

引文: 王欣, 陶敏峰, 俞徐林, 等. 复兴高含蜡页岩油冷输集输工艺关键参数确定[J]. 油气储运, 2024, 43(7): 809-818.

WANG Xin, TAO Minfeng, YU Xulin, et al. Determination of key parameters for gathering and transmission process of Fuxing highly waxy shale oil at low temperatures[J]. Oil & Gas Storage and Transportation, 2024, 43(7): 809-818.

复兴高含蜡页岩油冷输集输工艺关键参数确定

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摘要:【目的】中国石化复兴地区含凝析气轻质页岩油具有凝点高、含蜡量高的特点,易凝易结蜡。随着页岩油气生产时间增加,油井产量、含水率显著下降,加之油区自然条件差、高程落差大等不利因素,给页岩油气冷输(析蜡点以下)集输工艺带来巨大技术挑战。【方法】在分析复兴含蜡页岩油基础物性的基础上,研究低温流动条件下的油品黏度、屈服应力变化规律及含蜡页岩油乳化特征,揭示页岩油低温流动特性。分析集输工艺过程热处理温度、含凝析气及剪切作用等因素对页岩油凝点的影响,并探究不同含水率、不同溶气压力下的油品粘壁规律,得到影响管道安全输送的关键基础数据。【结果】复兴高含蜡页岩油为乳化能力较弱的轻质油,无法形成含水率大于20%的稳定乳状液,其黏度相对较低。热处理温度与剪切作用对该油品凝点几乎无影响,但油中轻组分的挥发性对凝点有很大影响,轻组分挥发会导致凝点大幅上升5℃。临界粘壁温度随含水率升高呈下降趋势,变化范围为13~18℃。随着溶气压力增加,低温流动条件下页岩油粘壁温度与黏度降低,流动性变好。冷输集输管道终点温度应高于临界粘壁温度,因此确定复兴高含蜡页岩油冷输集输终点最低温度为18℃,终点压力应不低于1.0 MPa。【结论】研究成果可为复兴地区高含蜡页岩油冷输集输工艺提供数据支撑,对高效开发非常规油气资源具有重要意义。(图10,表4,参44)

关键词: 含蜡页岩油; 粘壁规律; 粘壁温度; 冷输集输; 关键参数

中图分类号: TE832

文献标识码: A

文章编号: 1000-8241(2024)07-0809-10

DOI: 10.6047/j.issn.1000-8241.2024.07.010

Determination of key parameters for gathering and transmission process of Fuxing highly waxy shale oil at low temperatures

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Abstract: 【Objective】 Condensate gas-containing light shale oil extracted by Sinopec in the Fuxing area features high solidification points and wax contents, indicating susceptibility to condensation and wax precipitation. With the progression of shale oil and gas production, there has been a notable decline in the oil well output and water cut. Coupled with unfavorable natural conditions and substantial elevation differences in the oil area, the operational landscape presents significant technical hurdles in gathering and transmitting shale oil and gas at low temperatures, particularly below the wax precipitation point. 【Methods】 Following an analysis of the basic physical properties of Fuxing waxy shale oil, this study delved into its viscosity and yield stress variations under low-temperature flow conditions, alongside its emulsification characteristics. These investigations shed light on the flow behaviors of shale oil at low temperatures. Subsequent analysis highlighted the influences of various factors including heat treatment temperatures, condensate gas contents, and the shearing effect on the solidification point of shale oil during the gathering and transmission process. Additionally, the study examined the wall sticking behaviors of oil with different water cuts and dissolved gas pressures. And, the main parameters affecting the flow assurance of flowline are outlined. 【Results】 Fuxing highly waxy shale oil, characterized as a light oil with low emulsification performance, encountered challenges in forming a stable emulsion with a water cut exceeding 20%, despite its low viscosity. Its solidification point remained relatively unaffected by heat treatment temperature and shearing. Instead, the volatility of light components significantly impacted the solidification point, leading

to a notable 5 °C increase due to the volatilization of these components. The critical wall sticking temperature decreased as the water cut increased, ranging between 13 °C to 18 °C. Furthermore, with a rise in dissolved gas pressure, both the wall sticking temperature and viscosity of the shale oil decreased under low-temperature flow conditions, leading to enhanced fluidity. The study suggested that the terminal temperatures of gathering and transmission pipelines at low temperatures should surpass the critical wall sticking temperature. Consequently, the minimum terminal temperature for the Fuxing highly waxy shale oil gathering and transmission pipeline at low temperatures was determined at 18 °C, with a terminal pressure of not lower than 1.0 MPa. **[Conclusion]** The research findings provide data support for the gathering and transmission process of highly waxy shale in the Fuxing region at low temperatures, offering valuable insights for the effective development of unconventional oil and gas resources. (10 Figures, 4 Tables, 44 References)

Key words: waxy shale oil, wall sticking behavior, wall sticking temperature, gathering and transmission at low temperatures, key parameters

随着石油资源的枯竭,页岩油气资源开发已成为当今世界油气勘探开发的重要领域。中国页岩油地质资源储量丰富,主要分布在四川、鄂尔多斯、准噶尔、渤海湾及松辽等盆地^[1-7]。中国石化在四川盆地东部复兴地区经过十余年持续不断地探索实践,先后在侏罗系陆相页岩油气主力层系东岳庙、凉高山及大安寨组等获得页岩油气的勘探开发突破^[7-8]。

目前国外页岩油主要为轻质油与凝析油,如北美Eagle Ford页岩油密度0.816 g/m³,凝点小于20 °C,含蜡量20%~32%,气油比1 031 m³/t^[9-10]。中国页岩油大多为较重的中质与重质原油^[11],如新疆油田吉木萨尔页岩油密度0.875~0.940 g/cm³,凝点较低(平均8.7 °C),最大含蜡量12.4%^[12-14];鄂尔多斯盆地长庆油田庆城页岩油密度约0.85 g/cm³,凝点15~20 °C,黏度5~15 mPa·s,气油比90~110 m³/t^[15-16];渤海湾盆地胜利油田济阳的大部分页岩油密度0.85~0.91 g/cm³,凝点0~21 °C,黏度1.3~1.78 mPa·s,含蜡量低,气油比160~520 m³/t^[17-18];松辽盆地大庆油田古龙页岩油密度0.833 7 g/cm³,黏度低(15.6 mPa·s),凝点35.8 °C,含蜡量24%,气油比低(67 m³/t)^[19];中石化复兴地区页岩油平均密度0.774 g/cm³,凝点最高24 °C,含蜡量最大22.4%,且气油比平均为1 000 m³/t,为少见高凝点含蜡页岩油多采用加热集输流程,而中国通常采用加热或掺液集输流程^[21],对高凝点页岩油采用常温不加热输送或冷输集输工艺较为困难^[22],目前只有长庆油田在高含水、低气油比条件下实现了常温集输工艺^[23]。

冷输集输工艺是指含蜡页岩油以析蜡点与凝点之间的温度进入低温集输管道,在进入集输管道之前形成微蜡晶体悬浮于油基质中,以稳定的凝油结构输送

且蜡沉积较少^[24]。从理论角度来看,当集输温度降至凝点以下时,固态蜡晶体开始形成,但这并不意味着沉积。蜡沉积本质上是一种固液相分离,其受流体动力学、传热与传质过程以及固体表面相互作用等条件的影响^[25-29]。从集输管道水力与热力条件的影响因素来看,确定冷输集输温度的关键取决于页岩油物性、自然环境条件及页岩油开发生产特点等^[21],尤其是页岩油凝点、黏度的影响因素与变化规律^[30-32],以及低温流动条件下凝油粘壁温度、粘壁规律等^[33-35]。为此,以中国石化复兴地区含蜡量较高的主力层系代表油井(泰页1HF)现场产物油样为例,在分析页岩油物性与低温流动特性基础上,探究集输工艺过程热处理温度、含凝析气及剪切作用等因素对凝点的影响,研究不同含水率、不同溶气压力的含蜡页岩油粘壁规律,从而确定复兴高含蜡页岩油冷输集输的温度与压力参数,有效降低地面集输系统能耗,节约运行成本,简化工艺流程,为大规模开展复兴高含蜡页岩油地面工程建设提供理论依据。

1 页岩油物性

1.1 基础物性

不同区域、不同地层构造的页岩油,其物性与低温流动特性不同^[32,36],油品流动温度越低,黏度越大,流动性越差^[34]。以中国石化复兴地区含蜡量较高的主力层系代表油井(泰页1HF)现场产物页岩油样为例进行室内脱水测试,得到其密度、凝点、黏度、析蜡点及蜡含量等基础物性(表1)。测试结果表明,复兴地区主力层系页岩油的密度小、黏度低、凝点高、蜡含量高、胶质含量低、不含沥青质、气油比高,是中国较少的含凝析气高含蜡轻质页岩油。

表 1 泰页 1HF 井油样基础性参数表
Table 1 Basic physical property parameters of oil samples from Taiye Well 1HF

20 °C 密度/(kg·m ⁻³)	25 °C 黏度/(mPa·s)	凝点/°C	析蜡点/°C	蜡含量	胶质	沥青质	气油比/(m ³ ·t ⁻¹)
771	16.51	19	29.3	22.4%	1.01%	0	1 908

1.2 黏温曲线

在低温集输条件下,黏度对油品流动性有较大影响^[30]。根据 SY/T 0520—2008《原油粘度测定 旋转粘度计平衡法》,采用 Anton Paar 流变仪对泰页 1HF 井的页岩油样在恒温条件下进行不同温度、不同剪切率下的静态黏度测试,得到不同剪切率下的黏温曲线(图 1)。可见,该油样黏度随剪切率的增加而降低,剪切率超过 40 s⁻¹ 后降低幅度较小;随温度的降低而升高,高于析蜡点后黏度几乎不受剪切速率的影响。

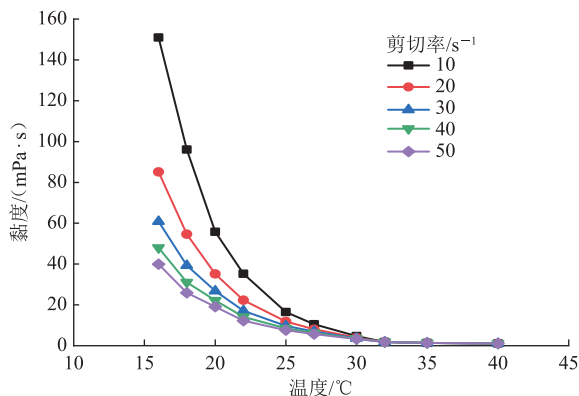


图 1 泰页 1HF 井页岩油在不同剪切率下的黏温曲线
Fig. 1 Viscosity-temperature curves of shale oil from Taiye Well 1HF at different shear rates

为模拟实际管输过程中页岩油动态黏度随温度的变化规律,采用 RS150H 流变仪对泰页 1HF 井页岩油进行动态黏度测试。将黏度计降温速率设置为 0.25 °C/min,测得不同剪切速率下的黏温曲线(图 2)。可见,在动态降温与黏度计转子剪切下,页岩油的动态

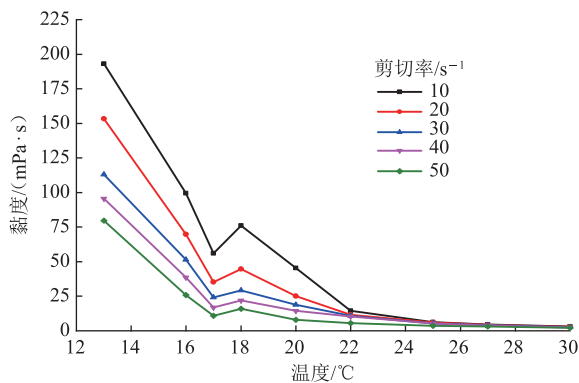


图 2 0.25 °C/min 降温速率下泰页 1HF 井页岩油在不同剪切率的黏温曲线

Fig. 2 Viscosity-temperature curves of shale oil from Taiye Well 1HF at different shear rates under a temperature drop rate of 0.25 °C/min

黏度低于静态黏度,如在温度 17 °C、剪切率 10 s⁻¹ 条件下,泰页 1HF 井页岩油的动态黏度(图 2, 56.03 mPa·s)仅为静态黏度(图 1, 123.51 mPa·s)的 45%。同时,不同剪切速率条件下的动态黏度均在凝点附近出现黏度迅速降低的现象。

1.3 页岩油屈服应力

为直观体现低温条件下页岩油的结构强度与流变性^[35,37],采用 Anton Paar 流变仪对页岩油屈服应力进行测试。在 80 °C 条件下预处理油样,开启循环水浴,水浴温度达到 45 °C 后装样,静置 5 min,保持流变仪温度与水浴温度一致,以 0.5 °C/min 的降温速率降至目标测试温度后测量屈服值,得到不同温度下的屈服应力曲线(图 3)。可见,泰页 1HF 井页岩油的屈服应力随温度的降低而增大,温度低于 16 °C 后,屈服应力快速升高,对流变性有明显影响。屈服应力增大表明推动管内凝油层剥落所需的剪切力增加,停输再启动的难度增大。因此,从屈服应力变化看,泰页 1HF 井页岩油冷输工艺的最低温度应为 16 °C,对应的屈服应力为 12.7 Pa。

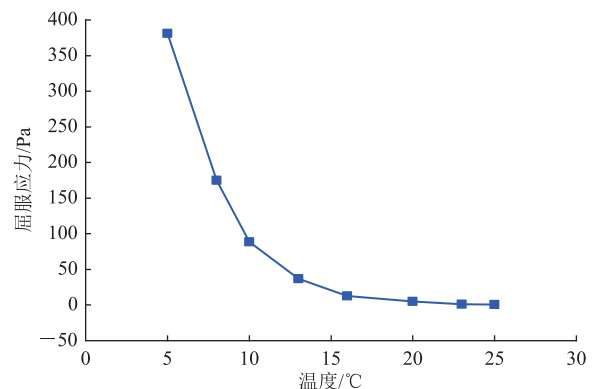


图 3 泰页 1HF 井页岩油不同温度下的屈服应力曲线
Fig. 3 Yield stress curve of shale oil from Taiye Well 1HF at different temperatures

1.4 凝点影响因素分析

1.4.1 热处理温度

含蜡页岩油的凝点主要取决于油品的含蜡量与蜡晶分子尺寸^[30],加热含蜡油会改变蜡晶形态从而影响凝点。将泰页 1HF 井页岩油样密闭升温至设定温度(40 °C、50 °C、60 °C、70 °C、80 °C 及 90 °C)并稳定 60 min,再以 0.5 °C/min 的速率降温至冷却温度(35 °C、

30℃、25℃),随后取出油样倒入试管中测试凝点(表2)。可见,泰页1HF井页岩油样在6种热处理温度、3种冷却温度组合下凝点变化不大,即热处理温度与冷却温度对页岩油凝点几乎无影响。因此,集输过程中加热处理对页岩油凝点不会造成影响。

表2 不同热处理温度及冷却温度组合下泰页1HF井页岩油的凝点数据表

Table 2 Solidification points of shale oil from Taiye Well 1HF under different heat treatment temperature and cooling temperature combinations

热处理温度/℃	凝点/℃		
	冷却温度 35℃	冷却温度 30℃	冷却温度 25℃
40	19	19	18
50	18	18	19
60	19	19	18
70	18	20	19
80	18	18	19
90	20	19	20

1.4.2 含凝析气

为分析流动状态下挥发性凝析气组分对含蜡页岩油凝点的影响,对泰页1HF井页岩油样分两组进行对比测试。其中一组油样密闭搅拌升温至测试温度25℃,对照组油样敞口搅拌升温至测试温度25℃,搅拌桨转速均为500 r/min,分别取搅拌时间为1 h、3 h、7 h的两组油样倒入试管中测试凝点(表3)。可见,轻组分的挥发对含凝析气页岩油的凝点影响较大,敞口搅拌加剧了页岩油轻组分挥发,凝点大幅上升至24℃。结果表明,在密闭条件下溶气可以降低页岩油凝点,这是由于含蜡页岩油中轻组分的增加使页岩油“变稀”,析蜡点降低,析出的微蜡晶含量减少,导致凝点降低,从而有利于页岩油冷输集输^[30-31]。

表3 含凝析气影响泰页1HF井页岩油凝点数据表
Table 3 Solidification points of shale oil from Taiye Well 1HF across different condensate gas contents

搅拌时间/h	凝点/℃	
	密闭搅拌	敞口搅拌
0	18	18
1	19	21
3	18	24
7	19	24

1.4.3 剪切作用

为分析剪切作用对含蜡页岩油凝点的影响,对泰页1HF井页岩油样分两组进行对比测试。其中一组油样密闭搅拌升温至测试温度25℃,搅拌转速设置为500 r/min;对照组油样在测试温度25℃密闭条件下无搅拌静置,分别取第1 h、3 h、7 h的两组油样倒入试管

中测试凝点(表4)。可见,在密闭条件下无论是搅拌还是静置对页岩油凝点几乎均无影响,表明剪切作用对页岩油的凝点影响较小,且与剪切时间无关。

表4 剪切作用影响泰页1HF井页岩油凝点数据表
Table 4 Solidification points of shale oil from Taiye Well 1HF under different shearing effects

测试时间/h	凝点/℃	
	密闭搅拌	密闭静置
0	18	19
1	19	18
3	18	19
7	19	19

2 冷输集输工艺关键参数确定

含蜡页岩油冷输集输工艺的关键是确定合理的集输温度,包括集输起始温度与终点进站温度,其不仅与低温集输条件下页岩油凝点、黏度等基本物性有关,而且与低温条件下页岩油的乳化特性、粘壁温度、粘壁规律、黏温变化规律等因素有关^[33-34,38]。

2.1 页岩油乳化特性

页岩油气在集输管道内为油气水三相混合物,油品部分乳化,乳化程度对油品流变性具有较大影响。乳化含水率越高,黏度越大,油品越易粘附于管壁上,低温油气集输条件下的危险性越高^[39-41]。乳状液制备方法:在脱水页岩油中采用一次性加水(加水量分别为20 mL、40 mL、60 mL、80 mL、100 mL、120 mL、140 mL、160 mL及180 mL)的方式配制成200 mL的乳状液,搅拌转速设置为1 000 r/min,搅拌温度为45℃,搅拌时间为10 min,搅拌完成后静置,从而配制成含水率为10%~90%的乳状液。

采用上述方法制备含水率为10%的45℃泰页1HF井页岩油乳状液(图4a),当搅拌停止后将其瞬时倒入锥形瓶中(图4b),发现油品快速分层并形成油水界面,存在少量乳化现象。静置10 min后乳化层内水滴很快聚集并完全破乳,显现清晰的油水界面,乳状液分层明显(图4c)。采用相同方法配制含水率分别为20%、30%的45℃泰页1HF井页岩油乳状液(图4d、图4e),可观察到更加明显的油水分层界面,且无法形成稳定的乳状液。结果表明:泰页1HF井页岩油乳化含水率在10%以下,无法形成稳定的含水率20%以上的乳状液,乳化能力较弱,且在轻微乳化后即迅速破乳。

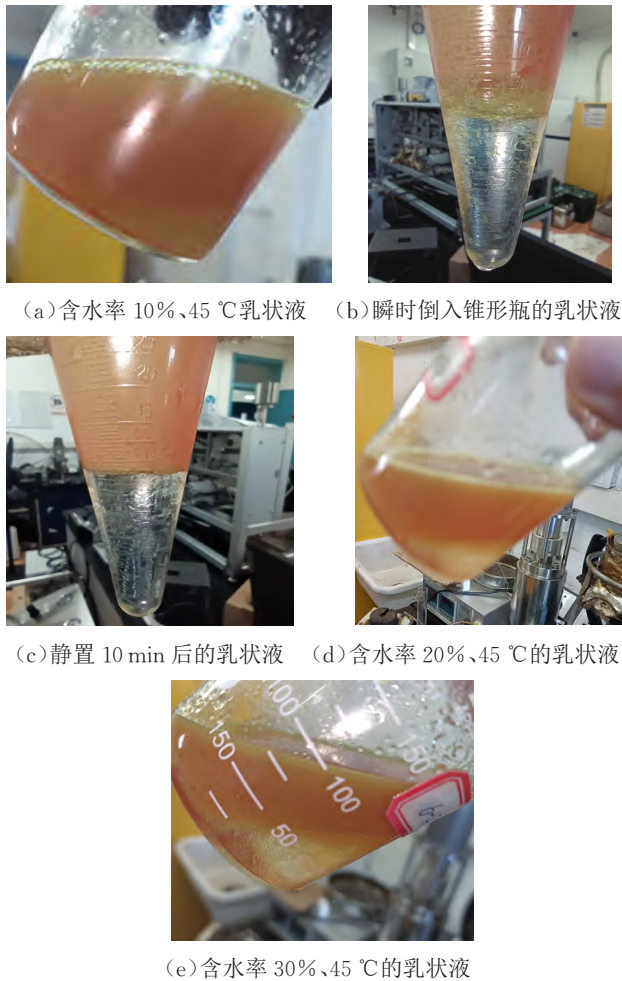


图4 泰页1HF井页岩油乳化特性实验结果实物图
Fig. 4 Experimental results of emulsification characteristics of shale oil from Taiye Well 1HF

2.2 含水页岩油粘壁规律

含蜡页岩油采用冷输集输工艺可以有效降低地面工程集输系统的能耗,节约产油成本,但由于集输进站温度在凝点附近,集输管道内部容易发生凝油粘壁现象,将会导致管道的有效流动面积减小,甚至堵塞集输管道,直接造成井口回压增加从而影响油井产量^[33-35]。

采用上述乳状液制备方法配置含水率为10%~90%的泰页1HF井页岩油乳状液,通过室内实验方法测试常压下不同含水率页岩油的粘壁温度与粘壁质量。实验方法:将配置好的含水率10%乳状液恒温30 min以上,后在搅拌槽内加入200 mL试样,以200 r/min的搅拌转速对试样进行搅拌,搅拌槽以0.5 °C/min的速率降温,到达设定温度后恒温10 min,在搅拌状态下排出油水,计量游离水体积,用刮板取下粘壁凝油并称其质量,此质量即为粘壁质量。随设定温度降低,以粘壁质量急剧增大时的温度为临界粘壁温度;当油样温度降至临界粘壁温度后,其粘壁质量即为临界粘壁质量。

采用上述实验方法即可得到泰页1HF井页岩油在常压、不同含水率下的粘壁质量与粘壁温度的关系曲线(图5)及常压下临界粘壁温度与含水率关系曲线(图6)。可见,泰页1HF井页岩油粘壁质量随温度的降低而增加;其临界粘壁温度随含水率升高呈下降趋势,变化范围为13~18 °C。在实验过程中发现粘壁凝油质地偏软、强度较低,容易脱落,有利于实现低温输送。泰页1HF井试采生产3~5个月后,其含水率稳定在8%~20%,因此,按含水率20%以下确定页岩油集输系统冷输终点进站温度应为18 °C。

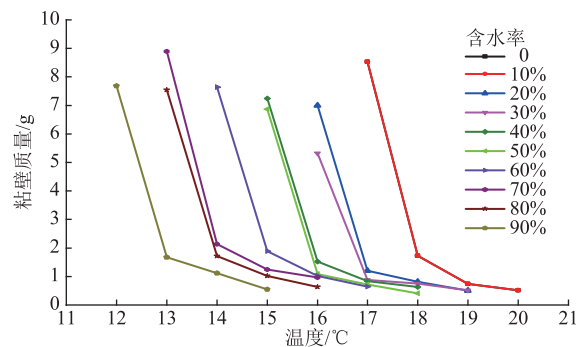


图5 泰页1HF井页岩油在常压、不同含水率下的粘壁质量与粘壁温度的关系曲线

Fig. 5 Relationship curves between wall sticking mass and wall sticking temperature of shale oil at different water cuts from Taiye Well 1HF under atmospheric pressure

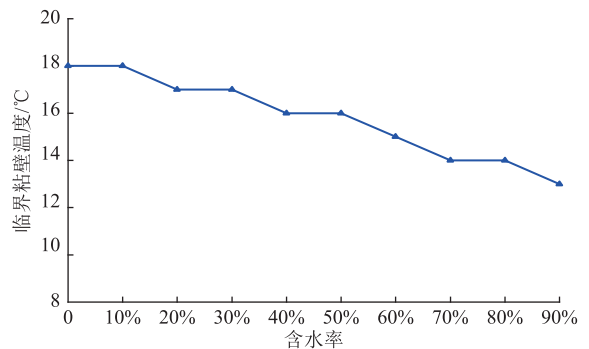


图6 泰页1HF井页岩油在常压下临界粘壁温度与含水率的关系曲线

Fig. 6 Relationship curve between critical wall sticking temperature and water cut of shale oil from Taiye Well 1HF under atmospheric pressure

2.3 溶气含水页岩油粘壁规律

采用上述乳状液配置方法配置含水率为10%~90%的泰页1HF井页岩油乳状液,实验得到1.0 MPa CO₂压力、不同含水率下页岩油的粘壁质量与粘壁温度关系曲线(图7)及1.0 MPa CO₂压力下临界粘壁温度与含水率关系曲线(图8)。可见,在1.0 MPa CO₂压力条件下泰页1HF井页岩油的粘壁质量随含水率升高整体呈下降趋势,与常压、不同含水率页岩油的粘壁规律

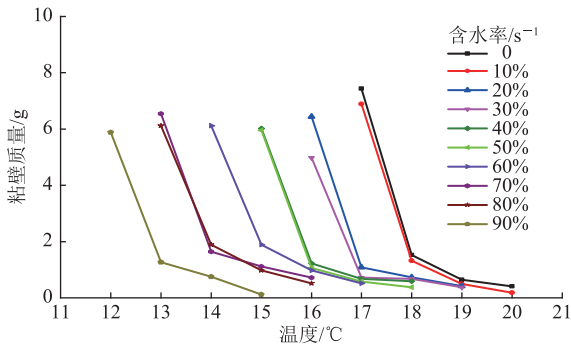


图7 泰页1HF井页岩油在1.0 MPa CO₂压力、不同含水率下的粘壁质量与粘壁温度的关系曲线

Fig. 7 Relationship curves between wall sticking mass and wall sticking temperature of shale oil at different water cuts from Taiye Well 1HF under 1.0 MPa CO₂ pressure

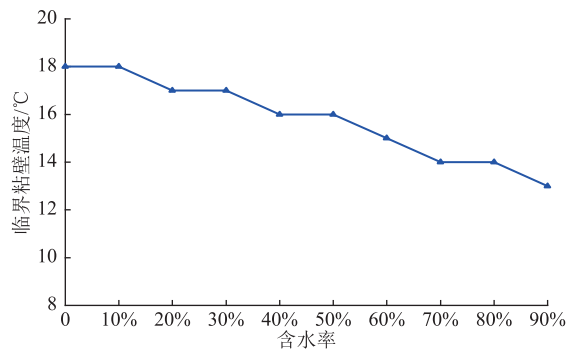


图8 泰页1HF井页岩油在1.0 MPa CO₂压力下临界粘壁温度与含水率的关系曲线

Fig. 8 Relationship curve between critical wall sticking temperature and water cut of shale oil from Taiye Well 1HF under 1.0 MPa CO₂ pressure

(图5)相似^[30-33],但相同温度(即含水率)下的粘壁质量有所降低。其原因是:页岩油溶气后,页岩油分子间

作用力降低,进而降低黏度与沉积物的黏附力。综上,随着溶气、含水含蜡页岩油输送压力的增加,在低温流动条件下其粘壁温度与黏度也随之降低,流动性变好,因此,集输管道终点进站压力应不低于1.0 MPa。

2.4 溶气页岩油黏度变化规律

为研究溶气页岩油黏度变化规律,采用高压反应釜对泰页1HF井页岩油进行黏度测试(图9)。测试方法:①检测整套装置的气密性。关闭阀门F3~F6,密闭高压反应釜,打开进气阀门F1与F2,然后打开高压气瓶并设置压力为1.0 MPa,待高压反应釜内压力达到1.0 MPa,关闭钢瓶并静止1 h观察高压反应釜压力变化,若压力稳定,说明整套装置密闭性良好,打开阀门F5放空气体。②打开循环水浴对高压反应釜进行预热,达到预热温度(10~30 °C)后,打开阀门F3注入3.0 L页岩油。③关闭阀门F3,打开高压气瓶并将压力设为0.5 MPa,对整套装置进行换气5 min,保证高压反应釜内充满CO₂。④打开在线黏度计与数据采集软件,采集频率设定为20 s/次。开启高压反应釜内搅拌桨,搅拌转速设为150 r/min。⑤关闭阀门F1、F2及F5,调节高压气瓶压力为2.0 MPa,控制阀门F1与F2使高压反应釜内压力达到设定压力(1.0 MPa、1.5 MPa)后恒温恒压3 h,然后设置循环水浴开始降温,降温速率为0.25 °C/min。⑥测试完毕后保存不同温度与压力下的黏度数据,关闭所有仪器,放空高压反应釜内气体,打开阀门F4放出页岩油并清洗高压反应釜。

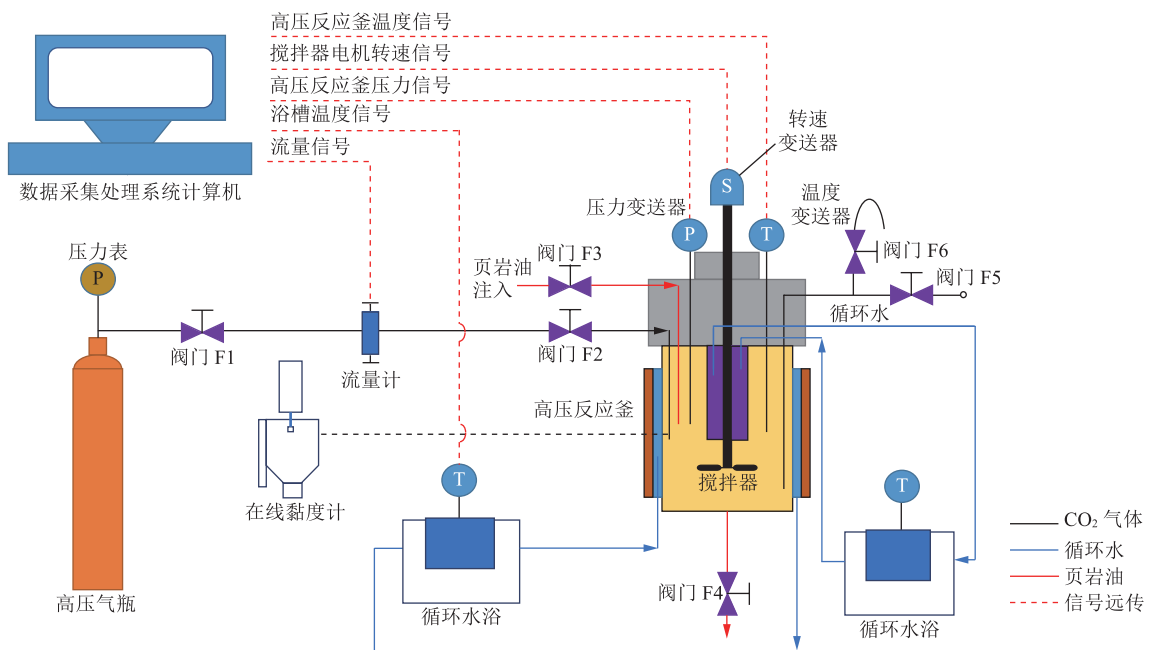


图9 泰页1HF井溶气页岩油黏度测试装置及流程图

Fig. 9 Flow diagram of experimental setup for viscosity of dissolved gas shale oil from Taiye Well 1HF

采用上述实验装置对泰页 1HF 井页岩油进行不同溶气压力下的动态温降黏度测试,得到其黏温曲线(图 10)。可见,随着温度降低,页岩油黏度逐渐升高;随着压力增加,溶气页岩油黏度下降,这是因为 CO₂ 溶气率从 0 增至 8%(1.5 MPa 下体积分数),溶解气阻碍了蜡晶间的絮凝作用,减小了分子间作用力^[39,42-44]。溶气可以破坏页岩油中蜡晶的大分子层状网络结构,减小分子间作用力,因此,相同温度下泰页 1HF 井页岩油黏度随压力增大而降低,集输压力越高越有利于冷输,但页岩油压力衰减快,结合工程实践经验得出进站压力不宜高于 2.0 MPa。

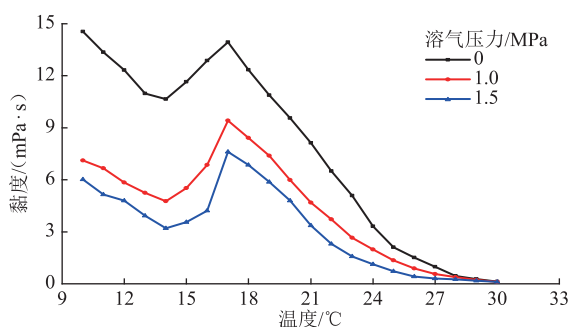


图 10 泰页 1HF 井页岩油在不同溶气压力下的动态温降黏度曲线

Fig. 10 Viscosity-temperature curves of shale oil from Taiye Well 1HF at different dissolved gas pressures

3 结论

中国石化复兴地区陆相含凝析气页岩油密度小、黏度低、含蜡量高、不含沥青质,具有常温流动性好,低温易凝、易结蜡的特点;密闭加热与剪切作用对页岩油凝点几乎无影响,而轻组分挥发对页岩油凝点有较大的影响;低温条件下黏度与屈服应力测试结果表明复兴地区页岩油低温流动性较好,凝油质地偏软、强度较低,容易脱落,有利于实现冷输集输工艺。

根据对泰页 1HF 页岩油乳化特性、不同含水率页岩油的粘壁温度与粘壁规律、溶气页岩油粘壁规律以及溶气页岩油黏度变化规律的分析,该页岩油在含水率 10% 时稳定乳状液黏度相对较大,在不同含水率与溶气含水条件下临界粘壁温度最高为 18 °C。随着压力增加,溶气页岩油的黏度降低,表明集输过程中压力越高越有利于油气输送。但考虑页岩油开发压力递减快,为尽可能多地释放产能,集输压力不宜高于 2.0 MPa。对于高含蜡页岩油,冷输集输管道终点进站温度应高于临界粘壁温度,泰页 1HF 页岩油冷输集输工艺关键

参数为:集输管道终点最低温度为 18 °C,终点进站压力不应低于 1.0 MPa。未来应结合低温冷输条件下悬浮于页岩油中的微蜡晶结构、蜡沉积规律及自然环境条件等因素作进一步优化,实现轻质高含蜡页岩油在山区复杂地形的安全低温输送。

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(编辑: 张雪琴)

基金项目: 中国石油化工集团有限公司重大科技专项子课题“高含蜡页岩油高效开发地面工程关键技术”, JP22082。

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- Received: 2023-06-25
- Revised: 2023-08-29
- Online: 2024-04-28

