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热作为油运移动力的物理模拟实验*

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摘要: 针对不同物性输导体、不同供油条件、不同温度差作用下油的运移情况进行了 5 组模拟实验。结果表明在温度差作用下油流体可以发生运移, 证实热(温度) 在一定条件下可以作为流体运移的直接动力。在实验条件下, 温度差(热) 是决定油运移进行与否、运移速度、运移距离大小的最主要因素。在其他条件相同的情况下, 温差越大, 运移距离越长; 干砂中比湿砂中运移距离长; 两端加热比一端加热运移距离长; 一端开放更有利于油运移; 不断补给供油量并不能使运移距离增大; 储层物性并不影响油运移距离。

关键词: 热/ 温度差; 运移动力; 模拟实验

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矿床成因的基本问题归根结底是成矿作用的动力学问题。目前, 国内外除对一些热液矿床外[1,2], 极少对成矿作用动力学尤其是对成矿作用的热动力学机制进行研究。沉积盆地中的油气流体作为一种特殊的流体矿床, 其输运(运移) 和聚集成矿(藏) 的动力学机制更加复杂。传统的石油地质学中将石油二次运移的主要动力归结为构造运动力、水压力和浮力[3], 许多学者对于油气在这种条件下的二次运移和聚集进行了大量的物理模拟实验[4~8]。

温度对油气运移的影响不仅表现在改变油气的物理性质(如比重、粘度等), 重要的是温度在一定条件下(尤其在深部地质条件下) 也可能作为运移的直接动力。在流体封存型成藏动力系统中热力将发挥重要的作用[9]; 在深部有热液作用的情况下, 热对油气流体运移作用的影响就更加显而易见了。李志安等[10] 对大庆长垣的热应力研究就认为油气运移的方向与热应力矢量方向有关。

本文主要介绍油在不同热力条件下运移的物理模拟实验, 初步探索和揭示热作为直接动力条件下油(流体) 的运移机理。

1 模型和参数

模拟实验装置的主体为两端装有可控温度的两个恒温装置的玻璃管(图 1)。玻璃管内径为 20 mm, 长度为 700 mm; 管内充填不同粒径的石英砂, 可随实验条件的变化而改变。玻璃管可以一端充满油另一端不充油, 也可以两端均充满油。玻璃管的两端均封闭或者一端封闭, 视实验条件而定。

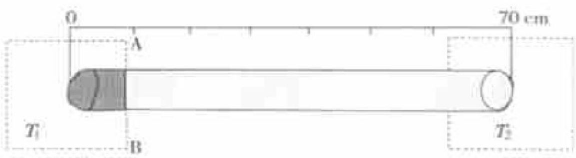

图 1 热动力模拟油运移实验装置示意图(T_1 和 T_2 为两个可控温度的恒温装置, 通过电阻率的调节可将温度控制在实验条件下并保持恒温)

Fig. 1 Sketch map of experimental apparatus for thermodynamic modeling of oil migration (T_1 and T_2 are controllable constant temperature units. The temperature can be controlled and kept constant through adjusting electric resistance)

为了使条件简化, 在该模型中将玻璃管水平放置, 可以消除浮力作用和重力位能差的影响。实验采用的石英砂粒度分别为 0.15 mm 和 0.25 mm, 对应的孔隙度为 30%, 渗透率为 $1\,665 \times 10^{-3}\ \mu m^2$ 和 $4\,625 \times 10^{-3}\ \mu m^2$。在玻璃管的两端各有一可充油的空间(相当于供油区), 并置于恒温装置内。为了增加可视性, 实验用油为淡黄色的柴油。

2 实验及结果

本研究中, 分别模拟了不同物性输导体、不同供油条件、不同温度差作用下油的运移情况。

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2.1　实验 I

玻璃管水平放置, 在图 1 的恒温装置 T_1 一端充满油, 另一端不充油, 玻璃管的两端均封闭, 玻璃管内不充水, 为“干砂”。石英砂粒度为 0.15 mm, 对应的孔隙度为 30%, 渗透率为 1 156 × 10^{-3} μm^2。模拟了 3 个温度差(ΔT 分别为 0 ℃, 30 ℃和 70 ℃) 下油的运移情况(图 2) 。

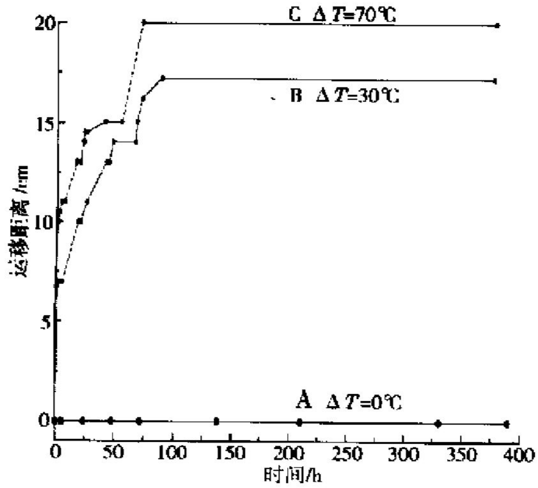

图 2　玻璃管两端封闭时不同温度差条件下油运移距离和时间的关系

Fig.2　Petroleum migration simulation in dry sands confined in the tube with temperature differences of 0 ℃(A) , 30 ℃(B) and 70 ℃(C)

在不存在温度差的情况下(T_1= T_2= 20 ℃) , 模拟实验进行了 389 h, 油没有任何运移的迹象(图 2A) 。当温差为 30 ℃(T_1= 50 ℃, T_2= 20 ℃) 时, 实验开始数小时后油即开始向温度低的一端运移。在实验进行了 2 h 后, 油的运移距离最大处已达7 cm, 90 h 后运移了 17.2 cm 。随后直到模拟实验进行了 378 h, 油不再向低温处运移(图 2B) 。在实验温差加大到 70 ℃(T_1= 90 ℃, T_2= 20 ℃) 时, 油很快向温度低的一端运移。0.2 h 后, 油的运移距离最大处已达 10 cm, 随后运移速度相对缓慢, 72 h后运移了 20 cm 。随后直到模拟实验进行了 379 h, 油不再继续向低温一端运移(图 2C) 。实验过程中油的运移状态与温差小时有差别, 油几乎是沿整个玻璃管运移的。

实验结果表明, 在封闭玻璃管中的油在温度差作用下可以运移, 在热力作用下油从温度高处移向温度低处; 油在温度差作用下的运移速度、运移距离取决于温度差的大小和时间。在时间相同时, 温度差越大, 运移的速度越快, 运移的量和距离也大。但对于某一温差而言其最远运移距离是恒定的, 不管受扇持续时间有多长(如果供油量一定的话) 。

2.2　实验 II

在实际盆地中, 储层是含水的, 因此必须考虑玻璃管内砂子充水的情况。实验在砂子饱和水、砂子粒径为 0.15 mm、玻璃管两端封闭条件下, 分别模拟了温度差为 30 ℃, 50 ℃和 70 ℃情况下油的运移情况。

砂子充满水后油的运移情况和上述的干砂子不同。温差为 30 ℃的条件下(T_1= 50 ℃, T_2= 20 ℃) , 在实验开始 70 h 后, 油才开始向温度低的一端运移。在实验进行了 400 h 后, 油的最大运移距离也才 1.5 cm 。明显比不充满水时要缓慢得多(图 3A) 。温差加大到 50 ℃(T_1= 70 ℃, T_2= 20 ℃) 时, 在实验进行了 9 h 后, 油的运移距离已达 0.5 cm 。随后运移速度相对缓慢, 直到模拟实验进行了300 h, 油不再继续向低温一端运移(图 3B) , 最大运移距离离仅为 4.0 cm 。温差继续加大到 70 ℃(T_1= 90 ℃, T_2= 20 ℃) 时, 油的运移速度很快, 在实验进行0.5 h后油的运移距离已达3 cm, 1 h后达9 cm, 20 h后运移了20.5 cm, 随后直到模拟实验进行了322 h, 油不再继续向低温一端运移(图 3C) 。高温差时, 油的运移状态与温差小时有差别, 油开始是沿整个玻璃管运移的, 后来主要在玻璃管上部运移且有少量水汽。

同时, 为了考虑不同储层物性情况, 改用粒径为 0.25 mm 的砂子进行模拟实验(其他条件相同) 。在温差为 50 ℃的条件下(T_1= 70 ℃, T_2= 20 ℃) 得到的结果与前述 0.15 mm 的砂子所得结果几乎一致, 但在实验初始阶段油运移的速度比细砂的实验快, 7.5 小时后运移了 2 cm, 120 小时后运移距离却是一样的, 且最终的运移距离相差也极细微(图 3D) 。

2.3　实验 III

玻璃管一端开放的实验模型以研究在温度差作用下油的运移距离。实验在温差为 50 ℃(T_1= 70 ℃, T_2= 20 ℃) 砂子粒径为0.25 mm且饱含水的条件下进行。结果表明开放体系有利于油运移(图 4) 。在玻璃管两端均封闭的情况下, 实验进行了300 h后油仅运移了4.5 cm, 但当玻璃管的另一端开放时, 油的运移速度和距离加大, 140 h内运移了51.5 cm 。这是由于原来封闭的玻璃管开放后, 压

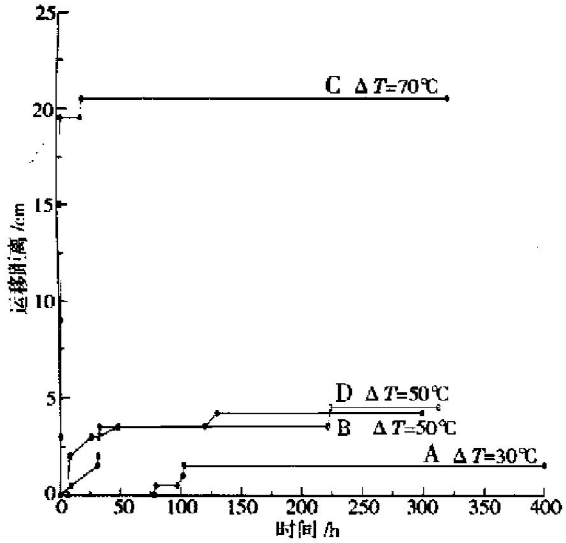

图3 饱和水条件下油运移距离和时间的关系

Fig.3 Petroleum migration simulation in water-saturated sand confined in the tube with temperature differences of 30℃(A), 50℃(B, D) and 70℃(C)

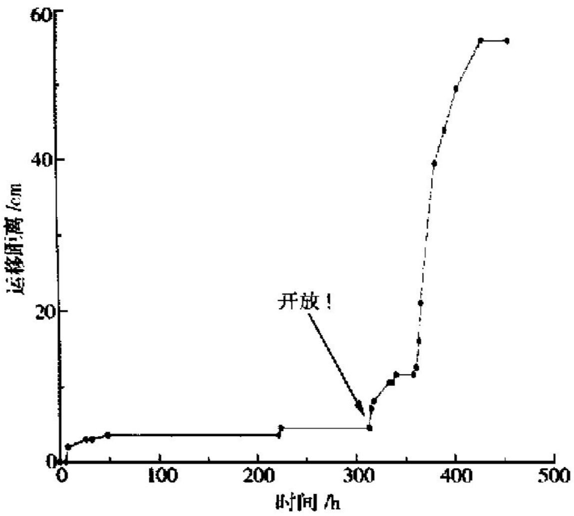

图4 一端开放条件下油运移距离和时间的关系

Fig.4 Petroleum migration simulation in water-saturated sand (d= 0.25 mm) in an open tube under temperature difference of 50℃, 70℃and 20℃.

力下降,加速了流体向压力低的一端运移。

2.4 实验Ⅳ

我们设置了在实验过程中不断供给油情况下的模拟实验。实验在饱和水的不同粒度砂子(d= 0.15 mm 和 0.25 mm),温差为 50℃(T_1= 70℃, T_2= 20℃)的条件下进行。在与模拟实验Ⅱ相同的条件下进行实验,直到油不再运移时再注入油。

结果表明,不同粒径的砂子对油的最大运移距离有微小的影响,但在一定的温度差下不管加热持续时间多长,"油源"补给充足情况下并不能使油运移的距离增大(图5)。说明在其他条件相同情况下油的运移距离取决于模拟实验玻璃管两端的温度差,与供给油量无关。

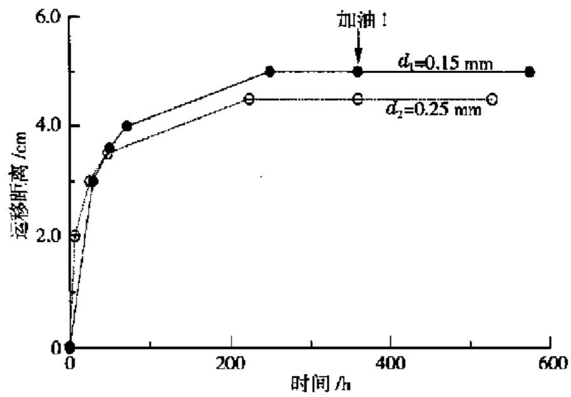

图5 油源不断供给条件下不同粒度砂子中油运移距离和时间的关系

Fig.5 Oil migration simulation in water-saturated sands of various grain sizes (d_1= 0.15mm, d_2= 0.25 mm) confined in the tube under temperature difference of 50℃ and continuous oil

2.5 实验Ⅴ

上述实验都是在玻璃管的一端置于室温条件下进行的,为了更接近实际情况,在玻璃管两端设置加热恒温装置,玻璃管内装粒级粗(d = 0.25 mm)砂子并饱和水,一端供给油。实验分别在20、30和40℃3种温度差下进行。

实验结果同样也证明了温度差大的情况下,油运移的距离长(图6)。在同样温度差下,两端加热的模拟实验其油运移的距离比一端加热的长。但在温度差为20℃(T_1= 70℃, T_2= 50℃)的一组实验中,尽管温度差较小,由于两端的温度相对较高,可能导致在密封玻璃管中流体发生微弱的对流作用,使得油的运移距离反而大于温度差较大的2组模拟实验。

3 结论

(1)模拟实验证实在温度差作用下玻璃管中的油可以运移,且在热动力的作用下油从温度高处移向温度低处。

(2)油在温度差作用下的运移速度和距离取决于温度差的大小和时间。在时间相同时,温度差越大,运移的速度越快,运移的量和距离也大;对于某一温差而言,无论受热持续时间有多长,无论供油量大小,油的最远运移距离是恒定的。

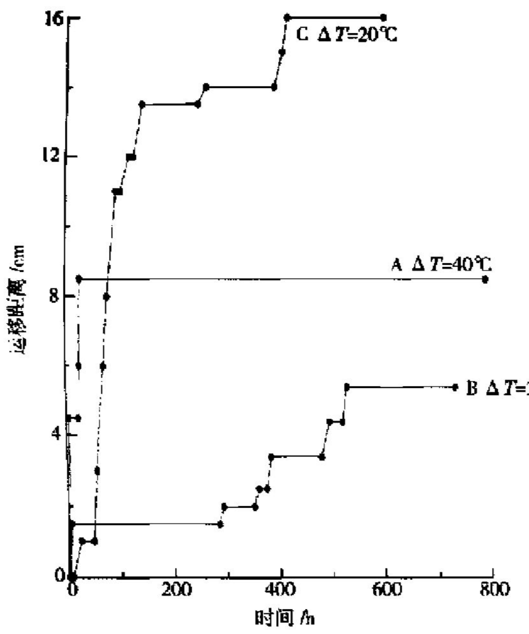

图 6　两端加热条件下不同温度差油运移距离和时间的关系

Fig. 6　Oil migration simulation in water-saturated sands (d= 0. 25 mm) confined in the tube with temperature differences of 40 ℃(A) , 30 ℃(B) and 20 ℃(C)

(3) 在开放体系中油的运移速度和运移量要大于在封闭体系中的情况, 且运移速度和运移量取决于温度差的大小。

(4) 在其他条件相同, 不同粒级的砂子所进行的模拟实验中, 油最终运移的距离几乎是一致的, 也证实了在温度作为运移动力的情况下, 储层物性对于油运移距离没有影响, 温度差是影响油运移距离的重要因素。

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PHYSICAL SIMULATION FOR PETROLEUM MIGRATION IN THERMODYNAMIC SYSTEM

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Abstract: The mechanism and genesis of ore deposit can be basically concluded as the dynamics of mineralization. Temperature will play an important role in hydrocarbon migration under subsurface environment, i. e. migration in reservoir rocks deeply buried in sedimentary basins with high temperature, high pressure and low permeability. Temperature can not only change the physical property of petroleum (e. g. specific gravity and viscosity) during migration, but can also act as the major dynamic force of fluid migration, especially in deep geological condition. An experimental equipment has been installed to simulate the petroleum migration with temperature difference to be the thermodynamic force under normal temperature and pressure environment. The installation is composed of two thermoregulators and a glass tube filled with sands of different sizes. The main objective is to explore the mechanism of heat as the direct diving force during the petroleum migration, by means of the physical simulation of petroleum migration under different thermodynamic systems. The result will provide some helpful information to the study of the mechanism of hydrocarbon accumulation, especially hydrocarbon charging and accumulating in deeper part of the basin. The modeling results include: (1) Oil can migrate under the action of temperature difference, and it migrates from the site with high temperature to the site with lower temperature, indicating that temperature can act as the dynamic force for fluid flow. Under the experimental condition, the temperature difference and time control, the migration velocity and distance. Given in the same time interval, the higher the temperature difference is, the higher velocity and larger distance the migration would be. However, the velocity of oil migration is much slower in water- saturated sands. (2) As to a certain temperature difference, the distance of oil migration is constant no matter how long the experiment would be continued, which indicates that the temperature difference is the most important force to oil migration under the experiment condition. (3) Since the pressure within the tube decreases when the confined glass tube is opened, the velocity and amount of oil migration in the open system would be larger than that in confined system, and they also depend on the temperature difference. (4) The migration distances of oil are almost the same in sands with different grain sizes. The result indicates that the poroperm characteristics of reservoir do not affect the migration distance, but the temperature difference does. (5) No matter how long the experiment would be continued under a certain temperature difference, more oil supple would not increase the distance of oil migration. This also shows that the migration distance has no relation to the amount of oil supply, it just depends on the temperature difference.

Key words: temperature difference; dynamic force of migration; simulating experiment

(Continued from Page 203)

basin, which would constitute the potential reservoirs in deeper part in the basin. The distribution of these sediments have clearly been controlled by the structural slope breaks in the basin margin. The study of the Paleogene in Dongying sag shows that there are multistage slope breaks , such as faulted, flexural, depositional and erosional slope breaks in the half graben-like rift lacustrine basin. The large syndepositional faults that act as the boundary of tectonic subunits, such as salient, slope (fault bench) and subsag, would often become faulted slope breaks. As a result, there will be various types of faulted slope breaks successively developed from the steep slope to gentle slope belts, including salient-steep slope, steep slope-subsag, salient-gentle slope, gentle slope-subsag margins. Nearby these slope breaks, some smaller syndepositional faults can become auxiliary faulted slope breaks and constitute various complex plane combination patterns. Above and below the faulted slope break on the edge of salient may develop erosional slope break. Flexural slope break are mainly associated with syndepositional anticline and nose, which are developed best on both limbs of central anticline-belt and on delta front. The most typical depositional slope break is that developed along the long-axis on Dongying delta front. Faulted slope break controls the development of lowstand fan and compound lithologic-structural traps, depositional slope break controls the distribution of lowland fan, highstand slumping turbidity fan and lithologic traps, while flexural and erosional slope breaks control not only the development of sandbody, but more apparently control the development of stratigraphic overlap, truncation wedge-out and stratigraphic traps. Finally, different kinds of slope breaks developed in the rift lake basin distribute extensively and appears multistage slope breaks. The slope break controls significantly the development of stratigraphic depositionnal and non-structural traps. Combination of oil and gas reservoirs usually occur near the slope break. A thorough study of the genetic type and distribution of slope breaks and their control on sedimentary facies and reservoirs in the maturely explored area as Dongying sag would certainly establish a vast domain in the study of rift basins in eastern China.

Key words: slope break; subtle trap; lowstand system tract; rift basin; Dongying sag; Tertiary