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RESEARCH ARTICLE

Investigation of lubricant transfer and distribution at head/disk interface in air-helium gas mixtures

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Abstract: Lubricant transfer and distribution at the head/disk interface in air-helium gas mixtures is investigated using a developed model that combines an air-bearing model with a molecular dynamics model. The pressure distribution is calculated by the air-bearing model at the head/disk interface with respect to the helium content and the pressure obtained is then input to the molecular dynamics model to understand the lubricant transfer mechanism. Finally, the effects of pressure at the boundary condition and disk velocity on lubricant transfer are discussed in relation to the helium fraction within the air-helium gas mixtures. Results show there is a decrease in the pressure difference with an increase in the helium percentage, which leads to a decrease in the volume of the lubricant transferred. The results also suggest that the lubricant is not easily to transfer in gas mixtures with a high percentage of helium, even when both higher disk velocities and pressure boundary conditions are applied.

Keywords: head/disk interface; lubricant transfer; air-helium gas mixtures; molecular dynamics

1 Introduction

The spacing between the slider and the disk is decreased to 1−2 nm in current hard disk drives (HDDs) to obtain high area recording density. However, with such a small spacing, lubricant covered on the disk surface is likely to be transferred and accumulated to the slider surface. The accumulation of lubricant on the slider surface can then cause failure (or insufficient performance) of the slider. A considerable amount of research has been conducted in relation to lubricant transfer at the head/disk interface. For example, Pan et al. [1] and Seo et al. [2] investigated the transfer mechanism of Zdol 2000 at the head/disk interface for various running conditions using a molecular dynamics model, which was proposed and validated by Li et al. [3]. Wong et al. [4] used a molecular dynamics simulation to study lubricant redistribution and transfer (and its relationship with intermolecular force) when the head makes near contact with the disk interface. In addition, Mate et al. [5] experimentally studied lubricant migration at the slider surface and found that an effective viscosity could be obtained by fitting the measured data with a viscous flow model. Li et al. [6] experimentally investigated lubricant transfer from the disk surface to the slider surface, and their results showed that molecular polarity, the bonding ratio, and the main chain stiffness of the lubricant play roles in lubricant transfer. The study of Tani et al. [7] charged the slider with a negative voltage to prevent lubricant transfer, because the lubricant was negatively charged by the airflow. Furthermore, Seo et al. [8] studied four types of lubricants to determine the effects of temperature, pressure, and velocity on lubricant fragmentation, respectively, and found that a local pressure change plays the most important role in lubricant fragmentation. A numerical model was developed by Mendez and Bogy [9] to simulate

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lubricant de-wetting on the slider surface by consideration of a disjoining pressure, and this model makes it easy to predict the distribution of the lubricant on the slider surface.

Based on the above literature, we can conclude that numerical and experimental researches had been carried out to fully understand the characteristics of lubricant transfer at the head/disk interface, and effective methods for preventing lubricant transfer and improving the performance of the slider have since been proposed.

In recent years, it has been determined that helium is a promising gas for replacing air in hard disk drives, owing to its excellent characteristics. The use of helium with the same air-bearing surface design currently employed, such as FEMTO slider, could reduce the flying height, suppress disk vibrations caused by air, and reduce power costs [10–13]. In addition, the positioning error of the magnetic head in pure helium is 50% that of air [12], and the temperature of an HDD is greatly reduced (by approximately 41%) in pure helium, due to its high thermal conductivity [13].

It has also been suggested that an air-helium gas mixture is superior to the use of pure helium. For example, Liu et al. [14] showed that a gas mixture composed of 60% helium by volume and 40% air considerably reduceds the power cost used by HDDs. Tang et al. [15] studied the effect of helium on the flying height and the head/disk contact force, their results showed that the flying characteristics of a slider can be significantly changed, but only if the helium fraction is more than 0.5.

Although the advantages of pure helium and air-helium gas mixtures filled HDDs have been reported, it has not yet been determined whether there would be any difference between the lubricant transfer process that occurs with pure air and that occurring when pure helium filled HDDs or air-helium gas mixtures filled HDDs are used. In the present study, a model is developed to study lubricant transfer at the head/disk interface for air-helium gas mixtures filled HDDs. The model combines an air-bearing model, which accounts for the pressure distribution, and a molecular dynamics model, which simulates lubricant transfer. Finally, the relation between the amount of lubricant transferred and the pressure boundary condition, pressure change, and velocity in air-helium gas mixtures is discussed, respectively.

2 Mode and simulation procedure

To investigate lubricant transfer in HDDs filled with various air-helium gas mixtures, it is necessary to determine the physical properties of the mixtures. An air-bearing model was developed to calculate equilibrium pressure with respect to the helium percentage. Thereafter, the obtained pressure was input to a molecular dynamics model to simulate the transfer and distribution of lubricant in air-helium filled HDDs.

2.1 Air-bearing model

The schematic of a partial slider surface with a designed step flying on a disk surface is illustrated as Fig. 1. The slider surface is stationary, but the disk is rotating with a velocity of U. The equilibrium pressure can be obtained by solving the typical compressible Reynolds equation using the finite element method:

$$\begin{aligned} &12\frac{\partial(ph)}{\partial t}+6\frac{\partial(pUh)}{\partial x}+6\frac{\partial(pVh)}{\partial y} \\ &=\frac{\partial}{\partial x}\left(\frac{ph^3}{\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{ph^3}{\mu}\frac{\partial p}{\partial y}\right) \end{aligned} \tag{1}$$

where p represents pressure, h is flying height, μ is dynamic viscosity, U and V represent the relative velocities between the slider and the disk in the x and y directions, respectively.

The rarefaction factor is introduced because the minimum flying height of the sliders is reduced to

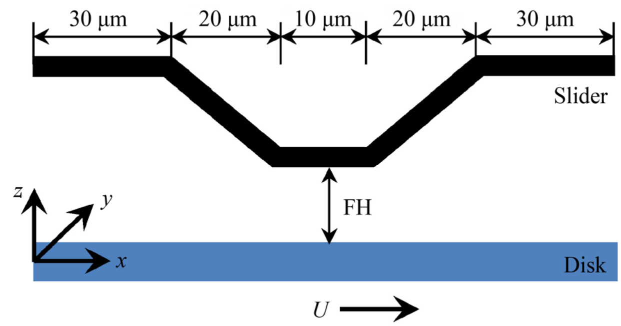

Fig. 1 Schematic of partial air bearing model.

several nanometers, in accordance with the study of Fukui and Kaneko [16]. Therefore, the modified Reynolds equation is shown as:

$$\Lambda_b \frac{\partial(PH)}{\partial X} + \sigma_b \frac{\partial(PH)}{\partial t} = \left(\frac{B}{L}\right)^2 \frac{\partial}{\partial X}\left(QPH^3 \frac{\partial P}{\partial X}\right) + \frac{\partial}{\partial Y}\left(QPH^3 \frac{\partial P}{\partial Y}\right) \quad (2)$$

where P, H, X, and Y are the dimensionless of p, h, x, y, respectively; L and B are the overall dimensions of the air-bearing surface in length and width, respectively; and Λ_b is shown as:

$$\Lambda_b = (B/L)^2 \frac{6\mu UB}{p_a h_0^2} \quad (3)$$

where p_a represents ambient pressure and h_0 represents the minimum head/disk spacing.

The Q shown in Eq. (2) is the rarefaction factor, which can be expressed as follows [16]:

$$Q = C_1 + C_2(PH)^{-1} + C_3(PH)^{-2} - C_4(PH)^{-3} \quad (4)$$

where C_1, C_2, C_3, and C_4 are constants.

The modified Reynolds equation is solved to obtain the pressure distribution using the finite element method. We assume that the partial slider length and width are $110\,\mu\text{m}$ and $4\,\mu\text{m}$, respectively, the disk velocity is 20 m/s, and the minimum slider/disk spacing is 2 nm. The boundary condition (BC) of pressure is 0.1 MPa.

2.2 Air-helium gas mixture

It is necessary to obtain the physical characteristics of air-helium gas mixtures with different helium percentages to calculate the pressure distribution at the head/disk interface. Details of the calculation method employed are shown in our previous research results [15]. Figure 2 shows the normalized variables of the gas mixtures with respect to the helium fraction, where it is evident that the mean free path significantly increases with an increase in the helium fraction (the mean free path is 67 nm for air and 194 nm for pure helium). However, the viscosity first increases then decreases, thereby reaching a maximum value of 2.07×10^{-5} N·s/m^2 when the helium fraction is 0.8. The density of the gas mixtures was calculated by a linear interpolation between air and pure helium.

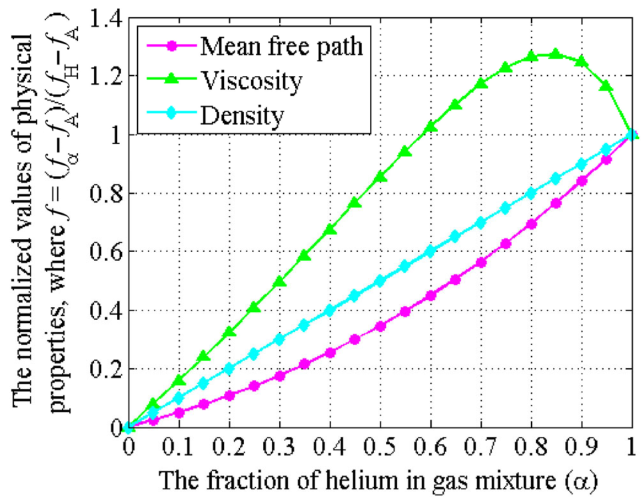

Fig. 2 Normalized variables of air-helium gas mixtures, where f represents the viscosity μ, the density ρ, and the mean free path λ, respectively.

2.3 Molecular dynamics model

To simulate molecule movement at the head/disk interface, a coarse-grained bead-spring (CGBS) model [1] is adopted in our study. The slider/disk interface is simplified to two parallel surfaces where a step is designed in the slider surface, as shown in Fig. 3. The molecular dynamics model is consistent with the air-bearing model shown in Fig. 1.

The disk is covered in two layers of perfluoropolyether (PFPE) molecules with a thickness of 1.4 nm, and the interactions between the molecules are governed by three types of potential functions: the Lennard-Jones function (LJ), the short-range attractive polar function (EXP), and the finitely extensible nonlinear elastic function (FENE) [3, 17, 18].

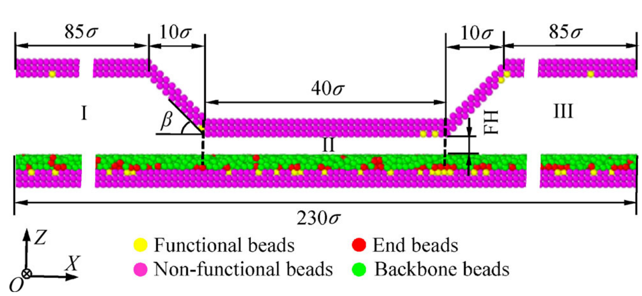

Fig. 3 Molecular dynamics model, where regions I and III are low-pressure regions, and region II is a high pressure region.

First, we employ the canonical ensemble (NVT) to calculate the LJ and FENE potentials without considering the EXP potential. In the simulation, the temperature is set as $T = 1\varepsilon / K_b$ (300 K) and a time-step of 0.005 τ is selected. After 20,000 time-steps, the lubricant molecules are uniformly distributed on the disk. Thereafter, the EXP potential is considered and the canonical ensemble (NVT) is replaced by the micro-canonical ensemble (NVE).

The pressure distribution at the head/disk interface with respect to helium fraction is calculated from the air-bearing model, and the effect of the helium fraction on the pressure distribution is discussed in the subsequent section. In addition, the pressure obtained is then input to the molecular dynamics model, and the effects of the helium fraction on lubricant migration at various disk velocities and boundary condition of pressures are investigated.

3 Results and discussion

3.1 Pressure distribution

Figure 4 shows the equilibrium pressure distributions on the slider surface with respect to helium percentages. It is evident that the maximum pressure decreases gradually with an increase in the helium percentage in relation to rarefaction of the gas mixtures (where the mean free path greatly increases with an increase in the helium percentage). It is also evident

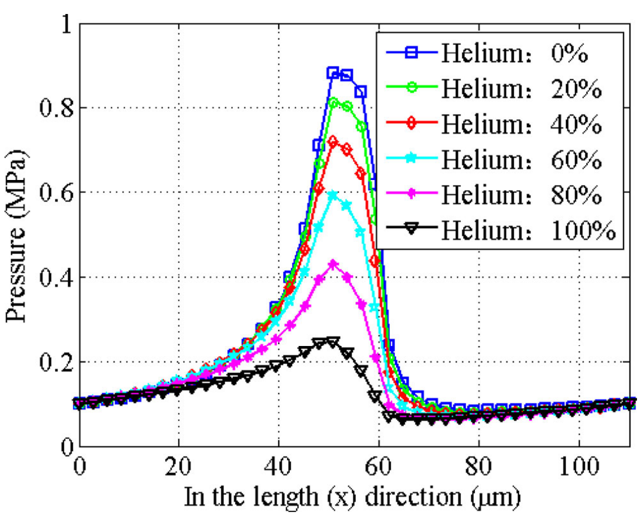

Fig. 4 Effect of helium percentage on pressure distribution of slider, U=20 m/s, FH=2 nm, BC=0.1 MPa.

that the pressure distributions are presented in a parabolic shape in the direction of length: the maximum pressure occurs at the step inlet of the slider where the minimum flying height locates and the pressure then gradually decreases. After the turning point of the slider, the pressure decreases to a value that is slightly lower than the boundary pressure: this type of pressure is defined as sub-ambient pressure [15, 19, 20].

Figure 5 shows the maximum pressures, minimum pressures, and the pressure differences at different flying heights, disk velocities, and pressure boundary conditions with respect to the helium percentage, and Fig. 5 (a) shows that for all flying heights, the maximum pressure decreases with an increase in the helium percentage. However, the influence of helium on the maximum pressure is reduced with an increase in the flying height. It can also be observed that all minimum pressures are lower than the boundary pressure (0.1 MPa), but that the minimum pressure increases with an increase in the flying height. The pressure difference between the maximum pressure and the minimum pressure (ΔP) is plotted with respect to the helium percentage and flying height, and it can be seen that the pressure difference decreases with an increase in the helium percentage: there is an enormous change in the pressure difference when the flying height is decreased to 2 nm. It is also evident that the helium has a significant effect on the pressure distribution if the slider flies very close to the disk. According to the study of Seo et al. [8], the pressure difference greatly affects lubricant transfer.

In Figs. 5(b) and 5(c), we observe that for all disk velocities and boundary pressures, the maximum pressure, minimum pressure, and the pressure difference decrease with an increase in the helium percentage. Comparing the three factors (flying height, disk velocity, boundary pressure), we can see that the flying height and the boundary pressure have larger effects than disk velocity on pressure distributions.

3.2 Lubricant distribution

In the molecular dynamics simulation process, the slider first decreases to the predefined flying height and the pressure distribution obtained from Section 3.1 is then applied. When the slider has been flying on the disk for 450τ, the slider returns back to its initial

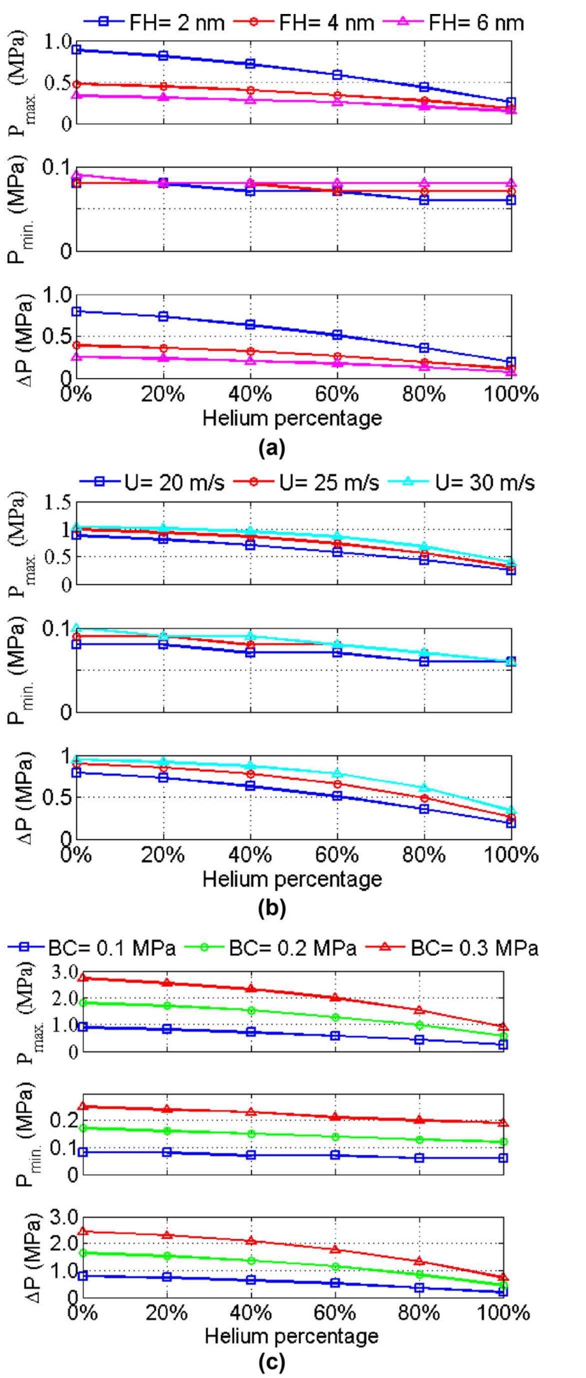

Fig. 5 Effect of helium percentage on pressure variation, (a) effect of flying height, $U = 20$ m/s, BC = 0.1 MPa; (b) effect of disk velocity, FH = 2 nm, BC = 0.1 MPa; (c) effect of pressure boundary condition, FH = 2 nm, $U = 20$ m/s.

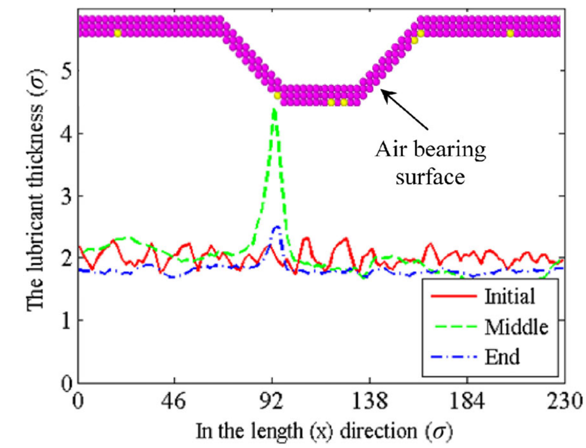

Fig. 6 Lubricant distribution on disk in a 50% helium and 50% air environment, FH = 2 nm, BC = 0.1 MPa, $U = 20$ m/s

position. Figure 6 shows typical variations in the lubricant distribution on the disk surface for three stages in a 50% helium and 50% air-filled environment. At the beginning of the simulation, the lubricant is randomly distributed on the surface of the disk and the average thickness is approximately 2σ (~1.4 nm). As the flying height decreases to 2 nm (marked as "Middle"), lubricant molecules accumulate in the area of the left step of the slider and form a peak of 4.5σ (~3.15 nm): it is likely that these lubricant molecules will be transferred to the slider. It can be observed that the lubricant distribution is relatively flat on the disk after the slider returns back to its initial position (marked as "End"): the lubricant molecules reflow in relation to pressure retraction and molecule self-repair [21].

Figure 7 shows the lubricant distribution with respect to helium percentage, where it is evident that the peak lubricant thickness value decreases with an increase in the helium percentage. This occurs because the pressure difference decreases to a minimum value if pure helium is used, as shown in Fig. 5.

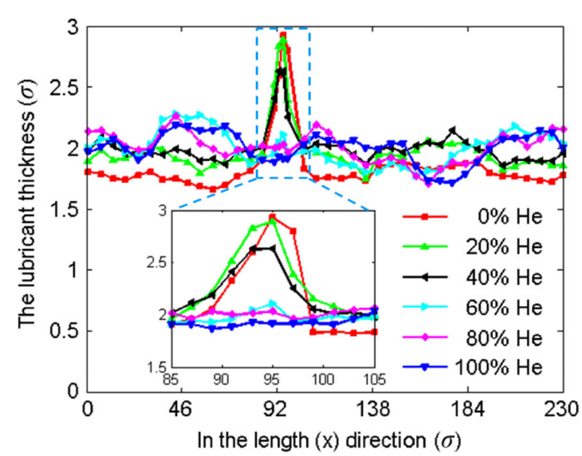

Fig. 7 Effect of helium on lubricant distribution, FH = 2 nm, $U = 20$ m/s, BC = 0.1 MPa.

Figure 8 shows the peak value of lubricant thickness and fitted curves with respect to the helium percentage at different flying heights. It is evident from this that the maximum thickness of the lubricant is inversely proportional to the helium percentage. The influence of helium on the maximum thickness of the lubricant reduces as the flying height increases, but this influence is negligible if the flying height increases above 5 nm.

3.3 Lubricant transfer

Figure 9 shows the lubricant transfer process at the head/disk interface in an air-filled environment, where the volume of lubricant transferred on the slider surface evidently increases with time. The lubricant molecules accumulate on the left step of the slider because they are pushed from the high-pressure region to the low-pressure region.

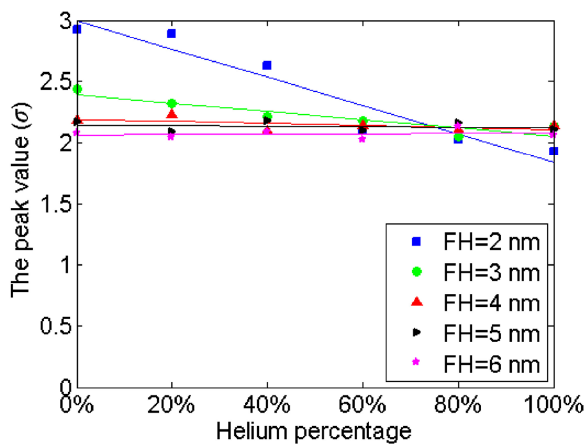

Fig. 8 Maximum thickness of lubricant as a function of helium percentage, $U = 20$ m/s, BC = 0.1 MPa.

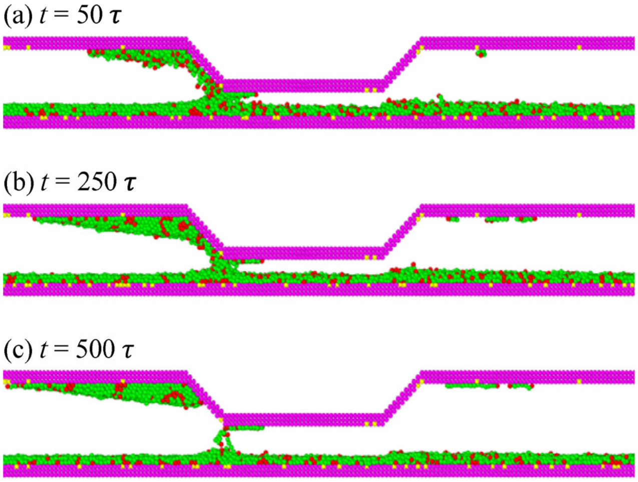

Fig. 9 Process of lubricant transfer in air environment, FH=2 nm, U=20 m/s, BC= 0.2 MPa

Figure 10 shows the effect of helium on the volume of lubricant transferred at different disk velocities, which evidences an increase in the volume of lubricant transferred with an increase in the disk velocity. This result is in good agreement with that of Pan et al. [1] and Seo et al. [2]. In addition, the transferred volume of lubricant decreases as the helium percentage increases from 0% to 100%. There is an extreme decrease in the volume of lubricant transferred when the helium percentage increases from 0% to 60%; however, as it further increases to 100%, the phenomenon of lubricant transfer is not easily observed. This is because the pressure difference decreases with an increase in the helium percentage, and a small pressure difference leads to minimal lubricant transfer. This result is consistent with that of the study of Pan et al. [1].

Figure 11 shows the effect of helium on the volume of lubricant transferred at different boundary pressures. The transferred volume evidently increases with an increase in the pressure boundary condition because changing the pressure boundary condition leads to a change in the pressure difference: the higher the boundary pressure, the higher the pressure difference, and the higher pressure difference causes larger volumes of lubricant to be transferred. The results show that in air-helium gas mixtures with a high percentage of helium, the lubricant is not easily transferred to the slider surface, even when the disk velocity and boundary pressure are both high.

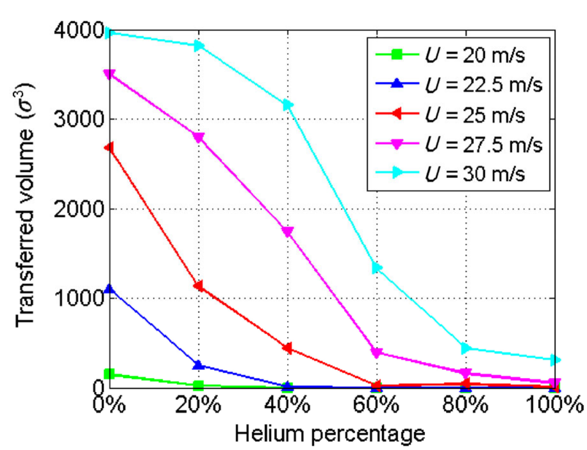

Fig. 10 Effect of helium on amount of lubricant transfer at different disk velocities, FH = 2 nm, BC = 0.1 MPa.

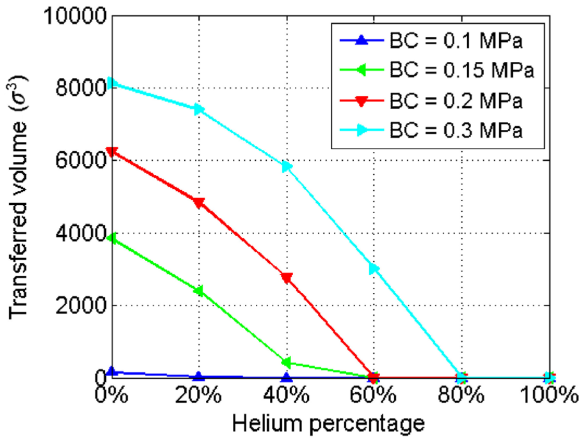

Fig. 11 Effect of helium on amount of lubricant transfer under different boundary pressures, U = 20 m/s, FH = 2 nm.

4 Conclusions

A numerical model that combines an air-bearing model and a molecular dynamics model is developed to study lubricant transfer from the disk surface to the air-bearing surface in air-helium filled HDDs. The pressure distribution at the head/disk interface in air-helium gas mixtures was calculated using the air-bearing model, and lubricant transfer at the head/disk interface with respect to the helium-induced pressure change is investigated. The results are summarized as follows:

1) The maximum pressure of the slider and the pressure difference both decrease with an increase in the helium percentage.

2) The peak value of lubricant thickness on the disk decreases with an increase in the helium percentage. However, if the flying height increases above 5 nm, the influence of helium on the lubricant distribution is negligible.

3) The amount of lubricant transferred decreases greatly as the helium percentage increases from 0% to 60%. As the helium percentage further increases to 100%, the phenomenon of lubricant transfer is not easily observed.

4) The volume of lubricant transferred increases with increases in the pressure boundary condition and disk velocity. However, it appears that the lubricant is not easily transferred to the slider in gas mixtures with a high percentage of helium, even when both a high disk velocity and boundary pressure are applied.

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