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Numerical Simulation of Erosion Characteristics for Solid-Air Particles in Liquid Hydrogen Elbow Pipe

Wenqing Liang ^{1,2}, Qining Xun ³, Zhiyong Shu ^{1,2}, Fuming Lu ^{1,2} and Hua Qian ^{1,2,*}

¹ School of Energy and Environment, Southeast University, Nanjing 210096, China; liangwenqing@seu.edu.cn (W.L.); shuzhiyong@seu.edu.cn (Z.S.); 220200592@seu.edu.cn (F.L.)

² State Key Laboratory of Technologies in Space Cryogenic Propellants-SEU Research Center, Nanjing 210096, China

³ Shandong Institute of Non-Metallic Materials, Jinan 250031, China; cse_xunqn@ujn.edu.cn

* Correspondence: qianh@seu.edu.cn

Abstract: The crystalline solid-air in the liquid hydrogen will cause erosion or friction on the elbow, which is directly related to the safety of liquid hydrogen transportation. The CFD-DPM model was used to study the erosion characteristics of solid-air to liquid hydrogen pipelines. Results show that the outer wall of the cryogenic liquid hydrogen elbow has serious erosion in the range of 60–90°, which is different from the general elbow. The erosion rate is linearly positively correlated with the mass flow of solid-air particles, and the erosion rate has a power function relationship with the liquid hydrogen flow rate. The fitted relationship curve can be used to predict the characteristics and range of the elbow erosion. The structure of the liquid hydrogen elbow also has an important influence on the solid-cavity erosion characteristics. The increase of the radius of curvature is conducive to the reduction of the maximum erosion rate, while the average erosion rate undergoes a process of increasing and then decreasing. The radius of curvature is 60 mm, which is the inflection point of the average erosion rate of the 90° elbow. The research results are expected to provide a theoretical basis for the prevention of liquid hydrogen pipeline erosion.

Keywords: liquid hydrogen; CFD-DPM; erosion rate; fitting relationship; hydrogen safety

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1. Introduction

Liquid hydrogen as a green, carbon-free, high-efficiency energy source is widely used in aerospace, industry, chemical, automotive, and other fields [1–3]. Among them, the liquid hydrogen pipeline transportation system makes it very easy to condense the air doped inside it due to its cryogenic conditions (20 K). The condensed solid-air particles have an erosion effect on pipes, valves, and other components and reduce the service life of the pipeline. Besides, solid-air particles are easily accumulated in local areas of the pipeline, which will lead to excessive local oxygen concentration, and thereby the risk of the pipeline transportation system increasing [4].

The process of solid-air particles flowing with liquid hydrogen after formation is a typical fluid–solid coupling complex problem. There are many studies on the erosion or wear of normal temperature pipelines, and many important research achievements in related fields have been obtained. Experimental studies of erosion characteristics are costly and make it difficult to quantify erosion rates. At present, CFD (Computational Fluid Dynamics) is one of the best ways to study erosion characteristics. Wallace et al. [5] studied the erosion of sand particles (solid mass fraction 0.51%) in water based on CFD on the erosion of two types of throttle valves and used a set of restorations in the model. The coefficient reflects the momentum loss after the particle collides with the wall. Dai et al. [6–8] developed the Gaussian process (GP) model to calculate the erosion in the pipeline and verify the difference and credibility of the model. Mazur et al. [9] studied the erosion phenomenon in the main steam valve of a steam turbine. The erosion rate can be reduced by 51% through

structural optimization, which further verifies that CFD-DPM (Discrete Phase Model) simulation can be used to guide optimization design. The CFD-DPM model has proven to be effective for studying the erosion characteristics of pipelines. Chen et al. [10] studied the erosion phenomenon of tees and elbows and adopted the recovery coefficient proposed by Frontier et al. [11]. By comparing the experimental value with the simulated value, it was found that the appropriate selection of the recovery coefficient helps to improve the prediction accuracy. Pereira et al. [12] studied the influence of different restoration coefficient selections, erosion models, particle numbers, and wall roughness on the accuracy of elbow erosion prediction. The combination of the erosion model proposed by Oka et al. [13] and the restitution coefficient proposed by Grant et al. [14] can obtain a more accurate elbow erosion position and erosion rate. However, there is no fitting relationship between the erosion rate and each parameter. Wang et al. [15] used the combination of CFD erosion simulation results and the response surface method to obtain the optimal design of the throttle valve. Optimization of the structure and operating parameters of valves and pipelines is an effective and economical way to reduce erosion. Banakermani et al. [16], based on the erosion law of 15° and 90° elbows under normal temperature conditions of gas-solid two-phase flow, found that when the angle increases from 15° to 90°, the maximum erosion rate steadily increases, but the total erosion rate remains relatively constant. Ossai [17–19] simulated and experimentally studied the internal and external erosion of the pipeline, and established a blast pressure prediction model to study the ratio of corrosion defect depth to pipe wall thickness and the ratio of corrosion defect length to the pipe diameter. In addition, particle-laden turbulent flow is a highly active and well-matured research field [20–24], and the turbulence of the fluid has a great influence on the movement, deposition, and erosion of particles. Rohit and Andrew [20] considered the effect of gravity on clustering and collision of bi-disperse inertial particles. Sarma et al. [25,26] studied the relative motion of monodisperse high Stokes number particle pairs. Nicholas et al. [27] experimentally studied the relative dispersion of tracer particles. Luca et al. [28] compared Lagrangian structure functions computed experimentally and using DNS (Direct Numerical Simulation). Riaz and Park [29–31] presented a two-dimensional tungsten disulfide (WS₂)-based material as a reinforcement additive to produce thermally stable, mechanically strong, and light-weight epoxy (EP) composites. In summary, many scholars have studied the analysis of the erosion of solid particles on pipelines in the transportation of petroleum, sand, gravel, and dusty flue gas, but there is little literature on the erosion of solid particles in cryogenic pipelines. In addition, most of the existing literature on the erosion of elbows focuses on the influence of a certain working condition parameter on the erosion of the elbow, while ignoring the comprehensive effect of various factors, and there is a lack of quantitative research on the fitting relationship between elbow erosion and influencing factors.

In this research, the CFD-DPM model is applied to obtain the erosion characteristics of solid-air in the elbow under cryogenic conditions. The simulation results are compared with the experimental values in the literature and the calculated values of the empirical formula. It is verified that the simulation results are basically credible. The erosion characteristics of different flow rates, particle sizes, and structural parameters are analyzed. Different from the existing literature, the fitting relationship was analyzed between the erosion rate and different parameters, and provides a technical basis for guiding the erosion optimization strategy of liquid hydrogen pipelines and hydrogen safety research.

2. Numerical Model and Verification

2.1. Numerical Model

This study ignores the phase change formation process of solid particles in the liquid hydrogen flow field, and adopts the DPM model in the Fluent Perform simulation.

To simplify the model, this study made the following assumptions in the simulation: (1) Only consider the movement of the solid particles after they are formed, and ignore the phase change formation process of the solid particles. (2) The solid particles only enter

the pipeline from the entrance, and the velocity direction is perpendicular to the inlet end face. (3) During the simulation, the particle movement only considers the influence of drag and volume forces, and ignores external forces such as Brownian force and Saffman lift. (4) Liquid hydrogen flows in the elbow cavity without cavitation. The temperature is constant at 20 K, and it always remains liquid, which is regarded as an incompressible fluid.

Since the viscosity of liquid hydrogen is small, the Reynolds number is usually in the order of 1×10^5 to 1×10^6 , and there are sudden changes in the flow field. The realizable k - ε turbulence model is used for the liquid phase [32]. Compared with the standard k - ε turbulence model, this model is more suitable for occasions with high Reynolds numbers, high strain rate, and large streamline curvature. The control equation is:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left(\rho \left(\mu + \frac{\mu_T}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon + S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left(\rho \left(\mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{1}{2} \rho C_1 \varepsilon \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} \right) - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon \mu / \rho}} + S_\varepsilon \quad (2)$$

where k is the turbulent kinetic energy, ε is the turbulent dissipation rate, G_k is the turbulent kinetic energy caused by the average velocity gradient, G_b is the turbulent kinetic energy caused by buoyancy, and σ_k and σ_ε are the turbulent kinetic energy and the Prandtl number corresponding to the dissipation rate. Special numbers C_1 and C_2 are empirical constants, and S_k and S_ε are user-defined source items.

The content of solid and empty particles in liquid hydrogen is far less than 10%, which meets the conditions of use of the DPM model, and the particles considered in this study are inertial and have finite size. When particles move in liquid hydrogen, they are mainly affected by volume force and drag force, so their motion equation is expressed in Equation (3):

$$\frac{d\mathbf{u}_p}{dt} = F_D(\mathbf{u} - \mathbf{u}_p) + \left(1 - \frac{\rho}{\rho_p} \right) \mathbf{g} \quad (3)$$

$$F_D = \frac{3\mu C_D \text{Re}_p}{4\rho_p d_p^2} \quad (4)$$

In the formula, $\mathbf{u}_p$ is the particle velocity, d_p is the particle diameter, C_D is the drag coefficient, ρ_p is the particle density, μ is the dynamic viscosity of the liquid hydrogen, and Re_p is the particle Reynolds number, and its value is given by Equation (5): the size of the particle is 5–10 μm in this study, and the Reynolds number based on the particle is 2.62–5.24.

$$\text{Re}_p = \frac{\rho d_p |\mathbf{u} - \mathbf{u}_p|}{\mu} \quad (5)$$

The movement of particles will be affected by turbulence. In this study, a random walking model will be used to reflect this effect. The instantaneous flow velocity of the fluid on the particle trajectory in the model is composed of two parts: the average flow velocity and the pulsating velocity, which can be expressed as:

$$\mathbf{u} = \bar{\mathbf{u}} + \mathbf{u}'(t) \quad (6)$$

After the particles collide with the wall, the direction of the velocity will change, and due to energy loss, the velocity will also decrease. In this study, a set of restitution coefficients related to the incident angle of the particles proposed by Forder et al. [8] will be used to represent the energy loss caused by the particle collision, which is defined as:

$$e_n = \frac{v_{2,n}}{v_{1,n}} = 0.988 - 0.78\theta + 0.19\theta^2 - 0.024\theta^3 + 0.027\theta^4 \quad (7)$$

$$e_t = \frac{v_{2,t}}{v_{1,t}} = 1 - 0.78\theta + 0.84\theta^2 - 0.21\theta^3 + 0.028\theta^4 - 0.022\theta^5 \quad (8)$$

In the formula, e_n is the normal recovery coefficient, e_t is the tangential recovery coefficient, $v_{2,n}$ and $v_{2,t}$ are the normal and tangential velocity of the particles after the collision, $v_{1,n}$ and $v_{1,t}$ are the normal velocity and tangential velocity of the particles before the collision, and θ is the incident angle of the particle.

Since the erosion rate is related to the particle incident angle and particle diameter, the inherent erosion model in Fluent cannot meet the calculation requirements. Therefore, the erosion model proposed by Zhang et al. [33] is used in this research. The specific erosion rate calculation formula is:

$$E_f = \frac{1}{A_f} \sum_s \dot{m}_s e_r \quad (9)$$

$$e_r = C(BH)^{-0.59} F_s u_p^n F(\theta) \quad (10)$$

$$F(\theta) = 5.4\theta - 10.11\theta^2 + 10.93\theta^3 - 6.33\theta^4 + 1.42\theta^5 \quad (11)$$

In the formula, E_f is the wall surface erosion rate, A_f is the erosion area, e_r is the erosion rate ($\text{kg}/(\text{m}^2 \cdot \text{s})$), C and n are constants, and their values are 2.17×10^{-7} and 2.41 respectively, BH is the Brinell hardness of the wall material, and F_s is the particle shape factor. The solid particles are simplified into spherical processing, so the shape factor is 0.2, and $F(\theta)$ is the incident angle function.

The range of particle Stokes numbers considered in this study is 1.11~9.84,

$$St = \frac{\tau_p}{\tau_f} = \frac{\rho_p d_p^2 \bar{U}_g}{18\mu_g L} \quad (12)$$

where τ_p is the particle response time and τ_f is the flow timescale.

2.2. Physical Model and Boundary Conditions

The elbow pipe model and grid division method studied are shown in Figure 1. The length of the inlet straight pipe is 80 mm, the radius of curvature at the elbow is 30 mm, the outlet straight pipe length is 80 mm, and the pipe diameter is 30 mm. The entrance is set as the velocity entrance boundary, and the exit is set as the free flow boundary. The fluid phase is liquid hydrogen (20 K), the particle phase is solid-empty particles with a density of $891 \text{ kg} \cdot \text{m}^{-3}$, and the particle diameter is assumed to obey the Rosin-Rammler distribution.

2.3. Simulation Model Verification

Due to the lack of experimental data on the erosion accumulation of cryogenic elbows, to verify the reliability of the selected model, the elbow erosion test results of Chen et al. [7] were used as a reference. In the simulation, the air was used as the flowing medium and the particle phase, and the simulation parameters are consistent with the experimental parameters, as shown in Table 1. The elbow adopts the O-Block grid division as shown in Figure 1, and the total number of volume grids is 776,832, which is slightly more than the 700,000 grids in the literature [9].

Figure 1. Schematic diagram of elbow structure and grid: (a) elbow structure (unit: mm) and (b) grid.

Table 1. Parameters used in model verification.

Physical Parameter	Parameter Value
Air velocity ($\text{m}\cdot\text{s}^{-1}$)	45.72
Particle diameter (μm)	150.00
Particle mass flow ($\text{kg}\cdot\text{s}^{-1}$)	2.08×10^{-4}
Particle volume fraction (%)	4.20×10^{-3}

Compared with the experimental value, the erosion rate is converted into the penetration rate. The calculation formula of the penetration rate (PR) is:

$$PR = \frac{E_f}{m_{in} \rho} \quad (13)$$

where m_{in} is the mass flow rate of the particles at the entrance, and ρ is the density of the wall material of the elbow, where the wall material is aluminum.

The relationship between the wall penetration rate of the elbow and the angle of the elbow is shown in Figure 2. It can be seen that the experimental value and the simulation value change with the angle almost the same, and the result can be better when the angle of the elbow is within the range of $0\text{--}50^\circ$. The simulated value is slightly smaller than the experimental value at $50\text{--}90^\circ$. This may be due to the idealized treatment of particle parameters in the simulation, and it is difficult to make the inlet particle size completely uniform in the actual test. The most severely worn area obtained by the simulation is at the bend angle of 47° , while the experimental value in literature [7] was about 45° . On the whole, the model used to quantitatively predict the erosion rate and determine the erosion location is credible.

To obtain grid-independent solutions, six groups of grids were used for calculation. In the calculation, the flow rate of liquid hydrogen is $5 \text{ m}\cdot\text{s}^{-1}$, the average diameter of solid-space particles is $5 \mu\text{m}$, and the average erosion rate in the calculation area is used as the reference basis. As shown in Figure 3, the average erosion rate is about $1.6 \times 10^{-10} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ when the number of grids reaches more than 800,000. As the number of grids increases, the magnitude of the value change is smaller. Based on determining the calculation accuracy to save the calculation cost, the number of grids used in the study was 8.30×10^5 .

Figure 2. The relationship between the wall penetration rate of the elbow and the angle of the elbow.

Figure 3. Grid independence verification.

3. Result and Discussion

3.1. The Erosion of Solid Particles

To obtain the erosion condition of the wall surface and the location of the severely worn area, the bend pipe with a radius of curvature, R , of 45 mm was taken as an example for analysis. The flow rate of liquid hydrogen in the simulation is $20 \text{ m}\cdot\text{s}^{-1}$, the flow rate of solid-air particles is $2.00 \times 10^{-4} \text{ kg}\cdot\text{s}^{-1}$, and the average particle size was selected as $5 \mu\text{m}$. The erosion of solid particles on the wall surface is shown in Figure 4. It was found that the erosion is mainly distributed on the outer wall of the elbow at $60\text{--}90^\circ$ (area of A) and where the side of the elbow meets the outlet end (area of B, C). The erosion is less at the entrance section. Different from the herringbone erosion area on the 90° air duct wall caused by dust in the literature [34], the erosion degree caused by the solid hollow particles in the liquid hydrogen appears more uniform.

From the liquid hydrogen flow rate and static pressure distribution diagram shown in Figure 5, it can be seen that the velocity and static pressure at the inlet section remained almost unchanged, and it can be considered that the flow at the inlet section also remained unchanged. The line direction is fixed, so the particles move axially in the inlet section, and only a few particles collide with the wall under the action of turbulent diffusion. At the elbow, due to the obstruction of the outer wall of the liquid hydrogen, the flow rate decreases, the static pressure increases, the static pressure in the inner wall area decreases, and the flow rate increases. A large number of solid particles will hit the outer wall of the elbow under the action of inertia (area of A) after the rebound. In this section, along the direction of the radius of curvature, the flow rate of the liquid hydrogen increases from large to small, and the centrifugal force on the fluid part also decreases from large to

small. Under the action of torque, the secondary flow will be generated on the downstream section of the elbow. Therefore, the solid-hollow particles that rebounded from the outer wall are driven by the secondary flow to scour the pipe wall (area of B, C) where the outlet section meets the elbow, which verified the erosion distribution characteristics in Figure 4.

Figure 4. The erosion of solid particles on the wall of the elbow: (a) XY plane view and (b) ZY plane view.

Figure 5. Flow velocity and static pressure distribution diagram of liquid hydrogen in the pipeline: (a) static pressure distribution diagram and (b) velocity distribution diagram.

3.2. Influence of Initial Conditions

When studying the influence of solid-air particle mass flow, the average particle diameter was set to $5\text{ }\mu\text{m}$, and the liquid hydrogen flow rate was $20\text{ m}\cdot\text{s}^{-1}$. The average particle diameters of 5 and $10\text{ }\mu\text{m}$ will be considered at the same time when studying the influence of the liquid hydrogen flow rate. Figure 6 shows the relationship between the average wall erosion rate, E_{ave} , the maximum erosion rate, E_{max} , and the solid-air mass flow, m_{in} , when the liquid hydrogen flow rate is $20\text{ m}\cdot\text{s}^{-1}$. It can be seen that both of them increased with the increase of the mass flow of solid-air particles. When the particle size is the same, the mass flow rate is larger, and the more particles that enter in a unit time, the greater the probability of collision with the pipe wall. It was found through a linear fitting that the E_{ave} and E_{max} have a linear functional relationship with the mass flow rate. When

the mass flow rate increased from 2×10^{-4} to $2.2 \times 10^{-3} \text{ kg}\cdot\text{s}^{-1}$, the average erosion rate, E_{ave} , changed to $4.42 \times 10^{-8} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and the maximum erosion rate, E_{max} , increased by $5.58 \times 10^{-7} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Figure 6. The relationship between the erosion rates and the solid-air mass flow rate: (a) E_{ave} and (b) E_{max} .

The relationships between the average erosion rate, E_{ave} , and the maximum erosion rate, E_{max} , with the velocity of liquid hydrogen are shown in Figure 7. It can be seen that the kinetic energy of the particles under the drive of the fluid is greater, and the erosion intensity caused by collision with the wall surface is greater, so the average erosion rate and maximum erosion rate both increase when the flow rate of liquid hydrogen increases. When the velocity of liquid hydrogen increased from 5 to $10 \text{ m}\cdot\text{s}^{-1}$, the average erosion rate increased by $6.76 \times 10^{-10} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. When the velocity of liquid hydrogen increased from 20 to $25 \text{ m}\cdot\text{s}^{-1}$, the average erosion rate increased by $2.97 \times 10^{-9} \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Based on this characteristic of change, the power function was used to fit the data, and the average particle diameters of 5 and $10 \mu\text{m}$ correspond to indexes of 2.37 and 2.51, respectively. At the same velocity of liquid hydrogen, comparing the erosion conditions of the average diameters, it was found that the average erosion rate at a diameter of $10 \mu\text{m}$ was greater than that at a diameter of $5 \mu\text{m}$, but the maximum erosion rate was less than that at a diameter of $5 \mu\text{m}$. For large-diameter solid particles, under the drag of liquid hydrogen, the kinetic energy will be greater, which increases the probability of contact with the wall, and the average wall erosion will be higher. Therefore, wall erosion reduction strategies can be achieved by reducing the velocity of liquid hydrogen and reducing the solid-air particle diameter.

3.3. Influence of Structural Parameters

The influence of the change of the radius of curvature on the degree of erosion of the pipe wall was studied in this work. In the simulation, the pipe diameter, D , remained unchanged at 30 mm , the liquid hydrogen flow rate was $20 \text{ m}\cdot\text{s}^{-1}$, the average particle diameter was $5 \mu\text{m}$, and the mass flow was $2.00 \times 10^{-4} \text{ kg}\cdot\text{s}^{-1}$. The relationship between the erosion rate and the radius of curvature was obtained as shown in Figure 8. As shown in Figure 8a, as the radius of curvature increases, the average erosion rate curve goes through a process of first increasing and then decreasing. It can be seen that the critical radius of curvature should be about 60 mm . The average erosion rate is based on the area weighting. Although the local erosion degree was reduced, the erosion range increased. Therefore, after weighing the two effects, the radius of curvature will have a critical value. When it is less than the critical value, the increase in the erosion range will have a greater impact and the average erosion rate will increase. When it is greater than the critical value, the effect of local erosion reduction will be more obvious, and the average erosion rate will decrease. As shown in Figure 8b, when the radius of curvature increases, the maximum wall erosion rate will decrease. This is because the maximum erosion rate depends on the

incident angle of the solid particles. According to the erosion model, the erosion rate is related to the incident angle, so the maximum wall erosion rate is negatively related to the radius of curvature. When the radius of curvature increases, the surface area of the elbow increases accordingly, which increases the possibility of particles colliding with the wall surface, and the erosion range could also increase, as shown in Figure 9. Therefore, the radius of curvature of the pipeline needs to be weighed in order to meet the transport efficiency and erosion rate of the liquid hydrogen pipeline.

Figure 7. The relationship between erosion rate with liquid hydrogen flow rate and particle diameter: (a) E_{ave} and (b) E_{max} .

Figure 8. The relationship of the erosion rate and the radius of curvature, R . (a) The average erosion rate, E_{ave} , and (b) the maximum erosion rate, E_{max} .

Figure 9. Erosion distribution diagram under the different radii of curvature, R : (a) $R = 45 \text{ mm}$, (b) $R = 60 \text{ mm}$, (c) $R = 75 \text{ mm}$, and (d) $R = 90 \text{ mm}$.

4. Conclusions

The erosion of solid particles on the wall of the elbow tube in cryogenic conditions was studied using the CFD-DPM model, and it was found that the outer wall of the elbow had the most severe erosion in the range of $60^\circ \sim 90^\circ$. The relationship between the erosion rate and the solid-air particle mass flow rate is a linear function, and the slope of the linear function is positive. Comprehensive analysis of the initial conditions and structural parameters showed that reducing the erosion of the elbow can be achieved by reducing the generation of solid-air, reducing the flow rate of liquid hydrogen, refining the solid-air particles, and increasing the radius of curvature.

However, this study has certain limitations. The growth process of solid-air was not considered in the process of simulating the movement. The shape is one of the important parameters for the erosion of the elbow wall: in this work, the particles were assumed to be spherical, while the solid particles were found to be snowflake-shaped in the experiment.

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