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Simulation and Analysis of Pressure Drop under Multiple Operating Conditions at a Natural Gas Gathering Station

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Abstract: Pressure loss in the pipeline network of a natural gas gathering and processing station directly impacts the energy consumption and operational safety of the gathering and transportation system. Traditional manual formulas for calculation are plagued by drawbacks such as low efficiency, a simplistic representation of operating conditions, and insufficient accuracy. This paper employs numerical simulation to develop a lightweight simulation model for the station's pipeline network. By setting up single-variable comparative scenarios for gas throughput, pipe diameter, and operating temperature, the study conducts pressure loss simulations under multiple operating conditions to quantify the effects of each parameter on both frictional (longitudinal) and local pressure losses. Based on the simulation results, process optimization strategies are proposed, focusing on pipe diameter matching, gas throughput regulation, and the layout of pipe fittings, and are subsequently validated through simulation. This research provides data-driven support for the design, retrofitting, and operational optimization of new, renovated, and expanded gathering and processing stations, thereby facilitating the energy-efficient and low-carbon operation of oil and gas field gathering and transportation systems.

Keywords: Gas Gathering Station; Pressure Drop; Numerical Simulation; Multi-Scenario; Pipeline Network Optimization

1. Introduction

As the oil and gas industry transitions towards greater efficiency, low-carbon operations, and smart technologies, the issue of pressure loss in natural gas gathering stations—the core hubs of surface gathering and transportation systems—is garnering increasing attention. Excessive pressure loss not only increases the energy consumption of compressors and reduces the efficiency of the gathering and transportation system, but also jeopardizes the stability of on-site production. Traditional manual calculation methods struggle to cope with the complex operating conditions involving the coupling of multiple parameters, and numerical simulation technology has progressively emerged as a vital tool for process analysis at these stations. To clarify the characteristics of pressure loss variation under different operating

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conditions, this paper develops a simplified pipeline network simulation model, conducts simulations under multiple scenarios, analyzes the influence of key parameters, and proposes feasible process optimization measures. This work provides a practical reference for the digital analysis and the optimization of operations and maintenance (O&M) for gas gathering stations.

2. Development of a Simulation Model for Pressure Loss in a Gas Gathering and Processing Facility

2.1 Station Process Flow and Pressure Loss Mechanism

A natural gas gathering and metering station (GM station) primarily comprises units such as an inlet, separators, a manifold, valves, elbows, and an export pipeline. Gas from the wellhead enters the station via the inlet, where it first passes through separators to remove liquid droplets and solid impurities. It then flows into the manifold for gas aggregation and distribution, subsequently passing through fittings like valves and elbows before entering the export pipeline for delivery to a downstream processing plant or end-user. The pressure loss within the station's piping network is categorized into two types: frictional pressure loss and local pressure loss. Frictional loss, which results from the friction between the gas and the pipe wall during flow, is dependent on the length of the pipe section, pipe diameter, gas velocity, and the frictional resistance coefficient. Local loss occurs at fittings such as elbows, valves, and the manifold, where abrupt changes in the gas flow direction and velocity cause energy dissipation; this loss is related to the local resistance coefficient and the gas velocity. The total pressure loss of the station is the sum of the frictional and local losses, and factors such as gas throughput, pipe diameter, operating temperature, and the layout of fittings all have a significant impact on this total loss. Specifically, the export pipeline, being the longest, accounts for the largest share of the frictional loss. Local losses at the manifold and elbows also constitute a significant proportion, and an improper layout of these fittings can exacerbate the station's energy loss [1].

2.2 Building a Lightweight Simulation Model

To strike a balance between computational accuracy and operational efficiency, this paper adopts a lightweight modeling approach. This is achieved by retaining the core process units of the station and pipeline, while simplifying the non-essential redundant piping network, to construct a simplified simulation model of the gas gathering station's pipeline network. The core parameters required for the modeling include: natural gas composition, base gas throughput, pipe diameter, operating temperature, and the number and type of pipe fittings. The natural gas composition is input based on on-site gas quality analysis data; the base gas throughput is selected according to the station's design capacity; the pipe diameter is set according to the actual pipeline specifications; the operating temperature is determined based on the on-site operating temperature range; and the number and type of pipe fittings are configured according to the station's actual process flow. After completing the parameter input for each unit, pipeline connections, and process debugging, a single-case simulation is conducted to verify the model's operational stability and computational accuracy. The simulation results are then compared with on-site measured data or manual calculations to calibrate the model parameters, ensuring the simulation results conform to actual engineering principles. This methodology resolves the issues of cumbersome model operation, difficult parameter calibration, and the unsuitability for batch calculations across multiple operating conditions, thereby yielding a standardized simulation model suitable for comparative analysis. This, in turn, lays the foundation for subsequent pressure loss simulations under various operating conditions.

3. Simulation Condition Design and Computational Analysis

3.1 Simulation Condition Setup

To isolate the effects of various factors on pressure loss, a single-variable-at-a-time (SVAT) approach was employed, establishing three sets of comparative simulation scenarios. The simulations were run by systematically varying the gas flow rate, pipe diameter, and operating temperature, while all other parameters were held constant. Data on the total pressure loss at the station and the pressure drop across each pipe segment were collected. The scenarios were defined as follows: Scenario 1: The gas flow rate was varied while the pipe diameter and operating temperature were held constant to analyze the impact of gas flow rate on pressure loss. Scenario 2: Pipes of different

specifications (diameters) were used while the gas flow rate and operating temperature were held constant to investigate the influence of pipe diameter. Scenario 3: The operating temperature was adjusted while the gas flow rate and pipe diameter were held constant to explore the effect of the temperature parameter on the pressure loss within the pipeline network.

3.2 Analysis of Simulation Results and Influencing Patterns

The simulation-exported data is collated, validated, and visualized to generate comparative charts and graphs, quantifying the correlation between various parameters and pressure loss. The simulation results indicate that as the gas throughput increases, the gas velocity rises, and both the frictional (longitudinal) and local (minor) losses within the station increase in tandem, leading to a significant rise in the total pressure loss. Increasing the pipe diameter can reduce the in-pipe gas velocity, thereby markedly suppressing the pressure loss. Furthermore, a change in operating temperature alters the physical properties of the natural gas, which in turn also affects the station's overall pressure loss. The local pressure loss from fittings, such as elbows and valves, constitutes a non-negligible portion of the total loss; an improper arrangement of these fittings will further exacerbate the station's energy loss [2]. A coupling effect exists among these multiple factors, where a change in a single parameter can trigger a cascade of changes in the overall flow regime of the pipeline network. It is difficult to accurately quantify this coupling effect using traditional manual calculations; simulation technology, however, can intuitively visualize the pressure distribution across each pipe segment under various operating conditions.

4. Process Optimization Plan and Simulation Verification for the Gas Gathering Station and Pipeline Network

Drawing upon the patterns of pressure loss variation derived from multi-scenario simulations, and integrating engineering constraints—including station investment, dispatching requirements, and the current state of equipment—this study explores four key areas: the optimization of pipe diameter matching, the operational regulation of gas throughput, the simplification of the piping layout, and the simulation-based validation of the proposed optimization scheme. The objective is to formulate a composite optimization plan tailored to on-site operational realities, the efficacy of which is subsequently verified through simulation.

4.1 Pipe Diameter Matching Optimization

Pipe diameter is the most critical hardware factor influencing the frictional pressure drop within a pipeline network. An undersized diameter leads to excessively high natural gas flow velocities, which directly amplifies the frictional losses along the pipeline. During the construction or renovation and expansion phases of a station, for main trunk pipeline sections with high throughput, it is advisable—subject to equipment investment and site constraints—to select a larger-diameter pipe specification. This reduces the internal gas flow velocity, thereby fundamentally mitigating the frictional pressure drop and avoiding the adverse operating conditions associated with small-diameter, high-flow-rate pipelines. For operational stations where a complete pipeline replacement is not feasible, priority can be given to upgrading the diameter of critical trunk pipeline sections that account for a significant portion of the pressure loss. Prior to the upgrade, a techno-economic comparison is essential. This process involves using simulation models to calculate the pressure drop for various pipe diameters, balancing the construction costs against the energy-saving benefits, and ultimately selecting the pipe diameter parameters that offer the optimal cost-effectiveness. This approach prevents wasteful investment in oversized pipes and strikes a balance between pressure drop control and project investment.

4.2 Rational Regulation of Gas Transmission Volume

The gas throughput directly determines the gas velocity within the pipeline and is a key parameter that can be flexibly adjusted during the station's daily operations. The pressure drop-versus-throughput curve, generated from simulation outputs, reveals a distinct upward trend in pressure drop as the throughput increases. In on-site operational dispatch, it is crucial to avoid prolonged periods of the pipeline network operating at excessively high throughputs. By balancing the incoming gas supply from upstream with the downstream demand, the station's throughput load should be judiciously managed within the dispatchable limits to maintain the pipeline network's pressure drop within its design-

specified range. When fluctuations in the upstream gas source cause a sudden surge in flow, simulations should be used in advance to predict the resulting increase in pressure drop, enabling proactive risk control for the operation. For multi-inlet gathering stations, it is essential to rationally distribute the gas flow across each branch line and balance the load on each pipeline segment. This prevents a single branch line from being overloaded, which could cause a sharp, localized increase in pressure drop, and allows for the mitigation of the pipeline network's energy and pressure losses through operational adjustments [3].

4.3 Simplified Pipe Fitting Layout

Fittings such as elbows, valves, and tees are the primary sources of local pressure loss. An improper piping layout can lead to a significant increase in the proportion of this local energy loss. For the existing pipeline network at a gas gathering station, a comprehensive review of the piping routes should be conducted to tally the number of components like elbows, globe valves, and redundant branch lines. Unnecessary fittings should then be removed, provided that the requirements for process safety and maintenance operations are met. To reduce local pressure loss, the overall piping layout should be simplified by minimizing sharp bends, replacing small-radius elbows with large-radius ones, and shortening convoluted or circuitous pipe sections. It is crucial that local losses are factored in from the very beginning of the station's process design stage to minimize the installation of unnecessary fittings at the source. It is important to note that this simplification of fittings must not compromise the requirements for operations and maintenance. Valves, for instance, must retain their essential function for providing isolation during maintenance. Before and after any modifications, simulation tools should be used to compare pressure variations in local pipe sections, ensuring that the reduction in local losses is achieved without jeopardizing process safety.

4.4 Simulation and Verification of the Optimized Solution

To validate the practical improvements of the aforementioned combined optimization scheme, the parameters following the adjustments to pipe diameter, gas throughput control, and the optimization of the piping layout were input into the previously calibrated lightweight simulation model of the gathering station for comparative validation calculations. While maintaining consistency with the original simulation conditions, boundary conditions such as natural gas composition and operating temperature were kept identical. Key data, including the station's total pressure loss and the pressure drops across each main pipeline section, were collected for a comparative analysis. The simulation results indicate that the comprehensive implementation of these optimization measures led to a significant decrease in the station's total pressure loss and effectively suppressed the flow energy loss within the pipeline network. This, in turn, reduces the energy consumption of subsequent compressors for pressurization, thereby achieving the energy-saving objective for the gathering and transportation system. This confirms that the proposed process optimization scheme is technically feasible and can provide data-driven, simulation-level support for the renovation, expansion, and operational adjustments of the gathering station [4].

5. Limitations and Recommendations for Simulation Studies

5.1 Limitations of the Current Simulation Model

To enable efficient, high-fidelity simulation under multiple operating conditions, this study adopts a lightweight modeling approach, appropriately simplifying certain secondary auxiliary pipelines and auxiliary equipment within the gas gathering station. While the simplified model is adequate for analyzing the pressure loss behavior of the main process piping network, it still exhibits some discrepancies when compared to the complete and complex on-site system. Some of the model's parameters were derived from literature and design documentation and have not been sufficiently calibrated with real-time on-site monitoring data, which results in minor discrepancies between the simulation results and the actual on-site operational data. Furthermore, the current simulation is primarily focused on single-variable analysis and does not provide sufficient coverage for the complex, dynamic, and multi-factor coupled operating conditions found on-site. This makes it difficult to fully replicate complex real-world scenarios, such as fluctuations in the gas source and changes in equipment status,

thereby constraining the model's engineering fidelity to a certain extent.

5.2 Model Optimization and Future Research Directions

To address the limitations of the lightweight model, future research could integrate real-time field monitoring data—such as pressure, flow rate, and temperature from the gas gathering and processing station—to further calibrate and refine the model's key parameters. This would reduce the discrepancy between simulation outputs and actual field conditions, thereby enhancing the model's adaptability to real-world operating scenarios. In terms of research scope, it is essential to move beyond the limitations of single-variable simulations and conduct coupled, multi-factor analyses that account for variables such as gas throughput, pipe diameter, and temperature. Furthermore, the research scope should be expanded to develop an integrated simulation of the entire gathering and transportation network—unifying the external transmission pipeline with the station's internal network into a single computational framework. This would enable a holistic, system-wide analysis of pressure loss distribution, more accurately reflecting the actual operating characteristics of the oil and gas field's gathering and transportation system and further unlocking the potential for energy conservation and optimization within the station system [5].

5.3 Developing a Standardized Simulation Operating Procedure

To promote the broader and more effective application of simulation technology in the engineering of oil and gas storage and transportation, it is recommended to establish a standardized simulation workflow. A complete paradigm should encompass the entire workflow, from the collection of station and field data, model building, and parameter calibration, to the configuration of various operational scenarios, simulation runs, data export and processing, and final result analysis. This paradigm must clearly define the key operational points, principles for parameter selection, and verification standards for each stage. A standardized workflow will lower the barrier to entry for using simulation software, reduce the subjective errors inherent in manual modeling, and enable researchers and on-site engineering personnel to rapidly conduct similar pressure loss simulations. Ultimately, this will provide a replicable and transferable technical reference for simulation studies on similar gathering stations and facilities within the oil and gas industry.

5.4 Recommendations for the On-site Application of Simulation Technology in Engineering

During the engineering design and the renovation and expansion of station facilities, the predictive capabilities of numerical simulation should be fully leveraged. By proactively running simulations for a variety of anticipated operating conditions, it is possible to identify pipe sections within the network prone to excessive pressure loss. This allows for the optimization of the network's process design at the source, thereby preventing issues of high energy consumption during subsequent operations. For existing, in-service gas gathering and processing stations, operations and maintenance (O&M) teams can utilize simulation as a supplementary tool. By integrating it with actual on-site operating conditions, they can model variations in pressure loss under different parameters. This, in turn, guides the appropriate adjustment of parameters such as gas throughput and operating temperature. Relying on simulation to support process-related decisions helps to reduce pressure loss at the station, lower the energy consumption of compression equipment, and contribute to the safe, energy-efficient, and low-carbon operation of the natural gas gathering and transportation system.

6. Conclusion

This paper leverages numerical simulation technology to develop a lightweight pipeline network model for a gas gathering station. By establishing multiple comparative scenarios with a single-variable approach, the study analyzes the effects of gas throughput, pipe diameter, and operating temperature on the station's pressure drop. Based on these findings, an optimized pipeline network design is proposed and subsequently validated through simulation. The results indicate that appropriately matching pipe diameters, regulating gas throughput, and simplifying the pipefitting layout can effectively reduce the station's pressure drop. Simulation technology addresses the limitations of traditional manual calculations, providing robust data-driven support for the design, retrofitting, and operational control of gas gathering stations. Moving forward, the model can be continuously refined

by incorporating field measurement data, thereby promoting the broader application of simulation technology in oil and gas field surface engineering and contributing to the green and low-carbon development of the gathering and transportation system.

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