Intelligent System and Minimum Energy Consumption Optimization for a Single Natural Gas Pipeline

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Abstract. There are many long-distance gas pipeline put into operation in recent years, it make certain research value of single gas pipeline. Minimum energy consumption has always been the goal of pipeline enterprises, so this paper studies the optimal energy consumption based on energy consumption calculation. The implementation of steady state optimization aims to minimize the total compressing operation cost of the compressor stations. Two sub-problems arise from the operation scheme, the pipeline-level optimization and station-level optimization. The problem is solved by the improved dynamic programming method and enumerative algorithm, and develop the energy consumption software with Visual Basic.net. This paper uses the second Shanxi-Beijing pipeline as example. A variety of working conditions is optimized by optimization software. The study found: the software can accurately calculate the optimal results; the more the amount of output closer to design input, the smaller saving space through contrast to the actual; it is need to consider transportation costs and energy consumption and select the appropriate value, which can achieve maximum benefit.

Keywords: Generality; Gas pipeline; Energy consumption.

1. Introduction
Looking at the foreign literature in recent years, it can be found that most of the scholars engaged in the operation optimization of natural gas pipeline focus on the unsteady operation optimization of long-distance natural gas pipeline. Up to 2011, there is still no mature scheme for the unsteady operation optimization model of long-distance natural gas pipeline with the minimum energy consumption of the whole line as the objective function, and the solution method for the unsteady operation optimization needs to be further explored[1-4].

In this paper, the energy consumption calculation software is developed for a single natural gas pipeline. Users can add stations easily, add valve rooms between stations, and input the basic parameters of compressor in the compressor station to calculate the energy consumption. At the same time, the software can optimize the energy consumption, and then calculate the optimal value of the pipeline energy consumption.

2. Software Introduction

2.1. Mathematical Model

2.1.1. Pipeline level optimization[5]. In the steady-state operation condition, the incoming state of the next station can be determined only for one outlet state of any compressor station[11]. As shown in the figure, when the dynamic programming model is established, the number of compressor stations is set as \( n \).
Figure 1. Schematic diagram of dynamic programming model.

The k stage means that the natural gas which is transported from the K-1 natural gas compressor station to the K natural gas compressor station. The state variable $X_k$ of stage k (i.e. the starting state of this stage) is the outlet pressure of station k-1 ($k\geq 2$), the decision variable $D_k$ is the pressure ratio of the station k, Phase effect is the energy consumption cost of station K. Then a dynamic programming model for the pressure ratio of each compressor station of the pipeline can be established as following.

State variables:
\[ x_k = P_{d_k}, \quad k=2 \sim n+1 \]  
(1)

Decision variables:
\[ d_k = e_k, \quad k=1 \sim n \]  
(2)

Equation of state evolution:
\[ x_k = T_k(x_{k+1}, d_k), \quad k=1 \sim n \]  
(3)

Stage effect:
\[ V_k = C_k(d_k, x_{k+1}), \quad k=1 \sim n \]  
(4)

Indicator function:
\[ V(x_1, P_{d_1}, x_n, P_{d_n}) = \sum_{i=1}^{n} C_i(d_i, x_{i+1}) \]  
(5)

Optimal index function:
\[ f_k(x_{k+1}) = \min_{d_k} (f_k(x_k) + C_k(d_k, x_{k+1})) \]  
(6)

The function recursion equation:
\[ f_k(x_{k+1}) = \min_{d_k} \{ f_k(x_k) + C_k(d_k, x_{k+1}) \} \]  
(7)

Initial conditions:
\[ x_1 = P_{d_0}, \quad f_0(x_1) = 0 \]  
(8)

① The $x_1$ is the air supply pressure of the air source.
② The $P_{d_k}$ is the outlet pressure of station k.
③ The $D_k(x_{k+1})$ is the allowable decision set corresponding to its end state $x_{k+1}$ at stage k.
④ The $C_k(D_k, X_{k+1})$ is the energy consumption cost function of the $K_{k+1}$ compressor station.

2.2. Compressor Characteristic Process Calculation[6]
If the driving machine is an electric motor, then the energy consumption cost of the compressor unit as following:
Cost is the energy consumption cost of a single set of compressor units, yuan per day. 
Ns is input power for the compressor set, kW, ηd is motor efficiency, Pd is the electricity prices, yuan/(kW.h).

2.3. Compressor Characteristic Curve
In the regression and application of the compressor characteristic equation, two problems need to be noted:
① If the flow on the characteristic curve is the volumetric flow under the standard state (101325Pa, 20°C), then the standard volumetric flow should be first converted to the volume flow under the actual inlet state when regressing the characteristic equation.
② When using characteristic equations to calculate the actual process parameters of the compressor, it is necessary to convert the characteristic equations under the measured conditions into the characteristic equations under the actual conditions according to the similarity principle. Convert the flow rate under standard conditions into the volume flow rate under the compressor inlet state according to requirements firstly. The conversion formula:

\[Q_1 = Q_0 \times 0.101325 \times Z_1 \times T / (R 	imes 293.15)\]  

(10)

Q1 is the flow rate of the compressor inlet, m³/d, T1 is the temperature of the compressor inlet, K, P1 is the pressure of the compressor inlet, MPa, Z1 is compression factors of the compressor inlet, Q0 is the rate under standard conditions, Nm³/d.

Then, Q1 is changed to the corresponding flow rate at the rotational speed N0, the calculation formula is as follows:

\[Q = Q_1 \times n_0 / n\]  

(11)

For a single set of compressor, it is necessary to calculate its input power:

\[W = H \times G / \eta\]  

(12)

H is pressure head, J/kg, G is mass flow rate, kg/s, H is compressor efficiency.

From the above equation, it is necessary to return to the pressure-flow curve and efficiency-flow curve of the compressor.
① head flow characteristic equation

\[H_b = b_0 + b_1 Q_1 + b_2 \times Q_1^2\]  

(13)

b0, b1 and b2 are coefficients, H0 is the pressure head corresponding to the volumetric flow Q1 in the compressor inlet state, m. The actual pressure head of the compressor:

\[H = H_b \times (n / n_0)^{\frac{1}{2}}\]  

(14)

② efficiency-flow characteristic equation

\[\eta_b = a_0 + a_1 Q_1 + a_2 \times Q_1^2\]  

(15)

a0, a1 and a2 are coefficients, η0 is the efficiency corresponding to the volumetric flow Q1 under the compressor inlet state.

Assume that the actual speed of the compressor is n and the volumetric flow under standard conditions is Q0. In order to use Formula (15) to calculate the efficiency of the compressor, it is necessary to use Formula (10) to convert Q0 into the volume flow rate under the inlet condition of the compressor, and then use Formula (3) to convert Q1 into the corresponding flow rate Q under the rotating speed N0. The obtained Q is substituted into the efficiency-flow characteristic equation (15) to get the efficiency η.
3. Case Study

In this paper, the second line of Shaxi-Beijing as an example.

3.1. Related Process Parameters

(1) The standard state: the Pressure is $1.01325 \times 10^5 \text{Pa}$ (absolute pressure), the temperature is 20°C. The annual working days are 350 days.

(2) The absolute equivalent roughness of the inner wall of the pipe is 10μm.

(3) The pressure drop in each compressor station is 0.2MPa. The pressure drop at the inlet of the compressor station is 0.15MPa. The pressure drop in each sub-transmission station is 0.05MPa. The total heat transfer coefficient along the line was 1.75W/(m²·K).

(4) In the case analysis of this paper, The minimum allowable inlet pressure in Tongzhou station is 4.2MPa.

(5) The gas transmission efficiency of each pipe segment is 0.94. The electricity price is 1.00 yuan per KWH, and the motor efficiency is 95%. Half of the gas will be distributed to the contact line at Anping station.

3.2. Case Study of Optimization

3.2.1. Air inlet (37,000,000 m³/day)

| Station       | Inlet Flow (10000 m³/day) | Inlet Press (MPa) | Outlet Press (MPa) | Compression ratio | Compressor running quantity | Inlet temperature (°C) | Outlet temperature (°C) | Energy consumption (10000 yuan/day) |
|---------------|---------------------------|-------------------|--------------------|-------------------|----------------------------|------------------------|--------------------------|----------------------------------|
| Yulin         | 3700                      | 5                 | 9.9                | 1.96              | 3                         | 8110                   | 10                       | 60                               |
| XingX         | 3700                      | 8.28              | 9.8                | 1.187             | 2                         | 5544                   | 27.4                     | 41.8                             |
| Yanggu        | 3700                      | 7.67              | 8.5                | 1.109             | 2                         | 4669                   | 19.8                     | 29.3                             |
| Shijiazhuang  | 3700                      | 6.26              | 6.26               | 1.000             | 0                         | 0                      | 17.4                     | 17.4                             |
| Tongzhou      | 1850                      | 4.32              |                    |                   |                           |                        |                          | 0.0                              |
| **Total**     |                           |                   |                    |                   |                           |                        |                          | 7                                 |
| **Energy**    |                           |                   |                    |                   |                           |                        |                          | 118.63                           |

As above, the software can quickly calculate the optimal operating conditions of the whole line under the condition of setting the air intake.

3.2.2. The Volume number changing of air inlet. Assume that the air inlet is increased from 31,000,000 m³ per day to 43,000,000 m³ per day, and the step length is set as 2,000,000 m³ per day.

| Inlet(10000m³) | 3100 | 3300 | 3500 | 3700 | 3900 | 4100 | 4300 |
|----------------|------|------|------|------|------|------|------|
| Energy on sumption | 77.36 | 86.43 | 98.98 | 118.63 | 136.04 | 156.04 | 180.54 |

Concluded:(1)With the increase of the transmission volume, the energy consumption cost of the whole line operation increases.(2)Compared with the actual operating cost, the energy saving effect becomes less and less obvious as the quantity increases.(3)With the increase of the same gas volume, the operation cost will increase with the increase of the starting point.

3.2.3. Benefit analysis. Assume that the unit cost of the pipeline transportation is 0.1 yuan/m³, 0.15 yuan/m³ and 0.2 yuan/m³. Combine this with the table in 2.2.2 to get the following table data.
Table 3. 0.1 yuan/m², 0.15 yuan/m², 0.2 yuan/m².

| Inlet (10000m³) | Energy consumption | Profits |
|-----------------|--------------------|--------|
| 3100            | 77.36              | 232.64 |
| 3300            | 86.43              | 243.57 |
| 3500            | 98.98              | 251.02 |
| 3700            | 118.63             | 251.37 |
| 3900            | 136.04             | 253.96 |
| 4100            | 156.04             | 253.96 |
| 4300            | 180.54             | 249.46 |

Concluded:
As long as the unit cost of the pipeline transportation is above 0.1 yuan/m², the profit is increasing with the increasing of gas transportation. With the increase of the unit price of pipe transportation cost, the profit is increasing with the increasing of gas transportation.

4. Conclusion
(1) Under the condition of setting air inlet, the software can quickly calculate the optimal operating conditions of the whole line.
(2) The energy consumption cost of the whole line operation is increasing with the increase of transmission volume. Compared with the actual operating cost, the energy saving is less and less with the increase of the quantity. With the increase of the same gas volume, the operation cost will be increased with the increase of the starting point.
(3) As long as the unit cost of the pipeline transportation is above 0.1 yuan/m², the profit is increasing with the increase of gas transportation.

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