ANALYSIS OF MICRO-MOTION OF NANOFLUID PARTICLES BASED ON MACHINE VISION

by

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In order to accurately analyze the motion characteristics of nanofluid particles in the flow state, a method for micro-motion analysis of nanofluid particles based on machine vision was proposed. The influence of temperature on the micro-motion of nanoparticles was studied by establishing a water-based near-wall flow simulation model of nanofluids, and the Lennard-Jones potential parameters of nanofluids were obtained. Machine vision imaging technology is used to establish a reference system for nanofluid particles micro-motion image acquisition. Based on this system, the micro-motion images of nanofluid particles are collected, and the micro-motion characteristics of nanofluid particles are accurately detected. An experimental measuring platform composed of optical system and electronic system is established. The rotational and translational motions of nanoparticles and the velocity and temperature distributions of nanofluids are obtained. It was found that the velocity gradient of the nanofluid near the wall was higher than that of the base liquid, and the temperature of the nanofluid near the wall was significantly higher than that of the single-phase base liquid. The experimental results show that the velocity and temperature distributions of nanofluids at different temperatures can be obtained by using this method.

Key words*: machine vision, nanofluid, particle micromotion, particle size, flow simulation model, micromotion image, temperature distribution*

Introduction

Nanofluid is a new type of heat transfer working fluid formed by adding nanoparticles to the base fluid in a certain manner and proportion. It has significantly improved thermal conductivity and flow and heat transfer characteristics. The coexistence of Brownian motion and directional motion in nanofluids has an important impact on some fields [1]. For example, the heat transfer efficiency of nanofluids is closely related to the movement characteristics of particles in the fluid. When measuring the particle size in nanodispersion system, the micro-convection will lead to the coexistence of directional motion and Brownian motion, affecting the credibility of measurement results [2]. Therefore, it is necessary to conduct a systematic study on the movement characteristics of nanoparticles (namely nanofluids) under flow conditions. However, measurement methods of movement characteristics of nanofluid particles are

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still lacking, and it is necessary to develop relevant measurement methods and detection technologies.

In recent years, researchers have developed a dynamic light scattering nanoparticle measurement method based on self-mixing technology by introducing laser self-mixing technology into nanoparticle testing technology. The Brownian motion effect of particles is studied using the self-mixing technology of semiconductor lasers. The laser self-mixing method detects the backscattered light of the particles, and sends the backscattered light signal into the resonant cavity of the laser, and a self-mixing phenomenon occurs to obtain a self-mixing signal. The frequency spectrum characteristics of the self-mixing signal reflect the movement characteristics of the particles in the Brownian motion, which indirectly reflects the particle size information of the particles. Therefore, the size of nanoparticles and their size distribution can be obtained by analyzing the self-mixing signal [3-5]. However, the traditional photon cross-correlation spectroscopy and dynamic light scattering based on self-mixing interferometry theories are both based on the Brownian motion of nanoparticles in nanosolutions (particle dispersion systems have no macroscopic directional motion, also called quasi-static particle dispersion systems), and they cannot realize particle dispersion. The study of the movement characteristics of nanoparticles in the dispersion system for macroscopic directional movement, that is, the nanoparticle two-phase flow system.

In order to solve the previous problems, a method of motion analysis of nanofluid particles based on machine vision is proposed in this paper. The effect of temperature on the micro-motion of nanofluids was studied by using the near wall flow model of water-based nanofluids. The Lennard-Jones (LJ) potential parameters of nanofluids are given. In order to accurately detect the fretting characteristics of nanofluid particles, the fretting images were collected for fretting detection. The experimental platform composed of optical system and electronic system is constructed. The rotational and translational motion of the nanoparticles, the velocity and temperature fields of the nanofluids were obtained. The results show that the velocity gradient of the near-wall nanofluid is greater than that of the base liquid, and the temperature of the near-wall nanofluid is significantly higher than that of the single-phase base liquid. The velocity and temperature distribution of nanofluids can be obtained by this method.

Analysis of micro-motion characteristics of nanofluid particles

Particle size distribution

In production practice, what is usually encountered is not a single particle, but an aggregate composed of many particles, that is, a cluster of particles. In a particle group, if the particle diameters of the particles are equal or approximately equal, the particle group is called a monodisperse system. Usually, the particle diameters of a particle group have a distribution range, which is called a polydisperse system. The narrower the distribution range of particle size, the smaller the degree of dispersion of the particle group [8]. For most particle groups, the particle size distribution of the particles is continuous, and can usually be expressed by frequency distribution or cumulative distribution.

The value of any point on the frequency distribution curve represents the percentage of particles in the unit particle size interval at that particle size, denoted by $x(t)$, which is called the frequency distribution function (or frequency distribution).

Cumulative distribution refers to the percentage of particles larger or smaller than a certain particle size, f, which is equal to the integral of the frequency distribution function to the particle size, as:

$$K(f) = \int_0^i g(f) s f' \tag{1}$$

$$K_n(f) = \int_i^\infty g(f) s f' \tag{2}$$

where the cumulative distribution function, $K(f)$, represents the percentage of particles smaller than a certain particle size f in the particle group and $K_n(f)$ the percentage of particles larger than a certain particle size f in the particle group. Obviously, for a certain particle size f of the particle group, the cumulative distribution function should satisfy the relationship $K(f)+K_n(f)=1$.

The particle size distribution of the actual particle group depends on its production conditions. The distribution of particle groups can be number distribution, surface area distribution or weight (volume) distribution, *etc.* [9]. Most common particle distribution functions are two-parameter distribution functions. The so-called dual parameter means that the function can be determined by two specific parameters, one is the characteristic size parameter characterizing the particle size of the particle group, and the other is the distribution parameter characterizing the particle size distribution of the particle group [10]. Some powders produced by aerosol and precipitation methods have a particle number distribution that approximately conforms to this distribution, as:

$$K(a) = \frac{K_a(f)\{H_\varepsilon[\phi(x)]\}}{K_b(f)} \tag{3}$$

where a and b represent size parameters and distribution parameters, respectively, which completely determine the distribution of particles. The normal distribution function is a symmetric function, so the size parameter a is equal to the average diameter of the particle group, and b determines the range of particle group distribution, that is, the degree of width. The H_ε represents the width of particle size distribution, $K_a(f)$ – the fractal dimension of the particle group, and $K_b(f)$ – the relative weight of particle properties.

The weight and particle size distribution of some pulverized fine particles is very skew, which is approximately in line with a distribution called Rosin-Rammler, referred to as R-R distribution function, which is:

$$K(f) = \theta\left[\phi(x) - \left(\frac{\nabla\phi}{|\nabla\phi|}\right)\right] \tag{4}$$

where θ represents the geometric standard deviation in the lognormal distribution, $\nabla\phi$ – the size parameter, and $|\nabla\phi|$ – the distribution parameter. The larger the $\nabla\phi$, the larger the particle size of the entire particle group. The larger the $|\nabla\phi|$, the narrower the particle size distribution.

Construction of simulation model of nanofluid flow

In order to investigate the influence of temperature on the micro-motion characteristics of nanofluid particles, a simulation model of nanofluid flow near the wall surface with water as the base liquid was established [11]. The base liquid is water molecules, and a Cu nanoparticle with a particle size of 4 nm is placed in the base liquid. The size of the built simulation box is 6.53 nm × 6.51 nm × 13.9 nm, and the height of the fluid area is 11.37 nm. All atoms in the initial model are located on the lattice points of the FCC lattice [12]. The number of particles contained in the model is also determined after the establishment of multiple test models for trial calculations. When the number of simulated particles exceeds 10000, the number of particles in the model has little effect on the calculation results, and the final nanofluid is near the wall surface. The flow simulation model contains a total of 25479 simulated particles.

For the interaction between water molecules, the semi-empirical SPCE rigid body potential energy model is used, of which the expression is:

$$D = \frac{\left|x_i \Phi(a)\theta(b)\right|^2}{E(\varepsilon_t)\varepsilon_r} \tag{5}$$

where x_i represents the potential energy of the molecule pair, $\Phi(a)$ – the charge of the atom, $\theta(b)$ – the distance between the atoms, ε_t – the distance between the oxygen atoms of two molecules, ε_r – the long-range electrostatic interaction, and E represents the potential energy parameter of the oxygen atom.

The LJ potential is used to describe the interaction between water molecules and Cu atoms. In the simulation, the interaction between hydrogen and Cu atoms is ignored, and only the interaction between O and Cu atoms is considered. The Cu is calculated according to the Lorentz-Berthelot average rule.

Detection method of micro-motion of nanofluid particles based on machine vision

With the development of machine vision imaging technology, the application of machine vision imaging analysis methods in image detection and target recognition can realize improved detection and recognition capabilities of target objects [13]. Therefore, based on the particle size and its distribution characteristics and combined with the nanofluid LJ potential parameters obtained through the nanofluid flow simulation model, the machine vision method is used to detect the micromotion characteristics of the nanofluid particles.

Micro-motion image acquisition of nanofluid particles

Based on machine vision imaging technology, a benchmarking image acquisition system of nanofluid particle micro-motion is built. The system consists of LED light source, benchmarking, camera, PC, *etc.* [14]. The environmental lighting condition is an important factor affecting the quality of the collected image. Since most of the bottled liquid are contained glass or plastic bottles, it is easy to reflect on the bottle body, which brings error to the subsequent image processing. Therefore, the system should not only ensure a certain brightness and uniformity of light, but also avoid the reflection of strong light on the bottle body [15, 16]. Therefore, the white baffle is used as the shooting background, and two LED light sources are used to illuminate from the top of the bottle body, so that the light can not only map the bottle body clearly, but also diffuse reflection on the surface of the bottle body evenly, in order to achieve ideal image effect.

Motion feature extraction of nanofluid particles based on machine vision

In order to accurately detect the micro-motion characteristics of nanofluid particles [17, 18], a multi-resolution image detection model is further constructed through machine vision based on the acquisition results of micro-motion image of nanofluid particles, and the multi-scale feature decomposition of the motion image of nanofluid particles is performed [19, 20]. The fuzzy edge feature reconstruction method is used to reconstruct the super-resolution information of the motion image of nanofluid particles, and the distribution matrix of the image gray pixels is:

$$W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nm} \end{bmatrix} \tag{6}$$

where w represents the nanofluid motion image, n – the homogenous area of the nanofluid, and m – the super pixel feature quantity in the nanofluid particle motion image.

In the sharpened area of the motion image of nanofluid particles, the edge contour segmentation curve of image $h(x, y)$ is set to R, thereby dividing the motion image of nanofluid particles into grayscale area r_1 and background area r_2. For images in different areas, the feature quantities of different regions of the multi-resolution image are expressed:

$$\begin{aligned} &\Phi(y_i) = \theta(b)\varepsilon_t \\ &\theta(b) = 1 - \theta_1 B - \theta_2 B' \\ &E(\varepsilon_t) = \varepsilon^2 \times h_{ij} \\ &E\varepsilon_t = (1-\alpha)^2 \end{aligned} \tag{7}$$

where θ_1 and θ_2 represent the significant radial gray distribution curve and edge contour curve of the image under machine vision, respectively, h_{ij} – the length of the edge contour segmentation curve, ε^2 – the internal area of the contour curve, and α represents the motion image of nanofluid particles under machine vision, the characteristic component of which is a constant greater than 0.

Through the previous analysis, the extraction of the movement characteristics of the nanofluid particles is realized, which provides basis for the analysis of the micro movement characteristics of the nanofluid particles.

Results

The numerical calculation results of the micro-motion characteristics of nanofluid particles based on machine vision are previously described in detail. In order to verify the rationality of the proposed method, an experimental measurement platform is built and tested.

Rotation and translation of nanoparticles

Figures 1-3 show the nanoparticle rotation velocity components at temperatures 292 K, 312 K, and 332 K, respectively. Figure 1 shows the rotation speed of nanoparticles at 292 K, fig. 2 shows the rotation speed of nanoparticles at 312 K, and fig. 3 shows the rotation speed of nanoparticles at 332 K. The rotational speed of the nanoparticles shows the characteristics of random variation between positive and negative values.

Through analyzing the movement behavior of nanoparticles at different temperatures, it is found that the nanoparticles have obvious rotation and translation movement in the base fluid. Temperature has a significant effect on the movement behavior of nanoparticles. As the temperature increases, the translation and rotation of nanoparticles are strengthened to a certain extent. Through the simulation of the H_20-based nanofluid flow process, the translational velocity of the nanoparticle is about several meters per second, and the rotation velocity is on the order of 109-1010 rad·1/s. The violent random rotation and translation movement of the nanoparticles enable the heat to be quickly transferred to the surrounding fluid along with the rotation and migration of the nanoparticles, thereby accelerating the heat transfer process in the nanofluid, which is beneficial to the balancing of heat distribution in the nanofluid.

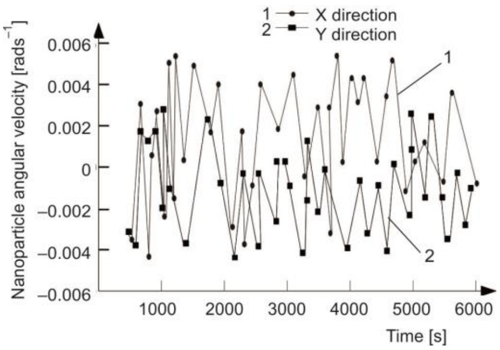

Figure 1. Angular velocity of nanoparticles at 292 K

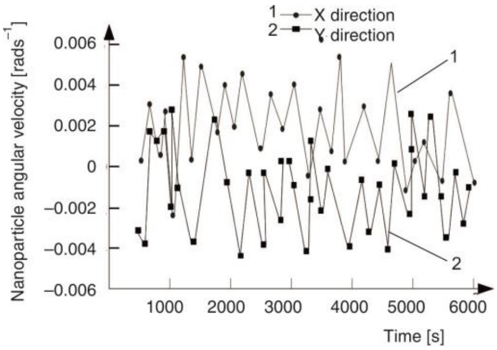

Figure 2. Angular velocity of nanoparticles at 312 K

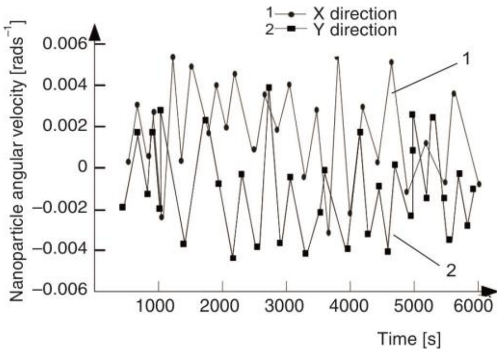

Figure 3. Angular velocity of nanoparticles at 332 K

Conclusion

This paper introduces the basic principle of quantitative analysis of fluid dynamics based on machine vision. The velocity field of the fluid was measured by the continuous imaging sequence of the nanofluid. The parameters needed for image processing and common digital technology are obtained. The micro-motion characteristics of nanofluid particles were obtained by using machine vision technology. The results show that this method can effectively obtain the particle size in nanometer solution, particle size in nanometer fluid, and velocity distribution and temperature distribution of nanometer fluid at different temperatures. However, there are still many defects and deficiencies in this work, which need to be further improved in the future work. In industrial production, many complex particles are often encountered, such as the multimodal distribution of particles, particles dispersed in liquid or gas media. Therefore, the method proposed in this paper should be further applied to various measurement situations.

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