Original Research Article

Technical upgrading and full life cycle economic evaluation of the sulfur shaping unit at Luojiazhai gas field

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Abstract: Addressing issues such as equipment aging, liquid sulfur transportation safety hazards, and insufficient market adjustment capacity in the sulfur recovery system of Luojiazhai Gas Field, this paper conducts a comparative analysis and feasibility study of technical upgrade options for the sulfur shaping unit, using Xuanhan Natural Gas Purification Plant as a case study. By comparing steel belt granulation, drum granulation, and water granulation processes, the technical route for constructing a new 1200 t/d water granulation unit was determined. Based on life-cycle cost (LCC) theory, an economic evaluation was conducted across three dimensions: investment estimates, operational maintenance costs, and synergistic production-sales efficiency gains. Results indicate that while this solution entails higher initial investment than retrofitting existing lines, it fundamentally eliminates long-distance liquid sulfur transportation risks. Furthermore, by implementing a "store during off-peak, sell during peak" strategy, it achieves potential annual efficiency gains of several million yuan. This approach demonstrates significant technological advancement and economic viability.

Keywords: high-sulfur gas fields; sulfur shaping; water granulation process; life cycle assessment; production-sales coordination

1. Introduction

As a key byproduct of natural gas purification, sulfur serves as a vital link connecting upstream energy extraction with downstream chemical industries. Although China is the world's largest sulfur consumer, the Sichuan-Chongqing production hub has long grappled with a structural mismatch between concentrated production capacity and seasonal fluctuations in downstream demand. Against the dual backdrop of ensuring energy supply and enhancing quality and efficiency, improving the operational resilience and risk resistance of sulfur recovery systems has become an industry consensus. Taking a purification plant at a high-sulfur gas field in northeastern Sichuan as an example, the "liquid sulfur as primary, solid sulfur as secondary" model established since its commissioning in 2016 has revealed increasingly evident shortcomings during long-term operation[1]. Technologically and safety-wise, aging steel belt granulation equipment operates far below design capacity, failing to fulfill emergency backup functions. Additionally, the 2,000-meter liquid sulfur pipeline gallery is prone to leaks due to thermal stress, compounded by frequent spontaneous combustion of ferrous sulfide in storage tanks—critical hazards demanding urgent remediation. Operationally, the lack of large-scale solid sulfur storage and inventory adjustment capabilities leaves the enterprise vulnerable during periods of sharp sulfur price volatility. This hinders the implementation of "off-peak storage and peak-season sales" strategies, resulting in significant economic losses.

Existing research predominantly focuses on isolated process improvements, with few systematic evaluations integrating market strategies. This paper employs the Life Cycle Cost (LCC) theory to propose facility upgrades addressing the plant's critical challenges. By comparing the technical and economic viability of processes like water granulation and incorporating price forecasting models to analyze production-sales synergy potential, it aims to explore an optimized path balancing "intrinsic safety" and "economic efficiency." This provides theoretical reference for resolving production, transportation, storage, and sales bottlenecks in similar gas fields.

2. Current situation analysis and problem identification

2.1.Operational bottlenecks and structural mismatch between production and sales

The plant currently operates three natural gas desulfurization and sulfur recovery units with a combined designed daily sulfur production capacity of approximately 1,200 tons. Constrained by initial logistics infrastructure limitations, the plant established a production-sales model prioritizing liquid sulfur transportation (approximately 80%) over solid sulfur shaping (approximately 20%)[2]. Under prolonged high-load operation, this rigid model has become the primary bottleneck hindering stable plant-wide production.

The solid sulfur shaping system, critical for balancing production and sales, currently suffers from severe efficiency degradation. The existing facility employs outdated shaping technology. After years of service, core equipment has aged significantly, and the Key components are no longer available for purchase has led to persistently high equipment failure rates. Operational data indicates its maximum daily capacity barely reaches 300 tons (less than 20% of the plant's total output). Under normal conditions, this capacity can manage minor liquid sulfur overflows; However, during downstream phosphorus chemical off-seasons or when logistics disruptions cause liquid sulfur stagnation, the desulfurization unit's critical "full production, full sales" safety net function completely fails. The resulting massive daily capacity gap of approximately 960 tons rapidly overflows the liquid sulfur tank farm, forcing upstream natural gas units to reduce output or even shut down, severely threatening the continuous and stable extraction of the gas field.

The buffer capacity of existing storage facilities is equally strained. The design storage capacity of liquid sulfur tanks and solidification warehouses is relatively limited, with dynamic inventory under full production sustaining only about 12 days. This extremely low inventory redundancy renders the production system highly sensitive to market fluctuations, lacking the strategic buffer period to "buy time with space." It struggles to adapt to the new normal of volatile sulfur market prices and regional logistics uncertainties.

2.2.Safety and environmental hazards in critical facilities

Analysis of operational data and failure mode studies over the past three years reveals two systemic safety risks within the existing sulfur storage and transportation system. These risks exhibit both frequent occurrence and concealed characteristics, constituting major accident hazards. The risk of spontaneous combustion of ferrous sulfide in liquid sulfur storage tanks has manifested multiple times. In July and October 2024[3], the liquid sulfur C tank at the plant triggered consecutive SO_2 concentration upper limit alarms at the tank top, activating interlocked fire suppression steam. Thorough investigation and sampling analysis confirmed that ferrous sulfide, formed on tank walls and coil surfaces due to long-term acid gas corrosion, underwent violent exothermic oxidation reactions when exposed to air during liquid level fluctuations, leading to spontaneous combustion. As existing storage tanks lack advanced nitrogen blanketing or suppression systems, such spontaneous combustion is unpredictable, posing significant risks of fire incidents and sulfur-containing gas releases that threaten the environment.

Liquid sulfur produced at the purification plant is transported via a 2,000-meter-long pipeline corridor to the sulfur plant. This pipeline traverses the plant area and surrounding sensitive zones. Due to the extended distance, liquid sulfur is highly susceptible to sudden viscosity changes caused by temperature drop along the pipeline. Particularly during plant startup/shutdown or periods of drastic temperature fluctuations, the pipeline faces not only the risk of physical blockage from sulfur phase transition (solid-liquid conversion), but also concentrated thermal stress from temperature differentials between inner and outer pipe walls. This can lead to rupture of the heating lines or seal failure at flange connections. Such "unplanned leaks," once occurring, are not only extremely difficult to contain but also directly violate critical safety and environmental regulations. Existing sulfur recovery systems fail to meet the demands of high-quality development in high-sulfur gas fields, both in terms of production capacity flexibility and the inherent safety of facility operations. Technological upgrades and system modifications are urgently needed .

3. Technical upgrade proposal evaluation

3.1. Comparison of renovation strategies

Existing Line Renovation Plan (Plan One): Focuses on "patchwork" in-situ technical upgrades to existing facilities. Specific measures include internal anti-corrosion repairs and nitrogen sealing modifications for liquid sulfur storage tanks at risk of spontaneous combustion, replacement of frequently malfunctioning drum granulators, and substitution of severely corroded pipe sections. Estimated investment: approximately 52.1775 million yuan. While initial costs are relatively low, limitations are significant: it only alleviates localized issues caused by equipment aging without physically disconnecting the 2,000-meter liquid sulfur pipeline gallery, leaving major thermal leakage risks unaddressed. Furthermore, constrained by limited space within the existing plant area, the enhanced solid sulfur production capacity after modification would be limited, failing to fundamentally reverse the passive situation of "strong liquid, weak solid" sulfur processing.

New Construction Solution (Option 2): This proposal advocates for constructing a complete sulfur shaping and storage facility on a reserved plot within the purification plant. This option carries a total investment estimate of approximately 98.3016 million yuan. While the one-time capital expenditure is nearly double that of Option One, the resulting safety benefits and strategic value are immeasurable. From an intrinsic safety perspective, the new facility's proximity to upstream purification units eliminates the 2,000-meter cross-site pipeline corridor, physically eradicating the risk of leaks along its route. From an operational efficiency standpoint, the new facility adopts an entirely new design concept, doubling production capacity and completely eliminating production bottlenecks.

Following a comprehensive lifecycle assessment, although Option 2 entails higher initial investment, its ability to fundamentally address major safety hazards and ensure long-term operational reliability aligns with the petroleum and natural gas industry's management orientation toward "intrinsic safety." Therefore, it is designated as the recommended implementation plan[4].

3.2. Process technology selection and parameter configuration

Following the selection of the new construction plan, the choice of shaping process became critical to determining the unit's operational efficiency and environmental performance. The mainstream sulfur shaping technologies currently used in the industry primarily include steel belt condensation granulation, drum granulation, and wet granulation. This study conducted a comparative analysis across four dimensions: single-unit production capacity, environmental impact, operation and maintenance costs, and product quality.

Table 1. Four-dimensional analysis.

Comparison Items	Steel Belt Granulation (Existing Process)	Tumbler Granulation	Water Granulation (Recommended Process)
Working Principle	Molten sulfur solidifies on the cooling steel strip.	Sulfur liquid is sprayed onto the material curtain on the rotating drum for cooling.	The sulfur solution is rapidly cooled by falling through the nozzle into water.
Single-unit production capacity	Small(<10t/h), difficult to scale up	Medium(15-20t/h)	Large(50t/h), suitable for large-scale production
Environmental Performance	Better,with less dust	Poor, high exhaust dust content, requires dust removal	Advantage: Wet process with no dust escape
Operation and Maintenance	Steel belts are wear parts that are costly and require frequent replacement.	Nozzles are prone to clogging, requiring significant cleaning effort.	Simple structure, few moving parts, low failure rate
Product Form	Regular hemispherical shape, aesthetically pleasing appearance	Irregular particles	Regular spherical shape, with slightly higher moisture content

The steel belt pelletizing technology employed in existing installations produces aesthetically pleasing products. However, as the core component, the steel belt is highly susceptible to mechanical stress and prone to breakage. This results in high maintenance costs and limited single-unit production capacity, rendering it unsuitable as a primary backup facility. While drum granulation is a mature technology, its open cooling process generates substantial sulfur dust emissions. Under increasingly stringent environmental regulations, complex dust collection systems are required, which also heightens the risk of dust explosions caused by static electricity. In contrast, the water granulation process utilizes water's buoyancy and cooling effect to rapidly solidify molten sulfur directly in water. This process offers significant advantages, including high single-unit processing capacity (up to 50 t/h or more). More importantly, its "wet operation" effectively suppresses dust generation, addressing environmental compliance and explosion prevention challenges at the source. Although the product's moisture content is slightly higher than that of dry processes, subsequent treatment through vibrating dewatering screens and air-drying systems fully meets the standards for industrial-grade sulfur first-class products (GB/T 2449.1). After comprehensive evaluation of environmental compliance and emergency requirements for large-scale production, the project ultimately selected the domestically developed water granulation process. The design includes two 50 t/h water granulation units, complemented by two newly constructed 3,000 m^3 liquid sulfur storage tanks and a 3,000 m^2 bulk storage warehouse. The facility is designed for 330 days of annual operation, achieving a maximum emergency production capacity of 1,200 tons per day. This enables 100% coverage during extreme conditions where upstream plants operate at full capacity and liquid sulfur faces oversupply. Under normal conditions, it operates at 600 tons per day, maintaining ample operational flexibility while ensuring economic equipment utilization[5].

4. Full life cycle economic evaluation

4.1. Investment estimate and capital structure

Based on the "Cost Standards for Petroleum Construction Projects" and relevant quota specifications, this project, classified as a technical renovation initiative, has a total investment estimate of 98.3016 million yuan. The capital composition primarily encompasses three core segments: Engineering costs amount to 73.9404 million yuan, accounting for approximately 75% of the total investment. This includes the procurement and installation costs for two 50t/h water pelletizing units, new storage tanks, and supporting utility systems; Other construction expenses amount to CNY 16.7406 million, primarily allocated to soft expenditures such as survey and design, environmental assessment, and digital delivery; The remaining CNY 7.6206 million serves as basic contingency reserves and construction period interest, addressing potential risks during construction such as design modifications or fluctuations in major material prices. Although the initial capital investment exceeds conventional maintenance projects, the high-standard equipment selection lays a material foundation for reducing subsequent operation and maintenance costs.

4.2. Operational benefits and production-sales synergy model

Unlike traditional oil and gas surface engineering projects focused solely on direct output value, this project's core economic value lies in capturing premium opportunities amid market fluctuations by enhancing the resilience of production-sales systems. Using long-term sulfur market data from 2016 to 2023, a multiple linear regression model for sulfur prices was constructed:

$$Y = -41.596 + 0.486X_1 - 0.105X_2 - 0.457X_3 - 0.039X_4 - 0.386X_5 - 0.025X_6$$

In the equation, Y represents the average market price of sulfur, X1 denotes the import CIF price, X2 indicates the inventory levels at major ports, X3 reflects the international crude oil price, X4 represents the sulfuric acid price, while X5 and X6 denote the prices of monoammonium phosphate and diammonium phosphate, respectively. This model reveals that sulfur prices exhibit pronounced cyclical fluctuations driven by dual factors: international energy prices (X3) and seasonal downstream fertilizer demand (X5, X6). Leveraging this pricing pattern, the project implements a "counter-cyclical adjustment" production-sales strategy based on its newly constructed 3,000m² bulk warehouse (with approximately 20,000 tons of dynamic storage capacity). During market troughs when prices fall below model forecasts (typically the third-quarter off-season), it increases sulfur inventory. Utilizing a roughly 4-month time lag, production capacity is concentrated for release when prices rebound during the spring fertilizer stockpiling peak season. Calculations indicate that under the average price differential observed over the past three years, a single inventory cycle (20,000 tons) can generate marginal efficiency gains ranging from 220,000 to 4.5 million yuan. In years of extreme market volatility, this "time-for-space" combination of futures and spot market operations can yield premium returns sufficient to cover the facility's annual electricity consumption and labor costs.

4.3. Risk mitigation benefits

Beyond explicit financial gains, the risk-hedging value (Shadow Price) delivered by the new facility constitutes the core weighting factor for project viability. Upon commissioning, the purification plant's sulfur fixation capacity share will surge from the current 20% to a normalized 50%, while maintaining 100% emergency backup capacity for full production and sales under extreme conditions. This "all-weather" production flexibility eliminates the enterprise's rigid dependence on liquid sulfur logistics and single-market structures.

During downstream phosphate chemical maintenance cycles or regional logistics disruptions (e.g., snowstorms, road restrictions) causing severe liquid sulfur oversupply, the facility can seamlessly switch to full-load sulfur fixation mode, ensuring stable, secure, long-term, full-capacity, and optimal operation of upstream gas fields. Without this safety net, forced gas field shutdowns due to sulfur stockpile overflows would result in daily direct output losses exceeding tens of millions of yuan based on a 9 million cubic meter natural gas production rate. Moreover, the high energy consumption, equipment corrosion risks, and safety hazards associated with restarting high-sulfur gas fields are incalculable. Therefore, the implementation of this project is equivalent to providing an indispensable "production interruption insurance" for gas field assets worth tens of billions of yuan.

Its implicit strategic benefits in safeguarding national energy security and maintaining continuous enterprise production far exceed the project's own book investment returns.

5. Conclusion

Taking a high-sulfur gas field in northeastern Sichuan as an engineering case study, this paper demonstrates the necessity of transitioning sulfur shaping units from "passive maintenance" to "proactive upgrades." Research indicates that although the new 1,200 t/d water granulation facility entails higher initial investment (approximately 98.3 million yuan), its strategic value is significant: Technologically, it achieves a qualitative leap in intrinsic safety by physically disconnecting long-distance pipeline corridors and eliminating the risk of spontaneous combustion in storage tanks; Economically, based on life-cycle assessment and price regression models, the new facility not only provides emergency backup capacity for "full production and full sales" but also captures millions of yuan in annual market premiums through production-sales coordination strategies like "off-peak storage and peak-season sales." This solution effectively resolves the structural imbalance of "strong liquids, weak solids" in gas fields, functioning as "production interruption insurance" for a hundred-billion-cubic-meter-scale production capacity. It provides a replicable model for enhancing the quality and efficiency of industrial chains in China's high-sulfur gas fields.

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