The Simulation of Natural Gas Gathering Pipeline Network

Peng Shanbi[*,1], Li Junying[2], Jiang Yong[3] and Liu Yuan[4]

[1]Civil Engineering and Architecture Department, Southwest Petroleum University, Chengdu, China

[2]Sichuan Kehong Oil & Gas Engineering Co., Ltd, China

[3]Beijing Oil and Gas Regulation and Control Center, Beijing, China

[4]Southwest Oil and Gas Field, Chongqing, China

Abstract: This paper focuses on developing a simulation model for the analysis of natural gas gathering pipeline network system. The simulation mathematical model of the pipeline element and non-pipeline element in natural gas pipeline network is established, the implicit difference method is used to change the partial differential model into the finite difference equations. In order to determine the unknown pressure and flow parameters, the Newton–Raphson solution technique is applied to solve the model. The simulation model is used to analyze the pipeline network in a gas field. The result simulated comparing with the actual parameter showed that the developed simulation model enabled to determine the parameters with less than 5% relative error. And we can see from the simulation results that: the pressure in each pipeline does not exceed the allowable pressure, the pressure drop is small in the pipeline network, and the flow in part of pipeline is very small. Therefore, we can adjust the gas transmission scheme, and increase the gas transmission volume properly.

Keywords: Natural gas, gathering, pipeline network, simulation.

INTRODUCTION

The gas gathering and transportation system is consists of gas gathering pipeline networks of the field, gas transmission pipelines and gas distribution networks, which combines gas gathering, gas purification, gas storage and gas distribution. It is estimated that the length of the gas pipeline in China will be close to 100,000 km in 2015. With the continuously growing development and demand scale of natural gas, the natural gas pipeline network system gradually becomes much bigger and more complicated, which makes it much more difficult to understand and master the operation law of the pipeline system. After completion of the pipeline project, the pipe structure parameters cannot be changed, while there is some contradiction between the gas production and the gas utilization due to the inhomogeneity of gas consumption. How to allocate the gas supply scheme of the natural gas pipeline network system, exploit the gas transmission potential to the greatest degree, guarantee the continuous production of the gas field, so as to obtain the maximum economic benefits; when pipeline leakage or compressor station outage occurs, how to adjust the gas transmission scheme and ensure the safe operation of the pipeline network system; when extending and reconstructing the pipeline network system, whether or not the newly-built or extended pipeline will affect normal operation of the system, all these problems above need to be solved by pipeline simulation technology. At present, there are two aspects to simplify the network simulation: Simplify the network model or use a new algorithm. This paper followed the second approach, which using the implicit difference method to solve the simulation model.

*Address correspondence to this author at the Civil Engineering and Architecture Department, Southwest Petroleum University, Chengdu, China; Tel: +86 - 28-83032453; Fax: +86 - 28-83032453;
E-mail: pengswpu@swpu.edu.cn

THE SIMULATION MODEL OF THE NATURAL GAS PIPELINE NETWORK

The basic elements of the gas gathering and transportation pipeline network system are pipeline, node, station and etc. When gas flows through these elements, the relative basic equations for mass conservation, energy conservation, momentum conservation and thermodynamics should be obeyed.

The equations for mass conservation, energy conservation, momentum conservation while gas is flowing in the pipeline are as follows [1-3]:

$$\frac{\partial P}{\partial t}+\frac{a^2}{A}\frac{\partial M}{\partial x}=0 \tag{1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(AP+\frac{a^2M^2}{AP}\right)+\frac{APg\sin\theta}{a^2}+\frac{\lambda}{2}\frac{a^2M^2}{DAP}=0 \tag{2}$$

$$\frac{\partial}{\partial t}\left[\left(h-\frac{P}{\rho}+\frac{M^2}{2A^2\rho^2}\right)\rho\right]+\frac{1}{A}\frac{\partial}{\partial x}\left[\left(h+\frac{M^2}{2A^2\rho^2}\right)M\right]+\frac{4K\left(T-T_0\right)}{D}+\frac{Mg\sin\theta}{A}=0 \tag{3}$$

In which:

ρ = gas density, kg/m^3

P = gas pressure, Pa

h = gas enthalpy, J/kg

T = gas temperature, K

θ = inclination between pipeline and horizontal plane, rad

t = temporal variable, s

M = mass flow of gas, kg/s

D = pipe diameter, m

K = total heat transfer coefficient of pipeline, $W/\left(m^2 \cdot K\right)$

T_0 = soil temperature at the buried depth of pipeline, K

g = local acceleration of gravity, m/s^2

x = length of pipeline, m

λ = hydraulic friction coefficient

A=the cross-sectional area of the pipeline, m^2

a =The wave velocity of natural gas, m/s

The unknown variables are ρ, P, T, h, M in the above three equations. It is needed to supply two equations, the state equation and enthalpy equation are as follow:

$$P = P\left(\rho, T\right) \tag{4}$$

$$h = h\left(\rho, T\right) \tag{5}$$

If there are non-pipeline components in the pipeline system, the influence caused by non-pipeline components on the flow must be considered. The non-pipeline components include compressor, valve and some local resistance devices, the flow model can be described by the inlet pressure (P_{in}), outlet pressure (P_{out}) and flow rate (M), its general form is:

$$f_1\left(P_{in}, P_{out}, M\right) = 0 \tag{6}$$

In addition, according to the law of mass conservation, the flow rate of flowing in and flowing out at any node n must be equal at any time, then

$$f_2 = \sum_{k \in C_n} \alpha_{nk} M_{nk} + L_n = 0 \tag{7}$$

In which:

M_{nk} = absolute value of flow which component k connected to the node n flows in (out) node n

L_n = flow which node n exchange with outside (inflow as positive, outflow as negative)

$$\alpha_{nk} = \begin{cases} 1 \quad \text{when flow rate in the component} \\ \text{k flows in the node n} \\ -1 \quad \text{when flow rate in the component} \\ \text{k flows out the node n} \end{cases}$$

In addition, the pressure near the node at two ends of each component is equal to the node pressure.

THE SOLUTIONOF THE SIMULATION MODEL

Because of the compressibility of the gas, the unsteady flow of natural gas in the pipeline is a slow transient process which is different from liquids, the requirement on time step is not strict when using center implicit difference method, it is convergent at any time step. And in the process of simulation, the value of time step can be long or short, which increases the flexibility of simulation and shortens the computing time required of the simulation process. As shown in Fig. (**1**), the plane composed of pipeline and time is gridded by step $\triangle x$ and $\triangle t$, the difference equations of the partial differential equation (1), (2), (3) in each grid can be obtained by adopting implicit difference method [4-8]:

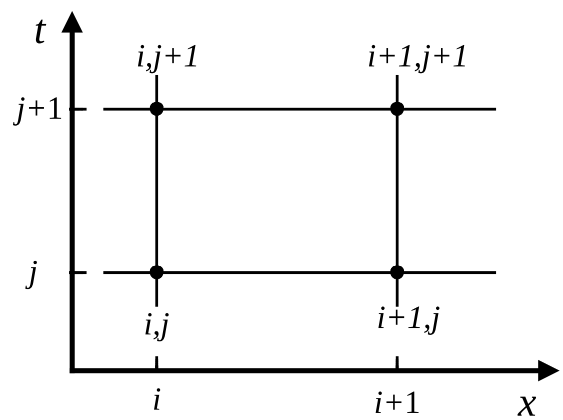

Fig. (1). Difference grid graph of pipeline.

In the four grid nodes in Fig. (**1**), the unknown variables are $P_{i,j+1}$, $P_{i+1,j+1}$, $M_{i,j+1}$, $M_{i+1,j+1}$, $T_{i,j+1}, T_{i+1,j+1}$, $\rho_{i,j+1}, \rho_{i+1,j+1}$, $h_{i,j+1}, h_{i+1,j+1}$, the known variables are $P_{i,j}, P_{i+1,j}$, $M_{i,j}$, $M_{i+1,j}$, $T_{i+1,j}, T_{i+1,j}$, $\rho_{i+1,j}, \rho_{i+1,j}$, $h_{i+1,j}, h_{i+1,j}$. The center implicit difference method is to apply the unsteady flow equations to the center point of four-point grid in finite difference form, namely:

$$\frac{\partial M}{\partial x} = \frac{M_{i+1,j} + M_{i+1,j+1} - M_{i,j} - M_{i,j+1}}{2\Delta x} \tag{8}$$

$$\frac{\partial M}{\partial t} = \frac{M_{i,j+1} + M_{i+1,j+1} - M_{i,j} - M_{i+1,j}}{2\Delta t} \tag{9}$$

$$\frac{\partial P}{\partial x} = \frac{P_{i+1,j} + P_{i+1,j+1} - P_{i,j} - P_{i,j+1}}{2\Delta x} \tag{10}$$

$$\frac{\partial P}{\partial t} = \frac{P_{i,j+1} + P_{i+1,j+1} - P_{i,j} - P_{i+1,j}}{2\Delta t} \tag{11}$$

$$\frac{\partial h}{\partial t} = \frac{h_{i,j+1} + h_{i+1,j+1} - h_{i,j} - h_{i+1,j}}{2\Delta t} \tag{12}$$

$$\frac{\partial h}{\partial x} = \frac{h_{i,j+1} + h_{i+1,j+1} - h_{i,j} - h_{i+1,j}}{2\Delta x} \tag{13}$$

$$M = \left(M_{i,j} + M_{i,j+1} + M_{i+1,j} + M_{i+1,j+1}\right)/4 \tag{14}$$

$$P=\left(P_{i,j}+P_{i,j+1}+P_{i+1,j}+P_{i+1,j+1}\right)/4 \tag{15}$$

$$T=\left(T_{i,j}+T_{i,j+1}+T_{i+1,j}+T_{i+1,j+1}\right)/4 \tag{16}$$

Substitute (8) to (16) into equation (1), (2), (3), and obtain the difference equation of continuity equation:

$$\rho_{i+1,j+1}-\rho_{i+1,j}+\rho_{i,j+1}-\rho_{i,j}+\frac{\gamma}{A}(M_{i+1,j+1}-M_{i,j+1}+M_{i+1,j}-M_{i,j})=0 \tag{17}$$

The difference equation of motion equation is as follow:

$$M_{i+1,j+1}-M_{i+1,j}+M_{i,j+1}-M_{i,j}+\frac{\gamma}{A}\Big[M^2_{i+1,j+1}/\rho_{i+1,j+1}+A^2P_{i+1,j+1} -M^2_{i,j+1}/\rho_{i,j+1}-A^2P_{i,j+1}+M^2_{i+1,j}/\rho_{i+1,j}+A^2P_{i+1,j}-M^2_{i,j}/\rho_{i,j}-A^2P_{i,j}\Big] +\frac{\Delta t\lambda\left(M_{i,j}+M_{i,j+1}+M_{i+1\blacklozenge j}+M_{i+1,j+1}\right)\left|M_{i,j}+M_{i,j+1}+M_{i+1,j}+M_{i+1,j+1}\right|}{4AD\left(\rho_{i,j}+\rho_{i,j+1}+\rho_{i+1,j}+\rho_{i+1,j+1}\right)} +\frac{A\Delta tg\sin\theta}{2}\left(\rho_{i+1,j+1}+\rho_{i,j+1}+\rho_{i+1,j}+\rho_{i,j}\right)=0 \tag{18}$$

The difference equation of energy equation is:

$$h_{i,j+1}\rho_{i,j+1}-P_{i,j+1}+\frac{1}{2A^2}\frac{M^2_{i,j+1}}{\rho_{i,j+1}}-h_{i,j}\rho_{i,j}+P_{i,j}-\frac{1}{2A^2}\frac{M^2_{i,j}}{\rho_{i,j}} -h_{i+1,j}\rho_{i+1,j}+P_{i+1,j}-\frac{1}{2A^2}\frac{M^2_{i+1,j}}{\rho_{i+1,j}}+h_{i+1,j+1}\rho_{i+1,j+1}-P_{i+1,j+1}+\frac{1}{2A^2}\frac{M^2_{i+1,j+1}}{\rho_{i+1,j+1}} +\frac{\gamma}{A}\Big[h_{i+1,j+1}M_{i+1,j+1}+\frac{M^3_{i+1,j+1}}{2A^2\rho^2_{i+1,j+1}}-h_{i,j+1}M_{i,j+1} -\frac{M^3_{i,j+1}}{2A^2\rho^2_{i,j+1}}+h_{i+1,j}M_{i+1,j}+\frac{M^3_{i+1,j}}{2A^2\rho^2_{i+1,j}}-h_{i,j}M_{i,j}-\frac{M^3_{i,j}}{2A^2\rho^2_{i,j}}\Big] +\frac{2K\Delta t}{D}\left(T_{i+1,j+1}+T_{i,j+1}+T_{i,j}+T_{i+1,j}-4T_0\right) +\frac{g\Delta t}{2A}\sin\theta\left(M_{i,j+1}+M_{i,j}+M_{i+1,j+1}+M_{i+1,j}\right)=0 \tag{19}$$

In which:

i=0, 1, 2,…………N_1, node number of pipe section

j=0, 1, 2, …………N_2, computing time level

$\gamma=\Delta t/\Delta x$ …………ratio of mesh

The above three central difference equations are established for the center point of the mesh in Fig. (**1**), and the object establishing difference equations is the mesh rather than grid point. If the pipe section of study is split into many small sections, then in $(t,t+\Delta t)$ period of time, we can obtain a series of meshes along the x-axis direction in $x-t$ domain, where each mesh corresponds to a subdivision pipe section. By establishing three central difference equations for each mesh, we can obtain a difference equation group corresponding to $(t,t+\Delta t)$ period of time for all meshes, the equation group contains only time t and variable values of all grid points at time $t+\Delta t$. If known the values of each grid point at time t, the equation group can be solved with the boundary conditions, and obtaining the variable values of each grid point at time $t+\Delta t$.

In order to solve them easily, the equations (17) to (19) can be written as:

$$\begin{cases}F_1(M_i,M_{i+1},P_i,P_{i+1},T_i,T_{i+1})=0\\F_2(M_i,M_{i+1},P_i,P_{i+1},T_i,T_{i+1})=0\\F_3(M_i,M_{i+1},P_i,P_{i+1},T_i,T_{i+1})=0\end{cases} \tag{20}$$

where $M_i,M_{i+1},P_i,P_{i+1},T_i,T_{i+1}$ are the unknown variables on time level, the frontal analysis shows that a closed equation group can be composed by the equations (17) to (19) of each mesh, flow balance of node (7) and boundary conditions, the

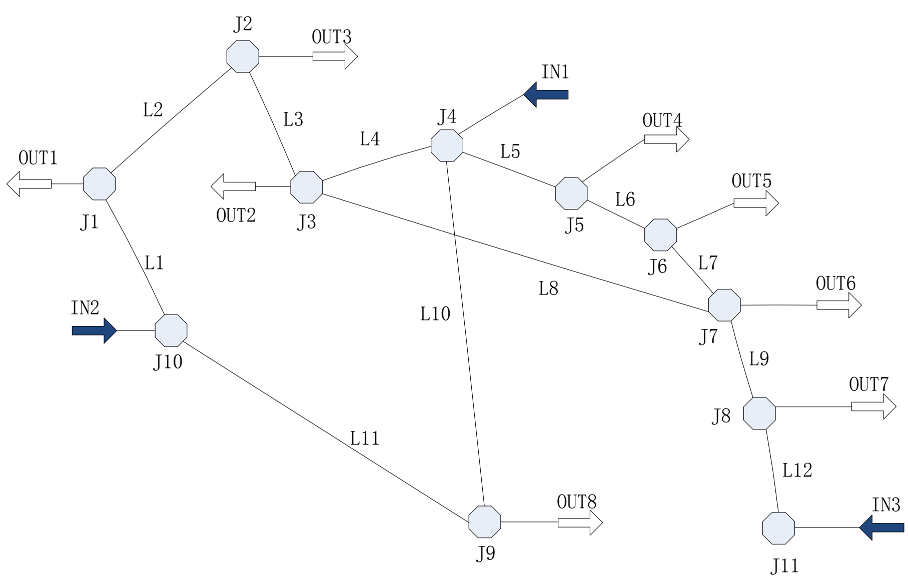

Fig. (2). Structure of pipeline network.

closed equation group is a nonlinear equation group, and can be solved by the generalized damping Newton-Raphson method.

APPLICATION

As shown in Fig. (**2**), the natural gas pipeline network is consists of 11 nodes (J_1 to J_{11}), 12 pipelines (L_1 to L_{12}), 3 intake points (IN_1 to IN_3) and 8 outlet points (OUT_1 to OUT_8), the length and diameter of each pipeline are shown in Table **1**, the flow of each outlet point and the pressure of each gas source are shown in Table **2**. The input flow of each gas source and pressure of user are obtained through simulation analysis, Table **2** shows that the minimum pressure of pipeline network is 2.9782MPa, the maximum flow of intake point is 136×10^4 m^3/d, the pressure in each pipeline does not exceed the allowable pressure, the pressure drop is small in the pipeline network, so the utilization is low, the network can transport more natural gas. Therefore, it is sufficient to meet the demand of new users along the line for gas in the next few years by adjusting the gas transmission scheme.

The results of the simulation model were compared with the actual parameters, which shown in Table **3**. The relative error for each nodal pressure is between -2.77%and 0.40%.

CONCLUSION

The natural gas pipeline network system is large and complicated; it is difficult to master the operation law of the pipeline system by conventional method. In order to simulate operation parameters accurately and efficiently, a simulation model was developed by incorporating the pipeline element and non-pipeline element. The Newton–Raphson solution technique was applied to solve the model, and the result simulated comparing with the actual parameter showed that

Table 1. Structure Parameters of Pipeline Network

Pipe	Upstream Node	Downstream Node	Diameter, m	Length, km
L1	J1	J10	359	28.6
L2	J1	J2	300	15.0
L3	J2	J3	300	19.0
L4	J3	J4	200	8.00
L5	J4	J5	300	2.30
L6	J5	J6	400	4.36
L7	J6	J7	250	3.03
L8	J3	J7	300	27.20
L9	J7	J8	300	2.00
L10	J4	J9	350	143.70
L11	J9	J10	250	142.80
L12	J8	J11	250	83.00

Table 2. Node Parameters and Simulation Results

Node	Type	Flow, m^3/d	Pressure, MPa
J1	Out1	-150×10^4	*2.9782
J2	Out3	-20×10^4	*2.9955
J3	Out2	-5×10^4	*3.0568
J4	IN1	$*46.6\times10^4$	3.10
J5	Out4	-7×10^4	*3.0974
J6	Out5	-6×10^4	*3.0967
J7	Out6	-5×10^4	*3.0941
J8	Out7	-6×10^4	*3.0953
J9	Out8	-10×10^4	*3.1017
J10	IN2	$*136\times10^4$	3.20
J11	IN3	$*26.8\times10^4$	3.30

Remark: the one with * is the value of simulation, inflow as positive, outflow as negative.

Table 3. Comparison of Nodal Pressures

Node	Type	Flow, m^3/d	Simulated Pressure, MPa	Actual Pressure, MPa	Relative Error, %
J1	Out1	-150×10^4	*2.9782	3.0221	1.45%
J2	Out3	-20×10^4	*2.9955	2.9453	-1.70%
J3	Out2	-5×10^4	*3.0568	2.9745	-2.77%
J5	Out4	-7×10^4	*3.0974	3.1098	0.40%
J6	Out5	-6×10^4	*3.0967	3.0546	-1.38%
J7	Out6	-5×10^4	*3.0941	3.1045	0.33%
J8	Out7	-6×10^4	*3.0953	3.1023	0.23%
J9	Out8	-10×10^4	*3.1017	3.0987	-0.10%

Remark: The one with * is the value of simulation.

the developed simulation model enabled to determine the parameters with less than 5% relative error. The developed simulation model could be easily extended to be applied for the analysis of gas gathering pipeline network systems for other petroleum products.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

Declared none.

REFERENCES

[1] Changjun, L. *Pipeline transportation of natural gas*. Petroleum Industry Press: Beijing, **2000**.

[2] Changjun, Li.; Ziqiang, Z. Simulation of gas pipeline network system. *Oil Gas Storage Transp.*, **1997**, *2*, 21-25.

[3] Zemao, J.; Yutang, X.; Wang S. *Simulation and analysis of gas transportation and distribution pipeline network*. Petroleum Industry Press: Beijing, **1995**.

[4] Changjun, L. Analysis of gas unsteady flow in pipeline system. *Nat. Gas Ind.*, **1994**, *6*, 54-59.

[5] Changjun, L.; Zemao. J. Analysis of gas unsteady flow in pipeline system. *Acta Petrol. Sin.*, **1998**, *19*(4), 99-103.

[6] Enbin, L.; Changjun, L. Study and application of emulation technology on the reformation of pipeline system for gas fields. *Nat. Gas Ind*., **2005**, *1*, 135-138.

[7] Shashi Menon, E. *Gas Pipeline Hydraulics*, CRC Press, USA, **2005**.

[8] Bruce, E.; Larock, R.W.; Jeppson, G.Z. *Watters, Hydraulics of Pipeline Systems*, CRC Press, USA, **2000**.

Received: April 8, 2013 Revised: July 21, 2013 Accepted: August 6, 2013