Nanoparticles-Laden Gas Film in Aerostatic Thrust Bearing

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Nanoparticles-laden gas film (NLGF) was formed by adding SiO_2 nanoparticles with volume fraction in the range of 0.014–0.330% and size of 30 nm into the air gas film in a thrust bearing. An effective viscosity of the gas-solid two phase lubrication media was introduced. The pressure distribution in NLGF and the load capacity of the thrust bearing were calculated by using the gas-solid two phase flow model with the effective viscosity under the film thicknesses range of 15–60 μm condition. The results showed that the NLGF can increase the load capacity when the film thickness is larger than 30 μm. The mechanism of the enhancement effect of load capacity was attributed to the increase of the effective viscosity of the NLGF from the pure air film, and the novel lubrication media of the NLGF can be expected for the bearing industry application. [DOI: 10.1115/1.4026503]

Keywords: nanoparticles, nanoparticles-laden gas film, pressure distribution, load capacity, volume fraction

1 Introduction

Nanoparticles as additives in lubrication oil have been widely applied in industrial lubrication and tribology. Recently, the effect of nanoparticles additives on the load capacity of fluid film has caused wide attention [1,2]. There were some studies concerning the effects of nanoparticles on the load capacity of lubricating oil [3–7]. Rapoport et al. [3] found that the addition of even a small amount of nanoparticles into oil could increase its load capacity. Liu et al. [4] found that when the average size of the additive particles was less than 30 nm, the oil exhibits an excellent load capacity. Hsin et al. [5] and Lin et al. [6] both confirmed that nanoparticles of different material can improve the load capacity of lubricating oil. Lee et al. [7] analyzed the load capacity enhancement mechanism of nanoparticles in lubricating oil. The above work all focused on the performance about the load capacity of the lubricating oil with nanoparticles additives. However, there were few studies discussing the performance of the gas-solid two phase mixture as a lubrication media.

In the present study, the performance of the new lubrication media of NLGF, which was formed by adding SiO_2 nanoparticles into gas film as additives, was studied experimentally from the viewpoint of improving the load capacity. An effective viscosity based on experimental data was proposed to describe the flow properties of the nanoparticles-laden gas. The pressure distribution and load capacity of the NLGF under different film thickness were calculated based on the effective viscosities. Finally, the numerical data of load capacity was verified with the experimental data.

2 Experimental Method

2.1 Experimental Process. The enhancement effect of nanoparticles on the load capacity of NLGF was found in our prior research as a case study of 45 μm in thickness [8]. To completely study on the effect of nanoparticles on gas film in other film thickness, the following experiments have been done.

Figure 1 gives the photo of the experimental apparatus. As shown in Fig. 1(*a*), the experimental apparatus consists of nanoparticles supply, working parts, an A/D converter, and data display four components. The test bearing is an aerostatic thrust bearing with a single inlet port in its center. Air is the working gas and SiO_2 nanoparticles are the additives. The experimental conditions are summarized in Table 1. It should be mentioned that the nanoparticles volume fraction in the paper refers to the volume fraction at the inlet spots.

The schematic sketch of the working parts is shown in Fig. 1(*b*). After the addition of nanoparticles, the value of film thickness changes, which is detected by a nanoprobe displacement sensor with a resolution of 0.01 μm [9]. According to the film thickness change, NLGF load capacity can be measured, and the detail process is given as follows. Firstly, an initial load of 70 N is applied on the bearing pad, and then clean air is blown into the bearing. The lubrication media is in a pure air film state after the film thickness reaches a stable value, which was recorded as the initial value. Secondly, when nanoparticles are added into the air film, the film thickness becomes larger and the NLGF forms. Thirdly, sand drops from the funnel to the box, by which the load is applied on the bearing pad. The film thickness decreases continuously with an increasing load until the initial value of thickness is obtained; by then, the lubrication media is in a loaded NLGF state. Fourthly, the supply of nanoparticles and gas are both stopped, and the weight of the dropped sand is measured as the added load. By taking the sum of the initial load and the added load, the NLGF load capacity is obtained.

Figure 2 depicts the film thickness variation with time during the experiment process. In the figure, the experimental process is divided into five stages (1–5) corresponding to the operation process. The first stage is for the experimental preparation. No air is supplied, and the film thickness is zero. In the second stage, air

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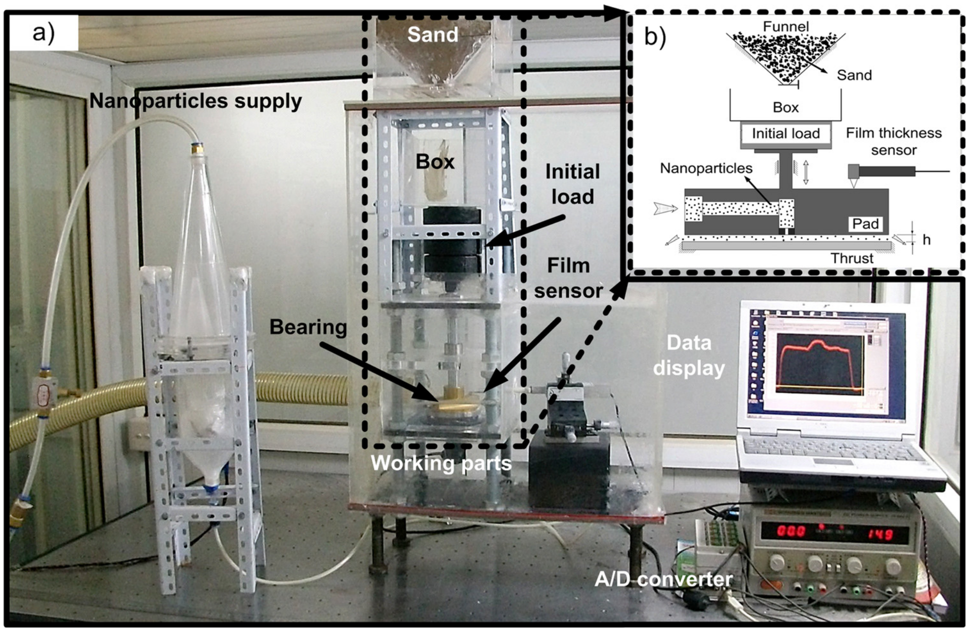

Fig. 1 The experimental apparatus: (*a*) photo of the whole apparatus and (*b*) schematic sketch of the working parts

Table 1 Experimental conditions

	Test parameters	Values
Bearing	Orifice radius r_i/mm	1
	Pad radius r_o/mm	45
Materials	Air density ρ_1/kg · m^{-3}	1.225
	Nanoparticles density ρ_2/kg ·m^{-3}	70.7
	Nanoparticles volume fraction φ_2/%	0, 0.014, 0.023, 0.047, 0.094, 0.190, 0.330
	Nanoparticles diameter Φ/nm	30
Operation Pressure	Supply pressure p_i /MPa	0.304
	Ambient pressure p_o /MPa	0.101

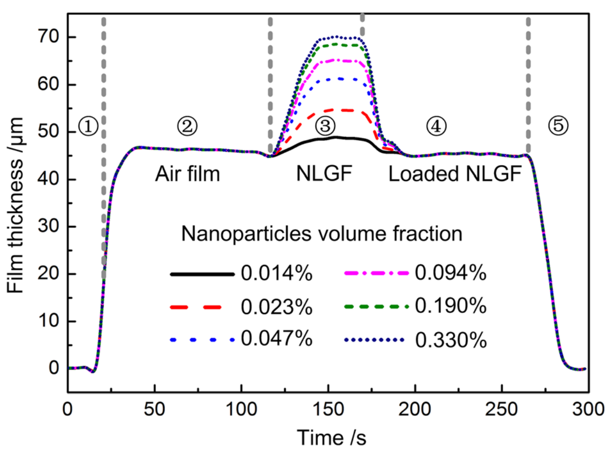

Fig. 2 Film thickness variations with time during the experimental process

enters the bearing, and the film thickness stays at about 45 μm when the film is stable. The variation of film thickness has a delay in the beginning of this stage, which is caused by the compressibility of air. In the third stage, nanoparticles are added. The film thickness rises gradually and reaches a stable value finally. The film thickness in this stage increases with the nanoparticles volume fraction increasing, but the increment becomes less. In the fourth stage, the film thickness decreases gradually upon increasing the load (the dropped sand weight), and returns to the initial value of 45 μm. In the last stage, nanoparticles and gas are all turned off, and then the film thickness goes back to zero.

2.2 Experimental Results. Figure 3 shows the load capacity of NLGF when the nanoparticles volume fraction is in the range of 0.014–0.330%. The initial load is 70 N, and it increased to 76 N immediately after adding nanoparticles even of a small amount (0.014%). With the increase of nanoparticles volume fraction, the load capacity increases. The increment of the load capacity is about 1.3 times the initial load when the nanoparticles volume fraction is approximately 0.030%, shown by the arrow position. Then, the increment of load capacity decreases. When nanoparticles volume fraction is 0.330%, the load capacity reaches 110 N.

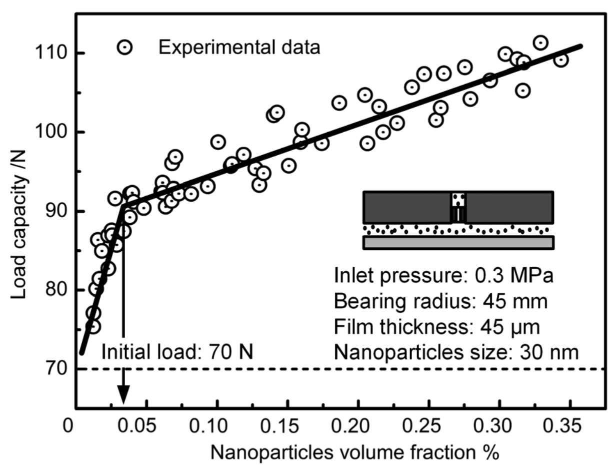

Fig. 3 Effect of the nanoparticles volume fraction on the load capacity of NLGF with thickness of 45 μm

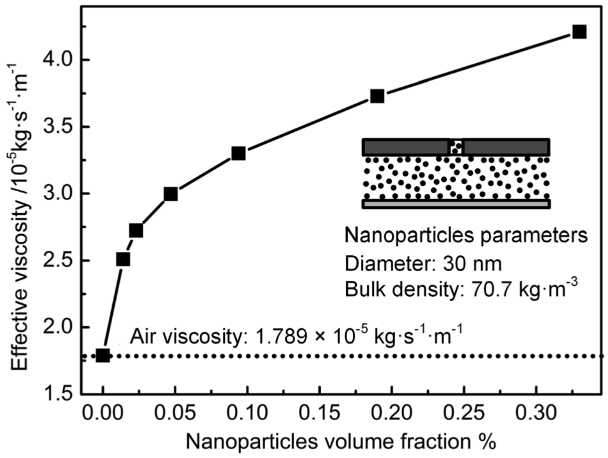

Fig. 4 Effect of the nanoparticles volume fraction on the mixture effective viscosity

In the experiment, the maximum volume fraction is just 0.330%. So the compressibility change caused by nanoparticles is negligible, and then the effect of compressibility change on the load capacity can be ignored. As is known, the load capacity of a fluid bearing is proportional to the viscosity of the lubricating fluid [10]. Therefore, the viscosity raise is considered as the dominating factor for the load capacity increase.

To confirm the reason for the load capacity increase of the NLGF, the viscosities of nanoparticles-laden gas under different nanoparticles volume fractions need to be measured. But it is difficult to do this as the nanoparticles-laden gas is a complex two phase fluid. Then, an effective viscosity is introduced to describe the fluidity properties of this NLGF lubrication media. Supposing the nanoparticles-laden gas is a uniform homogeneous mixture, it exhibits an effective viscosity. Using this effective viscosity, the pressure distribution of NLGF can be approximated by the following equation [10]:

$$p(r) = \sqrt{\frac{12\mu_e RT \cdot q_m}{\pi h^3}\ln\left(\frac{r}{r_o}\right) + p_o^2} \tag{1}$$

where μ_e is the effective viscosity of the mixture; $p(r)$ is the film pressure distribution along the film center in radial direction; R is the gas number, $8.314\,\mathrm{J \bullet mol^{-1} \bullet K^{-1}}$; T is the temperature of the mixture; q_m is the mass flow rate of the mixture; and h is the film thickness.

The load capacity of NLGF is the integral of film pressure distribution, and it can be expressed as

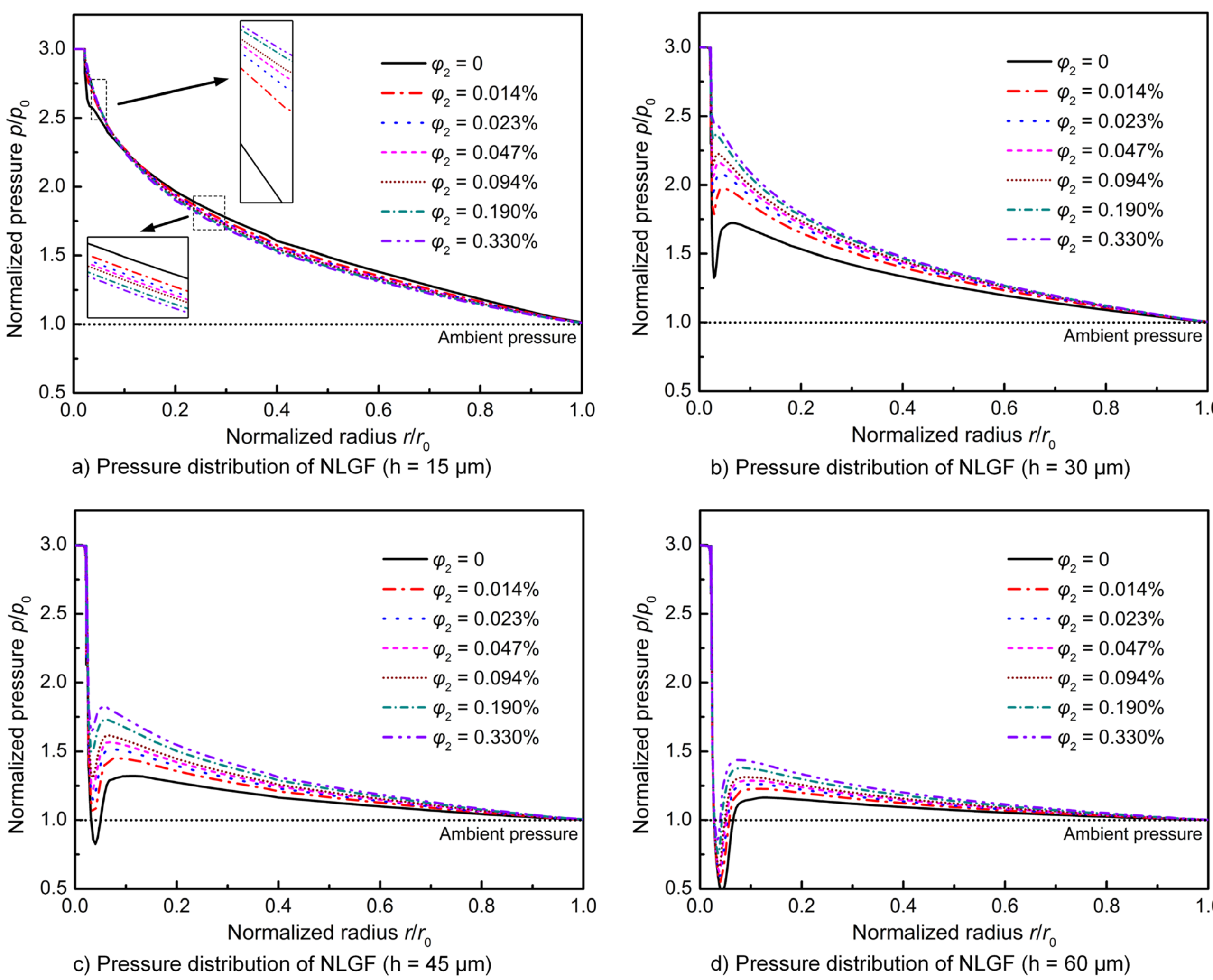

Fig. 5 Effect of the nanoparticles volume fraction on the film pressure distribution of NLGF with different film thickness; (*a*)–(*d*) pressure distribution of NLGF (h = 15 μm, 30 μm, 45 μm, and 60 μm, respectively)

$$W = \pi r_i^2 \cdot p_i + \int_{r_i}^{r_o} 2\pi r \cdot p(r) dr - \pi r_o^2 \cdot p_o \quad (2)$$

where W is the load capacity of the NLGF, $p(r)$ is the film pressure distribution along the film center in the radial direction, r_i is the radius of the inlet, r_o is the radius of the bearing pad, p_i is the inlet pressure, and p_o is the outlet pressure.

Based on the load capacity data from experiments, the effective viscosity of the mixture could be obtained by solving Eqs. (1) and (2) simultaneously, which are shown in Fig. 4. From the figure, the effective viscosity increases with the increase of nanoparticles volume fractions. The mechanism of the effective viscosity variation is considered as follows. As is known, the viscosity is a measurement of the fluid internal friction force. The friction force consumes energy in the flow, so the fluid exhibits a viscosity. Particles in a moving fluid obstruct the flow, then it consumes extra energy, which is measured as an increase in the viscosity [11]. With the particles volume fraction increasing, the energy consumption grows, and then the viscosity becomes larger.

3 Numerical Analysis

3.1 Numerical Model. Due to the experiment limitation in the present study, a simple numerical model was built to calculate the pressure distribution and the load capacity of NLGF under different film thickness. The nanoparticles-laden gas is a uniform compressible gas-solid two phase mixture. Among the calculation models for two phase flow, the mixture model [12] is well suited for the nanoparticles-laden gas flow. In this model, the nanoparticles-laden gas mixture is treated as one fluid; the air and silica nanoparticles are taken as two components of the fluid, and the sum of their volume fractions is one.

We had built in a viscosity formula based on a linear hypothesis [13], which can reflect the changing trend of load capacity after adding nanoparticles. However, in order to accurately analyze the nanoparticle-laden gas mixture, nonlinear effective viscosities in Fig. 4, which are derived from experimental results, are applied to this model in this paper. The compressibility of the gas is considered in the calculation. But, the compressibility change caused by nanoparticles is ignored as the nanoparticles volume fraction is very little (the maximum is 0.33%).

A commercial code (FLUENT 6.3) was employed to establish the numerical model as well as to calculate the film pressure distribution and load capacity of the NLGF. The calculation parameters of bearing and boundaries are all from Table 1.

3.2 Numerical Results. Figure 5 shows the pressure distribution of NLGF of 15–60 μm in thickness under different nanoparticles volume fractions. The pressure data are normalized to meet the general comparison under other bearing parameters. The normalized pressure is the ratio of film pressure p and the outlet pressure p_0; the normalized radius is the ratio of radial position r and the bearing radius r_0. In the 15 μm case (Fig. 5(*a*)), the pressure is larger than pure gas near the orifice but lower than that near the outlet after adding nanoparticles. In the 30 μm case (Fig. 5(*b*)), the pressure increases after adding nanoparticles. With the nanoparticles volume fraction increasing, the pressure increment becomes larger. When the film thickness is larger than 30 μm (Fig. 5(*c*) and Fig. 5(*d*)), the pressure distributions are similar to that of 30 μm but with a smaller value.

It is noticed that the effect of nanoparticles on pressure distribution is the opposite in thin films (15 μm) and thick films ($\geq$30 μm). The reason for this phenomena is as follows. From Eq. (1), it is clear that the pressure is proportional to the product of mass flow rate and effective viscosity. The effective viscosity rises with the nanoparticles volume fraction increasing, then the flow resistance becomes larger, and then the mass flow rate decreases. Compared to pure air, the decrement of mass flow rate is larger than the increment of effective viscosity in thin films, then the pressure decreases. But the situation is quite the reverse in thick films.

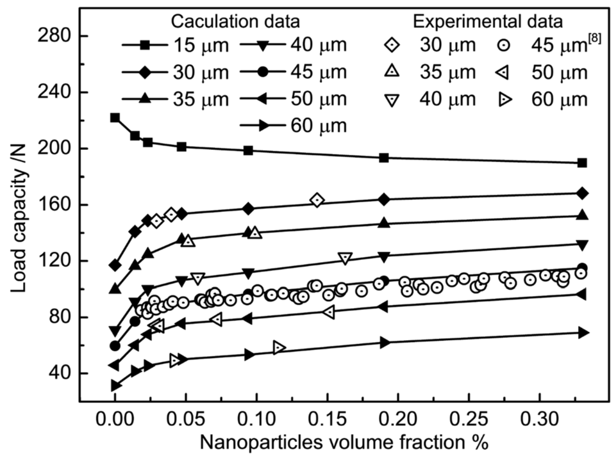

Fig. 6 The comparison between experimental results and numerical results obtained with effective viscosity

Based on the pressure distribution of NLGF, then the load capacity of the NLGF is obtained from Eq. (2). The comparison of modified numerical results and experimental results of NLGF load capacity are shown in Fig. 6. From the figure, the numerical results are in good agreement with the experimental data, which indicates that the effective viscosity is close to the actual viscosity, and the numerical model could be employed to calculate the load capacity of NLGF under different nanoparticles volume fraction and film thickness.

4 Summary

In this study, the load capacity effect of the NLGF thrust bearing was studied by both experimental and numerical approaches. An effective viscosity of the NLGF was introduced from the load capacity experimental data of the bearing. The pressure distribution in NLGF and the load capacity of thrust bearing were calculated by applying the effective viscosity. The results show that the addition of nanoparticles into a gas film can increase the load capacity of the NLGFs thicker than 30 μm. By comparing the numerical results with the experimental data, the validity of the numerical model is proved. Then, the application of this model for NLGF bearing design can be expected in the future.

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