items, and spare parts, as well as general plant and administrative expenses to operating costs was small. These expenses were considered to be constant, as shown in **Table 2**.

5. Relation between CO_2 recovery cost and cost-effective factors

5.1 CO2 recovery cost (base case)

When the utility cost is used as a base, namely, when the fuel gas cost is US$1.0/MMBtu, cooling water cost is US 1.5 cents/t, and power cost is US 3.0 cents/kWh, the results of trial calculations of CO_2 recovery and compression costs (hereafter referred to as CO_2 recovery costs) are as shown in **Table 3**. When attention is paid to the sum total of the capital cost and operation cost, plant boiler case 1, which has the largest CO_2 recovery volume and highest CO_2 concentration in the flue gas, has the lowest CO_2 cost.

Table 3 Study results

Case	CO_2 content in flue gas (vol %)	CO_2 recovering capacity (MMSCFD)	On-stream factor (%)	Capital cost (CAPEX) (US$/MSCF)	Operation cost (OPEX) (US$/MSCF)	Total cost (US$/MSCF)
Boiler case 1	8.5	100	90	0.472	0.444	0.916
Boiler case 2	8.5	60	90	0.533	0.515	1.048
Gas turbine case 1	3.0	90	90	0.609	0.830	1.439
Gas turbine case 2	3.0	50	90	0.609	0.838	1.446

5.2 Relation between CO_2 recovery cost and cost-effective factors

(1) CO_2 recovering capacity

The relation between the CO_2 recovery cost and the CO_2 recovering capacity from the flue gas CO_2 recovery plant is shown in **Fig. 4**.

Compared with the gas turbine case, the boiler case has a lower CO_2 recovery cost. This is because the CO_2 concentration of boiler flue gas is higher than that of gas turbine exhaust gas, consequently, the utilities required to recover CO_2 are less, and since the size of the equipment which handles the exhaust gas is smaller, the capital cost accordingly results in smaller.

In both the gas turbine and boiler cases, the CO_2 recovery cost decreases as the CO_2 recovering capacity increases. It remarkably decreases in the case of the boiler.

In addition, the equipment cost becomes higher since the concentration of CO_2 in gas turbine exhaust gas is low and the large amount of exhaust gas must be treated. The maximum CO_2 recovering capacity from the flue gas CO_2 recovery plant in the gas turbine case that can be constructed in one series using current technology is up to 50 MMSCFD.

On the other hand, with the boiler flue gas which is higher in CO_2 concentration than the gas turbine exhaust gas, the plant can be constructed in one series of up to a maximum of 100 MMSCFD using current technology.

Basically, the flue gas CO_2 recovery plant is a facility that enjoys the merits of scale construction. In the boiler case in which the plant can be constructed in one series capable of recovering CO_2 ranging from 50 to 100 MMSCFD, the plant can enjoy the merits of scale. The CO_2 recovery cost is significantly reduced due to the increased CO_2 recovering capacity.

Thus, from the above it can be seen that boiler flue gas can be selected as the most advantageous source of exhaust gas due to its higher concentration of CO_2 compared with the other sources.

(2) Relation between flue gas cost and CO_2 recovery cost

The relation between the cost of recovering CO_2 and the fuel gas cost is shown in **Fig. 5**. The CO_2 recovery cost decreases as the fuel gas cost becomes less. When CO_2 is recovered from boiler flue gas with a high concentration of CO_2, the CO_2 recovery cost falls within a range of US$0.8 to 1.0/MSCF.

A flue gas CO_2 recovery plant requires a large amount of low pressure steam to regenerate the solution and, hence, it could be confirmed that the CO_2 recovery cost is affected largely by the fuel gas which produces the steam. Thus, when constructing the flue gas CO_2 recovery plant, it is important to select an area where the fuel gas cost is low.

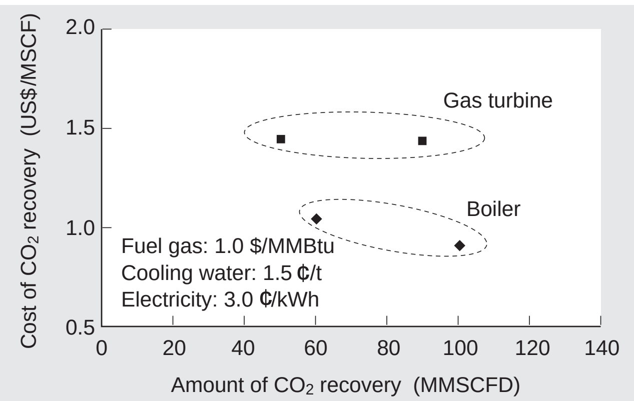

Fig. 4 Relation between CO_2 recovery cost and CO_2 recovery capacity in the flue gas CO_2 recovery plant

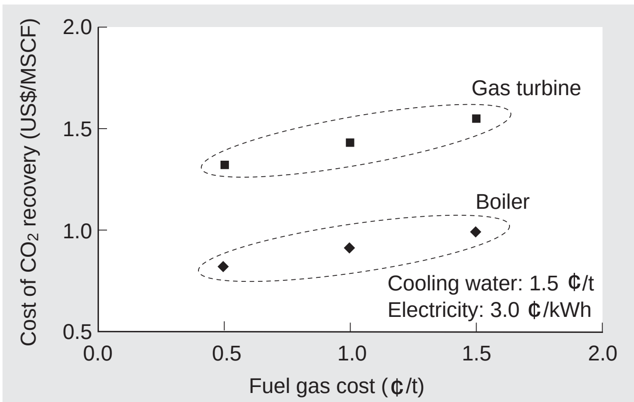

Fig. 5 Relation between CO_2 recovery cost and fuel gas cost

(3) Relation between cooling water cost and CO_2 recovery cost

The relation between the CO_2 recovery cost and the cost of cooling water is shown in **Fig. 6**. Though the degree of reduction in the CO_2 recovery cost is not higher than that for the fuel gas cost, it reduces as a result of a lowering of the cost of cooling water. A relatively large amounts of cooling water is used to cool the flue gas and the top section of the amine solution regenerator. It could be confirmed that the cost of cooling water affects CO2 recovery cost next after the fuel gas cost.

(4) Effects of pipeline on CO_2 recovery cost

MHI data for various areas in the Middle East showed that the cost for CO_2 pipelines ranged between US 6 to 10 cents/MSCF/100 km.

Assuming that CO_2 is transported from the flue gas CO_2 recovery plant to the reservoir through 100 km CO_2 pipeline, when the CO_2 recovery cost is US$ 1.0/MSCF, the ratio of the CO_2 pipeline cost to the cost of CO_2 at the destination in the field is approximately 6to 9%. The effect of the CO_2 pipeline cost on the CO_2 recovery cost can thus be said not to be so large.

(5) Observations

The economic study result shows that the calculated cost of CO_2 in the reservoir is US$ 1.0/MSCF or less when an excellent source of flue gas with a high CO_2 concentration such as boiler flue gas is present at a location that is within 100 km from the reservoir, and natural gas and cooling water are available at low cost. This cost value is equivalent to that of natural gas which competes with CO_2 as a medium for EOR.

At present, natural gas is injected as a medium for a secondary crude oil production in many cases. However, sufficient consideration could also be given to the use of CO_2 recovered flue gas, which is equivalent to natural gas in terms of cost, as a replacement for natural gas.

A number of benefits can be realized through the use of flue gas recovered CO_2 for EOR including the fact that CO_2 injected into the ground becomes sequestrated in the reservoir and thus can contribute to the prevention of global warming. When the EOR project using flue gas-recovered CO_2 is applied to a clean development mechanism (CDM) and joint implement (JI) of the Kyoto mechanism to prevent global warming, the reduced amount of CO_2 can be internationally traded as a credit of a reduced amount of greenhouse gas emission.

For CO_2, US$1/MSCF is equivalent to US$19/ton. Accordingly, when the trading price of the emission right for CO_2 is equal to or greater than US$20/ton, the cost of flue gas CO_2 can be completely offset by that price, and a CO_2 EOR project results in a large profit.

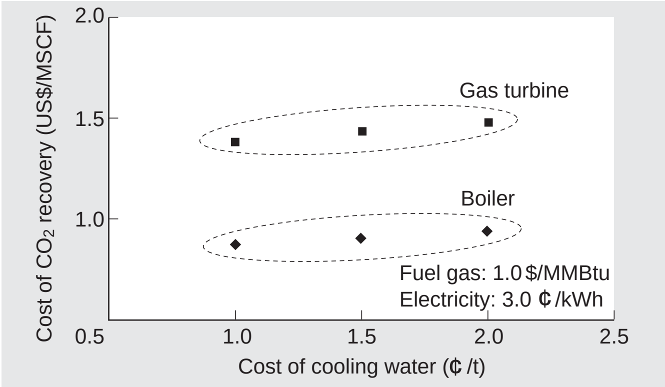

Fig. 6 Relation between CO_2 recovery cost and cooling water cost

6. Conclusion

When a large amount of CO_2 is recovered from a flue gas source with a high concentration of CO_2 in an area where inexpensive utilities are available, the cost of such CO_2 recovery is extremely competitive as a medium for use in EOR. In particular, the effect of the fuel gas cost on the CO_2 recovery cost is remarkably large, and the CO_2 recovery cost in a place with the low gas cost becomes very small. In addition, when the distance between the flue gas CO_2 recovery plant and the reservoir is approximately 100 km, the effect of the cost of the pipelines used to transport CO_2 on the cost of recovering CO_2 is relatively small. Accordingly, when the flue gas CO_2 recovery plant is located in an area that is within several hundred kilometers from the reservoir where inexpensive fuel gas and a large source of flue gas with a high CO_2 concentration are available, CO_2 EOR becomes feasible with a high level of economic efficiency.

When CO_2 is recovered on a large scale from fuel gas at a rate of approximately US$1/MMBtu with the flue gas CO_2 concentration of 8.5% by volume, which is a typical value for most gas-fired boilers, the CO_2 recovery cost falls within a range of US$0.8 to 1.2/MSCF (US$ 15 to 23/ton). This is equivalent to the average price level for CO_2 emission trading rights in Europe that can be expected in the future. When an EOR project using flue gas recovered CO_2 is adapted to CDM and JI, the cost of recovering CO_2 is offset by the cost of the emission trading rights and, hence, the EOR project becomes more advantageous over methods in terms of potential profit margin.

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