Numerical simulation on filling process of drag reduction agent in natural gas pipeline

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Abstract. In this paper, a numerical simulation is established to model the filling process of atomized natural gas drag reduction agent (DRA) at the pipeline inlet section. The computations are on the basis of the Euler-Lagrange method with the standard k-ε turbulence model. The effects of atomizing parameters on the droplets Sauter Mean Diameter (SMD) and the adsorption performance on the wall of pipe are investigated using the validated model. The results show that nozzle diameter and nozzle angle have little effect on the SMD of DRA droplets, whereas the size of the droplets SMD reduces with the increase of atomizing pressure, and the influence of atomizing flow rate is just the opposite.

1. Introduction

As an efficient, clean and environmentally friendly primary energy source and high-quality chemical raw material, natural gas has become the best choice for countries all over the world to optimize energy structure, improve atmospheric environment and promote sustainable economic development. Recently, with the continuous growth of the proportion of natural gas in the international energy structure, the problem of high energy consumption in pipeline transportation has attracted wide attention. At present, the best way to solve this problem is to apply drag reduction technology. Drag reduction agent (DRA) technology is one of the major methods of reducing the internal flow resistance in gas transmission pipeline [1, 2, 3], which makes up for the shortcomings of inner coating technology. It has the advantages of low construction cost, simple operation and wide application range of pipelines, which can be applied in new and old pipelines, large diameter and high pressure pipelines, and gathering pipelines [4, 5]. At present, scholars believe that the mechanism of natural gas DRA is that the polar end of the DRA molecule is adsorbed tightly on the wall of metal pipe and the non-polar long chain end of the DRA molecule extends on the surface of pipe along the direction of gas flow to form an elastic film [6, 7, 8]. This new interface makes the pipe wall smoother and restrains the radial pulsation of the natural gas. As a result, the total energy consumption of natural gas transportation is decreased and the purpose of drag reduction and transportation increasing is achieved.

At present, the researches of drag reduction technology of natural gas DRA at home and abroad mostly focus on the analysis of drag reduction mechanism, the design of DRA’s molecular structure, the...
experiment testing for reduction drag, the evaluation of drag reduction property, and so on [9, 10, 11, 12, 13]. However, there is rarely reported about the theoretical basis of filling technology for natural gas DRA, which is vital to the field application and wide promotion of the drag reduction agent technology. The natural gas DRA first needs to be atomized and injected into the pipeline in practical application. An atomizer enables the natural gas DRA droplets to disperse into the pipe, as pictured in Fig. 1. The fully atomized DRA droplets move with the natural gas flow, and hit the pipe wall by the turbulent diffusion of natural gas flow. Finally, the DRA droplets adhere to the wall of pipe to form a uniform drag reduction film. It can be concluded that the filling process of natural gas DRA is complicated, comprising of atomizing, carrying and film forming. Furthermore, the process is influenced by a number of factors, such as DRA properties and atomization parameters. Therefore, in order to achieve the optimal drag reduction effect and the longer drag reduction distance, it is necessary to consider the influence of various factors comprehensively.

In this paper, a numerical simulation of the filling process of atomized natural gas drag reduction agent at the pipeline inlet section by ANSYS Fluent with the DPM method is investigated. The effects of atomization parameters on the droplets Sauter Mean Diameter (SMD) and the adsorption performance on the wall of pipe are carried out, and relatively detailed results are discussed. It is considered that these studies will be able to provide the necessary theoretical guidance for the engineering practical application of natural gas DRA.

![Figure 1. Atomization and injecting process of DRA](image)

2. Simulation analyses

2.1. Model building

2.1.1. Physical model and mesh division. For the sake of investigating the effects of different factors on the filling process of atomized natural gas DRA at the pipeline inlet section, the 15-meter-long pipeline after the filling point, which is set at the central line of the pipe inlet end, is selected as the research object. The pipeline geometry structure is shown in Fig. 2 and the parameters and ranges of simulation are listed in Table 1. Table 2 shows the physical property parameters of natural gas and DRA. In order to simplify the physical model, the following assumptions are made:

1. The variation in temperature in the gas pipeline is negligible, and the heat transfer between natural gas and DRA droplets will not be considered;
2. Regardless of the gravitational effects of natural gas and DRA droplets, the model is symmetrical with respect to the axis of the pipeline;
3. The result of atomization is regarded as a thin spray to ignore the interaction between DRA droplets.
In this paper, the size of DRA droplets is measured by means of the Sauter Mean Diameter (SMD), which is always calculated based on the total volume and surface area, can be written as[14,15]:

\[ V = \frac{N}{6} \pi d_{\text{SMD}}^3 = \frac{\pi}{6} \sum N_i d_i^3 \]  
\[ A = N\pi d_{\text{SMD}}^2 = \pi \sum N_i d_i^2 \]  
\[ d_{\text{SMD}} = \frac{\sum N_i d_i^3}{\sum N_i d_i^2} \]  

To evaluate the adsorption characteristics of DRA droplets on the wall of pipe, the adsorption ratio is defined as:

\[ R(\%) = \frac{N_{\text{trapped}}}{N_{\text{total}}} \times 100 \]  

The quadrilateral structured mesh of the axisymmetric pipeline model shown in Fig. 3 is generated in ICEM CFD. A local mesh encryption is performed at the wall of pipeline and the area near the nozzle for improving the calculating precision. A mesh sensitivity analysis was carried out, and the results are shown in Fig. 4. It can be observed that the gas flow velocity along the pipeline axis does not change significantly. Hence, mesh 1 (cell number=121455) is chosen as the simulation calculation mesh.
2.1.2. Mathematical model. The problems researched in this paper belong to multiphase flow. There are two methods for the numerical simulation of multiphase flows: the Euler-Euler method and the Euler-Lagrange method [16]. The volume fraction of DRA droplets is less than 10%, and there is little to no interaction between droplets and the discrete phase (DRA droplets) has a small impact on the continuous phase (natural gas flow). Therefore, the problems can be solved by the Euler-Lagrange method, in which the natural gas flow is described with standard k-ε turbulence model, and the motion of DRA droplets is described with the particle stochastic trajectory model [17].

The governing equations for natural gas flow are described by Eqs. (5)-(8) [18].

Continuity equation:

$$\frac{\partial}{\partial x_i} (\rho g u_i) = 0$$

Momentum conservation equation:

$$\frac{\partial}{\partial x_i} (\rho g u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \right]$$

Turbulence model (standard k-ε):

$$\frac{\partial (\rho g k)}{\partial x_i} = -\frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial k}{\partial x_j} \right] + G_k - \rho g \varepsilon$$

$$\frac{\partial (\rho g \varepsilon)}{\partial x_i} = -\frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1e} \frac{\varepsilon}{k} G_k - C_{2e} \rho g \frac{\varepsilon^2}{k}$$

The control equations for DRA droplets are represented by Eqs. (9)-(11)[19].

Motion equation (x-direction):

$$\frac{du_d}{dt} = f_D (u - u_d) + \frac{g_x (\rho_d - \rho_g)}{\rho_d} + f_s$$

$$f_D = \frac{18\mu}{\rho_d a^2} \frac{C_D Re}{24}$$

Track equation:

$$\frac{dx}{dt} = u_d$$
The governing equations are discretized on the basis of the Finite Volume Method [20]. The governing equations are solved adopting the SIMPLE algorithm for pressure-velocity coupling with QUICK discretization scheme and a pressure-based steady solver. After obtaining a convergent gas flow field by simulating the steady state flow field at the pipeline, the DRA is filled as a series of discrete phase droplets from the inlet atomization nozzle for coupling calculation. The convergence criterion of residuals is $10^{-5}$.

2.1.3. Model validation. The gas flow velocity distribution of the base case along pipeline axis is presented in Fig. 5. As shown in Fig. 5, the velocity of gas flow increases rapidly from 10.0 m/s to 11.6 m/s, and then keeps nearly at a constant value. It suggests that the gas turbulent flow in pipe has been fully developed and the selected length of the inlet section of pipeline is appropriate. Fig. 6 shows the gas flow velocity contours of pipeline. It can be seen from Fig. 6 that the discrete phase droplets only affect the flow field near the atomization nozzle (less than 2 m from the pipeline inlet end) by comparing the velocity contours before (see Fig. 6(a)) and after (see Fig. 6(b)) the filling of DRA, and the flow field of the whole pipeline still conforms to the velocity distribution law of the inlet section of turbulent pipe, which verifies the rationality of the DPM model adopted.

![Gas flow velocity contours](image)

**Figure 5.** Distribution curve of the gas flow velocity along pipeline axis (base case)

**Figure 6.** Contours of the gas flow velocity (base case)

Fig. 7 shows the concentration distribution of DRA in the pipeline. As depicted in Fig. 7, the concentration of DRA near the atomization nozzle is higher and decreases continuously along the axial and radial direction, which conforms to the concentration diffusion theory. As a result of natural gas DRA is seldom used in the field at present, the field test data of corrosion inhibitor will be taken as an example to verify the feasibility of the model adopted in this paper. Previous studies on corrosion inhibitor have shown that with the increase of the axis distance, the concentration in the center of pipeline decreases very fast and rapidly approaches the average concentration of the cross section, and the radial concentration distribution tends to be uniform, namely independent of the radial position [21]. The theoretical simulated concentration distribution is in good agreement with the experimental results, which verifies that it is feasible to use this model for simulating calculation.
3. Results and Discussion

3.1. Effect of atomizing pressure

Fig. 8 presents the effect of atomizing pressure on the droplets SMD with the condition of atomizing flow rate, nozzle diameter and nozzle angle equals to 0.001 kg/s, 0.8 mm and 40° respectively. The atomizing pressure is kept at 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 MPa respectively. As shown in Fig. 8, the droplets SMD decreases with the increase of atomizing pressure. It also can be seen from the figure that the droplets SMD decreases smoothly when the atomizing pressure exceeds 3.0 MPa. This is because the bigger the atomizing pressure, the greater the swirling velocity of the liquid in the nozzle and the more intense the disturbance of the liquid film during the spraying, and the smaller the droplets SMD. However, when the atomizing pressure increases to a certain critical value, the liquid velocity in the nozzle increases slowly and the disturbance degree of liquid film decreases, and the droplets SMD decreases slowly. Therefore, increasing the atomizing pressure can refine the size of droplets to a certain extent.

Fig. 9 shows the distribution range and proportion of droplet diameters under different atomization pressure. The diameter of DRA droplets obeys the Rosin-Rammler distribution, in which most droplets are concentrated in the medium size. [17] For example, droplet size is 7-50 μm at the pressure of 3.0 MPa, while 24-34 μm diameter accounts for about 60%. With the increase of pressure from 0.5 MPa to 5.0 MPa, the range of diameter changes from 18-132 μm to 5-36 μm. It can be drawn that an increase in the atomizing pressure results in smaller droplets size and more concentrated droplet diameters distribution, which makes the atomization of DRA droplets more fineness and uniformity.

The effect of atomizing pressure on the adsorption of DRA droplets on the simulated pipeline is presented in Table 3. A comparison of the adsorption ratio data listed in Table 3 shows that the
atomization pressure clearly affects the adsorption ratio of DRA droplets. It can be seen that with the increase of atomizing pressure from 0.5 MPa to 5.0 MPa, the adsorption ratio of DRA droplets decreases from 22.1% to 13.8%. This is because the smaller droplets have good mobility, which makes them easy to be carried to a longer distance by the gas flow, while the larger droplets are apt to be adsorbed on the wall of pipe. Due to the change of droplet diameter is no longer obvious when the atomization pressure exceeds 3.0 MPa, the variation of adsorption ratio tends to be smooth and stabilize eventually at about 14%.

Table 3. Changes in droplet adsorption ratio with atomizing pressure

| Atomizing pressure (MPa) | Tracked number | Trapped number | Escaped number | Adsorption ratio (%) |
|-------------------------|----------------|----------------|----------------|---------------------|
| 0.5                     | 4000           | 848            | 3116           | 22.1                |
| 1.0                     | 4000           | 812            | 3188           | 20.3                |
| 2.0                     | 4000           | 656            | 3344           | 16.4                |
| 3.0                     | 4000           | 564            | 3436           | 14.1                |
| 4.0                     | 4000           | 556            | 3444           | 13.9                |
| 5.0                     | 4000           | 552            | 3448           | 13.8                |

3.2. Effect of atomizing flow rate

Fig. 10 illustrates the effect of atomizing flow rate on the droplets SMD with the condition of atomizing pressure, nozzle diameter and nozzle angle equals to 2 MPa, 0.8 mm and 40° respectively and the corresponding atomizing flow rate is 0.001, 0.002, 0.003, 0.004 and 0.005 kg/s respectively. It can be seen that the droplets SMD increases with the increase of atomizing flow rate, as shown in Fig. 10. When the atomization flow rate is less than 0.004 kg/s, the droplets mean diameter has a positive linear correlation with the atomizing flow rate and the size of the trapped and escaped droplets are nearly the same. When the atomization flow rate exceeds 0.004 kg/s, the droplets SMD increases dramatically and the mean diameter of the trapped droplets is much larger than that of the escaped droplets. These phenomena can be explained by the increase of the atomizing flow rate leads to a more dispersed droplet diameters distribution (see Fig. 11). As the increase of flow rate from 0.001 kg/s to 0.005 kg/s, the range of diameter shifts from 10-60 μm to 44-322 μm, which brings about a poor atomization uniformity.

Table 4 shows the impact of atomizing flow rate on the adsorption of DRA droplets on the wall of pipe. With the increase of atomizing flow rate, more and more droplets adhere to the pipe wall. It is worth mentioning that the adsorption ratio of droplets increases steeply from 22.3% to 94.8% as the atomizing flow rate changes from 0.004 kg/s to 0.005 kg/s, as shown in Table 4. This is because the size of droplets at flow rate of 0.005 kg/s is much bigger than that at flow rate of 0.004 kg/s, which deteriorates the mobility of droplets with the gas flow. As a result, most of the droplets are adsorbed on the wall of pipe near the atomizing nozzle, which can not guarantee the film forming distance of natural gas DRA. Therefore, selecting the appropriate atomization flow rate is a key to the forming of drag
reduction film, which can not only guarantee the adsorption quantity of DRA droplets, but also achieve a longer distance of film formation.

Table 4. Changes in droplet adsorption ratio with atomizing flow rate

| Atomizing flow rate (kg/s) | Tracked number | Trapped number | Escaped number | Adsorption ratio (%) |
|---------------------------|----------------|----------------|----------------|----------------------|
| 0.001                     | 4000           | 656            | 3344           | 16.4                 |
| 0.002                     | 4000           | 780            | 3220           | 19.5                 |
| 0.003                     | 4000           | 836            | 3164           | 20.9                 |
| 0.004                     | 4000           | 892            | 3108           | 22.3                 |
| 0.005                     | 4000           | 3792           | 208            | 94.8                 |

3.3. Effect of nozzle diameter

Fig. 12 shows the effect of nozzle diameter on the droplets SMD under the condition of atomizing pressure, atomizing flow rate and nozzle angle equals to 2 MPa, 0.001 kg/s and 40° respectively, and the nozzle diameter is in the range of 0.5-3.0 mm. As plotted in Fig. 12, the droplets SMD decreases with the increasing nozzle diameter and it should be noted that the variation range of the droplets SMD is small. With the increase of the nozzle diameter from 0.5 mm to 3.0 mm, the corresponding droplets SMD decreases from 44 μm to 34 μm, in which the reduction is only 10 μm. It means that the size of droplets is less affected by the nozzle diameter. As shown in Fig. 13, the distribution range and proportion of droplet diameters under the condition of different nozzle diameters are almost the same. The droplets diameters are mainly concentrated in the range of 10-60 μm. In the simulation, the hollow cone pressure-swirl-nozzle model is used [22], which has the property of the gas flow rate increasing with the increase of nozzle diameter. Because of the increased gas flow rate leads to the intensification of the disturbance between the conical liquid film and the gas flow, the mean diameter of DRA droplets decreases slightly.

![Figure 12. Changing curve of droplet SMD with nozzle diameter](image1)

![Figure 13. Distribution ratio of droplet diameter](image2)

The impact of nozzle diameter on the adsorption of DRA droplets on the pipeline is presents in Table 5. As shown in Table 5, the adsorption ratio changes slightly with the increase of nozzle diameter. As the nozzle diameter increases from 0.5 mm to 3.0 mm, the adsorption ratio varies from 19.1% to 17.7%. It can be concluded that the nozzle diameter has little effect on the adsorption ratio of DRA droplets on the wall of pipe. Therefore, on the premise of the film forming of DRA, the selection of nozzle diameter can be made according to the type of atomizer in field implementation.
Table 5. Changes in droplet adsorption ratio with nozzle diameter

| Nozzle diameter (mm) | Tracked number | Trapped number | Escaped number | Adsorption ratio (%) |
|----------------------|----------------|----------------|----------------|----------------------|
| 0.5                  | 4000           | 764            | 3236           | 19.1                 |
| 0.8                  | 4000           | 656            | 3344           | 16.4                 |
| 1.0                  | 4000           | 744            | 3256           | 18.6                 |
| 2.0                  | 4000           | 712            | 3288           | 17.8                 |
| 3.0                  | 4000           | 708            | 3292           | 17.7                 |

3.4. Effect of nozzle angle

Fig. 14 presents the effect of nozzle angle on the SMD of droplets under the condition of atomizing pressure, atomizing flow rate and nozzle diameter equals to 2 MPa, 0.001 kg/s and 0.8 mm respectively. The nozzle angle is set to be 40°, 60°, 90°, 120°, 140° and 160° respectively. As shown in Fig. 14, the values of the droplets SMD are basically constant in a large range of nozzle angle (from 40° to 140°). As the nozzle angle changes from 140° to 160°, the value of the droplets SMD increases apparently, especially the size of droplets captured by the wall of pipe is much larger than that of the escaped droplets. It can be drawn that there is little effect on the distribution of the droplets SMD as the nozzle angle is in the range of 40°-140°. When the nozzle angle reaches to 160°, the distribution of the droplets diameter is dispersed (see Fig. 15). As the increase of nozzle angle from 40° to 160°, the range of diameter varies from 10-60 μm to 44-322 μm, which results in a bad atomization uniformity.

Figure 14. Droplet SMD vs. nozzle angle

Table 6 shows the effect of nozzle diameter on the adsorption of DRA droplets on the simulated pipeline. The proportion of droplets adsorbed by the wall of pipe increases with the increase of nozzle angle, as shown in Table 6. The phenomenon of increasing adsorption ratio can be explained by the higher radial velocity and the lower axial velocity of droplets with the increasing nozzle angle. For the pipeline with a particular length, the more droplets are absorbed on the pipe wall, the less droplets can be carried by the gas flow, which results in the insufficient protection distance of pipeline. Hence, the nozzle angle should be selected reasonably.

Table 6. Changes in droplet adsorption ratio with nozzle angle

| Nozzle angle (°) | Tracked number | Trapped number | Escaped number | Adsorption ratio (%) |
|------------------|----------------|----------------|----------------|----------------------|
| 40               | 4000           | 656            | 3344           | 16.4                 |
| 60               | 4000           | 724            | 3276           | 18.1                 |
| 90               | 4000           | 820            | 3180           | 20.5                 |
| 120              | 4000           | 884            | 3116           | 22.1                 |
| 140              | 4000           | 1144           | 2856           | 28.6                 |
| 160              | 4000           | 3968           | 32             | 99.2                 |
4. Conclusions
This study set up a numerical simulation to model the injecting process of atomized DRA at the pipeline inlet section. The impacts of atomizing parameters on the droplets Sauter Mean Diameter (SMD) and the adsorption property on the inner wall of pipe are investigated. On the basis of the above analysis and discussion, it can be concluded that:

(1) With the increase of atomizing pressure, the SMD of DRA droplets will decrease, which results in the longer distance the DRA droplets can be carried by gas flow. However, the change is no longer obvious when the atomization pressure increase to a certain extent.

(2) Atomizing flowrate’s influence on the size of the droplets SMD is just the opposite of that of atomizing pressure. With increasing atomizing flow rate, the SMD of DRA droplets will increase, which make the DRA droplets can be easily adsorbed on the wall of pipe. However, when atomizing flow rate exceeds a certain value, almost all the DRA droplets are adsorbed by the pipe wall near the nozzle.

(3) Nozzle diameter and nozzle angle have little effect on the SMD of DRA droplets. However, when the nozzle angle gets larger, the DRA droplets can be adsorbed on the wall of pipe more easily.

(4) Reasonable selection of atomization parameters is the key factor to drag reduction effect and drag reducing distance of natural gas DRA in gas transportation pipeline according to gas flow rate and pipe diameter.

Nomenclature
- \( A \) surface of droplet [m²]
- \( C_D \) drag coefficient [-]
- \( D \) pipe diameter [m]
- \( D_n \) nozzle diameter [m]
- \( d \) diameter of droplet [μm]
- \( d_{SMD} \) Sauter mean diameter [μm]
- \( f_d \) drag force [m/s²]
- \( f_x \) additional acceleration force [m/s²]
- \( g \) gravity acceleration [m/s²]
- \( N \) number of the droplet [-]
- \( N_{trapped} \) number of the trapped droplet [-]
- \( N_{total} \) number of the total droplet [-]
- \( k \) turbulent kinetic energy [m²/s²]
- \( P \) pressure [Pa]
- \( Q \) atomizing flowrate [kg/s]
- \( R \) adsorption ratio [%]
- \( Re \) Reynolds number [-]
- \( t \) time [s]
- \( u \) velocity of gas flow [m/s]
- \( u_d \) velocity of droplet [m/s]
- \( V \) volume of droplet [m³]
- \( x \) axial coordinate

Greek letters
- \( \alpha \) optimal nozzle angle for D less than 0.5 m [°]
- \( \beta \) optimal nozzle angle for D more than 0.5 m [°]
- \( \epsilon \) turbulent dissipation rate [m³/s³]
- \( \mu \) viscosity [Pa·s]
- \( \theta \) Angle [°]
- \( \rho \) density [kg/m³]

Subscripts
- \( d \) droplet
- \( g \) gas
- \( i,j \) coordinate indices
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