SPE 38329

Efficiency of Steamflooding in Naturally Fractured Reservoirs

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This paper was prepared for presentation at the 1997 SPE Western Regional Meeting held in Long Beach, California, 25–27 June 1997.

Abstract

This study aims to identify the effective parameters on matrix heating and recovery, and the efficiencies of these processes while there is a continuous flow of steam in fracture. For this purpose, an experimental study was conducted on a single matrix-single fracture model and the results were used to verify the numerical solution of energy equation. A parametric analysis was performed using numerical output. The results show that as the steam injection rate is lowered, the contact time between matrix and steam flowing in fracture increases causing more conductive heat transfer to the matrix. On the other hand, more heat energy is introduced into the system with increasing steam injection rate and this results in more matrix heating desirably but it increases the cost of the process. Therefore, an optimization study is needed. It is observed that there is a critical injection rate optimizing the process and the critical injection rate for an efficient matrix heating is defined for different matrix sizes and matrix heat transfer coefficients.

In the second part of the study, similar analysis was performed to investigate the effect of injection rate on the matrix oil recovery. Efficiencies of steam injection processes in a laboratory scale single matrix-single fracture model and field scale case with different horizontal fracture configurations were investigated. The critical injection rate was defined for laboratory scale simulation for different matrix properties. Finally, critical rate concept was evaluated for different number of horizontal fractures and steam qualities in field scale simulations. The approach and results can be used in further studies to analyze the efficiency of thermal applications and to obtain correlations for steam injection performances in naturally fractured reservoirs.

Introduction

In order to recover heavy matrix oil in naturally fractured reservoirs (NFR), steam injection has been recognized as an effective enhanced oil recovery technique[1,2]. Many mechanisms are involved in the recovery process from NFR during steam injection[3]. Due to numerous parameters that are effective on the mechanisms, accurate recovery estimation becomes highly complex.

Limited number of experimental investigations is available on the recovery mechanisms under temperature effect in NFR. Reis[3] reviewed these mechanisms and the characteristic recovery times for them. Briggs *et al.*[1] numerically and Briggs *et al.*[2] both numerically and experimentally investigated the temperature effect on the matrix recovery. More recently, Babadagli[4] experimentally studied the effect of temperature on the capillary imbibition performance from a matrix containing heavy-oil. Most of these studies are based on the matrix recovery at static conditions. Matrix recovery under dynamic conditions, i.e. during steam flow in fracture, was also investigated. Jensen and Sharma[5] performed steam and hot water injection experiments on artificially fractured samples and evaluated the recovery performances for the fracture properties, the temperature of injected fluid and matrix lithology. Behavior of matrix recovery under different injection rates and injection patterns was examined both numerically and experimentally by Sumnu *et al.*[6] with the emphasis on the effect of fracture relative permeabilities and capillary pressure. Pooladi-Darvish *et al.*[7] studied fracture-matrix heat transfer analytically under static conditions for single matrix block. Babadagli[8] investigated the effect of injection rate on the matrix heating under dynamic conditions for single fracture-single matrix model experimentally and numerically.

Field scale simulation studies were also conducted for different purposes. Nolan *et al.*[9] numerically simulated steamflooding into a carbonate reservoir and investigated the effects of reservoir thickness, porosity, directional permeability and well spacing on the performance. A similar modeling study was done by Dreher *et al.*[10]. Their major concern was the effect of steam injection rate on the matrix imbibition recovery and gas production on the recovery performance. Later, Chen *et al.*[11] and Briggs[12] introduced new formulations of thermal simulators for steamflooding and cyclic steam injection, respectively. Oballa *et al.*[13] compared the responses of single and dual-porosity thermal models and investigated the effect of fracture and matrix properties as well as the matrix discretization models on the performance of steamflooding.

As seen, considerable attention was given to thermal response of naturally fractured reservoirs. It is obvious that the heat injection into naturally fractured reservoirs containing heavy oil is an applicable technique for an effective matrix recovery. Fractures create high permeability flow paths and this may generally increase the productivity. On the other hand, these high permeability streaks may cause a faster movement of steam and eventually earlier breakthrough without heating the matrix blocks effectively. This may cause an inefficient process because of decrease in oil recovery per unit amount of steam injected. Therefore, an optimization study is needed to design an efficient steam injection process in a NFR.

The objective of this study is to investigate the efficiency of the process. In the first part, heating and recovery efficiencies for single matrix-single fracture system were studied and a critical injection rate was defined for an efficient process. In the second part, critical injection rate concept was applied to field scale performance and the effect of injection rate, fracture density and steam quality on the efficiency of the process was clarified.

Two terms, effectiveness and efficiency that are used frequently throughout the paper, should be defined beforehand. The term of effectiveness is used to define the amount of matrix oil recovery or matrix heating. Regardless the amount of heat energy introduced into a system, higher the matrix recovery or higher the increase in matrix temperature, the more effective the process. Efficiency of the process denotes the oil recovery per amount of heat energy introduced into system. Efficiency might be high even though the oil recovery is low, for example, in case of very slow injection rates.

Laboratory Scale Modeling

For heavy-oil recovery from matrix, effective matrix heating is essential. To investigate the effect of fracture and matrix properties and injection rate on the increase in absolute matrix temperature and the efficiency of the process, an experimental study was conducted. The results were used to verify the numerical simulation of the process and a parametric analysis was conducted using numerical results.

Single matrix heating. Single matrix heating during steam flow in a fracture has been studied both experimentally and numerically.

Experimental Study. Experimental study was performed on 44x8x8 cm parallelepiped model made of 2-mm- thick chromium-nickel. The matrix portion was composed of firmly packed 20-42 mesh size sand and a fracture was created adjacent to matrix using a loosely packed larger size glass beads. Other model properties are given in **Table 1**. Water was injected at a constant rate through a tubing wrapped with a heating tape. Thus, water was introduced into the system in steam phase. Steam flow occurs only in fracture spanning through the injection and production ends due to much higher permeability. During this process matrix is heated by conduction and the temperature along the matrix centerline was continuously recorded by a data acquisition system and the thermocouples located along the center of the matrix. 2-D representation of the model is given in **Fig. 1**. Details of the experimental study and results can be found in Ref. 8. Here, the numerical study for parametric analysis and the results will be provided.

Numerical Modeling. The 2-D energy equation given below was solved by using finite difference discretization.

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{Q}{\rho c_p} \qquad (1)$$

The fracture portion in numerical gridding (Fig. 1) was represented as only one grid in y-direction. Thus, flow occurs only in x direction. Hence, the velocity term (v) in Eq. 1 vanishes and this equation is reduced to the following form:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{Q}{\rho c_p} \qquad (2)$$

In solving this equation, intrinsic matrix and fracture properties given in **Table 2** were assigned as data to each grid block. Source term was placed in the first grid of fracture and the sink term was located in the last grid block. The injected amount of heat per unit volume (Q) is calculated using the injection rate, density and enthalpy. Q is computed for the production point using this relationship[14]:

$$Q=\rho c_p u(T-T_r) \qquad (3)$$

Temperature distribution in the fifth grid block (in y direction) obtained from the solution of Eq. 2 was matched with the experimental values (recorded along the matrix centerline). Thermal diffusivity corresponding to fracture grids was obtained by trial-and-error until a good match of experimental and numerical results was achieved. Once the matching is accomplished, simulation runs were performed for different combinations of injection rates, matrix sizes and matrix thermal diffusivities. Then, the evaluation was done for the dimensionless group defined as the ratio of matrix thermal diffusivity to the product of steam velocity and matrix size.

$$\mathrm{FHTI} = \frac{\alpha_m}{uL_m} \qquad (4)$$

This dimensionless group called as Fracture Heat Transfer Index[8] (FHTI) indicates the degree of the heat transfer from fracture to matrix. The higher the FHTI, the higher the heat transfer to matrix per injected steam. This is provided by high matrix thermal diffusivities, low injection rates, or small matrix sizes. The change of normalized matrix temperature (average matrix temperature/temperature at the injection grid) with the 1/FHTI is shown in **Fig. 2** for three time values. The average matrix temperature is defined as the arithmetic average of the temperatures of 90 grids in matrix block. Lower values of 1/FHTI exhibit an efficient heat transfer. As 1/FHTI increases due to higher velocities or larger matrix sizes, or lower matrix thermal diffusivities, normalized matrix temperature decreases and eventually stabilizes. The region where this stabilization begins (FHTI between 0.2 and 0.1) can be considered as the critical FHTI for an efficient heat transfer. Beyond this region the process is no longer efficient.

Note that the efficiency is defined as the heat transferred to the matrix per amount of steam introduced. For very low rates, for example, steam velocity in fracture also decreases and this increases the time for steam to contact with matrix. Thus, more heat is transferred to matrix by conduction. This is an efficient process because most of the heat is consumed to heat the matrix. But, when the injection rate is lowered, less amount of heat energy is introduced and the increase in the matrix temperature is not significant per unit time. In this case, process is not effective although it is considered as efficient. Thus, both absolute matrix temperature (indicating the effectiveness of the heating process) and normalized matrix temperature (indicating the efficiency of the heating process) should be considered together. Both cases are illustrated in **Fig. 3**. Here different values of FHTI were obtained by changing only the injection rate and matrix properties were kept constant. In the region where an efficient heat transfer takes place (1/FHTI values between 0.2 and 8), there is no remarkable increase in absolute matrix temperature. Beyond this range of 1/FHTI, a sharp increase in absolute matrix temperature is observed. For higher values of 1/FHTI, more heat is introduced into the system per unit time and therefore, more heat is transferred to the matrix. However, in this region (1/FHTI values over 100) the amount and the cost of steam would increase drastically by increasing injection rate and process becomes inefficient as indicated by very low normalized matrix temperature values. Thus, the FHTI between 0.05 and 0.01 (1/FHTI between 20 and 100) can be considered as the critical value that gives both effective and efficient process.

Single matrix oil recovery. A similar analysis was done for oil recovery from a single matrix during steam injection. In this analysis, only numerical model study was performed. A thermal simulator was utilized to model oil recovery from a laboratory scale single matrix-single fracture system by steam injection. Model properties are given in **Table 3** and the schematic representation of the model is demonstrated in **Fig. 4**. Third layer (bottom one) was assigned fracture properties. Injection was only through this layer and steam preferentially flows in this layer due to much higher permeability than the matrix blocks (two upper layers). Straight line relative permeabilities were assigned to fracture grids. Simulations were performed for different FHTI values. As the base case, matrix dimensions are 2.5x0.75x0.755 ft., thermal conductivity of the rock is 35 BTU/ft-°F-day and heat capacity of the rock is 24 BTU/ft^3-°F (thermal diffusivity is 0.686 ft^2/day). To obtain different FHTI values, matrix length in z direction (first and second layers) was changed between 0.55 and 1.25 ft. First analysis was done to search the effect of injection rate on the efficiency of the process. Then, for more general results, same analysis was performed for different FHTI's.

The change of the cumulative oil recovery (COR) / total steam injected (TSI) with time for different injection rates is shown in **Fig. 5**. Total steam injected (TSI) is defined as the total cumulative energy in the injection well. As the rate is lowered, process becomes more efficient, i.e., the ratio of COR/TSI increases. In all cases, COR/TSI (efficiency) reaches a peak point eventually and then begins to decline. The higher the rate, the earlier the time to reach the peak point. For example, the peak point is reached in 2 and 0.2 day for 0.25 and 10 cc/min injection rates, respectively.

As pointed out previously, efficient process does not always mean that the process is effective. In other words, at lower rates, the heat introduced into fracture can be totally consumed to heat the matrix. But, due to decreasing injection rate, heat energy introduced into the system per unit time also decreases and this amount of heat may not be enough to increase absolute matrix temperature for additional matrix recovery. To investigate this, both COR/TSI and cumulative recoveries were evaluated and to generalize the results, analyses were performed for different FHTI values. These plots are given in **Figs. 6, 7** and **8** for different matrix/fracture permeability ratios. The plots of cumulative oil recovery vs. 1/FHTI and COR/TSI vs. 1/FHTI for the same permeability ratio of Fig. 5 are shown in Figs. 6-a and b respectively. COR/TSI ratio, that indicates the efficiency of the process, reaches the stabilization point around the 1/FHTI values of 20-50. Beyond this point, no matter how much the injection rate is increased, no significant change in the efficiency of the process is observed. However, for this 1/FHTI interval, no remarkable increase in cumulative oil recovery is observed for three time periods (Fig. 6-a). A sharp increase in recovery (more prominent for t=0.5 day) is seen over 1/FHTI value of 70. Thus, the critical value of 1/FHTI for both an efficient and effective process can be considered as between 20 and 100 (FHTI between 0.05 and 0.01). This value of FHTI is consistent with the critical FHTI value that provides both an effective and efficient matrix heating (Fig. 3).

This analysis was repeated for different matrix permeability ratios. Figs. 7-a and b show the cumulative oil recovery and COR/TSI change with 1/FHTI for much lower matrix permeability (0.3 md) than the previous case (30 md). In both cases, fracture permeability is the same (10000 md). Stabilization point of efficiency is between 10 and 30 (Fig. 7-b). In the third case, where the matrix/fracture permeability ratio has the highest value (100/5000 md), stabilization point is between 20-50 (Fig. 8-b). Considering an effective matrix recovery and an efficient process, the same 1/FHTI range can be assumed as the critical value (FHTI between 0.05 and 0.01) for these two cases if both cumulative oil recovery and COR/TSI plots are evaluated together.

Field Scale Modeling

A similar analysis was performed for field scale applications. Unlike laboratory scale idealized models, it is quite difficult to reach a general and "rule of thumb" type conclusion for field cases because each field behaves differently against injection processes due to complex structure of fracture pattern. However, for one injection and one production well system and a simple form of fracture configuration, the critical rate concept and the effect of fractures on the efficiency of the process were evaluated. Preliminary results are presented below and it is expected that this approach will later provide a generalization of critical rate concept for efficient steam injection strategies.

Model description. A data set was prepared as input into a thermal simulator and the simulation runs were conducted for different injection rates and fracture configurations. **Table 4** shows the reservoir and fluid properties used for the simulations. The reservoir has 50 md permeability and the horizontal fractures spanning through the production and injection wells were placed in the model. Fractures are considered as high permeability streaks with 0.05 ft thickness (10000 md) and the whole reservoir rock has the same relative permeability curves. Fracture configurations used in the simulations (Case I, II, III and IV) are given in **Fig. 9**. The injection and production wells are open to flow through the entire formation. In each case, matrix sizes are distributed uniformly throughout the formation. Similar representation of fracture distribution was used by Bodvarsson and Tsang[15] for a thermal breakthrough analysis in geothermal reservoirs. Simulations were performed at constant injection rate for 1000 days. The results and evaluations are given below.

Simulation results and efficiency analysis. The simulation results are presented in terms of cumulative oil recovery vs. time and COR/TSI vs. time. In such an analysis, different performance indicators can be used. Hong[16] performed a similar analysis to estimate an optimum injection rate and steam quality for different injection patterns and heterogeneous structures. In his analyses, he used cumulative oil recovery and discounted cumulative net sales oil against time and heat injected. This study can be considered as a specific case of Hong's analyses; however, the major target here is to investigate the fracture effect on the efficiency of the process. Thus, a different approach was made and the evaluations were done for the change of cumulative oil recovery and COR/TSI against time.

The plots of cumulative oil recovery vs. time and COR/TSI vs. time are given in **Figs. 10** through **13** for four different fracture configurations illustrated in Fig. 9. The COR/TSI vs. time plots (Fig. 10-b, 11-b, 12-b and 13-b) indicate that the efficiency of the process increases with decreasing injection rate. Also, as the number of fractures increases, the process becomes more efficient for all rates applied in the simulation runs. These are expected results because fractures provide high permeability paths that facilitate the production. This is the positive effect of fracture on the performance.

The efficiency of the process continuously increases and eventually reaches a peak point in all cases. The peak points can be seen only for higher injection rates (100 and 125 STB/day) for 1000 days of injection. Later, the efficiency of the process begins to decline. To indicate this decline more clearly, 150 STB/day injection case was also included for Case-IV (Fig. 13-b). The peak value of COR/TSI is a function of rate and the number of fractures. It is obvious that the peak values are reached more rapidly with increasing rate and number of fractures. For example, for 100 STB/day of water equivalent steam injection rate, times to reach the peak points are 870, 830 , 790 and 720 days for one, two, three and four fracture cases, respectively. These differences are due to increasing number of fractures that causes not only a faster production but also a faster movement of steam towards the production well. Another implication of these results is that the increase of rate from 20 to 50 STB/day reflects a significant decrease in COR/TSI ratio in all cases. However, once the rate is increased from 100 to 125 STB/day (and even to 150 for four fracture cases in Fig. 13-b), the change of COR/TSI with rate is trivial especially in early times. After nearly 600 days of injection, this difference becomes more distinguishable for all cases.

The two questions to be answered in this analysis are how much oil can be recovered and how much steam should be injected for this recovery. Obviously, increasing rate causes an increase in recovery as can be inferred from the Figs. 10-a, 11-a, 12-a and 13-a. However, increasing rate reduces the efficiency of the process as seen in Figs. 10-b, 11-b, 12-b and 13-b. The positive role of fractures on both efficiency and recovery (effectiveness) is clear when the same rate cases are compared. However, especially in late times, when the effect of breakthrough begins to be felt, the efficiency begins to decline and the project should be evaluated considering the fracture effect. Increasing number of fractures amplifies this effect and needs to be taken into account in strategy planning. The rate or the process type should be reconsidered when the fracture effect becomes prominent during project life. For example, it would be meaningful to reduce the injection rate towards the peak point to be in efficient region also taking into account the economics of the project.

As a final analysis, the cumulative recovery vs. time and COR/TSI vs. time curves are compared for two rates and two fracture configurations to clarify the critical rate concept (**Figs. 14-a** and b, respectively). For 1000 days of injection period, COR/TSI continuously increases for 50 STB/day rate. Whereas, the COR/TSI curves reach the peak points for 125 STB/day and even begin to decline for higher number of fractures (Fig. 14-b). Thus, the lower rate is desirable for an efficient process. However, if the cumulative oil recovery curves are compared (Fig. 14-a), total recovery at 1000 days is almost doubled if the rate is increased from 50 to 125 STB/day. Thus one may conclude that the decrease in the efficiency of the process by increasing rate is tolerable because of the remarkable increase in the recovery.

It should be emphasized that the purpose in the field scale evaluations is not to provide an exact rate that optimizes the process. Many parameters involve in the process and some of these parameters (such as fracture properties) cannot be determined in exact manner for real field applications. Instead, the purpose is to investigate the rate and fracture effect on the steam performance efficiency. The preliminary results imply that based on the fracture density (or configuration), the injection rate can be adjusted to optimize the process.

Finally, the efficiency was evaluated for steam quality. Two fracture configurations and two injection rates were considered and both effectiveness and efficiency were compared for two different steam qualities. **Figs. 15-a** and **b** show the cumulative recovery and COR/TSI curves against time for Case-I, respectively. With increasing steam quality from 0.3 to 0.9, considerable decrease in the efficiency is observed (Fig. 15-b) for both rates. However, when the recovery curves are compared, a slight increase in recovery is obtained for both rate cases. It can be stated that this decrease in the efficiency with the steam quality is intolerable for this amount of increase in recovery. Similarly, for higher number of fractures (Case-IV), the decreases in the efficiencies with increasing steam quality for both rates (**Fig. 16-b**) are not tolerable for the increases in oil recoveries (**Fig. 16-a**). Thus, steam quality is observed as more critical than the number of fractures on the efficiency of the process.

Conclusions and Remarks

Single matrix case: The efficiency and the effectiveness of both matrix heating and matrix oil recovery during steam injection were investigated experimentally and numerically for the injection rate. Increasing rate causes more effective (higher recovery) but less efficient (lower oil recovery / steam injected ratio) process. Therefore, a critical rate that optimizes the project can be defined. For more general evaluation, the analyses were done for a dimensionless parameter (FHTI) defined as the ratio of matrix thermal diffusivity to the product of steam velocity in fracture and matrix size. The results suggest that there exists a critical FHTI that optimizes the process for laboratory scale single matrix-single fracture model. This value was found to be between 0.01 and 0.05.

Field case: Field scale simulations were performed for different injection rates, fracture configurations and steam qualities for a similar analysis. Horizontal fractures spanning through the injection and production wells increase both effectiveness (cumulative oil recovery) and efficiency (oil recovery per amount of steam injected). However, the negative effect of fracture on the efficiency of the process begins to be felt in later times and decrease in the efficiency of the process begins earlier as the injection rate and the number of fracture increase. The purpose in field scale study was not to define an exact rate that optimizes the steam injection process. Instead, it was aimed to search whether the concept of critical injection rate that optimizes a field injection process is applicable. The results imply that there exists a critical rate providing an optimum recovery and the critical rate depends on the number of fractures and steam quality. The effect of steam quality on the efficiency of the process is more prominent than that of the number of fractures. It is rather difficult to generalize the critical injection rate for an optimum process because each naturally fractured reservoir behaves differently against an injection process and it is a difficult task to quantify the fracture structure. However, an injection strategy can be developed based on the injection rate and steam quality if the fracture properties can be approximated.

Nomenclature

c_p = Specific heat capacity.
COR = Cumulative oil recovery.
FHTI = Fracture heat transfer index.
k_m = Matrix permeability.
k_f = Fracture permeability.
L_m = Matrix size.
Q = Amount of heat injected or produced.
t = Time.
T = Temperature.
T_r = Reference temperature.
TSI = Total steam injected.
u = Velocity in x direction.
v = Velocity in y direction.
α_m = Matrix thermal diffusivity.
ρ = Density.

Acknowledgments

This study was partially supported by Research Fund of Istanbul Technical University and the Scientific and Technical Research Council of Turkey.

References

1. Briggs, P.J. *et al.*: "Development of Heavy-Oil Reservoirs," *JPT* (Feb. 1988) 206.
2. Briggs, P.J. *et al.*: "Heavy Oil From Fractured Carbonate Reservoirs," *SPERE* (May. 1992) 173.
3. Reis, J.C.: "Oil Recovery Mechanisms in Fractured Reservoirs During Steam Injection," paper SPE 20204 presented at the SPE/DOE Seventh Sym. on Enhanced Oil Recovery, Tulsa, OK, April 22-25 (1992).
4. Babadagli, T.: "Temperature Effect on Heavy-Oil Recovery by Imbibiton in Fractured Reservoirs," *J. Pet. Sci. and Eng.* Vol. 14, (1996), 197.
5. Jensen, T.B. and Sharma, M.P.: "Mechanism of Oil Displacement by Steam and Hot Water Injection in Fractured Porous Media: Experimental and Numerical Modeling Studies," paper presented at the 1991 ASME Winter Annual Meet., Atlanta, GA, Dec. 1-6.
6. Sumnu, M.D. *et al.*.: "Use of Simulators in the Design of an Experiment for Steam Injection Into a Fractured System," presented at the 1994 SPE/DOE Ninth Symp. on Improved Oil Rec., Tulsa, OK, April 17-20.
7. Pooladi-Darvish, M, Tortike, W.S. and Farouq Ali, S.M.: "Steam Heating of Fractured Formations Containing Heavy Oil: Basic Premises and a Single-Block Analytical Model," paper SPE 28642 presented at the 1994 SPE Annual and Technical Conference and Exhibition, New Orleans, LA, Sept. 25-28.
8. Babadagli, T.: "Heavy-Oil Recovery from Matrix During Thermal Applications in Naturally Fractured Reservoirs," *In Situ*, Vol. 20, No. 3 (1996) 221.
9. Nolan, J.B., Ehrlich, R. and Crookston, R.B.: "Applicability of Steamflooding for Carbonate Reservoirs," paper SPE 8821 presented at the 1980 First Joint SPE/DOE Symp. on Enhanced Oil Recovery, Tulsa, OK, April 20-23.
10. Dreher, K.D., Kenyon, K.E. and Iwere, F.O.: "Heat Flow During Steam Injection Into a Fractured Carbonate Reservoir," paper SPE 14902 presented at the 1986 Fifth SPE/DOE Symp. on Enhanced Oil Recovery, Tulsa, OK, April 20-23.
11. Chen, W.H., Wasserman, M.L. and Fitzmorris R.E.: "A Thermal Simulator for Naturally Fracutred Reservoirs," paper SPE 16008 presented at the 1987 Ninth SPE Symp. on Reservoir Simulation, San Antonio, TX, Feb. 1-4.
12. Briggs, P.J.: "A Simulator for the Recovery of Heavy Oil From Naturally Fractured Reservoirs Using Cyclic Steam Injection," paper SPE 17954 presented at the 1989 SPE Middle East Tech. Conf. and Exh., Manama, Bahrain, March 11-14.
13. Oballa, V., Coombe, D.A. and Buchanan, W.L.: "Factors Affecting the Thermal Response of Naturally Fractured Reservoirs," *JCPT* (Oct. 1993) 31.
14. Pratts, M: *Thermal Recovery*, Monograph Series, Soc. Pet. Eng., Dallas, Tex. (1982) 16-20.
15. Bodvarsson, G.S. and Tsang, C.F.: "Injection and Thermal Breakthrough in Fractured Geothermal Reservoirs," *J. of Geoph. Res.*, Vol. 87, No B2, (Feb. 1982) 1031.
16. Hong, K.C.: "Effects of Steam Quality and Injection Rate on Steamflood Performance," *SPERE* (Nov. 1994) 290.

Table 1- Matrix, fracture and flow properties used in the matrix-fracture heat transfer experiments.

Matrix Size	44x8x8 cm
Fracture Size	44x0.5x8 cm
Steam Inj. Rates (water eq.)	1.65, 2.35 and 3.5 cc/ min
Density of Steam	0.5 kg/m
Enthalpy of Steam (105 ^oC)	2260 kJ/kg
Injected Heat	0.03135, 0.04465 and 0.0665 W
Matrix Thermal Diffusivity	0.000005 m^2 / s
Fracture Thermal Diffusivity	0.0002 m^2 / s
Initial Temperature	20 ^oC

Table 2- Matrix, fracture and flow properties used in the numerical simulation of matrix-fracture heat transfer.

Model Grids	10x10x1
Matrix Size	10-90 x 10-90 x 8 cm
Fracture Size	0.5x8 cm
Velocities in Fracture	0.0001 - 0.00008 m / s
Injected Heat	0.0475 - 0.076 Watt
Matrix Thermal Diffusivity	0.000001-0.005 m^2 / s
Fracture Thermal Diffusivity	0.0002 m^2 / s
Initial Temperature	20 ^oC

Table 3- Model properties used in the laboratory scale numerical simulation of oil recovery by steam injection.

Model Dimension	2.5x0.75x0.755 ft
Model Grid 5x1x3	ΔX= 0.5, 0.6, 0.3, 0.6, 0.5 ΔY= 0.75 ΔZ= 0.45, 0.3, 0.005
Steam Injection Rates (water eq.)	Nine rates between 0.1 and 15 cc/min
Matrix Porosity	0.15
Fracture Porosity	0.85
Matrix/Frac. Perm. Ratios	100/5000, 0.3/10000, 30/10000 md
Heat Capacity of Rock	35 Btu/cu ft - ^oF
Thermal Conductivity of Rock	24 Btu/ft- ^oF-day
Viscosity of Oil	300 cp @ 75 ^oF 2 cp @ 500 ^oF
Initial Oil in Matrix	%75
Initial Oil in Fracture	%100
Steam Quality	1.0
Initial Temperature	125 ^oF

Table 4-Reservoir and fluid properties used in the field scale steam injection simulations.

Model Dimension	450x75x60 ft
Model Grid	6x1x10
Steam Inj. Rates (water eq.)	20, 50, 100, 125 STB/day
Matrix Porosity and Perm.	0.15 and 50 md.
Fracture Porosity and Perm.	0.85 and 10000 md.
Heat Capacity of Rock	35 Btu/cu ft - ^oF
Thermal Conductivity of Rock	24 Btu/ft- ^oF-day
Viscosity of Oil	1000 cp @ 75 ^oF 1.5 cp @ 500 ^oF
Initial Oil in Matrix and Fracture	%75
Steam Quality	0.7
Initial Temperature	125 ^oF

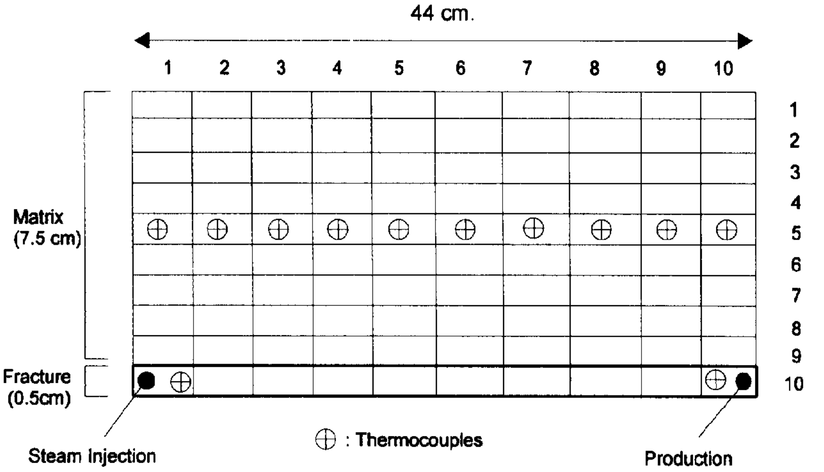

Fig. 1-Two-dimensional representation of single matrix-single fracture model used in experimental and numerical modeling studies of heat transfer from matrix to fracture (model height=8 cm)

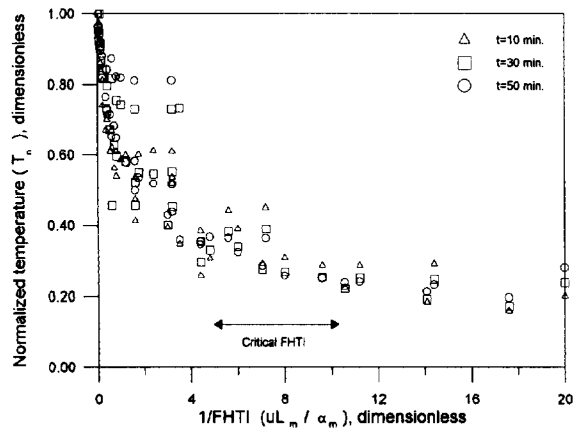

Fig. 2-The change of normalized matrix temperature (average matrix temperature/temperature at injection point) with 1/FHTI.

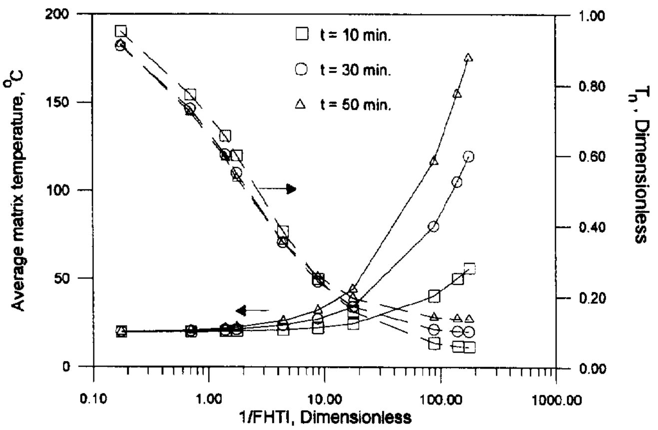

Fig. 3-The change of average matrix temperature and normalized matrix temperature with 1/FHTI.

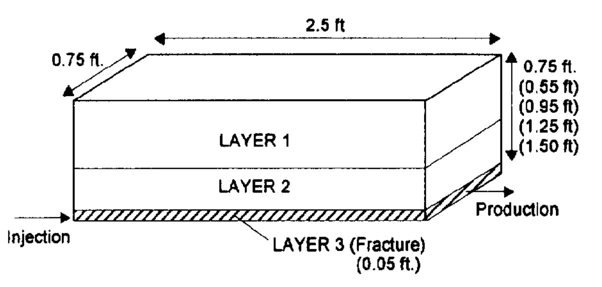

Fig. 4-Schematic representation of the laboratory scale model used in the numerical simulation of oil recovery by steam injection.

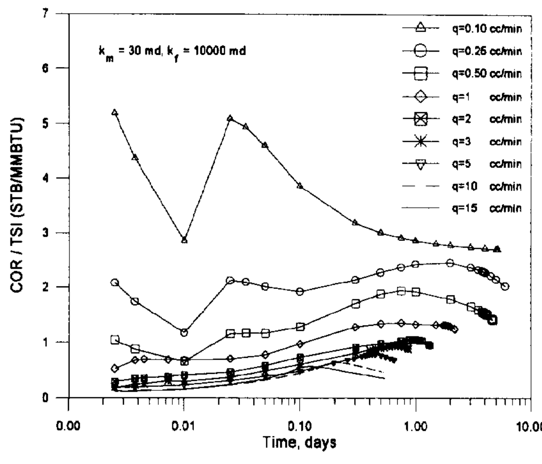

Fig. 5- The change of cumulative oil recovery (COR) / total steam injected (TSI) with time for different injection rates in laboratory scale numerical modeling.

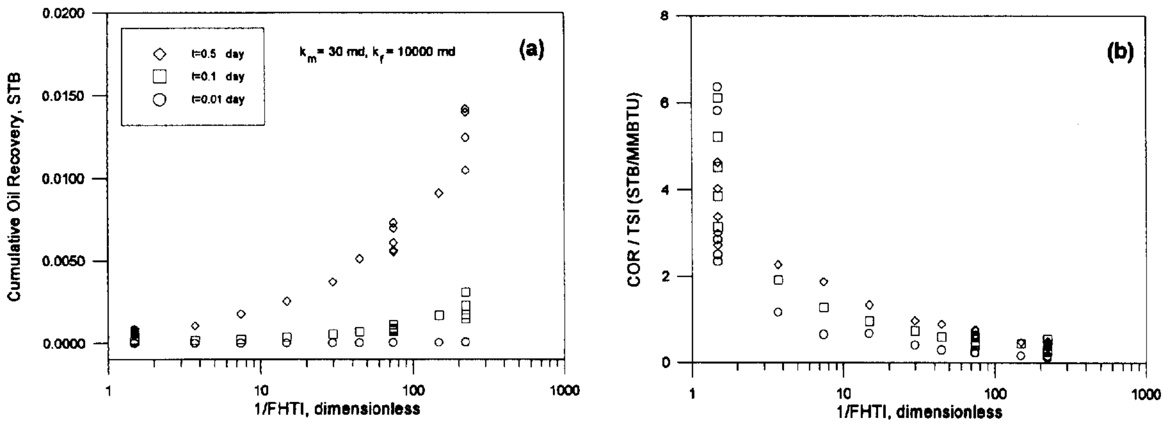

Fig. 6-(a) Cumulative oil recovery (COR) / total steam injected (TSI) and (b) cumulative oil recovery against time for fracture-matrix permeability ratio=333

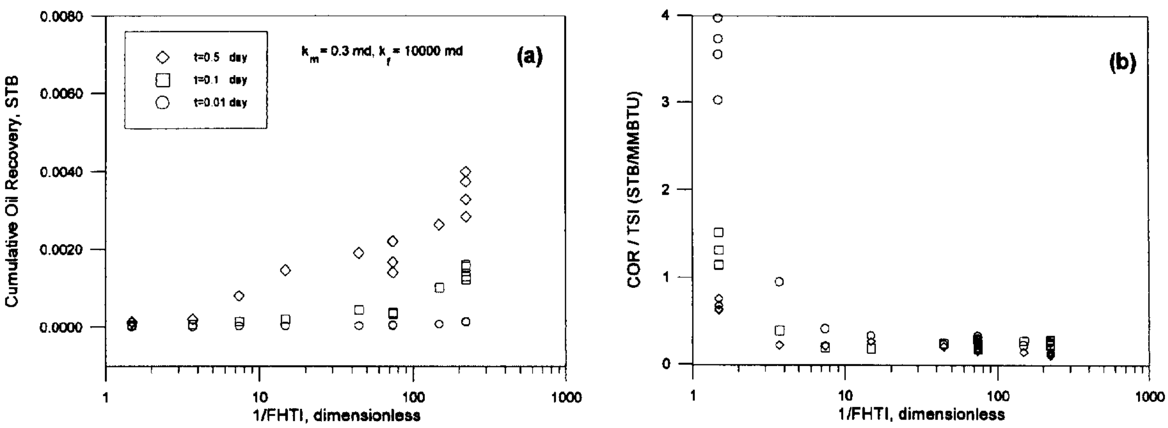

Fig. 7-(a) Cumulative oil recovery (COR) / total steam injected (TSI) and (b) cumulative oil recovery against time for fracture-matrix permeability ratio=33333.

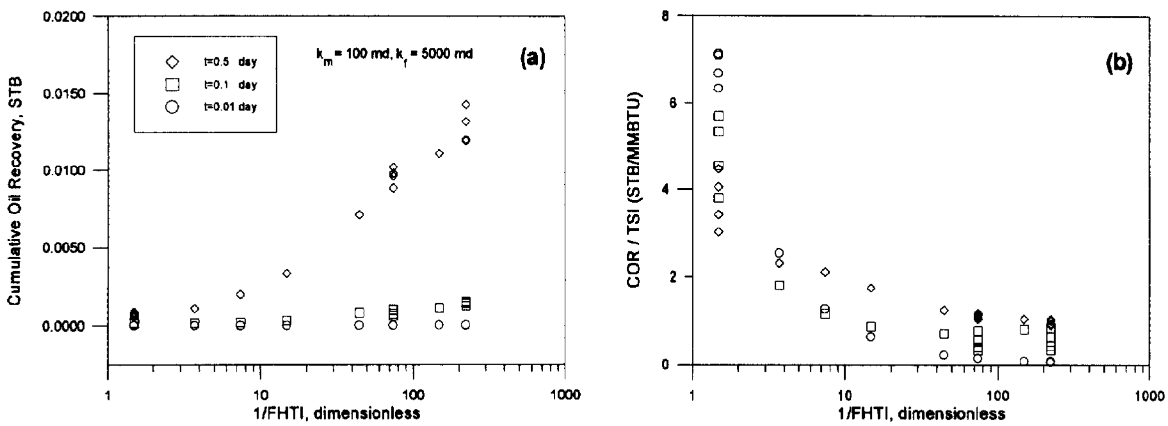

Fig. 8-(a) Cumulative oil recovery (COR) / total steam injected (TSI) and (b) cumulative oil recovery against time for fracture-matrix permeability ratio=50.

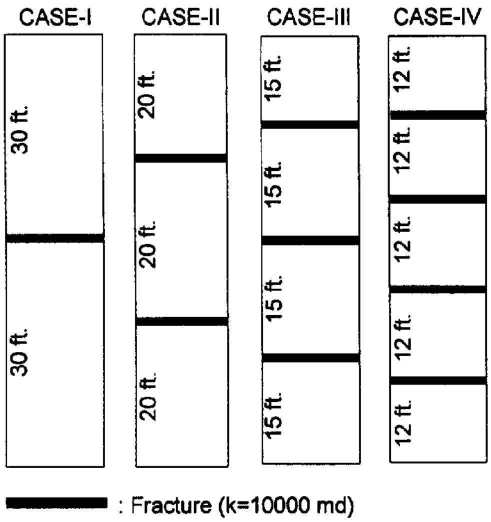

Fig. 9-Fracture patterns used in the field scale simulation runs.

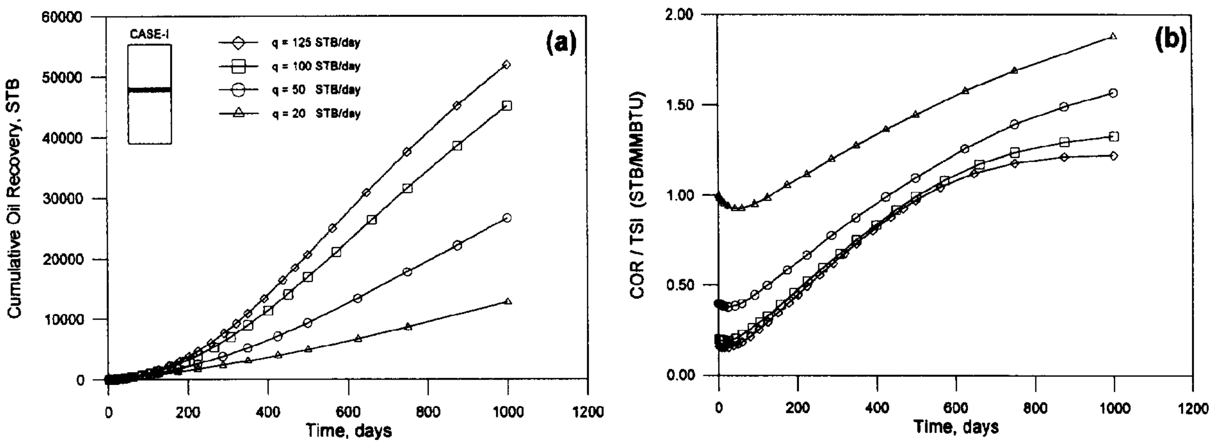

Fig. 10-(a) Cumulative oil recovery and (b) cumulative oil recovery (COR) / total steam injection (TSI) against time for Case-I in Fig. 9.

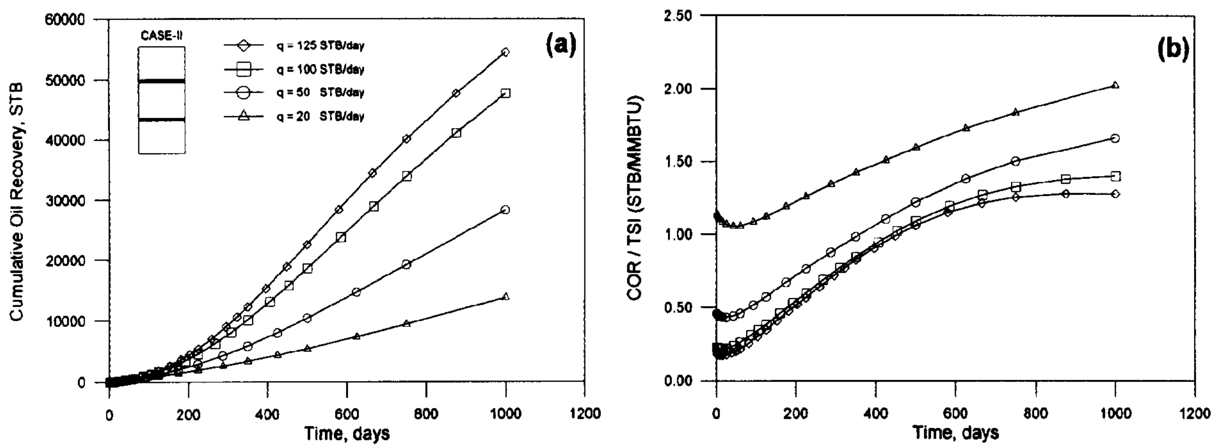

Fig. 11-(a) Cumulative oil recovery and (b) cumulative oil recovery (COR) / total steam injection (TSI) against time for Case-II in Fig. 9.

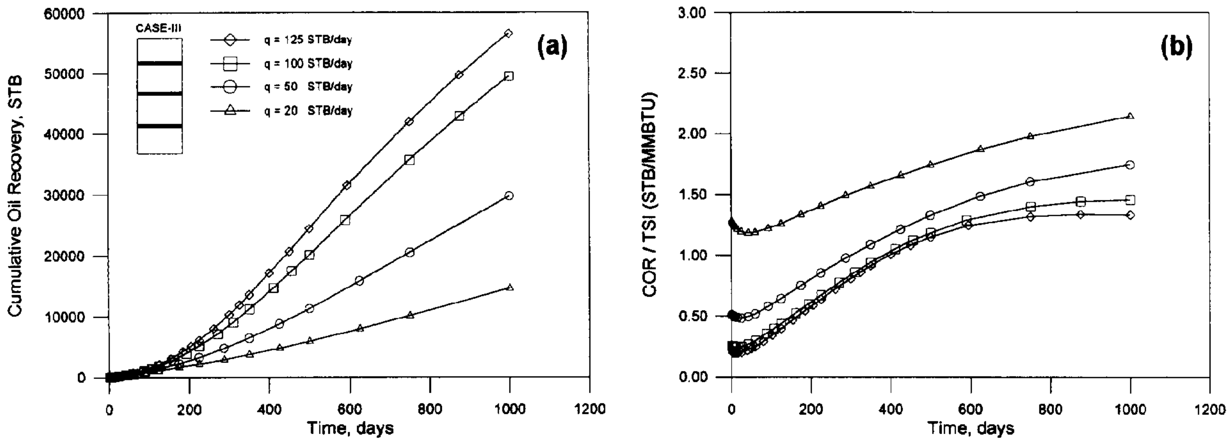

Fig. 12-(a) Cumulative oil recovery and (b) cumulative oil recovery (COR) / total steam injection (TSI) against time for Case-III in Fig. 9.

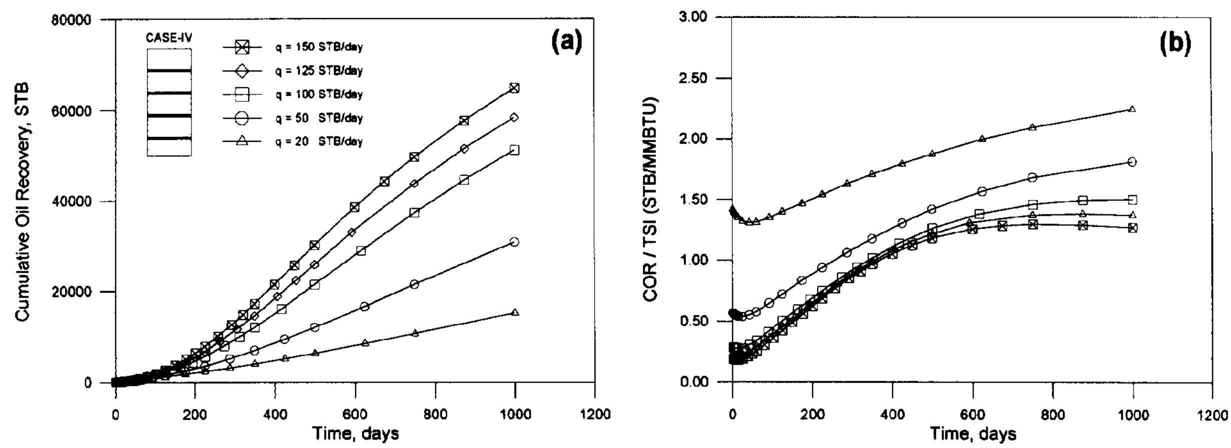

Fig. 13-(a) Cumulative oil recovery and (b) cumulative oil recovery (COR) / total steam injection (TSI) against time for Case-IV in Fig. 9.

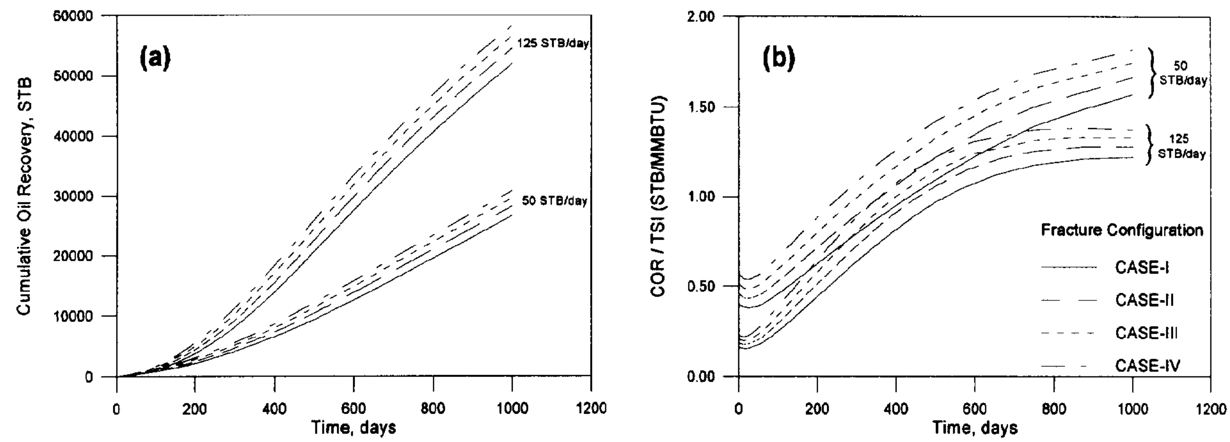

Fig. 14- Comparison of (a) cumulative oil recovery and (b) cumulative oil recovery (COR) / total steam injection (TSI) against time for different rates and four fracture patterns.

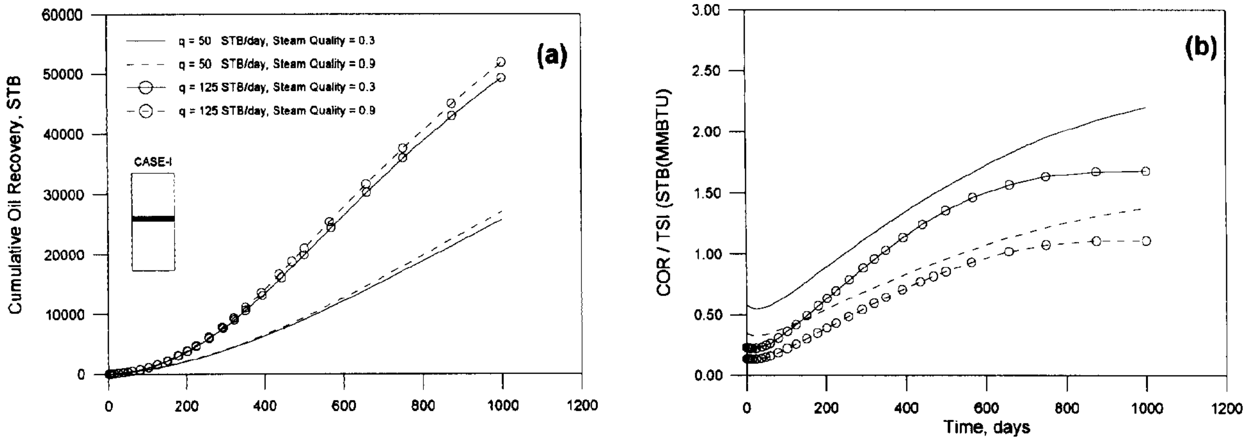

Fig. 15-(a) Cumulative oil recovery and (b) cumulative oil recovery (COR) / total steam injection (TSI) against time for different steam qualities.

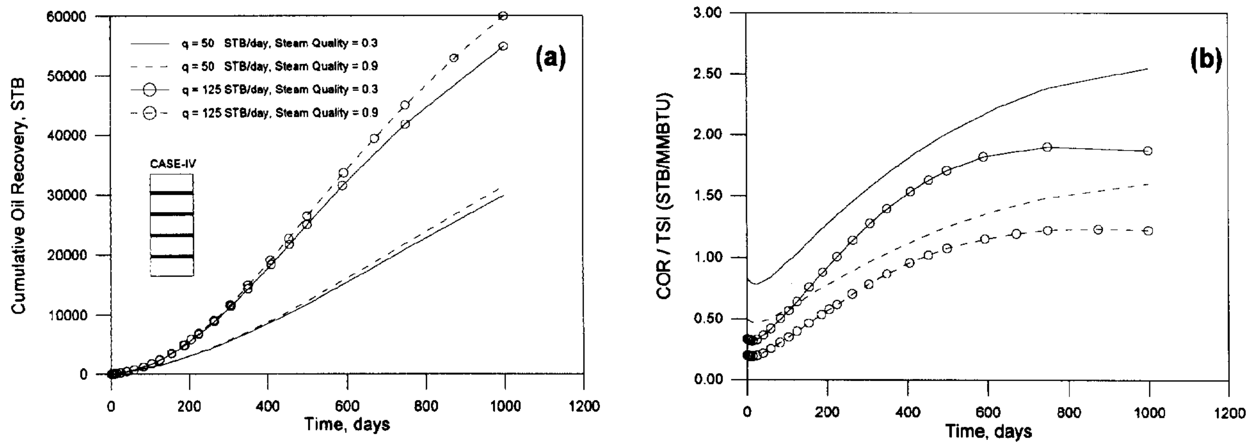

Fig. 16-(a) Cumulative oil recovery and (b) cumulative oil recovery (COR) / total steam injection (TSI) against time for different steam qualities.