文章编号：1000-3754（2005）04-0042-03

肇州油田水平井水平段压降计算及测试

董长银[1]，姬生柱[2]，王希涛[2]

（1. 中国石油大学 石油工程学院，山东 东营 257061；2. 大庆油田有限责任公司 第八采油厂，黑龙江 大庆 163514）

摘要：水平井水平段的流动为变径入流量的变质量流动，根据动量守恒方程建立了水平段流动的压力梯度基本方程；通过不同位置的采液指数变化，表征水平井筒中的流动与油藏渗流的耦合，考虑孔眼入流情况下的管壁摩阻系数，建立了一套系统的水平井水平段压降计算模型及方法。水平段压力损失由摩阻压力损失、加速压力损失、混合压力损失以及势能压力损失等四部分组成。对肇州油田州 62-平 61井水平段压降进行了计算，并在相同生产条件下进行了测试，计算值与实测值误差 6%。计算表明，肇州油田 9口水平井的水平段总压降大约在 0.048～0.26 MPa。

关　键　词：水平井；压降计算；变质量流动；流动耦合；压力梯度；肇州油田

中图分类号：TE243　　　文献标识码：A

大庆外围肇州油田为低渗透油层，主要采用水平井开发。为了解水平段压降对生产动态的影响，需要对水平段压降进行计算。水平井筒中的流动是一种变质量流动，其流动压降的计算与常规管道流动有很大的区别。笔者将从变质量条件下的质量和动量守恒方程出发，建立水平井段的变质量流动基本模型；研究水平井筒流动与油藏渗流的耦合，建立水平段压降梯度计算模型。

1　水平井段流动特征

水平井水平段井筒内的流动具有如下特征：①存在主流与径向入流两种流动。主流即水平井筒内从指端到根端的轴向流动，流量逐渐增大；径向入流即在生产压差驱动下油藏流体通过射孔孔眼向水平井筒的入流；②水平井筒内的流动存在压力损失，导致沿井筒的压力分布不均。压力损失除了摩擦损失外，还包括加速损失、流体混合损失以及势能损失；③水平井筒内的流动与油藏渗流存在流动耦合。正是由于水平井筒的压力分布不均，导致在各点上油藏压力与井筒压力之差即生产压差分布不均，因此沿井筒方向各位置的径向入流量也是变化的。

2　水平井筒流动压降计算

2.1　流动基本方程

图 1为水平井段流动微元段示意图，流体受表面力和质量力的作用。质量力在 x 方向上的合力为 $\rho g\sin\theta dx$；表面力包括：微元段上游端压力 $p(x)$，下游端压力 $p(x+dx)$，套管表面摩擦剪切阻力 τ_c。

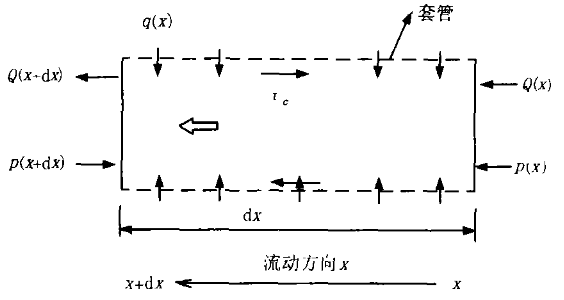

图 1　水平井段流动单元体

由于径向流入，微元体上、下游的流量发生变化使动量也发生变化；径向入流和主流流体的混合作用伴随着能量的损失。微元段流体的动量守恒方程为

$$Ap(x)-Ap(x+dx)=\pi D_c\tau_c dx+A\rho g\sin\theta dx+d(mv)+dp_m \tag{1}$$

式中　$p(x)$ 为 x 位置水平井段流动压力，Pa；D_c 为套管内径或裸眼井壁直径，m；τ_c 为流体与套管内壁摩擦剪切应力，Pa；θ 为水平井筒的倾角，弧度；A 为水平井段流通截面积，m^2；dp_m 为微元段由于流体混合造成的压力损失，Pa。

d (mv) 为由于流体流量发生变化而引起的动量变化项[1]

$$d(mv)=d(\rho A v^2)=2\rho A v dv \tag{2}$$

将方程（2）代入方程（1）得到

$$-\frac{dp}{dx}=\frac{\pi D_c\tau_c}{A}+\rho g\sin\theta+2\rho v\frac{dv}{dx}+\frac{dp_m}{dx} \tag{3}$$

收稿日期：2004-12-20

作者简介：董长银（1976-），男，黑龙江大庆人，博士，从事采油工程方面的教学与科研工作。

水平井段中流体流量的变化可用下式表示

$$\frac{\mathrm{d}}{\mathrm{d}x}Q(x)=q(x) \tag{4}$$

则有

$$\rho v\frac{\mathrm{d}v}{\mathrm{d}x}=\rho\frac{Q(x)}{A}\frac{\mathrm{d}Q(x)}{A\,\mathrm{d}x}=\frac{\rho}{A^2}Q(x)\cdot q(x) \tag{5}$$

当微元段长度 $\mathrm{d}x$ 趋近于零时，单元体内流体与井筒管壁的平均摩擦剪切应力为

$$\tau_c=\frac{1}{2}\rho f_c\frac{Q^2(x)}{A^2} \tag{6}$$

式中　f_c 为流体与井筒管壁的摩擦系数；v 为流体流速，m/s；$Q(x)$ 为 x 位置的流量，$\mathrm{m^3/s}$；ρ 为流体密度，$\mathrm{kg/m^3}$。

将方程（5)、(6）代入方程（3）得到

$$-\frac{\mathrm{d}p}{\mathrm{d}x}=f_x\cdot\frac{\pi D_c\rho}{2A^3}\cdot Q^2(x)+\rho g\sin\theta+\frac{2\rho}{A^2}Q(x)\cdot q(x)+\frac{\mathrm{d}p_m}{\mathrm{d}x} \tag{7}$$

方程（7）即水平井段流动的压力梯度方程。压力梯度主要由摩阻压降、势能压降、加速度压降与流体混合压降四部分组成。

2.2　井筒流动与油藏渗流的耦合

水平段内各点的压力不均匀，会造成各位置井筒压力与油藏压力的差值即生产压差不同，用 $J_s(x)$ 表示沿井筒方向变化的单位井段长度采油指数，则 x 位置单位长度上的入流量和压力为

$$q(x)=\frac{\mathrm{d}Q(x)}{\mathrm{d}x}=J_s(x)\cdot[p_r-p(x)],$$

$$p(x)=p_r-\frac{q(x)}{J_s(x)} \tag{8}$$

则有

$$\frac{\mathrm{d}p(x)}{\mathrm{d}x}=-\frac{\mathrm{d}}{\mathrm{d}x}\left[\frac{q(x)}{J_s(x)}\right]=-\left\{\frac{1}{J_s(x)}\frac{\mathrm{d}q(x)}{\mathrm{d}x}-\frac{q(x)}{J_s^2(x)}\frac{\mathrm{d}J_s(x)}{\mathrm{d}x}\right\} \tag{9}$$

将 $A=\pi r_c^2$ 以及方程（4)、（8）代入方程（7)，得到

$$\frac{1}{J_s(x)}\cdot\frac{\mathrm{d}^2Q(x)}{\mathrm{d}x^2}-\frac{\mathrm{d}Q(x)}{\mathrm{d}x}\cdot\frac{1}{J_s^2(x)}\cdot\frac{\mathrm{d}J_s(x)}{\mathrm{d}x}=f_c\cdot\frac{\rho}{\pi^2r_c^5}\cdot Q^2(x)+\rho g\sin\theta+\frac{\rho}{\pi^2r_c^4}\cdot\frac{\mathrm{d}^2Q(x)}{\mathrm{d}x^2}+\frac{\mathrm{d}p_m}{\mathrm{d}x} \tag{10}$$

将单位长度上的采油指数视为常数，则有

$$\frac{\mathrm{d}^2Q(x)}{\mathrm{d}x^2}=\frac{J_s(x)\rho}{\pi^2r_c^5}\cdot f_cQ^2(x)+J_s(x)\rho g\sin\theta+\frac{J_s(x)\rho}{\pi^2r_c^4}\cdot\frac{\mathrm{d}^2Q(x)}{\mathrm{d}x^2}+J_s(x)\frac{\mathrm{d}p_m}{\mathrm{d}x} \tag{11}$$

方程（11）即考虑油藏渗流与水平段流动耦合后的水平段压力计算模型。

2.3　混合压降与管壁摩阻系数计算

（1）伴有孔眼入流的管壁摩阻系数

用管壁粗糙度表示由于射孔孔眼存在造成的附加管壁粗糙度，用孔眼摩阻系数表示孔眼当量粗糙度造成的附加摩阻，其计算公式如下[2,3]

$$\sqrt{\frac{8}{f_{MR}}}=2.5\ln\left(\frac{N_{Re}}{2}\sqrt{\frac{f_{MR}}{8}}\right)+A-3.75-\frac{\Delta u}{u^*} \tag{12}$$

常数 A 根据常规摩阻系数 f 计算

$$A=\sqrt{\frac{8}{f}}-2.5\ln\left(\frac{N_{Re}}{2}\sqrt{\frac{f}{8}}\right)+3.75 \tag{13}$$

液相与管壁总的摩擦系数为

$$f_T=f+f_{MR} \tag{14}$$

式中　f_{MR} 为射孔孔眼粗糙度产生的管壁摩擦系数；A 为常数；f 为常规管壁摩阻系数；f_T 为射孔套管总摩阻系数。

（2）入流与主流混合压降梯度

周生田等通过室内实验研究了孔眼入流与主流混合造成的压力损失[4]。根据不同的孔眼流速与主流流速比，对混合压力损失随孔眼流速与主流流速比的关系进行多项式回归。得到如下相关式[4]

$$\Delta p_m=-1953.48+1838.47v-432.55v^2+487.08\frac{u}{v}-37.2858\left(\frac{u}{v}\right)^2 \tag{15}$$

式中　Δp_m 为单孔眼段混合压力损失，Pa；v 为管段入口主流流速，m/s；u 为孔眼入流流速，m/s。方程（15）中的 Δp_m 为单孔眼管段的混合压力损失，因此实际混合压力损失梯度为

$$\frac{\mathrm{d}p_m}{\mathrm{d}x}=\frac{\Delta p_m}{\Delta L_p} \tag{16}$$

式中　ΔL_p 为射孔套管的孔沿轴向间距，m。

3　压降测试结果及与计算结果的对比

3.1　水平段压降测试

肇州油田州 62-平 61井水平段垂深 1 397 m，水平段长 594.2 m，射孔密度 12孔/m。为了真实掌握水平段流动压降并于计算结果进行对比，于 2003年 9月对该井水平段压降进行了实际测试。测试时产量 2.9 t/d，含水 7.5%。压力计放置如图 2所示。

放置好测压管柱后，开井正常生产，压力计记录各点的压力随生产时间的变化。测试结果组合曲线如图 3所示，选取 a、b、c、d四个时间点的压力进行比较，如表 1所示。

经过分析，特征点 c表示正常生产阶段，能较真

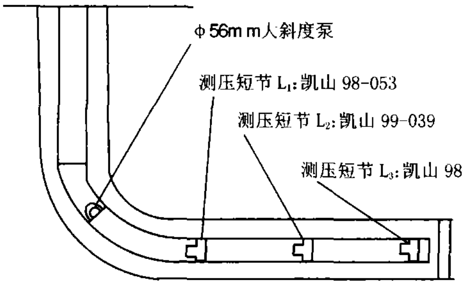

图 2 州 62- 平 61 井测压短节放置示意图

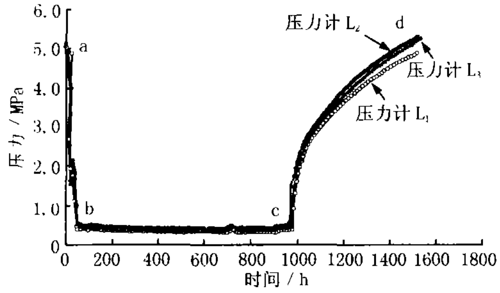

图 3 州 62- 平 61 井水平段压力测试组合曲线

实地反映测试井段 L_1、L_2、L_3 的压力。压力计 L_1 与 L_3 之间的差值为整个水平段的总压降。实际测量得到的产量 2.9 t/d的情况下，州 62-平 61井的水平段总压降为 0.09 M Pa左右。

表 1　州 62-平 61井水平段压降测试结果

时 间 点	L_1	L_2	L_3	L_2-L_1 压力差	L_3-L_2 压力差	L_3-L_1 压力差
a点压力 /M Pa	5.03	5.09	5.12	0.06	0.03	0.09
b点压力 /M Pa	0.42	0.47	0.52	0.05	0.05	0.10
c点压力 /M Pa	0.37	0.43	0.46	0.06	0.03	0.09
d点压力 /M Pa	4.89	5.23	5.27	0.34	0.07	0.41

3.2　水平段压降的计算结果

图 4为该水平井在产量 2.9 t/d生产条件下水平段的压力分布计算结果，水平段根端压力 0.368 9 M Pa，指端压力 0.453 2 M Pa，整个水平段总压降 0.084 3 M Pa，与实测值 0.09 M Pa的相对误差为 6.3%。各测试点的压力与计算值也基本符合。

对州 62-平 61井的水平段总压降进行了产量敏感性分析，如图 5所示。当产量在 1.37~ 10.61 t/d之间变化时，水平段总压降从 0.083 7 M Pa变化到 0.091 6M Pa。

使用上述方法对肇州油田的其它 8口水平井的水平段压降进行了计算，大约在 0.048~ 0.26 M Pa之间。由于肇州油田葡萄花油层为低渗透薄油层，水平井产量较低，因此 9口水平井的水平段压降均较低。

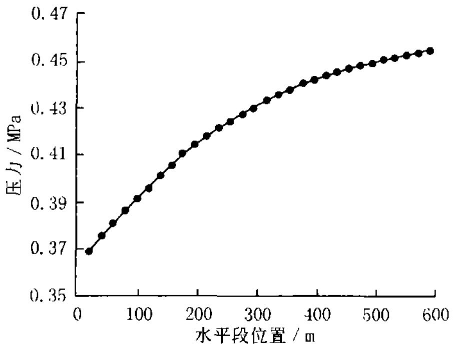

图 4 州 62- 平 61 井水平段压力分布计算结果

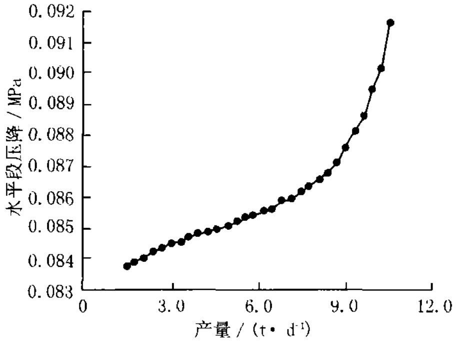

图 5 州 62- 平 61 井水平段压降随产量的变化

4　结　论

(1) 水平井水平段的流动为变径入流量的变质量流动，其流动总压力损失由摩阻压力损失、加速度压力损失、流体混合压力损失和势能压力损失组成；考虑射孔孔眼入流情况下的摩阻系数以及井筒流动与油藏渗流的耦合特征，建立了一套系统的水平井水平段压降计算模型及方法。

(2) 对肇州油田州 62-平 61井的水平段压降进行了实际测量，并对同条件下的压降进行了计算，计算值与实测值吻合较好，相对误差为 6%，这表明本文的水平井段压降计算方法是可靠的；另外，肇州油田其它 8口水平井的水平段总压降在各自生产条件下大约在 0.048~ 0.26 M Pa之间。

参考文献:

[1] 周生田，张　琪．水平井水平段压降的一个分析模型 [J] ．石油勘探与开发，1997，24 (3)：49-52.

[2] Su Z，Gudmundsson J S．Friction Fractor of Perforation Roughness in Pipes [R] ．SPE 26521，1993.

[3] Su Z，Gudmundsson J S．Pressure Drop in Pefrorated Pipes Experiments and Analysis [R] ．SPE 28800，1994.

[4] 周生田，张　琪，李明忠，等．孔眼流入对水平井中流动影响的实验研究 [J] ．实验力学，2000，15 (3)：307-310.

编辑：邵宪志

ance on fluids production and variation of water cut after the change of working parameters can be obtained. This will be useful for the optimization of working system of producers at the late period of high water cut stage.

Key words: multilayer pay zone; inflow performance; optimization; working parameters

Article ID: 1000-3754(2005)04-0033-02

Establishment of Measure-Benefit Evaluation Method of Producers and Its Application

XIE Yan-yan (Exploration and Development Economic Evaluation Center, Liaohe Oilfield Company, Panjin 124010, China)

Abstract: In the middle and later period of oilfield development, decrease of production and enlargement of investment in measures make it more difficult to control the cost. In order to raise the repay of investment in measures and increase the economic benefit of the enterprise, Liaohe oilfield improved the evaluation systems and some methods of stimulation evaluation in 2004, which had made them more accordant with the related industry standards. They had achieved their aims of strengthening the argument of investment in measures and increasing the level of decision-making by the application of oil well measures evaluation system and by forecasting and estimating the benefits from the measures.

Key words: measures of producers; evaluation system; input-output ratio; economic limit

Article ID: 1000-3754(2005)04-0035-02

Analysis of Influential Factors for Producing Low Permeability Oil Layers in Lasaxing Oilfield

TANG Qing-jin, et al (Exploration and Development Research Institute of Daqing Oilfield Company Ltd., Daqing 163712, China)

Abstract: Based on layered dissection of low permeability oil layers from 32 pressure coring inspection wells and succedent analysis, it is believed that under current well pattern the flushed producing performance of low permeability oil layers is poor. The effect of some factors, such as physical properties of oil layers, thickness, individual layer coefficient, oil-bearing features, connectivity types, well sites, producer-injector distance, etc., on flushed producing performance of low permeability oil layers are analyzed. It will be useful for latter development of low permeability oil layers.

Key words: low permeability oil layers; pressure coring; producing performance; influential factors

Article ID: 1000-3754(2005)04-0037-03

Remaining Oil Distribution and Techniques for Further Development After Polymer Flooding

SUN Jian-ying, et al (No.1 Oil Production Company of Daqing Oilfield Company Ltd., Daqing 163001, China)

Abstract: After polymer flooding, producing performance of oil layers is greatly improved, but there still exist some remaining oil after polymer flooding. In order to effectively develop remaining oil, distribution of different types of remaining oil is established according to laboratory tests and numerical simulation results. Effective development measures and matching technology should be applied to different types of remaining oil. Therefore, the matching techniques for further development of remaining oil in PuI Formation are formed. These matching techniques work well in practice. So, the remaining oil in PuI Formation after polymer flooding can be produced. This paper suggests a new method to further improve oil recovery after polymer flooding.

Key words: after polymer flooding; distribution of remaining oil; techniques for further development

Article ID: 1000-3754(2005)04-0040-02

Establishment of Mathematical Model for Horizontal Well SAG Flooding and Its Solution Method

ZHAO Tian, et al (Gudao Oil Production Plant of Shengli Oilfield Company Ltd., Dongying 257231, China)

Abstract: This paper is about solution method of mathematical model for SAG flooding with oil reservoir coupling horizontal well section. Based on this method, 1D multiphase conduit flow mathematical model along the direction of well bore of horizontal well can be established. If the corresponding oil reservoir simulation software can be developed, the dynamic changes for the size and shape of steam compartment during horizontal SAG flooding can be predicted, and the effect of capillary force, steam dryness and formation depth on the steam compartment can be simulated and calculated.

Key words: SAG flooding; multiphase flowing; horizontal well; steam compartment

Article ID: 1000-3754(2005)04-0042-03

Calculation and Measurement of Pressure Drop of Horizontal of Horizontal Interval Wells in Zhaozhou Oilfield

DONG Chang-yin, et al (China Petroleum University, Dongying 257061, China)

Abstract: The flow in horizontal interval of horizontal wells is characterized by variable mass flow with variable inflow through perforations. In this work, the basic equations of flow pressure gradient in horizontal interval are evolved from the momentum conservation equation. Considering the flow coupling between well bore flow and reservoir filtering flow by variable located fluid productivity index along the horizontal interval, an integrated model for pressure drop in horizontal well bore is established, which concerns the friction factor of perforated pipe with inflow. The pressure loss in horizontal well bore includes frictional loss, acceleration loss, fluid mixing loss and potential energy loss. The model has been used to predict the pressure drop in horizontal well bore of Well Zhou66-61 in Zhaozhou oilfield, and the result of which has a relative discrepancy of 6% comparing to the real tested value The total pressure loss of these 9 horizontal wells in Zhaozhou field varies from 0.048MPa to 0.26MPa

Key words horizontal wells; pressure drop calculation; variable mass flow; flow coupling; pressure gradient; Zhaozhou oilfield

Article ID: 1000-3754 (2005) 04-0045-02

Unstable Water Flood Improves the Development Effect of Heterogeneous Oil Reservoir

JIANG Bi-wu, et al (China Petroleum University, Beijing 102249, China)

Abstract Pressure conductivity rate is different in media with different seepage features in heterogeneous formation Injection water rate variably changed triggers a pressure difference between high and low permeable formations Both of them can change the elasticity of reservoir rock and fluids Pressure difference makes oil and water inter-flow and oil be replaced by elasticity. Therefore, oil recovery factor can be improved Field production reflects that water cut of conventional water injection is higher than that of unstable water injection at the same recovery factor The ultimate recovery factor of unstable injection is higher than that of conventional injection

Key words unstable water flood; heterogeneity; mechanism; development effect

Article ID: 1000-3754 (2005) 04-0047-02

Discussion about Well and Layer Selection for Refracturing at Late Period of High Water Cut Stage

YU Feng-lin, et al (No. 4 Oil Production Company of Daqing Oilfield Company Ltd , Daqing 163511, China)

Abstract The proportion of refractured wells in north Xingshugang area is higher, the potential of refracturing becomes less, and it is more difficult to select wells and layers Based on analysis of refractured wells since the ninth five-year-plan, the principles of optimal well and layer selection for refracturing in north Xingshugang area and the time for refracturing are summarized The application results are fairly good in practice

Key words producers; refracturing; well and layer selection; time for fracturing

Article ID: 1000-3754 (2005) 04-0049-02

Discussion about Sand Control Technology after Fracturing During Polymer Flooding in Xingbei Oilfield

WANG Zhong-guo, et al (No. 4 Oil Production Company of Daqing Oilfield Company Ltd , Daqing 163511, China)

Abstract According to research and experimental results of Xingbei oilfield, reasons for sand production of producers after fracturing during polymer flooding are analyzed in this paper The reasons concerned include consolidation strength, producing conditions, characteristics of fracture, and so on Based on field tests, proppant, sand control technology, sand discharge technology, and the method to adjust production parameters are evaluated. The measures suitable for sand control in Xingbei oilfield are discussed in this paper

Key words polymer flooding; fracturing; sand control

Article ID: 1000-3754 (2005) 04-0051-02

Laboratory Evaluation and Application Results Analysis of Deep Slowly Acidizing Technique

RENG Huai-feng, et al (No. 7 Oil Production Company of Daqing Oilfield Company Ltd , Daqing 163517, China)

Abstract Based on laboratory evaluation of deep slowly acidizing technique, various performance indexes of this technique are fully validated According to flowing simulation tests of cores, the application results in Putaohua oilfield, as well as technical predominance of seep slowly acidizing technique comparing to conventional acidizing technique, are analyzed. This technique may provide a new method for acidizing and deplugging of injectors

Key words deep slowly acidizing; technical evaluation; application results

Article ID: 1000-3754 (2005) 04-0053-03

Further Understanding about Features of Case Damage in Faulted Layer Area of Central Saertu Development Region

HUANG Yan-zhong, et al (No. 1 Oil Production Company of Daqing Oilfield Company Ltd , Daqing 163001, China)

Abstract In recent years, with the development in thin layers and poor quality layers, number of wells with case damage in central Saertu area increased one year after another By now, 2449 wells with case damage have been found and there are 9 regions with certain scale of case damage According to distribution features of regions with case damage and horizons with case damage, it can be concluded that there are certain relations between case damage and fault structure Based on existed results, this paper analyzes potential relation between case damage and geological structure in central Saertu area with respect to geologic structure and formation stress The necessity and feasibility of injection-production adjustment for case damage control in faulted layer regions is also discussed in this paper

Key words fault in reservoir; fault barrier; centralization of formation stress; expansion trend of case damage; injection-production system adjustment in faulted layer region

Article ID: 1000-3754 (2005) 04-0056-03

Profile Control and Water Shut-off Techniques for Heavy Oil Reservoirs in Menggulin Oilfield

CHEN Fu-you, et al (Erlian Branch Company of North China Oilfield Company, Xilinhaote 026017, China)

Abstract Menggulin oilfield is composed of conventional heavy oil sand reservoirs and conventional heavy oil bottom water conglomerate reservoirs Oil layers are simple