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Transient Operation Optimization Technology of Gas Transmission Pipeline: A Case Study of West-East Gas Transmission Pipeline

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ABSTRACT As the operation process of natural gas pipeline are affected by gas sources and the fluctuation of consumers' gas consumption, and the operation state changes with time, the transient optimization technology is more accurate and reliable for analysis. Based on the previous researches, this paper established a transient optimization model of natural gas pipeline for the purpose of minimum energy consumption. The model designer considered the switching condition of the compressor and the terminal condition of pipeline, introduced the measures of ''pressure-regulating'' and ''flow-restricted'', and proposed a heuristic algorithm. The case analysis of West-East Gas Pipeline I showed that the optimization calculation can be completed within 15 minutes by an ordinary computer within a 24-hour optimization period. Moreover, the feasibility of the model and the calculation method is verified by the comparison between the result of transient operation optimization and that of steady operation optimization.

INDEX TERMS Natural gas pipeline, transient optimization, west-east gas pipeline, heuristic algorithm.

I. INTRODUCTION

In 2018, China's natural gas consumption reached 277 billion cubic meters per year, and the length of natural gas pipelines exceeded 80,000 kilometers. During the ''Thirteenth Five-Year Plan'' period, China will build 40,000 kilometers of natural gas pipelines. The total mileage will reach 104,000 kilometers in 2020, and the gas deliverability will exceed 400 billion cubic meters per year [1]. According to statistics from the Beijing Oil and Gas Control Center, the ratio of energy costs to the cash cost of the pipeline company has reached 45%, and energy conservation and consumption reduction are imminent.

Steady-state optimization technology assumes that the decision variables such as temperature, pressure, flow, and sub-transmission of natural gas pipelines do not change with time, and the minimum energy consumption or maximum economic benefit of pipeline operation under steady state is the goal, and the steady-state optimization model of pipeline network is established [2], [3]. Throughoptimization calculation, the optimal operation plan of the compressor in the pipeline system is determined, and the energy consumption of the natural gas pipeline is reduced. At present, the steady state optimization model has been widely used [4]–[8].

Unlike steady-state operation, the operating state of the natural gas pipeline network is actually constantly changing. This makes the optimized operation scheme based on the steady-state optimization model often have a certain deviation from the actual operating parameters of the pipe network. In particular, the large pipe network is not only complex in its own structure, but also has complicated boundary conditions for its input and output. For example, the amount of civil gas used is characterized by significant fluctuations over time, while the amount of gas used by industrial users is subject to greater uncertainty. In addition, once the pipe network fails, measures will be taken to reduce the impact of the accident and bring the pipe network to the next stable operating state as soon as possible. These conditions are characterized by distinct dynamic changes. Therefore, in the operation and management process of natural gas transmission pipeline system, the simulation and analysis using transient optimization technology is more accurate and reliable.

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At present, the steady optimization model is widely used. The problem to be solved by transient optimization technology is to optimize the flowing of the pipe network to minimize the consumption of fuel gas and the cost of switching the compressor on the premise of meeting customer needs. The operation optimization model of transient gas pipeline network can be displayed as follows:

$$\begin{aligned} \min \quad & c^T x + h^T y \\ & Ax + Gy \leq b \\ & x \in Z^n, \quad y \in R^p \end{aligned} \tag{1}$$

where $c \in R^n$, $h \in R^p$ and $b \in R^m$ are vectors, and $A \in R^{m\times n}$ and $G \in R^{m\times p}$ are matrices. Since the model contains integer variable x and continuous variable y, it is called "mixed" integer programming [9], [8].

A. OBJECTIVE FUNCTION

Generally, the objective function is formulated based on the minimum total operating cost within a specified period of time. In most models, the total operating cost only includes the cost of fuel consumption or energy consumption of the compressor [10]–[17]. Only Mantri et al. considered the switching cost of the compressor in determining the objective function [10], which is more in line with the field practice.

B. CONSTRAINTS

The constraints of transient operation optimization vary according to different transportation requirements. Mantri et al. set the constraints from two aspects, the compressor station and the single compressor set: in terms of the compressor station, the range of input and output pressure and the maximum outlet temperature are taken into account; in terms of the compressor set, the ranges of horsepower, rotating speed and compression ratio of the compressor are considered. It is also guaranteed that no surge and stagnation will occur to any of the centrifugal compressor. Wong and Larson [11] considered the inlet pressure of compressor station, the hourly fluctuation of terminal distributed flow and the required terminal gas supply pressure. Rachford and Carter [12] for the first time proposed to take the target state of gas pipeline transient process as the constraint. Ehrhardt and Steinbach [13], [14] considered the constraint of flow and pressure in the connections of pipes, compressors and valves, and at the same time took into account the terminal constraints at the end of the optimization period to avoid the pipeline pressure to be so low to cause unnecessary fuel consumption. Kelling *et al.* [15] took a pipe section as a mesh size and, for each mesh size, pressure drop equation is substituted for momentum equation.

C. OPTIMIZATION VARIABLES

In most cases, the optimization variables are the flow of the compressor station in different time steps [11], [17], or the outlet pressure of the compressor station that changes with time [12]. Some scholars took the inlet flow of pipeline and the passing flow through compressor station in the optimization period as optimization variables [15], or took the time-dependent compressor power, the switching state of the compressor and the valve as optimization variables [18]. Based on these studies, as for the transient optimization of gas transmission pipeline, it could be found that it is more in line with engineering practice to consider the optimization variables with time variations, including switching scheme, overflow, inlet and outlet pressure and etc.

D. CALCULATION METHODS

The transient operation optimization model of natural gas pipeline network is a complex mixed integer nonlinear programming model which includes time dimension and features nonlinearity, modularity and randomness, etc. The model with a large number of variables and a huge scale is difficult to solve and requires more efficient algorithm. Generally, there are mainly three methods to solve mixed integer nonlinear programming. 1) nonlinear continuous optimization algorithm, such as sequential quadratic programming [19], [20] and interior-point algorithm [21]. Kelling and Sekirnjak et al. used sequential linear programming to deal with the optimization of transient gas pipeline network [15], [22]. 2) Spatial branching algorithm. Solver can be used to get the overall optimum in this algorithm. For example, BARON could be solved by adopting the branch reduction method [23], and FilMINT [24], Bonmin [24] and LaGO [25] can be used as heuristic solvers. Among them, FilMINT and LaGO could be solved with the help of branch-and-cut algorithm based on the combination of linear and nonlinear programming, while Bonmin could be calculated with the combination of nonlinear programming, branch and bound method and outer approximation method. 3) Mixed integer linear programming method; Moler [16] used SOS condition and piecewise linear function to approximately treat nonlinear constraints based on branch-and-cut algorithm.. Mahlke, Moritz, Domschke et al. in Martin's team [18], [26]–[29] used SOS method for linear approximation, proposed for the first time to use simulated annealing algorithm to solve the transient operation optimization, and used CPLEX as the solver of branch-and-cut algorithm. Behrooz and Boozarjomehry [30], taking the uncertainty of consumers' demands into consideration, introduced the prediction of gas consumption into the optimization model, and adopted the stochastic programming to solve the model, thus obtaining a quite good result.

To sum up, domestic and foreign scholars have summarized a large number of valuable theoretical achievements in the systematic analysis of transient operation optimization model and the solving algorithm. However, the influencing factors involved in the transient operation process of pipeline gas transportation are extremely complex. The number of variables involved in the model is large, the constraints are complex, and the solution of the model is difficult.

This paper, based on the study on West-East Gas Pipeline I, also involves the gas resource, the function of gas inflow and outflow at the gas terminal and their changing with time, together with all the constrains like the pipe upstream

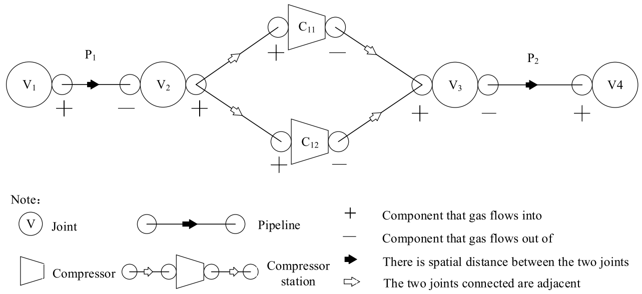

FIGURE 1. **Sketch of gas transmission pipeline model.**

and downstream pressure, flow, distribution flow and minimum inbound pressure, the performance of the compressor, the risk of start-stop operation of the compressor and others. We established a transient optimization mathematical model,introduced the measures of ''pressure-regulating'' and ''flow-restricted'' and put forward a kind of heuristic algorithm to solve the model. Case analysis showed that such a solution can quickly and effectively lead to the results.

II. TRANSIENT OPTIMIZATION MODEL

A. PIPELINE MODEL

The structure of the actual gas pipeline is very complex, so the pipeline structure must be abstracted into a simplified structure that can be expressed mathematically. For natural gas pipeline, directed graph is adopted for simulation [31]. See figure 1.

B. THE ESTABLISHMENT OF OBJECTIVE FUNCTION

As for the transient operation optimization problem of the gas transmission pipeline, the object is to achieve the minimum energy consumption or maximum economic benefit in the designated optimization period. So the optimal object is the minimum total operating cost of each time layer in the designated period (24H is generally selected as a cycle and one hour is the unit time).

The objective function of transient operation optimization mainly consists of two parts: the energy consumption of compressor operation and the switching cost of the compressor:

$$\min\sum_{s=1}^{S}\sum_{t=1}^{T}P_s^t\cdot k_s^t\cdot\tau+\sum_{s=1}^{S}\sum_{t=1}^{T}(C_{s,\mathrm{up}}^t k_{s,\mathrm{up}}^t + C_{s,\mathrm{down}}^t k_{s,\mathrm{down}}^t) \tag{2}$$

C. OPTIMIZATION VARIABLES

For gas transmission pipeline, gas flow in each pipeline station is determined by the gas source conditions and consumers' needs, thus it cannot be used as optimization variables. Hence, the outlet pressure of the compressor station that changes with time and the number of compressor station are selected as optimization variables, to research the transient operation optimization of gas transmission pipeline.

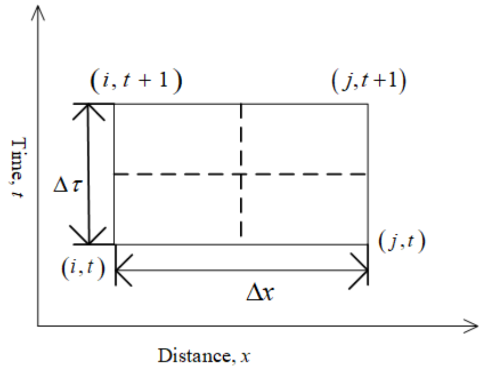

FIGURE 2. **Implicit central difference method.**

D. CONSTRAINTS

1) THE CONSTRAINT OF GAS TRANSMISSION PIPELINE

Without respect to the transient influence of temperature, the movement of gas in the pipeline are bound to obey the conservation law of mass and momentum [32]–[34].

$$\partial_t\bar{p}+C_0\partial_x q=0 \tag{3}$$

$$\partial_t q+C_0\partial_x\left(\frac{q^2}{\bar{p}}\right)+\frac{A}{\rho_0}\partial_x p+\frac{g}{C_0}\bar{p}\partial_x h+C_0\frac{\lambda}{2D}\frac{q^2}{\bar{p}}=0 \tag{4}$$

In order to perform numerical solution, the implicit difference scheme as shown in Figure 2 is adopted to discretize partial differential equations (3) and (4).

$$\frac{\bar{p}_i^{t+1}+\bar{p}_j^{t+1}}{2\Delta\tau}-\frac{\bar{p}_i^{t}+\bar{p}_j^{t}}{2\Delta\tau}+C_0\frac{q_j^{t+1}-q_i^{t+1}}{L_p}=0 \tag{5}$$

$$\begin{aligned}&\frac{q_j^{t+1}+q_i^{t+1}}{2\Delta\tau}-\frac{q_j^{t}+q_i^{t}}{2\Delta\tau}+C_0\left(I_p^{t+1}+R_p^{t+1}\right)\\&+\frac{A}{\rho_0}\frac{p_j^{t+1}-p_i^{t+1}}{\Delta x}+\frac{g}{C_0}\cdot\frac{h_p}{L_p}\frac{\bar{p}_i^{t+1}+\bar{p}_j^{t+1}}{2}=0\end{aligned} \tag{6}$$

$\bar{p}_i^t$ refers to the defined reduced pressure and R_p^{t+1} and I_p^{t+1} are nonlinear terms caused by loss and friction. Its expression is as follows [18]:

$$\bar{p}_i^t=\frac{p_i^t}{1+\alpha\cdot p_i^t} \tag{7}$$

$$R_p^{t+1}=\frac{\left(q_i^{t+1}\right)^2}{\bar{p}_i^{t+1}}\left(\frac{\lambda}{4D}-\frac{1}{L_p}\right) \tag{8}$$

$$I_p^{t+1}=\frac{\left(q_j^{t+1}\right)^2}{\bar{p}_j^{t+1}}\left(\frac{\lambda}{4D}+\frac{1}{L_p}\right) \tag{9}$$

In addition, in the consideration of the actual situation of the gas transmission pipeline, the pressure at each joint in the pipeline and the flow in the pipeline should be within a certain range, that is:

$$p^{\min}\le p_i^t,\quad p_j^t\le p^{\max} \tag{10}$$

$$q^{\min}\le q_i^t,\quad q_j^t\le q^{\max} \tag{11}$$

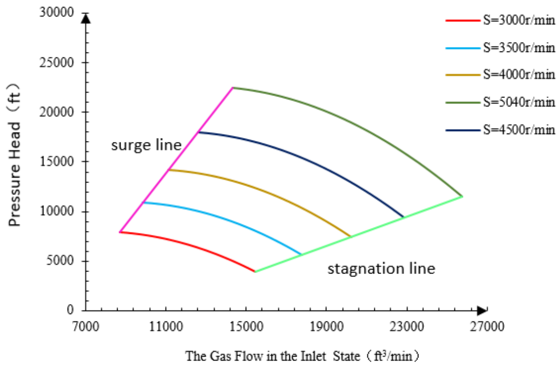

FIGURE 3. **The Graph of the Characteristics of Pressure Head of the Compressor.**

2) NODE CONSTRAINT

Each node v in the pipeline must obey the law of conservation of mass. Apart from that, the consumption of fuel gas should be subtracted from the gas flow at the terminal node of the compressor, that is:

$$\sum_{p\in \mathrm{N}_i^{p+}} q_{p+}(t) + \sum_{s\in \mathrm{N}_i^{s+}} q_{s+}(t) = \sum_{p\in \mathrm{N}_i^{p-}} q_{p-}(t) + \sum_{s\in \mathrm{N}_i^{s-}} q_{s-}(t) + \sum_{s\in \mathrm{N}_i^{s-}} f_s(t) \quad (12)$$

The boundary condition of gas flowing pressure and the flow set in the joint v should be:

$$p_v^{\min} \le p_v^t \le p_v^{\max} \quad (13)$$

$$q_{v,\min}^t \le q_v^t \le q_{v,\max}^t \quad (14)$$

3) COMPRESSOR AND STATION CONSTRAINT

a: FEASIBLE DOMAIN OF THE COMPRESSOR

As shown in figure 3, each compressor has a best working point. The region around the point is the working domain of the compressor [3].

$$\begin{cases} H_s^t = -h_{s3}\cdot\left(Q_s^t\right)^2 - h_{s2}\cdot Q_s^t\cdot W_s^t - h_{s1}\cdot\left(W_s^t\right)^2 \\ Q_S^t \ge s_{s1} + s_{s2}\cdot H_s^t \\ Q_S^t \le s_{s3} + s_{s4}\cdot H_s^t \\ W^{\min} \le W_s^t \le W^{\max} \end{cases} \quad (15)$$

The pressure head variable of the compressor is determined by the pressure into and out of the compressor:

$$H_s^t = \frac{1}{\gamma_s} R\overline{T}\left(\left(\frac{p_{s-}^t}{p_{s+}^t}\right)^{\gamma_s} - 1\right) \quad (16)$$

Without considering the temperature, the flow of compressor is the function of gas pressure, that is:

$$Q_s^t = \frac{1}{k_s^t}\rho_0 R\overline{T}\cdot\frac{q_{s+}^t}{\bar{p}_{s+}^t} \quad (17)$$

b: COMPRESSOR REGULATION

In actual production, the inbound pressure and flow is not necessarily able to meet the above conditions, and at the same time to ensure that the change of pipe flow and the pressure with tine is relatively stable. This paper introduced the "flow-restricted" and the "pressure-regulating" measures which limit the inlet flow of the compressor station and adjust the outlet pressure of the compressor station, to ensure the normal operation of the network. Therefore, the definition formula (17) of the actual flow is rewritten as:

$$Q_s^t = \frac{1}{k_s^t}\rho_0 R\overline{T}\cdot\frac{q_{s,act}^t}{\bar{p}_{s+}^t} \quad (18)$$

$$c_{q,s}^{lb}\cdot q_{s+}^t \le q_{s,act}^t \le c_{q,s}^{ub}\cdot q_{s+}^t \quad (19)$$

In which, c^{lb} and c^{ub} are the ratio of flow-restricted, i.e., the actual flow through the compressor can be floating within a range around the flow before entering into station. Outlet regulating pressure allows the outbound pressure to be slightly lower than the outlet pressure of the compressor. Likewise, the formula of pressure head of the compressor (16) is redefined as:

$$H_s^t = \frac{1}{\gamma_s} R\overline{T}\left(\left(\frac{p_{s-}^t}{p_{s+}^t}\right)^{\gamma_s} - 1\right) \quad (20)$$

$$c_{p,s}^{lb}\cdot p_{s,act}^t \le p_{s-}^t \le p_{s,act}^t \quad (21)$$

Ordinary compressors can be divided into gas-drive and electric-drive, according to different type of energy consumptions. In the gas-drive compressor, some gas will be consumed to provide energy for the compressor, so the outbound flow will be slightly lower than the inbound flow. Suppose:

$$n_s^{comp} = n_s^{gas} + n_s^{elec} \quad (22)$$

It is known that the gas consumption is proportional to the compressor power with the coefficient d_{gas}, and when there are gas-drive and electric-drive compressors, the electric-drive compressor is preferred to be used, and the constraints of this part are written as follows:

$$q_{s,consum}^t = \max\left\{k_s^t - n_s^{elec}, 0\right\}\cdot d_{gas} P_s^t \quad (23)$$

$$q_{s-}^t = q_{s,act}^t - q_{s,consum}^t \quad (24)$$

The above constraints are set on the premise that there are compressors that are on. When the s station is in the time layer t, all compressors are not turned on, i.e., when $k_s^t = 0$, gas is allowed to pass through the compressor station arbitrarily, and there are:

$$q_{s-}^t = q_{s,\mathrm{act}}^t \quad (25)$$

$$p_{s-}^t = p_{s+}^t \quad (26)$$

c: MINIMAL OPERATING TIME AND MINIMAL DOWNTIME CONSTRAINT

Due to the technical limitations of the compressor, the compressor is required to be in off state for a certain period of time before it can be restarted. This period of time is called the minimum downtime [27]. Similarly, when the minimum operating time is not reached, the compressor can only be in the operating state. A binary variable b_{si}^t is introduced to represent the switching state of the compressor i in the S station in the time layer t, namely:

When $b_{si}^t = 0\left(i = 1, \ldots, n_s^{\text{comp}}\right)$, it means the compressor is in off state.

When $b_{si}^t = 1\left(i = 1, \ldots, n_s^{\text{comp}}\right)$,, it means the compressor is in operating state.

Let $t_{\text{on}}, t_{\text{off}}$ represent the minimum operating time and the minimum downtime respectively, then the minimum operating time of the compressor is modeled by the following inequality:

$$b_{si}^t - b_{si}^{t-1} \le b_{si}^j, \quad (t+1 \le j \le \min\{t+t_{\text{on}}-1, T\}) \tag{27}$$

$$b_{si}^{t-1} - b_{si}^t \le 1 - b_{si}^j, \quad (t+1 \le j \le \min\{t+t_{\text{off}}-1, T\}) \tag{28}$$

In this way, it is guaranteed that the compressor must run at least time layer after it starts, or the compressor must keep the shutdown state for at least the time layer after it is closed.

4) TERMINAL CONDITIONS

The lower the flow of natural gas pipeline, the lower the energy consumption. The problem of excessive utilization of pipeline stock to reduce flow for energy conservation can be avoided by adding terminal condition constraints.

The total volume of the gas at the end point is required to be at least as large as that in the starting point within the time range studied, that is:

$$\sum V_e^1 \le \sum V_e^T \tag{29}$$

III. HEURISTIC ALGORITHM

Some scholars such as Mahlke, Martin, Moritz, Domschke [18], [26]–[29] have conducted specific researches on the solution to transient optimization model for natural gas pipelines, dealing with the similar issues through the combination of mixed integer linear programming and nonlinear programming. However, the length and the segmentation of pipelines between stations could result in a large computing scale, on which gravity also casts significant influence. Moreover, the continuous-time switching condition and the "flow-restricted" and "pressure-regulating" measures as required were not taken into account due to different compressor station modeling. Therefore, employing the methods proposed in the previous researches [18], [26]–[29] usually leads to more significant errors and even no solution: the CPLEX optimization solver fails to generate any good solution to 41, 20 and 10 compressor stations. In light of the situation mentioned above, a heuristic algorithm is proposed in this research in order to obtain a feasible solution in a more reasonable time and optimize it to a certain extent.

A. METHOD FOR GENERATING SOLUTIONS

During computing, main pipelines are divided into different computing units in accordance with the distribution of compressor stations: each computing unit consists of a compressor station and the pipelines connected at its rear, and there are distribution stations between these pipelines that gas can flow in or out. It can be assumed that there are a total of U computing units, and each unit will be recorded as $u = 1, 2, \ldots, U(n_s^{\text{comp}} \neq 0)$.

For a computing unit, in order to ensure a feasible solution to the pipeline equation, the appropriate compressor station outlet pressure is well advised to be the priority selection. For compressor station $s : n_s^{\text{comp}} > 0, f_s(s) = (i,j) \in \mathrm{E_S}$, given the inlet pressure p_{s+}^t and inlet flow q_{s+}^t, the compressor station outlet pressure can, therefore, be determined.

For pipelines, the outlet flow of each pipeline is required to be within a certain range above and below the inlet flow. In the meantime, the outlet pressure needs to maintain between a defined range of the outlet pressure of the same pipeline at the previous time layer, namely, the outlet pressure and flow of the pipelines are determined as the following forms. For $\forall p \in \mathrm{P}, f_p(p) = (i,j) \in \mathrm{E_p}, \forall t \in T \backslash \{0\}$ there are:

$$\left(1 - c_{q,p}^{lb}\right) \cdot q_{p+}^t \le q_{p-}^t \le \left(1 + c_{q,p}^{ub}\right) \cdot q_{p+}^t \tag{30}$$

$$\left(1 - c_{p,p}^{\mathrm{lb}}\right) \cdot p_{s-}^{t-1} \le p_{s-}^t \le \left(1 + c_{p,p}^{ub}\right) \cdot p_{s-}^{t-1} \tag{31}$$

$c_{q,p}^{lb}, c_{q,p}^{ub}, c_{p,p}^{\mathrm{lb}}, c_{p,p}^{ub}$ are determined constants.

By analyzing these pipeline equations, it can be concluded that given the inlet flow within the allowable pressure range, when the inlet pressure increases, the outlet pressure of the pipeline ascends along while the outlet flow decreases. Therefore, when the outlet pressure and outlet flow are determined, according to the set targets: Eq. (30) and Eq. (31), two situations can be obtained. It can be assumed to be a return value ret for each situation, then:

(1) If the outlet flow is at a rather low level or the outlet pressure is overly high, the outlet pressure of the compressors needs to be reduced, then ret = 1;

(2) If the outlet flow is at an overly high level or the outlet pressure is rather low, the outlet pressure of the compressors needs to be increased, then ret = 2;

When it comes to an extremely significant flow change, adopting the "flow-restricted" measure can be expected to guarantee the continuous-time switching condition to avoid the failure in solution. Specifically, selecting the step size of flow limit Δq in advance, and the flow into the compressor can be increased or reduced according to the change of the inlet flow relative to that at the previous time layer when the outlet pressure of the compressor station reaches the upper or lower bound, namely:

If $q_{s+}^{t+1} > q_{s+}^t$ set $q_{s,\text{act}}^{t+1} = q_{s+}^{t+1} - \Delta q$;

If $q_{s+}^{t+1} < q_{s+}^t$ set $q_{s,\text{act}}^{t+1} = q_{s+}^{t+1} + \Delta q$.

Based on this, the feasible solution of the $(t+1)$ time layer pipeline is obtained by random search under the given operating condition of the pipeline at the previous t time layers, and as shown in Figure 4,the steps for generating the solution are as follows:

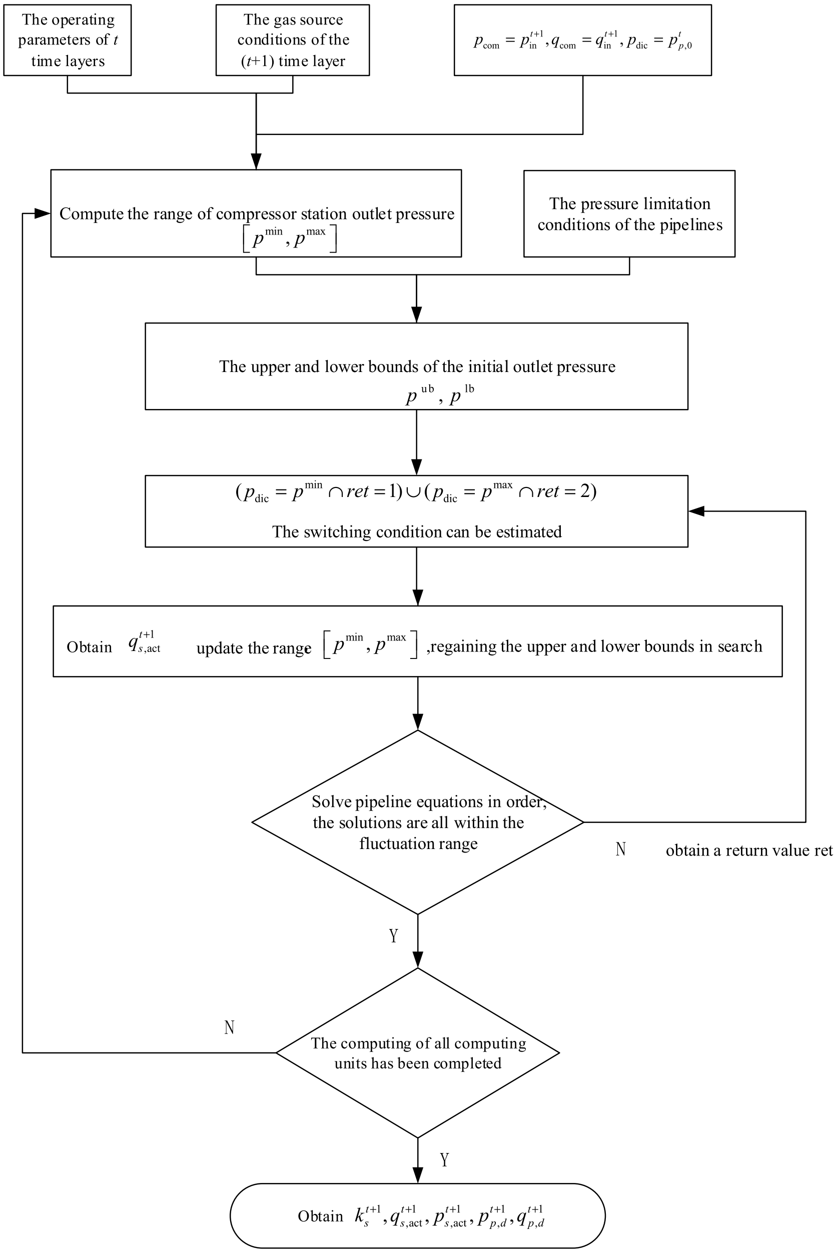

FIGURE 4. **The steps for generating the solution.**

(1) Input the operating parameters of t time layers of the pipeline and the gas source conditions of the $(t+1)$ time layer, and set $p_{\mathrm{com}} = p_{\mathrm{in}}^{t+1}, q_{\mathrm{com}} = q_{\mathrm{in}}^{t+1}, p_{\mathrm{dic}} = p_{p,0}^{t}$;

(2) For each computing unit, compute the range of compressor station outlet pressure $\left[p^{\min}, p^{\max}\right]$ by $p_{\mathrm{com}}, q_{\mathrm{com}}$;

(3) According to the range $\left[p^{\min}, p^{\max}\right]$ and the pressure limitation conditions of the pipelines, the upper and lower bounds of the initial outlet pressure $p^{\mathrm{ub}}, p^{\mathrm{lb}}$ are obtained;

(4) If $p_{\mathrm{dic}} = p^{\min}$ and ret $= 1$, or $p_{\mathrm{dic}} = p^{\max}$ and ret $= 2$, then the switching condition can be estimated to obtain $q_{s,\mathrm{act}}^{t+1}$ and to update the range $\left[p^{\min}, p^{\max}\right]$, regaining the upper and lower bounds in search;

(5) Solve pipeline equations in order. If the solutions are all within the fluctuation range, turn to step (6), otherwise obtain a return value ret, and return to step (4);

(6) Has the computing of all computing units been completed? If so, $k_s^{t+1}, q_{s,\mathrm{act}}^{t+1}, p_{s,\mathrm{act}}^{t+1}, p_{p,d}^{t+1}, q_{p,d}^{t+1}$ can be obtained, otherwise return to step (2).

Depending on the parameters taken, Beta distribution can have various distribution forms, which is very flexible. Therefore, Beta distribution is considered for random search method, namely:

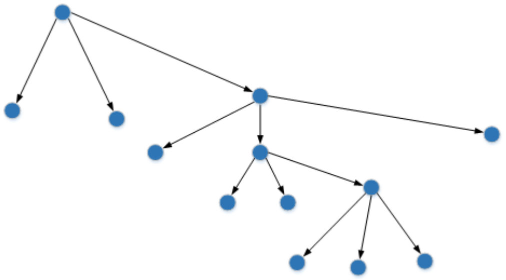

FIGURE 5. **Solution tree of random generation method.**

$$\text{If ret} = 1, \text{ set } p_{\text{dic}} = p^{\text{lb}} + V \cdot \left(p_{\text{dic}} - p^{\text{lb}}\right);$$
$$\text{If ret} = 2, \text{ set } p_{\text{dic}} = p^{\text{ub}} - V \cdot \left(p^{\text{ub}} - p_{\text{dic}}\right).$$

B. RANDOM GENERATION, COMPARISON, AND OPTIMIZATION

A solution to the previous t time layers can be used to obtain a set of solutions to $t+1$ time layers through random generation, and the number B of generated solutions can be selected in advance. In this way, given the initial solution t, a solution tree of t layers ($t = 0; 1; \ldots; T$) can be generated as shown in Figure 5, where the vertex of the row $t = t$' represents a feasible solution to the previous t' layers. However, since sometimes the total number T of time layers is expected to be significant, and the frequency of solutions computing increases exponentially with the number of time layers, depth-first search (DFS) method is therefore adopted to solve the previous T time layers. Specifically, given solutions to the previous t layers, it is advised to select a "better" solution in B generated solutions for the next computing until this solution and all feasible solutions generated by it have been thoroughly explored. And then, the next "better" solution is computed among this set of solutions.

For the definition of a "better" solution, now combining Eq. (29) and Eq. (30), the solution with the least influence of "flow-restricted" is selected each time since the "pressure-regulating" measure itself is inconsistent with minimizing energy consumption. In this way, the first solution to the previous T layers is approximately the least affected by "current limiting". If such a solution meets the requirements of the expected "flow-restricted" range, this solution will be compared with other solutions within this expected range for a solution with less energy consumption. The stack data structure will be employed to implement the above algorithm.

Finally, it should be pointed out that T, a large number of time layers, usually results in a significant amount of nodes in the entire solution tree. Therefore, it is almost impossible to traverse the solution within a reasonable time, and certain solutions need to be discarded at some point to improve efficiency. At present, the following three circumstances are taken into account in the case of discards.

(1) For larger energy consumption, namely, a feasible solution to the previous t layers ($t < T$), its total energy consumption is *Wt*. If a feasible solution has been obtained and the total energy consumption is *WT*, when *Wt/t*≫*WT/T*, the feasible solution to the previous t layers can be discarded.

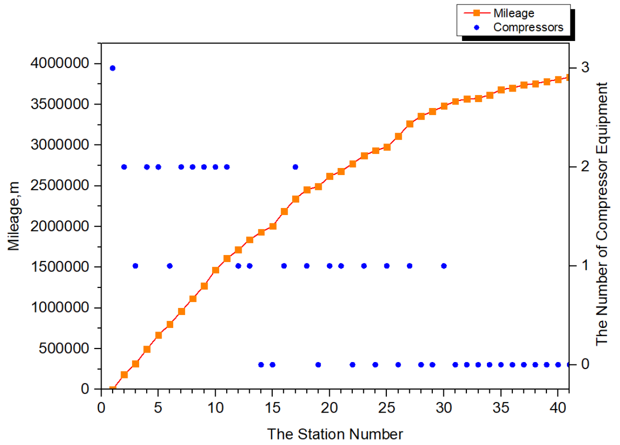

FIGURE 6. **Mileage and compressor configuration quantity of each station.**

(2) For a flow with a larger fluctuation, a feasible solution with flow fluctuation exceeding the limit value can be discarded directly; yet, the solutions outside the expected range and within the limited range can be discarded based on a certain probability first, and then discarded directly after the feasible solution of T layers is obtained.

(3) When the two above situations occur continuously, it can be assumed that the solution represented by a node of the solution tree is unreasonable, which makes it difficult for its sub-branches to obtain better solutions. Therefore, it is advised to jump back to a previous node. Such a jumping method would be determined by the remaining computing frequency, that is, after determining the upper limit of computing frequency in advance, the more remaining jumping, the more nodes to be discarded.

In this way, a feasible solution with less fluctuation and energy consumption can be well obtained through an algorithm of random generation.

IV. RESULTS AND DISCUSSIONS

West-East Gas Pipeline Line I can be taken as an example. The Pipeline has a total length of 3840 km, a designed capacity of 170 × 10^8 t/a, a pipe diameter of 1016 mm and a wall thickness of 17.5 mm. Also, there are 41 stations along the Pipeline, including 22 compressor stations and 33 compressors. The pipe length between stations and compressors in operation of each station are shown in Figure 6 [2]. A total of 24 hours from 8 o'clock to 7 o'clock on the next day is considered as an optimization period with a time step of 1 hour.

The starting gas source pressure of the Pipeline is 6.5MPa. Stations 1, 15, 22 and 32 have been incorporated 45.399 million cubic meters (mcm), 4.37 mcm, 1.94 mcm and 7.5 mcm

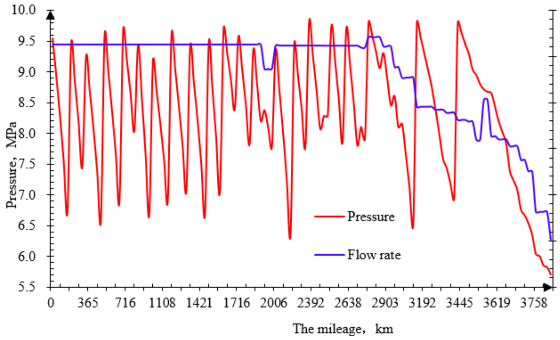

FIGURE 7. Initial conditions: Operating pressure and flow.

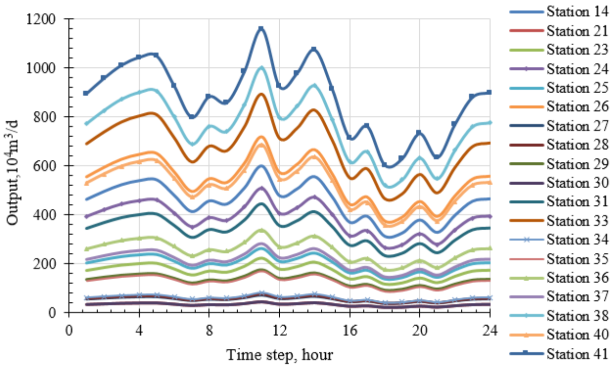

FIGURE 8. Boundary condition: User gas consumption (8: 00 a.m. in time step 1 and 7: 00 a.m. in time step 24 on the second day).

per day respectively. As shown in Figure 7, pressure and flow parameters in stable condition were obtained through steady-state simulation, which is also the initial condition for transient optimization, namely, the operation parameter at 7 a.m. It can be seen from Figure 7 that the maximum operating pressure of the Pipeline is 9.8 MPa and the minimum is 5.7 MPa. With no users in its front section (before Station 14), the Pipeline runs smoothly. However, the majority of users live around the second half of the Pipeline where a total of 19 stations producing gas are located. Due to the unstable gas consumption of users, the gas output variation curve of each station with time is computed based on the gas consumption imbalance coefficient provided by the pipeline company (a period is from 8: 00 a.m. to 7: 00 a.m. the next day), as shown in Figure 8. Moreover, Figure 8 displays that 8-12 o'clock and 17-22 o'clock is the peak of gas consumption while 6 o'clock is the highest peak and 23-7 o'clock is the trough of consumption.

In accordance with the initial conditions and the dynamic changes of gas consumption of each user, a transient optimal operation scheme was obtained by the optimization method proposed in this research. Figure 9 shows the optimization results of the operating pressure, only listing those within 1, 9, 17 and 24 time steps. It can be seen that the operating pressure at each moment fluctuates along with the gas consumption of users. Specifically, time step 1 and 9 are at the peak of gas consumption, where the pressure difference across the whole Pipeline is larger; time step 17 and 24 are at the trough, and the pressure difference is therefore narrowed. As a result, the energy consumption of the transient optimal operation result can be expected to be significantly reduced.

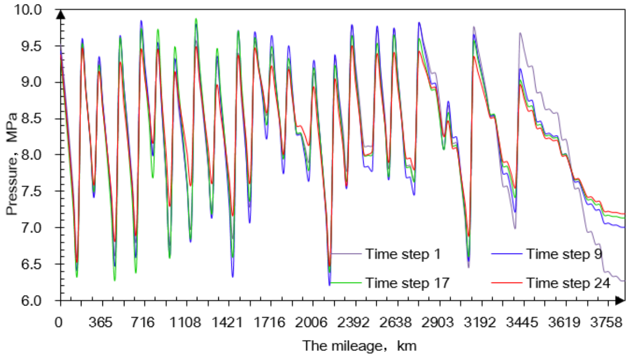

FIGURE 9. Optimization result: Pressure across the whole Pipeline.

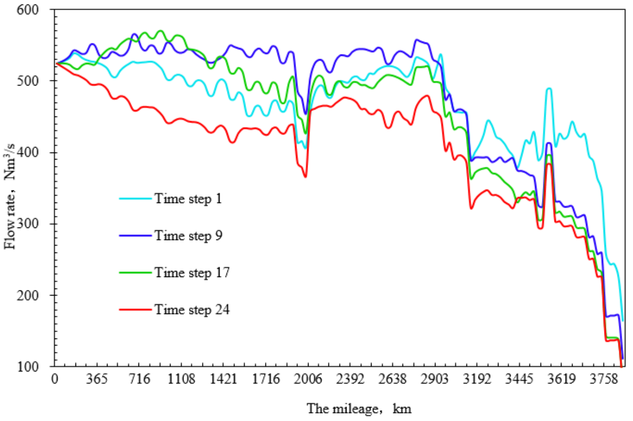

FIGURE 10. Optimization result: Flow across the whole Pipeline.

Figure 10 displays the flow distribution of the whole pipeline corresponding to the transient optimization result. It can be found that the uneven gas consumption of users leads to the Pipeline's pressure fluctuation, thus causing the flow fluctuation across the Pipeline. In particular, the time step 24 is when the gas consumption at its trough, and so is the flow of the whole pipeline.

(1) The flow increases gradually from time step 1. As users are mainly concentrated on the area over 2900 km away from the starting point, time step 1 is the peak of gas consumption at 8 a.m. Specifically, as shown in Figure 10, the flow reaches its peak beyond the front 2900km of the pipeline at this point, while it is lower in the previous section. Also, it can be found in figure 11 that the storage of the Pipeline mounts to its summit at this time and the peak load regulation by Pipeline storage can be used to meet the gas needs of users.

(2) Time step 9 is 16 o'clock. As can be seen from Figure. 10, the flow of the Pipeline within 2900km reaches its peak at this time and beyond, it gradually decreases. The Pipeline is gradually replenished in order to deal with the next gas consumption peak.

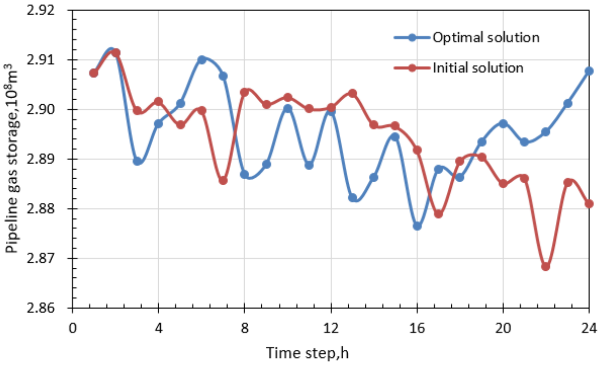

FIGURE 11. Optimization results: Pipeline storage.

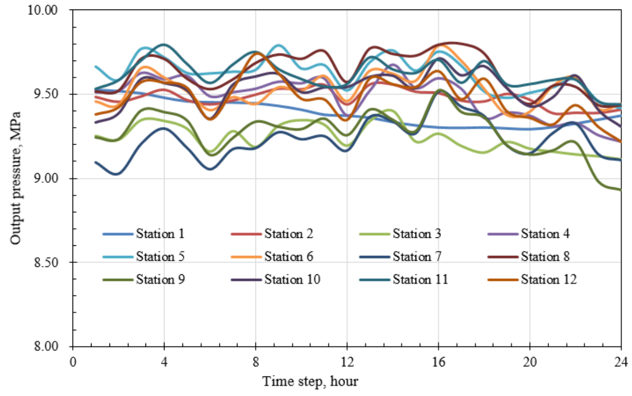

FIGURE 12. Optimization result: Outlet pressure of each compressor station.

(3) The time step 17 is 24 o'clock, and the time step 24 is 7 o'clock on the second day. During this period, the gas consumption is at its trough. To be specific, the Pipeline flow within the front 2900km is larger and beyond 2900km, it gradually decreases, reaching its minimum at the time step 24. It can be found from Figure 11 that the optimal solution is on a steady rise after the 16th time layer (24:00). At this point, although the user's gas consumption is descending, the optimal solution preserves a larger operating flow in order to keep the Pipeline running smooth, thus increasing the storage for the next day.

Figure 12 and Figure 13 show the pressure optimization results of each Station. It can be seen that due to the dynamic changes of the user's gas consumption, the pipeline flow and the friction loss generated vary accordingly. Therefore, adjusting the compressor outlet pressure based on the changes in friction loss in a dynamic way can be expected to save a large amount of energy. However, frequent adjustment of the compressor outlet pressure may increase the difficulty of operation, and hence it is well advised that no adjustment measures should be taken when the pressure fluctuation in the optimization scheme is within 0.2 MPa, given the actual situation of the control center. It can be found from Figure 14 and Figure 15 that the power variation of each compressor station with time is similar to the variation trend of compressor outlet pressure. It can be summarized by computing the energy consumption of each time layer that in the optimized operation scheme, the total gas consumption is 1.747 million cubic meters, and the total power consumption is 1.49×10^6 kWh. By converting the gas consumption into power consumption, total energy consumption throughout a day is 6.448×10^6 kWh.

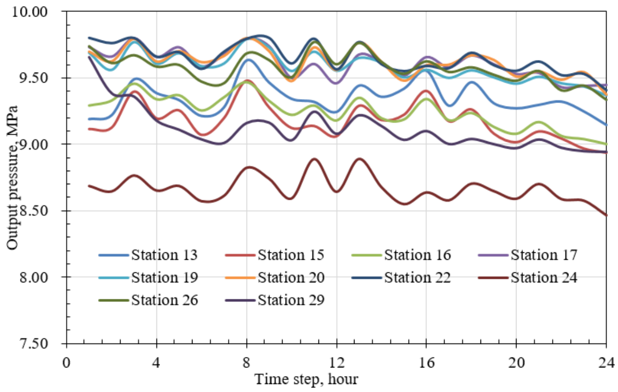

FIGURE 13. Optimization result of outlet pressure of each compressor station.

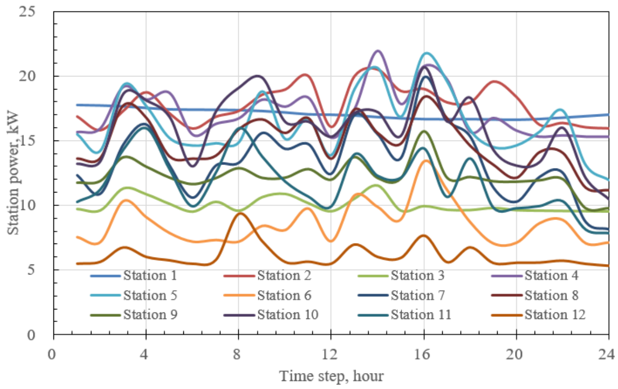

FIGURE 14. Optimization result: The power of each compressor station.

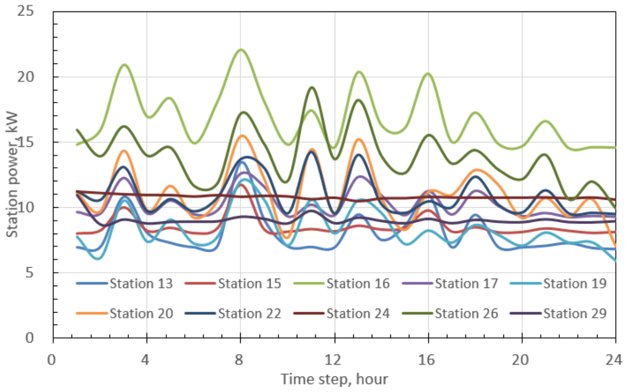

FIGURE 15. Optimization result: The power of each compressor station.

By contrast, through the steady-state optimization algorithm proposed in the previous researches [1], [2], the aggregate energy consumption in a day is 6.754×10^6 kW.h.

The energy consumption of transient optimization was 4.53% lower than that of steady-state optimization.

According to the large-scale pipeline system such as West-East Gas Transmission Pipeline I, the optimization model and algorithm that have been established in this research can be employed to compute the optimization scheme in 15 minutes by using a common computer (CPU: CORE i5). The computing speed meets the engineering requirements, proving that the algorithm proposed in this research is a success.

V. CONCLUSION

(1) Adding the constraints of minimum operation time and minimum shutdown time to the transient optimization model of the gas transmission pipeline can be expected to avoid frequent switching of the compressors in the optimization scheme, so as to reduce the switching cost and ensure the smooth operation of the gas transmission pipeline system.

(2) The lower the volume of gas transmission pipeline is, the lower the energy consumption will be. So it is necessary to add terminal condition constraints into the transient optimization model of gas transmission pipeline, which can avoid the excessive use of inventory to reduce energy consumption, thus ensuring the continuous and stable operation of the pipeline system.

(3) Considering the great number of large-scale compressor stations of gas transmission pipeline and the long distances between these stations, it is required to calculate the pipelines in sections for the accuracy of the hydraulic calculation, which leads to numerous optimization variables and a large computation amount in the transient optimization model. Moreover, the pipeline equations are very sensitive to pressure and flow. Therefore, the "pressure-regulating" and "flow-restricted" measures introduced in this research are more than effective and conducive to discarding invalid solutions in optimization computation and accelerating the solution speed of the model. Further, pertaining to the West-East gas pipeline, the solution time is within 15 minutes by using the ordinary Intel Core i5 CPU for optimization computation.

(4) Due to the dynamic change of the user's gas consumption, the pipeline flow and its friction loss may vary accordingly. Based on the changes in friction loss, dynamic adjustment of the compressor outlet pressure can be assumed to preserve a great amount of energy. Nevertheless, such frequent adjustment could increase the operation difficulty. Therefore, it is suggested not to take adjustment measures when the pressure fluctuation in the optimization scheme is within 0.2 MPa.

LIST OF SYMBOLS

$(\ )^t$	Superscript "t"represents the time layer
$(\ )_S$	Subscript "s" represents the number of compressor station, +is the inlet, and – is the outlet
$(\ )_p$	Subscript "p" represents the number of pipeline, + is the inlet and - is the outlet
p	Pressure, Pa
q	flow, m^3/s
P	Compressor power, kW
k	Number of working compressors
P_s^t	Compressor power of Station s at the t time layer, kW
k_s^t	Number of compressors in operation of Station s at the t time layer
τ	Set time intervals: $\tau = 1$h
$k_{s,up}^t$	The increased number of power-on compressors of Station s at the t time layer compared with the previous time layer
$k_{s,down}^t$	The reduced number of power-on compressors of Station s at the t time layer compared with the previous time layer
$C_{s,up}^t$	Consumption of switching on compressors at Station s at the t time layer, kW.h
$C_{s,down}^t$	Consumption of switching off compressors at Station s at the t time layer, kW.h
q_{p+}	Flow into the pipeline, m^3/s
q_{p-}	Flow out of the pipeline, m^3/s
$f_s\,(t)$	Consumption of fuel gas at Station s, m^3/s
h_{sk}	The fitting coefficient of pressure head curve in Station s, with the compressors in the same type at the same station (k = 1, 2, 3)
s_{sk}	The parameter of a compressor at Station s, with the compressors in the same type at the same station (k = 1, 2, 3)
H_s^t	Pressure head variable at Station s at the t time layer, m
Q_s^t	The actual flow of each compressor in operation at Station s at the t time layer, m^3/s
W_s^t	Rotating speed of Station s at the t time layer, r/min
γ_s	The absolute thermal expansion coefficient of compressors at Station s
ρ_0	The density of natural gas in a standard state,kg/m^3
n_s^{comp}	Total number of compressors at Station s
n_s^{elec}	Number of electrically powered compressors at Station s
n_s^{gas}	Number of diesel-powered compressors in Station s
$q_{s,consum}^t$	Fuel gas consumption of Station s at the t time layer, m^3/s
d_{gas}	Gas consumption coefficient of compressors
q_{s-}^t	Outlet flow of Station s at the t time layer, m^3/s
q_{s+}^t	Inlet flow at Station s at the t time layer, m^3/s
$q_{s,act}^t$	Actual flow of Station s at the t time layer, m^3/s

REFERENCES

[1] Z. Wang, D. Luo, and L. Liu, "Natural gas utilization in China: Development trends and prospects," *Energy Rep.*, vol. 4, pp. 351–356, Nov. 2018.

[2] E. Liu, C. Li, and Y. Yang, "Optimal energy consumption analysis of natural gas pipeline," *Sci. World J.*, vol. 2014, May 2014, Art. no. 506138.

[3] E. Liu, L. Lv, Q. Ma, J. Kuang, and L. Zhang, "Steady-state optimization operation of the west–east gas pipeline," *Adv. Mech. Eng.*, vol. 11, no. 1, Jan. 2019, Art. no. 1687814018821746.

[4] H. Lu, K. Huang, and M. Azimi, "Blockchain technology in the oil and gas industry: A review of applications, opportunities, challenges, and risks," *IEEE Access*, vol. 7, pp. 41426–41444, 2019.

[5] S. Wu, E. Boyd, and L. Scott, "Model relaxations for the fuel cost minimization of steady-state gas pipeline networks," *Math. Comp. Model. Dyn.*, vol. 31, pp. 197–220, Feb. 2000.

[6] E. Liu, L. Lv, Y. Yi, and P. Xie, "Research on the steady operation optimization model of natural gas pipeline considering the combined operation of air coolers and compressors," *IEEE Access*, vol. 7, pp. 83251–83265, 2019.

[7] J. Wilson, J. Wallace, and B. Furey, "Steady-state optimization of large gas transmission systems," in *Simulation and Optimization of Large Systems*, A. J. Osiadacz, Ed. Oxford, U.K.: Clarendon Press, 1988.

[8] F. Altiparmak, M. Gen, L. Lin, and I. Karaoglan, "A steady-state genetic algorithm for multi-product supply chain network design," *Comput. Ind. Eng.*, vol. 56, no. 2, pp. 521–537, Mar. 2009.

[9] S. Hu, Z. Wang, and W. Hu, *The Optimal Control Theory and System*. Beijing, China: Science Press, 2005, pp. 130–170.

[10] V. Mantri, L. Preston, and C. Pringle, "Transient optimization of a natural gas pipeline system," in *Proc. PSIG Annu. Meeting*, Jan. 1985.

[11] P. Wong and R. Larson, "Optimization of natural-gas pipeline systems via dynamic programming," *IEEE Trans. Autom. Control*, vol. 16, no. 5, pp. 475–481, Oct. 1971.

[12] J. Rachford and R. Carter, "Optimizing pipeline control in transient gas flow," in *Proc. PSIG Annu. Meeting*, 2000, pp. 1–26.

[13] K. Ehrhardt and M. C. Steinbach, "Nonlinear optimization in gas networks," in *Modeling, Simulation and Optimization of Complex Processes*. Berlin, Germany: Springer, 2003.

[14] K, Ehrhardt and M. Steinbach, "Nonlinear optimization in gas networks," in *Modeling, Simulation and Optimization of Complex Processes*. Berlin, Germany: Springer, 2005, pp. 139–148.

[15] C. Kelling, K. Reith, and E. Sekirnjak, "A practical approach to transient optimization for gas networks," in *Proc. PSIG Annu. Meeting*, 2000.

[16] M. Möller, "Mixed integer models for the optimisation of gas networks in the stationary case," *J. Gen. Microbiol.*, vol. 9, no. 2, pp. 546–547, 2004.

[17] B. P. Furey, "A sequential quadratic programming-based algorithm for optimization of gas networks," *Automatica*, vol. 29, no. 6, pp. 1439–1450, Nov. 1993.

[18] P. Domschke, B. Geißler, O. Kolb, J. Lang, A. Martin, and A. Morsi, "Combination of nonlinear and linear optimization of transient gas networks," *Informs. J. Comput.*, vol. 23, no. 4, pp. 605–617, Nov. 2011.

[19] P. Spellucci, "A new technique for inconsistent QP problems in the SQP method," *Math. Methods Oper. Res.*, vol. 47, no. 3, pp. 355–400, Oct. 1998.

[20] P. Spellucci, "An SQP method for general nonlinear programs using only equality constrained subproblems," *Math. Program.*, vol. 82, no. 3, pp. 413–448, Aug. 1998.

[21] A. Wächter and L. T. Biegler, "On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming," *Math. Program.*, vol. 106, no. 1, pp. 25–27, Mar. 2006.

[22] E. Sekirnjak, "Transiente technische optimierung (tto-prototyp)," PSI AG, Berlin, Germany, Tech. Rep. 3, 2000, pp. 30–32.

[23] N. Sahinidis and M. Tawarmalani, "BARON 7.2.5: Global optimization of mixed-integer nonlinear programs," User's Manual, 2005.

[24] K. Abhishek, S. Leyffer, and J. Linderoth, "FilMINT: An outer approximation-based solver for convex mixed-integer nonlinear programs," *Informs. J. Comput*, vol. 22, no. 4, pp. 555–567, Feb. 2010.

[25] I. Nowak and S. Vigerske, "LaGO: A (heuristic) Branch and Cut algorithm for nonconvex MINLPs," *Central Eur. J. Oper. Res.*, vol. 16, no. 2, pp. 127–138, Jun. 2008.

[26] D. Mahlke, A. Martin, and S. Moritz, "A simulated annealing algorithm for transient optimization in gas networks," *Math. Methods Oper. Res.*, vol. 66, no. 1, pp. 99–115, Aug. 2007.

[27] D. Mahlke, A. Martin, and S. Moritz, "A mixed integer approach for time-dependent gas network optimization," *Optim. Method. Softw.*, vol. 25, no. 4, pp. 625–644, Aug. 2010.

[28] S. Moritz, "A mixed integer approach for the transient case of gas network optimization," Ph.D. dissertation, Tech. Univ. Darmstadt, Darmstadt, Germany, 2007.

[29] B. Geißler, O. Kolb, J. Lang, G. Leugering, A. Martin, and A. Morsi, "Mixed integer linear models for the optimization of dynamical transport networks," *Math. Methods Oper. Res.*, vol. 73, no. 3, pp. 339–362, Jun. 2011.

[30] H. A. Behrooz and R. B. Boozarjomehry, "Dynamic optimization of natural gas networks under customer demand uncertainties," *Energy*, vol. 134, pp. 968–983, Sep. 2017.

[31] A. Demissie, W. Zhu, and C. Belachew, "A multi-objective optimization model for gas pipeline operations," *Comput. Chem. Eng.*, vol. 100, pp. 94–103, May 2017.

[32] E. Liu, X. Ma, and M. Zhou, "Analysis of discharge process of oil pipeline with complex topography," *Energy Rep.*, vol. 5, pp. 678–687, Jun. 2019.

[33] Z. Su, E. Liu, Y. Xu, P. Xie, C. Shang, and Q. Zhu, "Flow field and noise characteristics of manifold in natural gas transportation station," *Oil Gas. Sci. Technol.*, vol. 74, pp. 1–10, Jul. 2019. doi: 10.2516/ogst/2019038.

[34] E. Liu, W. Li, H. Cai, and S. Peng, "Formation mechanism of trailing oil in product oil pipeline," *Processes*, vol. 7, no. 1, pp. 1–18, Jan. 2019.

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