Research on Dynamic-State Optimized Operation of Natural Gas Pipeline Network

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Abstract. Natural gas is usually on unsteady-state condition, the change of volumes and pressures will bring different economic benefit at different time, so that the operation of natural gas pipeline should be optimized to guarantee the safety. By analyzing the pressure and volume varying with time, scheme could be made to increase the integrity of the system while minimizing cost. This paper develops a mathematic model to simulate the dynamic state of the system, considering maximum profit as the object function and the flow, pressure, dynamic flow equation of nodes as constraints. This paper adopts improved linearized algorithms to solve it. The result optimizes network operation.

Introduction

The major task natural gas pipeline manager faced with is to ensure the system operate economically and reasonably. A good operation scheme can guarantee safety and satisfy users' needs. Besides, the purpose of saving costs should also be concluded. So it is necessary to optimize natural gas pipeline network. When natural gas operate at steady state, it is a highly effective method to use steady-state optimized model to analyze and optimize the network^[1,2]. But natural gas is usually on unsteady-state condition in pipeline in practice production, the change of natural volumes and pressures of gas supply and users will lead to different economic benefits and pipeline flow^[3,4,5]. This situation calls for a research about dynamic-state optimized operation of natural gas pipeline network.

Dynamic-state optimized operation model of natural gas pipeline network

Temperature change is beyond consideration, which means gas flow is regarded as isothermal flow.

Object function. The gas sales revenue can be the object of the model:

$$\max F = \int_0^T \sum_{i=1}^{N_n} S_i Q_i dt \quad (1)$$

In Eq.(1), Q_i (m³/d) is the intake(distribute) flow of node i , it is positive when node i distribute gas and negative when intake flow, otherwise, the value of Q_i is 0. S_i (yuan/m³) is the cost coefficient about purchase/sale gas. N_n is the total number of nodes. T is time period and t means at any time.

Constraints. Users have different demands of gas volumes at different times, and production unit produces different amount of natural gas at different times due to reality. This situation leads to time differences of intake(distribute) flow of network system and different constraints at different times:

$$Q_{i \min}^j \leq Q_i^j \leq Q_{i \max}^j \quad (i = 1, 2, \dots, N_n) \quad (2)$$

In Eq.(2), Q_i^j (m³/d) means the intake(distribute) flow of node i at time j , $Q_{i \min}^j$ and $Q_{i \max}^j$ means the minimum and maximum intake(distribute) flow of node i at time j respectively.

The change of node pressure is also time-dependent. So the Pressure constraint is:

$$P_{i \min}^j \leq P_i^j \leq P_{i \max}^j \quad (i = 1, 2, \dots, N_n) \quad (3)$$

In Eq.(3), P_i^j (Pa) means the pressure of node i at time j , $P_{i\min}^j$ and $P_{i\max}^j$ means the minimum and maximum allowable pressure of node i at time j respectively.

If the total number of pipeline is N_p , then the gas pressure P_k must smaller than the MAOP:

$$P_k \leq P_{k\max} \quad (k = 1, 2, \mathbf{L}, N_p) \quad (4)$$

In Eq.(4), P_k (Pa) means the pressure in pipeline k , and $P_{k\max}$ means the MAOP of pipeline k .

The dynamic-state of gas flow can described by the continuity equation and motion equation [3,5]:

$$A \frac{\partial r}{\partial t} + \frac{\partial M}{\partial x} = 0 \quad (5)$$

$$\frac{\partial M}{\partial t} + \frac{1}{A} \frac{\partial}{\partial x} \left(A^2 P + \frac{M^2}{r} \right) + Ag r \sin q + \frac{1}{2} \frac{M^2}{DAr} = 0 \quad (6)$$

M (kg/s) means the mass flow rate, A (m²) means the flow area, gas density is r (kg/m³), time is t (s), pipeline length is x (m) and P (Pa) is gas pressure, q (rad) is the angle between pipeline and horizontal plane, D (m) is the inner diameter of pipe, and λ is the hydraulic coefficient of the pipeline.

The flow equilibrium equations for pipeline network with N_n nodes can be wrote as follows:[2]

$$\sum_{\substack{k \in C_i \\ i=1}}^{N_n} a_{ik} M_{ik} + Q_i = 0 \quad (7)$$

In Eq.(7), C_i means the set of units connect to node i , and M_{ik} (kg/s) is the absolute value of inflows or outflows at unit k connected to node i at one point, Q_i (kg/s) is the flow exchange between node i and outside, it is positive when flow inside and negative when outside, a_{ik} is the coefficient, its value is +1 when gas flow into node i , -1 when flow out, otherwise, the value of a_{ik} is 0.

After analyzing different time interval and space dimension, optimization variables are:

$$X = [Q_i^k, P_i^k, M_i^k] (i = 1, 2, 3 \mathbf{L} N; k = 1, 2, 3 \mathbf{L} n) \quad (8)$$

In Eq.(8), N means the total number of nodes, and n is the total number of time interval.

Calculation example

A pipeline network is shown in Fig.1[7]. The parameters are shown in Table.1. The pressure constraint is 0.5MPa~4.5MPa. After dividing the model into 12 time intervals, this paper use an improved linearized algorithm[8] to solve it. Gas price and constraints of node1 to node8 are listed in Table 2. The optimization goal is to maximum benefit. Table 3 lists optimized results and benefits.

Table 1 Pipeline Data

Pipeline	1	2	3	4	5	6	7	8	9	10	11
Up node	13	1	2	2	4	4	1	1	6	6	7
Down node	12	2	4	3	3	5	6	7	7	5	8
Length(km)	8.05	16.09	6.44	9.66	8.05	8.05	9.66	11.27	7.24	8.05	10.70
Diameter(mm)	406.4	304.8	304.8	304.8	254.0	254.0	355.6	406.4	304.8	254.0	254.0
Pipeline	12	13	14	15	16	17	18	19	20	21	22
Up node	5	5	3	11	9	10	8	14	8	12	11
Down node	9	10	11	10	8	9	11	15	14	1	16
Length(km)	14.48	14.48	19.31	9.66	12.87	11.27	17.70	4.83	2.00	2.00	2.00
Diameter(mm)	254.0	254.0	254.0	203.2	254.0	203.2	203.2	254.0	554.0	554.0	554.0

Fig. 1 Schematic diagram of natural pipeline network

Table 2 Node data(flow rate: $10^4 \text{ m}^3/\text{d}$)

Node	Price (yuan/ m^3)	Boundary	Time interval											
			1	2	3	4	5	6	7	8	9	10	11	12
1	0.00	Max	0	0	0	0	0	0	0	0	0	0	0	0
		Min	0	0	0	0	0	0	0	0	0	0	0	0
2	1.00	Max	70	55	55	80	65	55	85	55	40	30	30	40
		Min	60	45	45	70	55	45	75	45	30	20	20	30
3	1.10	Max	55	40	40	65	50	40	70	40	25	15	15	25
		Min	45	30	30	55	40	30	60	30	15	5	5	15
4	0.98	Max	55	55	55	55	55	55	55	55	55	55	55	55
		Min	45	45	45	45	45	45	45	45	45	45	45	45
5	0.95	Max	70	55	55	40	30	30	40	55	80	65	55	85
		Min	60	45	45	30	20	20	30	45	70	55	45	75
6	1.13	Max	40	40	40	40	40	40	40	40	40	40	40	40
		Min	30	30	30	30	30	30	30	30	30	30	30	30
7	1.15	Max	40	40	65	55	40	25	15	15	25	50	40	70
		Min	30	30	55	45	30	15	5	5	15	40	30	60
8	0.00	Max	0	0	0	0	0	0	0	0	0	0	0	0
		Min	0	0	0	0	0	0	0	0	0	0	0	0

Table 3 Optimized flow rate($10^4 \text{ m}^3/\text{d}$), pressure(MPa) and benefits on every time interval

Time interval		Node1	Node2	Node3	Node4	Node5	Node6	Node7	Node8	Benefits (10^4 yuan/d)
1	Flow rate	0.00	70.00	55.00	55.00	70.00	40.00	40.00	0.00	11.1
	Pressure	3.483	1.609	1.380	1.464	1.473	3.235	3.244	1.480	
2	Flow rate	0.00	55.00	40.00	55.00	55.00	40.00	40.00	0.00	9.9
	Pressure	3.371	1.890	1.722	1.774	1.779	3.148	3.155	1.609	
3	Flow rate	0.00	55.00	40.00	55.00	55.00	40.00	65.00	0.00	10.6
	Pressure	3.391	1.900	1.731	1.783	1.787	3.144	3.146	1.609	
4	Flow rate	0.00	80.00	65.00	55.00	40.00	40.00	55.00	0.00	11.6
	Pressure	3.470	1.637	1.402	1.544	1.641	3.217	3.221	1.513	
5	Flow rate	0.00	65.00	50.00	55.00	30.00	40.00	40.00	0.00	10.0
	Pressure	3.280	1.844	1.680	1.768	1.836	3.067	3.073	1.609	
6	Flow rate	0.00	55.00	40.00	55.00	30.00	40.00	25.00	0.00	8.9
	Pressure	2.709	1.441	1.314	1.370	1.411	2.513	2.522	1.208	

Table 3 Cont.

7	Flow rate	0.00	85.00	70.00	55.00	40.00	40.00	15.00	0.00	10.9
	Pressure	3.545	1.645	1.397	1.556	1.675	3.323	3.338	1.555	
8	Flow rate	0.00	55.00	40.00	55.00	55.00	40.00	15.00	0.00	9.2
	Pressure	3.350	1.872	1.704	1.758	1.764	3.148	3.161	1.599	
9	Flow rate	0.00	40.00	25.00	55.00	80.00	40.00	25.00	0.00	9.0
	Pressure	3.159	1.643	1.470	1.483	1.458	2.936	2.948	1.343	
10	Flow rate	0.00	30.00	15.00	55.00	65.00	40.00	50.00	0.00	8.7
	Pressure	3.138	1.928	1.786	1.791	1.769	2.925	2.929	1.594	
11	Flow rate	0.00	30.00	15.00	55.00	55.00	40.00	40.00	0.00	8.1
	Pressure	3.042	1.910	1.780	1.787	1.779	2.846	2.851	1.590	
12	Flow rate	0.00	40.00	25.00	55.00	85.00	40.00	70.00	0.00	10.5
	Pressure	3.381	1.814	1.624	1.636	1.596	3.116	3.117	1.478	

Conclusion

- 1、Ignore the temperature change, this paper build a dynamic-state optimized operation model on the basis of analyzing dynamic simulation model of pipeline network;
- 2、The features of this dynamic optimized model are as follows: multivariable, non-linear, non-convex feasible region composed by constraints, equality and inequality constraint equations;
- 3、This paper adopts improved linearized algorithm to solve the model of an example. The result shows that it can solve the model built in this paper quickly and effectively.

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