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Simplified Layer Model for Solid Particle Clusters in Product Oil Pipelines

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Abstract: Pipe corrosion caused by the pressure tests using water before starting the normal operation occurs often in Chinese product oil pipelines because of remaining water. To explore the migration of the corrosion impurities in the product oil pipelines, this study started from the force balance principle and considered the entire particle cluster as the research object. This paper established a one-dimensional migration model, and proposed the Froude number equality criterion to calculate the particle cluster length in the equilibrium state. The proposed criterion was verified by experiments. A loop was built to conduct the tests and obtain the migration velocities of the particle cluster from the non-equilibrium state to the equilibrium state in the pipeline. The proposed model was verified using the experimental data. Verification results demonstrate that the model can describe the development process from the non-equilibrium state to the equilibrium state of particle clusters after sudden external disturbance and accurately predict some important parameters, including the velocity of the particle cluster in the equilibrium state and the critical velocity that leads to the transition from fixed bed flow to moving bed flow. The model provides the theoretical basis and calculation method to remove corrosion impurities from product oil pipelines.

Keywords: product oil pipeline; solid particle cluster; moving-bed flow; migration model; critical flow velocity; migration velocity

1. Introduction

During the construction of product oil pipelines in China, great attention has been paid to the operation safety of product oil pipelines. It has been discovered that lots of impurities such as water, sand and welding slag were left in the oil pipelines [1]. The existing impurities damage pumps, sealing devices and filter devices [2,3], and also cause the scour corrosion of the pipe walls [4]. The impurities also adsorb the free water in the oil, causing the electrochemical corrosion of the pipeline [5]. The corrosion affects the oil transportation and oil quality, and even causes safety issues. Therefore, exploring the migration patterns of the impurity particles in product oil pipelines is of significance to prolonging the life spans of pipelines and auxiliary facilities.

Most previous studies on product oil pipelines focused on oil mixtures, interface detection, optimization of transportation, etc., and few research works on the problems of impurities in product oil pipelines have been reported; however, similar problems have been studied in the field of hydraulic transport.

The high concentration of solid particles promotes the agglomeration of particles at the bottom of the pipeline. In this case, it is not feasible to model by analyzing the mechanical behavior of individual particles [6,7]. Some works in the literature have studied the critical velocity of particle transition from

fixed bed to moving bed and put forward the corresponding calculation formula [8–13]. For liquid velocities larger than the critical velocity, the sand particles will be transported along the pipe, while at lower velocities below the critical value the sand particles will deposit [9]. Yan Yang [14] presented the sand transport and deposition characteristics in the complicated multiphase flow pipeline based on the numerical simulation method. Some scholars have established corresponding layer models to describe the migration process of particles. Doron [15] presented a three-layer model to predict the characteristics of solid–liquid mixtures in horizontal pipes close to the actual working condition. Gorji and Ghorbani [16] applied the concepts of the two- and three-layer models and predicted successfully the pressure losses in a slurry pipeline flow. Most recently, Matoušek and Krupička [17,18] presented a new two-layer model for pressure drop predictions. Matoušek’s model assumes a stationary layer at the bottom of the pipe and considers the friction and transport conditions associated with the interface between two layers. This semi-empirical approach follows the same analysis as the previous two-layer models based on a force balance. It incorporates empirical correlations to calculate different parameters such as shear stresses and solid transport rates for engineering applications. Rojas and Sáez [19] presented a two-layer model for horizontal pipe flow of Newtonian and non-Newtonian settling dense slurries, and the model gives a good estimate of the critical deposition velocity correlating the minimum pressure drop with the superficial slurry velocity. Matoušek et al. [20] suggested a layered model for the inclined pipe flow of settling slurry, and the predicted pressure drops and solids distributions by this model agreed reasonably well with the experimental results. A new four-layer model for gas, liquid, moving bed and stationary bed, which can predict total particle bed height, is proposed for high particle concentrations greater than 10,000 PPM by Dabirian et al. [21].

However, the research hotspots of hydraulic transportation are mainly focused on pressure drop and critical velocity, and there is a lack of relevant descriptions of solid-phase migration velocity. In the aforementioned studies, only Doron predicted the mean velocities of the moving bed through the model, but there was no experimental verification. The previous models made the default assumption that the solid phase was already in an equilibrium state, and it was impossible to describe the process of the solid phase from the non-equilibrium state to the equilibrium state. Furthermore, the critical velocity presented by Doron is actually the critical velocity of a single particle in the particle group, rather than the whole particle cluster. It is still questionable whether the two are equivalent. In addition, the forces of a certain particle in the cluster are more complex, which leads to low calculation accuracy.

Based on the force balance principle, this paper proposes a two-layer model that overcomes the shortcomings of previous models to solve the impurity-carrying problem. The calculation results show that the model can accurately describe the transition from the stationary bed flow to the moving bed flow, and predict the critical velocity, the migration velocity and the length of particle clusters.

To simplify the calculation and improve the engineering applications of the model, this paper assumes:

- (1) The height of the particle cluster is the same along the axis, and the force of each part is uniform.
- (2) The interstitial fluid can be ignored in describing the flow behavior and only the upper and lower surface contact with the oil [22]. In addition, the volume of the particle cluster remains unchanged.
- (3) In the deformation process of the particle cluster, the adjustment coefficient is a constant.
- (4) The effect of room temperature and usage time on diesel viscosity during the test is ignored.

Based on the above assumptions and simplifications, a mathematical model describing the migration characteristics of the particle cluster in the product oil pipeline was established.

2. Model

As shown in Figure 1, the shape of the particle cluster is irregular in the pipeline, forming a slope shape with a tall head and a short tail (as shown by the solid black line in Figure 1). In order to facilitate the analysis and calculation, its shape is simplified, as shown by the solid blue line in Figure 1.

Figure 1. Face and side view of particle cluster distribution in the pipeline.

The particle cluster is mainly affected by the shear force, the friction and the viscous resistance. Due to the discrete characteristics of the particle material, the particle cluster yields after being subjected to an external impact, and the solid state and liquid state coexist and evolve with each other [23]. Xu ZP [24] found that there was a balance length in the process of particle cluster migration, and the balance length depended on the oil flow rate. This paper introduces the concept of internal force to describe a particle cluster's ability to change its length under shear force.

The particle cluster is divided into two parts of equal length: the head and the tail. The motion equations of the two parts are shown as:

$$\frac{1}{2}m \frac{d^2x_1}{dt^2} = F_s - F_{f1} - F_{in} \quad (1)$$

$$\frac{1}{2}m \frac{d^2x_2}{dt^2} = F_s - F_{f2} - F_{in} \quad (2)$$

The head of the particle cluster is used as an example to study the respective forces in detail.

2.1. Shear Force

Shear force causes the shear deformation of materials. Due to its own viscosity and the existence of a velocity gradient in the radial direction of the pipe, the fluid applies a corresponding shear force to the particle cluster, causing its deformation and migration.

For shear force there is:

$$F_s + F'_s + \rho SLg \sin \varphi_0 = -\frac{1}{2}\Delta p \cdot S \quad (3)$$

The relationship between the shear force on the pipe wall and the shear force on the particle cluster is expressed as:

$$F'_s = \delta F_s \quad (4)$$

Δp can be obtained by Bernoulli's equation:

$$\Delta p = -\rho g(h_f + \Delta h) = -\lambda \cdot \frac{L}{D} \cdot \frac{u_0^2}{2g} \cdot \rho g - \rho Lg \sin \varphi_0 \quad (5)$$

$$D = \frac{4S}{l} \quad (6)$$

As shown in Figure 1, there is a geometric relationship:

$$l = R(2\pi - \theta + 2\sin \frac{\theta}{2}) \quad (7)$$

From the continuity equation:

$$u_0 = \frac{Q}{\pi R^2 - \frac{V_v}{L}} \quad (8)$$

Equation (9) can be obtained according to the assumption that the volume is unchanged during the migration process of the particle cluster:

$$L \cdot \left(\frac{\theta}{2} R^2 - \frac{R^2}{2} \sin \theta \right) = V_v \quad (9)$$

There is no analytical solution to Equation (9), so, use the Taylor expansion for $\sin \theta$:

$$\sin \theta \approx \theta - \frac{\theta^3}{6} \quad (10)$$

In order to correct the errors caused by the assumptions in the derivation process and to closely reflect the actual situation, the shear force coefficient C_D is introduced into the expression. The expression can be obtained by simultaneous equations from Equations (3) to (10):

$$F_s = C_D \cdot \frac{\rho \lambda Q^2 L R}{16(1+\delta) \left(\pi R^2 - \frac{V_v}{L} \right)^2} \cdot (2\pi - \theta + 2 \sin \frac{\theta}{2}) \quad (11)$$

$$\theta = \sqrt[3]{\frac{12 V_v}{R^2 L}}$$

2.2. Resistance

Suppose a two-phase solid–liquid mixture flows in a pipe. If the oil flow rate is not high enough, the solid particles whose density is higher than that of the carrier fluid tend to settle and agglomerate at the bottom of the pipe, and form a moving deposit [15]. In this case, the resistance of the particles includes the friction force exerted by the pipe wall, and the viscous resistance by the oil phase. For the inclined pipe, the component of gravity along the axis should also be considered.

2.2.1. Friction

The friction includes static friction and sliding friction. When the friction reaches the corresponding threshold, which can be approximated to the magnitude of the sliding friction, it changes from static friction to sliding friction. For the head of the particle cluster, the friction can be expressed as:

$$f = \begin{cases} F_s + F_{in} & (F_s + F_{in}) < \mu_f F_N \\ \mu_f F_N & (F_s + F_{in}) \geq \mu_f F_N \end{cases} \quad (12)$$

The positive pressure F_N is related to the curvature of the pipe wall. As shown in Figure 1, the positive pressure F_N is obtained using the calculus method.

$$\begin{aligned} F_N &= L(\rho_s - \rho)g \cdot 2 \int_0^{\frac{\theta}{2}} \left(\frac{d\varphi \cdot R^2}{2} - \frac{d\varphi}{2} \cdot \left(\frac{R \cos \frac{\theta}{2}}{\cos \varphi} \right)^2 \right) \cdot \cos \varphi \cdot \cos \varphi_0 \\ &= L(\rho_s - \rho)g \cdot \frac{\theta R^2 - \sin \theta \cdot R^2}{2} \cdot \frac{2(\sin \frac{\theta}{2} - \cos^2 \frac{\theta}{2} \cdot \ln \tan \frac{\theta + \pi}{4})}{\theta - \sin \theta} \cdot \cos \varphi_0 \\ &= \alpha \cdot \frac{(mg - \rho_1 g V_v)}{2} \cdot \cos \varphi_0 \end{aligned} \quad (13)$$

where the coefficient $\alpha = \frac{2(\sin \frac{\theta}{2} - \cos^2 \frac{\theta}{2} \cdot \ln \tan \frac{\theta + \pi}{4})}{\theta - \sin \theta}$. The value of α is related to the center angle θ , when $\theta \in [0, \pi]$, the smaller the central angle θ is, the greater the positive pressure is; when θ is 0° , the positive pressure tends to be the difference between gravity and buoyancy. The larger the central angle θ is, the smaller the positive pressure.

2.2.2. Viscous Resistance

Xu DZ [24] found that a liquid layer is formed when the pipe wall is moistened by the liquid phase. Thus, the viscous resistance applied to the underlying particles should be considered.

When a homogeneous particle group interferes with sedimentation, the interaction between particles, friction and the interaction through medium increases the resistance of particles. In this case, the sum of the resistance of the individual particle in the particle group can be given by:

$$f = \frac{\psi}{(1 - \lambda_0)^k} d^2 \rho v^2 \quad (14)$$

$\psi = \frac{3\pi}{Re_s}$, when the particle Reynolds number $Re_s \leq 1$

The total number of particles in the bottom layer of the particle cluster can be estimated by the following equation:

$$n = \frac{\theta RL}{\pi r^2} \quad (15)$$

Make $C_F = \frac{1}{(1 - \lambda_0)^k}$, according to Equations (14) and (15), the viscous resistance on the head of the particle cluster is:

$$F_{vis} = C_F \cdot \frac{3\eta\theta RLv}{r} \quad (16)$$

2.2.3. Component of Gravity

Denoting the inclination angle of the pipeline as φ_0 , the gravity component of the particle cluster head can be calculated from Equation (17):

$$G_1 = \frac{(mg - \rho g V_v)}{2} \sin \varphi_0 \quad (17)$$

Therefore, the expression of F_{f1} can be obtained:

$$F_{f1} = (\mu_f \alpha \cos \varphi_0 + \sin \varphi_0) \cdot \frac{(mg - \rho g V_v)}{2} + C_F \cdot \frac{3\eta\theta RLv}{r} \quad (18)$$

2.3. Internal Force

2.3.1. Expression of Internal Force

Wu BS [25] established the basic model to describe the process of the riverbed evolution from the original state to the new equilibrium state:

$$\frac{dy}{dt} = \beta(y_e - y) \quad (19)$$

Similar to the erosion deformation process of the riverbed, the deformation process of the particle cluster can be described by Equation (19). Taking the particle length L as the characteristic variable, Equation (20) is obtained by deriving the time t on both sides of Equation (19):

$$\frac{d^2L}{dt^2} = -\beta^2(L_e - L) \quad (20)$$

Equation (21) can be obtained by subtracting Equation (2) from Equation (1). Here the internal force expression takes the scalar form.

$$F_{in} \approx \left| \frac{1}{4} m \left(\frac{d^2x_1}{dt^2} - \frac{d^2x_2}{dt^2} \right) \right| = \frac{1}{4} m \beta^2 (L_e - L) \quad (21)$$

2.3.2. Calculation of L_e

The Froude number is a dimensionless parameter in fluid mechanics measuring the ratio of the fluid inertial force to gravity. When simulating the flow of a liquid with a free surface, such as the ship motion on the water surface or open channel flow, the Froude number must be considered.

$$Fr = \frac{u_0^2}{gL} \quad (22)$$

The particle cluster in the product oil pipeline is mainly affected by gravity and shear force. Therefore, Fr are assumed to be the same under different working conditions when the particle cluster reaches the equilibrium length L_e :

$$\frac{\left(\frac{Q}{\pi R^2 - \frac{V_v}{L_e}}\right)^2}{gL_e} = Fr_0 \quad (23)$$

The expression of L_e can be obtained by solving Equation (23):

$$L_e = \frac{2V_v^2 \cdot g \cdot Fr_0}{Q(Q^2 + 4\pi R^2 \cdot V_v \cdot g \cdot Fr_0)^{0.5} + Q^2 + 2\pi R^2 \cdot V_v \cdot g \cdot Fr_0} \quad (24)$$

Through Equations (1), (2), (11), (18) and (21), the one-dimensional migration model of the particle cluster in the product oil pipe can be obtained.

$$\begin{cases} m \frac{d^2 x_1}{dt^2} = C_D \cdot \frac{\rho \lambda Q^2 L R \cdot (2\pi - \theta + 2 \sin \frac{\theta}{2})}{8(1+\delta)(\pi R^2 - \frac{V_v}{L})^2} - (\mu_f \alpha \cos \varphi_0 + \sin \varphi_0) \cdot (mg - \rho g V_v) \\ \quad - C_F \cdot \frac{6\eta \theta R L}{r} \frac{dx_1}{dt} + \frac{m\beta^2}{2} (L_e - L) \\ m \frac{d^2 x_2}{dt^2} = C_D \cdot \frac{\rho \lambda Q^2 L R \cdot (2\pi - \theta + 2 \sin \frac{\theta}{2})}{8(1+\delta)(\pi R^2 - \frac{V_v}{L})^2} - (\mu_f \alpha \cos \varphi_0 + \sin \varphi_0) \cdot (mg - \rho g V_v) \\ \quad - C_F \cdot \frac{6\eta \theta R L}{r} \frac{dx_2}{dt} - \frac{m\beta^2}{2} (L_e - L) \end{cases} \quad (25)$$

3. Experiments

The test system is illustrated in Figure 2. During the test, the position of particles in the tube was recorded using a camera with frame ratio speed set to 120.

Figure 2. (a) Physical drawing of test loop device; (b) measurement system of test loop: A—oil storage tank; B—magnetic pump; C—flowmeter; D—test plexiglass pipe section; E—high-speed camera; F—gantry crane; G—settling tank; H—control cabinet.

3.1. Test Plan

3.1.1. Selection of Quartz Sand Particles

In this test, the quartz sand particles with regular shapes were selected as impurity particles instead of iron filings with irregular shapes, and the sizes of 25 mesh to 30 mesh (0.5–0.7 mm) were selected according to the sizes of filters in the actual project.

3.1.2. Viscosity Measurement of Oil

In order to simulate the phenomenon in the actual project accurately, the transportation medium used in the test is 0# diesel. Diesel is stable, transparent and easy to test. The average density of the test oil was 850 kg/m^3 , which was measured by a densitometer at the specified temperature.

The dynamic viscosity-temperature curve of the 0# diesel was measured in the test by the Physica MCR 301 cylinder viscometer. Table 1 lists the parameters of diesel oil.

Table 1. Parameters of diesel oil.

Diesel Model	Density (kg/m^3)	Dynamic Viscosity ($\text{mPa}\cdot\text{s}$)
0#	850	3.2

3.1.3. Test Procedure

The experiments were conducted under different flows. Taking condition I as an example, the flow range controlled by the test was $1.77 \text{ m}^3/\text{h} \leq Q \leq 2.03 \text{ m}^3/\text{h}$ to ensure the oil-impurity flow in the tube was moving bed flow. Table 2 shows the specific working conditions.

Table 2. Test working condition table.

Working Condition	Particles Mass (g)	Pipe Diameter (mm)	Pipe Inclination Angle ($^\circ$)
I	20	40	0
II	40	40	0
III	10	30	0
IV	10	30	10

3.2. Test Phenomena

The particles injected into the pipeline are naturally deposited in the lower surface of the pipe as shown in Figure 3a. After the pump starts, the particle cluster is rapidly stretched under the action of shear force, as shown in Figure 3b. The particles in the tail are continuously peeled off and rapidly flow through the upper surface of the particle cluster, and then deposit at the front under the action of reflux. When the balance between stripping and deposition is reached, the particle cluster migrates stably, which means the velocity and length no longer change apparently.

Figure 3. (a) Side view of particle cluster deposition after injection; (b) top view of particle group migration state.

Due to the discrete characteristics of the particulate matter, the head and tail velocities are not necessarily equal. Therefore, in this paper, the center velocity of the particle cluster was selected to characterize the migration velocity.

3.3. Data Processing

In the initial stage, due to the shape of the particle cluster, the movement of the particle cluster changes sharply, and then gradually becomes stable. The pipe segment from 30 cm to 180 cm is defined as the stable migration stage. This paper focuses on the velocity of the particle cluster at this stage.

Taking $Q = 1.84 \text{ m}^3/\text{h}$ in working Condition I as an example, Figure 4 indicates that the migration velocity is approximately uniform. We define the slope v_e as the velocity of the particle cluster in the stable migration stage. The average length L_e at each moment can be defined as the length of the particle cluster in the stable migration stage. Similarly, v_e and L_e under other working conditions can be obtained, as shown in Table 3.

Figure 4. Diagram of particle cluster migration under $Q = 1.84 \text{ m}^3/\text{h}$, Working condition I.

Table 3. Velocities and lengths of particle cluster in stable migration stage under different working conditions.

Working Condition I								
Flow/(m^3/h)	1.770	1.810	1.840	1.885	1.910	1.950	1.990	2.030
Velocity/($\times 10^{-4} \text{ m/s}$)	1.51	2.46	2.85	4.24	4.95	5.84	7.21	8.41
Length/(m)	0.148	0.154	0.159	0.168	0.172	0.180	0.189	0.196
Working Condition II								
Flow/(m^3/h)	1.840	1.880	1.910	1.940	1.970	2.000	2.030	2.060
Velocity/($\times 10^{-4} \text{ m/s}$)	1.64	2.90	3.44	4.04	5.50	6.47	7.00	7.92
Length/(m)	0.272	0.284	0.304	0.318	0.329	0.341	0.345	0.359
Working Condition III								
Flow/(m^3/h)	0.960	1.000	1.035	1.070	1.095	1.120	1.150	
Velocity/($\times 10^{-4} \text{ m/s}$)	0.44	1.36	3.06	5.20	7.12	8.00	10.91	
Length/(m)	0.181	0.201	0.216	0.232	0.245	0.259	0.271	
Working Condition IV								
Flow/(m^3/h)	1.000	1.035	1.070	1.095	1.120	1.150	1.180	
Velocity/($\times 10^{-4} \text{ m/s}$)	1.01	2.79	4.61	6.56	7.41	9.93	11.77	
Length/(m)	0.211	0.220	0.245	0.255	0.270	0.283	0.301	

Figure 5 presents the Froude numbers of the particle cluster corresponding to each working condition. It can be seen from the figure that Fr hardly changes with the flow rate for one working condition, which agrees with the assumption in Section 2.3.2.

Figure 5. Variation of Froude number of particles with flow rate.

4. Model Application and Verification

4.1. Model Application

In the process of stable migration of conditions I to III, the particles move at a uniform velocity, so there is:

$$A \cdot \frac{\rho Q^2 L_e R \cdot (2\pi - \theta + 2 \sin \frac{\theta}{2})}{8(\pi R^2 - \frac{V_v}{L_e})^2} - B \cdot \alpha (mg - \rho g V_v) - \frac{6\eta \theta R L_e}{r} v_e = 0 \quad (26)$$

where $A = \frac{\lambda C_D}{C_F(1+\delta)}$, $B = \frac{\mu_f}{C_F}$.

It can be easily seen from Equation (26) that v_e depends on the values of A and B, which can be obtained by fitting the experimental data. It was found that the experimental data of working Condition II could be fitted well with A and B in working Condition I. In other words, for conditions with the same pipe diameter, the values of A and B are the same.

For the stable migration process of Condition IV, there is:

$$A' \cdot \frac{\rho Q^2 L_e R \cdot (2\pi - \theta + 2 \sin \frac{\theta}{2})}{8(1+\delta)(\pi R^2 - \frac{V_v}{L_e})^2} - (B' \cdot \alpha \cos \varphi_0 + \sin \varphi_0)(mg - \rho g V_v) - C_F \frac{6\eta \theta R L_e}{r} v_e = 0 \quad (27)$$

where $A' = A \cdot C_F = \frac{\lambda C_D}{(1+\delta)}$, $B' = B \cdot C_F = \mu_f$.

Equation (27) indicates that v_e depends on the values of C_F , which can be obtained by fitting the experimental data. Substitute the parameters into Equation (25) and compare the calculated results with the rest of the experimental data. Taking Figure 6 as an example and it can be seen that the model can accurately describe the migration of the particle cluster after being suddenly disturbed by the external disturbance.

Figure 6. Model verification corresponding to working condition I, $Q = 1.84 \text{ m}^3/\text{h}$: (a) the forward velocity; (b) the tail velocity; (c) the length.

4.2. Verification of Critical Flow Velocity

The critical flow velocity of the transition from the stationary bed flow to the moving bed flow is an important indicator to evaluate the impurity carrying capacity of pipelines. Therefore, this paper chooses the critical flow velocity to verify the model.

During the transformation process of flow patterns, the particle cluster barely moves; therefore, both the acceleration and velocity are nearly 0. The critical flow velocity can be calculated by Equation (25). Table 4 shows the critical flow velocity of each working condition.

$$Q_0 = \left(\frac{8(1 + \delta)(\mu_f \alpha \cos \varphi_0 + \sin \varphi_0)(mg - \rho g V_v)(\pi R^2 - \frac{V_v}{L_e})^2}{\rho \lambda C_D L_e R \cdot (2\pi - \theta + 2 \sin \frac{\theta}{2})} \right)^{0.5} \quad (28)$$

Table 4. The critical flow velocity v_0 corresponds to each working condition.

Working Condition	I	II	III	IV
Test Value/(m/s)	0.385	0.393	0.369	0.377
Calculated /(m/s)	0.376	0.387	0.377	0.381
Absolute Error /(m/s)	0.009	0.006	-0.008	-0.004

4.3. Verification of Stable Migration Velocity

Figure 7 shows a comparison between the calculated and experimental values of the stable migration velocity.

Figure 7. Velocity comparison of test values and calculated values in the stable stage.

Figure 7 demonstrate that the migration velocities obtained by the model agree well with the experimental velocities in the stable stage, and the absolute errors are within 1.11×10^{-4} m/s. Therefore, the model can accurately predict the migration velocity of the solid particle cluster in the product oil pipeline.

5. Conclusions

This study proposes a simplified two-layer model which can be used to describe the migration characteristics of impurity particles in product oil pipelines. What follows is the main conclusions:

- (1) The particles were analyzed as a whole. The particle cluster is mainly subjected to the shear force and the viscous resistance exerted by the oil flow, the friction exerted by the pipe wall, and its own internal force mainly affecting the particle cluster length.
- (2) In the product oil pipeline, an equilibrium state exists during the migration of the solid particle cluster. After reaching the equilibrium state, the migration of the particle cluster tends to be stable, the velocity and length no longer change significantly, and the Froude number is considered the same at different flow rates.
- (3) The two-layer model based on the force balance principle can better describe the transformation process from the non-equilibrium state to the equilibrium state, and can accurately predict the critical flow velocity and stable migration velocity of the particle cluster.
- (4) At the same flow rate, the larger the mass of the particle cluster or the inclination of the pipe is, the lower the migration velocity.

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