Design and Finite Element Analysis of Bionic Non-smooth Surface Pipeline

Guangjun Yin [a], Yang Yang [b], Ran Li [c]

Shandong University of Science and Technology, Qingdao 266590, China

[a]992416839@qq.com, [b]sdkdyangyang@126.com, [c]sklr666@163.com,

Abstract

The drag reduction effect of bionic non-smooth surface is widely concerned because of its use value in engineering application. In this study, the biological characteristics of earthworm surface are introduced into the pipeline, and 2 kinds of non smooth wall pipes are designed, including the convex hull type and the concave type. Through theoretical design and simulation, the high-performance mechanism of bionic pipeline is studied. By comparing the fluent characteristics of the bionic pipe and the common pipe, the most excellent non smooth structure is obtained: the non-smooth wall pipe with convex hull. Compared with ordinary smooth pipe, the non-smooth pipeline has higher drag reduction rate, stronger transportation energy and higher flow velocity. This study can provide a reference for the further analysis of bionic drag reduction of transportation pipelines.

Keywords

Bionic, non-smooth surface, Drag reduction, Pipeline.

1. Introduction

Pipeline transportation is the main way of energy transportation such as oil and gas, and over 80% of the energy loss in pipeline transportation is on the surface frictional resistance. Therefore, reducing frictional resistance loss has been a concern of the storage and transportation researchers. The traditional drag reduction method is to make the pipe surface more smooth, but due to the limitation of the technical level, there is a limit to improve the smoothness of the inner wall of the pipe.

At the same time, earthworms , living in the soil, the skin like sandpaper can quickly move in the soil. This phenomenon shows that: there are some problems in the method of reducing the surface resistance by reducing the surface roughness. Chinese scientists Ren et al. analyzed the surface flexibility of earthworm and its anti-adhesion characteristics. It is believed that the body surface of earthworm has a non-smooth surface that is conducive to the movement in the soil. This special surface can produce non-smooth effects. Non-smooth effect refers to a kind of behavior that the organism reduces the resistance in the body surface adhesion system and the friction system by the morphological characteristics of the external surface. Non-smooth surface refers to the appearance of a smooth surface with a non-smooth effect in some directions.

Based on the principle of bionics, this paper studies the surface characteristics of earthworms and its drag reduction mechanism, and applies the biological characteristics of earthworm to pipelines, and designs two types of bionic pipes with non-smooth wall and concave non-smooth wall. and through the finite element analysis software, compare the bionic pipe with the ordinary pipe, study its internal flow field movement, analyze its drag reduction performance, and study the influence of the non-smooth wall on the drag reduction performance of the pipeline.

2. Surface characteristics of earthworms and drag reduction mechanism

The surface of the earthworm is a typical corrugated non-smooth element, consisting of the annular structure between the two internodes, the height and width of the non-smooth element are changed with the motion of the earthworm, and the non-smooth structure is regularly arranged on the body surface. The degree of non-smoothness in different parts of the body surface is different: the fine lines in the body are small and dense, the density of non-smooth elements is large, the fine lines in the head are large and sparse, and the density of non-smooth elements is small.

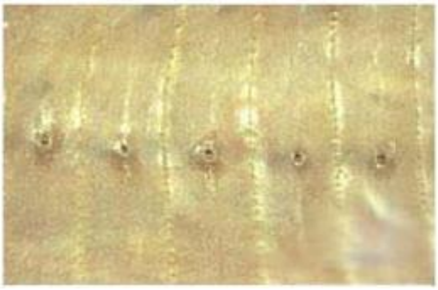


Fig. 1 The local amplification diagram of earthworm Surface

Fig. 2 Macroscopic non-smooth structure of earthworm

The earthworm is slightly cylindrical, the head is conical, the whole body is thin and long, no skeleton, the body is symmetrical on both sides, the whole body is divided into sections, the whole body is composed of multiple body sections, The outer layer of the body is the ring muscle, and the inner part is the longitudinal muscle. The body wall is flexible, the cavity contains an incompressible liquid. when the ring muscle diastolic, longitudinal muscle contraction, earthworms become shorter and thicker. When the longitudinal muscle relaxes and the annular muscle shrinks, the earthworm becomes longer and thinner.

Each body section has a non-smooth corrugated structure. There are small holes in the back groove, and the small holes are regularly arranged. They can be adjusted by themselves. When the earthworm surface is in contact with the soil, body fluids can be secreted through the feedback system. The non-smooth surface enhances the hydrophilicity of the body surface and inhibit the formation of continuous water film, achieving the purpose of reducing viscosity and resistance, making it easy to move in the soil.

3. Design of Bionic pipeline

The non-smooth structure of the surface of earthworm plays an important role in reducing viscosity and resistance, and the mechanism of reducing drag of the smooth element provides some inspiration to the pipeline with high design performance. Now the inner wall of the pipe is a smooth wall, and a considerable pressure loss occurs when the fluid passes through. If using bionic thinking, the internal wall of the pipeline is designed as a non-smooth structure to improve the flow field, which can reduce the loss of the fluid along the process. It is worth studying and discussing.

Firstly, the two-dimensional surface topography of earthworms is modeled, and the earthworm is simplified into rigid body for convenient calculation. Assuming that this section is a symmetric rotating body with the x-axis, the bus bar is

$$r = r_0 + a\sin\frac{2\pi x}{\lambda} \tag{1}$$

Where r_0 is the average radius of earthworm, a is half the height of the trough to the crest (that is, the amplitude), λ is the waveform period. To facilitate the waveform study, take a = 2.5mm, λ = 24mm. as shown in Fig. 2.

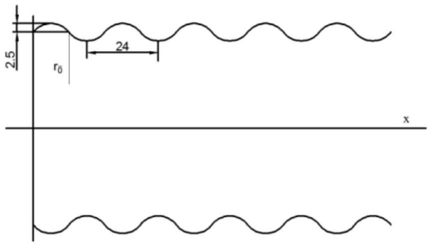
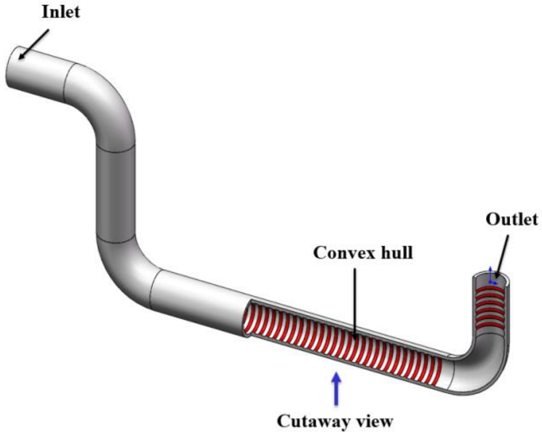


Fig. 2. Non-smooth surface of earthworm

Taking into account the corrugated non-smooth structure produces a complex calculation. In this study, the 1/4-period non-smooth structure of the two-dimensional earthworm model is studied, and two kinds of bionic pipelines are designed, which are non-smooth wall of convex hull and non-smooth wall of concave hull. The radius of the convex hull is 7mm, the thickness of the convex hull is 2.5mm, the arranging period of the convex hull is 24mm, and the centerline of the convex hull is 54.5mm from the central axis of the pipeline. The design of the bionic pipe structure is shown in Figure 3.



(a) Non-smooth wall pipe with convex hull (b) Non-smooth wall pipe with concave hull

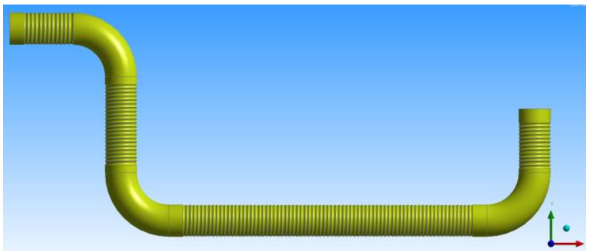
Fig.3 Design of non-smooth wall pipeline

4. Analysis of drag reduction performance of bionic pipeline

4.1 Finite element simulation

Fluent can be used to simulate the flow of fluid with complex shapes, and it has a great flexibility and computational power. The ability to simulate a wide range of physical phenomena, such as flow, turbulence, heat transfer and reaction, is widely used in fluid computing.

In this study, the flow field of the pipeline was analyzed by Fluent. To ensure that the calculation results of the non-smooth surface and the smooth surface are comparable, the same calculation domain is used in all calculations.



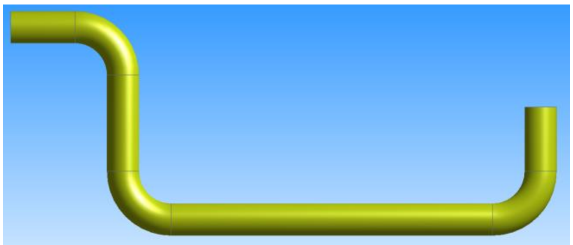


Fig. 4 Non-smooth wall calculation domain Fig. 5 smooth wall calculation domain

This research uses meshing platform to divide the grid, thephysics preference is the CFD model, which provides the grid partition for computational fluid dynamics. Use the“on proximity and on curvature”method in “Use Advanced Size Function”. Select “Fine” in the “Relevance Center ”in the grid control settings. Smoothing is set to high, transition is set to slow, and Span Angle Center is set to “Fine”. The maximum grid element is 4mm, others keep default. A total of 820,380 grids, 796,072 nodes are generated, and the meshing quality is better.

Since the turbulence phenomenon is highly complex, there is no method that can simulate the turbulence phenomenon in all flow problems comprehensively and accurately. In the calculation of turbulence, it is necessary to comprehensively consider the simulation capabilities of the turbulence model and the necessary resources for calculation, and then select an appropriate turbulence model for simulation. This study uses realizable K-epsilon model. The realizable K-epsilon model can keep the Reynolds stress consistent with the real turbulence, and can simulate the diffusion velocity of plane and circular jets more accurately. At the same time, it is more suitable to the actual situation in the flow calculation, the boundary layer calculation with the direction pressure gradient and the separation flow calculation. It also performed well in the complex flow with t secondary flow.

There are both liquid and gas in pipeline transportation, so multiphase flow model is needed. In the fluid transport, water and the surrounding air have a violent momentum exchange. In the flow process, the velocity of the water phase and the air phase is different. So choosing the “Mixture” model would be more appropriate. In this study, the main item is the water phase and the second is the air phase.

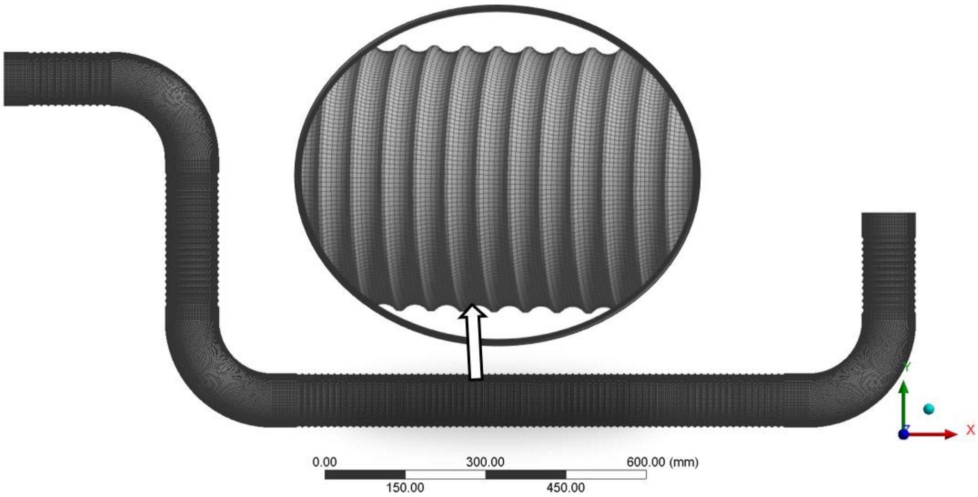
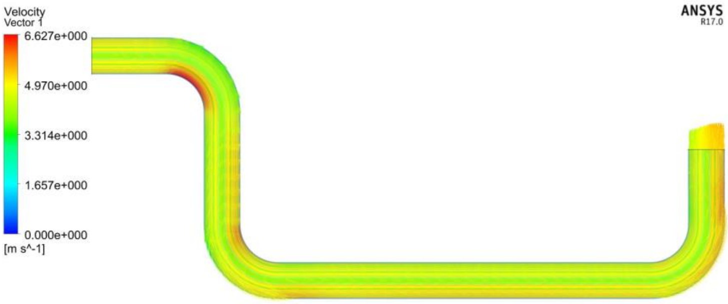


Fig. 6 Grid of the fluid calculation domain

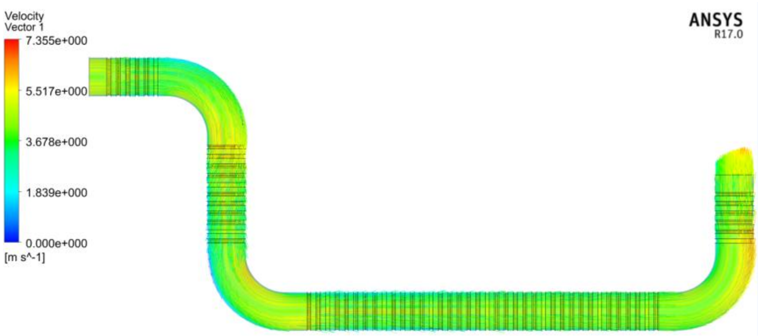
4.2 Results of finite element simulation

In this fluent simulation calculation, the boundary conditions are determined as follows: The inlet boundary uses the speed inlet, the inlet speed is 5m/s, the outlet is set to “outflow”, and the wall is fixed wall surface.

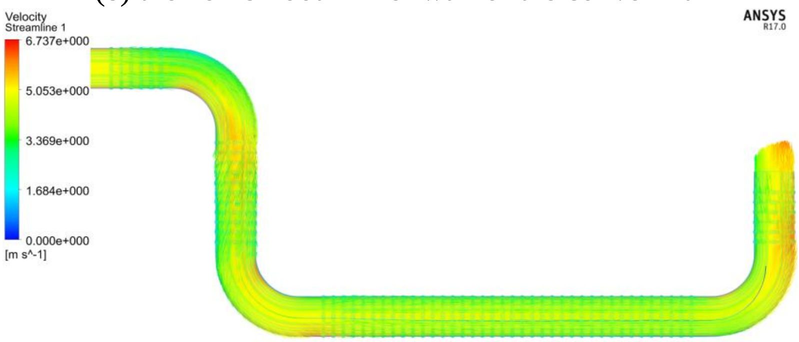
The result of fluid calculation is shown in Fig.7, (a), (b) and (c) are the velocity vector traces of the three types of pipeline structures. The more the color in the picture tends to be red, the greater the speed. The color is more area blue, representing the smaller the speed. It can be seen that the fluid velocity of the non-smooth inner wall of the convex hull is the highest, followed by the inner wall of the concave non-smooth, and the smallest one is the smooth pipeline.



(a) smooth pipeline



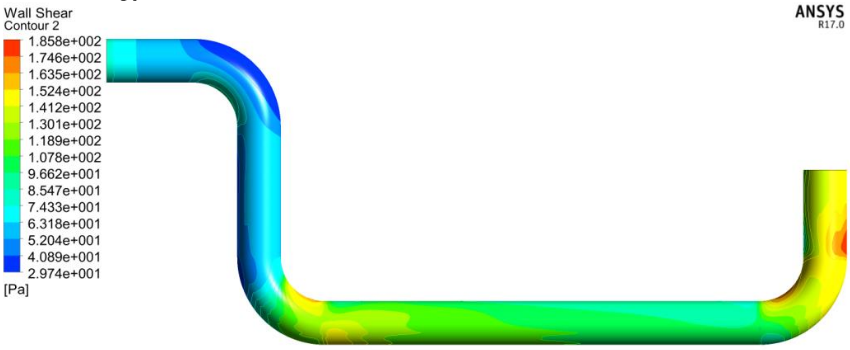
(b) the non-smooth inner wall of the convex hull



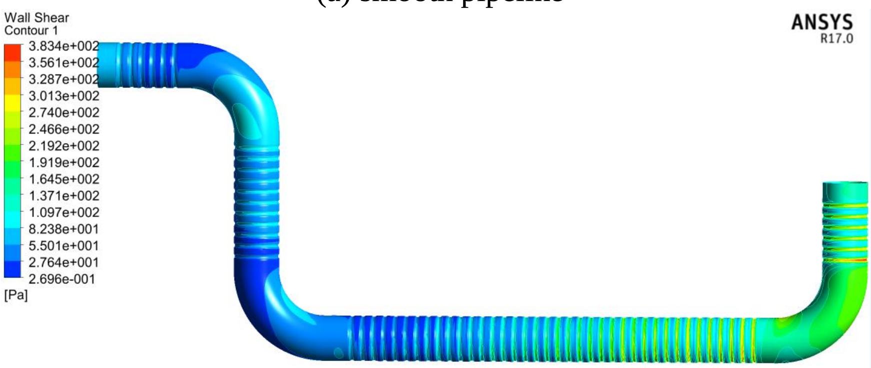
(c) the non-smooth inner wall of the concave hull

Fig. 7 Fluid Velocity Trace

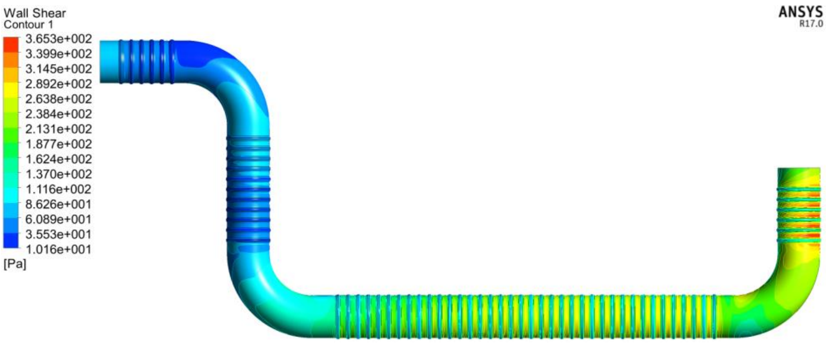
Fig. 8 shows the wall shear stress cloud diagrams of the three types of pipelines. It can be seen that the blue area in the non-smooth inner wall of the convex hull is the largest, followed by the concave non-smooth inner wall, and the blue area of the smooth inner wall is the least. The wall shear stress of the non-smooth inner wall is smaller than the smooth inner wall as a whole. The smaller the wall shear stress, the smaller the friction between the fluid and the pipe wall, the smaller the resistance of the fluid and the less energy lost in the flow.



(a) smooth pipeline

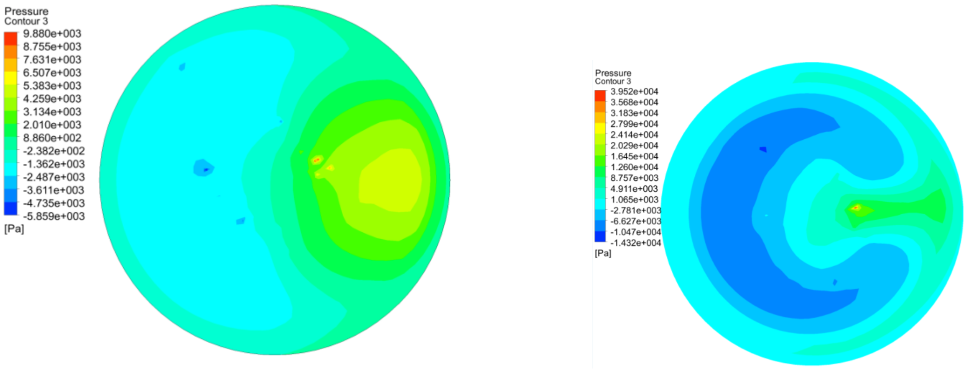


(b) the non-smooth inner wall of the convex hull

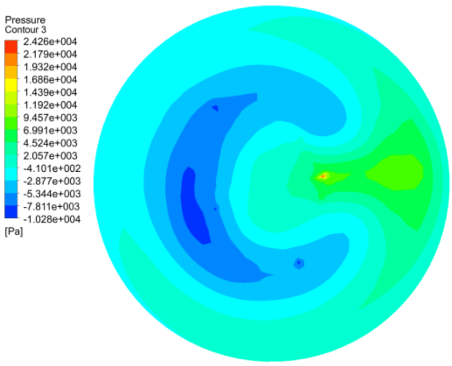


(c) the non-smooth inner wall of the concave hull

Fig. 8 cloud diagrams of wall shear stress



(a) smooth pipeline (b) the non-smooth inner wall of the convex hull



(c) the non-smooth inner wall of the concave hull

Fig. 9 cloud diagrams of pipe outlet pressure

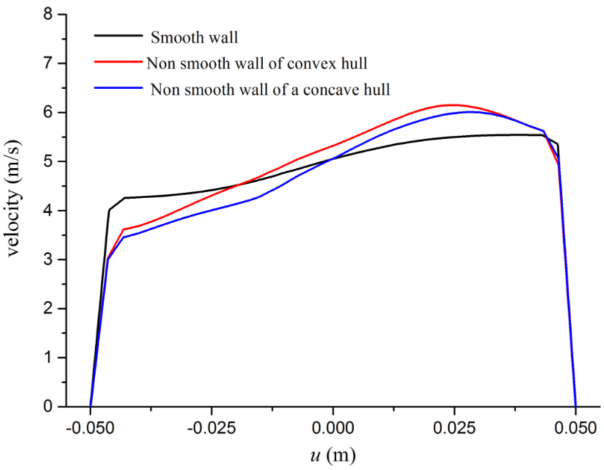


Fig.10. Fluid velocity at the outlet of the pipe

Figure 9 shows the pressure curve of the outlet of the pipeline, It can be seen that the fluid pressure at the outlet of the non-smooth wall of the convex hull is the largest, followed by the concave non-smooth wall surface, and the smallest is the smooth wall surface. The non-smooth wall of the convex hull allows the fluid to be delivered at a higher pressure, which means that the pressure loss of fluid loss in the pipeline transportation is smaller.

Fig. 10 is the velocity of the fluid at the horizontal line at the outlet of the pipe, and it can be seen that the velocity of the smooth wall is greater than that of the non smooth wall on the near wall surface. the fluid at the non-smooth wall generates secondary vortices, disturbs the original fluid flow, and makes the fluid flow near the wall more turbulent. The secondary vortex formed cuts the contact between the main flow channel and the wall surface, thereby reducing the frictional resistance.

Therefore, in the central area of the pipeline, the fluid velocity of the non-smooth wall surface is greater than that of the smooth wall surface. From the viewpoint of the overall flow velocity, the velocity of the fluid inside the non-smooth internal wall of the convex hull is the largest, and the fluid velocity inside the smooth wall surface is the smallest.

5. Conclusion

In this study, the non-smooth surface of the earthworm was observed and analyzed, and numerical simulation analysis was performed by computational fluid dynamics. The following conclusions were obtained:

(1) The whole body of earthworm is all over the non-smooth structure. It rubs against the soil. Ordered non-smooth elements play an important role in reducing resistance.

(2)Under the same velocity inlet conditions, the wall shear stress produced by the fluid in the non-smooth inner wall pipeline is smaller, with higher outflow velocity and stronger flow pressure.

Compared with the smooth wall surface, the non-smooth inner wall has a good drag reduction performance. Among them, the non-smooth inner wall of the convex hull has the most obvious drag reduction performance. Therefore, the bionic surface shows a significant drag reduction effect.

References

[1] LU-Quan Ren, Jin Tong, Jian-Qiao Li: Soil Adhesion and Biomimetics of Soil-engaging Components: a Review, Journal of Agricultural Engineer Research ,Vol.79 (2001) No.3, p.239-263.

[2] Koeltzsch K,Dinkelacker A,Grundmann R: Flow over convergentand divergent wall riblets, Experiments in Fluids,Vol.33 (2002) No.2, p.346-350.

[3] Ahn J，Choi H，Lee J S: Large eddy simulation of flow and heat transfer in a channel roughened by square or semicircle ribs,journal of Turbomachinery,Vol.127 (2005) No.2, p. 263-269.

[4] Auteri F，Baron A，Belan M，et al: Experimental assessment of drag reduction by traveling waves in a turbulent pipe flow, Physics of Fluids,Vol.22 (2010) No.11, 9. 115103—115103.

[5] Xu Zhong,Yang Wen-liang,Wang Xing-zhen: Optimization design and anti -friction performance analysis of the pit -shaped non -smooth surface, Journal of Harbin Engineering University，Vol.34 (2013), No.12, p. 1605-1610.

[6] Wang Fu-jun: *Computational Fluid Dynamics Analysis*.(Tsinghua University Press, China 2010).