

Impact of fluid characterization on compositional gradient in a volatile oil reservoir

Mahboobeh Kiani¹ · Shahriar Osfoury¹ · Reza Azin² · Seyed Ail Mousavi Dehghani³

Received: 2 September 2015 / Accepted: 25 November 2015 / Published online: 14 December 2015
© The Author(s) 2015. This article is published with open access at Springerlink.com

Abstract Compositional gradient known as a potential of vertically variations in composition (and sometimes areal changes) has a remarkable effect on reservoir management steps such as estimation of initial hydrocarbon in place, design of downstream equipments and prediction of gas–oil contact. One of the main steps in development of compositional grading is to characterize fluid sample. In this study, compositional grading is studied in a volatile oil sample from an oil field in south of Iran. Implemented models are based on isothermal and non-isothermal, i.e., zero diffusion, Hasse and Kempers models. Results illustrated that isothermal and zero diffusion models are in appropriate consistency with field data. Then, effect of C₁₀₊ splitting on compositional grading was studied. It was shown that splitting of C₁₀₊ to more pseudo-components does not have significant effect on variation in composition of hydrocarbon and non-hydrocarbon components.

Keywords Volatile oil · Fluid characterization · Compositional gradient · Reservoir

Abbreviations

MDT	Modular dynamic tester
CVD	Constant volume depletion
CCE	Constant composition expansion
DL	Differential liberation
QC	Quality control
CG	Compositional grading
TDF	Thermal diffusion factor

List of symbols

f_i^0	Fugacity of component i at reference depth
f_i	Fugacity of component i at each depth
f_i^*	Fugacity of component i corrected by volume shift factor
M_i	Molecular weight of component i
z^0	Reference depth
c_i^0	Volume shift factor
c_i	Volume shift factor
J_j	Flux of type j
X_k	Driving force of type k
L_{jk}	Phenomenological coefficient between flux j and driving force k
\bar{J}_i	Total mass flux
D_{ij}	Molecular diffusion coefficient
k_T	Thermal diffusion ratio of component i

Greek letters

α_T	Thermal diffusion factor
β	Skewness of exponential distribution function
τ	Minimum molecular weight included in the distribution
η	Total molar density
ξ	Number of driving forces

✉ Reza Azin
reza.azin@pgu.ac.ir

¹ Department of Chemical Engineering, Faculty of Petroleum, Gas, and Petrochemical Engineering, Persian Gulf University, Bushehr 7516913817, Iran

² Department of Petroleum Engineering, Faculty of Petroleum, Gas, and Petrochemical Engineering, Persian Gulf University, Bushehr 7516913817, Iran

³ Research Institute of Petroleum Industry (RIPI-NIOC), P.O. Box 1485733111, West End Entrance Blvd. Olympic Village Blvd., Tehran, Iran

Introduction

Compositional grading is defined as the potential of variation in composition, pressure, volume, and temperature (PVT) properties versus depth which is caused by increasing of reservoir pressure and temperature. These variations are not only limited to the depth, but also significant gradients have been observed laterally (Montel and Gouel 1985). It is expected that with increasing in depth, a hydrocarbon mixture get richer in heavy components such as plus fractions and leaner in light components such as methane. These gradients may be considerable in some reservoirs. Therefore, they cannot be ignored because of their substantial effect on reservoir PVT zoning, creation of PVT regions in reservoir depth, design of downstream equipment and reservoir production management. While reservoir temperature and pressure gradients are mentioned as the main causes of compositional grading, but this phenomenon is not limited to these factors (Hoier and Whitson 2000). In addition to the gravity segregation (Montel and Gouel 1985), thermal diffusion (Danesh 1998) and thermal convection (Saidi 1987; Ghorayeb and Firoozabadi 2000) which are affected by variations of temperature and pressure, other factors such as incomplete equilibrium distribution and immigration of hydrocarbons, presence of a dynamic aquifer in contact with a part of reservoir, asphaltene precipitation (Hirschberg 1988), heterogeneity of reservoir structure due to faults, variety of hydrocarbon distribution (such as paraffin and aromatic) in plus fraction (Danesh 1998; Schulte 1980) and biological degradation were cited in several publications (Ross and Farrimond 2010; Huang et al. 2004; Larter and Wilhelmsb 2003). From a thermodynamic point of view, compositional grading models could be classified into two categories of equilibrium and non-equilibrium thermodynamics. In the first category, with respect to the temperature equilibrium, reservoir condition is studied at constant temperature which leads to equality of chemical potential of each component. Thus, equilibrium thermodynamic relations are investigated the effect of gravitational field on chemical potential (Danesh 1998). The first model for predicting variation of composition related to gravity segregation at isothermal condition was proposed by Gibbs, known as gravity–chemical equilibrium model (GCE) (Whitson et al. 1994). Using this model in combination with equation of states such as PR, RK, and SRK, compositional gradient of several reservoirs was predicted (Schulte 1980; Sage and Lacey 1938; Muskat 1930; Metcalfe and Vogel 1988). In a study reported by Whitson et al. (1994), they proposed an algorithm for predicting compositional grading based on GCE model. They used SRK with volume shift factor as a correction of liquid phase density. Results of other investigations of GCE modeling on different reservoirs were also

published (Elshahawi and Hows 2007; Ratulowski and Fuex 2003; Joseph 2013; Ting and Ratulowski 2008; Mokhtari and Ashouri 2013; Luo and Barrufet 2004). Hydrocarbon fluids contain large number of components that are similar in chemical properties, and individual determination of their properties is very difficult and sometimes impossible. Thus, for these polydisperse fluids, continuous thermodynamic approach with distribution functions is widely used to estimate properties of heavy end, also known as plus fraction. This approach was adopted by Lira-Galeana et al. in modeling of compositional grading (Lira-Galeana et al. 1994). Their study focused on GCE modeling using 3-parameters distribution function with molecular weight as independent variable and PSRK as EOS.

There are many case studies that show GCE model is not capable to predict variation of compositions perfectly (Hoier and Whitson 2000). One of the well-known reasons which affected these predictions is assumption of isothermal condition in reservoir, while there are some cases that show temperature gradient in depth. This leads to apply non-equilibrium condition in which, mass transfer phenomena, in addition to the concentration diffusion, will be a function of pressure diffusion, external force diffusion and thermal diffusion (Bird et al. 2002). Onsager was the first who proposed a linear relationship between driving forces and fluxes of different phenomena in a process (Lebon and Jou 2008; Le Bellac and Mortessagne 2004). Based on the Onsager's theory, Ghorayeb and Firoozabadi developed a model to predict compositional grading in non-isothermal condition (Ghorayeb and Firoozabadi 2000). The main complexity of irreversible modeling is to evaluate the thermal diffusion factor. Thus, all the irreversible models proposed till now are based on two distinct approaches, i.e., static thermal diffusion and dynamic thermal diffusion.

Static thermal diffusion approach includes Hasse (1962) and Kempers (2001) models. Each model used enthalpy to evaluate the thermal diffusion factor. The only differences between these two models are that Hasse applied center of mass as frame reference while Kempers used center of volume.

Another expression of Hasse model was presented by Pedersen and Lindeloff (2003). In both models, it is required to estimate the enthalpies of each component. Hasse approximation assumes that these enthalpies are equal to the residual enthalpies, while Pedersen and Lindeloff proposed not to eliminate ideal gas enthalpies. For evaluating of ideal gas enthalpies, some reference states such as ideal gas at 273 K is needed. The authors introduced a correlation between this reference enthalpy and molecular weight of each component which was derived according to the data extracted from three reservoirs with a positive vertical temperature changes.

As previously stated, in contrast with the static thermal diffusion, there is dynamic thermal diffusion which applies energy of transport to thermal diffusion factor based on kinetic theory of gases. This application was carried out by Dougherty and Drickamer on a binary mixture (Dougherty and Drickamer 1955). After that, da Silva and Belery extended the theory to multi-component mixtures (da Silva and Belery 1989). Following these studies, Shukla and Firoozabadi presented a model which had a basis similar to Dougherty and Drickamer's. The difference is in estimating properties of pure components and solubility parameters (Shukla and Firoozabadi 1998). Validation of this model was evaluated by applying to the Yufutsu Fractured Gas Condensate Field in Japan (Ghorayeb et al. 2000). In another study, Shukla and Firoozabadi's model was performed to continuous thermodynamic with molecular weight as independent characterizing variable (Bakhtiari Nia and Movagharnejad 2007). Results showed suitable match between model prediction and experimental data. The recent study was also redone with implementing the effect of volume shift factor (Lohrenz et al. 1964). Finally, in another work, this model was compared with isothermal and other non-isothermal models such as Hasse, Kempers and Shukla–Firoozabadi models. It is investigated that Shukla–Firoozabadi model in combination with continuous thermodynamics is more consistent with experimental data (Nikpoor et al. 2013).

Even though finding an appropriate model to predict the variations is important in compositional grading study, an essential step remains as characterization of representative fluid. In many PVT analyses, the heavy hydrocarbons are typically lumped together and present as C_{n+} fractions. While the only available data of these plus fractions are molecular weight and normal boiling point, it is necessary to estimate other properties such as critical points and EOS parameters of these heavy ends. This is well done by mathematical characterization and define in three main steps of splitting the plus fraction into a number of single carbon number (SCN) groups, estimating critical properties and acentric factor of each group and finally, lumping SCN fractions into appropriate number of pseudo-components. Different characterization approaches and combination of mentioned steps are proposed for reservoir fluids. There are many different techniques proposed for splitting (Lohrenz et al. 1964; Ahmed et al. 1985; Ahmed 1989; Pedersen and Christensen 2007; Hosein and McCain 2012) among which splitting plus fraction into pseudo-components using semi-continuous thermodynamics as proposed by Behrens and Sandler and completed by Whitson and Brulé has attracted more attention (Ezekwe 2011). In this method, three-parameter gamma probability function is utilized to describe molar distribution (Whitson and Brulé 2000). Whitson investigated that light fluids such as gas condensate and

volatile oil usually have exponential distribution while some heavier ones follow gamma distribution (Ahmed 1989). After distributing the plus fraction, properties for each SCN are estimated by empirical correlations and at the end, synthetic distribution is lumped into a smaller number of hypothetical components. Whitson mentions that number of components used to describe a reservoir fluid depends mainly on the process being simulated (Whitson and Brulé 2000) and this is the main reason for variety of grouping schemes presented in numerous publications (Whitson and Brulé 2000; Lee et al. 1979; Behrens and Sandler 1986).

According to these descriptions, one would expect that prerequisite steps such as characterization of representative fluid, EOS selection and tuning may have remarkable impact on modeling compositional grading. An essential question raises as how much the compositional grading will be affected by fluid characterization and EOS tuning. Answering to this question is the main objective of present study. This answer could be a crucial step in hydrocarbon reservoir studies to prevent applying extra stages in modeling and calculations. Following in the next section, a brief review of existing mathematical models in compositional grading and also mathematical formula of exponential distribution function is presented. Then, field data and algorithm of characterization and modeling is described in detail. The proposed algorithm is then implemented on the collected fluid sample. Results and concluding remarks are presented afterwards.

Mathematical characterization and modeling

Descriptive formulas for compositional grading models

GCE model relates the fugacity of component i in any depth to the reference fugacity (fugacity of component i in reference depth) that is shown in Eq. (1) (Danesh 1998). By including the effect of volume shift factor, Eq. (1) converts to Eq. (2). Volume shift factor can be estimated from the equation presented by Péneloux et al. (1982).

The theory of irreversible thermodynamics was established by Onsager (De Groot and Mazur 1984). According to this theory, all driving forces that exist in a system such as temperature and concentration gradients can make fluxes with different natures. There is a linear relation between fluxes and driving forces which is known as Onsager's phenomenological relation, Eq. (3). Considering all driving forces in a hydrocarbon reservoir like pressure, temperature, compositional gradients, and molecular diffusion, Eq. (3) can be re-written in form of Eq. (4). The main assumption of compositional grading models in irreversible thermodynamic is zero component mass flux taken from stationary

condition in reservoir. Considering this assumption, Eq. (4) can be simplified to Eq. (5). Non-isothermal models are classified according to estimation of thermal diffusion ratio, k_T , which is related to some physical parameters such as enthalpy and viscosity. Among the proposed models, Hasse (1962) and Kempers (2001) are formulated k_T based on enthalpy, as shown in Eqs. (6), (7), and (8)

$$f_i = f_i^0 \exp\left[-\frac{M_i g(z - z^0)}{RT}\right] \quad (1)$$

$$f_i^* = f_i^0 \exp\left(-\frac{c_i P}{RT} + \frac{c_i^0 P^0}{RT^0}\right) \exp\left(-\frac{M_i g(z - z^0)}{RT}\right) \quad (2)$$

$$J_j = \sum_{k=1}^{\xi} L_{jk} X_k \quad j = 1, 2, \dots, \xi \quad (3)$$

$$\bar{J}_i = \sum_j \left(\eta^2 / \rho\right) M_i M_j D_{ij} \times \left[\sum_k \left(\frac{\partial \ln f_i}{\partial \ln x_k}\right)_{T,P,j \neq k} \nabla x_k + \frac{M_i x_i}{RT} \left(\frac{\bar{V}_i}{M_i} - \frac{1}{\rho}\right) \nabla P + k_T \nabla \ln T \right] \quad (4)$$

$$\sum_k \left(\frac{\partial \ln f_i}{\partial \ln x_k}\right)_{T,P,j \neq k} \nabla x_k + \frac{M_i x_i}{RT} \left(\frac{\bar{V}_i}{M_i} - \frac{1}{\rho}\right) \nabla P + k_T \nabla \ln T = 0 \quad (5)$$

$$\alpha_{T1} = \frac{M_1 M_2 \left(\frac{h_2}{M_2} - \frac{h_1}{M_1}\right)}{(x_1 M_1 + x_2 M_2) x_1 \left(\frac{\partial \mu_1}{\partial x_1}\right)_{P,T,N}} \quad (6)$$

$$\alpha_{T1} = \frac{v_1 v_2 \left(\frac{h_2}{v_2} - \frac{h_1}{v_1}\right)}{(x_1 v_1 + x_2 v_2) x_1 \left(\frac{\partial \mu_1}{\partial x_1}\right)_{P,T,N}} \quad (7)$$

$$\alpha_{T1} = \frac{k_T}{x_1 x_2} \quad (8)$$

$$F(M) = \frac{1}{\beta} \exp\left(-\frac{M - \tau}{\beta}\right) \quad (9)$$

In reality, there are some cases where thermal diffusion is negligible. On other words, temperature gradient exists but due to very small value of thermal diffusion, its effect is not considerable. The temperature gradient should be considered in calculations if other thermodynamic properties are temperature dependent. This is known as passive thermal diffusion model.

Exponential distribution function

Exponential distribution function is a special case of Gamma function, when scale parameter is set to 1. This function was found suitable for gas condensates and lighter

fluids (Whitson and Brulé 2000). The general form of this function is shown in Eq. (9) in which, β is skewness of exponential distribution function, M is molecular weight and τ is the minimum molecular weight included in the distribution. β is the only tunable parameter in this function.

Field data and simulation algorithm

A series of MDT samples, bottom hole samples, and separator samples were collected from one of the large oil filed located in offshore of Persian Gulf, Iran. MDT samples have PVT test data such as CCE, CVD, and also DL tests and all data were used to study its behavior. Table 1 indicates the details of selected sample.

Modeling of compositional grading is performed in Winprop 2013 from CMG (Computer Modeling Group 2013). Using selected set of data and Winprop 2013, modeling are applied refer to the flow chart shown in Fig. 1.

As mentioned in flow chart, thermodynamic modeling step starts after passing the QC and selecting the best sample. First, suitable correlations for estimating the physical and critical properties are selected so that the maximum compatibility with the representative fluid could

Table 1 Sample compositions and reference conditions

Component	Composition
H ₂ S	1.92
CO ₂	8.74
N ₂	5.22
C ₁	52.81
C ₂	5.16
C ₃	3.24
iC ₄	1.03
nC ₄	1.87
iC ₅	1.02
nC ₅	1.05
C ₆	1.74
C ₇	2.44
C ₈	2.64
C ₉	1.85
C ₁₀₊	9.28
C ₁₀₊ (MW)	237.5
C ₁₀₊ (γ)	0.854
Reference conditions	
Depth of sampling (ft)	12,270
Reservoir pressure (psia)	7150
Reservoir temperature (°F)	290
Reservoir temperature gradient (°F/ft)	0.018

be obtained. Among available correlations, combined set of Twu (1984) and Lee and Kesler (1975) correlations are used to estimate the physical and critical properties and also acentric factor of plus fraction. After that, characterization of plus fraction is carried out. According to the type of fluid and its properties, characterization procedure can include splitting of plus fraction to the single carbon groups using a suitable distribution function and/or grouping similar fractions in a single group. In this study, C_{10+} is split to four different groups include C_{20+} , C_{25+} , C_{30+} , and C_{34+} using exponential distribution function in order to study the effect of plus fraction on compositional gradient modeling. Next, lumping of pseudo-components is

implemented in each separate set of data depending on number of SCN groups and plus fraction. A lumping approach similar to Whitson 5-step procedure (Whitson and Brulé 2000) is followed in each set. In the next step, tuning of EOS parameters is carried out by minimizing square of errors between EOS existing data and experimental data. Experimental data are generally used among CCE and CVD tests. In present study, Peng–Robinson is used as EOS. Main parameters such as critical points, Omega a , Omega b and acentric factor of plus fraction and synthetic groups are selected as regression parameters. Finally and in the last step, compositional grading models are selected through the available models include isothermal, non-isothermal with Hasse and Kempers expressions and passive thermal model.

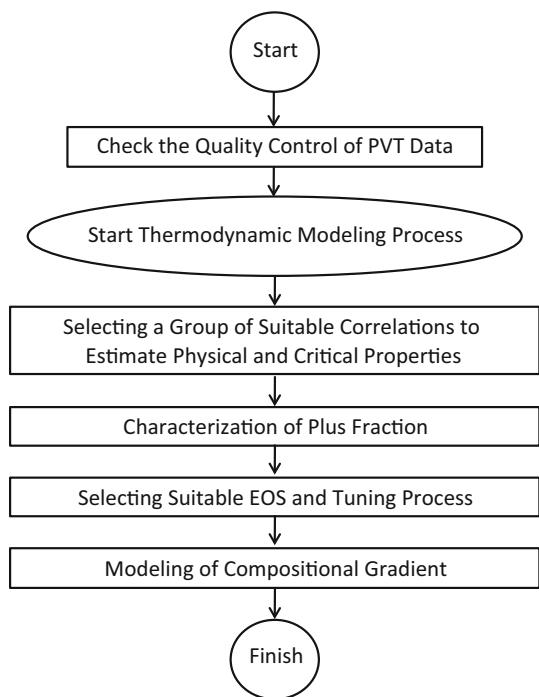
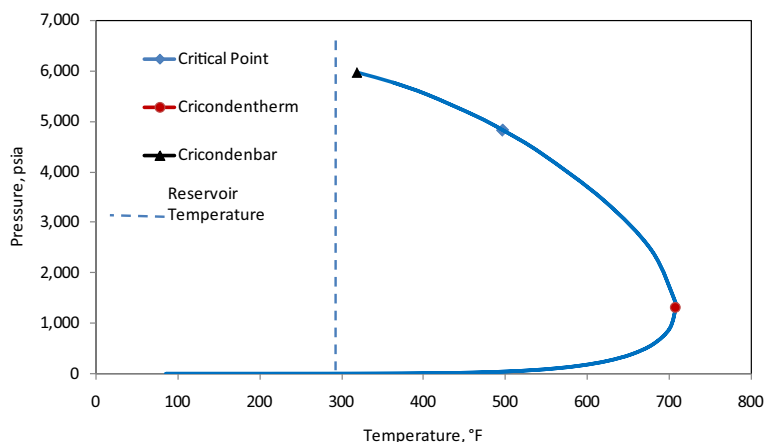


Fig. 1 Flowchart indicated steps of modeling compositional grading

Fig. 2 Phase diagram of representative fluid, original sample



Results and discussion

Evaluation of reservoir fluid type

Evaluation of reservoir fluid sample is accomplished by tracing its phase diagram. PVT data of original fluid is tuned by regression of related parameters. Characterization and EOS tuning was performed without splitting or grouping and phase diagram was constructed as shown in Fig. 2 diagram indicates that present sample is a volatile oil, as the reservoir temperature is below critical temperature. Cricondentherm and cricondenbar of sample is 708 °F and 5960 psia.

Selection of consistent model with accurate prediction

After characterization and EOS tuning of original fluid (up to C_{10+}), data were fed to the compositional grading (CG) module and prediction was carried out using four models

Fig. 3 Prediction of methane compositional grading with four available models

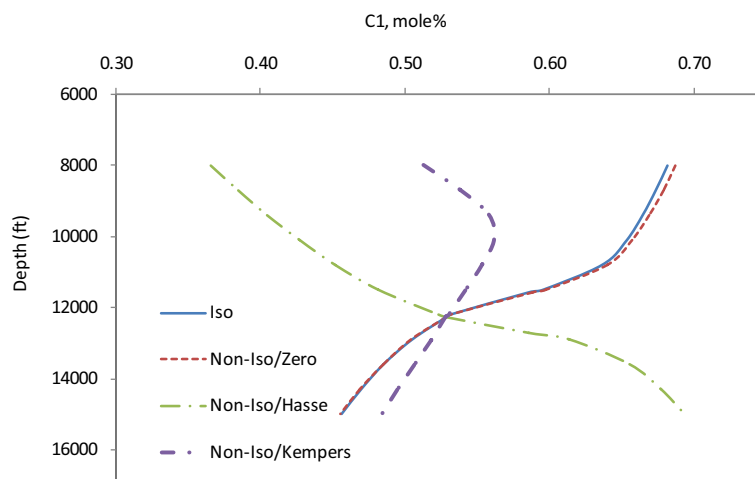
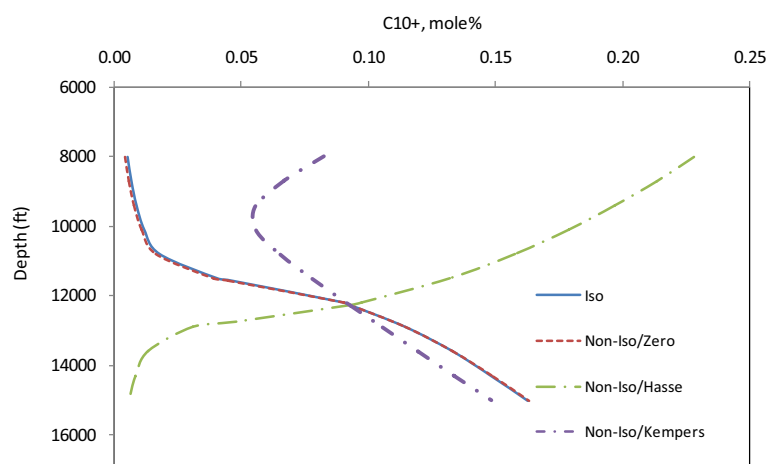


Fig. 4 Prediction of C_{10+} compositional grading with four available models



including isothermal, non-isothermal (zero diffusion), non-isothermal (Hasse), and non-isothermal (Kempers). C_1 and C_{10+} were selected as the key components to study the variation trend of their composition with depth. As indicated in Figs. 3 and 4, trends are similar for isothermal and non-isothermal (zero diffusion) models in contrast with the other two models. As discussed before, composition of lighter hydrocarbons decrease with increase in depth, while a reverse trend is observed for heavier ones. Thus, trends for the first two models are acceptable, whereas the two last ones are not consistent with reality. These observations are evident for isothermal model which considers only the effect of gravity on gradient. Behavior of non-isothermal model with zero diffusion can be explained as neglecting thermal diffusion ratio does not have considerable effect on variation of composition as long as the temperature gradient is small enough. Of course the value of temperature gradient is an important parameter. When the temperature gradient is small, predictions of non-isothermal models are very close to the isothermal one. It is obvious that the

product of temperature gradient and thermal diffusion ratio will be negligible while temperature gradient is small. It means that the effect of gradient related to the thermal diffusion will be insignificant and predictions are same as isothermal model. So, it seems that it would be a reliable prediction.

The unusual trend of non-isothermal models could be described as these models act against isothermal model. It means that gravity causes to segregate lighter components towards top of the reservoir, while thermal gradient forces lighter components towards higher temperature zones, i.e., bottom of the reservoir. This is also true for heavier components. Therefore, one can conclude that effect of thermal gradient which is related to thermal diffusion ratio is dominant compared to the effect of gravity. Whitson et al. claimed that this is due to the change in sign of thermal diffusion ratio in the studied depth range. They estimated thermal diffusion ratio for components such as methane and plus fraction and investigated that the sign of this parameter is negative in a depth range (from 2900 to

Fig. 5 Variation of thermal diffusion factor of C_1 with depth

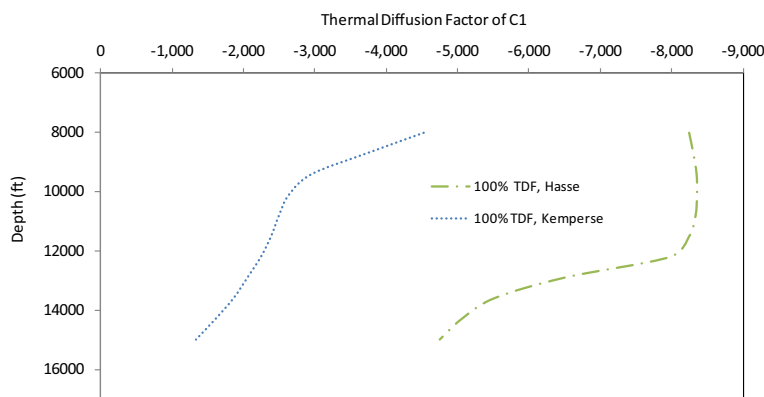
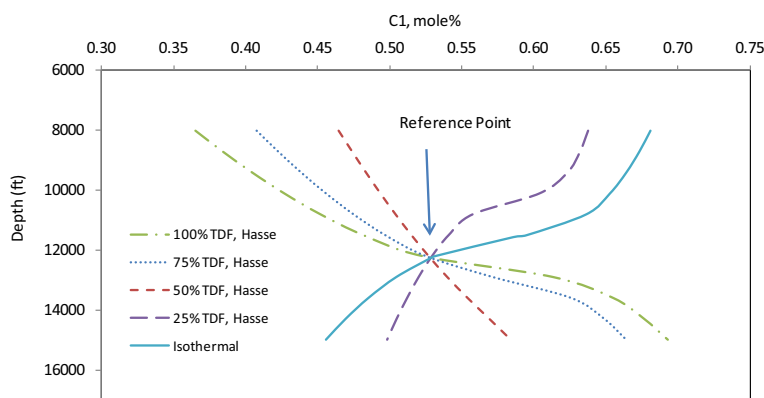


Fig. 6 Sensitivity analysis of C_1 thermal diffusion factor calculated by Hasse model



3200 m). That is why non-isothermal model acts against isothermal one. For greater values of this parameter, the effect of thermal diffusion will be dominant as far as the predictions of non-isothermal models get completely in contrast with isothermal (Whitson et al. 1994). This is same as what investigated in this study. Figure 5 shows the results of thermal diffusion factor (TDF) variation with depth. In depth range of 8000–15,000 ft (which is selected in this study), TDF has negative value which is decreasing with depth. It means that effect of this parameter is in contrast with gravity segregation. It is the reason that Hasse model predicts a reverse gradient for C_1 and C_{10+} . For Kempers model, TDF value still has negative sign. But as it is evident in Fig. 5, TDF value calculated by Kempers model is smaller than those calculated by Hasse model. Hence, it has some minor effects on gradient predictions. It seems that in upper depths (8000–10,000 ft) that TDF value is some more significant, the effect of thermal diffusion is dominant and it causes to have a reverse gradient. But as the value of TDF decreases with depth, its effect will be less and gradient trend will be same as isothermal and zero diffusion models in deeper regions. Figures 6 and 7 indicate the results of sensitivity analysis on TDF of C_1 . In order to investigate this effect, TDF was multiplied by some factors from 1 (as 100 % participation of thermal

diffusion) to 0.25 (as 25 % participation of thermal diffusion). As it is expected, with decrease in thermal diffusion participation, compositional gradients get similar to each other. So, one can conclude that the decrease in TDF approaches the isothermal model.

Figure 8 illustrates variation in saturation pressure with depth. With respect to this fact that critical pressure of system is less than reservoir pressure and also as there is no common point between reservoir and saturation pressure curves, it is investigated that the gas–oil contact (GOC) is under-saturated. As shown in this figure, isothermal and zero diffusion models have very close estimations of GOC depth, while Hasse model calculates GOC about 1000 ft higher than previous models. Kempers model also has a very smooth change from bubble point to dew point pressure.

With respect to the above descriptions, it can be deduced that non-isothermal models with considerable value of thermal diffusion ratio are not capable to have a reliable prediction of CG for present reservoir.

Effect of plus fraction splitting on compositional gradient prediction

Original data with C_{10+} was split into four separate groups including C_{20+} , C_{25+} , C_{30+} , and C_{34+} using

Fig. 7 Sensitivity analysis of C_1 thermal diffusion factor calculated by Kempers model

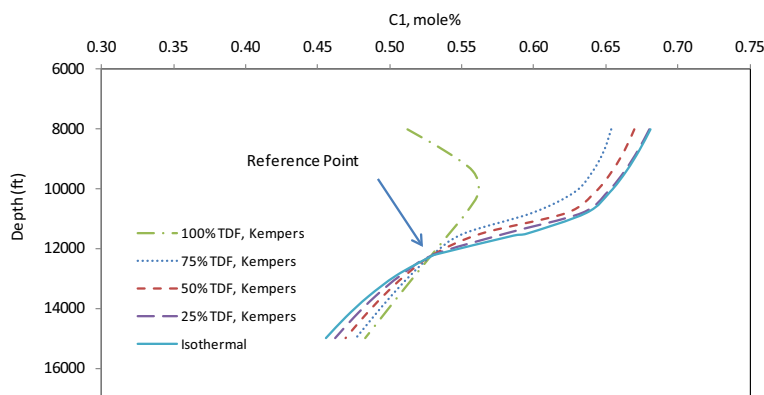
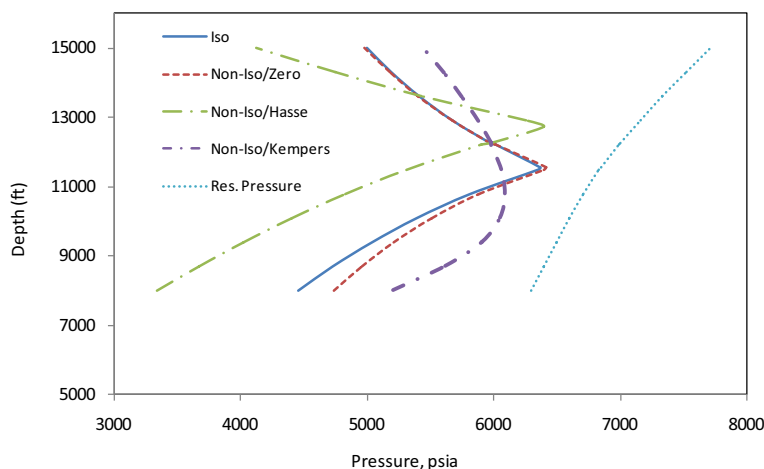


Fig. 8 Reservoir pressure and saturation pressure variation with depth



exponential distribution function. Each group of mentioned data were characterized and parameters of EOS were tuned accordingly. To perceive the effect of splitting on compositional gradient, the same EOS tuning approach was implemented in all four mentioned groups and tuned data were input to the CG module. Based on the results obtained in previous section, the isothermal model was selected for analysis, with C_1 as the key component. Figure 9 shows effects of these different groups of plus fractions. It is observed that there is no considerable difference between predicted compositions of key component in four sets of data. Therefore, with a high confidence, one can conclude that plus fraction splitting in a volatile oil sample has practically no significant effect on CG prediction.

To specify the effect of splitting on CG prediction of non-hydrocarbon components existed in a typical reservoir sample, trends of composition changes were studied for non-hydrocarbon components, H_2S and CO_2 . Figures 10 and 11 show compositional changes with depth for H_2S and CO_2 . According to these figures, trend of variation in composition are not affected significantly with splitting of plus fraction.

Conclusion

1. Isothermal and zero diffusion models are more appropriate for the studied case. Non-isothermal models (except zero-diffusion) show predictions in contrast with isothermal model.
2. These observations could be related to the change in sign of thermal diffusion ratio in studied range of depth which will cause dominance of thermal diffusion ratio compared to gravity.
3. It is investigated that by decreasing the effect of TDF with some multiplying coefficients (which is an index to the participation percentage of thermal diffusion in gradient mechanism), non-isothermal models approach isothermal model; this is more rapid in Kempers model because TDF calculated by this model is much less than that calculated by Hasse model.
4. Splitting of plus fraction to more pseudo-components does not have any significant effect on prediction of hydrocarbon compositional grading, nor for non-hydrocarbons such as H_2S and CO_2 .
5. Splitting procedure is not necessary for modeling of compositional grading in a volatile oil sample and can

Fig. 9 Effect of plus fraction on methane compositional grading predicted by isothermal model

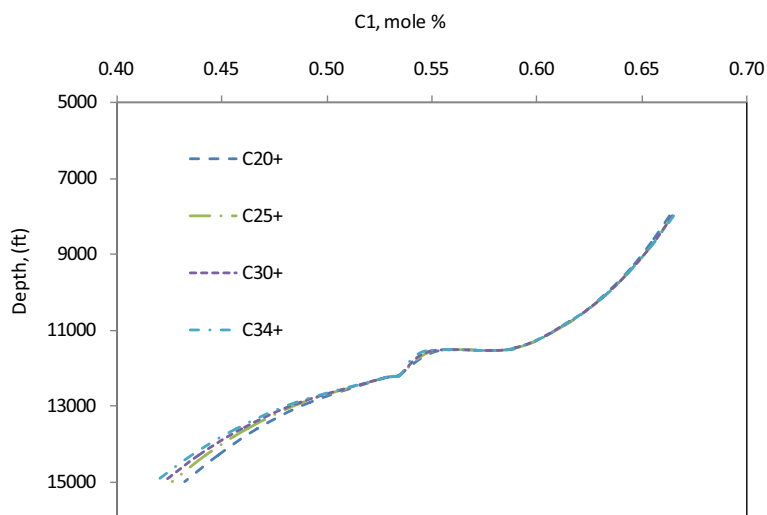


Fig. 10 Effect of plus fraction splitting on CO₂ compositional grading predicted by isothermal model

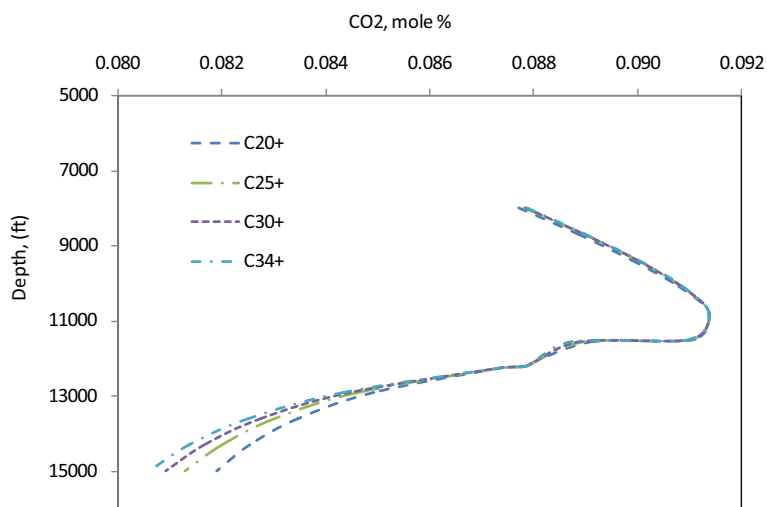
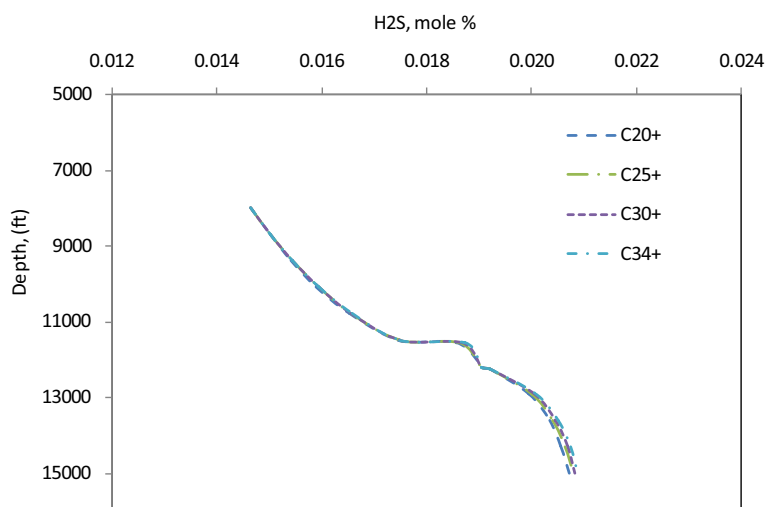


Fig. 11 Effect of plus fraction splitting on H₂S compositional grading predicted by isothermal model



be omitted in volatile oil compositional gradient CG studies with high level of confidence.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Ahmed T (1989) Hydrocarbon phase behavior. Gulf Publishing Company, Houston
- Ahmed TH, Cady GV, Story AL (1985) A generalized correlation for characterizing the hydrocarbon heavy fractions. In: SPE annual technical conference and exhibition, Las Vegas, Nevada
- Bakhtiari Nia N, Movagharnjad K (2007) Prediction of heptane plus fraction molecular weight variation in hydrocarbon reservoir. *Fluid Phase Equilib* 262:174–179
- Behrens R, Sandler S (1986) The use of semi-continuous description to model the C7 + fraction in equation-of-state calculation. *SPE* 14925
- Bird RB, Stewart WE, Lightfoot EN (2002) Transport phenomena. Wiley, New York
- Computer Modeling Group (2013) WinProp User's Guide
- da Silva FV, Belery P (1989) Molecular diffusion in naturally fractured reservoirs: a decisive recovery mechanism, *SPE* 19672, pp 428–442
- Danesh A (1998) PVT and phase behavior of petroleum reservoir fluids. Elsevier, Amsterdam
- De Groot SR, Mazur P (1984) Non-equilibrium thermodynamics. Dover Publications, New York
- Dougherty EL, Drickamer HG (1955) Thermal diffusion and molecular motion in liquids. *J Phys Chem* 59(5):443–449
- Elshahawi H, Hows M (2007) Integration of geochemical, mud gas and downhole fluid analyses for the assessment of compositional grading—case studies, *SPE* 109684
- Ezekwe N (2011) Petroleum reservoir engineering practice. Prentice Hall, Englewood Cliffs
- Ghorayeb K, Firoozabadi A (2000) Modeling multi-component diffusion and convection in porous media. *SPE J* 5(2):158–171
- Ghorayeb K, Anraku T, Firoozabadi A (2000) Interpretation of the fluid distribution and GOR behavior in the Yufutsu fractured gas condensate field, *SPE* 59437
- Hasse R (1962) Thermodynamics of irreversible processes, 1st edn. Addison-Wesley Publishing Company, Reading
- Hirschberg A (1988) Role of asphaltenes in compositional grading of a reservoir's fluid column. *J Pet Technol* 40:90–94
- Hoier L, Whitson CH (2000) Compositional grading—theory and practice, *SPE* 63085
- Hosein R, McCain WD (2012) A four coefficient model for extending the heptanes-plus fractions for gas condensate system. *J Pet Sci Eng* 100:59–70
- Huang H, Larter SR, Bowler BFJ (2004) A dynamic biodegradation model suggested by petroleum compositional gradients within reservoir columns from the Liaohe basin, NE China. *Org Geochem* 35:299–316
- Joseph P (2013) Prediction of oil rim presence from compositional gradient theory—a case study from Niger delta reservoirs, *SPE* 167604
- Kempers LJTM (2001) A comprehensive thermodynamic theory of the Soret effect in a multi-component gas, liquid, or solid. *J Chem Phys* 115(14):6330–6341
- Larter S, Wilhelmsb A (2003) The controls on the composition of biodegraded oils in the deep subsurface, part 1: biodegradation rates in petroleum reservoirs. *Org Geochem* 34:601–613
- Le Bellac M, Mortessagne F (2004) Equilibrium and non-equilibrium statistical thermodynamics. Cambridge University Press, Cambridge
- Lebon G, Jou D (2008) Understanding non-equilibrium thermodynamics. Springer, Berlin
- Lee BI, Kesler MG (1975) A generalized thermodynamics correlation based on three-parameter corresponding states. *AIChE* 21(4):510–527
- Lee S et al (1979) Experimental and theoretical studies on the fluid properties required for simulation of thermal processes. *SPE* 8393, pp 23–26
- Lira-Galeana C, Firoozabadi A, Prausnitz J M (1994) Computation of compositional grading in hydrocarbon reservoirs. *Appl Contin Thermodyn Fluid Phase Equilib* 102:143–158
- Lohrenz J, Bra BG, Clark CR (1964) Calculating viscosities of reservoir fluids from their compositions. *J Pet Technol* 16(10):1171–1176
- Luo Sh, Barrufet MA (2004) Compositional gradient: its role in near-critical reservoir development. *J Pet Sci Eng* 45:193–201
- Metcalfe RS, Vogel DL (1988) Compositional gradients in the Anschutz Ranch East field. *SPE Reserv Eng* 3(3):1–25
- Mokhtari R, Ashouri S (2013) Importance of compositional grading in reservoir development studies: a case study. *Sci Int (Lahore)* 25(3):457–459
- Montel F, Gouel PL (1985) Prediction of compositional grading in a reservoir fluid column, *SPE* 14410
- Muskat M (1930) Distribution of non-reacting fluids in the gravitational field. *Phys Rev* 35:1384–1393
- Nikpoor MH, Kharrat R, Chen Z (2013) The modeling of 3D compositional grading and plus fraction molecular weight change in non-isothermal petroleum reservoirs. *Energy Sour Part A* 35:99–109
- Pedersen KS, Christensen PL (2007) Phase behavior of petroleum reservoir fluids. Taylor & Francis, Boca Raton
- Pedersen KS, Lindeloff N (2003) Simulation of compositional gradients in hydrocarbon reservoirs under the influence of a temperature gradient. *SPE* 84364
- Péneloux A, Rauzy E, Fréze R (1982) A consistent correction for Redlich-Kwong-Soave volumes. *Fluid Phase Equilib* 8(1):7–23
- Ratulowski J, Fuex AN (2003) Theoretical and experimental investigation of isothermal compositional grading. *SPE Reserv Eval Eng* 6(3):168–175
- Ross AS, Farrimond P (2010) Geochemical compositional gradients in a mixed oil reservoir indicative of ongoing biodegradation. *Org Geochem* 41:307–320
- Sage BH, Lacey WN (1938) Gravitational concentration gradients in static columns of hydrocarbon fluids, *SPE* 939120, pp 120–131
- Saidi AM (1987) Reservoir engineering of fractured reservoirs, fundamental and practical aspects. TOTAL Edition Press, Paris
- Schulte AM (1980) Compositional variations within a hydrocarbon column due to gravity, *SPE* 9235
- Shukla K, Firoozabadi A (1998) A new model of thermal diffusion coefficients in binary hydrocarbon mixtures. *Ind Eng Chem Res* 37:3331–3342
- Ting PD, Ratulowski J (2008) Numerical investigation of gravitational compositional grading in hydrocarbon reservoirs using centrifuge data. *SPE Reserv Eval Eng* 12:793–802
- Twu ChH (1984) An internally consistent correlation for predicting the critical properties and molecular weights of petroleum and coal-tar liquids. *Fluid Phase Equilib* 16:137–150
- Whitson CH, Brulé MR (2000) Phase behavior. In: Monograph, vol 20. Henry L. Doherty series. Society of Petroleum Engineers Inc., USA
- Whitson CH, Trondheim U, Belery P (1994) Compositional gradients in petroleum reservoirs, *SPE* 28000, pp 443–459