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Thermal Flying-Height Control Sliders in Hard Disk Drives Filled with Air-Helium Gas Mixtures

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Abstract

Thermal flying-height control (TFC) sliders in hard disk drives (HDDs) filled with air-helium gas mixtures are expected to be able to balance the increase in production cost and the improvement in the HDDs' performance, such as better reliability and larger capacity, and they are currently being investigated for future commercial HDDs. This report employs established approaches to calculate the physical properties of the air-helium gas mixtures and investigates the TFC slider's flying performance in these environments. It is found that at a fixed heater power the slider's flying height first increases and then decreases with the fraction of helium in the gas mixture due to the combined effects of changes in the mean free path, viscosity and thermal conductivity of the gas mixture with helium content. These findings together with the proposed approach are useful for future designs of sliders in air-helium mixtures.

I. INTRODUCTION

To compete with other storage devices such as flash memory, hard disk drives (HDDs), which have served as the dominant storage device for several decades, need to have lower operational cost, better reliability and larger capacity. A key to the first goal is reducing the power consumption of HDDs during operation. The HDDs' power cost is becoming a bigger issue especially for data centers where a large number of HDDs are stored in a limited space, and this issue could be a barrier for HDDs to continue serving as a major storage device in the future [1] [2] [3]. The reliability issues faced by HDDs include the disks' corrosion and track mis-registration due to air-turbulence that introduces unpredictable vibration of the read-write head. Replacing current state-of-the-art HDDs by HDDs filled with the inert gas Helium promises to resolve most, if not all, of the above issues. Helium's low density and high conductivity requires less power to spin the disks and results in lower temperatures inside the HDDs, leading to less corrosion of the disks. Using helium also suppresses flow turbulence, resulting in less unpredictable vibration of the head, less track mis-registration and better reliability [4]. The inert property of helium further helps to protect the disk from corrosion. However, filling HDDs with pure helium increases production cost, and so air-helium gas mixtures are currently being investigated as a candidate to balance performance and cost.

Among the different requirements for increasing the HDDs' capacity, reducing the distance between the read-write transducer and the magnetic disk is an important one. The read-write transducer is embedded in a slider positioned over the rotating disk with a linear speed around 10m/s. By dragging gas into the region between the slider and the disk, known as the head-disk interface (HDI), the moving disk creates a flying height of the slider by the gas generated pressure on the slider's surface facing the disk, known as the air bearing surface (ABS). State-of-the-art sliders, known as thermal flying-height control (TFC) sliders, have an embedded heating element near the transducer. Supplying power to the heating element induces a temperature increase around the element, leading to the slider's thermo-elastic protrusion near the transducer and thereby produces a smaller spacing between the transducer and the disk. Putting TFC sliders in HDDs filled with an air-helium gas mixture seems to be an effective approach to increase the HDDs' capacity and reliability, to decrease their operational cost and power consumption, and to balance performance with production cost.

The flying performance of TFC sliders in air has been thoroughly investigated. Juang, Chen and Bogy [5], among others, proposed an iterative approach to numerically predict the TFC sliders' flying performance and obtained results agreeing well with experiments [6] [7] [8]. Sliders in pure helium have also been investigated. Aruga et al. [3] found that helium can significantly reduce the gas induced disturbance on the suspension and the read-write transducer's position errors. Zhou et al. [9] numerically investigated TFC sliders' flying performance in pure helium. However, no work has been done for an air-helium gas mixture instead of air or helium. In view of the advantage of combining TFC sliders with HDDs filled with air-helium gas mixtures, we investigate how the mixture affects the TFC sliders' flying performance.

II. NUMERICAL METHOD

The structural complexity of the TFC sliders' heating element and read-write transducer prohibits analytical studies, but the numerical iterative approach has proved effective and efficient for predicting the TFC sliders' flying performance [5] [6] [7] [8]. This approach iterates between two steps: in the first step, the generalized Reynolds equation, which is derived from the linearized Boltzmann equation and applies to the entire HDI [10], is solved, and the pressure on the sliders' ABS together with the slider-disk spacing are obtained. The solution of the generalized Reynolds equation requires the physical properties of the gas, namely, the mean free path, λ, and the viscosity, μ; in the second step, the detailed structure of the sliders' heating element and read-write transducer are modeled and the sliders' thermal protrusion is calculated by the finite element method with heat flux on the ABS as boundary conditions. The latter heat flux q is [5] [11]

$$q = -k \frac{T_s - T_d}{h + 2\frac{2-\sigma_T}{\sigma_T}\frac{2\gamma}{\gamma+1}\frac{1}{\mathrm{Pr}}\lambda} \qquad (1)$$

where k is thermal conductivity of the gas, σ_T is the accommodation coefficient, $\gamma = C_p/C_v$ is the heat capacity ratio of the gas, λ is the local mean free path of the gas, $\mathrm{Pr} = C_p\mu/k$ is the Prandtl number, μ is dynamic viscosity of the gas, T_s is the slider's temperature, T_d is the disk's temperature, h is the slider's local flying height, and C_p and C_v are the heat capacities of the gas at constant pressure and constant volume, respectively. In this report, we use the finite volume method to solve the generalized Reynolds equation and a commercial finite element solver ANSYS to perform the calculation in the second step [12].

Several physical properties of the air-helium mixture are required for the iterative calculation of the TFC sliders' flying performance, namely, the mean free path λ, the viscosity μ, the thermal conductivity k, heat capacity C_p, C_v and density ρ. The last three quantities are extensive ones and their value can be obtained by linear interpolation, for example, $\rho = \alpha\rho_H + (1-\alpha)\rho_A$ where α is fraction of the helium in the gas mixture, and ρ_H and ρ_A are the density of helium and air, respectively. The mean free path λ in the gas mixture is given by [13]

$$\lambda = \frac{\alpha}{\sqrt{2}\pi d_H^2 n\alpha + \pi d_{HA}^2 n(1-\alpha)\sqrt{1+\frac{M_H}{M_A}}} + \frac{1-\alpha}{\sqrt{2}\pi d_A^2 n\alpha + \pi d_{HA}^2 n(1-\alpha)\sqrt{1+\frac{M_A}{M_H}}} \tag{2}$$

where d_H, d_A are the diameters of gas molecule, n is the number density, or the number of molecules per unit volume, $d_{HA} = (d_H + d_A)/2$, M_H, M_A are the molecular weights, and the subscripts H and A refer to the values of helium and air, respectively. The viscosity is calculated by the method of Reichenberg, and the thermal conductivity is calculated by Wassiljewa's formula [14]. The latter two methods require the critical pressure and critical temperature of air and helium. The physical properties of air and pure helium required for the above calculation are listed in Table I and they are taken from Refs. [15] and [16].

III. RESULTS AND DISCUSSION

The change of the TFC sliders' flying performance with the fraction of helium in the gas mixture α is mainly a combined effect of the mean free path λ, viscosity μ and thermal conductivity k. Figure 1 shows the changes of the air-helium mixture's normalized mean free path $\hat{\lambda}$, viscosity $\hat{\mu}$ and thermal conductivity $\hat{k}$ with α, where $\hat{f} = (f - f_A)/(f_H - f_A)$ and f represents λ, μ and k. The mean free path and thermal conductivity, as well as their rates of change, increase with α. The viscosity of the mixture increases at almost a constant rate until α reaches about 0.8, beyond which the viscosity decreases quickly. Generally speaking, an increase in the mean free path leads to a more rarefied gas such that fewer molecules exist in the HDI to provide a bearing lift force; a decrease in the viscosity leads to lower pressure gradient and lower bearing load capacity; an increase in thermal conductivity leads to increasing cooling on the ABS. All of the above effects lead to the decrease of

Physical Properties	Air	Helium
molecular diameter (nm)	0.366	0.215
molecular weight M (g/mol)	28.966	4.003
Density ρ (kg/m^3)	1.164	0.160
viscosity μ (μPoise)	186	200
heat conductivity k (W/(m $\cdot$ K))	0.0262	0.1567
heat capacity C_p (J/(mol $\cdot$ K))	29.15	20.786
heat capacity C_v (J/(mol $\cdot$ K))	20.80	12.522
critical temperature T_c (K)	132.53	5.19
critical pressure P_c (bar)	37.86	2.27

TABLE I: Physical properties of air and helium. All the values, except the critical temperature and critical pressure, are for the temperature 300K. Note that 1Poise = 0.1Ns/m^2 and 1bar = 10^{5}Pa

TFC sliders' flying height (FH) [12] [17]. In the following studies, an industry-designed femto-sized (0.85mm×0.70mm×0.30mm) TFC slider is used.

Figure 2 shows the read-write transducer's flying height (FH) as a function of the fraction of helium in the gas mixture α when the heating element is turned off. Without any power supply, the slider's flying height is determined by λ and μ. When α is very small, the increases in λ and μ with α lead to opposite effects on the slider's flying height, and these two effects partially offset each other, resulting in a negligible overall effect on the slider's flying height. As α increases, the mean free path increases faster than the viscosity, leading to a decrease in the slider's flying height. When α is greater than 0.8, the viscosity decreases, which, combined with the increase in the mean free path, results in an abrupt decrease in the slider's flying height.

When power is applied to the heating element, the slider's deformation due to the gas pressure on the ABS is negligible, and the heat dissipation on the ABS due to the gas flow in the HDI dominates the change of the slider's deformation with the fraction of helium α. For gases, the Prandtl number and the heat capacity ratio are both on the order of 1, and the thermal accommodation coefficient is also close to 1. So the heat flux can be estimated

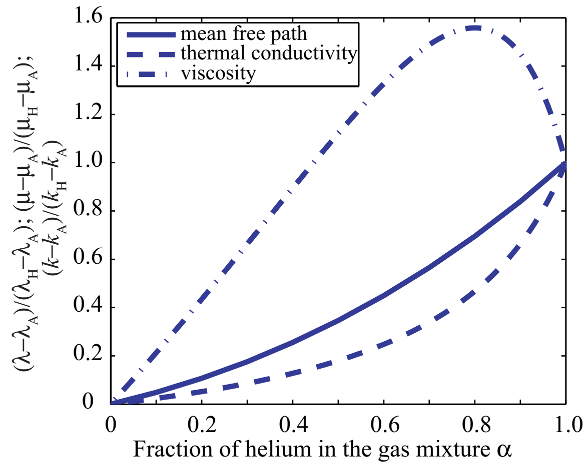

FIG. 1: The normalized mean free path $\hat{\lambda}$, viscosity $\hat{\mu}$ and thermal conductivity $\hat{k}$ of the air-helium gas mixture as functions of the fraction of helium in the mixture α, where$\hat{f} = (f - f_A)/(f_H - f_A)$ and f represents λ, μ and k. This normalization ensures that $\hat{f} = 0$ when $\alpha = 0$ and $\hat{f} = 1$ when $\alpha = 1.0$, so that the rates of change for each quantity can also be compared. The subscripts H and A refer to the corresponding values of helium and air.

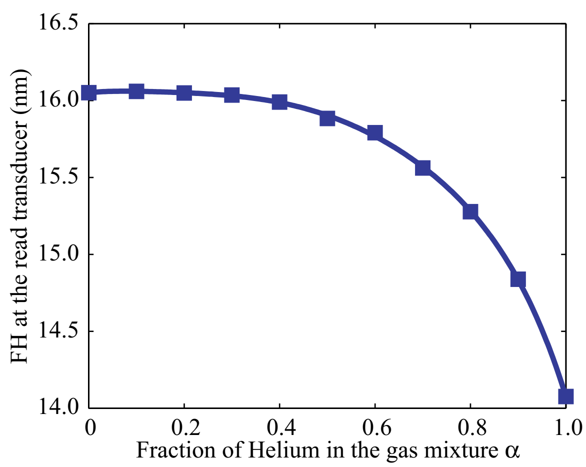

FIG. 2: The transducer's flying height (FH) as a function of the fraction of helium in the gas mixture when the heating element is turned off.

by

$$q = -k\frac{T_s - T_d}{h + C\lambda} \tag{3}$$

where C is on the order of 1. As seen from the numerical results, the heat dissipation is only significant near the read-write transducer [12], where the local mean free path λ, which is inversely proportional to the local pressure, is on the order of the local flying height h. As α increases from 0 to 1.0, the thermal conductivity k changes by 500%, which is much larger than the corresponding change of h, leading to the dominance of the heat conductivity in the change of the heat flux q with α. As the thermal conductivity increases with α, more heat is dissipated from the ABS at a given heater power and the maximum temperature rise on the ABS decreases, which results in the slider's protrusion decreasing with α, further leading to the slider's FH loss decreasing with α, as shown in Fig. 3. The FH loss is defined as the difference between the slider's flying height without heater power and that when the heating element is turned on.

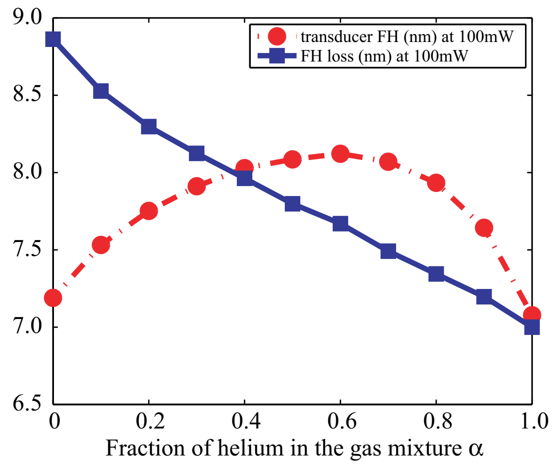

FIG. 3: Transducer's flying height (FH) and corresponding FH loss at different fractions of helium in the mixture.

The slider's flying height with heating on, $h_{w/}$, is the difference between the slider's flying height with no heater power, $h_{w/o}$, as shown in Fig. 2, and the FH loss, h_{loss}, i.e. $h_{w/} = h_{w/o} - h_{loss}$, and $h_{w/}$ is due to the combined effects of the mean free path λ, viscosity μ and thermal conductivity k. When the fraction of helium α is very small, the effect of λ and μ balance each other such that $h_{w/o}$ remains constant, as shown in Fig. 2, while the increase in the thermal conductivity reduces h_{loss}, resulting in the initial rise of $h_w/$ with α, as shown in Fig. 3. As α increases, the mean free path starts dominating and $h_{w/o}$ decreases, leading to the decrease of the rate of change of $h_{w/}$ and the final decrease of $h_{w/}$ when α is greater than 0.6. As α increases further, the mean free path increases and the viscosity starts decreasing, both of which contribute to the decrease of $h_{w/o}$, resulting in the rapid decrease in $h_{w/}$, as seen in Fig. 3.

IV. CONCLUSION

The TFC sliders' flying performance in hard disk drives filled with air-helium gas mixtures is investigated in this report. Due to the combined effects of the gas mean free path, viscosity and heat conductivity, the slider's flying height depends nonlinearly on the fraction of helium in the gas mixture α for a given heater power. The thermal conductivity dominates when α is small, resulting in an increase in the slider's flying height. As α increases, the mean free path effect starts dominating, resulting in a decrease of the slider's flying height for a high α. These findings shed light on the slider's flying performance in HDDs filled with air-helium gas mixtures, and are useful in future design of sliders for such disk drives.

Acknowledgments

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