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Current Situation, Challenges and Development Trends of Fracturing Flowback Fluids Treatment in Ordos Basin, China

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Abstract: Ordos Basin, a critical energy base in China, faces significant environmental challenges due to the complex composition of fracturing flowback fluids generated from hydraulic fracturing. This fluid, containing water, gases, salts, heavy metals, organic matter, and radioactive elements, is characterized by high total dissolved solid, high chemical oxygen demand, high total suspended solid, strong emulsification, and variable water quality. Current treatment methods, which integrate physical, chemical, and biological technologies, include the reinjection and reuse but are limited by issues such as the absence of oxidative viscosity reduction, lack of closed-loop filtrate treatment, unverified pollutant removal efficiency, and unclear resource recovery pathways. Future advancements aim to enhance treatment efficiency, promote resource reuse, and adopt green and intelligent technologies. Innovations like anti-fouling membrane materials, optimized microbial degradation, efficient desalination, heavy metal removal, and intelligent monitoring systems are expected to address these challenges, ensuring sustainable oil and gas development while protecting the environment.

Keywords: Hydraulic fracturing flowback fluids, Treatment technologies, Resue, Reinjection, Ordos basin

1 Introduction

Ordos Basin, located in the central-northern region of China, is one of the country's most significant energy production bases. Spanning across the provinces of Shaanxi, Inner Mongolia, Ningxia, and Gansu, the basin covers an area of approximately 250,000 square kilometers[1-2]. Known for its abundant coal, oil, and gas resources, Ordos Basin is one of the largest and most important coalbed methane (CBM) production areas in China, as well as a key region for shale gas development[3-4]. Over the past several decades, with the rapid growth of China's energy demand, the exploration and development of oil and gas resources in Ordos Basin have been continuously advancing, making it a crucial component of China's energy supply system[5-6].

Hydraulic fracturing, introduced in the 1940s, involves injecting high-pressure fluids to fracture rock formations and release oil and gas. It has become a key method for extracting unconventional resources globally, particularly in China, where it is vital for tapping tight oil, shale gas, and CBM[7]. In Ordos Basin, hydraulic fracturing has significantly boosted oil and gas production. However, the fracturing flowback fluids (FFBFs) —comprising water, gases, salts, heavy metals, organic matter, and radioactive elements—pose environmental challenges due to their complex composition and contamination[8]. Traditional wastewater treatment methods are inadequate, necessitating the development of efficient, cost-effective, and eco-friendly treatment technologies[9-10]. As environmental concerns rise, the proper management of FFBFs are crucial to prevent long-term damage to water, soil, and ecosystems, making innovative treatment and resource recovery key to sustainable oil and gas development[11].

In conclusion, the current status, challenges, and future technological directions of the FFBFs treatment in Ordos Basin are not only related to the sustainable development of unconventional oil and gas resources in the region, but also have profound implications for the formulation and implementation of China's energy and environmental policies. Therefore, in-depth analysis of the characteristics of the FFBFs in Ordos Basin, evaluation of the effectiveness of existing treatment technologies, exploration of challenges encountered during treatment, and the proposal of feasible development trends and recommendations are of significant importance for achieving the dual goals of oil and gas resource development and environmental protection.

2 Characteristics of FFBFs in Ordos Basin

Ordos Basin, as one of the most important unconventional oil and gas resource development regions in China, plays a critical role in shaping the selection and optimization of technologies for the treatment and utilization of FFBFs[12]. Understanding the fundamental composition, physicochemical properties, and variation patterns of the FFBFs are essential for developing more efficient, cost-effective, and environmentally friendly treatment technologies, thereby ensuring the sustainability of oil and gas extraction processes[13]. This section provides a detailed analysis of the main characteristics of FFBFs in Ordos Basin, focusing on aspects such as chemical composition, physical properties, and environmental risks.

FFBFs are the liquids that return to the surface during the hydraulic fracturing process, typically formed by a mixture of injected fracturing fluids and the reaction products from underground rocks, gases, and minerals. In Ordos Basin, the FFBFs primarily consist of water, chemical additives, oil and gas components, and minerals. The specific composition is influenced by various factors, including geological conditions, rock formation types, fracturing fluid formulation, and operational parameters[14-15]. Due to variations in fracturing fluid formulations,processes, reservoir properties, and other factors, the water characteristics of shale gas FFBFs can exhibits ignificant differences between different regions and even within the same region over time. Nevertheless, they commonly share characteristics such as high total dissolved solids (TDS), high chemical oxygen demand (COD), elevated total suspended solids (TSS), complex composition, and a wide range of water quality variations[16-18]：

（1）The composition of FFBFs is highly complex and influenced by multiple factors, including the quality of the makeup water used in fracturing fluid preparation, the chemical composition of the fracturing fluid itself, the geological and geochemical characteristics of the reservoir, the properties of formation water, and the residence time of the fluid both underground and at the surface[19]. FFBFs typically exhibit elevated concentrations of SS and contain a diverse array of chemical additives, such as crosslinkers, mulsion splitter, friction reducers, and other functional agents. These additives contribute to the fluid's stability and result in a wide range of physical appearances, varying from yellow to black in color. This complexity poses significant challenges for effective treatment and management of FFBFs, necessitating advanced analytical and remediation strategies to mitigate environmental impacts[20].

（2）FFBFs are characterized by their high viscosity and pronounced emulsification properties, which arise from the complex interplay of fracturing fluids, formation fluids, and produced well fluids. This heterogeneous mixture often results in a dark, viscous liquid with a distinct acrid odor, reflecting the presence of various organic and inorganic constituents[21-22]. The high viscosity is primarily attributed to the residual polymers and chemical additives used in the fracturing process, while the emulsification is driven by the interaction of hydrocarbons, surfactants, and other stabilizing agents. These physicochemical properties not only complicate the fluid's handling and treatment but also pose significant challenges for efficient separation and resource recovery processes.

（3）The treatment of FFBFs presents significant challenges due to its complex composition and elevated pollutant levels. The fluid contains a wide array of chemical additives, which, upon returning to the surface from the subsurface, result in substantially higher values of key parameters such as COD, color intensity, and SS concentration compared to conventional industrial wastewater. These characteristics render FFBFs one of the most recalcitrant and difficult-to-treat wastewater streams in industrial settings[23-24]. The high treatment difficulty is further compounded by the need for specialized and often costly remediation technologies, making it a focal point of research for both domestic and international scholars aiming to develop effective and economically viable treatment solutions.

the chemical composition of FFBFs in Ordos Basin is complex, involving a variety of water-based solvents, chemical additives, oil and gas constituents, mineral content, and potentially hazardous elements. These factors require careful consideration in the development of treatment technologies to mitigate environmental risks and ensure safe fluid management. Table 1 lists the specific water quality analysis parameters of produced water from CBM and tight gas wells in Ordos Basin, as shown in the table below. The appearance diagrams of water samples 1#-5# are shown in Fig.1.

Table1 Water quality analysis of shale gas and tight gas FFBFsin China

Test items	1#	2#	3#	4#	5#
pH	6.7	6.6	6.38	6.2	6.5
Surface tension (mN/m)	61.8	58.6	63.6	49.3	43.0
Calcium ion content (mg/L)	4609.2	3732.5	4859.7	12374.3	13527.0
Magnesium ion content (mg/L)	850.9	486.2	608.8	243.1	531.3
Sodium and potassium ions content (mg/L)	21245.6	13321.1	24414.21	34401.3	14046.0
Chloride ion content (mg/L)	42686.7	27391.5	46985.4	74976.6	46935.5
Sulfate ion content (mg/L)	0	1.8	2.2	1.3	18.5
Barium and Strontium ions content (mg/L)	2103.5	1403.6	863.4	2430.2	863.6
Total iron content (mg/L)	104.8	34.9	219.6	78.3	104.3
TSS (mg/L)	264.4	453.1	320.5	532.5	270.1
Turbidity（NTU）	194.6	326.3	267.3	465.6	322.5
TOC (mg/L)	1653.8	1238.7	2053.3	2473.4	1425.7
Conductivity (ms/cm)	94.9	66.5	95.4	146.1	88.2
Oil content (mg/L)	8.4	4.7	24.9	111.6	53.7

Water Type	$CaCl_2$	$CaCl_2$	$CaCl_2$	$CaCl_2$	$CaCl_2$

Fig 1. Appearance diagrams of water samples (1#-5#from left to right)

Based on the water quality analysis data of five FFBFs samples (1#-5#), the study reveals the high salinity and complex pollution characteristics of FFBFs in Ordos Basin: the ion composition dominated by calcium ions (4609.2-13527.0mg/L) and chloride ions (27391.5-74976.6mg/L) indicates the synergistic effect of calcium-based crosslinkers in fracturing fluid and formation brine, with the conductivity of sample 4# reaching 146.1 ms/cm, highlighting an extreme salinity environment; the enrichment of sodium and potassium ions (13321.1-34401.3mg/L) and barium/strontium ions (up to 2430.2mg/L) suggests the dissolution and accumulation of formation minerals. In terms of organic pollutants, the high values of total organic carbon (1238.7-2473.4 mg/L) and oil content (4.7-111.6 mg/L) reflect the mixed input of residual fracturing additives (such as surfactants and polymers) and hydrocarbons, along with total SS (264.4-532.5 mg/L) and turbidity (194.6-465.6NTU). All samples exhibit weak acidity (pH 6.2-6.7) and a $CaCl_2$ water chemistry type.

3. Treatment Technologies and Research Status of FFBFs in Ordos Basin

In early China, FFBFs were largely regarded as waste fluid from oil and gas operations. Typically, oilfield waste fluids encompass those generated during drilling, acidizing, fracturing, well washing, and similar procedures.[25] These waste fluids, however, exhibit diverse characteristics and properties. In recent years, research into the treatment of FFBFs have gained traction. The treatment processes vary based on distinct objectives, and there are four primary disposal methods for FFBFs in China: external discharge, reinjection, reinjection with reuse, and direct reuse[26].

The most ideal treatment method, however, is the reuse of treated FFBFs for subsequent fracturing fluid preparation. This approach allows for the efficient utilization of valuable components within the FFBF. Nevertheless, a standardized water quality criterion for fracturing fluid preparation remains undefined[27-28]. Prior to its use in fracturing operations, the treated fluid must pass rigorous testing of 16 indicators, including standard base fluid density, apparent viscosity, cross-linking time, temperature resistance, shear resistance, viscoelasticity, fluid loss, permeability damage rate, gel-breaking performance, slag content, and resistance reduction rate. Only once these tests are successfully passed can the fracturing fluid be used in future operations[29-30].

Currently, the treatment of FFBFs in Ordos Basin primarily depends on the integrated application of physical, chemical, biological, and other advanced technologies.The integrated application of multiple physical treatment technologies can effectively overcome the limitations of individual methods. Below are several commonly used and optimized combination schemes: The following is a detailed introduction to several of the currently advanced technologies applied to the treatment of FFBFs.

The process flow diagram for Y1 FFBFs treatment station at Yanchang Oilfield is depicted in Fig.2.

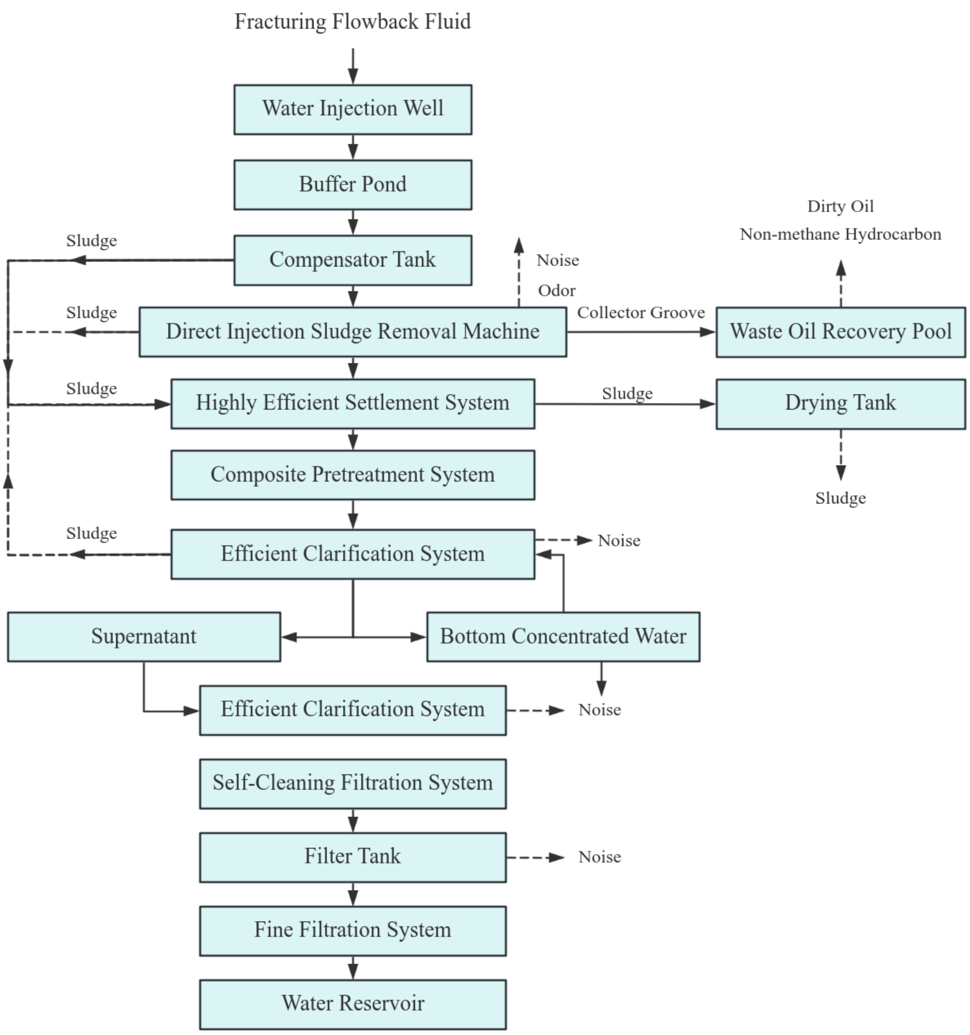

Fig. 2 Process flow diagram for Y1 FFBFs treatment station at Yanchang Oilfield

The process flow of the FFBFs treatment station commences at the discharge well, where the FFBFs are initially introduced into a buffer tank for flow stabilization and equalization. Subsequently, the fluid undergoes physicochemical conditioning in a conditioning vessel to optimize its treatability. The FFBFs are then directed through an oil skimmer and a direct-injection oil-sludge separator, where the oil phase is separated from the solid sludge. The recovered oil is transferred to an oil recovery tank for further processing, while the sludge is conveyed to a high-efficiency clarifier, where it is separated into a supernatant and a concentrated underflow. The supernatant undergoes additional treatment via a self-cleaning decontamination system and a filtration vessel to remove residual contaminants, while the concentrated underflow is dewatered in a sludge drying bed to produce dried solids. Finally, the treated liquid is polished through a precision filtration system and stored in a clear water tank, achieving effluent quality with SS≤20 mg/L, oil content≤30 mg/L, and viscosity≤0.5 mPa·s. However, a significant limitation of this treatment process is the lack of an oxidative viscosity-breaking step, which may impact the long-term stability and operational reliability of the system, particularly in handling high-viscosity FFBFs. This omission could pose challenges in maintaining consistent treatment performance under varying influent conditions.

The process flow diagram for the treatment of Y2 FFBFs at Yanchang Oilfield is illustrated in Fig.3.

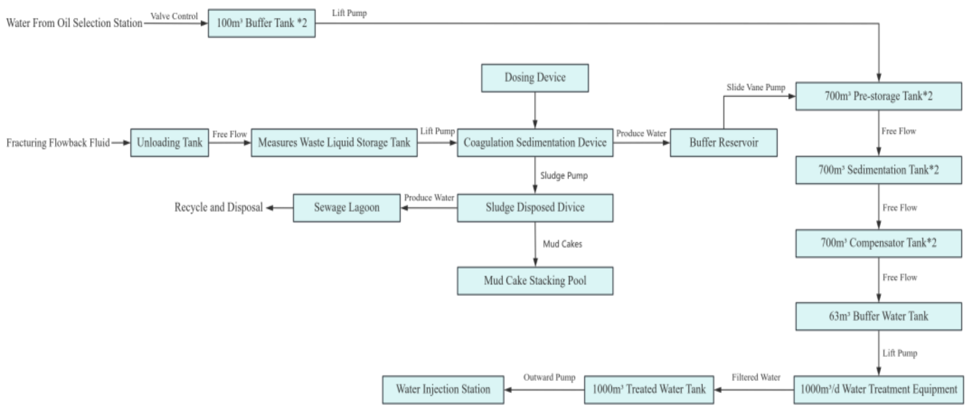

Fig.3 Process flow diagram for Y2 FFBFs at Yanchang Oilfield

The treatment process employs a multi-stage and multi-buffering design to achieve efficient management and resource recovery of FFBFs. The process begins with the transfer of FFBFs via lift pumps to a chemical dosing unit, where coagulants are added to facilitate flocculation. The fluid then enters a coagulation-sedimentation unit for the removal of SS and partial oil phases, achieving initial solid-liquid separation. The separated supernatant flows by gravity into settling tanks for further sedimentation, while the sludge is conveyed to a sludge treatment system via sludge pumps, where it undergoes thickening and dewatering to form sludge cakes, which are temporarily stored in a sludge stacking area. The treated water is further directed into conditioning tanks and buffer water tanks for quality stabilization, and finally pumped into a purified water tank by transfer pumps, meeting the daily treatment capacity of 1,000 m^3/d with effluent quality standards of SS≤20 mg/L and oil content≤30 mg/L. However, the absence of an oxidative viscosity-reduction unit may limit the system's adaptability to high-viscosity FFBFs. The integration of advanced oxidation processes is recommended to enhance process stability and applicability. Overall, this process, through modular design and multi-stage separation technologies, achieves compliant treatment of FFBFs and water resource reuse, offering both environmental benefits and engineering feasibility.

The process flow diagram of Y3 FFBFs treatment system at Yanchang Oilfield is shown in Fig. 4.

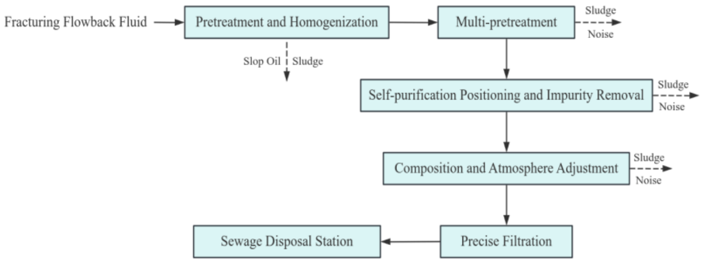

Fig.4 Process flow diagram of Y3 FFBFs treatment system at Yanchang Oilfield

The fluid undergoes flow equalization and property conditioning in the "pretreatment and homogenization" unit, followed by the "composite pretreatment" stage, where physical-chemical methods are employed to preliminarily separate oil, SS, and partial dissolved contaminants, while simultaneously controlling process noise. The core process segment includes a "self-purification and targeted impurity removal" system, which enhances impurity removal efficiency through directional adsorption and catalytic reaction technologies, coupled with "composition and atmosphere conditioning" to optimize the oxidation-reduction potential and ionic balance of the waste fluid. The treated fluid then passes through a "precision filtration" unit, where residual micron-sized particles and colloidal substances are captured by multi-stage filter cartridges, before being conveyed to the "wastewater treatment plant" for advanced treatment, ensuring effluent quality meets industrial reuse or discharge standards, with SS≤20 mg/L, oil content ≤30mg/L, and viscosity≤0.5mPa·s. However, the absence of an oxidative viscosity-reduction step in this treatment process, along with the ambiguous objectives of the composition and atmosphere conditioning, may limit its effectiveness in handling high-viscosity fluids and achieving consistent treatment performance.

The process flow diagram of Y4 FFBFs treatment system at Yanchang Oilfield is shown in Fig. 5.

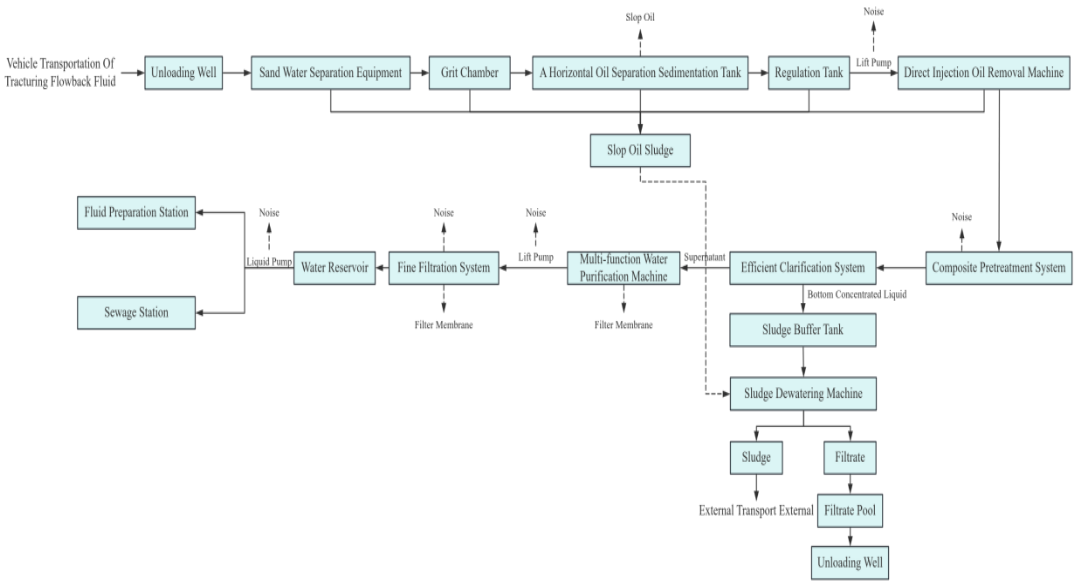

Fig.5 Process flow diagram of Y4 FFBFs treatment system at Yanchang Oilfield

This treatment process employs a multi-stage, quality-based treatment approach and integrated design to achieve efficient purification and resource utilization of oily wastewater. The process begins with the reception of wastewater at the discharge well, where preliminary solid-liquid separation is conducted using sand-water separation equipment and a grit chamber to remove coarse particles and gravel. The wastewater then flows into a parallel-plate oil separation and sedimentation tank, utilizing gravity settling principles to separate floating oil and SS, with flow and quality regulation achieved through a conditioning tank. The core treatment stage features a direct-injection oil removal integrated unit, which enhances oil phase removal efficiency through cyclone and adsorption technologies. The separated oily sludge is temporarily stored in a sludge buffer tank before being transferred to a sludge dewatering machine for mechanical dewatering, ultimately forming stabilized sludge cakes for off-site disposal. The liquid phase is pumped to a multi-functional water purification integrated unit, where the COD and turbidity are further reduced through a composite pretreatment system and a high-efficiency clarification system. Subsequently, the liquid passes through a fine filtration system to remove micron-level residual impurities, and the treated effluent is stored in a clear water tank, meeting discharge standards with oil content ≤50 mg/L and SS ≤50 mg/L. However, the process has limitations, including the lack of a closed-loop treatment pathway for the filtrate from sludge dewatering, which may lead to secondary pollution. Additionally, the synergistic mechanisms between the high-efficiency clarification system and the composite pretreatment unit require further quantitative research to enhance the overall energy efficiency and economic performance of the process.

The process flow diagram for C1 FFBFs treatment station at Changqing Oilfield is illustrated in Fig. 6.

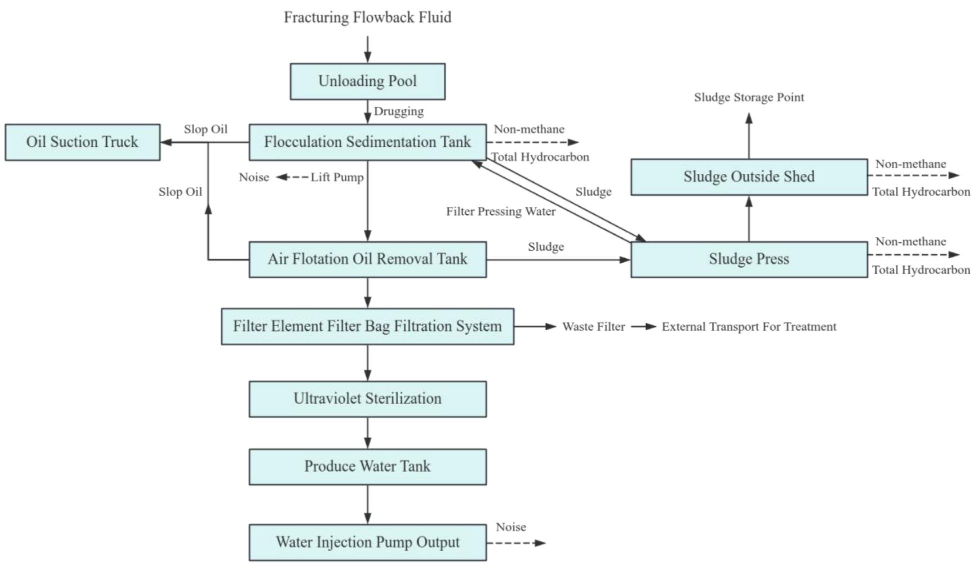

Fig.6 Process flow diagram for C1 FFBFs treatment station at Changqing Oilfield

The FFBFs are initially received at the discharge platform and treated with coagulants via a chemical dosing system, followed by solid-liquid separation in a coagulation-sedimentation tank to effectively remove SS, oil phases, and a portion of non-methane hydrocarbons. The separated sludge is mechanically dewatered using a filter press, yielding low-moisture sludge cakes temporarily stored in a containment shed, while the liquid phase undergoes further oil removal in a dissolved air flotation unit and micron-scale pollutant retention via a cartridge-bag filtration system. The treated effluent is disinfected by UV irradiation and stored in a clean water tank, ultimately meeting the Changqing Oilfield Produced Water Reinjection Technical

Specifications(Q/SY CQ 3675-2016) for reinjection. However, challenges remain regarding the implementation of dissolved air flotation, particularly in achieving adequate oxygen dissolution and ensuring that the effluent meets dissolved oxygen standards. Additionally, the lack of a defined closed-loop treatment pathway for the filtrate generated from sludge dewatering poses a risk of secondary pollution. Addressing these issues is critical to enhancing the overall efficiency and environmental compliance of the treatment process.

The process flow diagram of Y5 FFBFs treatment station at the Yanchang Oilfield is shown in Fig.7.

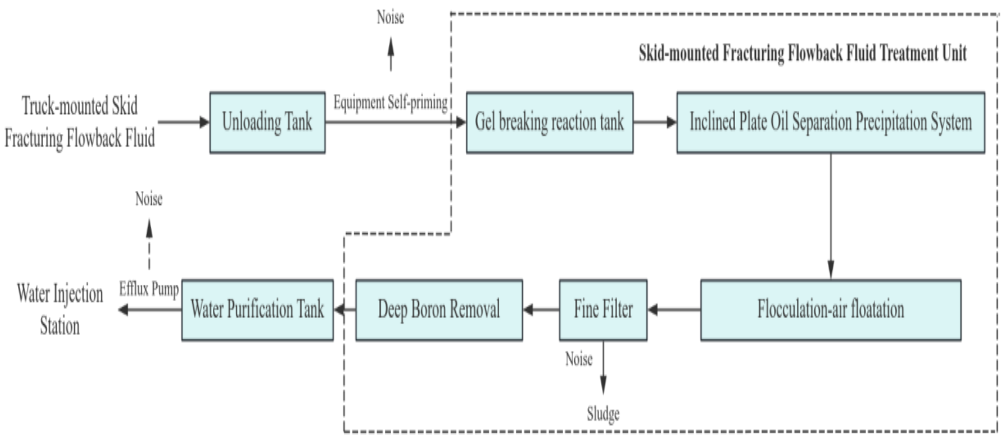

Fig.7 Process flow diagram of Y5 FFBFs treatment station at Yanchang Oilfield

The FFBFs are initially received by a skid-mounted unloading tank and subsequently transported via self-priming pumps to the pretreatment unit. In this stage, sequential processes including gel-breaking reaction for colloidal stability disruption and inclined plate oil separation/sedimentation for oil-water partitioning are implemented. The treatment system then progresses to the primary treatment phase where SS and emulsified oils are effectively removed through flocculation reaction-air flotation technology. The intermediate effluent undergoes hydraulic buffering in a clean water tank before entering the advanced treatment module, where specialized adsorption media are employed for boron-specific removal, followed by terminal solid-liquid separation through precision filtration. The purified effluent (with SS≤10 mg/L and oil content ≤30 mg/L) is ultimately delivered to the water injection station for reuse via external transfer pumps.

This integrated process emphasizes byproduct management, generating oily sludge during oil separation/sedimentation while incorporating noise suppression devices at all pumping nodes. The three-tiered treatment architecture (pretreatment - physicochemical separation - advanced purification) achieves efficient removal of characteristic contaminants including COD, petroleum hydrocarbons, and boron. However, the efficacy of the advanced boron removal module in this configuration warrants further investigation, as its technical necessity within the overall process chain remains scientifically debatable considering the specific water quality requirements for reinjection fluids in unconventional hydrocarbon recovery operations.

The process flow diagram of C2 FFBFs treatment station at Changqing Oilfield is illustrated in Fig.8.

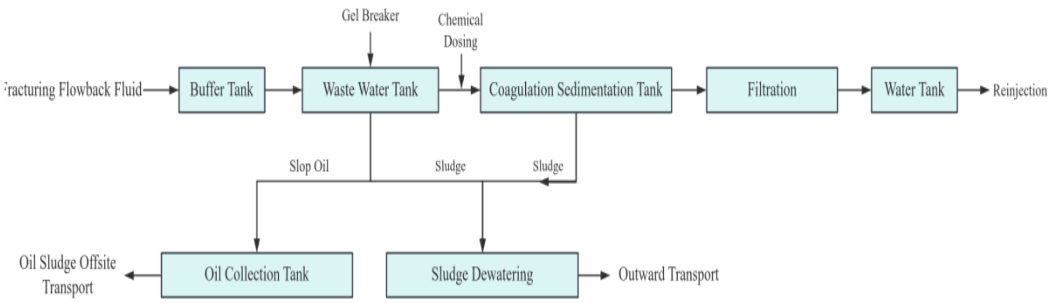

Fig.8 Process flow diagram of C2 FFBFs treatment station at Changqing Oilfield

This treatment process employs the addition of gel breakers and chemical agents to reduce the viscosity of FFBFs and enhance solid-liquid separation. The FFBFs are initially unloaded and directed into a buffer tank for flow and quality stabilization, after which it is transferred to a coagulation-sedimentation tank. Here, SS, oil phases, and partial dissolved contaminants are removed through coagulation and gravity sedimentation. The separated sludge undergoes dewatering before being transported offsite for disposal, while the floating oil is recovered via an oil collection tank. The liquid phase is further treated in a filtration unit to remove residual micron-sized impurities and is subsequently stored in a clean water tank, meeting reinjection standards. Although the process includes an offsite disposal pathway for oil sludge, the lack of a closed-loop treatment mechanism for the filtrate generated from sludge dewatering poses a risk of secondary pollution. Additionally, the dosing ratios of gel breakers and chemical agents, as well as the reaction kinetics, require further optimization to improve treatment efficiency and cost-effectiveness. Overall, this process achieves compliant management of FFBFs through staged treatment and resource recovery. However, further refinement in detailed design and operational parameter optimization is necessary to ensure efficient and stable performance under complex operational conditions.

The process flow diagram of Y6 FFBFs Treatment Station is depicted in Fig. 9.

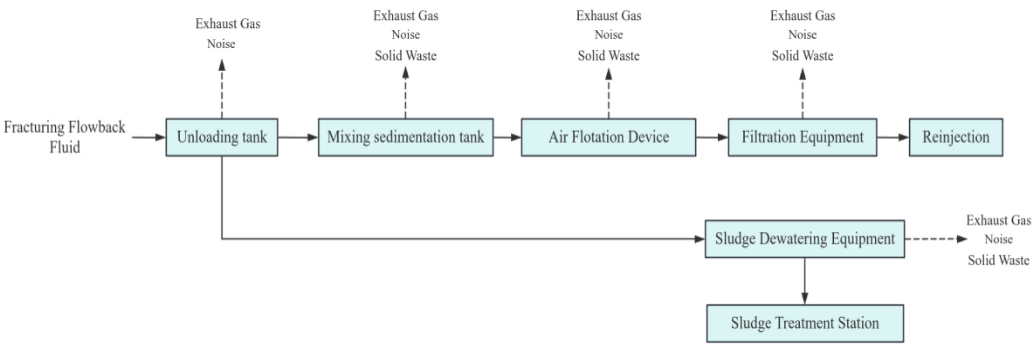

Fig.9 Process flow diagram of Y6 FFBFs Treatment Station

The FFBFs are initially homogenized in an unloading tank and then transferred to a mixing sedimentation tank, where SS and partial dissolved contaminants are removed through coagulation and gravity sedimentation. The liquid phase undergoes further separation of floating oil and micron-sized particles via an air flotation unit, followed by advanced purification through filtration equipment (multi-stage filter cartridges), ultimately achieving reinjection water quality standards: oil content≤10 mg/L, SS≤10 mg/L, viscosity ≤3mPa·s, pH 6-9, and sulfides<2.0 mg/L. The sludge discharged from the sedimentation tank and air flotation unit is mechanically dewatered using plate-and-frame filter press to form low-moisture-content sludge cakes, which are then transported to a sludge treatment station for harmless disposal. However, the process has several limitations: the absence of a closed-loop recycling pathway for the filtrate generated from sludge dewatering poses a risk of leachate overflow, and the removal efficiencies of specific contaminants (heavy metal ions, polycyclic aromatic hydrocarbons) have not been quantitatively validated, which impacts the assessment of the process's adaptability. Addressing these limitations is critical to enhancing the environmental performance and operational reliability of the treatment system.

The process flow diagram for C3 FFBFs treatment station at Changqing Oilfield is illustrated in Fig. 10.

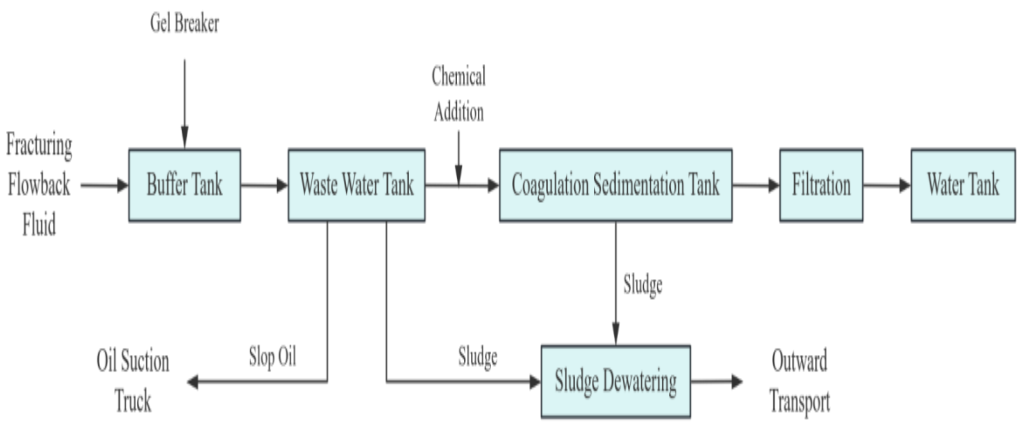

Fig.10 Process flow diagram for C3 FFBFs treatment station at Changqing Oilfield

The treatment process employs a multi-stage, quality-based treatment approach. Initially, a gel breaker is added to decompose the colloidal structure and reduce the viscosity of the FFBF. The wastewater then enters a buffer tank for flow homogenization and preliminary separation of floating oil. Following chemical dosing, the wastewater is directed to a coagulation-sedimentation tank, where SS and oil phases are removed through the synergistic effects of coagulation and gravity sedimentation. The separated sludge is dewatered using sludge dewatering equipment to form low-moisture-content sludge cakes, which are transported offsite for disposal. The liquid phase undergoes further treatment in a filtration unit to remove residual particulates and is ultimately stored in a clean water tank, meeting the reinjection standards specified in the "Technical Specifications for Produced Water Reinjection in Changqing Oilfield" (Q/SY CQ 3675-2016). While the floating oil is recovered using an oil suction truck, the absence of a closed-loop treatment mechanism for the filtrate generated from sludge dewatering poses a risk of secondary pollution. Addressing this issue is critical to enhancing the environmental performance and operational reliability of the treatment process.

The process flow diagram for C4 FFBFs treatment station at Changqing Oilfield is illustrated in Fig. 11.

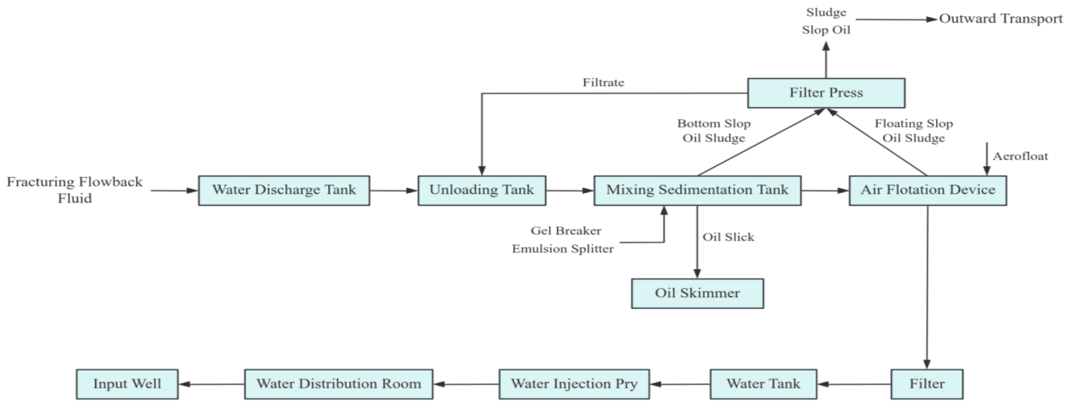

Fig.11 Process flow diagram for C4 FFBFs treatment station at Changqing Oilfield

The C4 FFBFs undergo initial homogenization and flow regulation through a discharge trough and unloading tank before entering a mixing unit, where gel breakers and mulsion splitter are added to decompose colloidal structures and emulsified oil phases. The wastewater is then treated in a flotation unit to enhance the separation of floating oil and SS. The separated floating oil is recovered using an oil skimming device, while the liquid phase is directed to a sedimentation tank for further removal of residual particulate matter through gravity settling. The sludge is mechanically dewatered using a filter press to form oily sludge, which is transported offsite for disposal. The filtrate is further purified through a filtration system (e.g., multi-stage filter cartridges) and stored in a purified water tank before being transferred to an injection tank and reinjected into injection wells. The treated water meets the requirements of the "Technical Specifications for Produced Water Reinjection in Changqing Oilfield" (Q/SY CQ 3675-2016). However, the process has limitations, including the lack of targeted measures for removing dissolved contaminants (e.g., polymer residues, heavy metal ions), which may affect the long-term stability of the reinjection water quality. Addressing these limitations is critical to enhancing the overall performance and reliability of the treatment process.

The process flow diagram for C5 FFBFs treatment station at Changqing Oilfield is illustrated in Fig. 12.

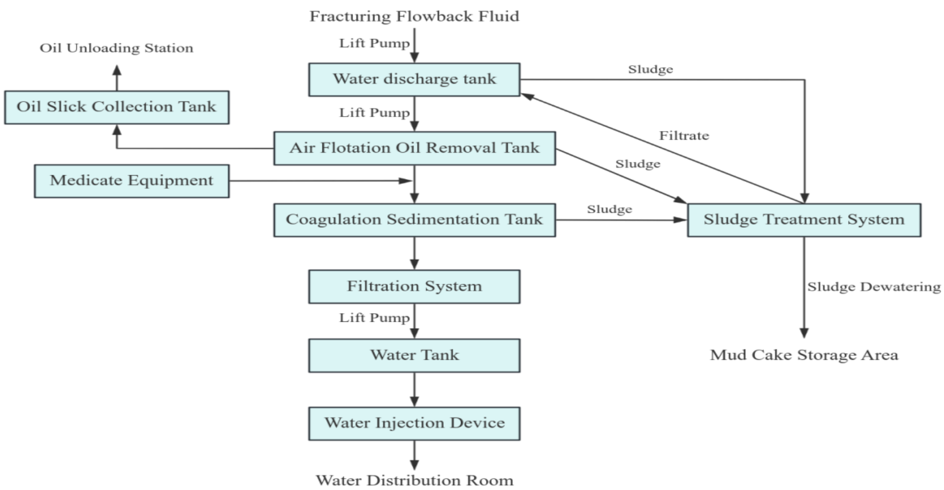

Fig.12 Process flow diagram for C5 FFBFs treatment station at Changqing Oilfield

The treatment process employs multi-stage synergistic technologies, where the FFBFs first enter the oil unloading station for preliminary oil-water separation. It is then transferred to a water discharge tank via a lift pump for flow homogenization. The oil slick collection tank recovers floating oil through gravity separation, while the liquid phase is further treated in an air flotation oil removal tank to remove residual oil phases and SS, utilizing dissolved air flotation (DAF) technology to enhance separation efficiency. The wastewater subsequently enters a coagulation sedimentation tank, where coagulants are added to promote the aggregation and settling of colloidal particles. The separated sludge is mechanically dewatered using sludge dewatering equipment to form low-moisture-content sludge cakes (moisture content ≤70%), which are stored in a mud cake storage area for offsite disposal. The treated liquid phase undergoes advanced purification through a filtration system and is stored in a water tank before being reinjected into the formation via a water injection device and a water distribution room. The effluent quality meets the requirements of the "Technical Specifications for Produced Water Reinjection in Changqing Oilfield" (Q/SY CQ 3675-2016).

The process flow diagram for C6 FFBFs treatment station at Changqing Oilfield is illustrated in Fig. 13.

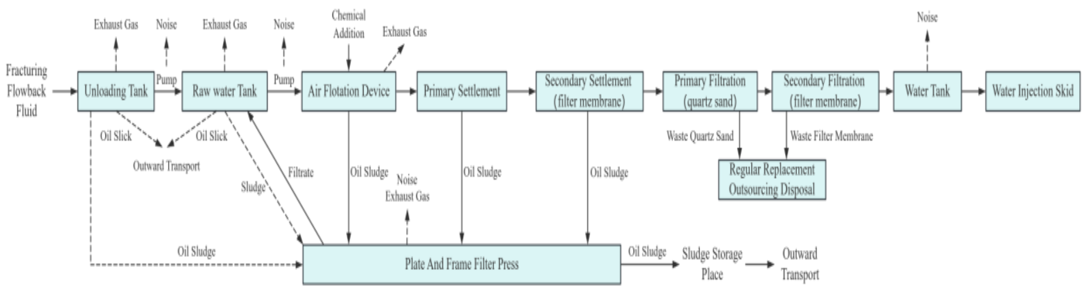

Fig.13 Process flow diagram for C6 FFBFs treatment station at Changqing Oilfield

The FFBFs are initially received in an unloading tank and then transferred to a raw water tank via pumps for homogenization. Subsequently, it enters a dissolved air flotation tank, where oil-water separation is enhanced using DAF technology. The FFBFs then sequentially pass through primary and secondary sedimentation tanks to achieve graded removal of SS via gravity settling. The purified liquid phase undergoes further treatment through primary quartz sand filtration and secondary membrane filtration to remove residual micron-sized impurities. The treated water is stored in a clean water tank and reinjected into injection wells, with the effluent quality meeting the Technical Specifications for Produced Water Reinjection in Changqing Oilfield (Q/SY CQ 3675-2016): oil content ≤80 mg/L and SS ≤80 mg/L for reinjection into the reservoir. Floating oil is periodically collected and transported offsite for disposal, while oily sludge is dewatered using a plate-and-frame filter press to form sludge cakes with a moisture content of ≤70%, which are temporarily stored and then transported offsite by certified units for harmless treatment. Spent filter media (quartz sand, membranes) are also disposed of by professional agencies in compliance with regulations. However, the absence of a gel-breaking oxidation step in the process raises concerns about the stability and reliability of the system during continuous operation. Addressing this limitation is critical to ensuring the long-term performance and environmental compliance of the treatment process.

The process flow diagram for Y7 FFBFs treatment at Yan'an is illustrated in Fig. 14.

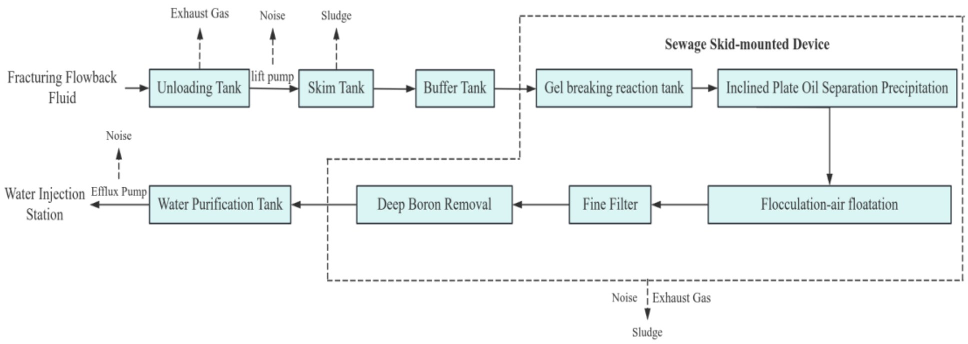

Fig.14 Process flow diagram for Y7 FFBFs treatment at Yan'an

The Y6 FFBFs are initially stored in a discharge pool and then transferred to an oil removal tank via a lift pump, where the oil phase is preliminarily removed through gravity separation and adsorption technologies. The wastewater subsequently enters a buffer tank for flow equalization and then proceeds to a gel-breaking reaction unit, where chemical agents are added to decompose the colloidal structure. After enhanced oil-water separation in an inclined plate oil separation and sedimentation device, the wastewater is directed to a flocculation reaction-flotation unit, where SS and micron-sized oil droplets are further removed through the addition of flocculants and dissolved air flotation technology. The purified liquid phase then passes through a deep boron removal unit and a fine filtration system to capture dissolved contaminants and residual particulates, ultimately being stored in a clean water tank. The effluent quality meets the standards of SS≤80 mg/L and oil content ≤80mg/L. However, the necessity of the deep boron removal step in this treatment process is questionable and warrants further evaluation.

The process flow diagram for C7 FFBFs treatment station at Changqing Oilfield is illustrated in Fig. 15.

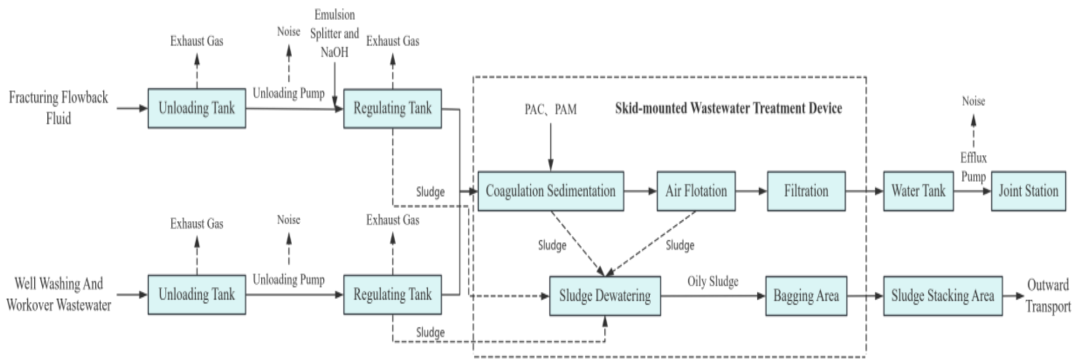

Fig.15 Process flow diagram for C7 FFBFs treatment station at Changqing Oilfield

This treatment process is designed for the staged treatment and resource utilization of FFBFs, well-flushing wastewater, and workover wastewater. The fluid is initially received in a discharge tank and then transferred to a conditioning tank via a truck unloading pump for homogenization. Subsequently, polyaluminum chloride and polyacrylamide are added to induce coagulation, promoting the aggregation of SS and colloidal particles. The wastewater sequentially enters a sedimentation unit and a dissolved air flotation unit, where SS, oil phases, and micron-sized pollutants are removed in stages through gravity settling and DAF technology. The purified liquid phase undergoes advanced treatment via a multi-stage filtration system and is ultimately stored in a purified water tank before being transferred to a central processing station via transfer pumps for reinjection into the formation. The treated water quality meets the following standards: oil content ≤100mg/L, SS≤100mg/L, viscosity≤3mPa·s, and pH 6-9. The sludge is dewatered using a plate-and-frame filter press to form sludge cakes with a moisture content of≤70%, which are temporarily stored in an oily sludge storage shed and transported offsite by certified units for harmless disposal. Spent filter media and packaging materials (filter bags) are also disposed of by professional agencies in compliance with regulations. However, a notable limitation is the use of air-dissolved flotation in the DAF unit, which makes it difficult to control dissolved oxygen levels in the effluent. Addressing this issue is critical to enhancing the overall performance and environmental compliance of the treatment process.

The process flow diagram for A1 FFBFs at Ansai Oilfield is illustrated in Fig. 16.

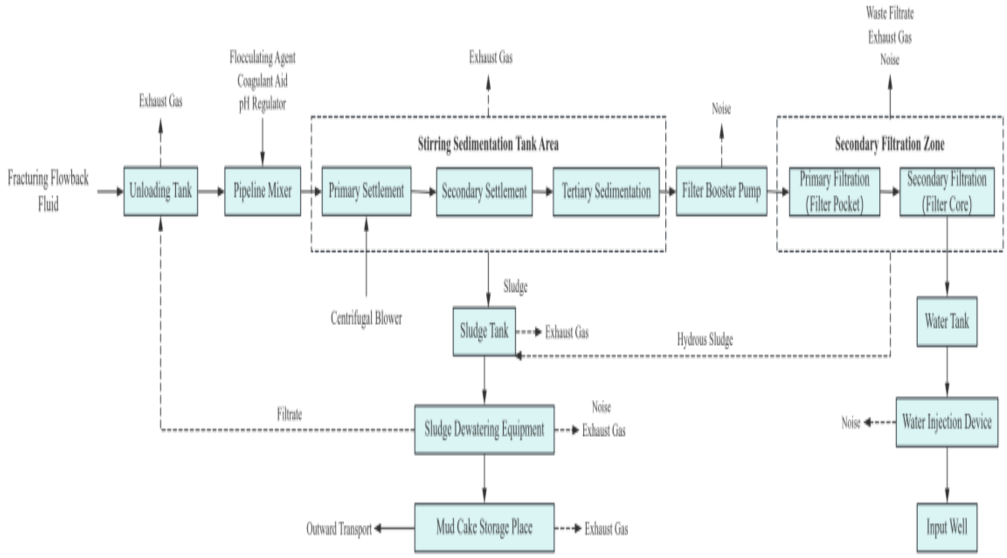

Fig.16 Process flow diagram for A1 FFBFs at Ansai Oilfield

The FFBFs are initially received in a truck unloading tank area and then directed through a pipeline mixer, where pH adjusters and flocculants are added. It subsequently enters a stirred sedimentation tank area for chemical coagulation and gravity sedimentation, achieving primary separation of SS, colloids, and partial oil phases. The wastewater then sequentially passes through a three-stage filtration system: primary bag filtration (removing particles >50μm), secondary cartridge filtration (capturing particles >10μm), and a fine filtration unit driven by a booster pump, further reducing turbidity and residual contaminants. The treated purified water is stored in a water storage tank and ultimately reinjected into the formation via water injection, with effluent quality meeting standards such as oil content ≤80 mg/L and SS ≤80 mg/L. However, the oxidation process in the treatment system is not clearly described. The aeration process introduces dissolved oxygen, raising concerns about how to ensure that dissolved oxygen levels meet the required standards. Addressing this issue is critical to enhancing the overall performance and environmental compliance of the treatment process.

The process flow diagram for Y8 FFBFs treatment project at Baota District, Yan'an City, is illustrated in Fig. 17.

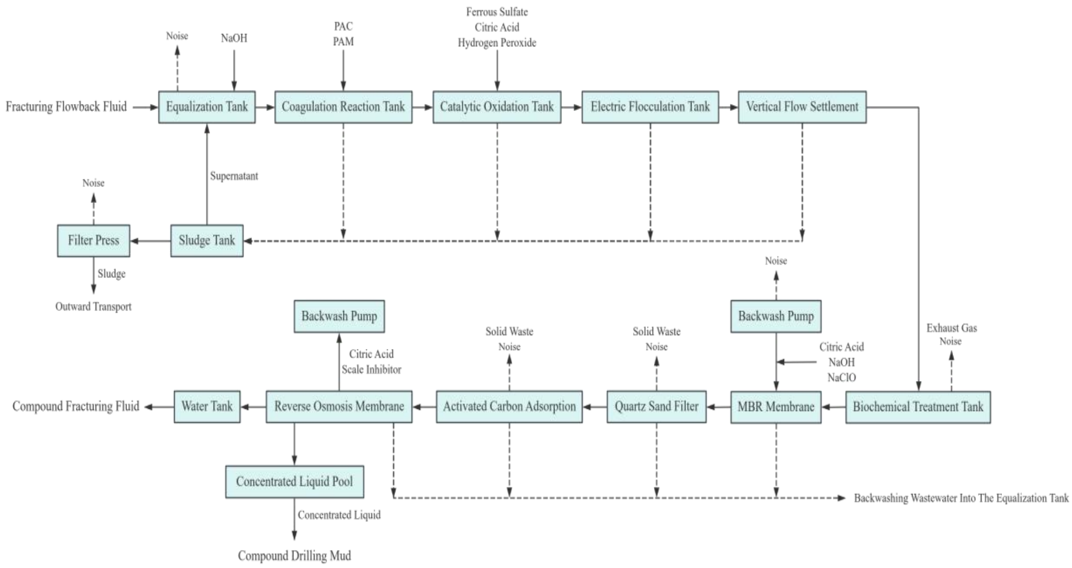

Fig.17 Process flow diagram for Y8 FFBFs treatment project at Baota District, Yan'an City

The FFBFs are initially directed to a conditioning tank for homogenization, followed by the addition of NaOH, polyaluminum chloride (PAC), and polyacrylamide (PAM) in a concrete reaction tank to promote the aggregation of SS and colloids through coagulation. The wastewater undergoes solid-liquid separation in a vertical flow sedimentation tank, and the supernatant is further treated in a quartz sand filter and an activated carbon adsorption tank to remove residual particulates and adsorb dissolved organic matter, respectively. The treated water is stored in a clean water tank, with a portion undergoing further desalination via reverse osmosis membranes for reuse, while the concentrate is temporarily stored in a concentrate tank and disposed of by professional agencies. The sludge is dewatered using a filter press to form low-moisture-content sludge cakes, which are temporarily stored in a sludge tank and transported offsite for harmless disposal.

To address refractory pollutants, the process integrates catalytic oxidation (using citric acid, ferrous sulfate, and hydrogen peroxide) and electrocoagulation technologies to enhance the degradation of organic compounds and the removal of SS. Additionally, a biological treatment tank utilizes microbial metabolism to degrade biodegradable organic matter, further improving water quality stability. Noise control is achieved through equipment soundproofing and acoustic design, but exhaust gas treatment relies on physical containment, lacking targeted measures such as activated carbon adsorption or catalytic combustion, which may affect the compliance of volatile organic compound (VOC) emissions.

Limitations include the absence of a defined resource recovery pathway for RO concentrate, posing challenges for high-salinity wastewater management, and insufficient details on dissolved oxygen control, which may impact the reinjection water's dissolved oxygen levels. Recommended optimizations include introducing evaporation crystallization or membrane distillation for concentrate treatment, determining optimal chemical dosages through experimental studies, adopting pulsed electrocoagulation or electrode material modification to reduce energy consumption and maintenance costs, and integrating online monitoring systems for real-time control of oxidation-reduction potential (ORP) and dissolved oxygen levels.

The process flow diagram for centralized treatment of mud cuttings, FFBFs and produced water injection is illustrated in Fig. 18.

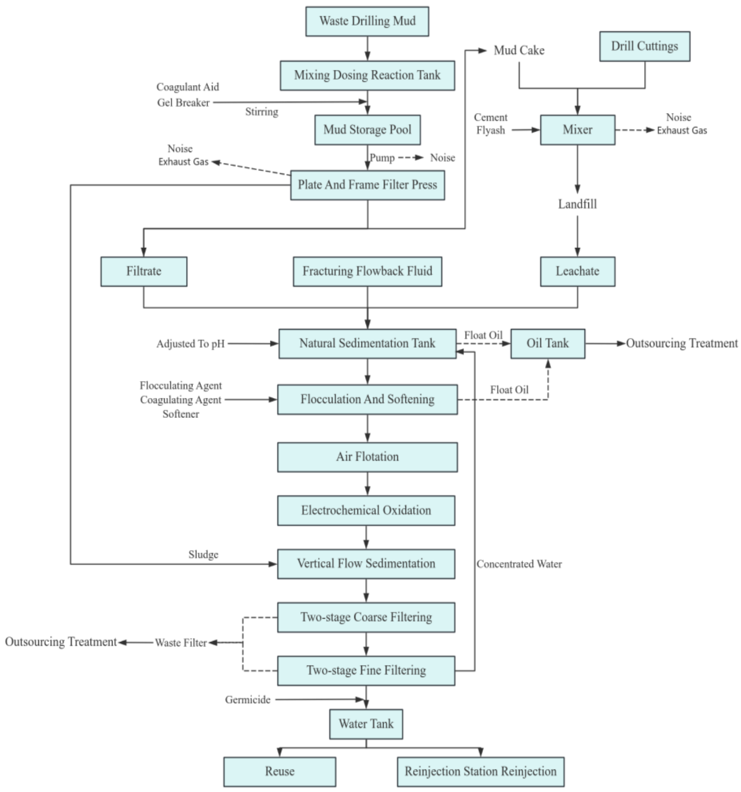

Fig.18 Process flow diagram for centralized treatment of mud cuttings、FFBFs and produced water injection

The waste drilling mud is initially directed to a mixing and dosing reaction tank, where coagulant aids (e.g., polyaluminum chloride) and gel breakers are added to promote the decomposition of colloids and the aggregation of SS, while stirring enhances reaction efficiency. The mud is then stored in a mud storage pool and transferred via pumps to a plate-and-frame filter press for mechanical dewatering, separating the filtrate from the sludge cake. The filtrate undergoes further pretreatment through the addition of flotation agents and a flocculation-softening unit (e.g., softeners), followed by treatment in an air flotation unit combined with electrochemical oxidation to remove residual oil phases and organic matter. Solid-liquid separation is achieved using a vertical flow sedimentation tank. The liquid phase is further purified through two-stage coarse filtration (e.g., quartz sand) and fine filtration (e.g., activated carbon), after which a biocide is added, and the treated water is stored in a clean water tank for reinjection into the formation or reuse via a reinjection station. The sludge cake is mixed with drill cuttings, cement, and other solid wastes in a mixer before landfill disposal. However, the treatment pathway for leachate is not clearly defined, posing a risk of secondary pollution. Floating oil and concentrated water are outsourced to professional agencies for treatment.

Limitations include the inadequate solidification of fly ash and the difficulty in ensuring the compliance rate of cuttings filtrate, as well as the inability to guarantee that the fracturing fluid meets formulation standards. Additionally, the reuse pathways before and after treatment are inconsistent. Addressing these issues is critical to enhancing the overall performance and environmental compliance of the treatment process.

The process flow diagram for the comprehensive treatment of oil and gas field operational wastewater is illustrated in Fig. 19.

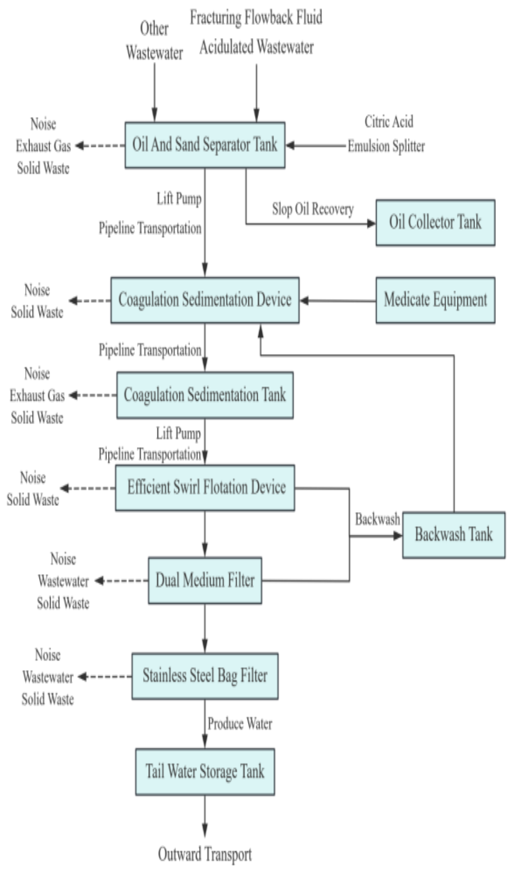

Fig.19 Process flow diagram for the comprehensive treatment of oil and gas field operational wastewater

The FFBFs and acidic wastewater undergo initial separation in an oil and sand separator tank, where gravity settling and flotation are used to remove floating oil and sand, while enclosed designs control exhaust gas and noise. The separated wastewater is then transferred via a lift pump to a coagulation sedimentation device, where coagulants (citric acid, PAC) are added to promote the aggregation and settling of SS and colloids. Subsequently, the wastewater is treated in an efficient swirl flotation device, which combines centrifugal separation and microbubble flotation to further remove micron-sized oil droplets and residual particulates. The purified liquid phase is then processed through a dual-medium filter (quartz sand + anthracite) and a stainless steel bag filter (filtration precision ≤10 μm) for advanced treatment, capturing dissolved organic matter and residual impurities. The treated water is stored in a tail water storage tank for offsite reuse, while the backwash wastewater is recycled to a backwash tank for reuse. Recovered floating oil is collected in an oil collector tank for centralized treatment, and solid waste is disposed of by certified professional agencies.

However, the exhaust gas treatment (volatile organic compounds, VOCs) relies solely on physical containment, lacking targeted measures such as activated carbon adsorption or catalytic oxidation, which may affect emission compliance. Additionally, the backwash water system lacks a defined mechanism for controlling salt accumulation, which could lead to membrane scaling or reduced filtration efficiency over time. Addressing these limitations is critical to enhancing the overall environmental performance and operational reliability of the treatment process.

The process flow diagram for Y9 FFBFs treatment at Yanchang Oilfield is illustrated in Fig. 20.

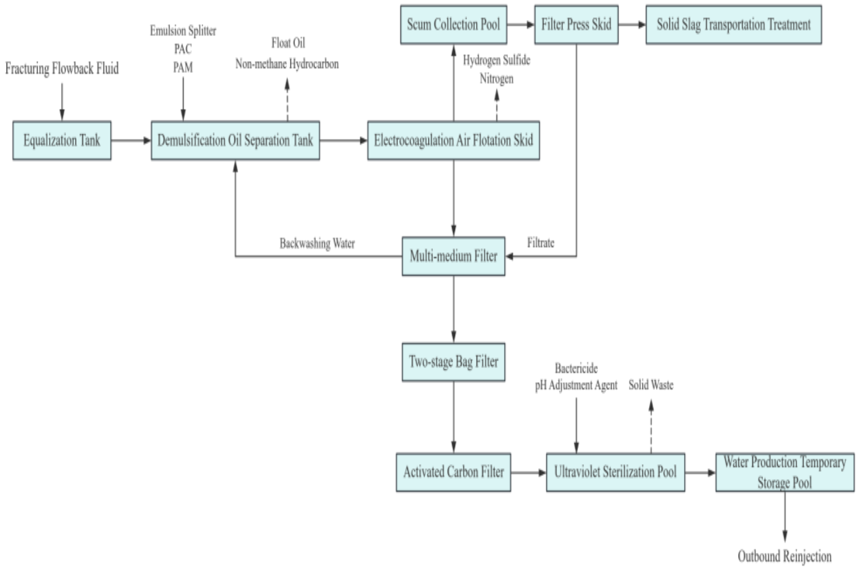

Fig.20 Process flow diagram for Y9 FFBFs treatment at Yanchang Oilfield

The Y9 FFBFs first enter an equalization tank for preliminary adjustment of water quality and quantity, creating homogeneous conditions for subsequent treatment. It then flows into a demulsification oil separation tank, where mulsion splitter, PAC, and PAM are added to achieve oil-water separation, removing non-methane hydrocarbons and floating oil. The separated backwash water is recycled to the demulsification oil separation tank. Next, the liquid enters an electrocoagulation flotation skid, where gases such as hydrogen and hydrogen sulfide are generated during the process, further separating impurities to form scum. The collected scum is treated by a filter press skid to form solid slag, which is outsourced for disposal. The filtrate from the electrocoagulation flotation skid is sequentially passed through a multi-media filter and a two-stage bag filter. During the two-stage bag filtration process, bactericides and pH adjusters are added to optimize water quality. Subsequently, the liquid enters an activated carbon filter for deep adsorption of impurities, followed by disinfection in an ultraviolet sterilization tank. Finally, the treated water is stored in a temporary storage tank and transported by tanker trucks to reinject.

Limitations of the process include: (1) exhaust gases (NH_3, H_2S, NMHC) rely solely on physical containment, lacking biological filtration or catalytic oxidation processes, which may fail to meet the *Integrated Emission Standard of Air Pollutants* (GB 16297-1996); (2) the backwash water system lacks a desalination pathway, which may lead to salt accumulation and membrane fouling over time; (3) the absence of an activated carbon regeneration mechanism increases operating costs and generates secondary solid waste; (4) the lack of an oxidative viscosity-reduction step raises concerns about the process's adaptability to FFBFs. Addressing these limitations is critical to enhancing the overall environmental performance and operational reliability of the treatment process.

The process flow diagram for Y10 FFBFs Treatment Station project is illustrated in Fig. 21.

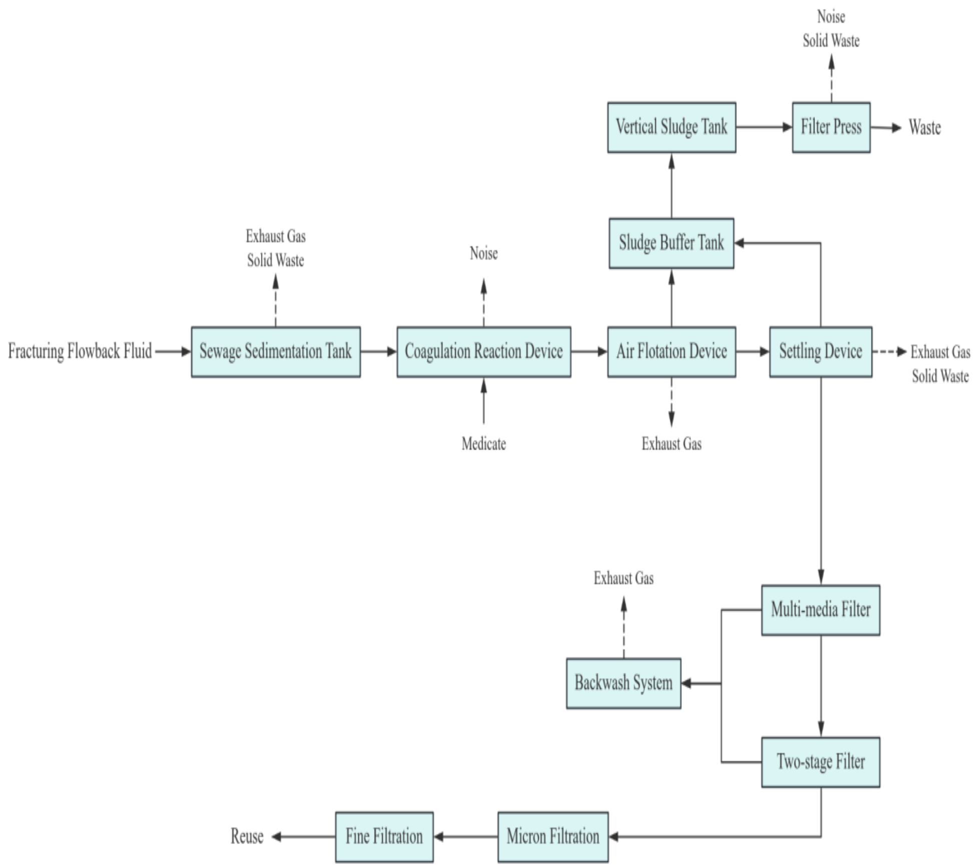

Fig.21 Process flow diagram for Y10 FFBFs Treatment Station project

The liquid first flows into a sewage sedimentation tank for preliminary settling, separating out some impurities. Subsequently, it enters the coagulation reaction stage, where chemicals are added to aggregate suspended particles and other impurities in the water, a process that generates noise. The mixed liquid then enters the air flotation system and air flotation skid, utilizing the principle of bubble flotation to further separate suspended matter and other pollutants, while generating exhaust gases. The separated solid-containing material first enters a sludge buffer tank and then flows into a vertical sludge tank, where it is treated by a filter press, and the waste is discharged. The separated liquid enters a sedimentation tank for further settling, producing additional solid waste and exhaust gases. The settled liquid sequentially undergoes multi-stage filtration steps, including multi-media filtration, secondary filtration, micron filtration, and fine filtration, to further remove impurities of different particle sizes. A backwash system is used to clean and maintain the filtration equipment. The final treated liquid can be reused in subsequent production processes.

Limitations of the process include the absence of an oxidative viscosity-reduction step, raising concerns about the adaptability of the effluent quality. Addressing this limitation is critical to enhancing the overall performance and reliability of the treatment process.

The process flow diagram for Y11 FFBFs treatment construction project is illustrated in Fig. 22.

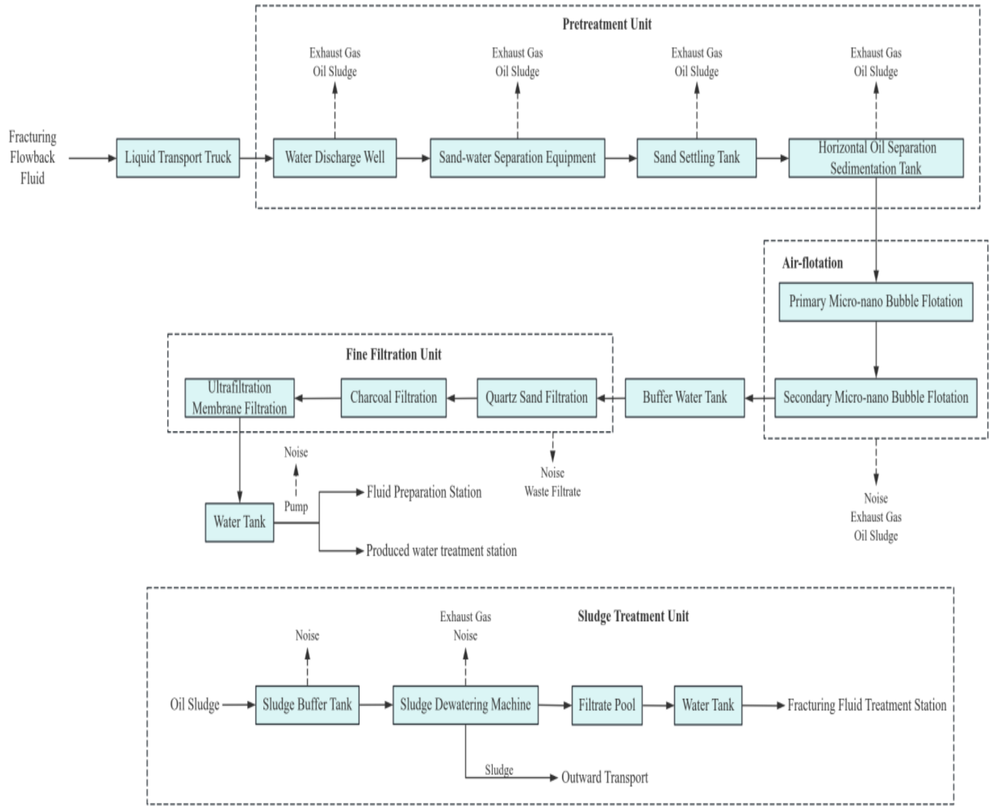

Fig.22 Process flow diagram for Y11 FFBFs treatment construction project

The tanker trucks transport FFBFs to the discharge well, where coarse particles and gravel are removed by a sand-water separator. The wastewater then enters a grit chamber for gravity settling. In the parallel-plate oil separation and sedimentation tank, floating oil and SS are removed via the laminar flow separation principle, after which the wastewater is directed to a conditioning tank for water quality homogenization. The pretreated wastewater sequentially undergoes two-stage micro-nano bubble flotation units, utilizing nanoscale bubbles to enhance the removal of oil droplets and colloids. It is further purified through a fine filtration unit (ultrafiltration membrane, activated carbon, and quartz sand filtration) to capture residual micron-sized contaminants. The treated water is stored in a buffer water tank and then transferred to Oil Production Plant's fluid preparation station or Centralized Produced Water Treatment Station for reuse.

Sludge and oily sludge are temporarily stored in a sludge buffer tank before being mechanically dewatered by a sludge dewatering machine to form low-moisture-content sludge cakes (≤75% moisture), which are transported offsite for disposal by certified units. The filtrate is recycled to a filtrate tank and returned to the fracturing fluid treatment station for reprocessing. However, the process has limitations: the absence of an oxidative gel-breaking step raises concerns about the adaptability of the process to variations in FFBFs properties. Addressing this limitation is critical to ensuring the long-term stability and environmental compliance of the treatment system.

The process flow diagram for Y12 expansion and renovation project of the centralized disposal of oil and gas development waste is illustrated in Fig. 23.

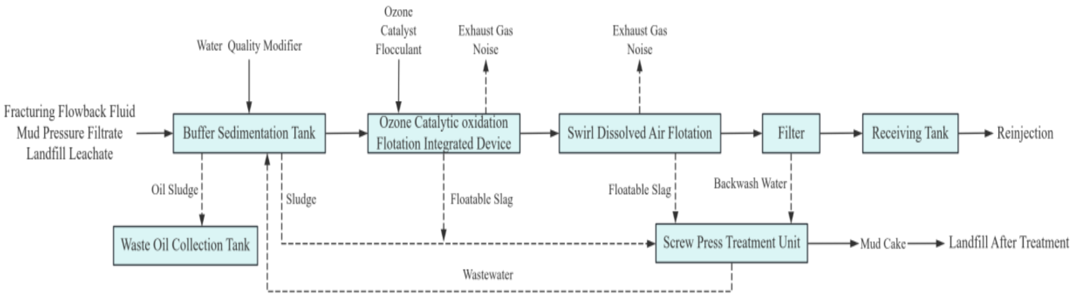

Fig.23 Process flow diagram for Y12 expansion and renovation project of the centralized disposal of oil and gas development waste

The fluid first enters a buffer sedimentation tank for preliminary solid-liquid separation, followed by the addition of flocculants (e.g., PAC, PAM) and water quality modifiers (e.g., ozone, catalysts) to enhance the aggregation of SS and colloids and the oxidative degradation of organic matter. The ozone catalytic oxidation unit decomposes refractory organic compounds (e.g., polycyclic aromatic hydrocarbons) through free radical chain reactions, while the filtration system (multi-stage filters) captures residual micron-sized contaminants. The backwash water is recycled through a washing machine treatment unit to reduce water resource consumption. The separated oily sludge is collected in an oil collection tank, while the sludge and residues are dewatered by a filter press to form low-moisture-content solid waste, which is transported offsite for sanitary landfill disposal. The landfill leachate is pretreated (e.g., through chemical oxidation or biological reactions) to reduce pollutant concentrations before being reinjected or discharged in compliance with regulations.

However, the process has limitations: the sludge is classified as general industrial solid waste without testing, making it ineligible for landfill disposal. Addressing this issue is critical to ensuring the environmental compliance and operational reliability of the treatment process.

The process flow diagram for treatment and reinjection project of Y13 FFBFs is illustrated in Fig. 24.

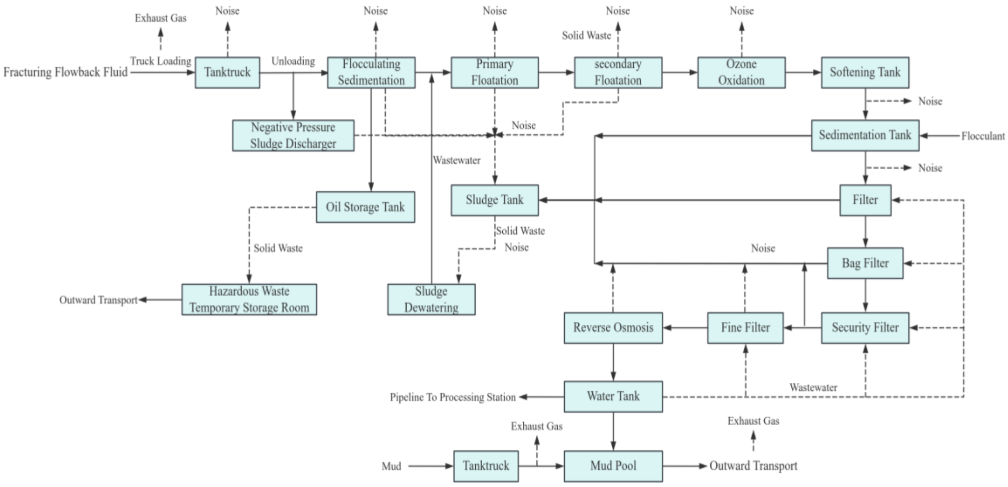

Fig.24 Process flow diagram of treatment and reinjection project of Y13 FFBFs

The raw water is transported by tanker trucks to the treatment station, where it is unloaded and directed to a coagulation-sedimentation unit, with coagulants (e.g., PAC, PAM) added to promote the aggregation and settling of SS and colloids, followed by primary and secondary dissolved air flotation (DAF) units utilizing microbubble flotation technology to remove floating oil and micron-sized pollutants in stages. The wastewater is then treated in an ozone oxidation unit to degrade refractory organic compounds before entering a softening tank, where hardness is reduced through ion exchange or chemical precipitation to prevent scaling in subsequent membrane systems, and the purified liquid phase is sequentially filtered through bag filters, precision filters, and cartridge filters to capture residual particulates, and finally desalinated via a reverse osmosis (RO) system before being stored in a purified water tank, with a portion reinjected into oil production wells or transported for reuse. For sludge treatment, the sludge generated from the sedimentation tank and DAF units is transferred to a sludge tank via a vacuum sludge extractor and then dewatered using sludge dewatering equipment (e.g., plate-and-frame filter press) to form low-moisture-content solid waste, which is temporarily stored in a hazardous waste storage room before being disposed of by certified units, while oil-based pollutants are collected in an oil storage tank, and the RO concentrate requires further treatment, such as desalination or evaporation crystallization, to avoid salt accumulation. Limitations of the process include the RO system's high energy consumption and the lack of integrated electrodialysis or evaporation crystallization technologies for concentrate treatment, posing challenges for high-salinity wastewater management, as well as the absence of advanced purification measures, such as activated carbon adsorption or biological filtration, limiting the system's ability to achieve comprehensive pollutant removal, and addressing these limitations is critical to enhancing the overall sustainability, environmental compliance, and operational efficiency of the treatment process.

The process flow diagram for treatment of solid (liquid) waste, including FFBFs, is illustrated in Fig. 25.

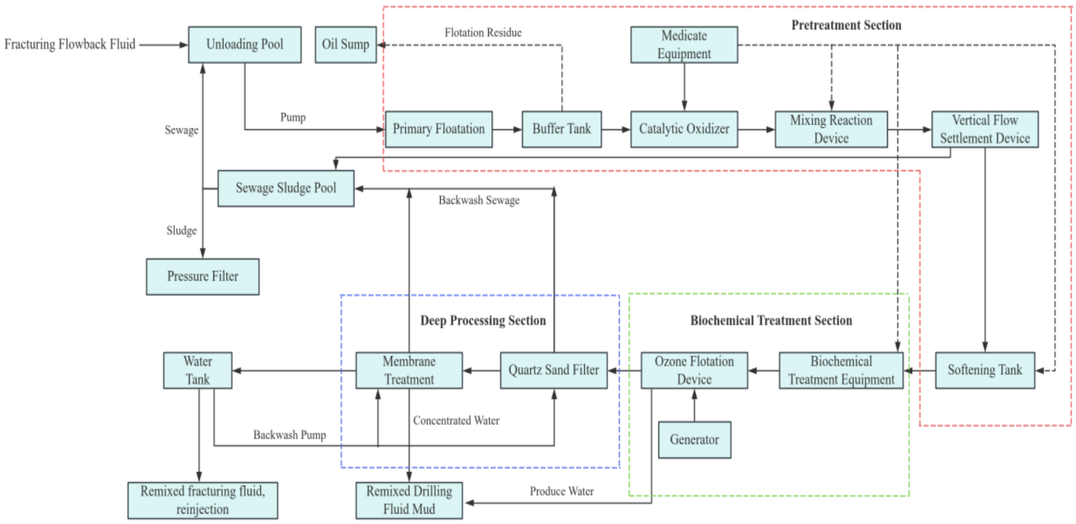

Fig.25 process flow diagram for treatment of solid (liquid) waste, including FFBFs

The liquid is initially received in a discharge tank, after which mulsion splitter, flocculants, and other chemicals are added via a dosing device, and in the primary dissolved air flotation unit, microbubble flotation technology is used to separate floating oil and SS, with the scum collected by an oil recovery device, while the pretreated wastewater enters a catalytic oxidation unit to degrade refractory organic compounds, followed by a mixing reaction unit to adjust water quality parameters and a vertical flow sedimentation tank for solid-liquid separation, with the separated sludge transferred to a sludge storage tank for temporary storage, and the biological treatment section employs activated sludge or biofilm processes to degrade biodegradable organic matter, while the advanced treatment section integrates membrane treatment systems, quartz sand filters, and ozone-dissolved air flotation units to further remove dissolved pollutants and micron-sized particles, with a softening tank reducing water hardness through ion exchange to prevent membrane scaling, and the purified water stored in a product water tank, with a portion recycled via a backwash pump for fracturing fluid preparation or reinjection into oil wells, while the remaining concentrate requires further treatment, such as evaporation crystallization, and the sludge is dewatered using a filter press to form low-moisture-content solid waste, which is disposed of by certified professional agencies, with limitations including the membrane system's high energy consumption and membrane fouling risks due to the lack of an online chemical cleaning mechanism, the concentrate treatment's undefined resource recovery pathway posing a risk of secondary pollution, and the absence of sludge resource recovery technologies and reliance on landfill disposal creating environmental risks from leachate contamination, and addressing these limitations is critical to enhancing the overall sustainability, environmental compliance, and operational efficiency of the treatment process.

4.Challenge and Development Directions of FFBFs Treatment in Ordos Basin

With the ongoing development of oil and gas resources in Ordos Basin, the widespread application of hydraulic fracturing has led to the generation of large volumes of fracturing FFBF. Due to the presence of complex harmful components in the FFBF, such as high salt concentrations, high levels of organic pollutants, and heavy metals, its treatment is challenging. Therefore, efficiently, safely, and economically treating these FFBFs have become a pressing issue in the field of oil and gas development. With technological advancements and increasing environmental protection requirements, the trends and development directions for FFBFs treatment in Ordos Basin will evolve in the following key areas:

4.1 Enhancing the comprehensiveness and efficiency of water treatment technologies

Currently, single water treatment methods often face issues such as low efficiency and high costs in the treatment of FFBFs. Therefore, the future trend in technology development will be the integration and optimization of various treatment technologies to form an efficient and comprehensive treatment process. Membrane separation technologies, such as reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF), have shown great potential in treating high salinity and organic pollutants[31]. However, membrane fouling and scaling remain major challenges. Key future directions will include the development of anti-fouling, high-salinity-resistant membrane materials and improvements in membrane cleaning and regeneration technologies[32]. At the same time, the combined application of membrane technologies with other physicochemical methods (such as chemical precipitation and adsorption) is expected to significantly enhance overall treatment efficiency. Considering the complexity of FFBF, a single process cannot meet the need for efficient treatment. Therefore, future developments may focus on multi-stage combined treatment solutions, such as the integration of physical, chemical, and biological methods[33-34]. For example, sedimentation can first be used to remove most SS and heavy metals, followed by membrane filtration to remove dissolved salts and organic compounds, and finally, biological treatment can be employed to degrade some organic pollutants, thus achieving efficient and comprehensive water quality improvement[35].

4.2 Strengthening resource reuse and regeneration utilization

As water scarcity becomes an increasingly severe issue, especially in arid regions like Ordos Basin, the recycling and reuse of FFBFs will become a key focus for future water treatment. Reusing FFBFs not only help alleviate water resource pressure but also reduce environmental pollution. In the future, treated FFBFs may be reused in the fracturing process itself or even for other purposes such as back to the fracturing fluid or preparation of drilling fluid mud[16]. To achieve this, it is necessary to further enhance the pollutant removal capacity of treatment processes, ensuring that the water quality meets reuse standards, particularly in terms of removing organic compounds, heavy metals, and microbial contaminants[36]. At the same time, with the increasing demand for reuse, there is an urgent need to establish more stringent water quality standards, especially regarding harmful components in fracturing fluids, such as chlorides, benzene derivatives, and heavy metals. This will drive technological advancements and policy implementation, promoting the reasonable reuse and resource recovery of FFBFs[37-38].

4.3 Develop environmentally friendly green treatment technologies

As environmental protection policies become increasingly stringent, traditional chemical treatment methods may lead to secondary pollution or difficulties in waste disposal[39].Therefore, green, low-pollution, and low-energy consumption environmental technologies will become an important trend for future development. Green chemical treatment methods, such as using natural adsorbents, biodegradable chemical agents, and green solvents, can effectively reduce environmental burdens[40]. In recent years, research has started exploring the use of plant extracts, natural minerals, and other green materials to adsorb and remove harmful substances from FFBFs, thereby reducing the use of chemical agents. In addition, biological treatment technologies, as an environmentally friendly water treatment method, have broad application prospects, especially in the treatment of FFBFs[41-44]. By optimizing the microbial community structure, its degradation efficiency can be improved, particularly for the degradation of difficult-to-degrade high-molecular organic compounds, driving the further development of biological degradation technologies.

4.4 Effectively remove high salinity and high-concentration pollutants

Due to the unique geological characteristics and climate conditions of Ordos Basin, FFBFs often contain high concentrations of salts, minerals, and some difficult-to-remove pollutants, such as heavy metals and radioactive substances. Effectively removing these high-salinity and high-concentration pollutants has become a key direction for the future development of treatment technologies.

In terms of saline water treatment, traditional membrane technologies often struggle to achieve complete desalination when dealing with high-salinity FFBFs, and they tend to have high energy consumption. Therefore, more efficient saline water treatment technologies may be developed in the future, such as the combination of CO_2 softening, electrodialysis, evaporation concentration, reverse osmosis, and other methods, to reduce treatment costs and improve effectiveness[31,45].

For the removal of heavy metals and other harmful substances, advanced technologies such as chemical precipitation, ion exchange, and adsorption can be employed to remove heavy metal ions from water. For specific pollutants, especially radioactive elements, more targeted materials and methods may need to be developed, such as using nano-materials with strong adsorption capabilities or functionalized carbon-based materials to achieve efficient removal.

4.5 Apply intelligent and automated technologies

With the continuous development of big data, the Internet of Things (IoT), artificial intelligence (AI), and automation technologies, the process of FFBFs treatment will become more intelligent and automated in the future[46].

Firstly, some intelligent monitoring and control systems will use sensors and monitoring devices to track the changes of FFBFs water quality in real time, such as pH, concentration, temperature, and SS content. Based on the monitoring data, these systems will automatically adjust the treatment processes, enabling automated management and optimization of the entire process. For example, AI algorithms can predict the changes in pollutants within FFBFs, thereby optimizing the water treatment plan and improving processing efficiency[47].

In addition, data analysis and decision support systems will leverage big data analytics to conduct in-depth analysis of historical water quality data and treatment outcomes, providing precise treatment recommendations and optimization solutions to help decision-makers formulate scientifically-based water treatment strategies[48]. At the same time, with the aid of machine learning and deep learning technologies, these systems will further enhance the predictive and adjustment capabilities of treatment technologies[49].

The future development direction of FFBFs treatment in Ordos Basin will focus on improving the overall efficiency of water treatment technologies, promoting the development of resource reuse and green environmental technologies, and enhancing the application of intelligent and automated management. In addition, policy support and cross-industry collaboration will play an important role in driving technological advancements and market expansion. Through technological innovation and system optimization, the future treatment of FFBFs is expected to achieve more efficient, cost-effective, and environmentally friendly solutions, thereby supporting the sustainable oil and gas extraction in Ordos Basin.

5. Conclusion

（1）The characteristics of FFBFs in Ordos Basin are complex. Its composition is influenced by multiple factors such as geological conditions and fracturing fluid formulations, exhibiting high TDS, high COD, high Total SS, high viscosity, and strong emulsification properties. For instance, the ionic composition is dominated by calcium and chloride ions, with elevated levels of organic pollutants, weakly acidic water quality, and diverse water types, making treatment extremely challenging.

（2）Existing treatment technologies are diverse but have limitations. The treatment processes in Ordos Basin often integrate physical, chemical, and biological methods. For example, treatment systems at Yanchang Petroleum and Changqing Oilfield can partially purify FFBFs, but common issues such as the lack of oxidative viscosity reduction, absence of closed-loop treatment for filtrate, unverified removal efficiency for certain pollutants, and unclear resource recovery pathways affect treatment efficacy and environmental compliance

（3）Treatment faces multiple challenges. The complex composition and high pollution levels of FFBFs make traditional methods inadequate. There is a need to develop efficient, cost-effective, and environmentally friendly technologies to meet increasingly stringent environmental standards and prevent long-term damage to water, soil, and ecosystems.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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