A Very Simple Multiple Mixing Cell Calculation To Compute the Minimum Miscibility Pressure Whatever the Displacement Mechanism

Jean-Noël Jaubert* and Luc Wolff

Laboratoire de Thermodynamique des Séparations, Institut National Polytechnique de Lorraine, École Nationale Supérieure des Industries Chimiques, 1 Rue Grandville, 54.000 Nancy, France

Evelyne Neau

Laboratoire de Chimie-Physique, Faculté des Sciences de Luminy, 163 Avenue de Luminy, 13288 Marseille Cedex 9, France

Laurent Avaullee

SE3T, 5 Boulevard Général Koenig, Résidence Michelet-Delattre, Bât. A9, 13009 Marseille, France

In this paper, an easily computable algorithm, allowing the calculation of the minimum miscibility pressure (MMP) whatever the displacement mechanism, is described. Such an algorithm is based on a multiple mixing cell calculation without any porous media. Only thermodynamic equations are taken into account i.e., a P/T flash routine is only required. Computational speed is from 15 to 80 times faster than using a commercial one-dimensional (1D) simulator, but the accuracy is the same.

Introduction

Gas injection processes are among the most effective methods of enhanced oil recovery. A key parameter in the design of a gas injection project is the minimum miscibility pressure (MMP), the pressure at which the local displacement efficiency approaches 100%. Until now, computational attempts to calculate the MMP include essentially six approaches:

First approach: Some investigators have tried to fit experimental MMP's to a variety of expressions for specific gas systems.[1−3] Although those approaches reproduce reasonably well the experimental observations on which they were based, they should be used with caution for injection gases or oils with compositions substantially different from those used to build the correlation.

Second approach: use of a direct tie line approach.[4] In this approach, a negative flash algorithm[5] is used in order to find the lowest pressure at which the line whose extension is passing through the composition of the crude oil (initial tie line) or through the composition of the injected gas becomes critical. If the initial tie line first becomes critical, the miscibility process is assumed to be a vaporizing gas drive mechanism (VGDM). In the opposite case it is concluded that the process is a condensing gas drive mechanism (CGDM). Such an algorithm was developed, assuming that the behavior of a real petroleum fluid was analogous with the behavior of ternary systems what is scarcely exact. Indeed, Jaubert et al.[6] have shown that working on real petroleum fluids modeled with a realistic number of compounds, a crossover tie line[7] different from the initial or the gas tie line was almost always controlling the miscibility process. It means that, if a negative flash is used to make critical either the initial or the gas tie line, the MMP will be in most cases over estimated. As a conclusion, this approach must be regarded with cautiousness.

Third approach: use of a one cell simulation algorithm i.e., a mixing cell calculation based on a single cell.[4,8] In this approach, forward or backward contacts are performed in a single cell to calculate the MMP corresponding either to a vaporizing or to a condensing mechanism. Such an algorithm is suitable to compute the correct MMP when the initial or the gas tie line controls the process. Moreover, it has been recently explained[6] that a one cell algorithm could calculate properly the MMP if increasing pressure a mixed condensing/vaporizing mechanism (C/VM) controlled by a crossover tie line turns into a pure vaporizing process. If at a pressure strictly equal to the MMP, miscibility is reached by a series of condensation fronts followed by a series of vaporization fronts, i.e., if the mechanism is a C/VM, a one cell algorithm will always overestimate the MMP.

Fourth approach: a direct calculation of the MMP from an analytical solution to the flow problem. Such a method will be probably, in the near future, the quickest way to determine the MMP for a combined condensing/vaporizing mechanism. Wang and Orr[9] began to develop such a method, but at the moment, their procedure is not yet completely general since it may only apply if the injected gas contains less than two components. Very recently, Jessen and Michelsen[10] obtained very interesting results in their attempt to generalize the approach initially developed by Orr.

Fifth approach: use of a one-dimensional compositional simulator. It is the slowest but safest way to compute the MMP.[11] Even if the mechanism is a mixed condensing/vaporizing process, as initially put in evi-

* To whom the correspondence should be addressed. Fax: (+33) 3 83.35.08.11. Phone: (+33) 3 83.17.50.81. E-mail: jaubert@ensic.u-nancy.fr.

10.1021/ie980348r CCC: $15.00
Published on Web 11/12/1998

dence by Zick,[12] the MMP can be determined by finding the point of breakover in a plot of the recovery factor ($RF_{1.2}$) at 1.2 PVI (pore volume injected) versus pressure.[13] The same authors[11−13] also explain that to use properly such a simulator it is necessary to run displacements for varying numbers of grid blocks at each pressure (e.g. 50, 100, 200, and 500 grid blocks) and to smooth the oil recovery at 1.2 PVI obtained for each run in order to determine the oil recovery (at 1.2 PVI) corresponding to an infinite number of grid blocks ($RF^{\infty}_{1.2}$). Indeed, they observed that the displacement behavior was very sensitive to the number of grid blocks used in the simulation. They explain that numerical dispersion was responsible of this behavior. Stalkup[13] tried several extrapolation methods and found that the recovery factor at 1.2 PVI was a linear function of the inversed square root of the number of grid blocks used to model the tube. Very recently Høier[14] tested different mathematic functions to extrapolate $RF_{1.2}$ to an infinite number of grids and concluded that a straight line extrapolation most often gives MMP predictions significantly higher than other functions. He advised to perform additional runs near the estimated MMP at new pressures and for larger number of grids (typically 1000). As clearly demonstrated by Høier,[14] a slim tube simulation with correct elimination of numerical dispersion requires at least six−seven pressures, run with 50, 100, 200, and 500 grid cells each. If a few more runs are made in the vicinity of the estimated MMP, the procedure requires a minimum of 30 runs, including extrapolation to $RF^{\infty}_{1.2}$ and interpolation to determine one MMP. Such slim tube simulations are thus tedious, not completely automated, and time-consuming.

Sixth approach: use of a multiple mixing cell calculations (cell to cell simulation) as initially developed by Cook et al.,[15] Metcalfe et al.,[16] and Pedersen et al.[17] Unfortunately, such algorithms were developed more than 10 years ago ignoring the presence of the crossover tie lines and cannot be used in their published version to calculate properly the MMP. Very recently, in his thesis, Høier[14] cites unpublished work by Zick allowing one to compute the MMP through a multiple cell calculation.

As a conclusion, only 3 approaches are (or soon will be) suitable to compute the MMP: (1) the use of a 1D compositional simulator which has the disadvantage to be long, tedious, not automated, and time-consuming; (2) the use of the global approach initially developed by Orr and co-workers[9] and generalized at the moment by Jessen and Michelsen[10] (such a method is very fast but has the disadvantage to be difficult to compute); (3) the use of the excellent unpublished algorithm developed by Zick.

In this paper, an alternative method is proposed to avoid the disadvantages of the previous ones. The developed algorithm is automated, from 15 to 80 times faster than the use of a 1D simulator, and very easy to compute. Such an algorithm relies on the following key point: the MMP is completely independent of the porous material through which the flow is occurring. Like any equilibrium thermodynamic property of a system, the MMP is not influenced by the relative permeability, capillary pressure, and interfacial tension. Minimum miscibility pressure is only dependent on the phase behavior of the system. All these points were verified experimentally by the French petroleum company TOTAL SA. In particular, more than 50 MMP were determined with two slim tubes: the first one full of sand and the second one full of glass beads. In all cases, the measured MMP's were exactly the same. It means it should be possible to compute the MMP with a very simplified slim tube, i.e., with a cell to cell simulation in which no porous media and very simple flow dynamics are considered. This is the basis of our work.

Table 1. Number of Compounds Used To Characterize the Fluids with MMP Calculated at the Reservoir Temperature Using a Commercial 1D Simulator (Reference Value)

system	n_{Oil}[a]	n_{Gas}[b]	temp/K	true MMP/bar (1D simulator)
O_1/I_1	15	1	374.85	504.8
O_2/I_2	15	9	374.85	423.8
O_3/I_3	15	9	366.45	221.6
O_4/I_4	15	11	394.25	382.6
O_5/I_5	27	13	383.15	395.6
O_6/I_6	14	7	368.65	246.6
O_7/I_7	28	12	387.45	429.6
O_8/I_8	16	11	394.25	433.1

[a] n_{Oil} is the number of compounds used to characterize the crude oil. [b] n_{Gas} is the number of compounds contained in the injected gas.

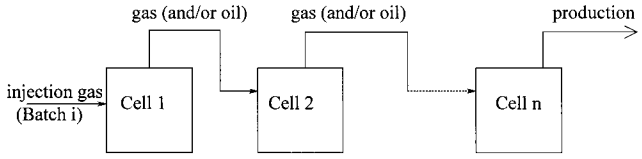


Figure 1. Logic of the cell to cell simulation.

From a Slim Tube Simulation to an Efficient Multicell Algorithm

To be able to have reference values and to know the accuracy of the algorithm described in this paper, the MMP's were first determined using a commercial 1D simulator.

(1) MMP Calculations Using a 1D Simulator. In a first step eight pairs of oil/gas fluids were selected in the database of the French Petroleum Co. TOTAL SA. These crude oils will be noted O_1 to O_8, and the associated injection gases, I_1 to I_8. Actually, O_1 and O_2 are strictly identical, but since two different gases (I_1 and I_2) were injected, we found it easier to understand if the oil had two different names. The C_{11}+ characterization procedure developed by Jaubert[18] and by Neau et al.[19] was applied for all the calculations. Since we decided not to apply any lumping method, each crude oil is described with a number of compounds varying between 14 and 28 (see Table 1) depending on the availability of TBP distillation data obtained from the associated tank oil. The injected gases are mixtures containing from 7 to 13 hydrocarbons lighter than *n*-nonane except I_1, which is pure methane (see Table 1). Please, do not hesitate to contact the authors if you need the detailed composition of the fluids investigated in this paper. For each system, the MMP was determined very carefully with a commercial 1D simulator (the procedure described by Høier[14] was applied). Some runs were performed with 2000 or 5000 grid cells in order to obtain an excellent accuracy on the calculated values. The results are summarized in Table 1.

(2) Proposed Algorithm. In this paper a multiple mixing cell calculation is used in order to compute first the recovery factors ($RF_{1.2}$) and then the MMP. It means that the procedure used is strictly the same as

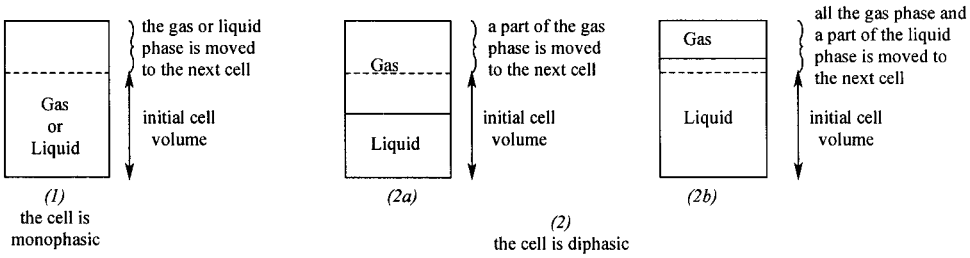


Figure 2. Moving procedure in the cell to cell simulation.

when a 1D simulator is used. However, as explained below, only 4 runs are necessary, and because of the very simple flow dynamics, time computation for each run is not so long.

The multicell technique used in this paper and described below is identical to the one developed by Metcalfe et al.[16] Such a simulation may be summarized as follows: In a first step, the program simulates a number of cells of equal volume in a series as shown in Figure 1. The temperature and the pressure are the same in each cell, and the volume is kept constant. All the cells contain initially the same fluid (the reservoir oil). A specified amount of gas is added to cell 1. It is assumed that perfect mixing takes place and that thermodynamic phase equilibrium is reached. This means that the conditions in the cell can be described by a *P*/*T*-flash calculation, here based on a modified Peng−Robinson (PR) equation of state.[20] After mixing of the injected gas and the cell fluid, the total volume of the cell will be larger than the assumed cell volume. The volume in excess is transferred from cell 1 to cell 2 (see Figure 2). If two phases are present, the gas phase is first moved. If moving all the gas phase the cell volume is still larger than the initial cell volume, a part of the liquid phase is also moved. In a second step, the excess volume formed in cell 2 is transferred to cell 3 and so on until production is obtained from the last cell. When one batch calculation has been completed, a new injection into cell 1 can take place and the cell to cell transfer calculation is resumed.

In this study, 500 cells were considered. Since the amount of gas added to cell 1 is at each batch equals 33% of the assumed cell volume, it will be necessary to perform $n = 500 \times 1.2/0.33 = 1800$ batch calculations to inject 1.2 PV of gas at the tube entrance. The biggest advantage of such a cell to cell simulation comes from at a given pressure, a unique run allows the calculation of the recovery factors ($RF_{1.2}$) corresponding to runs made with 50, 100, 200, and 500 cells. Indeed it is easy to record $RF_{1.2}$ in the cells 50, 100, 200, and 500 simultaneously. Let us take an example: since the tube is modeled with 500 cells, when the number of batch calculations reaches $n = 50 \times 1.2/0.33 = 180$, the value of the recovery factor in cell 50 is strictly the same as if a simulation had been performed with 50 cells only. Let us recall that the recovery factor $RF_{1.2}^{N}$ corresponding to a given cell number N is defined by a/b where the following are defined: a is the cumulative oil volume exiting cell N at tube conditions converted to surface conditions (15 °C, 1 atm). At each step, the matter exiting cell N (N = 50, 100, 200, or 500) is perfectly known. This matter is flashed at 15 °C and 1 atm, and the liquid phase volume is cumulated until the quantity of injected gas reaches 1.2 PV. To reach 1.2 PV in the cells 50, 100, 200, and 500 it is necessary to perform respectively 180, 360, 540, and 1800 batch calculations.

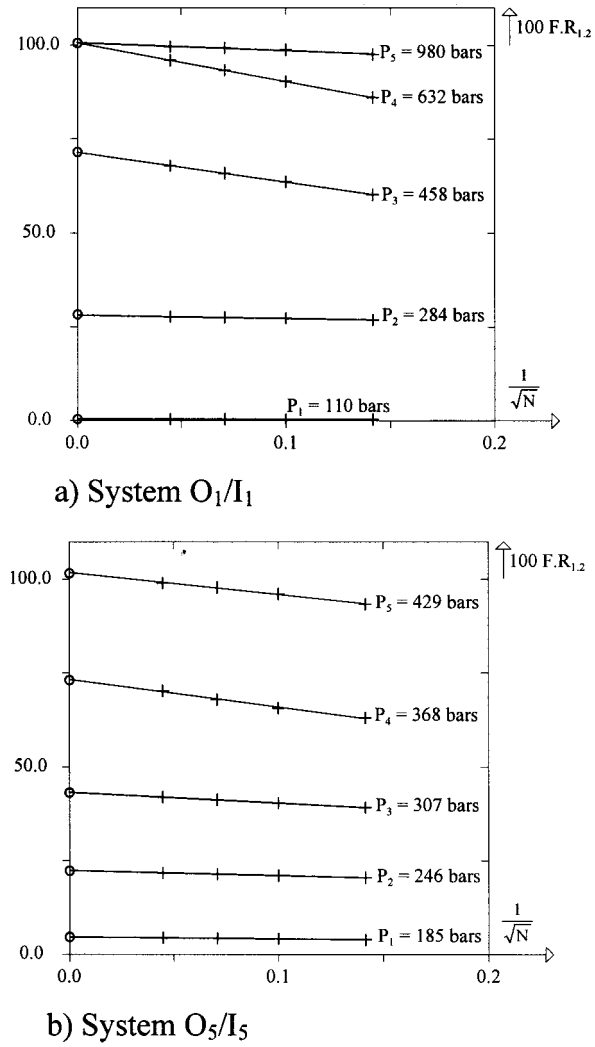


Figure 3. Illustration of the linear dependence of $FR_{1.2}$ versus $1/\sqrt{N}$: (+) recovery factors in the cells 50, 100, 200 and 500; (○) $RF_{1.2}^{\infty}$.

b is the oil volume (at tube conditions) initially introduced in the section of the tube which includes cells 1 to N and converted to surface conditions (it is thus obvious that b is 10 times smaller when $RF_{1.2}^{50}$ than when $RF_{1.2}^{500}$ is computed).

Once for a given pressure the four $RF_{1.2}$ values ($RF_{1.2}^{50}$, $RF_{1.2}^{100}$, $RF_{1.2}^{200}$, $RF_{1.2}^{500}$) are known, the $RF_{1.2}^{\infty}$ is simply determined by plotting $RF_{1.2}$ versus $1/\sqrt{N}$ (N = number of cells) and extrapolated to infinite number of cells by a simple straight line. As shown in Figure 3, working with such a simple simulator (without any porous media and with very simplified flow dynamics), $RF_{1.2}$ is a perfect linear function of $1/\sqrt{N}$.

Table 2. Main Results Obtained on the 8 Systems Selected in This Study

system	no. of runs	selected pressures	$RF^{\infty}_{1.2}$	P_{sat}/bar	FCMP/bar	calcd[a] MMP/bar	% deviation[b]	mechanism of miscibility
O_1/I_1	5	110	0.37	108.9	989.3	514.0	1.82	VGDM
		284	28.08					
		458	71.39					
		632	100.53					
		371	45.70					
O_2/I_2	4	105	0.085	108.9	581.0	424.0	0.05	C/VM
		200	20.43					
		295	42.27					
		390	74.95					
O_3/I_3	3	155	39.11	151.5	289.9	221.4	−0.11	C/VM
		180	55.90					
		205	77.24					
O_4/I_4	4	155	2.33	153.6	474.0	381.0	−0.43	C/VM
		218	18.99					
		281	38.40					
		344	65.60					
O_5/I_5	4	185	4.61	183.9	495.4	394.7	−0.22	C/VM
		246	22.39					
		307	43.31					
		368	73.19					
O_6/I_6	4	195	58.12	196.4	332.2	245.1	−0.60	C/VM
		222	75.15					
		249	97.28					
		168	42.33					
O_7/I_7	4	255	6.84	257.2	544.7	430.9	0.30	C/VM
		312	26.66					
		369	51.23					
		426	90.87					
O_8/I_8	3	365	38.88	365.5	497.3	434.6	0.36	C/VM
		390	54.78					
		415	74.68					
av	4						0.49%	

[a] With the proposed algorithm. [b] By comparison to results obtained with a commercial 1D simulator.

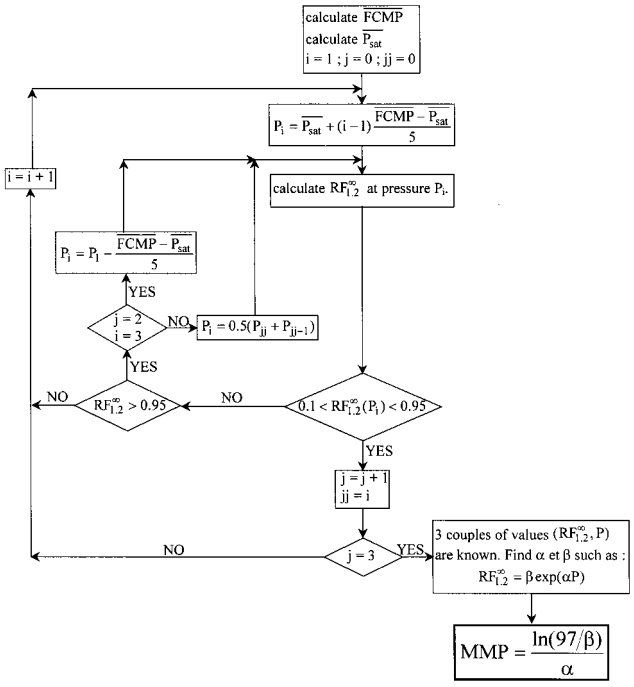


Figure 4. Flow sheet diagram allowing to compute the MMP.

To determine the MMP, it is necessary to make such simulations at 3, 4, or 5 pressures properly chosen and to plot $RF^{\infty}_{1.2}$ versus pressure. Such a procedure is explained in the next section and summarized in Figure 4.

(3) Choice of the Pressures. To reduce the number of runs, it is advised to follow the steps described below:

Step 1: Determine the FCMP (first contact minimum miscibility pressure) at the reservoir temperature. For more information on this kind of calculation, see for example Neau et al.[8] or Jaubert et al.[6] To work with round pressures, it is advised to decrease the calculated value of the FCMP so that it becomes a multiple of 10. This rounded value will be noted $\overline{FCMP}$.

Step 2: Calculate the bubble point of the crude oil under study at the reservoir temperature. Round this value in order it becomes a multiple of 5. This rounded value will be noted $\overline{P_{sat}}$.

Step 3: Divide the difference ($\overline{FCMP} - \overline{P_{sat}}$) by 5 in order to define 6 pressures (P_1, P_2, ..., P_6) equitably distributed. Select the lowest pressure ($P_1 = \overline{P_{sat}}$) and calculate the corresponding $RF^{\infty}_{1.2}$. Later on, increase the pressure (i.e. select P_2, P_3, ..., P_6) until $RF^{\infty}_{1.2}$ becomes higher than 0.95. As an example if $RF^{\infty}_{1.2}$ (P_4) = 0.99, do not simulate pressures P_5 and P_6. Moreover if a $RF^{\infty}_{1.2}$ value is lower than 0.1 the corresponding pressure must be rejected (such a case may typically appear when $P = P_1 = \overline{P_{sat}}$ is selected). As soon as 3 pairs of values ($RF^{\infty}_{1.2}$, P) are known, stop the simulation.

Two unfavorable cases may appear as follows. *Case 1:* $RF^{\infty}_{1.2}(P_1) < 0.1$ and $RF^{\infty}_{1.2}(P_4) > 0.95$. It is thus impossible to find 3 couples of values ($RF^{\infty}_{1.2}$, P) for which $0.1 < RF^{\infty}_{1.2} < 0.9$. If such a case appears, select as third pressure (P_2 and P_3 are acceptable) $P = 0.5(P_2 + P_3)$. *Case 2:* Pressures P_1 and P_2 are acceptable but $RF^{\infty}_{1.2}(P_3) > 0.95$. Select as third pressure $P_3 = P_1 - (\overline{FCMP} - \overline{P_{sat}})/5$.

It is on average necessary to perform 4 runs (multiple cell simulation at 4 different pressures) in order to

obtain 3 couples of values ($RF^{\infty}_{1.2}$, P) for which $RF^{\infty}_{1.2}$ stands between 0.1 and 0.95.

Step 4: Plot $RF^{\infty}_{1.2}$ versus pressure. Typically, the recovery factors increase rapidly with increasing pressure. Working with such a very simple multiple cell procedure, we found that the evolution of $RF^{\infty}_{1.2}$ versus pressure could be perfectly correlated by an exponential function: $RF^{\infty}_{1.2} = \beta \exp(\alpha P)$. It means that $\ln RF^{\infty}_{1.2}$ is a linear function of pressure. A simple least-squares fit on the three couples of values determined at step 3 allows an easy location of α and β. We found that the intersection of this exponential function and of the straight line the equation of which is $RF^{\infty}_{1.2} = 0.97$ allows one to estimate the MMP. In other words, MMP $= (\ln(97/\beta))\alpha$.

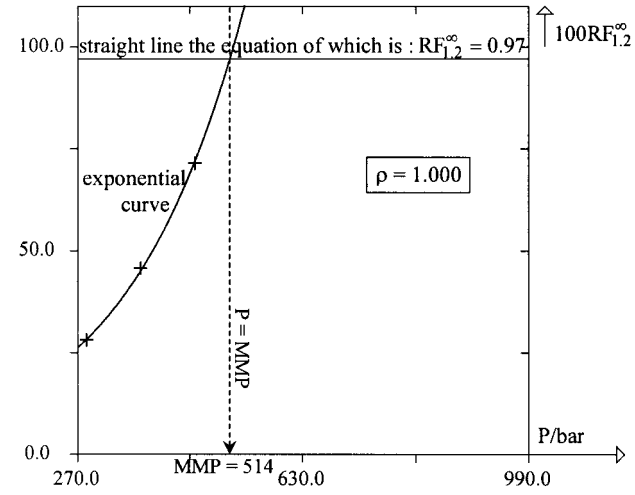
Results

The previous algorithm was used in order to compute the MMP for the 8 systems investigated in this paper. Table 2 gives, for each system, the bubble point P_{sat} at the reservoir temperature, the FCMP, and the different pressures selected in order to obtain 3 pressures for which $0.1 < RF^{\infty}_{1.2} < 0.95$. The calculated MMP's are also given and comparison is made with the value issued from the 1D simulator. The exponential variation of $RF^{\infty}_{1.2}$ versus pressure is shown for systems 1 and 5 in Figure 5. The least-squares fit coefficient (ρ) is given in each subplot.

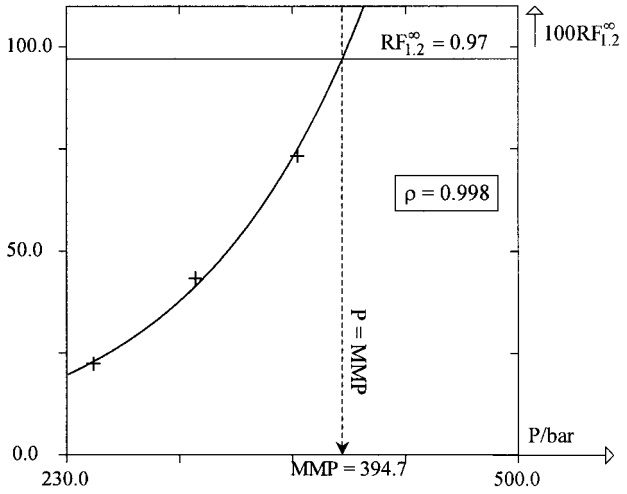
Table 2 puts clearly in evidence that the calculated MMP using the algorithm described in this paper is extremely close (less than 0.5% deviation) to the value obtained by a commercial 1D simulator. However with the algorithm described, only four runs are necessary instead of 30 for a classical 1D simulator. Moreover, due to the very simple flow dynamics, a run made with the multicell approach is from 3 to 10 times faster (depending on the number of grid blocks and of the number of compounds) than a run made with a 1D simulator. It means that this algorithm is from 15 to 80 times faster than the use of a 1D simulator.

As stated in the Introduction, it was experimentally shown that the MMP was not influenced by the porous media through which the flow is occurring. This paper, in which the MMP is accurately calculated using only a P/T flash algorithm, confirms such results and gives proof that capillary pressure and interfacial tension do not affect the MMP value. Only a few examples are shown in this study, but such a result is general and applies to all the oil/gas systems of our extended database (about 140 crude oils from different countries). Due to the very small difference observed between the MMP calculated using either our algorithm or a 1D simulator, it can be concluded that the speed of calculation is obtained without decreasing the generality of the use of a 1D simulator.

It is well-known that a slim tube simulator gives limited information about the actual mechanism taking place during the experiment. The best way to determine the process mechanism is to apply the method recently described by Jaubert et al.[6] Using such a procedure, we found that, for the 8 systems under study, a crossover tie line different from the initial or the gas tie line was always controlling the miscibility process. As explained by Jaubert et al.,[6] it does not mean that the process is a mixed C/VM. As an example, system O_1/I_1 exhibits the feature of a pure VGDM (increasing pressure the mixed C/VM turns into a pure VGDM) whereas systems O_2/I_2 to O_8/I_8 are effectively of the C/V type. A one cell algorithm would be suitable to compute the MMP for system O_1/I_1 even if a tie line different from the initial tie line controls the miscibility process.[6] The CGDM was never observed with the 8 systems studied. Such a result is not surprising since as previously explained by Jaubert et al.[6] such a mechanism probably does not exist if one works with real crude oils modeled with a realistic number of compounds.



a) System O_1/I_1



b) System O_5/I_5

Figure 5. MMP determination: (+) calculated $RF^{\infty}_{1.2}$ values for the 3 selected pressures; (thick line) exponential correlation of $RF^{\infty}_{1.2}$ versus pressure, where ρ is the least-squares fit coefficient; (—) straight line, the equation of which is $RF^{\infty}_{1.2} = 0.97$; (- - -) straight line, the equation of which is P = MMP. Such a line is passing through the intersection point of the exponential curve and of the straight line the equation of which is $RF^{\infty}_{1.2} = 0.97$.

Conclusion

A simple slim tube simulator with very simple flow dynamics and without any porous media has been developed in order to compute the MMP whatever the displacement mechanism. Such a multicell algorithm uses only thermodynamic equations (a P/T flash is only required) and allows the determination of the MMP with an excellent accuracy when compared to a classical 1D

simulator. All the extrapolation procedures appearing in this algorithm are very simple to compute. Its main advantage is its speed in comparison to a commercial 1D simulator and its simplicity in comparison to the global approach developed at the moment by Jessen and Michelsen.[10] According to the information's given by Høier,[14] it can be concluded that computing time is similar to what can be obtained with the excellent unpublished algorithm developed by Zick. Our method is thus an interesting alternative solution to compute the MMP whatever the displacement mechanism.

Acknowledgment

The authors gratefully thank the French Petroleum Co. TOTAL SA for sponsoring this research and especially Dr. Marc Durandeau, expert in thermodynamics, for helpful discussions during this research.

Nomenclature

C/VM = condensing/vaporizing mechanism
CGDM = condensing gas drive mechanism
FCMP = first contact minimum miscibility pressure
MMP = minimum miscibility pressure
n = number of batch calculations
N = number of cells
P = pressure
P_{sat} = crude oil bubble point at the reservoir temperature
PVI = pore volume injected
$RF_{1.2}$ = recovery factor after injection of 1.2 pore volume of gas
$RF_{1.2}^{\infty}$ = recovery factor after injection of 1.2 pore volume of gas corresponding to an infinite number of cells.
VGDM = vaporizing gas drive mechanism

Literature Cited

(1) Kuo, S. S. Prediction of Miscibility for the Enriched-Gas Drive Process. *SPE* **1985**, 14152, 1−12.

(2) Glasø, O. Generalized Minimum Miscibility Pressure Correlation. *SPEJ* **1985**, 927−934.

(3) Orr, F. M.; Silva, M. K. Effect of Oil Composition on Minimum Miscibility Pressure-Part 2: Correlation, *Soc. Pet. Eng. Res. Eng.* **1987**, *27* (6), 479−491.

(4) Jensen, F.; Michelsen, M. L. Calculation of First Contact and Multiple Contact Minimum Miscibility Pressure. *In Situ* **1990**, 1−17.

(5) Whitson, C.; Michelsen, M. L. The Negative Flash. *Fluid Phase Equilib.* **1989**, *53*, 51−71.

(6) Jaubert, J. N.; Arras, L.; Neau, E.; Avaullée, L. Properly Defining the Classical Vaporizing and Condensing Mechanisms When a Gas Is Injected Into a Crude Oil. *Ind. Eng. Chem. Res.* **1998**, *37*, 4860.

(7) Monroe, N. N.; Silva, M. K.; Larsen, L. L.; Orr, F. M. Composition Paths in Four Component Systems: Effect of Dissolved Methane on 1D CO_2 Flood Performance. *SPERE* **1990**, 423−432.

(8) Neau, E.; Avaullée, L.; Jaubert, J. N. A New Algorithm for Enhanced Oil Recovery Calculations. *Fluid Phase Equilib.* **1996**, *117*, 265−272.

(9) Wang, Y.; Orr, F. M. Analytical Calculation of Minimum Miscibility Pressure. *Fluid Phase Equilib.* **1997**, *139*, 101−124.

(10) Jessen, K.; Michelsen, M. L. Minimum Miscibility Pressure Calculation. IFP seminar: Production of reservoir fluids in frontier conditions, Rueil-Malmaison, Dec 4−5, 1997.

(11) Whitson, C. H. Trends in Modeling Reservoir Fluids. Seventh International Conference on Fluid Properties and Phase Equilibria for Chemical Process Design, Snowmass, CO, June 18−23, 1995.

(12) Zick, A. A. A Combined Condensing/Vaporizing Mechanism in the Displacement of Oil by Enriched Gases. *SPE* **1986**, 15493, 1−11.

(13) Stalkup, F. I. Displacement Behavior of the Condensing/Vaporizing Gas Drive Process. *SPE* **1987**, 16715, 171−182.

(14) Høier, L. Miscibility Variations in Compositionally Grading Petroleum Reservoirs. Ph.D. Dissertation, The Norwegian University of Science and Technology, 1997.

(15) Cook, A. B.; Walter, C. J.; Spencer, G. C. Realistic K-values of C_7+ Hydrocarbons for Calculating Oil Vaporization During Gas Cycling at High Pressure. *J. Pet. Technol.* **1969**, 901−915.

(16) Metcalfe, R. S.; Fussel, D. D.; Shelton, J. L. A Multicell Equilibrium Separation Model for the Study of Multiple Contact Miscibility in Rich Gas Drives. *SPEJ* **1973**, 147−155.

(17) Pedersen, K. S.; Fjellerup J.; Thomassen, P. Studies of Gas Injection into Oil Reservoirs by a Cell to Cell Simulation Model. *SPE* **1986**, 15599, 1−8.

(18) Jaubert, J. N. Une méthode de caractérisation des coupes lourdes des fluides pétroliers applicable à la prédiction des propriétés thermodynamiques des huiles et à la récupération assistée du pétrole. Ph.D. Dissertation, The French University of Aix-Marseille III, 1993.

(19) Neau, E.; Jaubert, J. N.; Rogalski, M. Characterization of Heavy Oils. *Ind. Eng. Chem. Res.* **1993**, *32* (6), 1196−1203.

(20) Rauzy, E. Les méthodes simples de calcul des équilibres liquide-vapeur sous pression. Ph.D. Dissertation, the French University of Aix-marseille III, 1982.

Received for review May 29, 1998
Revised manuscript received September 14, 1998
Accepted September 15, 1998

IE980348R