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# 杂质气体对二氧化碳驱影响模拟研究

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摘要:二氧化碳驱是一种行之有效的提高采收率的技术,为设计经济可行的二氧化碳驱方案,需要对二氧化碳中的杂质气体对原油相态和驱替效果的影响进行研究。在实验基础上建立了纯二氧化碳—原油体系模型,计算不同杂质气体对该体系的相态影响;采用细管实验和状态方程方法确定最小混相压力,分析杂质气体对最小混相压力的影响;通过拟合长岩心纯二氧化碳驱替实验数据,计算了不同杂质气体对驱替过程的影响。研究结果表明,氮气和甲烷的混入不利于原油降粘和膨胀;最小混相压力随氮气和甲烷摩尔分数的增加而增加,随中间烃组分摩尔分数的增加而降低;中间烃组分能使二氧化碳的驱油效率增加,而氮气和甲烷的存在使驱油效率降低。

关键词:二氧化碳驱 最小混相压力 杂质气体 细管实验 驱替实验
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自20世纪50年代二氧化碳驱应用于现场以来,日益引起重视。该技术不仅能提高油田采收率,还可以减少二氧化碳的排放,保护大气环境[1-2]。二氧化碳的气源主要有:天然二氧化碳气藏、碳捕捉得到的二氧化碳以及注二氧化碳采出气。这些二氧化碳气源均难以达到完全纯净,尤其是在注二氧化碳采出气中,氮气、甲烷或其他中间烃组分($C_2$—$C_6$)的摩尔分数更高,一般将这些组分作为杂质气体。对于二氧化碳驱提高采收率的研究,通常都是采用纯二氧化碳为注入气,很少考虑杂质气体的影响,而在现场条件下,提纯二氧化碳会使成本急剧增加[3]。研究杂质气体对原油相态和驱替效果的影响,对优化二氧化碳驱的工艺控制及气体高效利用具有重要意义。笔者采用实验与模拟相结合的方法,研究了杂质气体对二氧化碳驱油体系的相态、最小混相压力以及驱替效果的影响,为设计经济可行的二氧化碳驱替方案提供了参考。

## 1 相态分析

相态对于混相驱替是相当重要的,当存在多相流动过程时,油气体系会产生不同相态之间的传质和传热。当气体注入时,流体的物理化学性质(如体积系数、粘度、界面张力等)会发生变化。对相态的研究,是研究驱替机理的主要依据。

### 1.1 实验方法

实验用油根据对长庆油田白153井区原油组分的分析进行配制。原油性质较好,饱和压力为11.34 MPa,气油比为95.27 $m^3/m^3$,脱气原油密度为0.847 4 $g/m^3$。

对注气原油进行PVT实验,以分析杂质气体在二氧化碳注入过程中对膨胀和降粘作用的影响。当原油配样恢复到地层条件后,在泡点压力下,对原油进行若干次注气;每次加入气体后,饱和压力和油气性质均发生变化,当达到气液平衡时,对油气系统的压力和体积系数等参数进行测试;再继续加入一定量的气体,重复以上过程。基于膨胀实验研究,对不同注入气组分条件下的原油PVT数据进行分析,包括膨胀系数、粘度等[4]。

### 1.2 实验结果及分析

通过PVT实验对二氧化碳—原油体系的研究表明,注入相同量的不同气体,对原油粘度和膨胀系数的影响不同。由图1可见,注入气体使原油的饱和压力上升,含氮气的二氧化碳使原油饱和压力上升幅度最大,含有中间烃组分的二氧化碳使原油饱和压力上升幅度最小;含中间烃组分的二氧化碳使原油膨胀系数增大,原油粘度急剧降低,其次是纯二氧化碳,氮气和甲烷的混入使原油膨胀系数和粘度变化不大,不能有效地降低原油粘度、增大膨胀系数。

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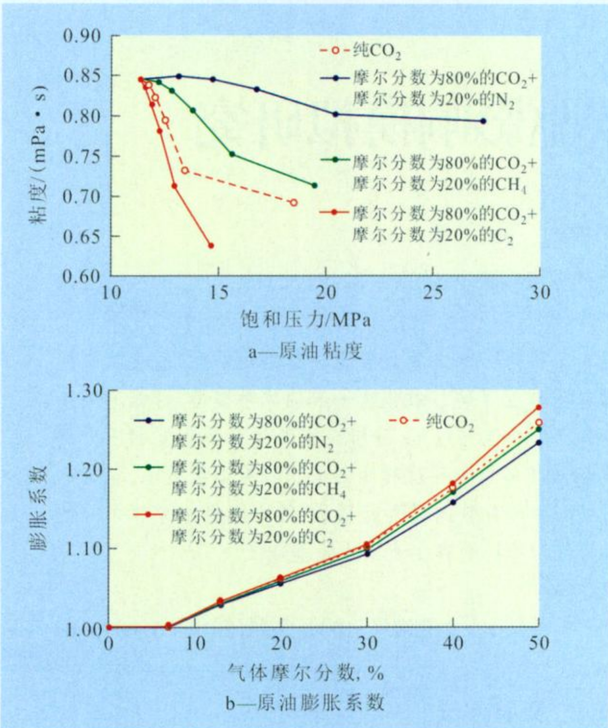


图1 不同注入气组分条件下原油的粘度和膨胀系数

## 2 最小混相压力确定

### 2.1 实验方法

为模拟油藏温度，将实验温度设定为70.6 ℃。在地层压力下将天然气溶于原油中，由于在11.34 MPa下脱气，所以天然气溶解压力和实验压力都应大于11.34 MPa。

细管实验模型长度为12.5 m，内径为4.7 mm，外径为6 mm，采用粒径为140～230 μm的石英砂进行充填，测得孔隙度为35%，气测渗透率为5 $\mu m^2$。

细管实验步骤包括模型孔隙体积测定、原油样品饱和、溶剂驱替原油以及模型清洗等。按照标准实验流程，在实验温度、实验压力和恒定注入速度下，用注入气驱替细管模型中的地层原油样品。驱替速度一般为100～300 cm/h。每注入0.1～0.2倍孔隙体积，测量一次产出油、气体积，记录泵读数、注入压力和回压，并可测定产出油、气组分组成及性质。气体突破时，应加大数据记录密度。累积进泵量超过1.2倍孔隙体积后，停止驱替。在地层饱和压力以上选取4～6个实验压力分别重复以上过程，进行细管驱替实验[1,5-7]。

### 2.2 细管实验结果及分析

一般将气体突破时的驱油效率80%或者最终驱油效率90%～95%定为混相驱的标准。由不同实验压力下，注入量为1.2倍孔隙体积时的驱油效率（图2）可见，驱油效率存在转折点，表明在该点驱替机理发生变化，转折点对应压力为最小混相压力。在最小混相压力以上，驱油效率增加幅度一般很小，压力对驱油效率没有实质上的影响[4]。所以，通过评价驱油效率随驱替压力的变化幅度来确定混相条件，转折点视为油层驱替时的最小混相压力。根据以上原则，确定纯二氧化碳与原油的最小混相压力为16.9 MPa。

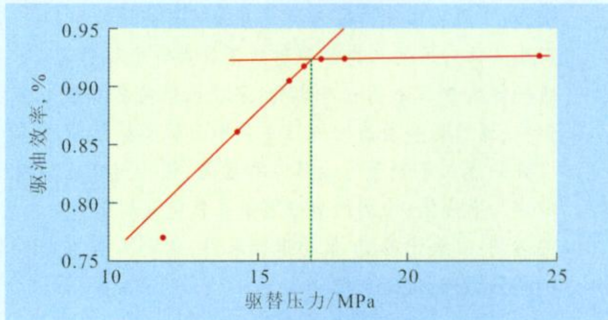


图2 驱油效率与驱替压力的关系

### 2.3 状态方程确定最小混相压力

采用基于Peng-Robinson（PR）状态方程的模拟软件包PVTprop[8-10]，通过调整原油重组分的临界温度、临界压力以及偏心因子等参数，并拟合实验结果，以此参数为基础，通过状态方程模型预测含有不同杂质气体的注入气的最小混相压力。由图3可见，当二氧化碳中混入了氮气和甲烷，会使最小混相压力增大，当二氧化碳中含有20%的氮气时，二氧化碳与原油的最小混相压力增加60.9%，从16.9 MPa增至27.2 MPa。而中间烃组分会使二氧化碳的最小混相压力降低。

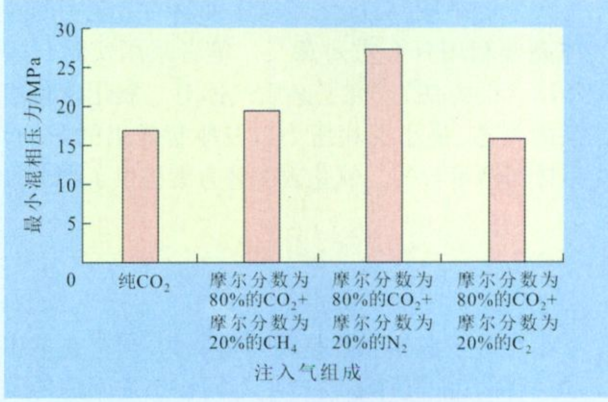


图3 不同注入气组成条件下的最小混相压力

## 3 杂质气体对驱替过程的影响

### 3.1 实验材料及仪器

多次接触混相过程为动态过程，因此模拟过程

中必须进行长岩心驱替实验,从而更接近于地层实际情况,在油藏条件下,对不同气体组分进行驱替实验研究[11]。

实验岩心为天然岩心拼接组成,岩样总长度为48.04 cm,直径为2.50 cm,水测渗透率为$0.63\times10^{-3}$ $\mu m^2$,孔隙度为11.3%。实验仪器主要由岩心夹持器、回压控制器、高压计量泵、压力传感器和恒温箱等组成。

### 3.2 实验结果及分析

实验结果(图4)表明,不同的杂质气体对驱替过程的影响不同,中间烃组分使二氧化碳驱替过程驱油效率增加,而氮气和甲烷的存在使驱油效率降低,氮气的摩尔分数达到20%时,驱油效率降低幅度达到15.7%。

氮气和甲烷等杂质气体的混入,使混合气体的粘度和密度均有所降低,造成重力分异和粘性指进严重,使最终驱油效率降低。

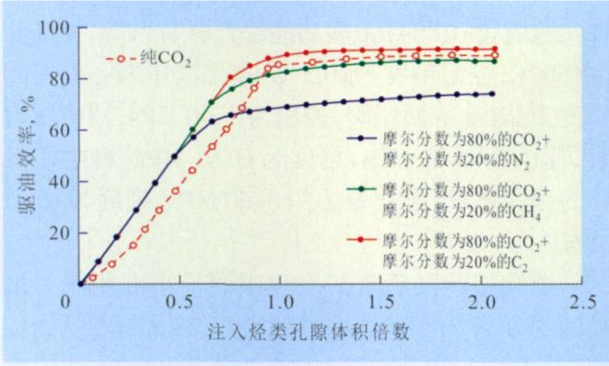

图4 不同注入气组分条件下的驱油效率

## 4 结论

注入气体使原油的饱和压力上升,含中间烃组分的二氧化碳使原油膨胀系数增大,原油粘度急剧降低,其次是纯二氧化碳,而氮气和甲烷的混入对原油膨胀系数和粘度产生不利影响。

最小混相压力随着注入二氧化碳中的氮气和甲烷摩尔分数的增加而增加,随注入二氧化碳的中间烃组分的增加而降低。氮气和甲烷的混入不利于混相的形成。当二氧化碳中含有20%的氮气时,最小混相压力增加60.9%。

状态方程方法可以作为一种预测最小混相压力的有效方法。在适当范围内调整状态方程模型,可以预测不同组分注入气体的最小混相压力。

不同的杂质气体对驱替过程的影响不同,中间烃组分会使二氧化碳驱油效率增加,而氮气和甲烷的存在使驱油效率降低。当氮气的摩尔分数达到20%时,驱油效率降低幅度达到15.7%。采用实验和模拟相结合的方法可以快速有效地预测注气效果。

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oxygen in the end gas and acid value, viscosity and group composition of the oil with additives in the high temperature autoclave. The heavy oil was from the producing well 951217 in the Block J230 of Xinjiang Oilfield. It is found that the acid value of the oxidized oil is 8.37 mg/g and its viscosity is 3 787 mPa · s but oxygen volume fraction decreases to 4.75 vol% after 72 h with 0.10 wt% catalyst of FeL and air injected at 1.2 MPa and 200 ℃. Furthermore, the viscosity of emulsion is 42 mPa · s at 50 ℃ after mixing 70 g oxidized oil, 30 g water and 0.07 g caustic additives R1. Good results can be achieved through decreasing the volume fraction of oxygen with catalyst and reducing the viscosity of heavy oil with caustic additives during the process of cyclic steam with air.

**Key words**: steam stimulation; air; low-temperature oxidation; catalysis; viscosity reduction

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**Zhang Enlei, Gu Daihong, He Shunli et al. Experiment study on effect of impurities on $CO_2$ drive. *PGRE*, 2012,19(5): 75-77.**

**Abstract**: Carbon dioxide flooding is a promising tertiary oil recovery technology in respect both to technical and, if operating costs are properly controlled, to economic benefit. Moreover, the injection of this greenhouse gas also has environmental merits. Flue gas from power plants and natural $CO_2$ gas is the main available source of the $CO_2$, however, $CO_2$ sources are rarely pure. Purifying the flue gas will increase operating costs significantly. Therefore, understanding the roles of impurities in fluid phase behavior and miscibility characteristics is necessary for designing a cost-effective $CO_2$ enhanced oil recovery process. This paper studies the effect of the different impurities in the $CO_2$ stream on the phase behavior and the MMP. With the effect of impurities on the $CO_2$ MMP, it is shown that the presence of intermediate hydrocarbon gas solvents in the $CO_2$ gas stream can reduce the $CO_2$ MMP, whereas, the $N_2$ and $CH_4$ tend to have the opposite effect. EOS simulation is demonstrated to be an effective toll to analyzing the miscibility of oil-gas systems. Core flood tests are conducted to investigate the oil recovery behavior resulting from $CO_2$ injection. The ultimate oil recoveries of the tests show that the miscibility and near-miscibility have the same mechanism. The presence of intermediate hydrocarbon gas solvents in the $CO_2$ gas stream can enhance the ultimate recovery, whereas, the $N_2$ and $CH_4$ tend to have the opposite effect.

**Key words**: $CO_2$ drive; minimum miscibility pressure; impurities; slim tube test; displacement experiment

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**Lou Yi, Yang Shenglai, Zhang Xing et al. Experimental research on $CO_2$ miscible flooding by advanced gas injection in low permeability reservoir-case of H79 block, Jilin oilfield. *PGRE*, 2012, 19(5): 78-80.**

**Abstract**: In order to enhance the oil recovery in low permeability reservoir by $CO_2$ miscible flooding through advanced gas injection, its feasibility is tested in laboratory. The minimum miscible pressure is determined by micro-tubes tests; the laboratory result of $CO_2$ miscible flooding by advanced gas injection with long core physical simulation device is researched and the result is compared with that of synchronous gas injection and water flooding. The ultimate recovery of $CO_2$ miscible flooding by advanced gas injection is 77.03%, synchronous gas injection is 73.09% and water flooding is 56.47%. Results show that, since the advanced gas injection can increase the formation pressure and energy, the oil's viscosity is reduced and its mobility is increased because gas injected in advance is contacted with oil, recovery of advanced gas flooding is higher than that of synchronous gas injection and water flooding.

**Key words**: low permeability reservoir; $CO_2$ miscible flooding; advanced gas injection; physical simulation; Jilin oilfield

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**Zhang Jiyao, Gao Ruimin, Yu Huagui et al. Preliminary study about oxygen consumption of injecting air into low-temperature and low-pressure reservoir. *PGRE*, 2012, 19(5): 81-83.**

**Abstract**: The Ganguyi blocks is the main production area of Yanchang oilfield, the main developing oil layer is Chang 6 reservoir with low pressure, low permeability and low temperature characteristics. Since 2007, the air-foam enhance oil recovery technology is used, and it achieved good results. An instrument is used to simulate the oxygen consumption of injecting air into a reservoir with 30 ℃ and 6 MPa, and the oxygen content diminishes with index, it will drop under the explosion limit after 80 days, and it can run out if the time is long enough, the law is verified in field test based on a low-temperature and low-pressure reservoir. So, the air-foam enhance oil recovery technology can be used in the low-temperature and low-pressure reservoir.

**Key words**: low-temperature and low-pressure reservoir; air injection; oxygen consumption; Yanchang oilfield; Ganguyi blocks

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**Wang Duanping, Yang Yong, Niu Shuanwen et al. Layer block classification evaluation and adjustment of complicated fault block oil reservoir. *PGRE*, 2012, 19(5): 84-87.**

**Abstract**: In order to improve the water flooding recovery factor of the fault block oil reservoir and adapt to the needs of the development, this paper considers the static geological features and dynamic development features, then, it proposes layer block classification method of comprehensive evaluation for complicated fault block oil reservoir. A single sand body is the classification object in the vertical, moreover, the cutting of fault block and the change of lithological boundary are considered in the plane. In other words, using "layer block" for the basic elements of the reservoir classification, this paper classifies and evaluates precisely the fault block oil reservoir, and proposes combination of different layers block developed and adjustment program. The practice shows that this method is the base for carrying out potential assessment and adopting the accurate adjustment policies, it has the guiding signifi-