Transfer Behaviors of PFPE Lubricant from Disk Surface to Slider

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Abstract. The rapid growth in storage areal density of hard disk drive (HDD) forces the flying height of slider has been currently reduced to less than 2 nm. In such a narrow spacing, perfluoropolyether (PFPE) lubricant is easier to transfer from disk surface to slider under fluid force field and heat transfer field, which is found to have a great effect on date storage reliability. Firstly, the lubricant transfer volume expression with respect to lubricant molecular weight is established. Secondly, the finite element models (FEM) of both Tri-pad positive pressure slider and flat slider are developed, and based on this, the PFPE lubricant transfer behaviors in HDD are investigated. Finally, four type unite cells composed of lubricant molecules and air molecules are established by using Materials Studio software, then both dynamic temperature and diffusion coefficients are researched based on molecular dynamics theory. Results show that the PFPE lubricant amount decreases with increasing pitch angles, rotation angles, slider flying height and disk rotation velocity, while it increases when heat source power increases. The diffusion coefficients of ZTMD lubricant is the maximum in the four lubricants we researched, while the temperature change ratio of Z-15 lubricant is the maximum.

1. Introduction
With rapid development in high areal density and successful drive integration, heat assisted magnetic recording (HAMR) technology has proved to be a viable technology in promising magnetic data storage density [1]. The advent of big data, cloud computing and artificial intelligence put forward more technical challenges toward data storage devices, such as fast read and write data and large storage capacity, forcing slider flying height has been currently reduced to less than 2 nm to reach a 1TB/in² disk storage areal density[2-3]. In such a narrow spacing, perfluoropolyether (PFPE) lubricant is easier to flow from disk to slider although this is no contact between slider and disk under fluid force field as well as heat transfer field, which has a dominant effect on date storage reliability. So, it is very important to investigate the transfer behaviours when the slider is not in contact with disk surface.

Important transfer behaviours and PFPE lubricant molecules responses can arise at a myriad of length scales ranging from atomic to mesoscopic to macroscopic. Behaviours of HDD such as lubricant transfer and accumulation as a function of slider air bearing pressure and lubricant molecular weight were investigated [4]. Results indicate that air bearing pressure has little effect on lubricant transfer, while both lubricant transfer and accumulation amount decrease with increasing lubricant molecular weight. Li et al.[5] experimentally studied PFPE lubricant transfer behaviours from disk surface to slider as a function of lubricant thickness, bonding ratio, molecular polarity, and main chain stiffness when the slider flies below critical clearance. The effects of pitch static angles and roll static angles on lubricant transfer behaviours in a HDD were researched by using a precision spin stand, and
the lubricant distribution on the disks was obtained by using optical surface analysis [6]. Studies of lubricant transfer build a foundation in improving slider flight stability and disk drive performance. However, its behavior as a function of disk rotation velocity, heat source power, and the lubricant diffusion in air were rarely researched.

In this paper, firstly, based on Marchon model and Clausius-Clapeyron equation, the relationship between lubricant transfer volume and lubricant molecular weight was established; secondly, the finite element model of both flat slider and tri-pad positive pressure slider were developed by using COMSOL software, and then the effect of slider flying posture, slider flying height, disk rotation velocity, heat source power on PFPE lubricant transfer behaviors were investigated; finally, both dynamic temperature and diffusion coefficients were researched based on molecular dynamics theory.

2. Lubricant Transfer Theory

In a HDD, the lubricant transfer between slider and disk surface can be divided into three components (seen in Figure 1), including an inflow into slider surface, an evaporation coming from slider surface and a lubricant accumulation into slider surface under fluid shear force.

![Figure 1. Schematic of PFPE Lubricant mass transfer [7].](image)

The PFPE lubricant transfer volume is given by

\[ Q_{\text{cond}} = A \cdot R_{\text{cond}} = \frac{AP_{\text{vap}}}{\rho} \left( \frac{M_n}{2\pi RT} \right) \exp \left( -\frac{\Pi(t_d)M_n}{\rho RT} \right) \] (1)

where \( A \) is the effective head slider area (m\(^2\)), \( R_{\text{cond}} \) is the lubricant mass flux, \( P_{\text{vap}} \) is the bulk vapor pressure, \( \rho \) is the lubricant density, \( M_n \) is the molecular weight, \( t_d \) is the disk lubricant thickness, \( \Pi(t_d) \) is the disjoining pressure [8] for liquid lubricant films at disk surface lubricant thickness of \( t_d \).

3. Molecular Dynamics and Boundary Conditions

3.1. Molecular Dynamics Simulation

Based on Newton's second law and given a multi-body system containing \( n \) atoms, the atomic force can be obtained from the negative gradient of molecular mechanical potential energy.

\[ F_i(t) = \frac{d}{dt} \frac{d}{dt} + \frac{1}{2} b(t) \delta t^2 + \frac{1}{6} c(t) \delta t^3 + \cdots \] (2)

where \( F_i(t) \) is atomic force that atom \( i \) bears at time \( t \), \( U_i \) is molecular mechanical potential energy function, \( r_i(t) \) is position vector of atom \( i \) at time \( t \).

Based on finite element difference method, the dynamic behaviors of an atom, such as position and velocity at any time \( t \) can, therefore, be expressed by using Taylor expansion equation
3.2. Boundary Conditions
The adjusted system temperature \( T_m \) is expressed as
\[
T_m = \frac{3Nk_B}{\sum_{i=1}^{N} m_i \left( v_{x,i}^2 + v_{y,i}^2 + v_{z,i}^2 \right) x f^2}
\]
where \( v_{x,i}, v_{y,i} \), and \( v_{z,i} \) is the velocity of atom \( i \) in the direction of \( x, y, \) and \( z \) axis (Å/fs), respectively.

4. Finite Element Simulation

4.1. Slider Models
Different sliders may result in different lubricant transfer amounts. To select a reasonable slider is extremely useful. In this paper, two sliders (seen in Figure 2), including a Tri-pad positive pressure slider and a flat slider are investigated.

![Working surface](image1)

(b) Tri-pad positive pressure slider

![Working surface](image2)

(a) Flat slider

**Figure 2.** 3D models of sliders.

4.2. PFPE Lubricant Adsorption Models
Table 1 shows four typical PFPE lubricants and its chemical properties. In this table, \( m=5, n=6, [Z]=OCH_2-(CF_2O)_m-(CF_2CF_2O)_n-CF_2CH_2O.\)

| Lubricant type | Chemical formula | End functional group | The degree of polarity | Symmetry degree |
|---------------|------------------|----------------------|------------------------|-----------------|
| Z-15          | CF_3-O-(CF_2-CF_2-O)_m-(CF_2-O)_n- | -CF_3                 | Nonpolar               | Poor            |
| Z-Dol         | HO-CH_2-CF_2-O-(CF_2-CF_2-O)_m-   | -OH                   | Polar                  | Good            |
| D-SA          | F-(CF_2-CF_2-CF_2-O)_m-CF_2-CF_2- | -OH, -F               | Polar                  | Poor            |
|               | CH_2-OH           |                       |                       |                 |
|               | HO-CH_2CH(OH)CH_2-[Z]-CH_2CH(OH)CH_2CH(OH) | -OH                   | —                      | Very good       |
|               |                   |                       |                       |                 |
|               | CF_2CF_2CF_2CH(OH)CH_2-O-CH_2CH(OH) -CH_2-[Z]-CH_2CH(OH)CH_2-OH | -OH                   | —                      |                 |
DLC’' properties, very similar to diamond properties, are considerably varies depending on those structures [9]. For facilitating finite element modeling, the DLC unit cells are simplified to diamond unit cells, and in this means those 3D models are developed by means of Materials Studio software, as shown in Figure 3. The schematic of PFPE molecules adsorb with DLC molecules is shown in Figure 4, taking ZTMD molecular adsorption as an example. In this figure, the gray color represents DLC unit cells and other colors on behalf of ZTMD unit cells.

4.3. PFPE Lubricant Diffusion Models
Figure 5 shows four representative lubricants unite cells.

5. Results and Discussion
5.1. PFPE Lubricant Transfer
5.1.1. Effect of slider flying posture
Figure 6 shows the transfer amounts of PFPE lubricant from disk surface to Tri-pad slider and flat slider with increasing pitch angles, rotation angles.
5.1.2. Effect of slider flying posture

It can be seen that PFPE lubricant transfer amounts decrease when pitch angles, rotation angles increase, while those of Tri-pad slider are greater than those of flat slider. The reason might be that the lower surface area of Tri-pad slider to accommodate lubricant molecules and exchange heat is bigger than that of flat slider.

5.1.3. Effect of slider flying height

Figure 7 shows the relationship between PFPE lubricant transfer amount and slider flying height.

Results indicate that PFPE lubricant transfer amounts increase with increasing slider flying height. The reason may be that the increase in slider flying height would increase air heat transfer between magnetic head and disk, and thereafter decrease air bearing temperature. At such, a part of PFPE lubricant may be transfer to disk again, which would increase slider flight instability [10].

5.1.3. Effect of disk rotation velocity

The PFPE lubricant transfer amount from disk to slider as a function of disk rotation velocity is shown in Figure 8. It can be seen that PFPE lubricant transfer amount decreases with increasing rotation velocity.
5.1.4. Effect of heat source power
In the process of magnetic data reading and writing, a very thin laser beam coming from magnetic head internal laser would heat disk storage unit to specific temperature in a short time to reduce coercive force and promise magnetic data storage density [11]. The PFPE lubricant that covering on disk would flow rapidly, and even evaporate substantially from disk to magnetic head, however, which presents some significant technical challenges in maintaining slider flying stability. The PFPE lubricant transfer amount as a function of heat source power is shown in Figure 9. It can be seen that PFPE lubricant transfer amount increases with increasing of heat source power.

5.2. PFPE Lubricant Diffusion

5.2.1. Dynamic temperature
Both Figure 10 and Table 2 show the dynamic temperature distribution and the temperature changes of four type lubricants molecules, respectively. It can be seen that the required time for ZTMD lubricant to reach a stable temperature is the minimum, which is only 0.3 Ps, while that of Z-15 lubricant is the maximum. In addition, the temperature change ratio of Z-15 lubricant is also the maximum.

| Lubricants Type | Equilibrium temperature (K) | Change ratio (%) |
|-----------------|-----------------------------|------------------|
| Z-15            | 319.48                      | 145.51%          |
| Z-Dol           | 282.05                      | 113.5%           |
| D-SA            | 236.89                      | 82.81%           |
| ZTMD            | 289.67                      | 111.6%           |

5.2.2. Diffusion coefficients
Figure 11 shows the diffusion coefficients of four type lubricants in air. It can be seen that the diffusion coefficient of ZTMD molecular is the largest, which indicates that the diffusion coefficient is related to the hydroxyl group and molecular structure.
6. Summary
In the present study, the lubricant transfer volume expression with respect to lubricant molecular weight is described, and modeled by using the models including Tri-pad positive pressure slider and flat slider. The PFPE lubricant transfer behaviors in HDD are simulated by using four type unite cells composed of lubricant molecules and air molecules based on molecular dynamics theory. The influencing factors related to the PFPE lubricant transfer behaviors at the head/disk interface are analyzed. These results are to be beneficial to the study of dynamic behavior of head/disk interface.

7. References
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