Determination of gas-diffusion and interface-mass-transfer coefficients in fracture-heavy oil saturated porous matrix system

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For the modeling and simulation of oil recovery from naturally fractured reservoirs during the gas injection process, an accurate value of the molecular diffusion coefficient (MDC) of gases from a gas filled fracture into the oil matrix is essential. During the injection of miscible fluids with oil, transport of the injectant and oil are controlled by fracture and matrix properties. Diffusion is a significant-oil recovery mechanism between matrix and fracture. However, experimentally determined data concerning to gas transfer between fracture-matrix systems by diffusion mechanism are relatively rare.

In this study the pressure-decay method is applied to obtain effective molecular diffusion coefficient of CO_2 and CH_4 in heavy oil saturated porous matrix media at different conditions of temperatures. Gas-diffusion and interface-mass-transfer coefficients are determined by applying a transient-state equilibrium diffusion model. The effect of porous media presence on these coefficients has also been investigated.

It is expected that the experimental results will be useful in deriving the matrix-fracture transfer function by diffusion, which is required for simulation of recovery in naturally fractured reservoirs.

Key words: molecular diffusion coefficient, interface-mass-transfer, fracture, porous matrix, heavy oil, fractured reservoir

1. Introduction

A large proportion of the world's proven oil reserves have been found in naturally fractured reservoirs (NFRs). The target oil in NFRs exists in rock matrix. During the injection of tertiary recovery materials that are miscible with matrix oil, i.e., hydrocarbon solvents, alcohols, CO_2, CH_4, etc., fracture network creates the path for the injected solvent to bypass and leave the unswept oil zones in the matrix. Significant amount of oil can be recovered from this upswept bypassed zone by maximizing the subsequent crossflow or mass transfer between fracture and media. In this type of reservoirs, the transport of the injectant and the oil is controlled by fracture and matrix properties. Diffusion is a significant-oil recovery mechanism for mass transfer between matrix and fracture. Similar processes can be encountered during the sequestration of greenhouse gases, and the transport of contaminants in subsurface reservoirs. More over, in heavy oil recovery from naturally fractured reservoir by miscible EOR technique, like miscible gas flooding the role of diffusion mechanism in improving oil recovery is crucial.[13]

For the heavy oil NFRs, the role of diffusion process in miscible oil recovery methods such as miscible gas flooding will be stronger due to very high viscosities of them. Therefore an accurate value of the molecular diffusion coefficient (MDC) of gases from the gas filled fracture into the heavy oil saturated matrix is essential for calculating the rate of gas dissolution in heavy oils.

However, experimentally determined data concerning to gas transfer between fracture-matrix systems by diffusion mechanism are relatively rare in the open literature and most of the published values of diffusivity data are related to the bulk systems, in absence of the porous media.

Diffusion within porous matrix has been studied since the early years of the 20th century, especially in homogeneous media with intergranular porosity. Some studies[7,11] focused on finding the relationship between the molecular diffusion, tortuosity, formation resistivity factor and effective matrix MDC. However, some others were interested in measuring the MDC utilizing indirect methods. For example, one common applied methodology is to establish a gas flow at one end of a liquid saturated matrix block and measure the concentration changes in the resulting current flow.[12] In such a system it is very difficult to measure the concentration variations in the current flow, because changes are generally very small. Renner[8] measured diffusion coefficients of hydrocarbon gases in consolidated porous media saturated with decane and brine at pressures up to 6 MPa. He developed a correlation as a function of liquid viscosity and thermo-physical properties of the diffusing gases for predicting diffusion coefficient. However, in this study diffusivity of light gases into heavy oil is correlated as a function of temperature, oil viscosity and molecular weight of the diffusing gases.

Amongst all experimental methods developed to measure gas diffusivity in liquids, pressure-decay technique used first by Riazi[9] has attracted much attention due to its simplicity and robustness of the approach. He mea-

sured methane diffusivity in liquid pentane by recording both the rate of pressure drop and the interface movement of gas-liquid due to pentane swelling. Later, Zhang et al.[14] used this method for dilute solutions of a solvent gas in heavy oil. They developed a simplified experimental procedure and mathematical solution to relate the rate of pressure decline to diffusivity. Civan and Rasmussen[3,4] developed a mathematical model for further study on the experimental work of Zhang et al.[14] in order to estimate the gas diffusion coefficient. They ended up with two models including; equilibrium and non-equilibrium ones. The non-equilibrium model accounted for the delay in gas transport in the liquid phase. Though, their work was limited to the bulk system, without a proper investigation of the porous media effect on the diffusion.

In the present research, a comprehensive experimental investigation on the effective molecular diffusion determination of CO_2 and CH_4-heavy oil systems in homogeneous porous matrix was undertaken. In particular, glass beads of well-defined size in the range of 0.0177 - 0.0297 cm and porosity of 0.43 were used. The so-called pressure decay method was applied to measure the molecular diffusivity of gases in heavy oil. This paper also presents a methodology that can differentiate between the various stages in the diffusion process.

2. Experiments

A pressure-decay experimental setup was constructed to measure the effective MDC of pure CO_2 and CH_4 in packed glass beads saturated with heavy oil. The heavy oil components and related compositions were determined previously, using gas chromatography technique are shown in Table 1.

Preliminary tests were conducted to debug the setup. The diffusion cell was surrounded by a temperature controlled air bath in order to increase the temperature of the diffusion cell to the desired value up to 50 °C, as shown in Fig. 1. The bath is also equipped with a high-pressure stainless steel gas storage tank having a volume of 20 000 cm³, to store gas at the desired temperature and pressure. The tank was connected to the top of the diffusion cell. A blind diffusion cell with a volume of 730 cm³ was designed to be partially filled with oil saturated glass beads, which was an unconsolidated porous media. A sieve was used in order to have grain size ranging between the meshes 50 and 80. The measured porosity was 43%. Also a visual cell with a volume of 559 cm³ was used which allowed the observation of the liquid level during the diffusion process. The observations clarified that the position of the interface does not change significantly with time. In order to measure the pressure change inside the cell,

Table 1. Heavy oil composition

Components	Dead Oil Composition (mol%)
C_6	2.84
C_7	2.76
C_8	4.63
C_9	5.63
C_{10}	5.26
C_{11}	2.33
C_{12+}	76.55
Total	100.00

during the experiment, an accurate digital pressure transducer was also connected to the top flange. The diffusion cell can tolerate pressures up to 200 bar and temperatures up to 130 °C.

In preparation for a pressure-decay diffusivity test, the gas is initially introduced into the storage tank at high pressure. The system was left at the desired temperature for about 24h to ensure isothermal condition throughout the system. Then, the top three-way valve of the cell was connected to the high-pressure gas storage. When the initial pressure in the cell reached the desired value, the top valve was closed and the experiment began. To avoid interference between convection and diffusion the gas injection time (~2 minute) must be very small compared to characteristic diffusion time. As time passes, gas diffuses into the oil and pressure tends to drop very slowly in the gas space. Acquisition of a complete set of pressure-time data usually requires 10-30 days. The diffusion coefficient may then be determined from the pressure-time data.
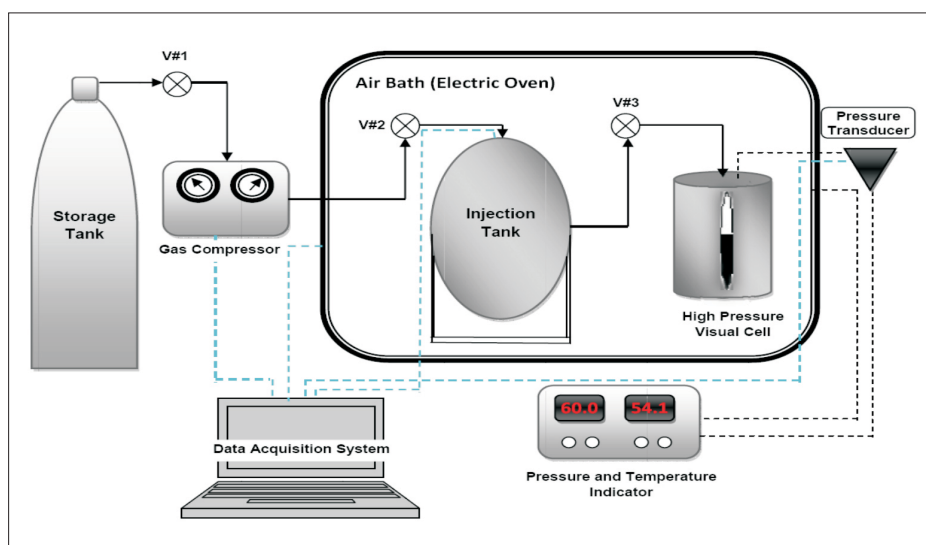

Fig. 1. Schematic of high pressure-decay experimental setup
Sl. 1. Shematski prikaz postavki eksperimentalnog pokusa snižavanja visokog tlaka

3. Theory

3.1 Mass transfer Model

When a gas is injected into a pressure cell containing heavy oil sample, direct contact between the injected gas and heavy oil takes place at their interface. Subsequently, the gas is gradually dissolved in the heavy oil until the latter is completely saturated with the former. A schematic diagram of the gas-heavy oil system is shown in Fig.2, where the gas-heavy oil interface is located at $x = 0$ and the bottom of the pressure cell is located at $x=L$.

Dissolution of gas into the heavy oil is modeled by assuming that the rate of gas leaving the supply cell is equal to the rate of gas dissolution in the oil. This is valid because theoretically, no gas accumulates in the gas cap. Thus, knowing the initial pressure of the supply cell tank and subtracting the measured pressures from it, one can have the amount of gas transfer from the supply cell to the diffusion cell verses time. As it is explained in the experimental part, this transfer happens only when there is gas demand in the diffusion cell. As a result of dissolution, this gas demand diminishes when the liquid column concentration is equal to its saturation concentration. Therefore, equation (1) models the gas balance in the supply cell. The mass balance equation for the gas in the supply cell is:

$$\frac{M_g h}{RT}\left(\frac{p_0}{z_0} - \frac{p}{z}\right) = Q, \quad t > 0 \tag{1}$$

where p and T are the pressure and temperature of the gas, R is the universal gas constant; $z=z(p,T)$ represents the real-gas deviation factor, correlated empirically as a function of pressure and temperature and Q denotes the cumulative mass of the dissolved gas in the liquid phase per unit cross-sectional area of the gas/liquid interface.

Civan (2001) derived an alternative expression for Q as follow:

$$Q(t) = \int_0^L [C(x,t) - C_0]dx = L\int_0^1 \left[C\left(\frac{x}{L}, t\right) - C_0\right]d\left(\frac{x}{L}\right) \tag{2}$$

where L is the height of the liquid column.

By applying the continuity equation and the Fick's law, the molecular diffusion process can be described by an unsteady state condition and one-dimensional system is represented by[1]:

$$\frac{\partial C}{\partial t} = D_{eff}\frac{\partial^2 c}{\partial x^2} \tag{3}$$

where $C(x,t)$ is the molar concentration of the gas in the heavy oil, x is the distance from the bottom of the pressure cell, t is time and D_{eff} is the effective MDC of gas in heavy oil, assuming that it is independent of gas concentration.

The following boundary and initial conditions can be considered for concentration:

• The solvent mass transfer flux at the interface is assumed to be proportional to the difference between the saturation concentration under the equilibrium pressure and the existing concentration at the interface:
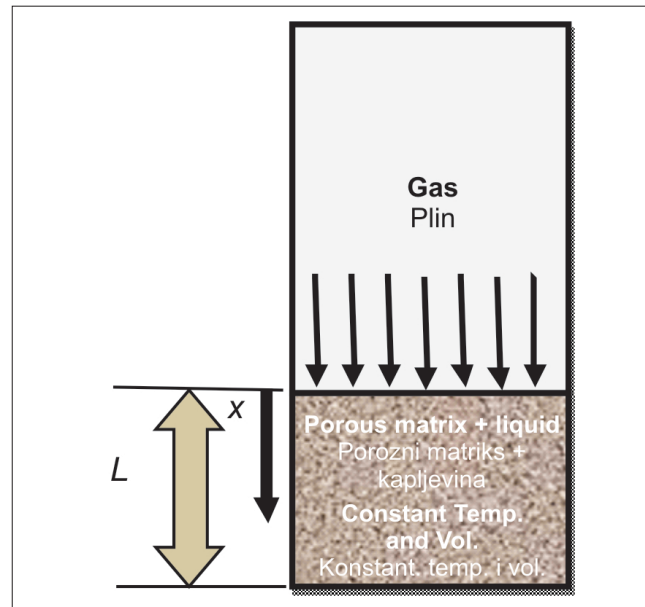

Fig. 2. Schematic of the PVT cell
Sl. 2. Shematski prikaz PVT čelije

$$D\frac{\partial C}{\partial x}\bigg|_{x=0} = \left(C_{sat}(p_{eq}) - C(x,t)\right), \quad t > 0 \tag{4}$$

• Oil sample is a dead oil and the initial condition is:

$$C(x,t)\big|_{t=0}, \, 0 \le x \le L \tag{5}$$

• The infinite-distanced condition is:

$$C(x,t)\big|_{x\to\infty}, \quad t > 0 \tag{6}$$

• The sealed tank bottom condition is:

$$\frac{\partial C}{\partial x}\bigg|_{x=L} = 0, \quad t > 0 \tag{7}$$

The dimensionless form of the equations can be organized by introducing the following dimensionless parameters:

$$C_D = \frac{C(x,t)}{C_{sat}(p_{eq})} X_D = \frac{x}{L} t_D = \frac{t_D}{L^2} k_D = \frac{k_D}{L} \tag{8}$$

Here, k_D is referred to as the mass transfer Biot number.

The dimensionless mass-accumulation function can be expressed as

$$Q_D(t_D) = \int_0^1 C_D(x_D, t_D)dx_D \tag{9}$$

Eq. (1) can also be written in the non-dimensional form

$$\frac{M_g h}{RTL\left(C_{sat}(p_{eq})\right)}\left[\frac{p_0}{z_0} - \frac{p}{z}\right] = Q_D(t_D), \quad t > 0 \tag{10}$$

Eq. (10) can be applied to any conveniently selected reference pressure value pr measured at a dimensionless time t_{Dr} to obtain

$$\frac{M_g h}{RTL\left(C_{sat}(p_{eq})\right)}\left[\frac{p_0}{z_0} - \frac{p_r}{z_r}\right] = Q_D(t_{Dr}), \quad t > 0 \tag{11}$$

Choosing the reference pressure equal to equilibrium pressure, the following expression will be obtained by combination of Eqs. (10) and (11)[4]:

$$Q_D(t_D) = \frac{\left[\dfrac{p_0}{z_0} - \dfrac{p(t_D)}{z(t_D)}\right]}{\left[\dfrac{p_0}{z_0} - \dfrac{p_{eq}}{z_{eq}}\right]} \tag{12}$$

All the parameters for determining the right hand side of Eq. (12) are known or can be calculated from our experimental data. The left hand side of Eq. (12) is found by Civan[4] method. The forward solutions of Eqs. (2) to (6) for both finite and infinite acting was given as follows:

• **Short-time (Semi-Infinite) Solution, $(L \to \infty)$.**

The analytical solution for semi-infinite regions is given by the following equation:

$$Q_D^{ST}(t_D) = \frac{1}{k_D}\exp\left(k_D^2 t_D\right) erfc\left(k_D\sqrt{t_D}\right) - 1 + 2k_D\sqrt{\frac{t_D}{\pi}} \tag{13}$$

When t_D is very large, the short-time approximation of Eq. (13) approaches the asymptote[4]:

$$Q_D^{ST}(t_D) \cong 2\sqrt{\frac{t_D}{\pi}} - \frac{1}{k_D}, \quad k_D\sqrt{t_D} \to \infty \tag{14}$$

In practice the large-time behavior of the short-time approximation applies to some midrange of the overall time variation. Thus, when Q_D is plotted against $\sqrt{t_D}$, we might expect some midrange portion of the curve to be nearly parallel to, or coincident with the straight -line asymptote by Eq. (14).

• **Long-Time (Finite-Length) Solution**

The analytical solution for the finite-acting model is expressed in the following dimensionless form:

$$Q_D(t_D) = 1 - 4\sum_{m=1}^{\infty}\frac{\sin^2\lambda_m}{\lambda_m[2\lambda_m + \sin(2\lambda_m)]}\exp\left(-\lambda_m^2 t_D\right) \tag{15}$$

where λ_m denotes the roots of

$$\lambda_m \tan\lambda_m = k_D \tag{16}$$

When the time t_D is large, only the leading term in the infinite-series solution is significant, and Eq. (15) can be simplified as:

$$Q_D(t_D) = 1 - Q_1(\lambda_1)\exp\left(-\lambda_m^2 t_D\right) \tag{17}$$

where

$$Q_1(\lambda_1) \equiv \frac{4\sin^2\lambda_1}{\lambda_1[2\lambda_1 + \sin(2\lambda_1)]} \tag{18}$$

This is known as long-time approximation. The parameter λ_1 is the smallest positive root of the transcendental equation $\lambda_1 \tan\lambda_1 = k_D$. The upper bound $\lambda_1 = \pi/2$ corresponds to $k_D \to \infty$, which in turn corresponds to the case for the surface Diriclet-type boundary condition

which its concentration is equal to equilibrium condition. The natural logarithm of Eq. (17) leads to the result[4]:

$$\ln\left[1 - Q_D^{LT}(t_D)\right] = \ln\left[Q_1(\lambda_1)\right]\lambda_m^2 t_D \tag{19}$$

Thus, plotting the natural logarithm of $\ln\left[1 - Q_D^{LT}(t_D)\right]$ against t_D produces a straight-line curve. Using this method, the two unknown coefficients D_{eff} and k can be extracted from a given set of pressure-decline data.

4. Experimental Results and discussions

The measured data for four pressure-decay runs are plotted in Fig. 3. Fig. 3 includes the data related to 4 runs in the presence of the porous media and in the Bulk system (in the absence of the Porous medium). The objective is to interpret experimental data and find the values of diffusion coefficient D and interface-mass-transfer coefficient k.
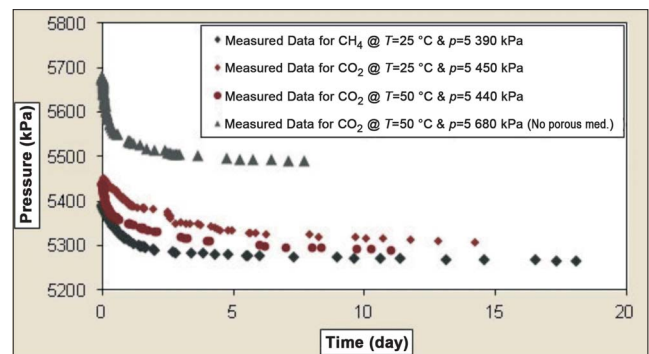

Fig. 3. Pressure-decay data for the four different runs in the present and absent of porous media
Sl. 3. Podaci o padu tlaka za četiri izvođenja uz postojanje i nepostojanje poroznog medija

4.1. Analysis of the Asymptotic Long-Time Behavior for the short Time.

The straight-line character of the curves for asymptotic long-time behavior for the short time solution on $Q_D(t_D)$ versus $\sqrt{t}$ plots (see Fig. 4 to 7) suggests a systematic method for extracting the diffusion coefficint D and the interface-film coefficient k values from the data associated with a given physical experiment. By means of Eq. (14), this relation can be expressed as

$$Q_D(t_D) = -a_{ST} + b_{ST}\sqrt{t} \tag{20}$$

in which the intercept and slope of the straight line are given by

$$a_{ST} = \frac{1}{K_D}, \quad b_{ST} = \frac{2}{L}\sqrt{\frac{D}{\pi}} \tag{21}$$

Therefore, the diffusion coefficient D and interface-mass-transfer coefficient k can be calculated as follows:

$$D = \frac{\pi L^2 b_{ST}^2}{4} \tag{22}$$

Table 2. Experimental pressure-decay results, diffusivity and mass transfer coefficient

| Parameters	Run 1	Run 2	Run 3	Run 4
Solute	CO_2	CH_4	CO_2	CO_2
System	Porous Media	Porous Media	Porous Media	Bulk
T (°C)	25	25	50	50
p_i (kPa)	545 0	539 0	544 0	568 0
a_{ST}	0.107 89	0.14	0.062 7	0.090 5
b_{ST} (day^{-1})	0.013 4	0.020 4	0.949 5	1.273 9
a_{LT}	0.393 88	1.396 8	0.543 5	0.876 9
b_{LT} (day^{-1})	0.000 192	0.000 11	0.372	0.573 0
λ_1	2.127 3	2.280 9	2.275 7	2.517 5
$D \times 10^9$(m^2/s) (Short-Time)	13.26	30.88	44.68	226.8
$D \times 10^9$(m^2/s) (Long-Time)	9.195	0.2194	10.78	37.05
$k \times 10^7$ (m/s) (Short-Time)	17.77	29.39	94.90	202.1
$k \times 10^7$ (m/s) (Long-Time)	4.19	0.031 9	3.846	5.416
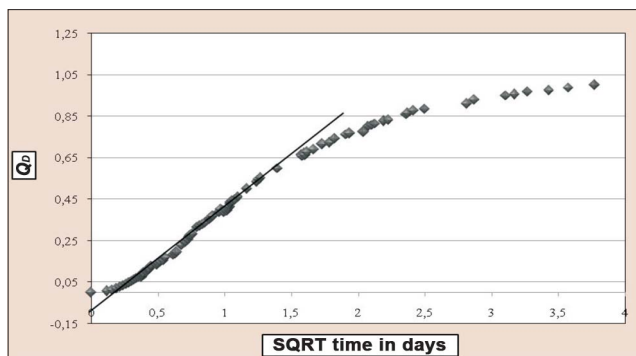
Fig. 4. Q_D vs $t^{1/2}$ regression of the CO_2/heavy oil data in the porous matrix system, short-time approximation (T=25 °C & p=5 450 kPa)

Sl. 4. Q_D nasuprot $t^{1/2}$ regresija, podaci CO_2/teška nafta u sustavu poroznog matriksa, kratkoročna aproksimacija (T=25 °C & p=5 450 kPa)
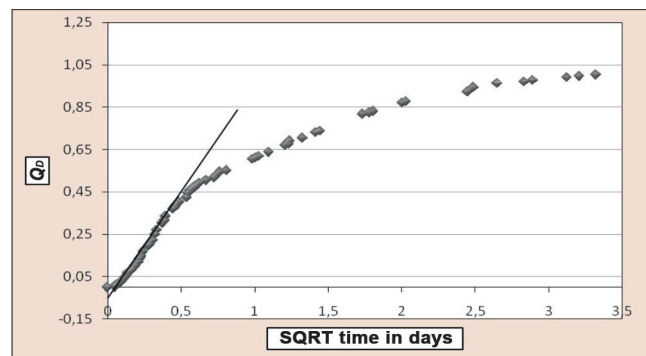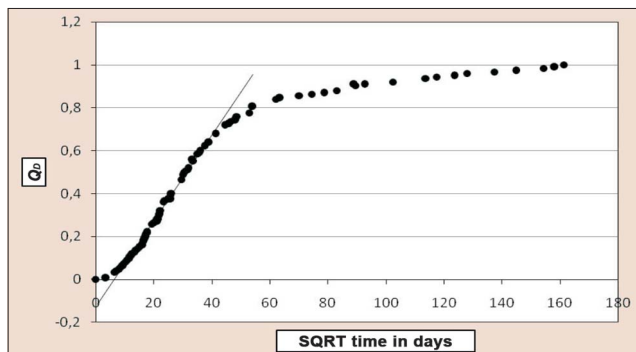

Fig. 6. Q_D vs $t^{1/2}$ regression of the CO_2/heavy oil data in the porous matrix system, short-time approximation (T=50 °C & p=5 440 kPa)

Sl. 6. Q_D nasuprot $t^{1/2}$ regresija, podaci CO_2/teška nafta u sustavu poroznog matriksa, kratkoročna aproksimacija (T=50 °C & p=5 440 kPa)

Fig. 5. Q_D vs $t^{1/2}$ regression of the CH_4/heavy oil data in the porous matrix system, short-time approximation (T=25 °C & p=5 390 kPa)

Sl. 5. Q_D nasuprot $t^{1/2}$ regresija, podaci CO_4/teška nafta u sustavu poroznog matriksa, kratkoročna aproksimacija (T=25 °C & p=5 390 kPa)
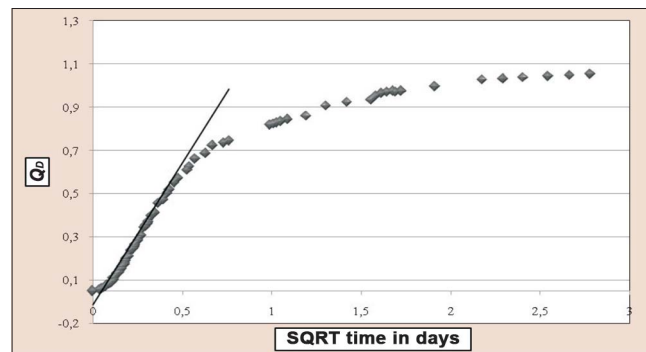

Fig. 7. Q_D vs $t^{1/2}$ regression of the CO_2/heavy oil data in the bulk system, short-time approximation (T=50 °C & p=5470 kPa)

Sl. 7. Q_D nasuprot $t^{1/2}$ regresija, podaci CO_2/teška nafta u sustavu poroznog matriksa, kratkoročna aproksimacija (T=50 °C & p=5 470 kPa)
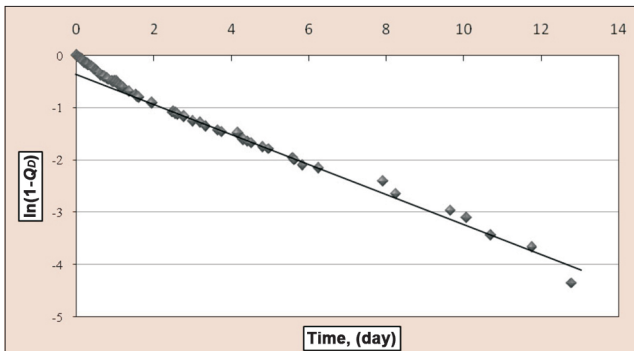
Fig. 8. ln(1-Q_D) vs t plot of the CO_2/heavy oil data in the porous matrix system, the long time behavior (T=25 °C and p=5 450 kPa)

Sl. 8.   ln (1-Q_D) nasuprot t za podatke CO_2/teška nafta u sustavu poroznog matriksa, ponašanje kroz dugi vremenski period (**T=25 °C & p=5 450 kPa**)

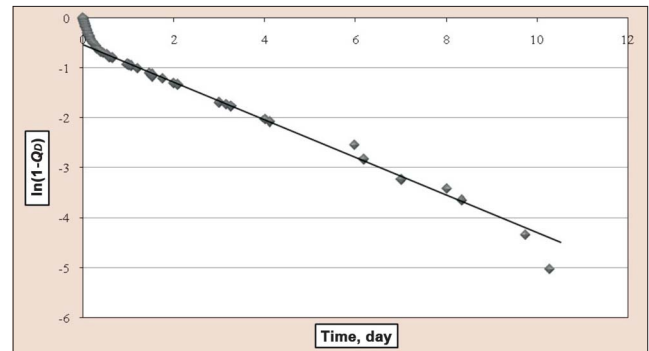**Fig. 10.** ln(1-Q_D) vs t plot of the CO_2/heavy oil data in the porous matrix system, the long time behavior (**T=50 °C and p=5 440 kPa**)

Sl. 10.   ln(1-Q_D) nasuprot t za podatke CO_2/teška nafta u sustavu poroznog matriksa, ponašanje kroz dugi vremenski period (**T=50 °C & p=5 440 kPa**)
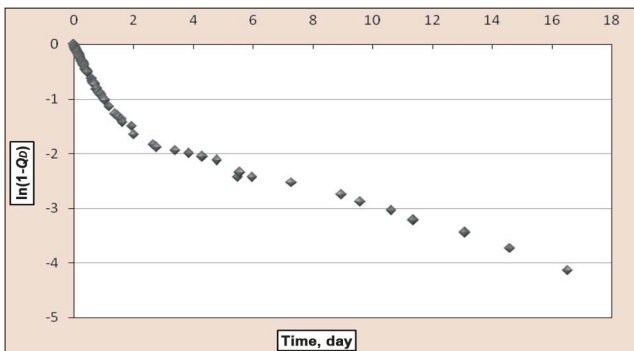

Fig. 9. ln(1-Q_D) vs t plot of the CH_4/heavy oil data in the porous matrix system, the long time behavior (**T=25 °C and p=5 390 kPa**)

Sl. 9.   ln(1-Q_D) nasuprot t za podatke CH_4/teška nafta u sustavu poroznog matriksa, ponašanje kroz dugi vremenski period (**T=25 °C & p=5 390 kPa**)

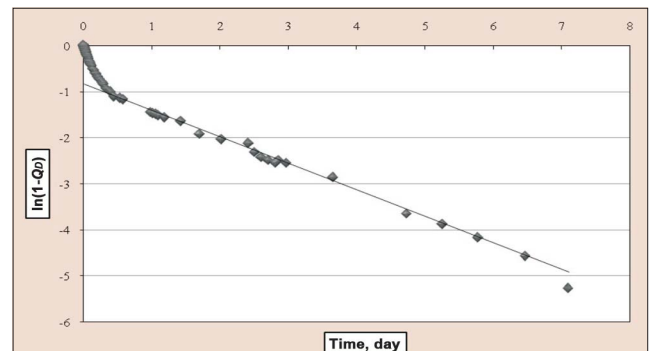**Fig. 11.** ln(1-Q_D) vs t plot of the CO_2/ heavy oil in the bulk system, the long time behavior (T=50 °C and p=5 680 KPa)

Sl. 11.   ln(1-Q_D) nasuprot t za podatke CO_2/teška nafta u sustavu poroznog matriksa, ponašanje kroz dugi vremenski period (**T=50 °C & p=5 680 kPa**).

$$k = \frac{D}{L} k_D = \frac{D}{L a_{ST}} \qquad (23)$$

The coefficients obtained by this approximtion are given in Table. 2.

4.2 Analysis for Large Times

The striaght-line character of the curves for large times on semilog plots (see Fig. 8 to 10) suggests a systematic method for extracting the values of the diffusion coefficient D and the interface-film coefficient k from the data associated with a given physical experiment. The large-time approximation Eq. (17) is expressed in terms of the actual time t. The experimental data can be correlated with a stright line by means of a regression analysis in the form of

$$\log_{10}[1 - Q_D] = -a_{LT} - b_{LT} t \qquad (24)$$

where the y-axis intercept and the slope of the line, measured per unit time, are, respectively

$$a_{LT} = -\log\left[Q_0^{LT}(\lambda_1)\right] = -\log\left\{\frac{4\sin^2(\lambda_1)}{\lambda 1\left[2\lambda 1 + \sin(2\lambda_1)\right]}\right\} \qquad (25)$$

$$b_{LT} = 0.4343\lambda_1^2 \frac{D}{L^2} \qquad (26)$$

Eq. (25) allows determination of λ_1 and thus k_D by virtue of the relation $\lambda_1 \tan\lambda_1 = k_D$ given by Eq. (16). Consequently, the mass-transfer k_D is determined entirely by the y-axis intercept.

Having λ_1, the diffusion coefficient D is found from Eq. (26):

$$D = \frac{b_{LT} L^2}{0.4343\lambda_1^2} \qquad (27)$$

k_D is calculated by Eq. (16):

$$k_D = \lambda_1 \tan\lambda_1 \qquad (28)$$

Finally, the interface film mass-transfer coefficient k can be determined:

$$k = \frac{D}{L} k_D \qquad (29)$$

The diffusivity coefficient and interface mass transfer coefficient obtained by this method are given in Table. 2. The result indicates that the short time diffusivity is higher than long time values and also the rate of mass transfer will be decreased in long time.

The results in Table 2 also indicate that the molecular diffusion in the presence of the porous medium was less than that in its absence. This is due to the system's pore interconnections, known as the tortuosity which directly affects the path movement of the gas molecules and the effective contact area of the gas and heavy oil which is equal to the area times porosity (i.e.; $A_{effective} = A \cdot \phi$). Comparison of pressure decay trends in both the bulk and porous systems indicate that the rate of pressure decay is lowered and the necessary time for the equilibrium pressure is enhanced in the porous systems, as shown in Figure 3. This means that in the porous media both solubility and diffusivity are decreased comparig with bulk system. Also at the same temperature the difusivity of carbon dioxide had relatively the same order as methane diffusivity during infinite period, while at the long time the diffusivity of CO_2 was more than that of methane. That could be due the fact that as the molecular similarity increased, the molecular diffusivity and the solubility at the final equilibrium state of the experiment also enhanced. Therefore, the resulting diffusivity of carbone dioxide would be enhanced because of its higher molecular weight than methane.

Furthermore, by comparison the results of runs 1 and 3 experiments (Figure 3) one can observe the effect of temperature on diffusion process. They showed that as the temperature increased, the rate of pressure decay enhanced and final equilibrium pressure lowered. This meant that at higher temperatures both solubility and diffusivity increased. In other words, more gas at higher rates dissolved into heavy crudes under such conditions.

5. Conclusion

A high pressure experimental setup is designed and constructed to measure the effective molecular diffusion of methane and carbon dioxide between a gas filled fracture and heavy oil saturared matrix system at desired conditions. Various experimental runs at different conditions were performed. The molecular diffusion coefficients are determined using a transient-state equilibrium diffusion model. Short-time and long-time molecular diffusion coefficient and the mass transfer coefficient were determined. The result shows that diffusivity and mass transfer coefficient of methane are less than that of carbon dioxide, so the injection of CO_2 woud be more effective than CH_4. Also, the presence of porous media will considerably decelerate the difusion process and consequently decrease the gas diffusivity. Moreover, it was observed that temperature has a direct effect on the both solubility and diffiusivity of the gases, so that as the temperature increased the rate of dissolution of the gas in heavy oil through diffusion proces was also increased.

Finally, these result of this work will be useful in compossotional simulation and modeling mass transfer into matrix during solvent injection in fractured and heavy oil reservoirs.

6. Nomenclatures

A	Cross sectiononal area of the cell (cm²)
$C(x,t)$	Gas concentration in oil saturated porous media (mol/cm³)
$C_{sat}(p_{eq})$	Saturation concentration of the gas in the oil under the equilibrium pressure (mol/cm³)
D_{eff}	Effective molecular diffusion coefficient (m²/s)
D_0	Pre-exponential factor (m²/s)
E_a	Activation energy required for diffusion (cal/mol)
h	Height of the gas in the cell (cm)
k	Interface mass-transfer coefficient (m/s)
$p(t)$ p_{eq}	Measured and equilibrium pressures, respectively (kPa)
Q	Cumulative gas mass, per unit cross section area, disolved in th liquid phase (kg/m²)
R	Universal Gas constant (8314 kPa.cm³/mol.K) or (1.987cal/mol.K)
t	Time (s)
T	Temperature (°C or K)
V	Volume of the gas in the vessel (cm³)
n	Number of time series, $t=t_i$, $i=1,2,\ldots,n$
x	Position along diffusion vessel (cm)
L	Height of the oil in the vessel (cm)
z	Gas deviation compressibility factor

7. Greek symbols

λ	Roots of Eq. 25, Dimensionless

8. Subscripts

D	Dimensionless

9. References

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