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Research Article

Numerical Investigation of Gas Mixture Length of Nitrogen Replacement in Large-Diameter Natural Gas Pipeline without Isolator

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Nitrogen replacement is a key process for natural gas pipeline before it is put into operation. A computational fluid dynamic model coupled to a species-transportation model has been used to investigate the gas mixture length of nitrogen replacement in large-diameter pipeline without isolator. A series of numerical simulations are performed over a range of conditions, including pipe length and diameter, inlet rate, and inclination angle of pipe. These affecting factors are analyzed in detail in terms of volume fraction of nitrogen, the maximum gas mixture length, and gas mixture length varied with time. Gas mixture length increases over time, and the maximum gas mixture length is present at outlet of pipe. Long and large-diameter pipe and fast speed of nitrogen lead to long length of mixed gas, while large inclination angle of pipe brings about short length. Several fitting formulas have been obtained, which can predict the maximum gas mixture length in gas pipelines. The used method of fitting formula is shown in the paper by examples. The results provide effective guidance for practical operation of nitrogen replacement.

1. Introduction

Facing the increasing gas consumption, natural gas pipeline is progressing towards large diameter and long distance, resulting in high investment. It is very important to ensure the safety of gas pipeline operation. However, explosion is easily caused when the content of natural gas in air reaches 5~15% [1, 2]. Therefore, before the natural gas pipeline is put into operation, the air in pipe must be replaced by an inert gas. In practice, nitrogen, as the most readily available and least expensive inert gas, is usually used to replace air in pipe. And qualified replacement is performed when the content of air in pipe is less than 2% [3].

To ensure safety, isolator is commonly employed to separate the nitrogen and air. As shown in Figure 1(a), before pumping the nitrogen into pipe, isolator is firstly placed at the entrance of pipe. Then nitrogen flow pushes the isolator moving forward together [4]. However, a number of natural gas pipelines are laid in mountains and plateaus. The undulating terrain makes the passing through of isolator more difficult. And in larger diameter, the cost of isolator is doubled up. In addition, the isolator seal failure usually occurs due to wear. Therefore, nitrogen replacement without isolator is popular in today's natural gas pipeline engineering as shown in Figure 1(b). After all, the receiving and transmitting cost of isolator can be saved. In this process, the gas mixture length becomes a key parameter to determine the displacement effect. According to the gas mixture length, appropriate operating parameters such as pumping volume and forward speed of nitrogen can be defined. However, in China, the amount of nitrogen is mainly determined by experience with great blindness [5–7]. And the mixture rule of nitrogen and air and affecting factors on mixture length are still unclear.

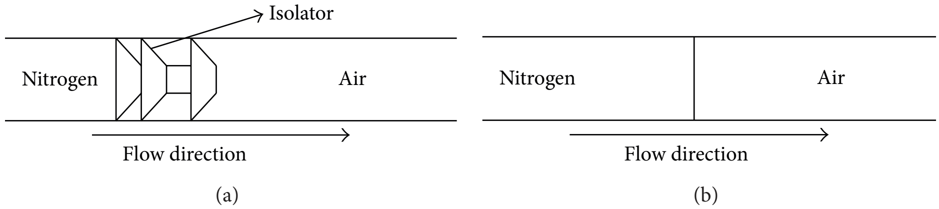

FIGURE 1: Schematic diagram of nitrogen replacement: (a) with isolator; (b) without isolator.

Several works in the literature focus on nitrogen injection to develop gas and gas condensate fields [8–10]. However, the mixture rule in formation pore is different with it in large-diameter pipeline, due to the great difference in scales. Therefore, an in-depth research for gas mixture length of nitrogen replacement in large-diameter pipeline without isolator is urgently needed in natural gas pipeline engineering.

Since numerical simulation can provide detailed information of flow field which is not easily obtained by physical experiments and has advantages of low cost and short research time, in present work, CFD model coupling with a species-transportation model has been employed to investigate the gas mixture length of nitrogen replacement in large-diameter pipeline without isolator. The gas mixture length has been examined in terms of volume fraction of nitrogen. By conducting a series of numerical simulations, effects of pipe length, pipe diameter, inlet rate, and inclination angle of pipe are examined. Then, the maximum gas mixture length is analyzed and the fitting formulas are obtained. Using these formulas, we can predict the maximum gas mixture length in gas pipelines. The used method of fitting formula is shown in the paper by examples. The results provide useful guidance for practical operation of nitrogen replacement.

The remaining part of this paper is organized as follows. In Section 2, the description of simulation problem is provided; Section 3 presents the governing equations and numerical method; Section 4 presents the numerical results and discussion; Section 5 is the concluding remarks.

2. Problem Description

Straight pipe and undulating pipe with an inclined upward section are adopted in this study. Figure 2 shows a sketch of the geometry and numerical grid for computational domain. The straight pipe is placed horizontally. And the length of it (L_1) ranges from 50 m to 1000 m in comparing cases, in order to examine the effect of pipe length on gas mixture length, while the diameter of straight pipe is set to 346.0 mm, 647.2 mm, 851.2 mm, and 1000.2 mm to explore the effect of pipe diameter.

The undulating pipe consists of three sections: straight pipe section, bend section, and inclined upward section. The bend curvature (R/D) is defined as 3, the common one used in practice. The length of inclined upward section is fixed at 600 m, while the inclination angle changes from 10° to 40° in comparing cases conducted to observe the effect of pipe inclination.

Gas flow in pipeline is a symmetric problem, so two-dimensional flow simulation is accurate enough to capture the gas mixture length. In addition, three-dimensional simulation needs a higher CPU cost. Due to time limitations, 2D simulation is applied in this work. All geometry generation and meshing are performed using GAMBIT 2.3 mesh-generator. As shown in Figure 2, quadrilateral grids are used in the whole computational domain of both straight pipe and undulating pipe. And progressive mesh is used near the pipe wall. The computational domain of undulating pipe is divided into three blocks. Denser mesh is employed in the bend section. A suitable grid density is reached by repeating computations until a satisfactory independent grid is found. For example, the number of quadrilateral cells for straight pipe with diameter of 647.2 mm and length of 600 m is 480000 at last.

The velocity of gas flow is slow in pipe (2~5 m/s), so both nitrogen and air can be seen as incompressible fluids. In simulations, density and viscosity of nitrogen are defined as 1.138 kg/m^3 and 1.663 × 10^{-5} Pa·s, respectively. And the density and viscosity of air are set to 1.225 kg/m^3 and 1.8 × 10^{-5} Pa·s, respectively.

3. Governing Equations and Numerical Method

3.1. Governing Equations. The gas flows of nitrogen and air are governed by the Reynolds-Averaged-Navier-Stokes (RANS) equations, including continuity and momentum equations written as follows [11]:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0,$$
$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i}\,\overline{u_j}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \upsilon \nabla^2 \overline{u_i} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} + g_i, \quad (1)$$

where

$$\rho = \alpha \rho_n + (1-\alpha)\,\rho_a,$$
$$\upsilon = \alpha \upsilon_n + (1-\alpha)\,\upsilon_a, \quad (2)$$

where u_i represents instantaneous velocity component in i direction, for example, u and v are velocity in x and

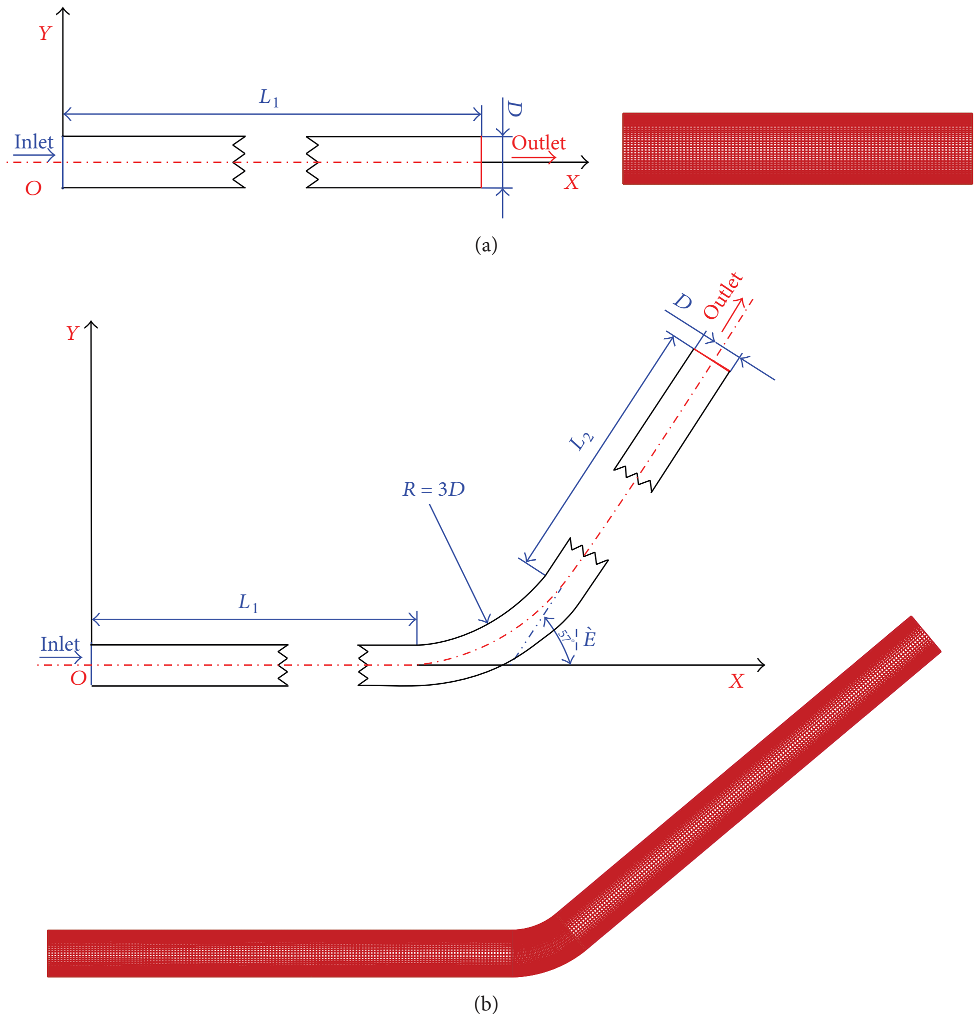

Figure 2: Sketch of the geometry and numerical grid for computational domain: (a) straight pipe; (b) undulating pipe with an inclined upward section.

y direction, respectively, while u_i' is fluctuation velocity component in i direction, x_i is space coordinate in i direction, g_i is gravitational acceleration in i direction, t is time, p is pressure, ρ is density of mixed gas, ρ_n and ρ_a are density of nitrogen and air, respectively, υ is kinematic viscosity of mixed gas, and υ_n and υ_a are viscosity of nitrogen and air, respectively.

Reynolds number ranges from 7.06×10^4 to 2.21×10^5 in calculations. Thus, a realizable k-ε turbulence model [12–14] is employed to close the flow governing equations and describe the turbulent properties:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon,$$
$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\upsilon\varepsilon}} + C_{1\varepsilon}\left(1 - C_{3\varepsilon}\right)\frac{\varepsilon}{k}G_b, \tag{3}$$

where

$$C_1 = \max\left(0.43, \frac{\eta}{\eta + 5}\right),$$
$$\eta = S\frac{k}{\varepsilon},$$
$$S = \left(2S_{ij} \cdot S_{ij}\right)^{1/2},$$
$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \tag{4}$$
$$G_k = -\rho\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_i},$$
$$G_b = -g_i \frac{\mu_t}{\mathrm{Pr}_t}\frac{\partial \rho}{\rho \partial x_i},$$
$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon},$$

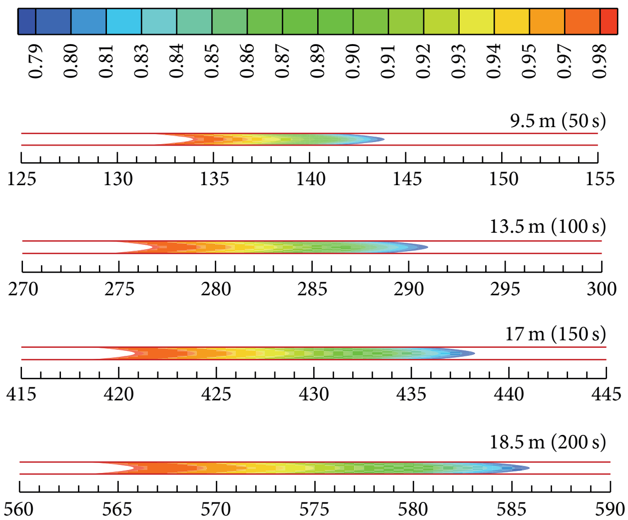

Figure 3: Gas mixture length at different times.

where k and ε represent turbulent kinetic energy and turbulent kinetic energy dissipation rate per unit mass, respectively, η is the relative strain parameter, S is the strain rate, G_k and G_b represent production term of turbulent kinetic energy due to the average velocity gradient and production term of turbulent kinetic energy due to lift, respectively, μ_t is turbulent viscosity, pr_t is Prandtl number taken as 0.85, C_μ, $C_{1\varepsilon}$, C_2, and $C_{3\varepsilon}$ are empirical model constants taken as 0.09, 1.44, 1.9, and 0.9, respectively, and σ_t and σ_ε are turbulent Prandtl numbers taken as 1.0 and 1.2, respectively.

There is no reaction between nitrogen and air in the replacement process, so a simplified species-transportation model is employed to capture the mixture of nitrogen and air written as [15] follows:

$$\frac{\partial(\alpha\rho_n)}{\partial t}+\frac{\partial(\alpha\rho_n u)}{\partial x}+\frac{\partial(\alpha\rho_n v)}{\partial y}=\frac{\partial}{\partial x}\left[D_n\frac{\partial(\alpha\rho_n)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_n\frac{\partial(\alpha\rho_n)}{\partial y}\right], \tag{5}$$

where α is nitrogen volume fraction and D_n and D_a are diffusion coefficient of nitrogen and air, respectively.

3.2. Numerical Method. Finite volume method (FVM) is employed to discretize above equations. All the calculations are performed using a commercial software package FLUENT 14.5. Patankar's well-known SIMPLE algorithm [16] is adopted to solve the pressure-velocity coupling. In order to ensure the accuracy of calculation, second-order upwind scheme and second-order central-differencing scheme are used for convective terms and diffusion terms, respectively. The convergent criteria for all calculations are set as that the residual in the control volume for each equation is smaller than 10^{-5}.

3.3. Boundary and Initial Conditions. Velocity inlet boundary condition is used for the inlet, and the inlet rates of nitrogen are taken as 2 m/s, 3 m/s, 4 m/s, and 5 m/s in comparing cases. In the outlet of computational domain, pressure outlet boundary condition is employed, and the value is defined as 0 Pa in order to facilitate comparative analysis. No slip boundary condition is imposed on the pipe wall.

Since it is an unsteady problem, the whole computational domain of pipe is defined as being filled with air at the initial time. And the time step in simulations is set to 0.001 s. The information of simulation cases is listed in Table 1, in which pipe length, pipe diameter, and inlet rate and inclination angle are the four variables.

4. Numerical Results and Discussion

4.1. Standard Case Analysis. Case 6 is adopted as the standard case. Figure 3 shows the gas mixture length at different times, which is reflected by the volume fraction of nitrogen. The volume fraction of nitrogen more than 98% can be considered to meet the safe replacement requirement. And the content of nitrogen in air is 79%. Therefore, volume fraction of nitrogen ranging from 0.79 to 0.98 corresponds to the mixed gas. And the length of this mixed gas is called gas mixture length.

It is seen that the head of the mixed gas shows a bullet-shaped distribution. Frictional resistance at pipe wall is the major cause for this phenomenon. It is well known that there is a viscous sublayer near pipe wall. The closer the gas is to the wall, the greater the viscosity resistance gas gets. So the gas in the axis of pipe moves ahead. It is worth noting that the gas mixture length increases over time. At the time of 50 s, the gas mixture length is 9.5 m, while it increases to 18.5 m at the time of 200 s. In the mixed gas, the volume fraction of nitrogen gradually decreases along the pipe axis direction. And the decreasing rate is gradually reduced with time. This is because nitrogen is mixed with air more fully as time passes. However, the growth rate of mixture length is reducing over time. In the period from 50 s to 100 s, the mixture length is increased by 4 m, while it is increased by 3.5 m in the same

Table 1: Simulation cases.

Case	The length of straight pipe, L_1 (m)	Pipe diameter, D (mm)	Inlet rate, v (m/s)	Inclination angle, θ (°)	The length of inclined pipe, L_2 (m)
1	50	647.2	3	0	0
2	150	647.2	3	0	0
3	300	647.2	3	0	0
4	400	647.2	3	0	0
5	500	647.2	3	0	0
6	600	647.2	3	0	0
7	700	647.2	3	0	0
8	800	647.2	3	0	0
9	900	647.2	3	0	0
10	1000	647.2	3	0	0
11	600	346.0	3	0	0
12	600	851.2	3	0	0
13	600	1000.2	3	0	0
14	600	647.2	2	0	0
15	600	647.2	4	0	0
16	600	647.2	5	0	0
17	600	647.2	3	10	600
18	600	647.2	3	20	600
19	600	647.2	3	30	600
20	600	647.2	3	40	600

interval of time (from 100 s to 150 s). And the increment is just 1.8 m for time increased from 150 s to 200 s. It can be explained that kinetic energy of nitrogen flow is consumed continuously as time goes. Therefore, the driving force and forward speed decrease gradually.

4.2. Effect of Pipe Length. Since gas mixture length increases over time, the maximum mixture length will appear at the outlet of pipe. Figure 4 illustrates the maximum gas mixture length for different pipe lengths. It is observed that the maximum gas mixture length increases with the increase in pipe length. The maximum gas mixture length reaches 24 m in 1000 m long pipe, which is about six times longer than that in 50 m long pipe. The main reason is that the longer the pipe is, the more the time is required for gas flow passing through, resulting in more gas mixed. However, the increment of the maximum gas mixture length reduces for pipe with length ranging from 400 m to 1000 m. And the increment is not decreased linearly.

The gas mixture length curves, as shown in Figure 5, also show nonlinear relationship. Gas mixture length increases rapidly at the beginning, while the growth rate decreases after a period of time. This main reason is that, at the beginning of replacement, the volume fraction gradient and velocity gradient in pipe are both large, but the two gradients decrease gradually over time.

The longest pipeline used in simulation is just 1000 m. However, actual piping often has hundreds or thousands of kilometers. In order to predict the maximum gas mixture length in longer pipelines, the maximum gas mixture length (l_m) versus the pipe length (L) is analyzed, and we have obtained the fitting formula, as shown in Figure 6. The adjusted R-squares reach 0.98722. Namely, the error in mixing length prediction is of the order of 1~2%. The fitting formula is written as

$$l_m = 2.03004 + 0.03149L - 8.67344 \times 10^{-6}L^2. \quad (6)$$

If the actual parameters are the same as that used in this paper such as $D = 647.2$ mm and $v = 3$ m/s, we can calculate the maximum gas mixture length in an arbitrary long pipe using this formula. For example, if the length of pipe is 1×10^5 m, l_m would be calculated as 1998.13 m. In order to detect the accuracy of this prediction equation, 1D simulation for pipe length 1×10^5 m has been conducted. One order central difference method is employed to discrete one-dimensional governing equations. For 1×10^5 m long pipe with diameter 647.2 mm and inlet rate 3 m/s, the calculated maximum mixing length by 1D simulation is 1959.62 m. So the error in mixing length prediction is less than 2%.

Therefore, the actual replacement time is not simply equal to pipe length divided by the flow speed. Qualified replacement is achieved until the mixed gas flows out thoroughly. So the replacement time should be more than the sum of pipe length divided by flow velocity and the maximum gas mixture length divided by flow rate.

4.3. Effect of Pipe Diameter. Figure 7 presents the maximum gas mixture length for different pipe diameters. It can be seen that the maximum gas mixture length increases with the increase in pipe diameter. The main cause of this result is

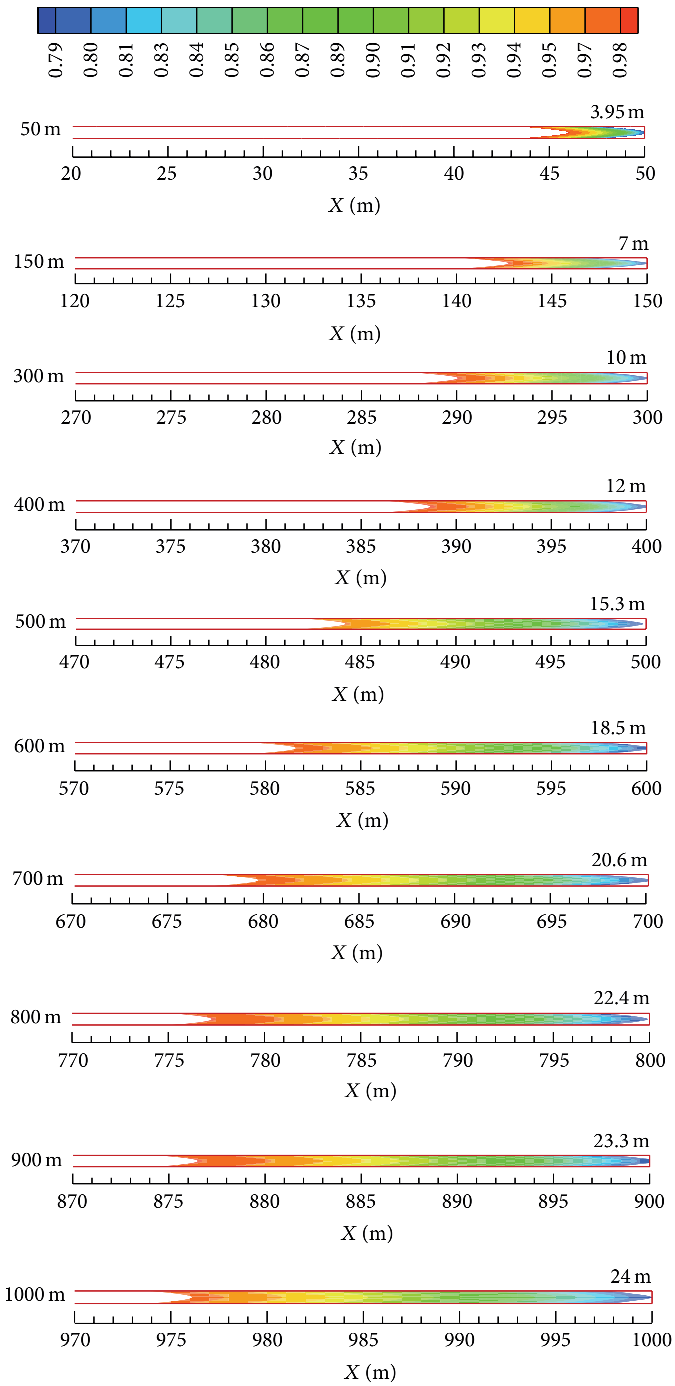

Figure 4: The maximum gas mixture length for different pipe lengths.

that the total kinetic energy of nitrogen flow is more in large-diameter pipe as the same inlet rate. Affected by the impact of friction, the smaller the pipe diameter is, the sharper the bullet-shaped head is.

The gas mixture length varied with time in pipes of different diameters is shown in Figure 8. The growth trend of mixture length is similar for different diameters. However, in small-diameter pipe, the growth rate of mixture length is relatively small. It is attributed to the joint action of kinetic energy and frictional resistance.

The actual pipe diameter is not only the four we have studied. So we also get the fitting formula of l_m versus D, as shown in Figure 9. The fitting line meets the linear distribution well, and the adjusted R-squares are 0.99295. The fitting formula is written as

$$l_m = 16.30719 + 0.00561D. \quad (7)$$

If the pipe diameter is 800.2 mm, l_m would be calculated as 20.8 m.

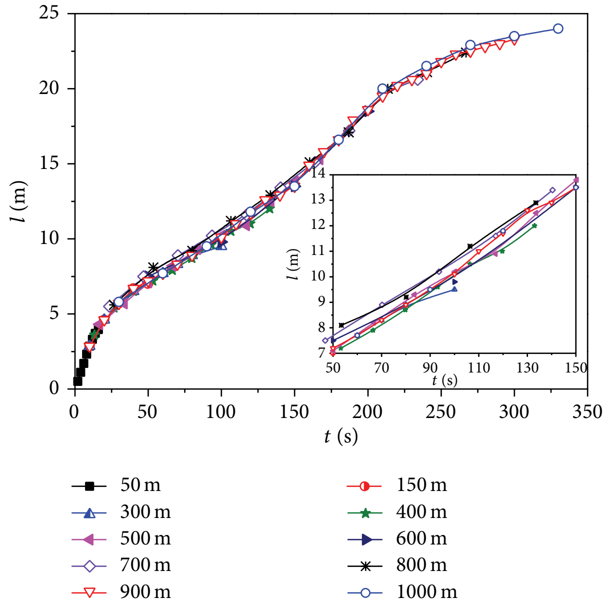

FIGURE 5: The gas mixture length varied with time in pipes of different lengths.

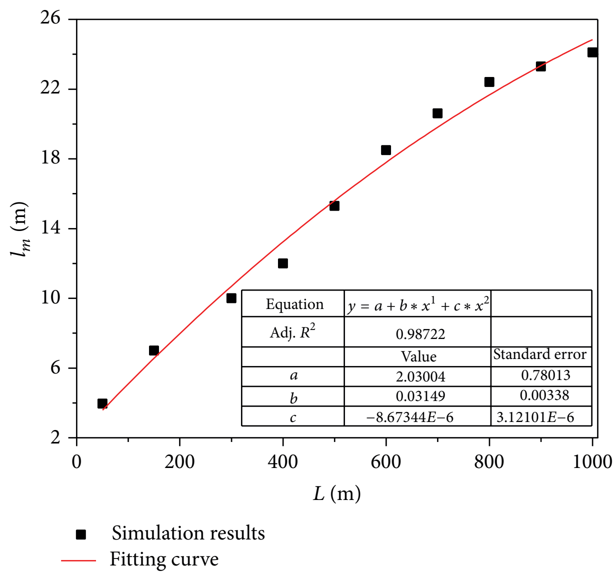

FIGURE 6: The maximum gas mixture length (l_m) versus the pipe length (L).

4.4. Effect of Inlet Rate. Figure 10 depicts the maximum gas mixture length at different inlet rates. The faster the nitrogen forward, the longer the maximum gas mixture length. It is attributed to that high speed of nitrogen flow has more kinetic energy. Gas mixed more fuller at large inlet rate, resulting in the longer mixture length. As inlet rate increases 1 m/s, the increments of the maximum gas mixture length are basically the same, about 1.9 m.

The gas mixture length varied with time at different inlet rates is shown in Figure 11. The growth rate of mixture length presents the maximum value (0.2 m/s) at $v = 5$ m/s, which is about 3.33 times than that at $v = 2$ m/s. Less time required for high-speed flow to pass through the pipe is the main cause. Though faster replacement is reached by high inlet rate, the rate cannot be set to too large. Residue particles will be carried by high-speed flow and strike pipe wall, leading to electric spark. Therefore, inlet rate should be controlled in a certain range. In practice, 4 m/s is an appropriate choice.

As shown in Figure 12, the fitting formula of l_m versus v is obtained. This fitting line also meets the linear distribution, and the adjusted R-squares are 0.99483. The fitting formula is as follow:

$$l_m = 13.86 + 2.04v. \quad (8)$$

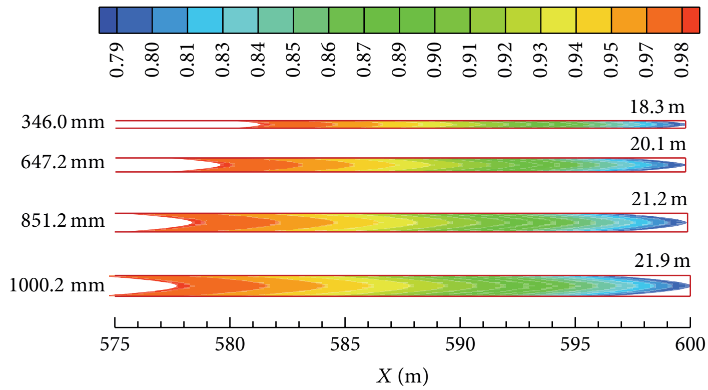

Figure 7: The maximum gas mixture length for different pipe diameters.

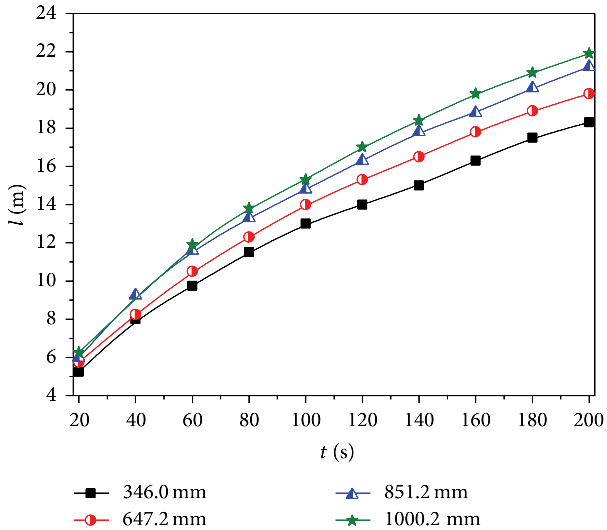

Figure 8: The gas mixture length varied with time in pipes of different diameters.

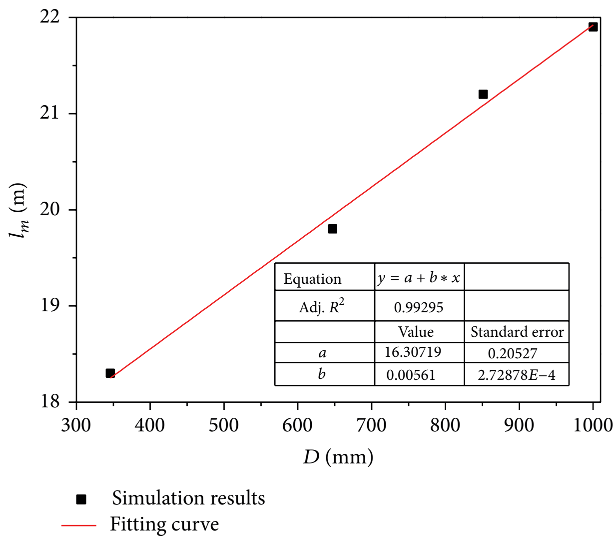

Figure 9: The maximum gas mixture length (l_m) versus the pipe diameter (D).

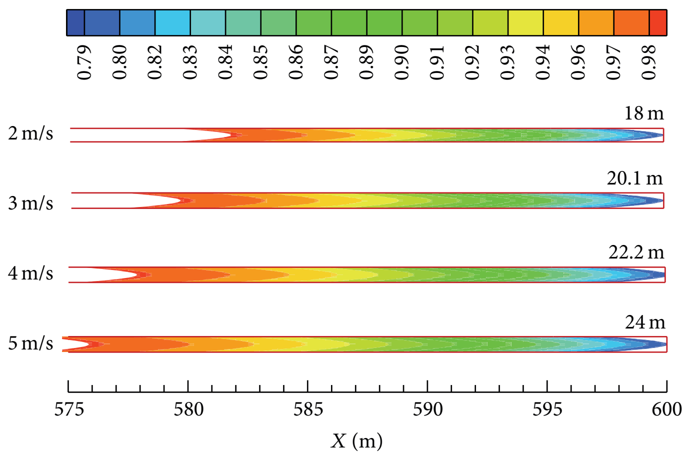

Figure 10: The maximum gas mixture length at different inlet rates.

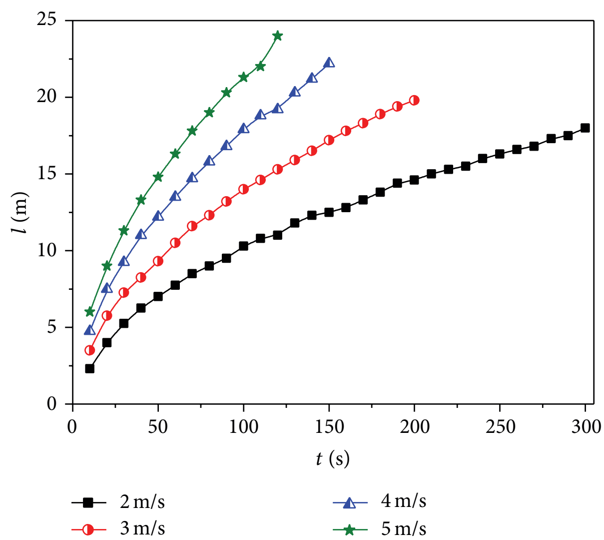

Figure 11: The gas mixture length varied with time at different inlet rates.

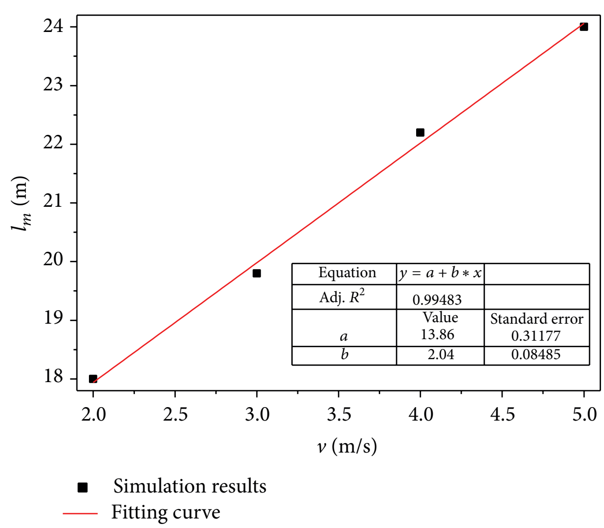

Figure 12: The maximum gas mixture length (l_m) versus the inlet rate (v).

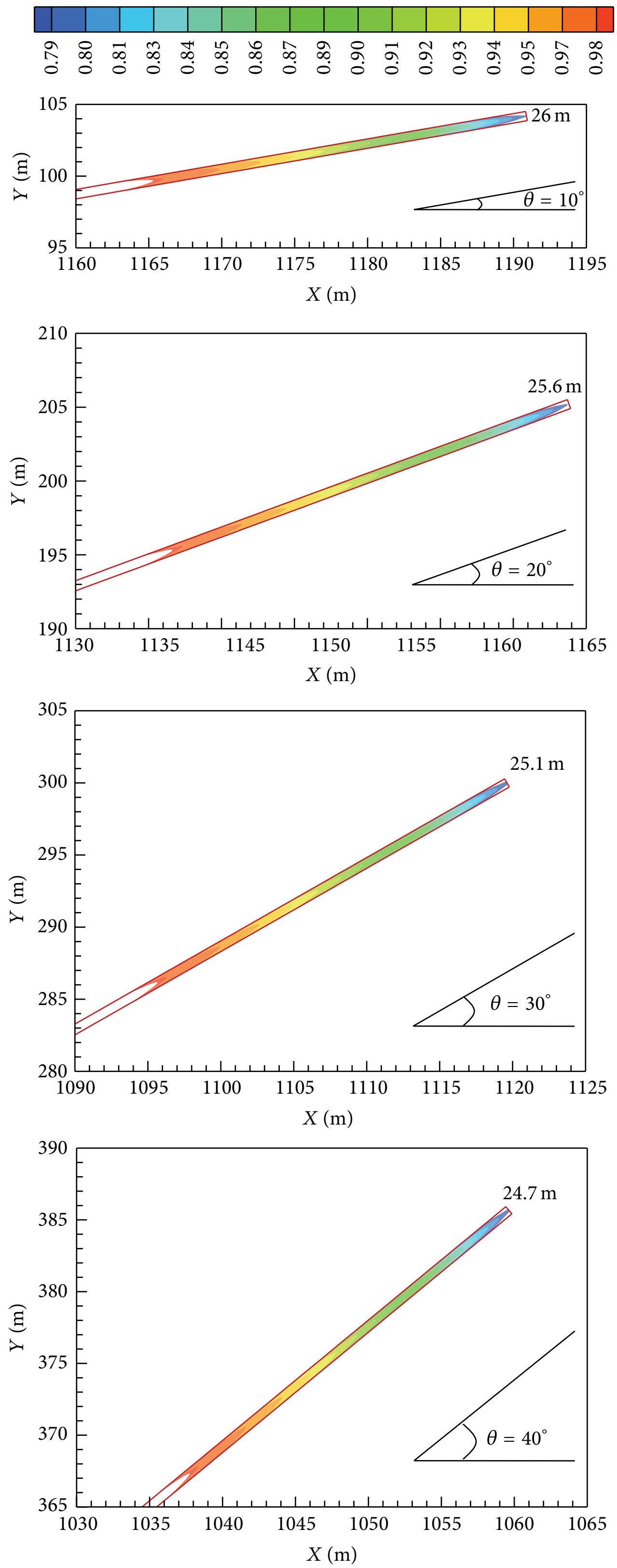

FIGURE 13: The maximum gas mixture length at different inclination angles.

Using this formula, l_m would be calculated as 21 m if the inlet rate is 3.5 m/s.

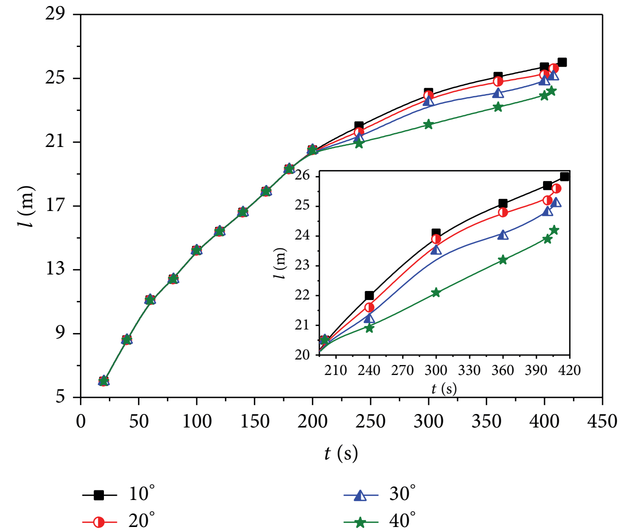

FIGURE 14: The gas mixture length varied with time at different inclination angles.

4.5. Effect of Inclination Angle of Pipe. Taking the terrain into account, four undulating pipes with different inclination angles are analyzed. Figure 13 provides the maximum gas mixture length at different inclination angles. We find an obvious reduction in mixture length as inclination angle increases. For $\theta = 10^{\circ}$, the maximum gas mixture length is 26 m, while it decreases to 24.7 m for $\theta = 40^{\circ}$. The main cause is that partial energy of gas flow is used to overcome gravity acting, and more energy is consumed for steep pipe.

Figure 14 shows the gas mixture length varied with time at different inclination angles. There is no difference in straight pipe section. The significant difference appears in inclined upward section. The larger the inclination angle, the smaller the growth rate of mixture length.

The fitting formula of l_m versus θ is shown in Figure 15. This fitting line is a negative slope straight line, and the adjusted R-squares reach 0.99691. The fitting formula is

$$l_m = 26.45 - 0.044\theta. \tag{9}$$

If the inclination angle is 50°, l_m would be calculated by the formula as 24.25 m.

5. Conclusions

A computational fluid dynamic model coupled to a species-transportation model has been used to investigate the gas mixture length of nitrogen replacement in large-diameter pipeline without isolator. Effects of pipe length and diameter, inlet rate, and inclination angle of pipe are examined by conducting a series of simulations. Based on the numerical results, the following conclusions can be drawn.

(1) Gas mixture length increases over time, and the maximum gas mixture length is present at outlet of pipe. Long and large-diameter pipe and fast speed of nitrogen lead to long length of mixed gas, while large inclination angle of pipe brings about short length.

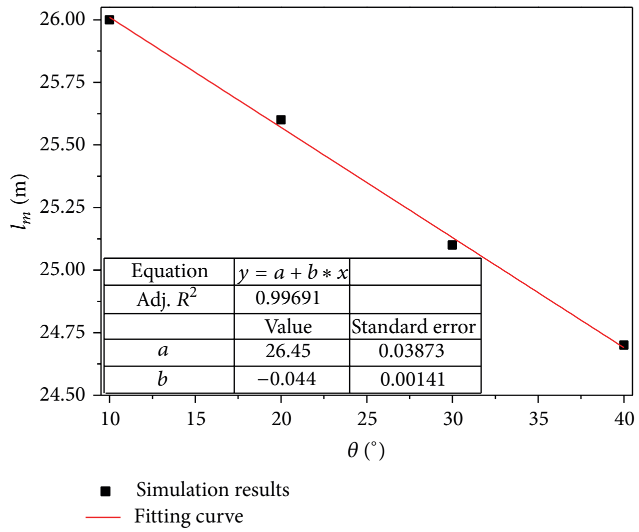

FIGURE 15: The maximum gas mixture length (l_m) versus the inclination angle (θ).

(2) Four fitting formulas have been obtained, which can predict the maximum gas mixture length in gas pipelines. Besides that the formula for pipe length is a quadratic polynomial, the other formulas meet linear relationship. The calculation results provide effective guidance for practical operation of nitrogen replacement.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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