CO₂ IOR in the Szank Field Using CO₂ from Sweetening Plant

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Abstract

Field scale CO₂ EOR operations started in 1972 in Hungary. Partially miscible EOR recovery was completed in the sandstone reservoirs of Budafa and Lovászi fields and recovery by artificial CO₂ gas cap has been accomplished in the carstic/cavernous limestone reservoir of the Nagylengyel field. A sweetening plant was built in the area between the Danube and Tisza to utilize the high CO₂ content natural gases. The "by-product" of this plant is CO₂ gas. Using this gas immiscible CO₂ EOR operation was realized in the SE zone of the Szank field. The injection of CO₂ started in 1992. The former production experiences could well be utilized during the CO₂ recovery.

The paper presents the production technology, the results, the plant facilities, introduces the experiences gained during the production and gives a summary of Hungarian experiences in the field of EOR recovery projects and reservoir management.

CO₂ EOR recovery operations in SW Hungary

EOR research and investigations started as early as in the 50's in Hungary. Pilot plant experiments started in the 60's with the injection of carbonated gas made of flue gas of boilers.

A high CO₂ content natural gas reservoir has been discovered under the Budafa oil field (Budafa deep horizon) which rendered possible wide-spread use of CO₂ EOR methods in SW Hungary (1), (2), (3).

Field-scale EOR operations started between 1969 and 1981 based on this high pressure gas reservoir containing an 81% by mole CO₂ concentration natural gas. The reservoir rock of the fields is sandstone and the CO₂ EOR is of partially miscible type.

A special segregation recovery method has been developed in field-scale for the Nagylengyel field. The reservoir rock is carstic limestone. Pilot plant experiments started in 1979 and the so-called "recovery by artificial CO₂ gas cap" method is used in field-scale since 1988 (4). It is an extraordinary luck by the nature of things that the 150 bar wellhead pressure of the Budafa deep horizon rendered possible the operations without compressor (5).

Approximately 2,5 million ton additional oil was produced till the end of February 1995 from the Budafa, Lovászi and Nagylengyel fields by CO₂ EOR method. The production is in its final stage in the Budafa and Lovászi fields, but in Nagylengyel the recovery by artificial CO₂ gas cap will probably continue after 2000, too.

The mechanism and experiences of CO₂ EOR operations in SW Hungary

It is a basic fact from recovery technology point of view that the natural parameters of the sandstone reservoirs (reservoir pressure and -temperature), the reservoir fluid and the composition of the given carbonated natural gas do not render possible the establishment of dynamic miscibility.

Stages of recovery:

- . increase of reservoir pressure by injection of carbonated natural gas from 30 bar to 110 bar;
- . water flooding;
- . depletion.

The high gas saturation of the layers resulted in a favourable volumetric flood efficiency. However, the initial GOR was high due to the high gas saturation. It was necessary in some cases to restore the pressure of the gas cap, too, and consequently, the specific gas demand increased.

The recovery technology improved continuously as a result of increasing experience. E.g. WAG injection was accomplished in the Lovászi field after increasing the pressure. Similar injection method is used in the Zala-Kerettye layers of the Budafa field by the use of "elastic well pattern". The primary recovery mechanism was the active water drive in the Nagylengyel field. Substantial amount of oil was left behind in closed domes and on the top of the structure during primary recovery. This oil is displaced by establishing an artificial gas cap which results in a gravitational segregation and drainage of this attic oil.

The stages of recovery are:

- . gas injection; the producing wells operate in this period depending on the position of the oil belt and GOC;
- . blow-down: all of the producers are in operation;
- . transfer of the produced gas to other blocks of the field where this process is repeated.

The aim of reservoir management systems was to minimize the specific use of carbonated natural gas and to maximize volumetric flood efficiency in porous sandstone reservoirs. To reach these aims the production wells were produced without limitation until the CO₂ concentration of the associated gas reached 65% by mole. The production rate of the wells was reduced, periodical production or longer shut-in period was prescribed if the CO₂ concentration exceeded the limit value mentioned above or if the production GOR reached the 500 cu.m/cu.m limit. The aim of the control in carstic limestone reservoir was to follow the oil belt formed, to maximize the oil production and to minimize the production of free gas both in the period of gas injection and gas blow-down. The wells have an average production rate of 100 cu.m/d including water cut, too and are produced after the appearance of oil until the expansion of the gas cap results in a sudden increase of the gas production.

Production technology experiences

The wells of the fields used for primary recovery are utilized in general for CO₂ EOR operations, too, together with the necessary modification of functions and the re-completion of the wells. New wells were drilled only if it was absolutely necessary. Special methods had to be used in the Nagylengyel field to well completion where several wells broke down during drilling. The treating of the carbonated natural gas was restricted to the separation of free water, however the pipeline transport to Nagylengyel necessitated the adjustment of the dew point, too. High pressure drying was chosen (by the use of glycerol) so pressure boosting was not necessary (6). Large-scale facility system was established to the injection of carbonated natural gas and water, to gather and to treat the well effluents and to service- and auxiliary activities (7), (8).

The corrosion caused by the gas containing H_2S , too, was very severe in the first period. However, the highly efficient gas processing reduced significantly these problems.

Quality and quantity considerations caused and cause problem for the injection water in Budafa and Lovászi field; the injection water is a mixture of reservoir water and surface waters. The dissolved in water CO_2 is a significant source of corrosion in open production facilities when treating well effluents. Hungarian specialists gained widespread experience in the planning, reservoir management, construction and operation of facilities of EOR projects, which rendered possible to start new EOR recovery project(s).

Oil and gas production in the area between the Danube and Tisza

The hydrocarbon production started in this area in 1964 (Fig.1). The cumulative production of 35 reservoirs was appr. 4.2 million ton crude oil, 16.9 million cu.m. natural gas and 1.3 million ton gascondensate till the beginning of 1995. Initially, the gas of the most important field, Szank, was uniform good quality (35-38 MJ/cu.m) and could be sold without any problem in the area and could be pipelined to the domestic gas network. The prospecting in this area resulted in many new fields, however, the gas of these fields had lower heating value so they could not be put into production.

The specific features of gas reservoirs in the area:

- relatively many, separated reservoirs,
- little, or medium reserve,
- the quality and composition of the gas of individual gas reservoirs differs significantly,
- the share of good quality gas sharply decreases,

the reservoirs are located in a relatively large area.

The gas quality in the area can be divided into three groups:

- gases of high heating value (35-38 MJ/cu.m.): Szank Miocene gas cap, oil associated gases from Szank-Szank West reservoirs, Szank W II. free gas reservoir, Tázlár-lower Pannonian, Kiskunhalas free gas reservoir;
- gases of medium heating value (32 MJ/cu.m): Zsana North, Eresztő;
- gases of low heating value (25-30 MJ/cu.m): Tázlár Miocene massive type reservoir, Kiskunhalas NE-N, NE-S oil associated gases, Harka, Jánoshalma, Soltvadkert, Kiskunmajsa-S.

A possible way of selling gases of different quality is to establish a "mixing circuit" which mixes a uniform gas quality from different gases. This mixing circuit was built in 1986 and operated properly until sufficient quantity and good quality "leading gas" was at disposal and could satisfy the basic and peak demands of the given region. The discovery of the Kiskunmajsa-S field with high reserve but low heating value gas increased gas reserves which can not be utilized by mixing, so new solutions had to be developed to fulfil gas demands.

The construction of a sweetening plant has been decided to ensure the gas quality prescribed by the standard and to sell the gas. The aim of this plant was to remove CO_2 from natural gases.

Theoretical questions of CO_2 removal from natural gases

Several processes are known to remove CO_2 from natural gas. The choice among them is influenced by the quality and parameters of input gas and the prescribed parameters of output gas.

In our case the natural gas contains 5-6% by mole of N_2 , so it was necessary to reduce the CO_2 content of the output gas under 2% by mole (removing the sour component the hydrocarbon natural gas enriches in nitrogen). The solvent technologies are favourable under such conditions. Most of the offers for the sweetening plant proposed the tertiary amine process. The "a-MDEA" (BASF licene) technology has been chosen.

The sweetening plant

The scheme of the technology: the gas contacts in counterflow with the solvent in the absorber. The gas enters on the bottom of the tower and leaves it on the top. This gas containing max. 2% by volume CO_2 can be pipelined after processing. The a-MDEA entering on the top of the tower will be saturated with CO_2 and leaves the tower on the bottom. The regeneration of the solvent - removal of CO_2 - happens in three pressure stages and by heating. The liberated CO_2 will be compressed in three pressure stages (fitted to the pressure of desorbers) to 56-58 bar. After the third stage the CO_2 gas is treated with TEG to set the necessary - 18°C dew point and is compressed by the fourth stage compressor to the EOR injection pressure (180 bar).

The technical parameters of the facility:

Input gas stream: 40 thousand cu.m/h
natural gas
17-26% CO_2 content
55-60 bar pressure

Output gas stream: 33-29,6 thousand cu.m/h
sales gas (CO_2 content
max. 2%)
50-55 bar pressure
7-10 thousand cu.m/h
95% purity CO_2 at 180
bar

The carbon dioxide is a by-product of the enrichment process which can not be vented into the atmosphere any more because of environmental assumptions.

It seemed obvious to use this gas for EOR purposes based on the experience gained in SW Hungary and, simultaneously the environmental problems would also be eliminated.

The Szank field

The Szank oilfield has been explored between 1964 and 1975. It is a massive type reservoir with great gas cap and is superimposed on an elevated block of the basement.

The reservoir rock is middle Miocene limestone and calcareous sandstone, the porosity is 10-25%, the permeability - $10 - 500 \times 10^{-3} \text{ um}^2$. The lithological variability of the Miocene formations is extremely high both in horizontal and vertical direction so the hydrodynamic interconnections are very limited in some areas. The reservoir was subdivided into several zones because of the above mentioned, the different phase boundaries, the different crude oil composition and the different reservoir pressure depletion:

- the NW zone interconnected with the great gas cap,
- the SW zone interconnected with the great gas cap, too,
- the NE zone with little gas cap having a limited interconnection with the central gas cap, and
- the SE zone which can well be separated from the gas cap and the other zones.

The manner of operation of the different zones is defined first of all by their position related to the gas cap and the edge water body. The reservoir has an overpressure. The reservoir parameters and the properties of reservoir fluid are summarized in Table 1.

The NE zone has a little gas cap and has a limited hydrodynamic interconnection with the central big gas cap through the water body and the gas cap. Water drive is the basic production mechanism of this zone.

Experience of the primary recovery

The NE and SE flank of the Szank field became suitable for CO₂ EOR operation. The NE zone has a gas cap, the SE zone has no gas cap and is independent from hydrodynamic point of view. The crude oil of the SE zone is undersaturated, its bubble point pressure is 172 bar and $R_{Si} = 79,3$ cu.m/cu.m. The initial reservoir pressure was 244 bar, the reservoir temperature was 113 centigrade on the reference plane in -1756 m s.s.l. The SE zone of the field would give probably 90% of the additional oil. The SE zone based on production past data can be divided into two areas: Middle and South.

Cumulative production data of the SE zone (end of 1992):

Area	Oil producti on 10 ³ cu.m.	Recov ery %	Water producti on 10 ³ cu.m.	Reserv oir ressure bar
SE Middle	454,6	17,9	645,3	196,0
SE South	992,2	40,7	342,5	197,0
SE total	1446,8	29,1	987,8	196,5

Both area of the SE zone watered out as a consequence of the production since 23 years and the intensive water encroachment. As the water displaced intensively the oil, the reservoir pressure remained above the bubble point pressure and no gas saturation was formed. Because of the inadequate exploration of the middle zone of the area the oil recovery is substantially lower than average. 3D measurements were performed in 1991 for the whole SE zone and the vertical wells Szk-142, -143 and 144 and the

horizontal well Szk-145 were drilled to improve the recovery.

Extention of the geological knowledge and refinement of the reservoir model

The geological re-evaluation of the zone was urged by the fact that the control of reserve by material balance method indicated increasing reserve with time. The work started in 1986. The analyses have shown that the SE zone has not been confined from the east and the reserve of this east zone is greater than calculated earlier. To complement research, new 2D seismic line measurements were accomplished in 1989 and in 1991 the whole area was surveyed by 3D measurements.

The wells drilled to complete the well pattern of CO₂ recovery proved the assumptions based on seismic data. The up-to-date 3D seismics and a horizontal well (260 m horizontal section) has been also utilized in the Szank CO₂ EOR.

Laboratory investigations

The aim of laboratory investigations was to obtain informations about the character of processes initiated by CO₂ injection and to determine the parameters of the crude oil/natural gas/CO₂ system.

These investigations included:

- the determination of minimum miscibility pressure (MMP),
- modelling of the process in a PVT cell,
- displacement tests.

The measured MMP was 250 bar which is slightly higher than the initial reservoir pressure and 50 bar higher than the abandonment pressure of the primary recovery. The PVT measurements indicated a substantial vaporization of the crude oil under reservoir conditions caused by CO₂.

PVT measurements have shown that complete miscibility can be approached but can not be reached. Consequently, the CO₂ EOR has been planned for immiscible displacement.

Projected recovery process

The experience gained in SW Hungary has been taken into account in the planning of Szank CO₂ EOR.

The planned CO₂ EOR for Szank SE is characterized by:

The gas is injected on the top of the structure. The gas injection rate is determined so that the gas front stabilizing effect of gravity forces may prevail, the flow velocity will be less than the critical one. As there is no mobile water on the top of the structure, the volumetric sweep efficiency of the CO₂ gas increases. The pressure increase with gas injection increases oil swelling and vaporization and reduces oil viscosity. The heterogeneity of the reservoir may lead to local pressure increase and in these locations the displacement may approach dynamic miscibility. A part of the residual oil vaporizes in the pore space where gas cap is formed due to the gas injection and this oil can be recovered during the gas recuperation. The planned technology has two main phases:

- gas injection
- recovery.

The displacement by CO₂ and the segregation effect of the gas cap also will be effective in the Szank prorus/fractured carbonate reservoir. The reservoir management has to take into account both the CO₂ concentration of the associated gas and the rapid increase of production GOR. The aim of the control of gas injection into individual wells is to maintain a uniform GOC.

The additional oil recovery and production parameters are shown in Fig.2. The GOR increment after 2002 is the consequence of gas cap blow-down. The effect of CO₂ injection appears mainly in the reduction and stabilization of water cut.

The gas injection has started in 1992, its planned duration is 11 years and will terminate at the end of 2002. The production starts in 2003 and will terminate probably in 2013. The cumulative volume of injected gas will be 734,4 million cu.m.

The characteristic features of injection and recovery:

Injection	Recovery
Increase of reservoir	Depletion of reservoir
Swelling of reservoir	Shrinkage of reservoir
Vaporization of	Condensation
Gasing of production	Watering of

The initial results of CO₂ EOR operation Table 2

The gas injection started in July 1992 into the SE zone of the reservoir. 90% of the CO₂ gas has been injected into the SE reservoir. The annual injected gas volume is less than planned. The main reason of this lag was that the sweetening plant has been operated to fulfil sales gas requirements and so, the volume of CO₂ differed from the prescribed quantity. The effect of injected CO₂ can be observed in the top of the SE zone, mainly because of the breakthrough of CO₂. The production parameters are:

Year	NP, cu.m.	GP, 106 cu.m.	Water %	GOR, cu.m/cu .m
1992	24363	2,011	67,4	82,5
1993	26214	3,051	69,4	116,4
1994	25352	5,353	71,4	211,1

The first result of CO₂ EOR operation was to maintain the production on a constant level, although the production of the four new wells contributed to it. Two "huff and puff" experiments were made in the NE zone.

The experiments were not successful but in the vicinity of the injection wells some wells showed oil inflow.

Injection and production system

The gas leaving the sweetening plant has a -18 centigrade dew point and 180 bar pressure. This treated CO₂ gas goes through a ND 100 and rated pressure 210 bar pipeline to the injection and production facility of the Szank SE reservoir. The components of the reception unit are the separator and the heat exchanger. The CO₂ gas is injected into the injection wells after individual metering. The volume of gas injected into the individual wells is controlled by throttle gate valve. The production wells are flowing or are pumped. The gathering, separation and processing of the well stream(s) is traditional. The separated oil associated gas - with increasing CO₂ concentration with time - is fed back to the sweetening plant as feed gas. If the CO₂ concentration of this gas exceeds 80% then it is compressed and reinjected into the reservoir. The scheme of technology is shown in Fig.3.

Experience of the preliminary operation of sweetening plant

The preparation, evaluation, report on tenders and the construction was directed by expert teams. The operator took part in the work of the teams from the very beginning. Larger and smaller problems arise even today, but the sweetening technology ensures the necessary parameters both for the hydrocarbon and CO₂ gas. The technical operation is satisfactory, too. Serious corrosion problems arose in the inhibitor elution system of the feed gas. The selection of proper material and exchange of the unit could solve this problem.

Operation experience of the CO₂ injection system

The CO₂ injection system operates trouble-free.

Serious corrosion problems occurred in the gas- and liquid treating units of the production facilities. Corrosion prevention was solved by inhibitor dosage and coatings. Several measurements were performed to choose the proper solution and a corrosion monitoring system has been established. The liquid pipeline between the gathering station and main gathering station has been lined with plastic pipe to prevent corrosion damage.

General experiences of EOR operations

EOR has a more than thirty year past in Hungary. The successes and unsuccesses offered several general experiences. It is attempted to summarize them according to the general basic principles published in the JPT Dec. 1994 (9). Determination of the aim, planning, realisation, monitoring and control of results and during the operation modification of EOR projects necessitates an integral reservoir management. This management system requires the perfect knowledge of the reservoir, has to take into account the economic, political conditions and the environment, the human and technical resources and the technical culture of the company. The integrated reservoir management must be realized with the coordinated team work of the specialists of geosciences (geology, geophysics), reservoir engineering, drilling and well completion and plant operation. No doubt, these statements are valid in general for the reservoir management system of every field, but particularly for EOR projects because of their greater uncertainty. EOR makes necessary and indispensable the team work and the first unsuccess enforces it if the project as a whole was not properly organized.

The geology and petrophysics have especially great importance in the planning of EOR. The domestic experience indicates, too, that new geological evaluation and significant modification of the geology was necessary for the planning of EOR.

The production history of the given field must be thoroughly processed, analyzed and interpreted by the reservoir engineer planning an EOR project. The reservoir model and production technology have to be elaborated in close team work by the geologist and the reservoir engineer. The simulation and use of new technologies (e.g. horizontal drilling) is necessary and economical for minor fields, too. The proper planning, construction and operation of well equipments and surface facilities contributes also to the success of a given EOR project.

A continuous dialog must run on between reservoir- and production engineers, because new and unexpected events always may occur even if the project is planned with utmost care and several versions.

Economic optimization is a crucial field of EOR projects. The aim of EOR is profit which is determined by forecasted production, investment, overhead costs and financial conditions, e.g. tax. The continuous economic optimization needs a continuous and detailed cost follow-up.

The economic results, or the change of economic and financial environment, e.g. change of the oil price, needs change of the technology which may lead to necessary simplification, changes and compromises.

It is absolutely necessary to take into account the special technical, economic and human factors of abandonment following the production in the planning of EOR as the field is in the final stage of production.

Summary and conclusions

- The operation experience of EOR in SW Hungary rendered a firm base to plan and realize the Szank CO₂ EOR facility.
- The application of new scientific and technical achievements increases the efficiency of EOR projects.
- EOR operations need the re-evaluation of the geology of field and a thorough engineering preparatory activity.
- The reliable operation of the CO₂ gas source - in this case the sweetening plant - is indispensable.

- The solution of production technology problems is decisive in EOR operations.
- EOR needs an integrated reservoir management and an effective team work.
- The economic environment in EOR operations is decisive.

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FIG 3.

RESERVOIR PARAMETERS TABLE 1.

• O.O.I.P	5·10 ⁶ m ³
• RESERVOIR TEMPERATURE	113 C ⁰
• INITIAL RESERVOIR PRESSURE	244 bar
• POROSITY LIMESTONE-BRECCIA-METAMORPHITE	17-13-2%
• PERMEABILITY	10-300 md
• OIL DENSITY (UNDERSATURATED)	0,85 t/m ³
• SOLUTION GAS/OIL RATIO	79 m ³ /m ³
• OIL VISCOSITY	2,9-7,6 mPa·s
• MASSIVE TYPE RESERVOIR (LIMESTONE-BRECCIA-METAMORPHITE)	
• PARTIAL EDGE WATER-DRIVE	

FIELD RESULTS

TABLE 1.

- CO₂ INJECTION COMMENCED AT THE END OF JULY 1992 ALONG THE HIGHEST STRUCTURAL POSITION AT PINCH LINE OF THE MIOCENE ROCK
- NUMBER OF INJECTION WELLS: 6
- NUMBER OF PRODUCTION WELLS: 18

STATUS (1ST OF JAN 1995)

☐ VOLUME OF INJECTED CO ₂ GAS	82·10 ⁶ m ³
☐ RECOVERED OIL	52,5·10 ³ m ³
☐ AVERAGE GOR	~200m ³ /m ³
☐ PRESSURE INCREMENT	~6 bar