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Influence analysis on the storage capacity of hydrogen-blended natural gas pipeline

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Abstract:
Blending a certain proportion of hydrogen into existing natural gas pipelines is an efficient way to achieve large-scale hydrogen delivery. The line pack is crucial for balancing the gas supply-demand and determining the gas loss of natural gas transmission or distribution system. It is essential to investigate the influence of hydrogen blending on line pack when the natural gas pipeline is used for transporting hydrogen-blended natural gas. In this paper, a calculation model of hydrogen-blended natural gas line pack is established, and the line pack and its influencing factors are analyzed under the hydrogen blending ratio of 0-90%, inlet pressure of 4.0-6.0 MPa, inlet temperature of 253.15-323.15 K, and pipeline throughput of 1.4×10^9-3.5×10^9 Nm^3/a. Results indicate that increasing the hydrogen blending ratio usually reduces the line pack, but the effect depends on a complex interaction of inlet pressure and pipeline throughput. Under low inlet pressure and high pipeline throughput conditions, the line pack may increase with the raise of hydrogen blending ratio due to the low viscosity of hydrogen. In addition, an increase in inlet pressure has a significant positive effect on the line pack, and the storage capacity of pipeline is proportional to the pressure. However, the increase of pipeline throughput induces a larger pressure drop, resulting in a decrease in the average pressure and hence reduces the storage capacity. The influence of inlet temperature is more limited because the physical properties of hydrogen-blended natural gas change slightly over the operating temperature range of the pipeline, leading to a slight decrease in the line pack. For the regulation of hydrogen-blended natural gas pipeline storage capacity, the inlet pressure is the key influencing factor and it is effective to regulate the storage capacity by change the inlet pressure, increasing the hydrogen blending ratio, pipeline throughput and inlet temperature are unfavorable to increase the pipeline storage capacity.

1. Introduction

In the background of global energy transition and carbon neutrality target, the application of hydrogen blending technology in natural gas pipeline transportation is regarded as an important way to achieve clean energy conversion and reduce carbon emissions (Li et al., 2021a; Hu et al., 2023). In the pipeline transportation of natural gas, the line pack (natural gas that is stored in the pipelines) is commonly used as an important index for balancing the gas inflow and outflow from the pipeline, and analyzing the gas loss of the pipeline system (Ding et al., 2018). The line pack is a comprehensive index reflecting the pressure, temperature, and throughput of pipeline operation. However, due to the difference between the physical properties of hydrogen and natural gas, the hydraulic and thermal characteristics of pipeline operation will be affected when hydrogen is mixed into the natural gas pipeline (Ding et al., 2018; Pedersen et al., 2022), resulting in the change

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of line pack. Therefore, revealing the influence of hydrogen blending on the line pack of natural gas pipeline is an urgent issue to be solved.

In recent years, many researches have been devoted to the line pack of natural gas. For example, Lin et al. (2020) calculated the inventory of the West-East Natural Gas Pipeline based on the theoretical method, using the Sukhov's formula to correct the valve chamber temperature and ground temperature, whereas the density was calculated using the gas relative density collected by SCADA, which improves the reliability of the calculation to a certain extent. Based on the theoretical formula of line pack, Ettouney and El-Rifai (2009) obtained a more accurate estimation of line pack by considering the variation of pressure, temperature, compressibility factor, and velocity along the pipeline. Although above studies can provide valuable reference for the calculation of line pack, most of them are relying on the assumption of steady state operation of natural gas pipelines, which is difficult to accurately reflect the dynamic change of pipeline storage capacity in actual operation. Zhu and Guo (2016) regarded the dynamic change of pipeline parameters as a change process of thermodynamic parameter with a multivariate index of n, then the calculation formula for unsteady line pack was derived based on the gas equation of state (EoS) and the equation of motion, and the results were close to that of TGNET software. Wen et al. (2022) proposed a method for calculating the dynamic line pack using a transient flow simulation model of natural gas pipelines. The calculation method for unsteady flow line pack used by Li (2017), and the calculation formula of End-of-pipeline gas storage proposed by Zhang et al. (2012), provide important perspectives for understanding the transient storage behavior of natural gas pipelines.

Based upon above representative works, although the calculation of line pack of natural gas has gained increasing attention, it should be noted that above investigations all focused on the natural gas pipelines. The investigation of line pack calculation in the presence of hydrogen blending is still rarely reported. Only a few scholars have conducted relevant research. For example, Quarton and Samsatli (2020) evaluated the effect of hydrogen blending on natural gas line pack by considering changes in the compressibility factor and kinematic viscosity of HBNG under the assumption of a constant pipeline pressure drop. It was found that HBNG pipelines have less flexibility to regulate pipeline storage than traditional natural gas pipelines, especially for high-pressure (80 bar) transmission pipelines, where the storage flexibility of pure hydrogen pipeline is only 17% of that of natural gas pipeline. Haeseldonckx and D'haeseleer (2007) proposed an analytical formula for determining the line pack, results indicated that under the conditions of satisfying the energy demand and considering the calorific value of hydrogen and natural gas, the pipeline storage energy of hydrogen is approximately one quarter smaller than that of natural gas, which can jeopardize the short-term supply security. These studies suggest that the hydrogen blending has significant influence on the pipeline storage capacity of natural gas, reducing the gas supply security.

In addition, some scholars investigated the influencing parameters of HBNG line pack. For example, Zhu et al. (2021) used the SPS software to simulate the gas volume storage and energy storage at the end segment of a HBNG pipeline. Compared with traditional natural gas pipeline, the gas storage capacity at the End-of-pipeline is reduced by about 6%, 10%, and 13% when the hydrogen blending ratios (HBRs) are 10%, 20%, and 30%, while the energy storage capacity is reduced by approximately 12%, 22%, and 30%, respectively. Feng et al. (2024) established a mathematical model for HBNG pipeline transmission based on the empirical formula of gas properties, it was found that hydrogen blending reduces the storage capacity and regulation ability of the pipeline network to a certain extent. Uilhoorn (2013) investigated the line pack calculation for high-pressure HBNG pipelines under non-isothermal conditions, results indicated that the flow rate has significant influence on the pipeline storage capacity. Qadrdan et al. (2017) found that the line pack is proportional to the pipeline average pressure by using the Panhandle-A equation to simulate the gas flow while considering the constraints of pipeline pressure and gas supply capacity. Although scholars have conducted preliminary investigations on the calculation of HBNG line pack, the range of HBRs investigated is small, and the large range of HBRs has not been considered; Furthermore, the effects of pressure, temperature, and pipeline throughput have not been sufficiently studied in above literature, requiring further in-depth exploration.

To comprehensively investigate the calculation of HBNG line pack and its influencing parameters, particularly the effect of a large range of HBR, a calculation model for HBNG line pack is established based on the BWRS-EoS, hydraulic and thermal governing equations. Predictions and comparative analysis of HBNG line pack at the hydrogen blending ratio (HBR) of 0-90%, inlet pressure of 4.0-6.0 MPa, inlet temperature of 253.15-323.15 K, and pipeline throughput of 1.4×10^9-3.5×10^9 $\mathrm{Nm^3/a}$ are conducted, and the effects of different influencing factors on HBNG line pack are discussed in detail.

2. Calculation model for HBNG line pack

2.1 Model of line pack

The formula for calculating line pack can be derived from the real gas EoS, which is given by:

$$V_0 = V_1 \times \frac{P_{av}}{P_0} \times \frac{T_0}{T_{av}} \times \frac{Z_0}{Z_1} \tag{1}$$

where V_0 is the theoretical line pack at standard state, $\mathrm{Nm^3}$; V_1 is the pipeline volume, $\mathrm{m^3}$; P_{av} is the average pipeline pressure, Pa; T_{av} is the average pipeline temperature, K; Z_1 is the real gas compressibility factor; P_0 is the standard pressure, Pa; T_0 is the standard temperature, K; Z_0 is the gas compressibility factor at standard condition.

2.2 Gas equation of state

To solve Eq. (1), the state parameters of HBNG need to be calculated and suitable gas EoS should be selected. The BWRS-EoS (Starling and Powers, 1970) has been the most widely used real gas model in engineering practice for describing the state of natural gas. The performance of

BWRS-EoS in calculating the thermodynamic properties of light hydrocarbons and mixtures is satisfactory, and it can be extended to mixtures with a significant non-hydrocarbon gas content. Thus, the BWRS-EoS is applied in this study and the calculation formula for gas density can be derived from BWRS-EoS, as shown in Eq. (2). To solve Eq. (2), the parabolic method is usually adopted.

$$\begin{aligned} F(\rho) = \rho RT &+ \left(B_0RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4}\right)\rho^2 \\ &+ \left(bRT - a - \frac{d}{T}\right)\rho^3 \\ &+ \alpha\left(a + \frac{d}{T}\right)\rho^6 + \frac{c\rho^3}{T^2}(1+\gamma\rho^2)e^{-\gamma\rho^2} - P \end{aligned} \tag{2}$$

where P is the gas pressure, kPa; T is the gas temperature, K; ρ is the gas density, kmol/m^3; R is the gas constant, R=8.3143 kJ/(kmol·K); A_0, B_0, C_0, D_0, E_0, a, b, c, d, α, γ, are the equation parameters.

2.3 Hydraulic model

The relationship between flow rate and pressure can be established according to the hydraulic equation to characterize the gas flow in the pipeline (Li and Yao, 2009), as shown below:

$$P_z = \sqrt{P_q^2 - \frac{\lambda Z \Delta_* T}{C_0^2 d^5} Q^2 L} \tag{3}$$

where P_z is the pressure at the end of pipeline, Pa; P_q is the pressure at the start of pipeline, Pa; T is the gas temperature, K; Z is the gas compressibility factor; Q is the volume flow rate, m^3/s; d is the inner diameter of pipeline, m; L is the pipeline length, m; Δ_* is the gas relative density; C_0 is a constant of 0.03848 m^2·s·K$^{0.5}$·kg^{-1}; λ is the actual friction coefficient, which ca be calculated by the F-Colebrook equation (Wang, 2018):

$$\frac{1}{\sqrt{\lambda_L}} = -2.01 1g\left(\frac{Ke}{3.71d} + \frac{2.51}{Re\sqrt{\lambda_L}}\right) \tag{4}$$

where Ke is the absolute roughness of pipeline wall, m; Re is the Reynolds number; λ_L is the theoretical friction coefficient, it can be obtained through the iterative calculation of the F-Colebrook equation. Combined with the transmission efficiency coefficient E (taking the value of 0.95), the actual friction coefficient can be calculated by $\lambda = \lambda_L / E^2$.

2.4 Thermal model

The equation for calculating temperature considering the Joule-Thomson effect can be derived from the energy conservation equation:

$$T_z = T_e + (T_q - T_e)e^{-aL} - \mu_{J-T}\frac{P_q - P_z}{aL}(1 - e^{-aL}) \tag{5}$$

where T_z is the temperature at the end of pipeline, K; T_q is the temperature at the start of pipeline, K; T_e is the ambient temperature, K; a is a constant, $a = K\pi D / MC_p$, K is the total heat transfer coefficient, W/(m^2·K); D is the outer diameter of pipeline, m; M is the gas mass flow rate, kg/s; C_p is the specific heat capacity at constant pressure, which can calculated by Eq. (6); μ_{J-T} is the Joule-Thomson coefficient, which can be calculated by Eq. (7).

$$C_P = C_V + \frac{T}{\rho^2}\frac{\left(\frac{\partial p}{\partial T}\right)_\rho^2}{\left(\frac{\partial p}{\partial \rho}\right)_T} \tag{6}$$

$$\mu_{J-T} = \frac{1}{C_p}\left[\frac{T}{\rho^2}\left(\frac{\partial p}{\partial T}\right)_\rho \Big/ \left(\frac{\partial p}{\partial \rho}\right)_T - \frac{1}{\rho}\right] \tag{7}$$

In Eqs. (6) and (7), the partial derivatives of pressure with respect to temperature and density can be obtained using the BWRS-EoS, as shown in Eqs. (8) and (9). Since the model coefficient of BWRS-EoS depend only on the critical parameters and acentric factor, and are independent of system temperature and density, the expressions of partial derivatives are same for both gas mixtures and pure gas component (Li et al., 2021b).

$$\begin{aligned} \left(\frac{\partial p}{\partial T}\right)_{\rho,BWRS} &= \rho R + \left(B_0R + \frac{2C_0}{T^3} - \frac{3D_0}{T^4} + \frac{4E_0}{T^5}\right)\rho^2 \\ &+ \left(bR + \frac{d}{T^2}\right)\rho^3 - \frac{\alpha d}{T^2}\rho^6 \\ &- \frac{2c\rho^3}{T^3}(1+\gamma\rho^2)e^{-\gamma\rho^2} \end{aligned} \tag{8}$$

$$\begin{aligned} \left(\frac{\partial p}{\partial \rho}\right)_{T,BWRS} &= RT + 2\left(B_0RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4}\right)\rho \\ &+ 3\left(bRT - a - \frac{d}{T}\right)\rho^2 + 6\alpha\left(a + \frac{d}{T}\right)\rho^5 \\ &+ \frac{3c\rho^2}{T^2}\left(1 + \gamma\rho^2 - \frac{2}{3}\gamma^2\rho^4\right)e^{-\gamma\rho^2} \end{aligned} \tag{9}$$

3. Numerical methods and model validation

3.1 Numerical methods for line pack calculation

As shown in Fig. 1, firstly the studied pipeline is divided into many segments with the same length of Δl. The pressure, temperature, and compressibility factor at inlet face 1 are marked as P_1, T_1 and Z_1 respectively, while at outlet face 2 they are marked as P_2, T_2 and Z_2 respectively.

On the pipeline segment, it is assumed that the change of temperature, pressure, and compressibility factor is linear with length. Based on the real gas EoS, the formula for calculating the line pack of a pipeline segment can be written as follows:

$$dV_0 = dV_1 \times \frac{T_0 \times Z_0}{P_0} \times \left(\frac{f_1 + f_2}{2}\right) \tag{10}$$

where dV_0 is the line pack of pipeline segment; dV_1 is the fixed volume of pipeline segment; f_1 and f_2 are defined as $f_1 = P_1 / T_1 Z_1$, $f_2 = P_2 / T_2 Z_2$.

For a long pipeline, summing the line pack of pipeline segments gives the total line pack of the pipeline:

$$V_0 = \Sigma dV_0 \tag{11}$$

To accurately simulate the hydraulic and thermal characteristics of HBNG pipeline, a refined calculation method for

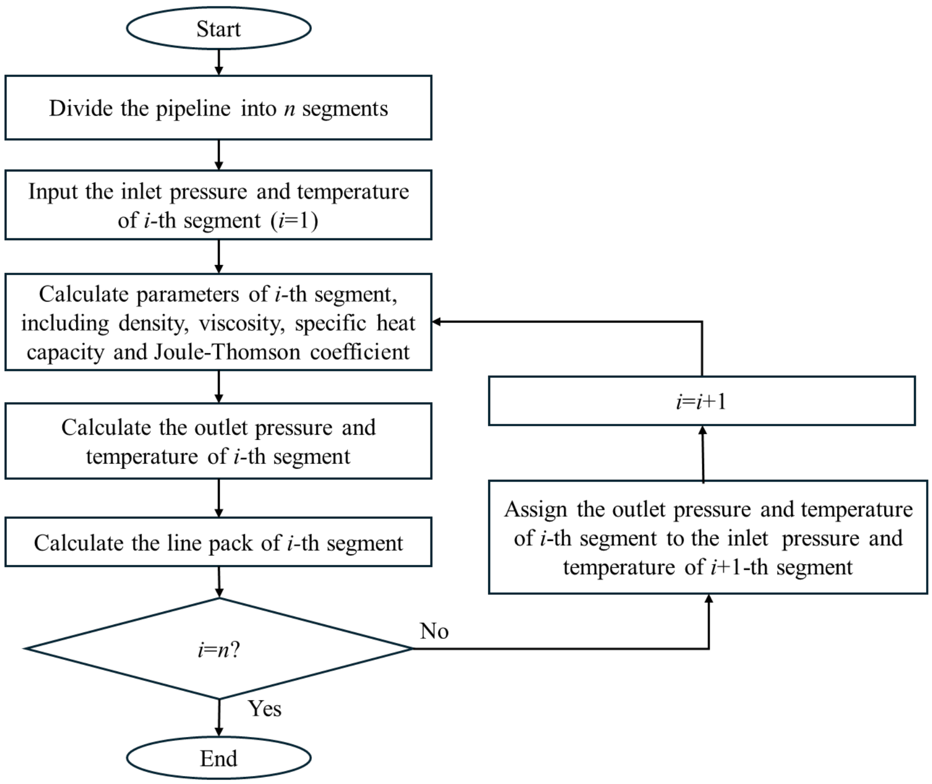


Fig. 2. Flowchart for line pack calculation.

line pack is adopted in this study. The calculation process is depicted by the flowchart in Fig. 2.

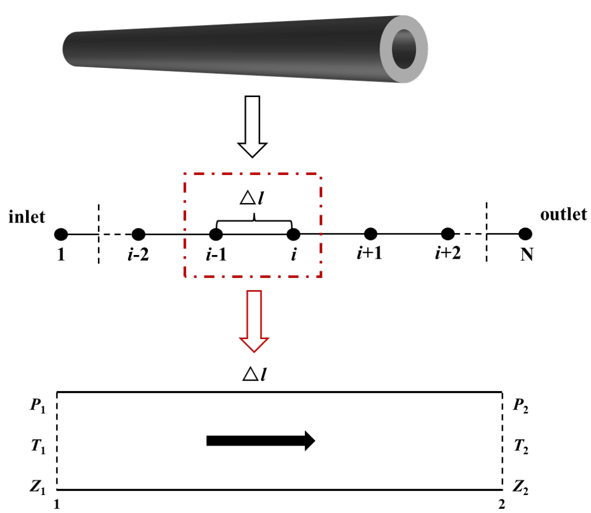


Fig. 1. Schematic diagram of the pipeline segment.

3.2 Model validation

In this study, a specific HBNG pipeline is taken as an example, the pipeline parameters are shown in Table 1 and the composition of natural gas are shown in Table 2. The hydrogen blending ratios are set as 0, 5, 10, 15, 20, 30, 40, 50, 70, and 90%, respectively.

The commercial software TGNET is used to validate the calculation model established in this study. TGNET is a well-tested gas pipeline simulator that can offer high computational accuracy for steady-state flow simulation (Kong et al., 2021). To validate the calculation model by TGNET, the pipeline inlet is set as a pressure boundary at 6.0 MPa, and the outlet is set as a flow boundary at 115.74 Nm³/s for test case 1 and 69.44 Nm³/s for test case 2. The calculated outlet pressure, outlet temperature, relative error e, and mean absolute relative error e_{av} between the calculation model and TGNET are shown in Tables 3 and 4.

From Tables 3 and 4 it can be clearly seen that in the two test cases, the mean absolute relative error of proposed calculation model for predicting outlet pressure is 1.88% and 0.44% respectively, and the mean absolute relative error for predicting outlet temperature is 1.95% and 0.86% respectively. These mean absolute relative errors are all below 2%, indicating the proposed calculation model maintains high prediction accuracy and stable reliability across different test cases.

3.3 Grid independent test

The mesh division of pipeline should strike a balance between computational efficiency and accuracy. Theoretically, finer grid indicates higher prediction accuracy and heavy computational burden. Based on validated calculation models, the grid sizes (segment lengths) of 50, 100, 500, 1,000, 2,000, 5,000, 10,000, 20,000 and 50,000 m are selected to calculate the outlet pressure of HBNG pipeline with HBRs of 0%, 15%, and 30%, as shown in Fig. 3. It can be observed that the predicted outlet pressure changes slightly when the grid size is within 1,000 m. Therefore, the segment length is set as 1,000 m in this study.

Table 1. Parameters of HBNG pipeline.

Pipeline length (km)	Outer diameter (mm)	Inner diameter (mm)	Ambient temperature (K)
91	660	648	293.15

Table 2. Composition of natural gas.

Substance	CH_4	C_2H_6	C_3H_8	i-C_4	n-C_4	i-C_5	n-C_5	n-C_6	n-C_7	n-C_8	N_2	CO_2
Mole fraction (%)	92.45	3.64	1.37	0.16	0.13	0.20	0.05	0.05	0.09	0.02	1.30	0.54

Table 3. Comparison of outlet pressure obtained by calculation model and TGNET.

	Test case 1			Test case 2		
HBR (%)	P_{Model} (MPa)	P_{TGNET} (MPa)	e (%)	P_{Model} (MPa)	P_{TGNET} (MPa)	e (%)
0	4.76	4.64	2.68	5.59	5.55	0.65
5	4.80	4.68	2.64	5.60	5.57	0.49
10	4.85	4.73	2.45	5.61	5.58	0.53
15	4.89	4.78	2.33	5.62	5.59	0.59
20	4.94	4.84	2.05	5.64	5.61	0.49
30	5.04	4.95	1.81	5.67	5.64	0.51
40	5.15	5.06	1.71	5.70	5.68	0.40
50	5.26	5.18	1.47	5.74	5.72	0.33
70	5.49	5.43	1.05	5.82	5.80	0.28
90	5.72	5.69	0.58	5.90	5.89	0.15
e_{av}%			1.88			0.44

Table 4. Comparison of outlet temperature obtained by calculation model and TGNET.

	Test case 1			Test case 2		
HBR (%)	T_{Model} (K)	T_{TGNET} (K)	e (%)	T_{Model} (K)	T_{TGNET} (K)	e (%)
0	292.87	298.61	1.92	293.09	296.33	1.09
5	292.91	298.77	1.96	293.10	296.21	1.05
10	292.95	298.91	1.99	293.11	296.10	1.01
15	292.98	299.02	2.02	293.11	295.99	0.97
20	293.01	299.10	2.04	293.12	295.89	0.94
30	293.05	299.18	2.05	293.13	295.69	0.87
40	293.09	299.17	2.03	293.14	295.50	0.80
50	293.11	299.08	2.00	293.14	295.32	0.74
70	293.14	298.70	1.86	293.15	294.97	0.62
90	293.15	298.13	1.67	293.15	294.64	0.51
e_{av}%			1.95			0.86

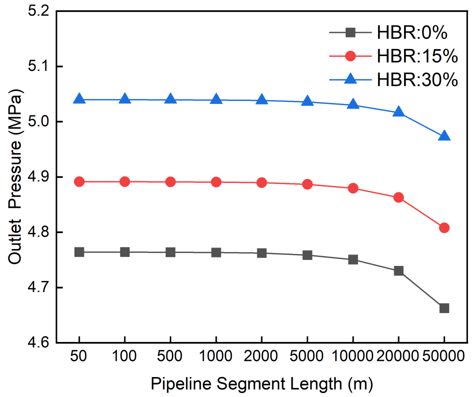


Fig. 3. Grid independent test for mesh division of pipeline.

4. Results and discussion

To comprehensively evaluate the HBNG line pack and its influencing factors, the validated calculation model is used to analyze the effects of HBR, inlet pressure, pipeline throughput, and inlet temperature on line pack, with the parameters of pipeline and natural gas detailed in Tables 1 and 2. The specific case settings are described as follows: the HBR gradually increases from 0 to 90%, including 5, 10, 15, 20, 30, 40, 50, 70, and 90% respectively; the inlet pressure is set as 4, 4.5, 5, 5.5, and 6 MPa respectively; the pipeline throughput is set as 1.4×10^9, 2.1×10^9, 2.8×10^9, and 3.5×10^9 Nm^3/a respectively; and the inlet temperatures covers a range from 253.15 to 323.15 K, including 263.15, 273.15, 283.15, 293.15, 303.15, and 313.15 K, respectively. These parameter settings aim to deeply analyze how each influencing factor individually and comprehensively affects the HBNG line pack, providing a scientific basis for optimization of pipeline operating conditions.

4.1 Influence of hydrogen blending ratio on line pack and storage capacity

In this part, the impact of hydrogen blending ratio on the line pack and storage capacity of HBNG pipeline is investigated through eight cases, the detailed parameter settings are shown in Table 5.

Table 6 displays the line pack of HBNG under different HBRs. It indicates the overall the line pack decreases with the reduction in pressure, the increase in pipeline throughput, and the rise in HBR. For example, for Cases 1 & 2, 3 & 4, 5 & 6, 7 & 8, the line pack decreases under all HBRs as the inlet pressure drops. For Cases 2 & 3, 4 & 5, 6 & 7, the line pack decreases under all HBRs as the pipeline throughput increases. For Case 1, the line pack decreases by 6.61%, from 1,799,700 to 1,680,700 Nm³ when the HBR increases from 0 to 90%. For other Cases the line pack decreases by 3.22, 7.73, 4.83, 8.69, 6.27, 9.41, and 7.45%, respectively.

Fig. 4 shows the variation of HBNG line pack with HBR. The variation trend reveals that below the HBR of 70%, the line pack consistently decreases with rising HBR across all Cases due to the lower density of hydrogen compared to that of methane. However, this trend reverses at HBRs of 70% and 90% in some Cases, indicating an increase in line pack as HBR rises. This phenomenon can be attributed to the lower viscosity of hydrogen, which reduces the friction and pressure loss of HBNG flow in the pipeline, enabling the pipeline to store more gas at higher pressures. Initially, the decrease in line pack is primarily caused by the density change, but beyond an HBR of 70%, the viscosity-induced improvement in gas flow leads to an increase in line pack, marking a critical transition point in the variation trend of HBNG line pack with HBR.

To maintain a continuous gas supply, balancing the supply with user consumption is crucial in natural gas transmission engineering. Utilizing the storage capability of pipeline systems for peak shaving (storing gas during low demand period and releasing gas during high demand period) can effectively manage this balance. For HBNG pipeline, it is vital to accurately determine the storage capacity as the hydrogen blending can obviously affect the storage capacity. Thus, comprehending the influence of hydrogen blending on the storage capacity of HBNG pipeline is essential for optimizing peak shaving and ensuring efficient supply operation.

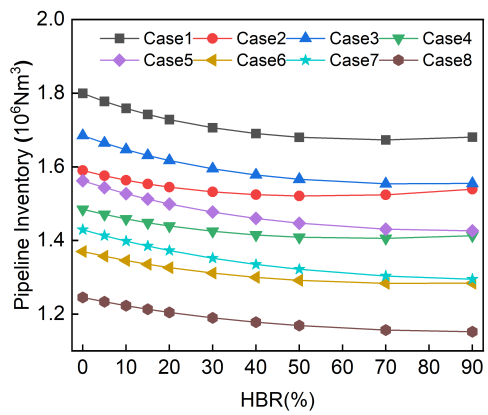


Fig. 4. Variation of HBNG line pack with HBR.

By pairing conditions with same pipeline throughput, where the condition with the lower inlet pressure serves as the initial gas storage state and the one with the higher inlet pressure as the final gas storage state, the storage capacity of HBNG pipeline can be determined by the difference in line pack between these paired conditions:

$$V_{gas} = V_{final} - V_{initial} \tag{12}$$

where V_{gas} is the storage capacity of HBNG pipeline; V_{final} is the final line pack; $V_{initial}$ is the initial line pack.

Table 7 presents the gas storage capacity (GSC) of HBNG pipeline under different HBRs. A clear trend can be seen from Table 7 that the pipeline GSC declines as the HBR increases. Specifically, Cases 1 & 2 demonstrate a 32.36% drop in GSC from 209,500 Nm³ at HBR of 0% to 141,700 Nm³ at HBR of 90%. Similar variation trend of GSC of HBNG pipeline is observed in other Cases, with GSC reductions of 29.16%, 25.92%, and 22.59%, respectively. Fig. 5 demonstrates the variation of HBNG pipeline GSC with HBR, showing the GSC

Table 5. Parameter settings for eight cases.

Case number	Pipeline throughput (10^9 Nm^3/a)	Inlet pressure (MPa)	Other conditions
1	3.5	6.0	Inlet temperature: 323.15 K
2	3.5	5.5	
3	2.8	5.5	
4	2.8	5.0	
5	2.1	5.0	Ambient temperature: 293.15 K
6	2.1	4.5	
7	1.4	4.5	
8	1.4	4.0	

Table 6. HBNG line pack under different HBRs (Unit, Nm^3).

HBR (%)	Case number							
	1	2	3	4	5	6	7	8
0	1799700	1590200	1685100	1484500	1562100	1370000	1429200	1245100
5	1777700	1575800	1664700	1470700	1543600	1357100	1412900	1233500
10	1758800	1563600	1646900	1458600	1527100	1345600	1398100	1222900
15	1742200	1553200	1631000	1448100	1512200	1335300	1384600	1213300
20	1728200	1544700	1617200	1439100	1499100	1326200	1372500	1204600
30	1706000	1531900	1594700	1424900	1477100	1311300	1351800	1189900
40	1690300	1524200	1577900	1415000	1459900	1300000	1334900	1178000
50	1680100	1520600	1566000	1408700	1446800	1291800	1321600	1168700
70	1673000	1523900	1553800	1405500	1430800	1283300	1303400	1156700
90	1680700	1539000	1554800	1412700	1426300	1284000	1294800	1152300

decreases as the HBR rises, yet the decline rate moderates at higher HBRs. The reason can be attributed to the lower viscosity of hydrogen, which reduces the flow resistance and pressure loss more effectively at higher HBRs, thereby mitigating the GSC reduction caused by the lower density of HBNG at lower HBRs. In essence, while the increasing HBR leads to a decrease in GSC primarily due to the lower density of HBNG, the improvements of gas viscosity partially counteract this effect at higher HBRs.

4.2 Influence of inlet pressure and pipeline throughput on line pack

To investigate the impact of inlet pressure and pipeline throughput on the HBNG line pack, in this part the pipeline inlet pressure is set as 4.0, 4.5, 5, 5.5 and 6.0 MPa, and the pipeline throughput is set as 1.4×10^9, 2.1×10^9, 2.8×10^9 and 3.5×10^9 Nm^3/a, respectively. In these Cases, the inlet temperature is set as 323.15 K and the HBR is still set as the range of 0-90%.

Tables 8-11 show the predicted HBNG line pack under different pipeline throughputs. It can be found that the line pack increases with the rising inlet pressure under different

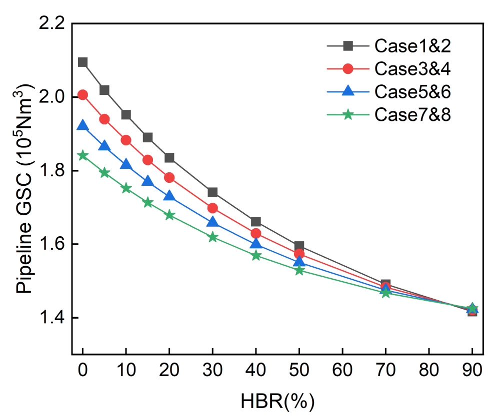


Fig. 5. Variation of HBNG pipeline GSC with HBR.

HBRs and fixed pipeline throughput. For example, Table 8 indicates that at HBR of 0% and pipeline throughput of 1.4×10^9 Nm^3/a, the line pack increases from 1,245,100 Nm^3 at 4.0 MPa to 1,997,300 Nm^3 at 6.0 MPa, marking a surge of 60.41%. Similarly, at HBR of 90%, the line pack increases from 1,152,300 Nm^3 at 4.0 MPa to 1,715,400 Nm^3 at 6.0 MPa,

Table 7. HBNG pipeline GSC under different HBRs (Unit, Nm^3).

HBR (%)	Case number			
	1&2	3&4	5&6	7&8
0	209500	200600	192100	184100
5	201900	194000	186500	179400
10	195200	188300	181500	175200
15	189000	182900	176900	171300
20	183500	178100	172900	167900
30	174100	169800	165800	161900
40	166100	162900	159900	156900
50	159500	157300	155000	152900
70	149100	148300	147500	146700
90	141700	142100	142300	142500

Table 8. HBNG line pack at the pipeline throughput of 1.4×10^9 Nm^3/a (Unit, Nm^3).

HBR (%)	Inlet pressure (MPa)				
	4.0	4.5	5.0	5.5	6.0
0	1245100	1429200	1615800	1805200	1997300
5	1233500	1412900	1594100	1777400	1962700
10	1222900	1398100	1574600	1752500	1931800
15	1213300	1384600	1556700	1729800	1903900
20	1204600	1372500	1540800	1709700	1879200
30	1189900	1351800	1513500	1675300	1837100
40	1178000	1334900	1491400	1647400	1803000
50	1168700	1321600	1473700	1625100	1775800
70	1156700	1303400	1449000	1593500	1737000
90	1152300	1294800	1436200	1576400	1715400

Table 9. HBNG line pack at the pipeline throughput of 2.1×10^9 Nm^3/a (Unit, Nm^3).

HBR (%)	Inlet pressure (MPa)				
	4.0	4.5	5.0	5.5	6.0
0	1178400	1370000	1562100	1755600	1950900
5	1170600	1357100	1543600	1730900	1919300
10	1163700	1345600	1527100	1708900	1891300
15	1157600	1335300	1512200	1689000	1866000
20	1152400	1326200	1499100	1671500	1843700
30	1144100	1311300	1477100	1642000	1806200
40	1138400	1300000	1459900	1618600	1776400
50	1135000	1291800	1446800	1600500	1753100
70	1134100	1283300	1430800	1576800	1721500
90	1140100	1284000	1426300	1567200	1706800

Table 10. HBNG line pack at the pipeline throughput of 2.8×10^9 Nm^3/a (Unit, Nm^3).

HBR (%)	Inlet pressure (MPa)				
	4.0	4.5	5.0	5.5	6.0
0	1077300	1282700	1484500	1685100	1885900
5	1075500	1275000	1470700	1664700	1858400
10	1074500	1268500	1458600	1646900	1834200
15	1074100	1263100	1448100	1631000	1812700
20	1074300	1258700	1439100	1617200	1793900
30	1076500	1252600	1424900	1594700	1762900
40	1080500	1249500	1415000	1577900	1739100
50	1086100	1249000	1408700	1566000	1721400
70	1102000	1255100	1405500	1553800	1700300
90	1123300	1269000	1412700	1554800	1695300

Table 11. HBNG line pack at the pipeline throughput of 3.5×10^9 Nm^3/a (Unit, Nm^3).

HBR (%)	Inlet pressure (MPa)				
	4.0	4.5	5.0	5.5	6.0
0	922550	1158500	1377700	1590200	1799700
5	931890	1158800	1370600	1575800	1777700
10	941290	1159900	1365000	1563600	1758800
15	950880	1161900	1360600	1553200	1742200
20	960440	1164500	1357600	1544700	1728200
30	979690	1171600	1354400	1531900	1706000
40	999130	1180700	1354800	1524200	1690300
50	1018600	1191400	1358100	1520600	1680100
70	1059100	1217800	1372400	1523900	1673000
90	1101400	1249700	1395400	1539000	1680700

the growth rate is up to 48.87%.

Tables 12-14 display the calculated HBNG line pack under different inlet pressures. The calculation results illustrate that for a fixed inlet pressure, the line pack decreases with the increasing pipeline throughput across all HBRs. For instance, Table 12 shows at the HBR of 0%, the line pack decreases by 25.91% from 1,245,100 Nm^3 under the pipeline throughput of 1.4×10^9 Nm^3/a to 922,550 Nm^3 under the pipeline throughput of 3.5×10^9 Nm^3/a. Moreover, at the HBR of 90%, the line pack decreases from 1,152,300 to 1,101,400 Nm^3, with the reduction rate up to 4.41% as the pipeline throughput rises from 1.4×10^9 to 3.5×10^9 Nm^3/a.

Figs. 6-7 demonstrate the change of HBNG line pack in relation to the HBR under different inlet pressures and pipeline throughputs. It can be clearly observed that the diminishing influence of pipeline throughput and inlet pressure on HBNG line pack as the HBR increases. A comparative analysis in Fig. 6 reveals the decline trend of line pack across different inlet pressures with increasing HBR. However, this trend inverses at larger pipeline throughputs. For example, Fig. 6(c) shows an increment in line pack from the HBR of 0% to 90% at a fixed inlet pressure of 4.0 MPa. Similarly, Figs. 6(d) and 7 confirm that the line pack tends to increase with the rising HBR at higher pipeline throughputs and lower inlet pressures.

The analysis indicates that blending hydrogen into natural gas pipelines reduces the density of HBNG mixtures, typically leading to a decreasing line pack, yet concurrently the gas viscosity and pressure loss decreases. Therefore, the gas storage capacity of HBNG pipeline is augmented under higher pressures. At lower inlet pressures, the density reduction effect caused by hydrogen blending is relatively diminished, weakening the decreasing trend of line pack with the increasing HBR. Meanwhile, the positive impact of reduced gas viscosity is amplified by the higher pipeline throughput, leading to an enhanced increasing of line pack with higher HBRs. It emphasizes the importance of considering the interaction between inlet pressure and pipeline throughput when evaluating the influence of hydrogen blending on line pack.

Table 12. HBNG line pack at the inlet pressure of 4.0 MPa (Unit, Nm^3).

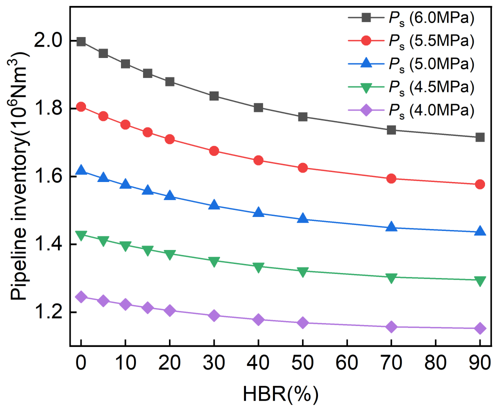
HBR (%)	Pipeline throughput (10^9 Nm^3/a)			
	1.4	2.1	2.8	3.5
0	1245100	1178400	1077300	922550
5	1233500	1170600	1075500	931890
10	1222900	1163700	1074500	941290
15	1213300	1157600	1074100	950880
20	1204600	1152400	1074300	960440
30	1189900	1144100	1076500	979690
40	1178000	1138400	1080500	999130
50	1168700	1135000	1086100	1018600
70	1156700	1134100	1102000	1059100
90	1152300	1140100	1123300	1101400

Table 13. HBNG line pack at the inlet pressure of 5.0 MPa (Unit, Nm^3).

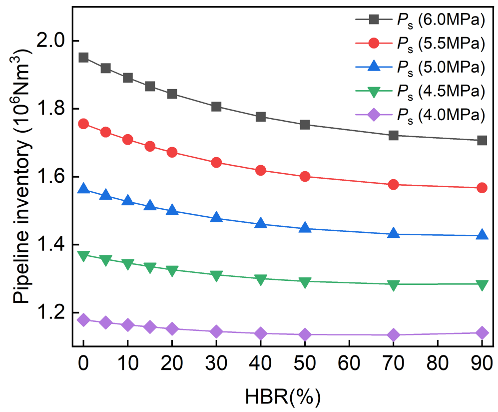
HBR (%)	Pipeline throughput (10^9 Nm^3/a)			
	1.4	2.1	2.8	3.5
0	1615800	1562100	1484500	1377700
5	1594100	1543600	1470700	1370600
10	1574600	1527100	1458600	1365000
15	1556700	1512200	1448100	1360600
20	1540800	1499100	1439100	1357600
30	1513500	1477100	1424900	1354400
40	1491400	1459900	1415000	1354800
50	1473700	1446800	1408700	1358100
70	1449000	1430800	1405500	1372400
90	1436200	1426300	1412700	1395400

Table 14. HBNG line pack at the inlet pressure of 6.0 MPa (Unit, Nm^3).

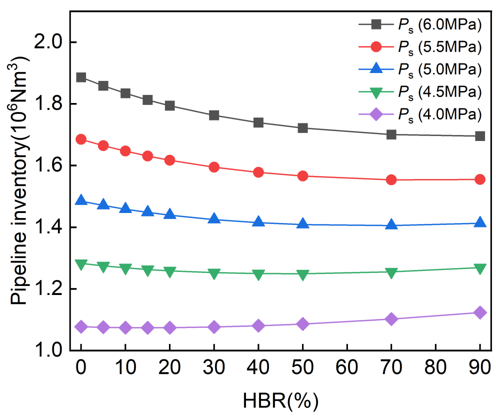
HBR (%)	Pipeline throughput (10^9 Nm^3/a)			
	1.4	2.1	2.8	3.5
0	1997300	1950900	1885900	1799700
5	1962700	1919300	1858400	1777700
10	1931800	1891300	1834200	1758800
15	1903900	1866000	1812700	1742200
20	1879200	1843700	1793900	1728200
30	1837100	1806200	1762900	1706000
40	1803000	1776400	1739100	1690300
50	1775800	1753100	1721400	1680100
70	1737000	1721500	1700300	1673000
90	1715400	1706800	1695300	1680700



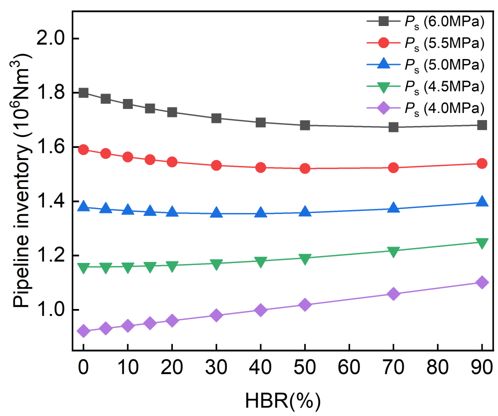
(a) Pipeline throughput=1.4×10^9 Nm^3/a



(b) Pipeline throughput=2.1×10^9 Nm^3/a



(c) Pipeline throughput=2.8×10^9 Nm^3/a



(d) Pipeline throughput=3.5×10^9 Nm^3/a

Fig. 6. Variation of HBNG line pack at different inlet pressures (P_s) and pipeline throughputs.

4.3 Influence of inlet temperature on line pack

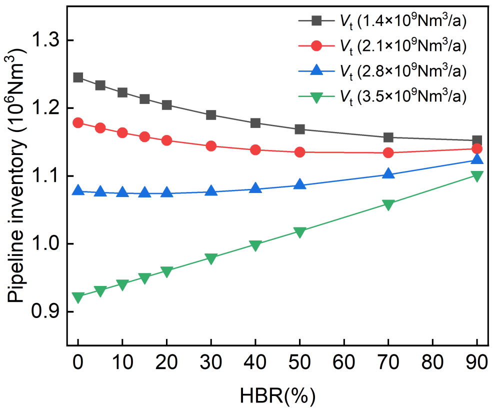
To investigate the impact of inlet temperature on HBNG line pack, the inlet temperature is set as the range of 253.15-323.15 K, including 263.15, 273.15, 283.15, 293.15, 303.15, and 313.15 K, respectively. The pipeline throughput is set as 2.1×10^9 Nm^3/a, the inlet pressure is set as 4.0 and 6.0 MPa, and the HBR is still set as the range of 0-90%.

Tables 15 and 16 present the calculated line pack at different inlet temperatures and inlet temperatures. The two tables demonstrate that the HBNG line pack declines almost linearly with the increasing inlet temperature at the inlet pressure of 4.0 MPa and 6.0 MPa. Specifically, Table 15 indicates that at the HBR of 0%, the line pack decreases from 1,189,800 Nm^3 at 253.15 K to 1,178,400 Nm^3 at 323.15 K, the reduction rate is 0.96%. At the HBR of 90%, the same temperature increase results in the decrease of line pack from 1,143,900 to 1,140,100 Nm^3, the reduction rate is 0.33%. Fig. 8 shows the variation of HBNG line pack with inlet temperatures under different inlet pressures and HBRs. It shows a linear decrease in line pack with the increasing inlet temperature at the HBR range of 0–90%. In addition, the decline slope of line pack with the increasing inlet temperature is weakened with the increase of HBR.

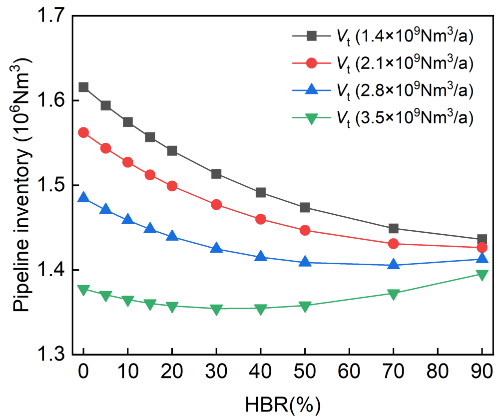
Overall, the influence of inlet temperature on HBNG line pack is insignificant compared to that of HBR, inlet pressure and pipeline throughput. The reason can be attributed to that within common temperature variations, the changes of physical properties like gas density and viscosity are slight. Therefore, the inlet temperature is not adopted as the approach for regulating the storage capacity of HBNG pipeline in engineering practice.

5. Conclusions

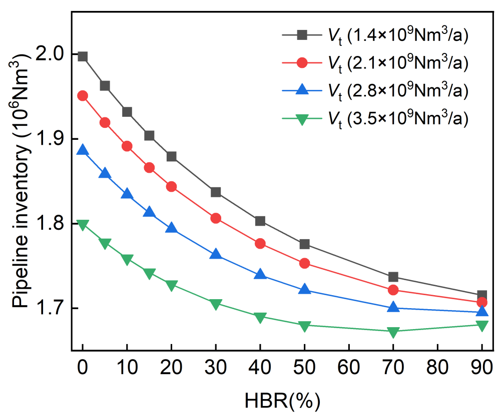
1) A calculation model for HBNG line pack is established based on the BWRS-EoS, hydraulic and thermal equations in this study. This model can predict the HBNG line pack under different conditions, and the accuracy and reliability of this model have been verified by the TGNET software.
2) Hydrogen blending usually reduces the line pack due



(a) Inlet pressure=4.0 MPa



(b) Inlet pressure=5.0 MPa



(c) Inlet pressure=6.0 MPa

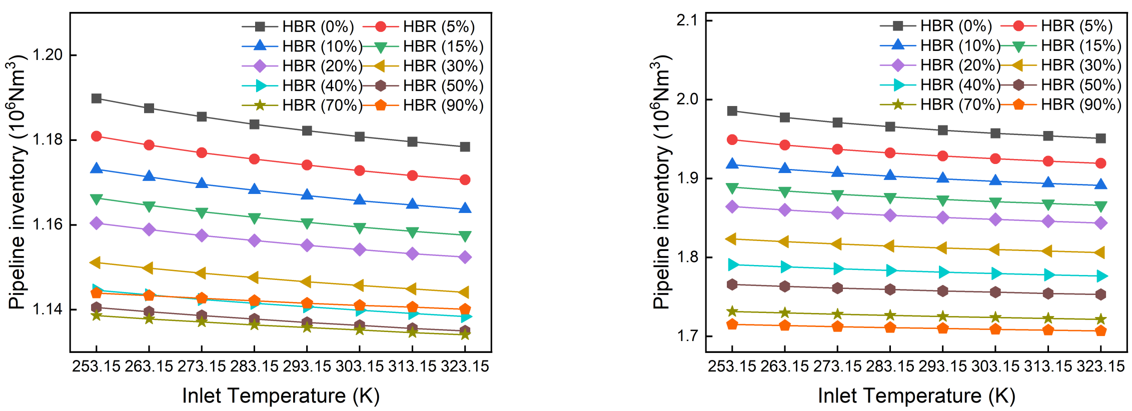
Fig. 7. Variation of HBNG line pack at different pipeline throughputs (V_t) and inlet pressures.

Table 15. Line pack at different inlet temperatures with inlet pressure of 4.0 MPa (Unit, Nm^3).

HBR (%)	Inlet temperature (K)							
	253.15	263.15	273.15	283.15	293.15	303.15	313.15	323.15
0	1189800	1187500	1185500	1183700	1182200	1180800	1179600	1178400
5	1180900	1178800	1177000	1175500	1174100	1172800	1171600	1170600
10	1173100	1171300	1169600	1168200	1166900	1165700	1164700	1163700
15	1166300	1164600	1163100	1161800	1160600	1159500	1158500	1157600
20	1160400	1158900	1157500	1156300	1155200	1154200	1153200	1152400
30	1151100	1149800	1148600	1147600	1146600	1145700	1144900	1144100
40	1144600	1143500	1142400	1141500	1140700	1139900	1139100	1138400
50	1140500	1139500	1138600	1137800	1137000	1136300	1135600	1135000
70	1138600	1137800	1137100	1136400	1135800	1135200	1134600	1134100
90	1143900	1143300	1142700	1142100	1141500	1141000	1140600	1140100

Table 16. Line pack at different inlet temperatures with inlet pressure of 6.0 MPa (Unit, Nm^3).

HBR (%)	Inlet temperature (K)							
	253.15	263.15	273.15	283.15	293.15	303.15	313.15	323.15
0	1985600	1977400	1970900	1965700	1961200	1957300	1954000	1950900
5	1949200	1942500	1937000	1932400	1928500	1925100	1922000	1919300
10	1917500	1911800	1907000	1903000	1899600	1896500	1893800	1891300
15	1889200	1884300	1880200	1876600	1873500	1870700	1868300	1866000
20	1864500	1860200	1856600	1853400	1850600	1848100	1845800	1843700
30	1823300	1819900	1817000	1814400	1812000	1809900	1808000	1806200
40	1790800	1788100	1785600	1783400	1781400	1779600	1777900	1776400
50	1765600	1763300	1761200	1759300	1757500	1755900	1754400	1753100
70	1731400	1729600	1728000	1726500	1725100	1723900	1722700	1721500
90	1715100	1713600	1712300	1711000	1709900	1708800	1707800	1706800



(a) Inlet pressure=4.0 MPa

(b) Inlet pressure=6.0 MPa

Fig. 8. Variation of HBNG line pack with inlet temperatures under different inlet pressures and hydrogen blending ratios.

to the lower density of hydrogen compared to that of methane. However, the effect depends on a complex interaction by inlet pressure and pipeline throughput. Under low inlet pressure and high pipeline throughput conditions, the line pack may increase with the rise of HBR due to the low viscosity of hydrogen which promotes the gas fluidity. Consequently, evaluating the influence of hydrogen blending on HBNG line pack demands careful consideration of specific pipeline operating conditions.

3) An increase in inlet pressure has a positive effect on line pack because the gas storage capacity is proportional to the pressure. A raise in pipeline throughput induces a larger pressure drop, which leads to a decrease in the average pressure and hence reduces the gas storage capacity. The influence of inlet temperature on line pack is more limited because the physical properties of gas change slightly over the range of pipeline operating temperature, leading to a slight decrease in the line pack.
4) The inlet pressure is the key factor to increase the storage capacity of HBNG pipeline, and increasing the HBR, pipeline throughput and inlet temperature are unfavorable to increase the storage capacity. Therefore, the regulation of HBNG pipeline storage capacity needs to be evaluated based on specific pipeline operating conditions.

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Conflict of interest

The authors declare no competing interest.

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