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ORIGINAL PAPER

Air Entrapment in Nanometer-Thick Lubricant Films and its Effect on Slider Flying Height in a Hard Disk Drive

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Abstract Experimental data are presented, showing that the flying height of a slider in a hard disk drive can be altered by the chemical nature of the molecularly-thin lubricant film on the disk surface. It is suggested that this effect is likely due to entrapment of the air molecules, both nitrogen and oxygen, within the lubricant film, which results in pressurization loss within the air bearing gap, and lower slider flying height. For the two advanced multidentate lubricants reported in this study, the amount of flying height change is almost insignificant for one of them, but amount to about 0.7 nm, i.e. a significant fraction of the magnetic spacing budget for the other. Bulk air solubility data suggest that the magnitude of this effect is diminished for lubricant molecules with a lower density of backbone ether linkages.

Keywords Head-disk interface · Flying height · Lubrication

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1 Introduction

Now that the head-medium spacing (HMS) in commercial disk drives has crossed the 10 nm milestone [1], it is important to identify and account for every Angstrom of the spacing budget [2]. This includes thickness of the overcoat (disk and slider) and the disk lubricant, disk touch-down height (TDH), and slider-disk clearance. In today's drives, clearance is controlled using thermal flying height control (TFC) [3]: electrical power is progressively injected into a resistive heater, allowing the trailing end portion of the slider to protrude and to come into contact with the disk. After contact is detected, power is lowered until a desired clearance value is achieved. A power-height calibration is usually obtained using the Wallace readback method [4]. It is customary to use this touch-down method to also quantify disk touch-down height differences: a given slider is used on different disks, and allowed to touch-down. Assuming that the slider flying height (FH) is the same over the disks being measured, differences in touch-down power, once converted into height, is a direct estimation of the touch-down height. This method has been used, for instance, to quantify the effect of lubricant on disk TDH [5].

Recently, it has been shown that humidity can affect slider FH [6–8], presumably because of condensation of water vapor at the head-disk gap and subsequent pressure drop [9, 10]. In this paper, experimental data will be shown, demonstrating that the disk lubricant can also affect slider FH significantly. A model will be presented suggesting that air entrapment (both oxygen and nitrogen) within the lubricant film can account for a significant pressure and FH drop. Furthermore, this effect is dependent on the type and possibly the thickness of the lubricant film being used. Bulk air solubility data will be shown that are consistent with this hypothesis.

2 Results and Discussion

Two recently described multidentate lubricant structures, ZTMD [5] and 24TMD [11], both approximately 1 nm thick, are studied in this paper. In addition, air solubility data was also obtained for Zdol and Ztetraol, two members of the perfluoropolyether Fomblin lubricant family [12], as well as their non-functional counterpart Z. Structures of these lubricants are reproduced on Fig. 1 (structure for Z and Zdol are not shown, as their backbone is the same as Ztetraol, their difference being in the number of terminal hydroxyl groups, see later in the text). In an earlier paper, we showed that the mechanical clearance of a slider flying on 24TMD lubricated disks was ca. 0.70 nm higher than on ZTMD coated disks [11]. This increase in the observed mechanical clearance can be due to a difference in the disk touchdown height (TDH) or a change in the flying height (FH) of the slider or a combination of the two, as seen on Fig. 2. To further understand this, optical FH measurements were performed using transparent glass disks, coated with both lubricant types, and it was found that in fact, sliders flying on 24TMD-coated disks flew higher than on ZTMD-coated disks by about 0.69 nm (Table 1), suggesting that most if not all of the clearance difference between the two lubricants can be attributable to slider FH changes. These measurements were based on the average FH near

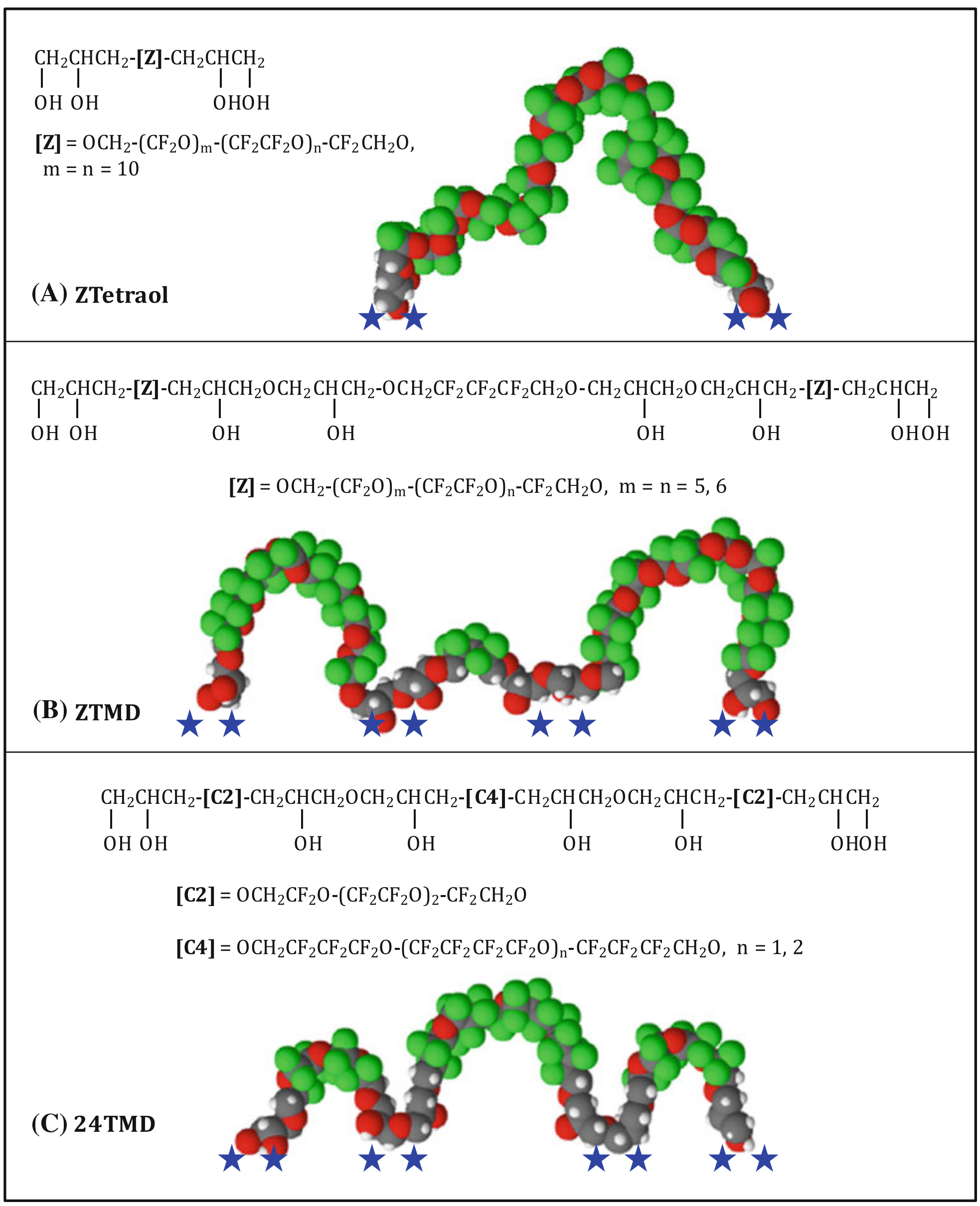

Fig. 1 Molecular structures of Ztetraol (**a**), ZTMD (**b**), and 24TMD (**c**) lubricants. Color code: *green* fluorine, *red*: oxygen, *dark gray*: carbon, *light gray*: hydrogen. Hydroxyl groups provide strong interaction with the disk surface, and they have been highlighted with blue stars

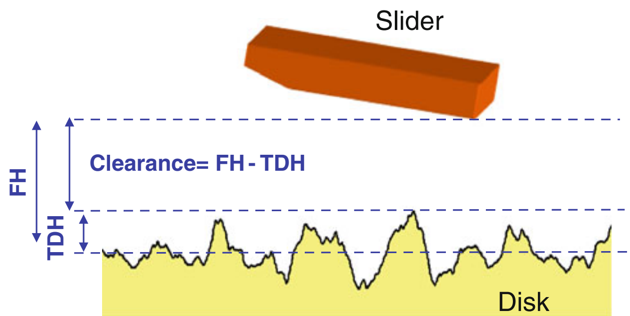

Fig. 2 Schematic of the Slider-disk interface

the trailing edge of sliders from six heads and at three different TFC power levels, for a standard error of 0.05 nm.

To confirm the effect of the two lubricants on flying height, special disks were prepared by dip coating two halves of the same disk with the two lubricants (ZTMD or 24TMD) at the same thicknesses of 1 nm (Fig. 3). Magnetic readback-based spacing measurements were then performed on a given disk track, with the same head flying over both halves of the disk, differing only in lubricant type [13]. The experimental procedure was as follows: A single frequency at 240 MHz was written once on the disk track (divided into 256 sectors) using a Guzik spin-stand. The written signal was then read back (using the same head), and its FFT computed. Spacing changes were then calculated from the magnitude of the readback signal's FFT peak at 240 MHz using the Wallace spacing loss law, which states that in logarithmic scale, the intensity of the read back signal is inversely proportional to the head media spacing [4]. Figure 4 shows the spacing measurement computed over one disk revolution on the two lubricated disk halves. Each data point on the plot (obtained with excellent measurement repeatability of less than 0.1 nm) is the relative spacing measured on that sector after 50 averages. It is apparent that the magnetic spacing (and hence the FH) is ca. 0.66 nm higher on the disk portion coated with 24TMD compared to that with ZTMD from these experiments. It is noteworthy that using this experimental technique, the spacing on the 24TMD area is ca. 1.43 nm higher than on the small unlubricated portions

Table 1 Clearance, optical FH, magnetic spacing differences, and bulk air solubility for 24TMD and ZTMD lubricants

	Delta clearance (nm) from ref [11]	Delta optical FH (nm)	Delta magnetic spacing (nm)	Corrected delta magnetic spacing (nm)	Bulk air solubility (mL gas/ mL liq.)
24TMD	0.70	0.69	0.66	0.47	0.060
ZTMD	–	–	–	–	0.159

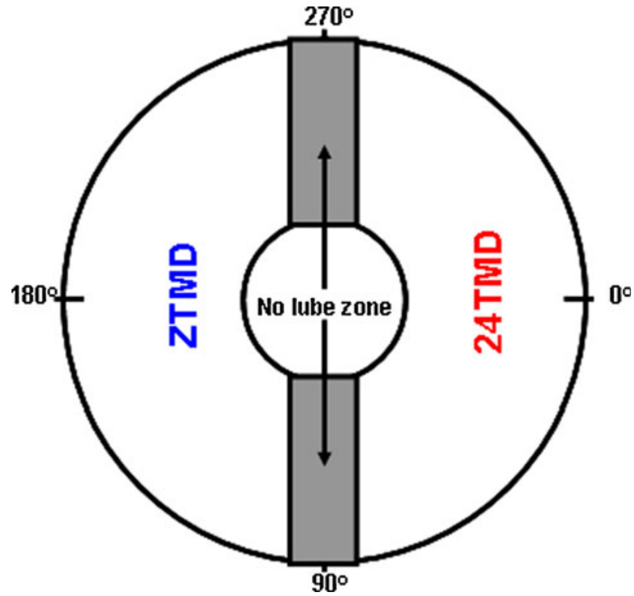

Fig. 3 Schematic of the half-lubricated disk used in the experiments

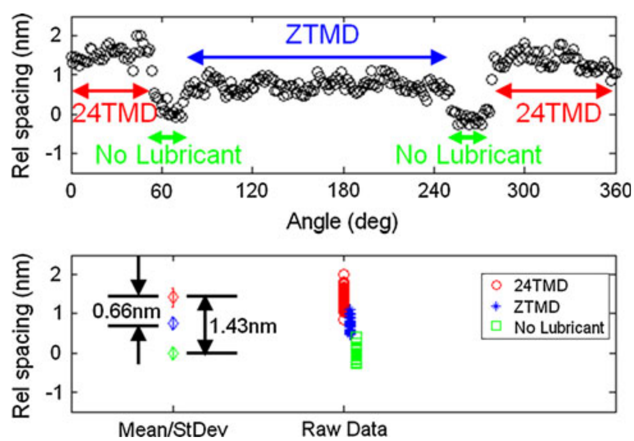

Fig. 4 Relative spacing measured over one disk revolution, showing the effect of the lubricant film type. *Top*: complete waveform. *Bottom*: averages over the three sections

between the two halves. This value is higher than the nominal lubricant thickness of 1 nm, and the main reason for this difference is a subtle artifact of the experimental measurement technique. On the unlubricated sections, the writing as well as reading occur with lower spacing compared to the lubricated section of 24TMD, both of which will result in a stronger read back signal amplitude on the unlubricated disk section, thereby exaggerating/amplifying any spacing differences that exist between the lubricated and unlubricated sections.

A separate experiment clarifies this effect. Tests were conducted to see the sensitivity of the readback signal intensity and the measured spacing change by deliberately changing the spacing between the head and the disk using the TFC power setting during both the read and write processes. For this measurement, a disk coated with 1 nm of ZTMD was used. Figure 5 shows the spacing change against the Read-TFC power, i.e. the track is written at Write-TFC power setting of 75 mW, and read back at different Read-TFC powers. This spacing change (essentially the Wallace spacing loss) illustrates the method, and shows that the readback signal is stronger when the reader is closer to the disk. Similarly, the insert on Fig. 5 shows the 'apparent spacing change' against the Write-TFC power, when the track is written with different Write-TFC powers and read back at a constant Read-TFC power of 75 mW. This 'apparent spacing change' captures the effect of stronger writing when the head is closer to the disk at the higher Write-TFC power. In other words, for the same read-spacing condition, the signal is stronger if the track was written at smaller spacing. Hence, in our experiments, there is a compounded effect of a 'stronger write' and a 'stronger read' in the unlubricated disk section, which exaggerates/amplifies spacing differences between the unlubricated and lubricated disk sections.

We can quantify this effect from these sensitivity plots as follows: for our experiments using half lubricated disks conducted at 50 mW of Read and Write TFC, we can derive sensitivities of $S_R = 0.0953$ nm/mW due to spacing changes during read (slope of the read sensitivity curve for 50 mW of Read TFC power), and $S_W = 0.0378$ nm/mW due to spacing changes during write (slope of the write sensitivity curve for 50 mW of Read TFC power). Assuming that the write spacing effect is additive to the Wallace readback effect, it can be shown that a correction factor equal to $(1 + S_W/S_R)^{-1} = 0.716$ needs to be applied to the spacing differences shown on Fig. 4, leading to a 24TMD-unlubricated spacing difference of 1.02 nm, and a 24TMD-ZTMD difference of 0.47 nm. This corrected

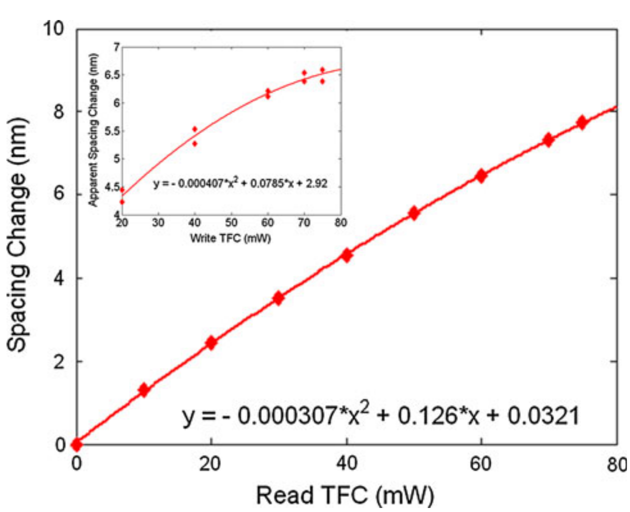

Fig. 5 Sensitivity to spacing during Read. *Inset*: sensitivity to spacing during Write

spacing change between the unlubricated area and the 24TMD-coated zone is now what is expected from the nominal film thickness, and the difference between the 24TMD and ZTMD lubricant is slightly below the one measured by clearance and optical FH measurements shown in Table 1. As discussed earlier however, the clearance difference between the two lubricants could stem from either a lower TDH, higher slider FH, or a combination of the two (Fig. 2). Optical FH data suggested that most of the clearance difference stemmed from FH changes, but the recording data is consistent with a combination of the two, namely 0.47 nm in FH change and the remainder, or 0.23 nm, in TDH difference. The lower molecular roughness, or higher confinement, of 24TMD [5] could in fact lead to a 0.1–0.2 nm improvement in disk TDH, which would be consistent with the recording data. At this juncture, the accuracy of our experimental technique does not allow a more accurate quantification of the relative contribution of these two effects. It is clear, however, that these recording data confirm that lubricant type has a significant impact on the slider's FH, and that ZTMD lubricant leads to a lower FH than 24TMD.

The fact that lubricant type can affect the slider FH could originate from electrostatic or Van der Waals forces acting on the slider which could change according to the molecular nature of the lubricant film. Given the nominal FH for this type of slider (ca. 10 nm), Van der Waals effects seem highly unlikely [14, 15]. As far as electrostatic pressure is concerned, it is well established that contact potentials that develop between the slider and the disk can cause small fly-height changes [16]. However, the differences between the two lubricated halves have been measured, and they amount to significantly less than 0.25 V, resulting in possible fly-height changes in the 0–0.2 nm range only. Hence electrostatic forces by themselves cannot fully account for the spacing changes observed in our experiments, although they could admittedly account for a small part of it.

A more plausible reason is that some of the air molecule (i.e. oxygen and nitrogen) in the slider air bearing gap could somehow be entrapped in the lubricant film, therefore reducing air bearing pressure and lowering FH. As pointed out earlier, a similar effect with humidity has in fact already been reported and modeled [6, 7, 9, 10], although in that particular case, FH changes were attributed to condensation of water at the slider and disk surface, and not entrapment of air molecules within the lubricant film as in this present description.

In order to find out whether the different amount of air may be trapped in different types of lubricant films on the disk under the flying slider, air solubility under standard conditions (20 °C and 1 atmosphere) was measured for these lubricants in their bulk state. Air solubility was measured with an apparatus constructed with some modifications based on earlier work by Schaffer and Haller [17]. Briefly, a reaction flask of 100 mL was connected to house vacuum through a valve and also to a gas burette with a leveling bottle and a differential manometer containing low vapor pressure oil and to open air through a three-way valve. The flask, with a magnetic stirring bar inside, was immersed in a water bath sitting on top of a hotplate stirrer. The procedure for measuring air solubility in a bulk lubricant is as follows: (1) Measure precise volume of lubricant inside the flask with a scale cylinder accurate to 0.1 mL; (2) Heat lubricant to 90 °C under vacuum while stirring for 4 h to remove all dissolved gases; (3) Cool down to 20 °C under vacuum while stirring for 1 h; (4) Record initial volume on the gas burette; (5) Stop stirring and turn the three-way valve to let atmospheric air in for half a second (during which air adsorption on the surface of lubricant is negligible) and then to the burette; (6) Start stirring and keep adjusting leveling bottle to keep atmospheric pressure in the burette; (7) Record burette volume from time to time till its value stabilizes; (8) If bubbles form on lubricant surface, stop stirring and let bubbles burst, and record final volume. The difference between the final and initial volume in the burette, divided by the lubricant volume, is the air solubility in the unit of mL gas/mL liquid. The lubricant volume increase is negligible with dissolved air. A typical air uptake curve is shown on Fig. 6. Three measurements were carried out for each type of lubricant, and average values are listed in Table 1. Air solubility in bulk 24TMD is in fact only about a third of that ZTMD, and this is qualitatively consistent with the clearance and FH data shown earlier: assuming that solubility in the lubricant film scales with that of the bulk liquid (point discussed later in this paper) there would be less air entrapped in the 24TMD film, leading to higher air pressure at the slider-disk interface, and higher flying height than on ZTMD coated disks.

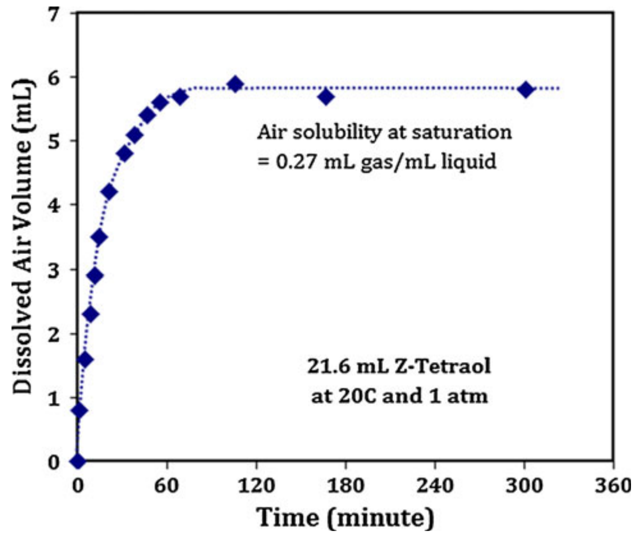

Fig. 6 Kinetics of air uptake in Ztetraol lubricant

The difference in air solubility between 24TMD and ZTMD may ultimately be attributable to the difference in their molecular structures. There are a number of such differences, such as the number of hydroxyl functional groups, molecular weight, and the number of ether segments in the backbones. In order to determine which particular structural characteristic affect air solubility most significantly, additional measurements were performed using several commercial perfluoropolyether (PFPE) lubricants: Fomblin Z, Zdol, and Ztetraol. Figure 7(a) shows air solubility as a function of the number of OH end groups for Z (no OH), Zdol (2 OH's), and Ztetraol (4 OH's) while their molecular weights (2,000 Dalton) and backbone structures are the same. Clearly, the number of OH groups does not affect air solubility. Figure 7(b) shows air solubility as a function of molecular weight for Zdol at 1000, 2000, and 4000 Daltons. Only a very slight increase is observed in air solubility with increasing molecular weight. However, the most significant effect is exhibited by the ratio of the number of ethers group over backbone molecular weight, as determined with fluorine-NMR analysis [18], as shown in Fig. 7(c). The observation is consistent with published data showing that the solubility of oxygen in ethers is twice the one in alcohols [19], presumably originating from its affinity to the electron lone pair in the ether linkage.

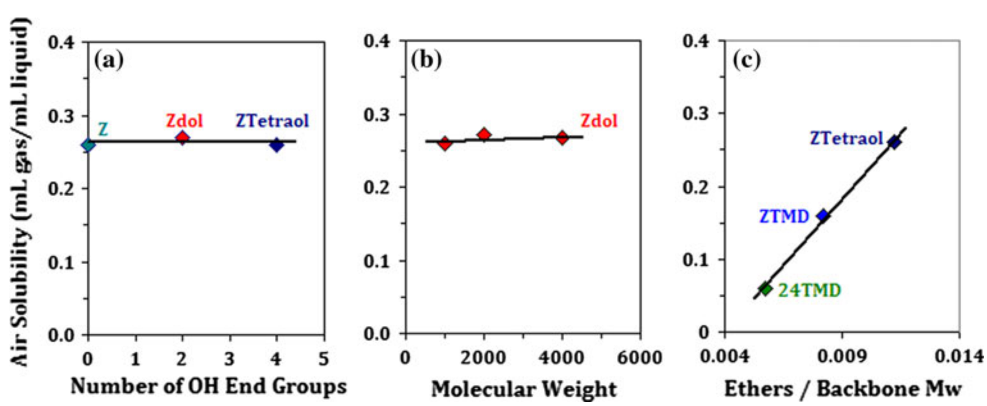

Fig. 7 Air solubility of various disk lubricant versus molecular characteristics

Since air solubility appears to be a property governed by the molecular structure of the lubricant and the density of ether moieties in the backbone, one would expect this difference to also apply to the thin film case. Accordingly, the difference in air solubility measured in bulk ZTMD and 24TMD may, at least qualitatively, scale with the thin film case. As far as the time scale of the effect is concerned, one cannot simply use the uptake data from Fig. 6, since stirring of the solution was used, making the extraction of the diffusion coefficient impossible. Literature data from Tham et al. [20], on the other hand, have shown that the diffusion coefficients of O_2 and N_2 in fluorinated ethers are about twice as large as those in water [20], with a value of $D = 4 \times 10^{-5}$ cm^2/s. From this, it is estimated that it would take a time t roughly equal to $t = d^2/2D = 125$ ps for air molecules to equilibrate into the $d = 1$ nm thick lubricant film. This characteristic diffusion time is therefore almost instantaneous at the scale of relevance to the head/disk interface, which implies that the air entrapment in the lubricant film under the flying slider is at near-equilibrium. It is also important to point out that the lubricant film, outside of the slider area, is also equilibrated with one atmosphere of ambient air. However, solubility is expected to scale with pressure through Henry's law, and it is therefore expected that entrapment within the air bearing area, where pressure is as high as 40 atmospheres for this particular slider, will be far greater than outside of it. Molecular dynamics simulations, not discussed in this paper, have in fact confirmed the different entrapment amount for the two lubricants, and also the short time scale of the process.

Finally, it is important to point out that the mechanism suggested in this paper implies that for a given lubricant structure, different thickness levels would lead to different entrapment and therefore different flying height. This thickness effect would be stronger in the case of lubricant with higher entrapment probability, such as ZTMD. Experimental verification of these predictions would lend further credence to the present hypothesis. Also, the fact that the spacing difference (after correction for write spacing effect) between the unlubricated and the 24TMD zones is very close to the nominal thickness of the 24TMD film leads us to conclude that little air entrapment occurs for this lubricant type, although bulk solubility was not completely negligible. It is possible, therefore, that second order surface effects are taking place. In fact, the strong molecular confinement observed for the 24TMD structure [11] is likely to reduce access for the air molecules to the lubricant molecule ether sites.

3 Summary

We have shown experimental data that demonstrate that the steady state flying height of a slider in a hard disk drive is affected by the chemical nature of the lubricant film on the disk surface. It is suggested that a partial air entrapment in the lubricant film of the disk and subsequent decrease of the air bearing pressure is responsible for this effect, as different lubricant structures have different affinity with oxygen and nitrogen molecules. The strongest interaction sites seem to be the ether linkages along the lubricant backbone. This entrapment is fast ($\sim$125 ps) compared to the residence time of the slider over a given disk area ($\sim$µs). In addition to chemical affinity, our data offers a hint that a denser, more confined surface lubricant structure such as 24TMD films would exhibits an even lower degree of entrapment from what would be derived from the bulk solubility alone. For today's lubricant systems, the magnitude of this effect can be as high as 0.5–1 nm, which is a significant fraction of the head-medium spacing budget. Finally, it is expected that lubricant film thickness would also affect slider flying height, especially for lubricants with high air entrapment probability, as thicker films would lead to a higher degree of pressure loss.

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