IMPORTANCE OF COMPOSITIONAL GRADING IN RESERVOIR DEVELOPMENT STUDIES; A CASE STUDY

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ABSTRACT *: IN any comprehensive reservoir study, the first step, which is necessary to be done before estimating the fluid in place, initializing reservoir simulators, and planning the reservoir development, is accurate assessment of the spatial distribution of the fluid components in horizontal and vertical directions. The fluid composition varies with depth in many reservoirs, and this phenomenon is referred to as "compositional grading" which, in most cases, is observed as an increase in the oil density with depth. This phenomenon can significantly affect different aspects of reservoir development.*

In this study, an Iranian oil reservoir with low shrinkage undersaturated oil of API gravity of 30 was selected. Two simulation models were prepared, one with compositional grading taken into consideration and the other for uniform fluid condition without including compositional grading. The two models were compared and the effect of compositional grading on calculations of initial hydrocarbon in place (IHCIP) and gas injection was studied. This work is another step forward in our understanding of the compositional grading and its importance in reservoir development studies.

The results of this study show that considering compositional grading leads to a more realistic complex simulation model, and simulation run time would increase, but because of the drastic difference between the two cases, especially when the injection and production rates are increased, it cannot be ignored.

Keywords: *compositional grading, initial hydrocarbon in place, gas injection, field development, reservoir simulation*

1. INTRODUCTION

The variation of the reservoir fluid composition with depth is called compositional grading. As depth increases, the mole fraction of light components decreases, density increases, and bubble point pressure, oil FVF, and GOR decrease. The effects of compositional grading in near-critical oils and volatile fluids are the largest while black oils have less variation in properties with depth. Compositional grading is the least in highly undersaturated systems [1,2,3 and 4].

Numerous examples of petroleum reservoirs with considerable compositional gradients can be found in the literature [5,6 and 7]. Most of the examples report decreasing methane content with increasing depth, but increasing amount of heptane and other heavier components. It is desirable to determine the importance of these effects prior to any simulation studies and consideration of the development plan of the reservoir. The effects of compositional grading are particularly more noticeable where the reservoir thickness is relatively high and/or the structural relief is large [8].

Assessment of compositional grading is important in calculation of initial hydrocarbons in place (stock-tank oil and surface gas), prediction of gas-oil contact, design of surface production equipments, design of immiscible gas and water injection processes (variation in mobility ratio with depth), design of developed miscible gas injection processes (variation in miscibility conditions with depth), initialization of reservoir simulators, and consideration of production alternatives. These factors can significantly affect the field development strategies from the economic standpoint [8].

In gas injection projects, compositional effects such as miscibility development, saturation pressure, and other fluid properties change as the depth increases [9]. While compositional grading effects are more considerable in volatile oils, they may influence the field development in reservoirs with heavier oils as well. An example is a North African field in which strong grading in stock-tank oil gravity and a related variation in reservoir oil viscosity have been observed. In this case, presence of highly viscous oil near the oil/water contact has forced production from updip and would be a serious obstacle for downdip water injection due to mobility difference [1].

Compositional grading is reported in some gas reservoirs, too. Ghawar Khuff is one of the huge gas reservoirs in which compositional grading is observed. In this reservoir, as the depth increases, all hydrocarbon components, including heavy ends, decrease in composition, but the non-hydrocarbon gases, hydrogen sulfide, carbon dioxide, and nitrogen all increase in composition, and condensate gas ratio (CGR) and dew point pressure decrease [10].

Since reservoir simulation is the first step in any reservoir development plan, and the other decisions are based on this preliminary step, the accuracy and reliability of the reservoir simulation appears to be very important. In any comprehensive reservoir study, the first step, which is necessary to be done before estimating the fluid in place, initializing reservoir simulators, and planning the reservoir development, is accurate assessment of the spatial distribution of the fluid components in horizontal and vertical directions. This work is another step forward in our understanding of the compositional grading and its importance in reservoir simulation and development studies.

2. SIMULATION MODEL

To investigate the effect of compositional grading on reservoir studies and reservoir simulation, an Iranian undersaturated oil reservoir with the oil gravity of 30 °API was selected. Well test analysis, DST tests and PVT samples confirm the compositional change through the reservoir column. The thickness of the reservoir was 500 ft and it was produced under natural depletion mechanism for all of its life time. Because of the nearby power plants, this reservoir is a good candidate for CO_2 injection. Also there are some underground high pressure nitrogen reservoirs in the vicinity which could make nitrogen injection applicable and economic. So a comprehensive study about any gas injection scenarios and the parameters affecting the process appears to be necessary.

2.1. Reservoir Parameters

A full compositional simulation model was first prepared with complete petrophysical, geological, and PVT data. Table 1 indicates the characteristics of the reservoir used for this study.

Table 1. Reservoir Parameters

Parameter	Value
Porosity (%)	13.4
Net to Gross (NTG) (%)	67.3
Permeability (md)	11
Reservoir reference depth (ft)	12468
Reservoir reference pressure (psi)	6279
Depth of water-oil contact(ft)	12950
Depth of gas-oil contact(ft)	12401
Reservoir temperature (°F)	230
Water formation volume factor (B_w) at reference pressure (rb/stb)	1.0290
Rock compressibility (1/psi)	4.00E-06

Two wells were introduced to the model with their actual distance to each other as they are in the field. One of them was used as injection well and the other one as the production well.

In order to have a good prediction of fluid properties and their behavior during simulation, 3-parameter Peng Robison equation of state was chosen. PVT laboratory sample data included differential liberation (DL) experiments, constant-composition-expansion (CCE), swelling and separator tests were used in the tuning of the EOS.

2.2. History Matching

History matching was conducted over 30 years of production data to confirm the validity of the model. The model was constrained by oil rate while reservoir properties were changed to match average reservoir pressure and condensate production rate. Permeability, porosity, and permeability distribution of the model were altered to achieve this match. Figure 1 indicates the production rate that is completely matched with the history data.

2.3. Compositional Grading Model

Montel and Gouel (1985) proposed a method for predicting the compositional variations based on the assumption that the system is at stationary state which means that the net material flux of the components is zero. Material flux is described as any deviation from the equilibrium condition due to chemical potential variation, gravitational forces, and

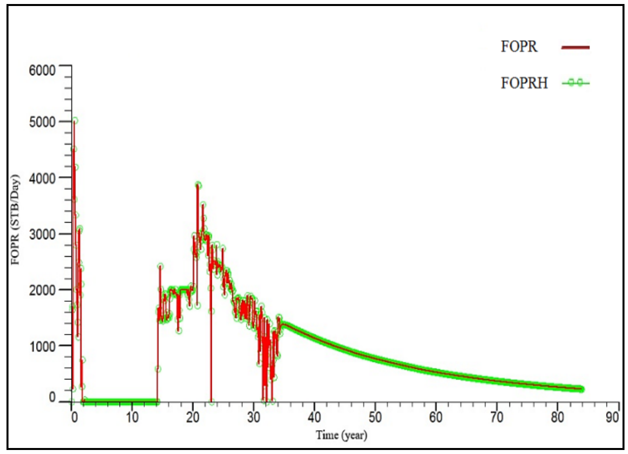

Fig 1. History matching

thermal gradient. The general equation they used is:

$$\sum_{k=1}^{n-1}\left(\frac{\partial \mu_i}{\partial Z_k}\right)\left(\frac{\nabla Z_k}{\nabla H}\right) = F_i^g - F_i^T \quad (1)$$

Where μ_i is the chemical potential of component i, Z_k is the mole fraction of other components, H is depth, F^g_i and F^T_i are the gravitational segregation force and the thermal force of the i^{th} component respectively.

The main factor controlling the compositional variations with depth is the gravitational force. Thermal forces act against the gravity and tend to mitigate its effect on the compositional grading phenomenon, but their order of influence is much less than that of the gravitational force [11 and 12].

Based on the assumptions, two most important compositional grading models are isothermal and thermal models. The isothermal compositional gradient model solves the gravity/chemical equilibrium problem. If the composition and pressure are known at a reference depth, they can be determined at any other specified depth. The saturation pressure at the specified depth is also calculated. If there is a transition from bubble point to dew point saturation conditions over the calculation interval, the GOC depth will be estimated. This is done with a simple halving algorithm to locate the depth at which the transition from bubble point to dew point occurs [13].

The thermal model incorporates the effect of the geothermal temperature gradient on the compositional gradient. Thermal diffusion effects as well as the variation of fluid properties as a function of temperature can be included in the model. Like isothermal model, the location of the GOC will be estimated if it exists. When the temperature is not constant, the system is not in equilibrium [12].

Compositions at other depths with respect to datum were calculated, using the isothermal compositional grading model — known to be the best model for Iranian oil reservoirs [14] — and imported into the model to simulate the case of compositional grading. A cross sectional view of the reservoir for oil density variation in the models at the initial condition is shown in figures 2 and 3. When compositional grading is not considered in the reservoir model and the fluid is defined uniformly throughout the reservoir depth, no considerable variation in the density with depth is observed (figure 2), while incorporating the compositional grading in the model leads to better recognition of the density variations in the oil column (figure 3).

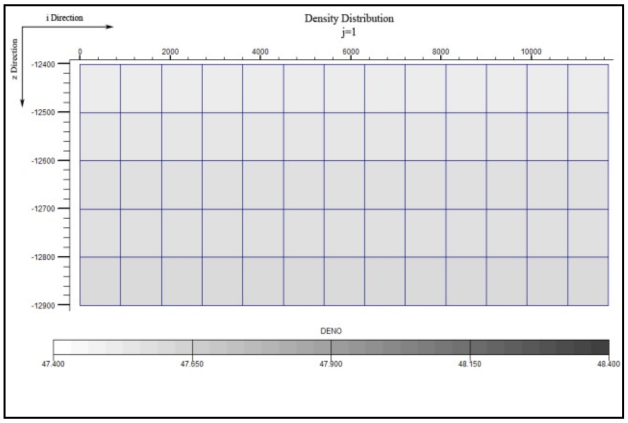

Fig 2. Density variation when single composition is considered

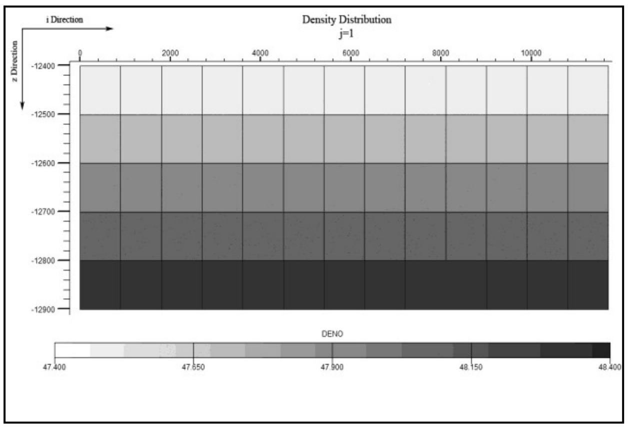

Fig 3. Density variation when compositional grading is considered

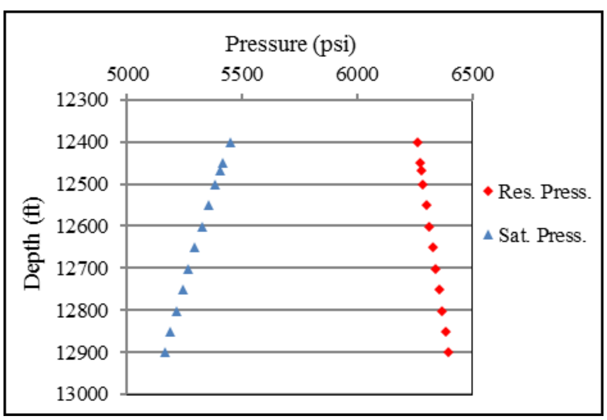

Fig 4. Effect of compositional grading on saturation pressure

The effect of compositional grading on saturation pressure and reservoir pressure is illustrated in figure 4. As the result of compositional change saturation pressure is changed. By increasing depth the fluid becomes heavier and saturation pressure is reduced. As one can see from figure 4, saturation pressure gradient is about 0.127 bar/m. Whitson had been implied that expected gradients in saturation pressure range from 0.025 bar/m for black oils to a maximum of about 1 bar/m for near critical oils approaching a GOC [13].

It should be mentioned that although taking the compositional grading into consideration in reservoir simulation leads to a more realistic model but as the complexity of the model rises when considering the compositional grading, the simulation run time increased about ten times.

3. RESULTS

3.1. The Effect of Compositional Grading in Calculation of Initial Hydrocarbon in Place (IHCIP)

Compositional gradients in the reservoir can affect some very important aspects of the field development plan. One of the factors that may change significantly in reservoirs with compositional grading is the oil FVF, which must be considered in calculation of the IHCIP [1 and 5].

$$IHCIP = \frac{A * H * \phi * (1 - S_{wi})}{FVF} \quad (2)$$

In equation (2), it is obvious that any change in FVF causes a change in IHCIP. When the reservoir composition is considered uniform, the value of FVF is constant through the reservoir depth, while this value decreases as the depth increases in case compositional grading is observed in the reservoir.

In order to calculate the IHCIP, five cases were studied. In case 1 to 4, uniform composition was considered and compositional grading was ignored. In these cases fluid composition used, belong to different depths of the reservoir; top, middle, bottom and datum depth. In the fifth case, compositional grading was considered. The results of this study are shown in figure 5.

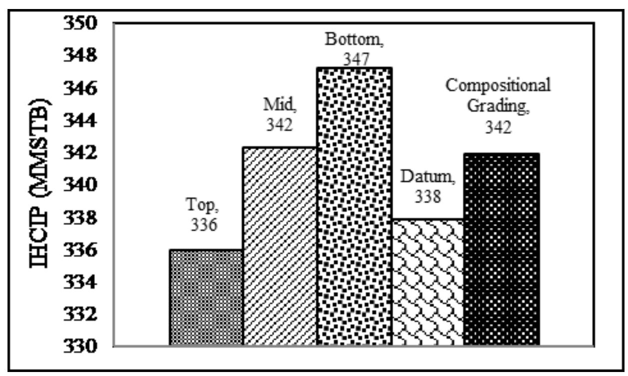

Fig 5. IHCIP for different represented reservoir fluids

As it is clear from figure 5 the values of calculated IHCIP are close to each other, but increases as depth increases because of the decrease in FVF. The difference in calculated values of IHCIP is rather large and could be less or greater than the real case. The IHCIP value for compositional grading condition is close to the value calculated for the condition where represented sample is from the middle of the reservoir column and could hence be used as a good estimation of IHCIP. Jaramillo and Barrufet also provided a procedure to select a single reference sample composition and the depth at which it should be located such that the estimates of the original hydrocarbons in-place are equivalent to those using the compositional gradient [15], but it should be mentioned that, although using this method could eliminate the error in calculation of IHCIP but the error in calculation of the gas injection recovery factor still remains as high.

The reservoir under study is a low shrinkage one, with a relatively thin oil column. Because of these reasons the effect of compositional grading in IHCIP calculations is not so pronounced, while any error in calculation of IHCIP propagates in other calculations as well.

3.2. Importance of Compositional Grading in Gas Injection Efficiency Prediction

In gas injection, variations of compositional effects such as miscibility development and some other fluid properties with depth must be taken into consideration [1]. Although different parameters such as the amount of the injected gas, injection well bottom hole pressure, miscibility, etc., are influenced if compositional grading model is used in gas injection simulation studies, we only deal with the recovery factor as it is affected by all the other parameters.

For this purpose, one of the two wells in the reservoir is considered as an injection well, and the other well is assumed to be a production well. The model was used two times. At the first time, the compositional grading was ignored and a uniform composition case was simulated based on the composition of the datum depth (12,468 ft). At the second time, the compositional grading was included. A gas injection process with different gases (C_1, N_2, CO_2 and separator gas) was conducted for 50 years. C_1 is a hydrocarbon gas which is injected immiscible. N_2 and CO_2 are both non-hydrocarbon gases. N_2 injection is immiscible but CO_2 is injected miscible in the reservoir condition. Separator gas reinjection is chosen in order to establish the condition of switching from miscible injection into the top portion of the reservoir column to the immiscible injection into the lower parts of the reservoir. Simulation is done for the case of a gas injection rate of 15 MMSCFD and oil production rate of 2500 STBD. The simulation results are shown in figures 6-9.

As it is seen in figures 6-9, the difference in recovery factors of the two cases is considerable. The ultimate recovery factor difference for C_1, N_2, CO_2 and separator gas injection is 2.57, 2.25, 5.70 and 7.35 percent respectively. It is clear that this recovery factor difference for the case of separator gas injection in which miscibility condition is changed during the injection is much higher than other cases. Recovery factors for all types of injection gases except

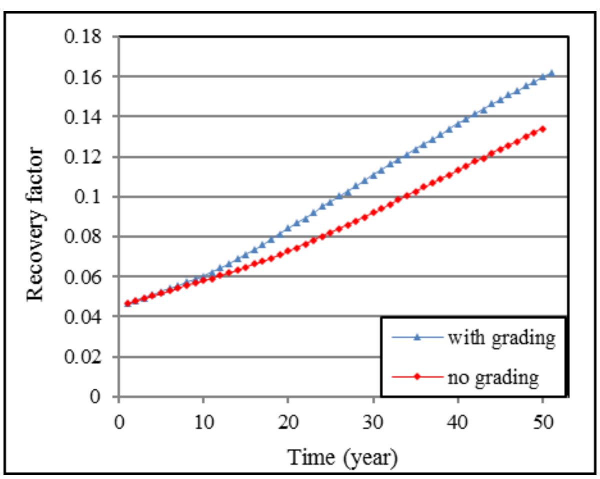

Fig 6. Recovery factor for C_1 injection

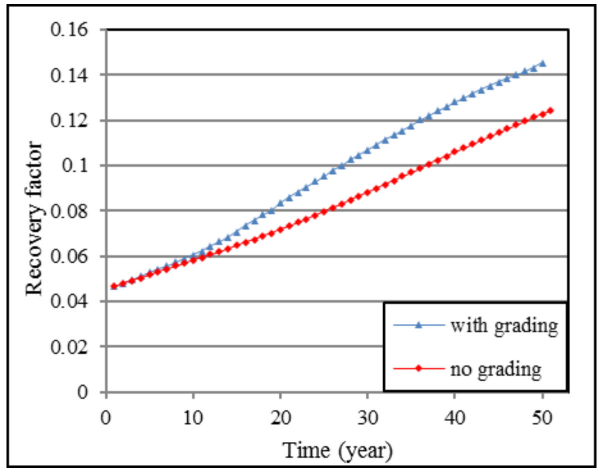

Fig 7. Recovery factor for N_2 injection

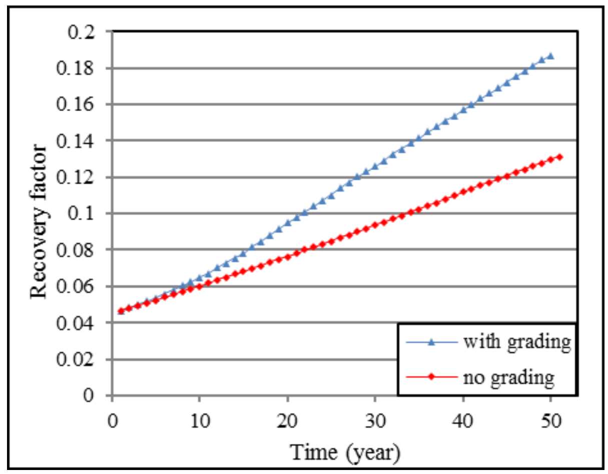

Fig 8. Recovery factor for CO_2 injection

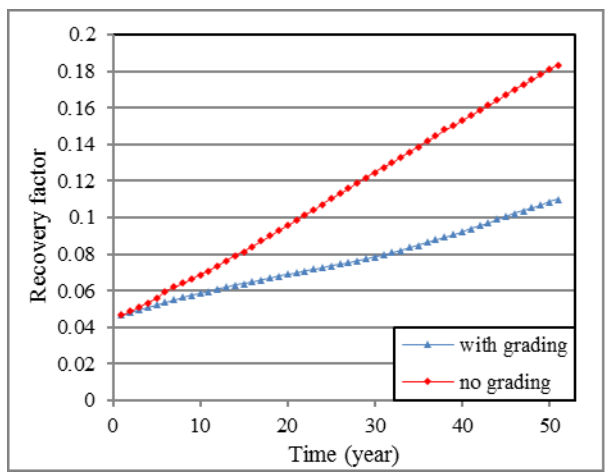

Fig 9. Recovery factor for separator gas reinjection

separator gas reinjection are more than uniform fluid composition if compositional grading is considered.

In order to check the effect of injection and production rate, simulation was repeated for the injection rate of 10 MMSCFD and oil production rate of 1500 STBD for CO_2 injection. Figure 10 in comparison with figure 8, illustrate the effect of injection and production rate. As one can see, the difference between recovery factor for the two cases of including and excluding the compositional grading is increased as the rates are increased. The ultimate recovery factor difference for the case of injection and production rates of 10 MMSCFD and 1500 STBD respectively, is 0.67 percent.

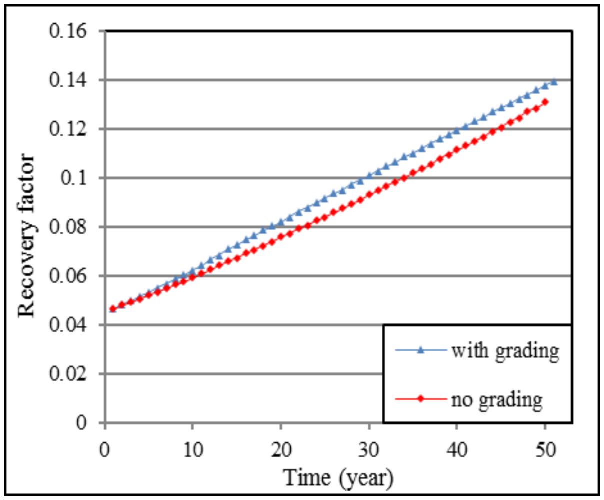

Fig 10. Recovery factor for CO_2 injection, injection rate = 10 MMSCFD, production rate = 1500 STBD

4. CONCLUSIONS

1) Taking the compositional grading into consideration in reservoir simulation leads to more realistic models.
2) As the complexity of the model rises when considering the compositional grading, the simulation run time would increase, but because of the drastic resultant difference, it cannot be ignored.
3) The case under study in this work was a low shrinkage oil reservoir with relatively thin hydrocarbon column. For these reasons compositional grading is not crucial for determining IHCIP.
4) While the reservoir thickness is relatively small, the saturation pressure change in the reservoir column is noticeable.
5) When several fluid samples from different depths are available, using their composition instead of compositional grading model is preferred for predicting composition at other depths.
6) Although using midpoint reservoir fluid sample as the representing fluid causes venial error in calculation of IHCIP, the error in gas injection calculations cannot be neglected.
7) The error in recovery factor calculation is noticeable. As the injection and production rates increase the difference between two cases increases.

Nomenclature

A	Area
CCE	Constant composition expansion
DL	Differential liberation
DST	Drill stem test
Fgi	Gravitational segregation force of the component i
FTi	Thermal force of the component i
FOPR	Field oil production rate
FOPRH	History of field oil production rate
FVF	Formation volume factor
GOC	Gas oil contact
GOR	Gas oil ratio
H	Depth
IHCIP	Initial hydrocarbon in-place
MMP	Minimum miscible pressure
MMSCFD	10^6 standard cubic feet per day
PVT	Pressure-volume-temperature
STBD	Stock tank barrel per day
Swi	Initial water saturation
Zk	Mole fraction of other components
ϕ	Porosity
μi	Chemical potential of the component i

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