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Dynamic simulation of an underground gas storage injection-production network

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Abstract

Underground gas storage is a well-known strategic practice to seasonal peak shaving and emergency facility. The changing operation conditions of injection-production network directly affects the reliability of downstream gas supply of the city. In the present study, a model of injection-production network on the basis of field data analysis and research was established. By comparing the actual node pressure and simulation results, the reliability of model was verified. Based on the volume of underground gas storage and downstream gas consumption, the best seasonal peak-shaving schedule of the whole year was set. According to dynamic analysis of network, 20% increase in downstream demand could be fulfilled. Besides, the study also analyzed the well pressure and flow rate changes after shutdown of gas well, which is most likely to fail, and concludes that the best rescue time should be within 4 hr after gas supply interruption. The results would help in making decisions about the operation of injection-production network, which have important significance in the environmental protection.

Key words

Injection-Production Network, Operation Condition, Simulation

Introduction

Underground gas storage has a history of nearly 100 years (Ding, 2011), and is a well-known strategic practice to cope with the growing demand of natural gas market(Teatini, *et al.,* 2011; Malakooti and Azin, 2011; Shahvali Adib *et al.,* 2014), balancing the supply-demand chain throughout the year. The Chinese energy sector has undergone significant changes in recent decades. In particular, consumption and production of natural gas have intensified, and more infrastructures for its transport and storage have been built(Figueira *et al.,* 2014; Mohanty and Vandergrift, 2012). It is estimated that the length of the natural gas pipeline in China will be close to 100,000 km in 2015 (Peng *et al.,* 2013), and a large number of natural gas pipeline projects such as West-to-East Gas Transmission Pipeline, Sichuan to East Gas Pipeline have been completed. Moreover, two underground gas storage feedings have been constructed in Bohai region (Guo *et al.,* 2012). Some underground gas storages such as Xiangguosi underground gas storage, Hutubi underground gas storage, Bannan underground gas storage are under construction. However, as the growth of natural gas consumption demand, underground gas storage demand increase, it is reported that the natural gas consumption of China will amount to $3000\times10^{8}\,m^{3}$ in 2020 (Ding, 2010), and the maximum peak demand will appear in 2025. A significant amount of research has been conducted on the underground gas storage.

Figueira *et al.* (2014) investigated the relationship between storage and various characteristics of gas sector by linear regression analysis, and conducted on all 38 countries with operational underground natural gas storage, evaluated the extent to which storage capacity is affected by proven reserves, production, consumption, infrastructure, total gas imports and exports, and the use of natural gas as a percentage of total national energy consumption. Malakooti and Azin (2011) used a modified Peng-Robinson equation to estimate the phase behavior of reservoir and injection fluid[0]. The compositional model was verified by performing a history matching on gas production rate. Results showed that the use of a horizontal well was superior to vertical well because of less water production during storage cycles. Bojan and Stojan (2011) presented the cost optimization of an underground gas storage. Optimization was performed by a non-linear programming (NLP) approach.

Teatini *et al.* (2011) presented a methodology to evaluate the environmental impact of underground gas storage and sequestration from the geomechanical perspective, particularly in relation to ground surface displacements. Shahvali *et al.* (2014) invented a new formulation in order to prevent cement cracking. Mohanty and Vandergrift (2012)discussed a novel approach for the analysis of the long term stability of an underground propane gas storage cavern in sedimentary rock formations. Kyung-Seok *et al.* (2011) analyzed the groundwater flow in the underground storage caverns.

It should be noted that previous research aiming at optimization of underground gas storage and stability of cavity, only few studies have considered the injection-production network. Hu *et al.*, (2011) established design procedures for the injection and production scale of seasonal-peak-shaving UGS. Ma *et al.* (2013) established domestic pioneer Ma-Cheng (MC) foumula to describe mathematical relationship between operate well, well numbers and other parameters. Meanwhile, with the growth of underground gas storages, extensive injection-production networks will be needed. In order to fulfill the reliability, safety and efficiency of underground gas storage, the operation condition of injection-production network plays a significant role. The changes is node pressure and flow rate directly affects the reliability of downstream gas supply.

Furthermore, with the development of gas pipelines, awareness of the environmental problems caused by natural gas has become more and more central in the last decades. Methane gas released in the atmosphere can cause global warming. Similarly, green house gases like CO_2, CH_4, O-3 and N_2O contribute similar about 60%, 20%, 10% and 6% to global warming, respectively (Dalal *et al.*, 2008). By analyzing peak-shaving and failure condition, the scheme of peak-shaving and best rescue time can be determined according to simulation, thus providing basis of reliable operation, which can give some useful suggestions for petroleum company.

It is worth pointing out that although many researchers had do a large number of work on the operate condition and the stability of underground gas storage,it is significant to research operate conditions of the injection-production network. This paper presents the use of Pipeline Studio for feasibility analysis of the natural gas network.

Materials and Methods

Theoretical basis : Assuming that during the process of injection and production, gas in pipeline is one dimensional flow and the basic flow equations are the continuity equation, momentum equation, energy equation, gas state equation, enthalpy equation and so on (Li and Zeng, 1997; Liu *et al.*, 2014).

The continuity equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial x} = 0 \qquad (1)$$

Where, ρ-gas density, (kg m^{-3}); v-gas velocity, (ms^{-1}); t- time, (s); x- pipe length, (m).

The momentum equation for gas is:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v^2)}{\partial x} = -g\rho - \frac{\partial P}{\partial x} - \frac{\lambda}{D}\frac{v^2}{2}\rho \qquad (2)$$

Where, g-gravitational acceleration vector, (ms^{-2}); ρ-pipeline pressure, (Pa); λ-hydraulic friction coefficient; D-pipeline diameter, (m).

The energy equation is:

$$-\rho v\frac{\partial Q}{\partial x} = \frac{\partial}{\partial t}\left[\rho\left(u + \frac{v^2}{2} + gx\right)\right] + \frac{\partial}{\partial x}\left[\rho v\left(h + \frac{v^2}{2} + gx\right)\right] \qquad (3)$$

Where, Q-released heat per mass, (Jkg^{-1}); u-internal energy of the gas, (Jkg^{-1}); h-enthalpy of the gas, (Jkg^{-1}).

The gas state equation is:

$$P = P(\rho, T) \qquad (4)$$

The enthalpy equation is:

$$h = h(\rho, T) \qquad (5)$$

Where, T—temperature (K).

Injection-production network model of underground gas storage : Assumption when establishing gas storage injection-production network model: The gas flow in pipeline was one dimensional; Ignoring the pressure loss of pigs, regulating valves,

Table 1: Monthly peak-shaving volume in 2013 ($10^4 m^3$)

Month	Consumption prediction	Average flow volume	Production volume
January	33457.36	27000	6457.36
February	27667.17	27000	667.17
March	26835.07	27000	-164.93
April	24949.56	27000	-2050.44
May	24205.17	27000	-2794.83
June	22638.12	27000	-4361.88
July	29411.51	27000	2411.51
August	29435.19	27000	2435.19
September	26694.61	27000	-305.39
October	28771.86	27000	1771.86
November	27606.83	27000	606.83
December	31965.14	27000	4965.14

block valve and other small resistance elements (Jiang *et al*., 2004); the underground gas storage of each well was simplified as gas resource(Liu *et al.,* 2014); The maximum pressure of each gas source was less than 10MPa, while the minimum pressure was greater than 7MPa (Yang *et al.,* 2013; Huang *et al.,* 2013; Azin *et al.,* 2008). According to gas storage injection-production network, combining with relevant parameters, the established model is shown in Fig.1 which includes parameters like pressure , flow and other relevant parameters.

Results and Discussion

Steady-state simulation analysis of injection-production network : According to the applicable scope of three conventional gas equation (Sarem, Peng-Robinson, BWRS), simulation was done by software TGNET. Assuming that the inlet and outlet pressure was unknown and comparing the inlet/outlet pressure simulated to the actual inlet/outlet pressure (Ma *et al.,* 2013; Tibor *et al.,* 2013). The relative errors of these three equations were less than 0.5% (Fig. 2) of which BWRS equation was minimum, so BWRS was selected to analyze the network.

Analysis of injection-production network peak-shaving scheme : The downstream city of underground gas storage supply was symbolized as M, the gas flow of main pipeline per month was 27000×10^{4}m^3 and the peak-shaving volume of each month in 2013 is shown in Table 1. According to Table 1, consumption of gas in March, April, May, June and September can be fulfilled without supplement, while the demand of underground gas storage was peaked during December and January.

Seasonal peak-shaving analysis : Gas production of each gas well was (50~200)×10^{4}m^3 d^{-1}; volume of each cavity was (2800~3000)×10^{4}m^3, while the operation pressure of wellhead varied from 7MPa to 10MPa and the optimal wellhead pressure

Table 2: Summary of underground gas storage seasonal peak-shaving in 2013

Month	Prediction of peak volume (10^{4}m^3)	Simulated peaking capacity (10^{4}m^3)	Gas recovery time	Number of recovery wells	Gas production conditions
January	6457.36	6234.134	16days+11hours	8	Well10Well2:8.1388~8.0899MPaWell30Well40Well50Well6:8.126~8.0814M aWell7: 8.1224~8.0791MPaWell8:8.1205~8.0778 MPa All the wells' flow: 20.84~16.64km^3 hr^{-1}All the wells' flow: 20.84~16.64km^3/h
February	667.17	683.552	41hours	8	Well10Well2: 7.16MPaWell3~Well6: 7.15MPaWell7~Well8: 7.14MPaAll the wells' flow: 20.84km^3 hr^{-1}
July	2411.51	2563.5	9days	4	Well1: 10MPa, 27.6~36.67km^3 hr^{-1}Well2: 10MPa, 29.7km^3 hr^{-1} Well40Well5: 9.946~9.961MPa,29.7km^3 hr^{-1}
August	2435.19	2283.4	8days	4	
October 1	1771.86	1771.89	8days	3	Well3: 9.99 MPa,30.762km^3 hr^{-1}Well6: 9.99MPa,30.762km^3 hr^{-} Well7: 10MPa,30.762km^3 hr^{-1}
November	606.83	609.087	2days+18hours	3	
December	4965.14	5201.664	13days	8	Well10 Well2:8.1388MPaWell3~Well6: 8.126MPaWell7:8.1224 MPa, Well8: 8.1205MPaAll the wells' flow: 20.84 km^{3}hr^{-1}

Table 3 : Operation pressure on the condition of production increase (MPa)

Pipeline	Production	10% increment of production			20% increment of production		
	Pressure drop	Inlet	Outlet	Pressure drop	Inlet	Outlet	Pressure drop
Pipe 1	0.02859	8.20047	8.15997	0.0405	8.27019	8.2159	0.05429
Pipe 2	0.01504	8.18128	8.15997	0.02131	8.24447	8.2159	0.02857
Pipe 3	0.01503	8.18126	8.15997	0.02129	8.24444	8.2159	0.02854
Pipe 4	0.00487	8.173	8.16774	0.00526	8.23725	8.22799	0.00926
Pipe 5	0.00233	8.16897	8.16569	0.00328	8.22799	8.2236	0.00439
Pipe 6	0.00371	8.17588	8.16897	0.00691	8.23338	8.22633	0.00705
Pipe 7	0.00145	8.16774	8.16569	0.00205	8.22633	8.2236	0.00273
Pipe 8	0.00402	8.16569	8.15997	0.00572	8.2236	8.2159	0.0077
Pipe 9	0.05546	8.07866	8	0.07866	8.10579	8	0.10579

was over 9MPa (Figueira *et al.,* 2014). The peak volume was predicted by the flow of pipeline and gas consumption of the city every month. Based on the conditions above, seasonal peak-shaving simulation was set by TGNET and the scheme of gas production of each well was determined (Table 2).

As shown in Table 2 and Fig. 3, the simulated peaking capacity of January was less than the peak volume predicted, but it could be supplied by the extra volume of December. In the same way, July produced gas for August, the scheme of gas injection-production network could fulfill peak-shaving consumption for the whole year.

Analysis of forward peaking capacity : With the intensive focus on environment protection by the Chinese government and promotion of clean energy in recent years, the demand of natural

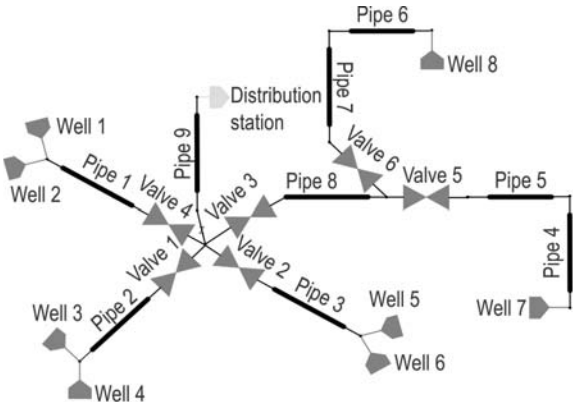

Fig. 1 : The underground gas storage injection-production network model

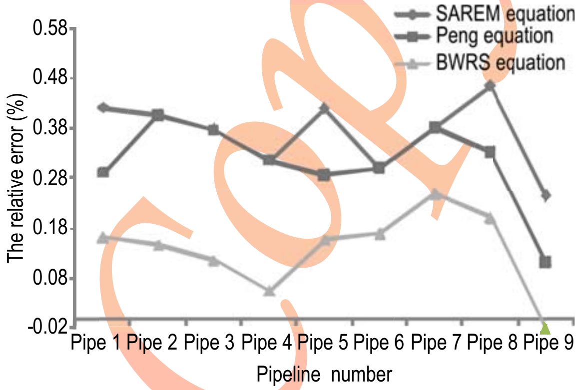

Fig. 2 : Comparing three equations' relative error

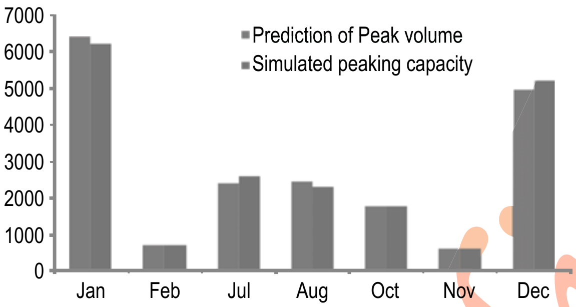

Fig. 3 : Comparing of peaking capacity forecast with peaking capacity reality in 2013

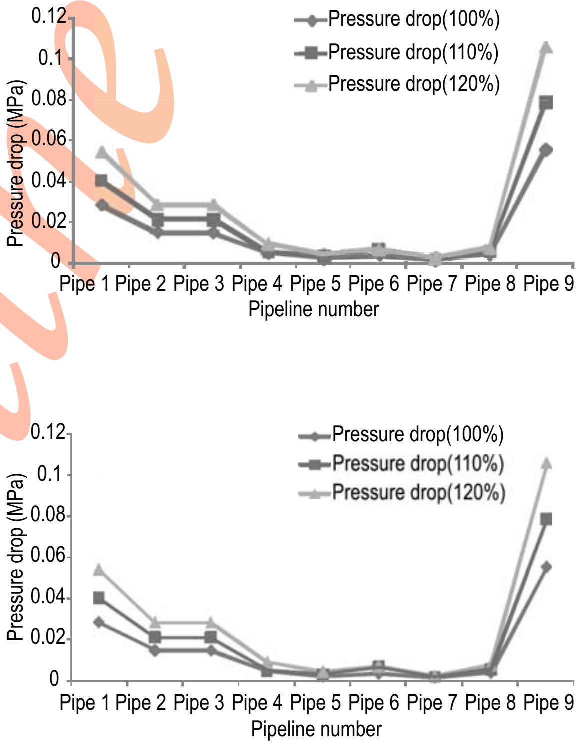

Fig. 4 : Pressure drop of the underground gas storage's pipeline under different mining

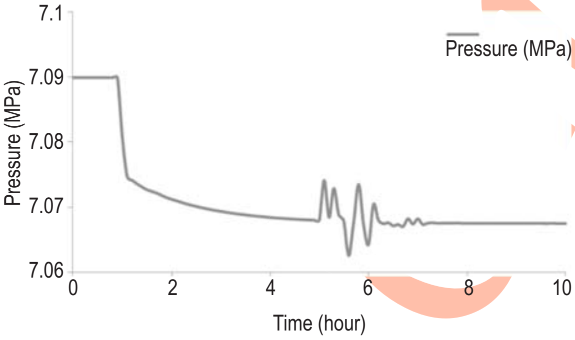

Fig. 5 : Variation on pressure after interruption of well 8

gas is increasing 15% each year. According to the peak-shaving data from 2010 to 2013 of the city M, the demand of natural gas increased by 5%~40% each month. Based on the basic parameters of gas pipeline and actual peak-shaving working condition on 31st, December 2013, simulation was done with an increment of 10% and 20% on the original production. Gas production on 31st, December 2013 was 400.13×10^{4}m^3, plus with an addition of 10%, the flow rate of each well was 22.924 km^3 hr^{-1}, while plus with an addition of 20%, the flow rate of each well was 25.008 km^3 hr^{-1}. According to forward peaking capacity analysis, the pressure is shown in Table 3 and Fig. 4, with an increment of 10% and 20% of the total production.

As seen in Table 3 and Fig. 4, with increase in production,

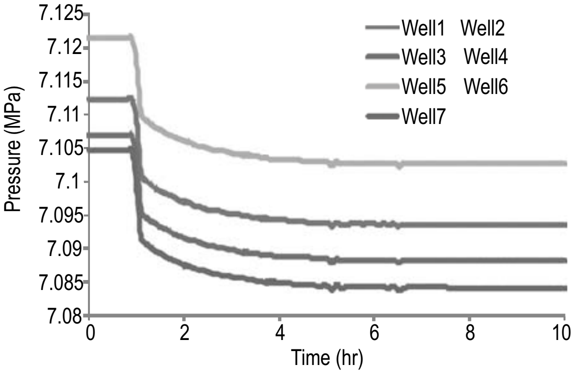

Fig. 6 : Pressure variation of other gas wells after supply interruption of well 8

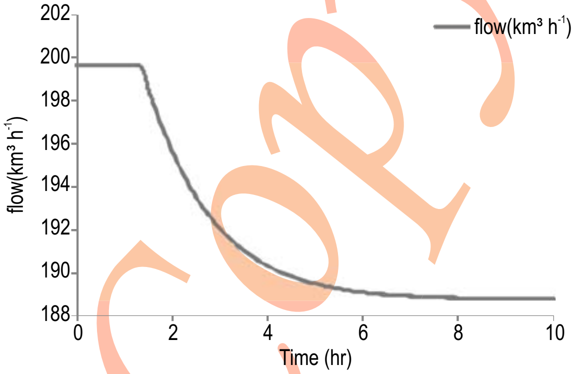

Fig. 7 : Variation on flow rate of distribution station after a supply interruption of well 8

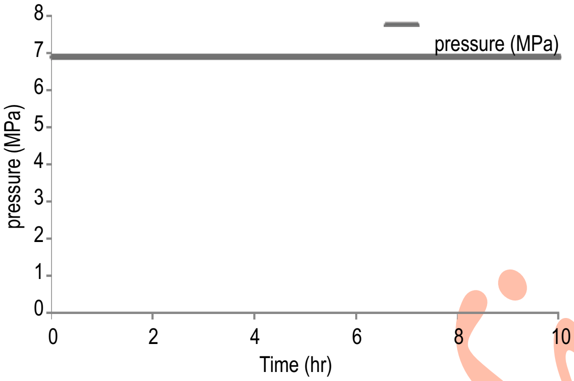

Fig. 8 : Variation on pressure of distrubiton station after supply interruption of well 8

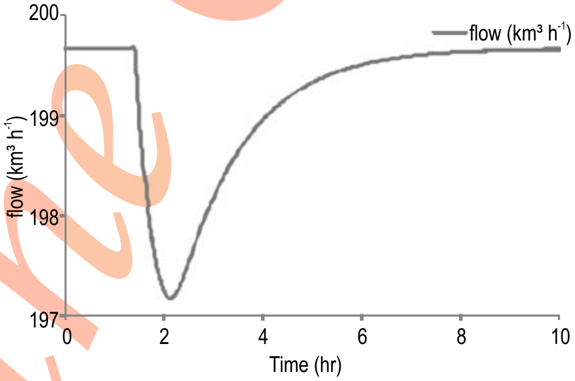

Fig. 9 : Recovery process of flow rate of distribution station

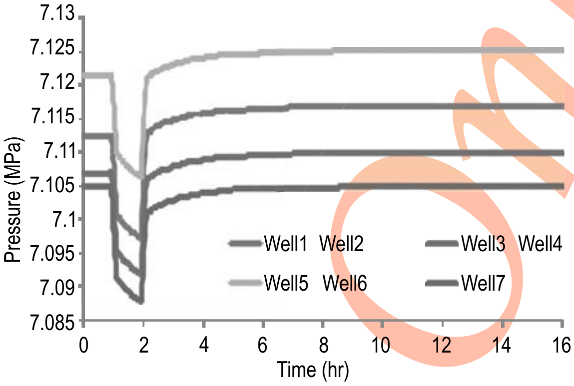

Fig. 10 : Recovery process of pressure of each gas well

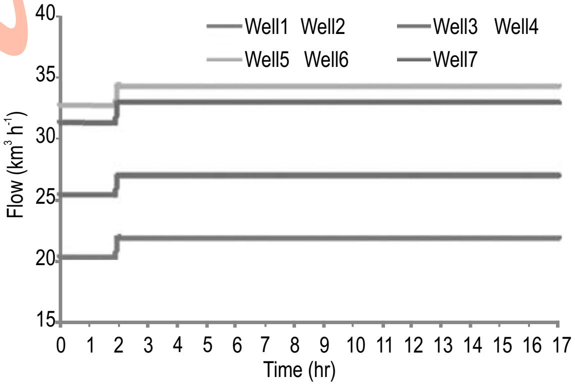

Fig. 11 : Variation on flow rate of each gas well

the pressure drop increased in pipeline. The pressure drop of pipeline connected to gas well tends to be bigger than that of other pipelines, so during operation single well should avoid full-load running. When production increased by 20%, the maximum pressure of network was 8.27MPa and fulfilled the pressure requirement during production period. In short term, the peaking capacity was sufficient with 20% increase in demand.

Duration time and recovery process with interrupted gas supply : Throughout gas production process, the capacity of dissolution cavities became small, thus affecting gas pressure. When pressure dropped to a certain extent, it could not meet the needs of gas production. In case of fire, abnormal pressure, gas tree damage and other accidents, the safety valve would be automatically shut down, underground, and cut off the gas supply to avoid accidents (Ding, 2010). Assumed that the supply of well 8 interrupts at 1 hr, analyze the simulation within 10 hr after interruption.

Influence on the injection-production network when supply interrupts :

Working condition of other production well : When the supply of well 8 interrupted after 1 hr, the flow rate became zero pressure dropped sharply and became stable. As shown in Fig. 5, the pressure fluctuated most from 4th hr to7th hr, this was a transition from one stable state to another. Pressure fluctuation damages the gas well, therefore it should be avoided.

Fig. 6 shows the pressure trend of other wells after interruption of well 8, from which the pressure of other wells shared almost same trend with well 8, while fluctuation was not that severe as well 8. It should be noted that the pressure change of well 1 was similar to well 2, well 3 was similar to well 4 and that of well 5 was similar to well 6.

Influence on pressure and flow of distribution station : After supply interruption of well 8, the variation of flow rate and pressure of the distrubution station was shown in Fig. 7 and 8. The pressure of distribution station is maintained at 6.9 MPa, and the flow rate was kept 199.67 km^3 hr^{-1} from 1~1.3 hr, but decreased to 199.374 km^3 hr^{-1} at 1.4 hr. After 10 hrs, the flow rate decreased to 188.774 km^3 hr^{-1}.

Recovery process : The flow rate of well 8 was 10.91km^3 hr^{-1} before interruption. In order to recover its production, the flow rate

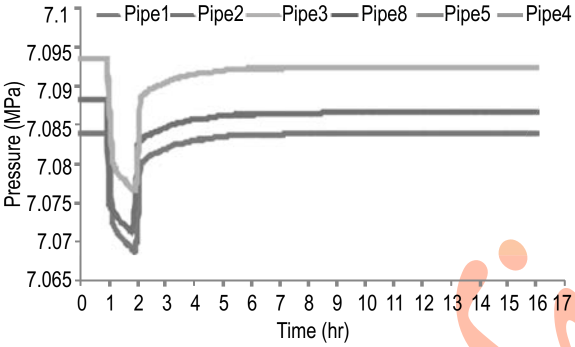

Fig. 12 : Recovery process of pressure of each pipeline

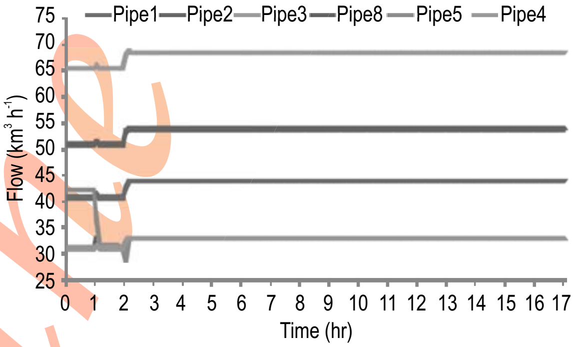

Fig. 13 : Variation of flow rate of each pipeline after interruption of well 8

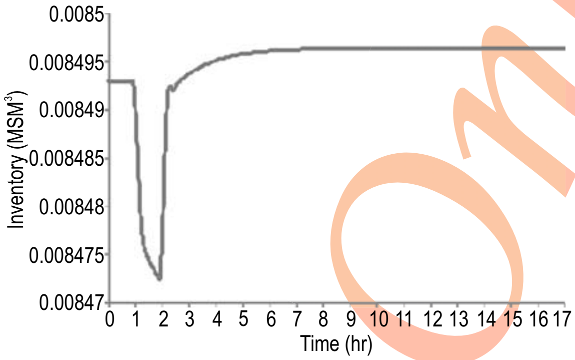

Fig. 14 : Variation on inventory of pipe 1; (MSM3: million standard cubic meters)

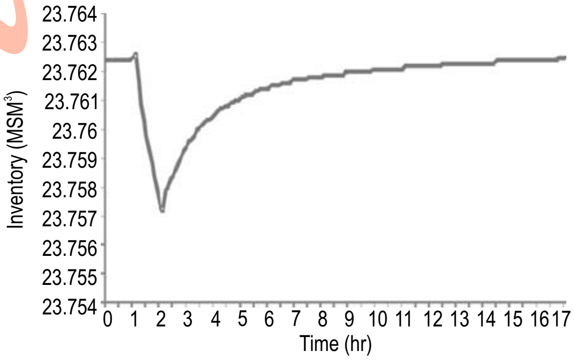

Fig. 15 : Variation on inventory of pipe 9; (MSM3: million standard cubic meters)

of other wells were increased appropriately. Assumed that when the interruption occurred , the block valve would be shut down 1 hr later.

Variation of flow rate of the distribution station : Increase in flow rate of other gas wells and the recovery process of distribution station is shown in Fig. 9. The flow rate started rising after 2.4 hr, revived after 9.7hr and was stable at a flow rate of 199.67km^{3}hr^{-1}.

Variation on pressure and flow rate of each gas well : As shown in Fig. 10, after increasing the production of each gas well, the trend of recovery process was same. The pressure rose again when production of each gas well increased and was stable at a higher level, because the increase of flow rate leds to an increasing demand of pressure correspondingly. The flow rate of each gas well varied, based on the setting value, from the very beginning to the final level, the flow rate was stable, as shown in Fig. 11.

Variation on pressure and flow rate of each pipeline : The recovery process of pressure of each pipeline is shown in Fig. 12, and it was same for each gas wells (normally 9.8 hr). The pressure of pipe 9 revived at 6.99MPa after 4.3 hr and was stable at this level. Furthermore, it was observed that closer to well 8, pressure declined.

As shown in Fig. 13, the flow rate of pipe 1~pipe 5 all increased with increase in production of each gas well during 2nd hr and was stable at a constant flow rate. However, the flow rate of pipe 8 decreased during 1st hr, due supply interruption of well 8, pipe 8 only contained the flow of well 7 and shared similar trend of flow variation with pipe 4 and pipe 5 after 1 hr. After increasing the flow rate of other gas wells, the flow rate gradually revived and reached 199.67km^{3}hr^{-1} after 15.6 hr.

Variation in inventory of each pipeline was similar to pipe9 (Fig. 15). Inventory of each pipeline started rising at 2nd hr and was stable at constant value. Storage of pipe9 increased all along 17 hr of simulation, the pressure of each pipeline increased, according to the previous analysis, the increase in storage was reasonable.

In the present study, a simulation model of injection-production gas network was built based on continuity equation, momentum equation, energy equation, gas state equation and enthalpy equation, to simulate the steady working conditions to verify the reliability of model.

Peak-shaving scheme of injection-production network and seasonal peak-shaving scheme of gas production of each well was determined. Through research it found that peaking capacity was sufficient with an increase of 20% in demand.

The working conditions of other production well and pipes after a well interrupted was simulated, duration time and recovery process were also analyzed.

The results simulated will help the people in taking decisions about the operation of injection-production network, shortening rescue time, decreasing natural gas released into the atmosphere and there is no doubt that it will do something on the environment protection.

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