Study on microscale flow characteristics of electrorheological Fluids

Shisha Zhu, Xianhua Lei

1Departments of mechanical, Guangdong University of Science and Technology, dongguan, guangdong, China.
2Departments of mechanical, Hunan Institute of Traffic Engineering, Hengyang, Hunan, China.

e-mail: zssxtdx@xtu.edu.cn
b Corresponding author: 283058178@qq.com

Abstract: Electrorheological fluid is a kind of intelligent material whose rheological properties change rapidly and reversibly under the action of external electric field. It has a broad prospect in practical engineering application. It is found in the research progress of electrorheological fluids. The time scale and space scale of the electrorheological effect are very small, and the flow process has some micro-scale flow characteristics. In this paper, the dynamics of dielectric particles in electrorheological fluids under static and dynamic coupling fields is numerically simulated by dissipative particle dynamics method. The influence of surface force under static field on the submicrostructure of Electrorheological fluid and the influence of electroviscosity under dynamic coupled field on the flow rate of Electrorheological fluid are also studied.

1 Introduction

In general, the influence of channel size on er effect is not considered in the dynamics studies of ER fluids, and the influence of micro-scale flow characteristics of channels on ER dynamics is not comprehensively considered when the theoretical model of ER fluids is established. The response time of the er effect is millisecond, the displacement of the dielectric particles of er fluid is micron level within the response time range, and the flow damping of er fluid is large and the characteristic scale of the dielectric particle motion is small, which conforms to the micro-scale flow characteristics. The flow of er is considered as a microscale flow to study its dynamic characteristics, and the relationship between the submicrostructure and dynamic characteristics of ER under coupling field is interpreted from a new perspective. Bonnecaze et al. [1] simulated and studied the formation of chain structure in electrorheological fluids under the coupling effect of electric field and flow field, and analyzed the relationship between viscous resistance and chain structure deformation. Sim et al. [2] studied the nonlinear effect of electrorheological fluids under stable shear flow and the change of submicro-structure, and analyzed the change of shear stress in the system during the dynamic process of structure formation. Enomoto et al. [3] simulated and studied the relationship between the submicrostructural changes and viscosity of electrorheological fluids under the coupling of electric and shear fields. Cao et al. [4] simulated the formation of the submicrostructure of the electrorheological fluid in the shear flow and the changes in its rheological properties, indicating that in the process of the submicrostructure from the chain structure to the volumetric cubic structure and
then to the layered structure, the shear force of the system increases to a certain value instantaneously and then fluctuates up and down. Huang[5-6] et al. established the continuous model of dielectric particles' electric rotation under the action of Couette and Poiseuille fields respectively, and discussed the changes of the submicroscopic structure and macroscopic mechanical properties of electrorheological fluids from the perspective of multi-field coupling. Researchers' simulation of ER mainly focuses on the coupling effect of electric field and shear field, and rarely comprehensively considers the influence of micro-scale flow characteristics on ER in flow process.

In this paper, based on the electrorheological fluid dynamics model with micro-scale flow characteristics, the kinetic law of dielectric particles in electrorheological fluids coupled with electric and flow fields was simulated and analyzed by means of dissipative particle dynamics method, providing theoretical basis for the accurate and comprehensive characterization of the dynamic characteristics of electrorheological fluids under the action of coupled fields.

2 Numerical simulation method

With the development of electrorheological fluid research and computer simulation technology, the researchers used a variety of effective numerical simulation method to study the electrorheological fluid and the microstructure change and the relationship between the macroscopic dynamic characteristics. The commonly used numerical simulation method are: Monte Carlo Method (MCM), Molecular Dynamics (MD), Boltzmann (LBM) and Dissipative Particle Dynamics (DPD), etc.

Dissipative particle dynamics method (DPD) is a suitable for simulation of the complex fluid dynamics behavior and rheological properties of mesoscopic scale method, with different molecular dynamics method a DPD particle on the DPD method represents a mass of molecules or atoms, not in the system of individual molecules or atoms[7-8]. Compared to classical molecular dynamics, DPD method can simulate larger particle size and longer time step. Therefore, it has better computing power and can simulate fluids from micro scale to sub-macro scale.

DPD method is the basic theory of hypothesis in the system have the same quality of DPD N size particles, for any particle, its dynamic equation can be given by Newton's second Law:

\[
m \frac{d^2 \mathbf{r}_i}{dt^2} = \mathbf{F}_{ij}^c + \mathbf{F}_{ij}^p + \mathbf{F}_{ij}^\delta (1)
\]

In the above equation, \( m \) is the mass of each particle, \( \mathbf{r}_i \) is the displacement of particle \( i \), \( \mathbf{F}_{ij}^c \), \( \mathbf{F}_{ij}^p \) and \( \mathbf{F}_{ij}^\delta \) are the conservative force, dissipative force and random force of particle \( j \) on particle \( i \) respectively. All the forces between the particles in the system act only within the cutoff radius \( r_c \) shown in Figure 1.

![FIG. 1 Range of particle forces](image)

The conservative force \( \mathbf{F}_{ij}^c \) represents the soft repulsion between particles, acting in the direction of the line between the centers of mass of two particles, as the most important force in DPD system, conservative force can reflect the mapping relationship between particles and macro system. The expression is:
In the above equation, \( a_{ij} \) is the conservative force coefficient representing the maximum repulsive force between particle \( i \) and particle \( j \). \( w^C(r_{ij}) \) is the conservative force weight function, \( r_{ij} = \frac{\mathbf{r}_i - \mathbf{r}_j}{|\mathbf{r}_i - \mathbf{r}_j|} \) is its unit vector, \( \mathbf{r}_j = \mathbf{r}_i - \mathbf{r}_j \) is the relative position vector. Dissipation force \( \mathbf{F}^D_{ij} \) represents the resistance in the DPD system, prevent relative velocity between particle and force direction is always the relative speed between particles in the opposite direction, the expression is:

\[
\mathbf{F}_{ij}^D = -\gamma w^D(r_{ij}) (\mathbf{r}_{ij} \cdot \mathbf{v}_{ij}) \mathbf{r}_{ij}^\wedge \tag{3}
\]

In the above equation, \( \gamma \) is the dissipation coefficient, \( w^D(r_{ij}) \) is the dissipative force weight function related to particle spacing, \( \mathbf{v}_{ij} = \mathbf{v}_i - \mathbf{v}_j \) is the relative velocity between particle \( i \) and particle \( j \).

Because the dissipative force always hinder the relative motion between particles, Therefore, the existence of dissipative force will reduce the kinetic energy of the system, this reduced kinetic energy will be compensated by the kinetic energy generated by the particle motion caused by random force \( \mathbf{F}^R_{ij} \), the dissipation force can be expressed as:

\[
\mathbf{F}_{ij}^R = \sigma w^R(r_{ij}) \xi_{ij} \mathbf{r}_{ij}^\wedge \tag{4}
\]

In the above equation, \( \sigma \) is the random force coefficient, \( w^R(r_{ij}) \) is the random force weight function related to the distance between particles, \( \xi_{ij} \) is a random variable, meet \( \langle \xi_{ij}(t) \rangle = 0 \).

Both the stochastic and dissipative forces act in the same direction as the conservative forces in the line direction of the particle's center of mass. In order to maintain the kinetic energy balance of the system, the system should meet the principle of diffusion fluctuation, the conservative force weight function \( w^D(r_{ij}) \) and dissipative force weight function \( w^R(r_{ij}) \) and the dissipative force coefficient and random force coefficient satisfy the following relation:

\[
w^D(r_{ij}) = [w^R(r_{ij})]^\gamma \tag{5}
\]

\[
\sigma^2 = 2\gamma K_B T \tag{6}
\]

In the above equation, \( K_B T \) is the Boltzmann temperature of the system.

For the electrorheological fluid system under coupling field, the dielectric particles are mainly affected by electrostatic polarization force, viscous force, surface force and Brownian force, according to the properties of each force, electrostatic polarization force and surface force are considered as conservative forces in DPD simulation, viscous force of flowing base fluid as dissipative force, and Brownian force as random force. The magnitude and range of each force are determined by force coefficient and weight function. According to literature [9-10], the initial value and boundary conditions are determined (the initial velocity of DPD particles needs to meet the Boltzmann distribution, and the rebound image is used as a treatment method for the boundary conditions of the solid wall). Simulation parameters (\( \Delta t = 0.002 \), \( \epsilon = 10 \sigma \)), \( w^D(r_{ij}) = (1 - r)^{1/2} \) weight function, Velocity-Verlet integral algorithm.

### 3 Numerical simulation results and analysis

Based on dissipative particle dynamics simulation method, the electrorheological fluid flow as a micro-scale flow field coupling to research and under the action of dynamic characteristics of...
electrorheological fluid, aimed at a comprehensive understanding of the mechanism of the electrorheological effect. The dynamics of dielectric particles in electrorheological fluids under static field and coupled field (electric field and flow field) were numerically simulated. The selected simulation domain is a 35x35x35 cube region, the number of DPD particles is 600, and the dimensionless diameter is 1.
3.1 Simulation analysis of electrorheological Fluid dynamics under static field

This section simulates the dynamic law of dielectric particles under static field action, and requires that dielectric particles in the initial state should be dispersed in the entire simulation domain as far as possible. The uniform electric field intensity applied to the simulation domain was $E = 1.0 \text{kV/mm}$, the direction was parallel Z axis, and the XOY plane of the simulation domain was vertical, the uniform electric field intensity applied to the simulation domain was $E = 1.0 \text{kV/mm}$, the direction was parallel Z axis, and the XOY plane of the simulation domain was vertical.

Picture 2 shows the dynamic law of dielectric particles under static field action. At $t=0$ s, no electric field was applied in the simulation domain at the initial stage, and the dielectric particles were randomly distributed in the simulation domain. At this point, a uniform electric field in the parallel Z-axis direction is applied to the simulation domain. With the change of the effect of the applied electric field and the integration...
time, when $t=4\text{s}$, electrostatic polarization force is generated between the dielectric particles under the action of electric field polarization, which makes the position of the dielectric particles change, and the adjacent dielectric particles attract each other and gather to form part of the short-chain structure. When $t=8\text{s}$, the dielectric particles around the simulation domain gradually attract closer to the center, so that the density of the dielectric particles in the central region of the simulation domain increases and gradually arrange along the direction of the electric field, forming a short chain structure along the direction of the electric field. When $t=12\text{s}$, the adjacent short chain structures attract each other to form a long chain structure along the direction of the electric field, and the part of the long chain structures parallel to each other on the right of the simulation domain attracts and aggregates each other. When $t=16\text{s}$, the long chain structure on the right of the simulation domain attracts nearby dielectric particles to form a thicker chain structure, and the other short chain structures gradually form a long chain structure along the direction of the electric field. $T=20\text{s}$, the long chain structures formed in each region of the simulation domain attract each other, and converge towards the central region of the simulation domain, finally forming a complete column structure.

The simulation results under the static field show that when the ER fluid is subjected to the electric field, the internal dielectric particles show the dynamic law from random distribution to forming a chain structure along the direction of the electric field to further forming a complete columnar structure, and the change of its macroscopic mechanical properties is mainly due to the significant change of the submicroscopic structure.

3.2 Simulation and analysis of electrorheological fluid dynamics under dynamic coupled field

In order to simulate the change rule of the submicrostructure of electrorheological fluids under the coupling action of electric field and flow field. The applied electric field is the same as that under the static field, and the applied flow field is a Poiseuille flow field with a size of $2\text{cm/s}$ from left to right.
FIG. 3 Dynamics of dielectric particles in a dynamically coupled field

Picture 3 the dynamic law of the dielectric particles under the action of dynamic coupling field. It can be found from the simulation results that: at the initial stage of $t=0s$, the dielectric particles are
randomly distributed in the simulation domain. At this time, the coupling field in the direction of picture (1) is applied to the simulation domain. When \( t = 4\) s, the dielectric particles are attracted to the center of the simulation field and gradually form a short chain structure along the direction of the electric field. When \( t = 8\) s, part of the short chain structures attract each other to form a long chain structure along the direction of the electric field, and part of the short chain structures aggregate each other to form a dense structure, which is concentrated in the upper and lower ends of the simulation domain. When \( t = 12\) s, the longer chain structure attracts each other, the density of dielectric particles in the central region of the simulation domain further increases and a relatively complete columnar structure is formed, while the short chain structure at the left end is slightly deformed. When \( T = 16\) s, as the dielectric particles are further affected by the coupling field, especially by the flow field, the chains formed by the dielectric particles in the whole simulation domain produce obvious deformation and bending along the direction of the flow field, especially in the region where \( Z = 10-25\), the deformation of the chain structure is the most obvious due to the maximum velocity. When \( t = 20\) s, because the effect of the flow field on the chain structure is greater than the shear stress value, especially the middle part of the simulation domain, the chain structure finally begins to yield fracture from the middle part, and the density of the dielectric particles at the upper and lower ends of the simulation domain increases. Because of electrostatic polarization, the broken dielectric particles reaggregate towards the two ends of the simulation domain to form shorter chain structures, and the chain structures aggregate with each other to form close short columnar structures inclined along the direction of the flow field. By comparing the simulation results under the static field, it can be found that under the coupling field, the dielectric particles first aggregate to form a chain structure with relatively complete structure, then deform and break along the flow field direction, and finally the broken structure attracts and gathers again. The chain structure formed by the electrorheological fluid under the action of coupling field is in a quasi-stable state.

![Fig. 4 Dynamics of dielectric particles in the shear flow region under a dynamically coupled field](image)

**FIG. 4** Dynamics of dielectric particles in the shear flow region under a dynamically coupled field

Picture 4 the results are the simulation results of the dynamics of dielectric particles in the shear flow area under the action of coupling field, and 100 particles in the range of \( Z = 0-10\) are selected as the research objects. It can be seen from the picture that the dielectric particles are uniformly distributed in the simulation domain at the initial stage. With the action of the coupling field, the
particles gradually aggregate to form a short chain structure. When \( t=10 \text{s} \), the short-chain structure attracts each other gradually, and at the same time attracts the particles moving towards both ends in the plunger area under the action of the flow field, which increases the density of particles in the simulation domain and forms a tight chain structure. When \( T=15 \text{s} \), the upper part of the chain structure is inclined along the flow direction due to a large flow velocity, while the particles at the lower end are subject to a large polarization effect and less flow influence, so they are basically adsorbed near the lower part of the simulation domain. Particles in the entire simulation domain appear to be subjected to flow shear.

3.3 Influence of electroviscosity effect under dynamic coupling field

![FIG. 5 Velocity distribution of er under coupling field](image)

FIG. 5 Velocity distribution of er under coupling field

Picture 5 the cross section distribution of instantaneous velocity of er fluid under coupling field (\( E=1.0 \text{kV/mm}, V=2 \text{cm/s} \)) is shown. In the figure, the solid line represents the velocity distribution curve considering the electro-viscosity effect, while the dotted line represents the velocity distribution curve without considering the electro-viscosity effect. The electrorheological fluid under the action of coupling field shows the velocity distribution characteristics of Bingham plunger flow. With the increase of electric field intensity, the flow velocity of the electrorheological fluid decreases gradually, indicating that the flow damping of the electrorheological fluid increases with the increase of electric field intensity, resulting in the decrease of flow velocity. Under the same electric field intensity, the peak value of the flow velocity of the electrorheological fluid is lower when the electrorheological viscosity effect is taken into account than when the electrorheological viscosity effect is not taken into account, indicating that the electrorheological viscosity effect has an impeding effect on the flow of the electrorheological fluid. In addition, the difference between the solid line and the dashed line under the same electric field intensity increases with the increase of the electric field intensity, indicating that the influence of the electro-viscosity effect on the flow velocity of er increases with the increase of the electric field intensity, which is consistent with the law of the influence of the electric field on the electro-viscosity effect.

4 Conclusion

The dynamics of dielectric particles under static and dynamic coupling fields are simulated by DPD method.

The DPD model was established by selecting reasonable initial values and boundary conditions and combining with the dynamic characteristics of electrorheological fluids at micro scale. The dynamic law of dielectric particles in electrorheological fluids under static and dynamic coupled action fields was simulated and analyzed by the modified Velocity Verlet integral method. The influence of the surface force under the static field on the dynamics of the dielectric particle and the influence of the electroviscosity under the dynamic coupled field on the flow rate of the electrorheological fluid are also studied.

References:
[1] Wu chang, niu rui. 2020,Research status of electrorheological fluids and electrorheological effects [J]. Communication power supply technology, 37(02):163-165.
[2] Bao Fang, Cao Xicun, Li Qiang. 2019, Application of magnetorheological fluid device in construction machinery [J]. Construction machinery technology and management, 32(03):68-70.

[3] Zhu Shi-sha, ZHOU Xiao, 2018, LEI Xian-hua, YUAN Jia-ying. Capture effect in Current dynamics based on Visualization [J]. Journal of Materials Science and Engineering, 36(03):418-422.

[4] Liu Ziang. 2018, Application of Electrorheological Fluid Intelligent Materials in Engineering Technology [J]. China Building Materials Science and Technology, 27(05):68-69.

[5] Huang H F, Zahn M, Lemaire E. 2011, Negative electrorheological responses of micro-polar fluids in the finite spin viscosity small spin velocity limit. I. Couette flow geometries[J]. Journal of Electrostatics, 69(5):442-455.

[6] Huang H F, Zahn M, Peters F, et al. 2012, Negative electrorheological responses of micro-polar fluids in the finite spin viscosity small spin velocity limit. II. Poiseuille flow geometries[J]. Journal of Electrostatics, 70(6):481-488.

[7] Zhu S S, Qi L, Liu J G, et al. 2014, Dynamic modeling and numerical simulation of electro-rheological fluids based on Lattice Boltzmann Method[J]. Applied Mechanics & Materials, 487:494-499.

[8] Tong Jiong. Electrorheological Fluid Shear model construction and its application in shock absorber [D]. Jilin University, 2019.

[9] Revenga M, Nol P E, 2007, Pagonabarraga I. Boundary model in DPD[J]. International Journal of Modern Physics C, 9(08):1319-1328.

[10] Wu Liming. 2013. Fluid flow simulation based on Dissipative Particle Dynamics [D]. North China University of Science and Technology,