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Experiment and mechanism of dynamic drag reduction in pipeline transportation①

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[Abstract] Based on the analysis of the disadvantages of traditional methods in reducing pipeline resistance, the new conception of dynamic drag reduction in pipeline transportation has been proposed. The experimental results and mechanism of dynamic reduction of pipeline resistance were also discussed in detail. The main conclusion is that the dynamic reduction of resistance exerts forces on the moving materials along both the radial direction and the axial direction. The radial force throws the materials upwards to depart from the pipe wall to reduce the frictional force, while the axial force directly reduces the resistance by providing the force to overcome the drag.

[Key words] pipeline transportation; dynamic drag reduction; mechanism

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1 INTRODUCTION

In order to save energy and improve economical benefits, reducing resistance has become an important topic in pipeline transportation. For example, the filling systems of pipeline transportation are widely applied in mines which utilize filling methods for mining. If reducing resistance is successful used in these filling systems of mines, it can increase the concentration of filling materials and the output, reduce the attrition of pipeline and the work of drainage and mud removal, as well as the consumption of energy.

The common reducing resistance methods at present are: 1) Adding macromolecular polymer; 2) Adding fibrous materials; 3) Ventilation or adding water; 4) Adding tenuous mud or sand. All of them are effective but very difficult to use in application, because the macromolecular polymers are not only expensive ,but also exist the problems of degenerating and aging; the added polymers may probably change the nature or elements of conveying materials; the fibrous materials and tenuous mud are difficult to demolish; reducing resistance through adding water is effective only in the circumstances of laminar flow, its effects will clearly decrease with the lengthening of the conveying distance. So searching for a new and more effective technique for reducing resistance is an imminent problem.

2 CONCEPT OF DYNAMIC DRAG REDUCTION

People have found out that the swimming velocity of dolphin is faster than that of ships. The secret lies in the specialty of dolphins skin, which can secrete an oily liquid to reduce the swimming resistance. Moreover, dolphin's skins are divided into two layers, the outside layer is thin and elastic; the inside layer is the nipples' layer full of tenuity ducts system, this layer is like an elastic layer which can prevent the surface laminar flow from turning into turbulent flow and reduce the water resistance. In addition, the dolphin's muscle beneath skin can make the wave-like action, it can reduce water resistance furthermore and delay the transition process of the laminar flow into turbulent flow. Based on this new bionics' discovery, Kramer put forward the new method of reducing drag by applying elastic cover or elastic film in early 1960's. He covered the surface of materials with sealed rubber, so that it could improve the velocity two times while consuming the same amount of energy. Davies put an elastic soft tube inside the steel tube, as a result, it could reduce the resistance by 35%.

In fact, the elastic film is a man-made elastic boundary to fit for the wave motion of the subsidiary stratum of laminar flow passively, and to produce the motion corresponding in boundary of subsidiary layer simultaneously. This situation can be called passive reduction of resistance. We now present a new concept of dynamic drag reduction. As shown in Fig.1, the directional vibration, $F\cos \omega t$, is provided here to form an angle α with the flowing direction across the conveying pipeline. The support systems are simplified as two springs K_1 and K_2. The vibrations of the pipeline and the materials in it comprise two aspects: the vibration of supporting system and the vibration from the flinch of slim pipeline. If the rigidity of pipeline is constant, that is to say, K_1 and K_2 are

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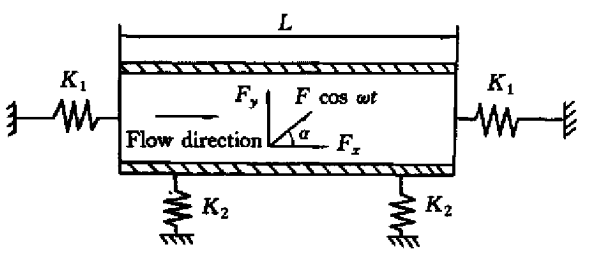

Fig.1 Mechanical model of dynamic drag reduction

boundless, then the former can not produce the vibration, but the vibration of pipeline itself exists. In dynamic drag reduction, it is helpful for the support systems of pipelines to have certain elasticity[1,2].

3 MECHANISM OF DYNAMIC DRAG REDUCTION

The experimental study on mechanics of dynamic drag reduction was done through DSA-1 type direct shear apparatus. The test device consists of excitement system, vibration-measuring system, shear-driving system, vertical force exertion system offset surveying system; it can be used to measure the stress-strain curve of bulk solid in the course of shear, the dynamic and static shear strength, the internal and external friction angel and the cohesion, etc[3,4]. The test materials come from the tailings(less than 2 mm) and the powder iron ore(less than 1 mm) taken from some mines. The main results of the experiment are as follows.

3.1 Stress-strain relationships of native behavior on dynamic shear

Numerous experimental results show that the effects of vibration exertion is to reduce the rigidity of the bulk solid and its shear strength. Fig.2 shows the shear force vs displacement curve of typical comparison experiment of dynamic to static. The sample used is the powder iron ore whose moisture content w_c is 13 %. The dynamic circumstances are that the vibration frequency $f = 30$ Hz, the amplitude $A = 0.01$ mm. In this circumstances the materials are in saturated situation, the shear strength greatly declines and tends to zero, which indicates that the sample has

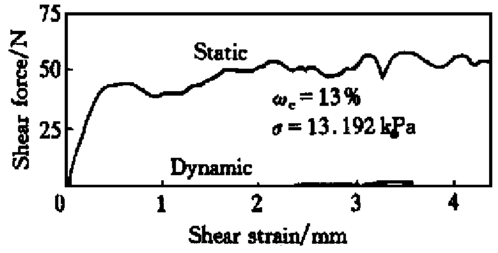

Fig.2 Shear force vs displacement curve of bulk solid in static-dynamic comparison experiment

been liquefied. In static situation, however, the sample has relatively large shear strength.

3.2 Changes of shear strength τ, cohesion c and external friction angle Φ

The experimental results indicate that the dynamic force can change the mechanical behavior of bulk solid and improve the fluidity of bulk solid. Generally the ratio of dynamic shear strength to static shear strength is 1/2 ~ 1/4. The cohesion c is half of its original value; the external friction angle will decrease 6.92° to 20.48°, the former's wall material is steel, the latter's wall material is wood. The larger the roughness of wall material is, the clearer the effect of the dynamic power on the drag reduction of bulk solid is[5].

3.3 Influence of vibration frequency f and amplitude A to shear strength

Relatively high frequency f (above 10 Hz) and relatively high amplitude A (above 0.15 mm) have not obvious effects on the decrease of shear strength τ, but the amplitude's effect is larger than the frequency's[6].

3.4 Vibration liquefaction and vibration transportation on demolition of blockage of conveying pipeline

When the water content in the sample is close to saturation, after exerting the vibration on the blockage locality of the elbow in the simulating pipeline, the vibration liquefaction will come out within 5 ~ 25 s, the original blocked material will become suspended and possess fluidity, thus the blockage in the elbow can be demolished. If the materials are acrid, the blockage comes from the manual tamping, but the vibration transportation can cause the whole materials to vibrate in the blockage locality to demolish the blockage[7].

In a word, the dynamic action can greatly decrease the shear strength and cohesion of filling materials, clearly lower the external friction force between the filling materials and wall sides, and it can bring beneficial influence on the transportation of the filling materials under the action of vibration liquefaction and vibration transportation. From experimental point of view we have shown the probability of the application of dynamic drag reduction.

4 DISCUSSION ON MECHANISM OF DYNAMIC DRAG REDUCTION

Since the filling mining methods are very suitable to mine the rich ore and the deeply buried ore body, much attentions have been paid to the study on the structural flow which is formed from dense filling materials. The structural flow in pipeline transportation, however, is much the same as the two-phase flow, but the former has more complicated motion form. So we now analyze the structural flow, which (such as concrete) moves in pipeline like a bottle-cork. The model of bottle-cork and its velocities on the transverse directional surface are shown in Fig.3. It can approximately be divided into two regions: the subsidiary layer of laminar flow and the core flow zone. The velocity on the subsidiary layer of laminar flow increases constantly until it reaches the velocity of the core flow[8].

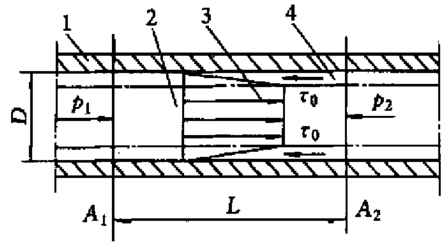

Fig.3 Dynamical model of bottle-cork motion and its velocity distribution

1 —Pipe wall; 2 —Bottle-cork; 3 —Distribution line of velocity; 4 —Subsidiary layer

Assume a random flow body flowing at a fixed velocity in the tube, then all the forces which are exerted on a certain unit can be expressed:

$$F_f = \frac{D}{4} \times \frac{\mathrm{d}p}{\mathrm{d}x}$$

where F_f is the flowing resistance (similar to τ), refering to the force on the unit area of internal pipe wall; $D/4$ is the hydraulic radius of the circular tube; $\mathrm{d}p/\mathrm{d}x$ is the various ratio of the pressure along flowing direction.

The equation states that the flowing resistance is proportional to the hydraulic radius of the circular tube and the pressure p.

We can summarise the mechanism of dynamic drag reduction as follows.

1) Generally the pipeline transportation of structural flow occurs only in its saturated situation. The saturated situation of the conveying materials provides favorable conditions for vibration liquefaction. If the vibration with certain intensity can liquefy or partly liquefy the conveying materials, which will become suspended or partly suspended. Experiments have indicated that the shear strength is very small and tends to zero, the frictional drag of solid particles to pipe wall can partly be demolished.

2) Experimental study have shown that the vibration can greatly decrease the coefficient of friction and is helpful to reduce resistance if the friction force comes from the contact between the solid particles and pipe wall.

3) The wave motion of boundaries delays the change of the subsidiary layer, makes the state of subsidiary layer more stable, but the resistance is still the drag of laminar flow.

4) The wave motion of boundaries decreases the velocity gradient at the subsidiary layer of laminar flow and the shear stress on the boundary surface. As a result, it directly reduces consumed energy of the shear stress action.

5) The wave motion of boundary leads to the increased thickness and velocity of the subsidiary layer of laminar flow, and narrows the velocity difference between the subsidiary layer and the core-flow area to get the drag reduction.

6) Different from the passive reduction of resistance, the dynamic drag reduction exerts the forces actively on the materials along both the radial direction and the axial direction ,the radial force throw the materials upwards to depart from the wall sides to reduce the frictional force, the axial forces directly reduce the resistance by providing the force to overcome the drag.

In the field of pneumatic pipeline transportation of powder, the semi-industrial experiments of drag reduction of vertical vibration have been done to study the parameters of pneumatic transportation initially. The results show that, the index of motive force decreases by 58 %, the ratio of load increase by 107 %, the capability of transportation rises by 62 %. It is obvious that the drag reduction of vibration has remarkable effects on pneumatic transportation.

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