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Thermal Flying-Height Control Sliders Fly in Air-Helium Gas Mixtures

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Abstract

Filling hard disk drives with air-helium gas mixtures instead of pure helium can balance performance improvement, such as reduced power cost, increased capacity and improved reliability, against cost increase. A consistent approach is proposed here to investigate the flying performance of thermal flying height control sliders flying in gas mixtures. It is found that the smallest power required for a designated flying height appears when the gas mixture is composed of about half helium and half air. The proposed numerical approach can also find application in investigating a slider's flying performance in a humid environment.

I. INTRODUCTION

In state-of-the-art hard disk drives (HDDs), information data are stored on magnetic disks; they are read from and written onto the disk by a read-write transducer embedded in a thermal flying-height control (TFC) slider flying over the moving disk, as shown in Fig. 1 [1, 2]. The distance between the transducer and the disk is closely related to the HDDs' capacity since closer spaced and smaller data bits require lower spacing of the read-write transducer to resolve them. So the distance is required by the data density, and this specified distance is realized through the design process by choosing a specific pattern on the slider's surface facing the disk. This air bearing surface (ABS) compresses the gas dragged by the moving disk into the region between the slider and the disk, known as the head disk interface (HDI). Reducing this distance used to require a re-design of the slider's ABS. To simplify this task and also to make the HDI more reliable, the TFC sliders were introduced. Different from their traditional counterparts, TFC sliders have a heater element embedded near the transducer. During the HDDs' operation, power is applied to the heater element, which induces a nonuniform temperature field near the transducer and, due to thermomechanical coupling, causes the slider's local protrusion near the transducer. This approach effectively reduces the distance between the transducer and the disk without the heavy burden of redesigning the slider's ABS [2].

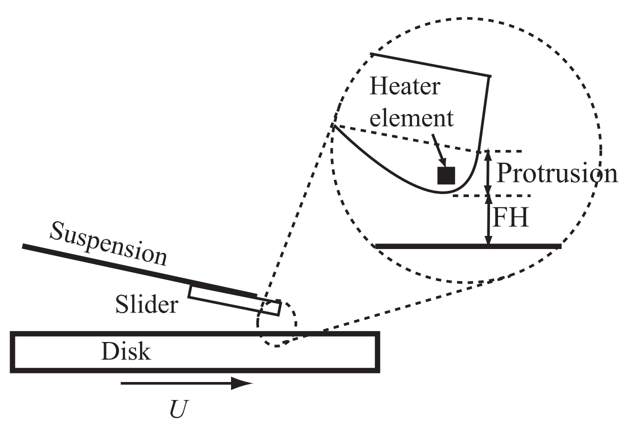

FIG. 1: Sketch of a protruded thermal flying height control slider flying over a moving disk at a linear speed U. The read-write transducer is located near the heater element and is not shown in the figure.

Most modern HDDs are not sealed and the entire HDD is filled with air at ambient pressure, which relates to several issues concerning the HDDs' reliability [3–5]. Compared to some other gases such as hydrogen and helium, air has a higher density and lower thermal conductivity. Since power required to operate the HDD increases with the gas density, more power is required to operate HDDs in air. Higher gas density also results in a larger Reynolds number, defined as Re= $Ul\rho/\mu$ where l is a characteristic length in the HDD, ρ is the density of the gas, U is the disk's linear speed, and μ is dynamic viscosity of the gas. The higher Reynolds number is associated with the occurrence of turbulence in state-of-the-art HDDs causing the slider's nonrepeatable vibration. Air's low thermal conductivity corresponds to its low capacity to dissipate the heat generated in the HDD during operation, leading to a higher operating temperature, which increases the disk's tendency to corrode. Among all the gases, helium has the smallest density except for hydrogen and its thermal conductivity is one order of magnitude lower than that of air. Given its inert property and desirable safety considerations, helium becomes a good candidate use in the HDDs. However, making a sealed HDD with helium is more costly, so to balance performance improvement and cost increase, filling the HDDs with air-helium gas mixtures may be a more effective approach.

Several investigations have been concerned with TFC sliders in air. Due to the complex structure of the heater element and transducer, an iterative numerical approach, first proposed by Juang *et al.* [6] and Juang and Bogy [7], has become the *de facto* method for calculating a TFC slider's flying performance, and it serves as the basis for designing TFC sliders in the HDD industry. Juang *et al.* [8] later improved the original approach by including the slider's deformation induced by the air pressure on the slider's ABS. Their numerical results compared well with experiments [8]. Using this approach, Zhang *et al.* [9] studied the dependence of a TFC slider's performance on its ABS design and found several general criteria that increase the TFC slider's thermal actuation efficiency, while Li *et al.*[10] investigated the optimization of the heater design and proposed several guidelines.

Investigations on non-TFC sliders in helium can be traced back to the 1980s when prototyped HDDs filled with helium were reported [4]. Most of the advantages obtained from filling HDDs with helium and mentioned above have been confirmed experimentally. Sato *et al.* [5] experimentally observed that helium significantly reduces the operational power and maximum temperature in HDDs. Aruga *et al.* [4] found that helium significantly suppresses the turbulence in HDDs thereby reducing the slider's nonrepeatable vibrations. With the recent technical advances in filling HDDs with different gases, the uses of helium and air-helium gas mixtures are becoming more feasible [11, 12]. However, compared with helium, much less is known about a TFC slider's flying performance in air-helium gas mixtures. This issue is addressed in this paper, and a general approach for investigating a TFC slider's flying performance in a gas mixture is discussed.

This paper is organized as follows. In Sec. II, the numerical approaches used to calculate the TFC sliders' flying performance, together with the related background theories, are discussed. In Sec. III, established approaches for calculating the physical properties of gas mixtures are discussed and compared with experiments. Numerical results are presented and discussed in Sec. IV. A summary and conclusion is given in Sec. V.

II. NUMERICAL APPROACH

The iterative approach originally proposed by Juang *et al.* [6] iterates between two steps: in one step, the finite volume method is used to solve the generalized Reynolds equation for the slider's flying attitude, the air flow field and pressure distribution in the HDI for a given slider's geometry [13]; in the other step, the finite element method (FEM) implemented in a commercial FEM solver is used to solve for the slider's deformation for a given power applied to the heater element with previously obtained gas pressure and heat flux on the ABS being boundary conditions.

The gap spacing in the HDI changes from several nanometers to several micrometers over the entire ABS, and the mean free path of a gas is usually in the middle of this range, so the gas in the HDI is locally rarefied in certain regions. An indication of gas rarefaction is the Knudsen number, defined as Kn$= \lambda/h$ where λ is the mean free path of the gas and h is local gap spacing, and, it is widely accepted that the continuum theory only applies for Kn$\ll 1$ [14]. For air, λ is about 65 nm at ambient condition, and the Knudsen number in the HDI is then at least on the order of 1 after considering that the local mean free path is inversely proportional to the local pressure. Thus continuum theory is not appropriate to describe the flow in the HDI; kinetic theory is needed. To address this problem the generalized Reynolds equation was derived from the Boltzmann equation under the assumption that the gap spacing is much smaller than the slider's length L and its width b [15]. This assumption holds for state-of-the-art sliders for which h is no larger than several micrometers while L and b are on the order of one millimeter. For gas flow in the HDI at steady state, the generalized Reynolds equation is

$$\frac{\partial}{\partial X}\left(Q_P P H^3 \frac{\partial P}{\partial X} - \Lambda_X P H\right) + \frac{\partial}{\partial Y}\left(Q_p P H^3 \frac{\partial P}{\partial Y} - \Lambda_Y P H\right) = 0 \tag{1}$$

where $X = x/L, Y = y/L$ are dimensionless distances along the slider's length and width directions, $P = p/p_0$ is the dimensionless pressure, p_0 is the ambient pressure, $H = h/h_m$ is the dimensionless gap spacing, and h_m is the gap spacing at a reference location. This equation involves three parameters, namely, the bearing numbers $\Lambda_X = 6\mu U_X L/p_0 h_m^2$ and $\Lambda_Y = 6\mu U_Y L/p_0 h_m^2$, where U_X and U_Y are the disk's linear speeds along the slider's length and width directions, and the mass flow rate in Poiseuille flow Q_P which is a function of the local Knudsen number. Thus two physical properties of the gas are required for solving Eq. (1), namely, the viscosity μ and the mean free path λ.

The heat flux on the ABS has been shown to be dominated by the heat conduction between the slider and the disk at different temperatures, which can be calculated to sufficient accuracy by [16, 17].

$$q = -k \frac{T_s - T_d}{h + \frac{2-\sigma}{\sigma}\frac{4\gamma}{\gamma+1}\frac{1}{\mathrm{Pr}}\lambda} \tag{2}$$

where k is the thermal conductivity of the gas, σ is the accommodation coefficient of the slider's ABS, $\gamma = C_p/C_v$ is the heat capacity ratio, C_p and C_v are heat capacities at constant pressure and constant volume, $\mathrm{Pr} = \mu C_p/k$ is the Prandtl number, and T_s and T_d are the temperatures of the slider and the disk, respectively. The physical properties involved in Eq. (2), in addition to the mean free path and viscosity, include the thermal conductivity and heat capacities, which can be divided into two categories: the intrinsic ones including the mean free path, the viscosity and the thermal conductivity; and the extrinsic ones including the heat capacities. In the next section, we discuss how to obtain these properties for gas mixtures.

III. PHYSICAL PROPERTIES OF GAS MIXTURES

The values of the extrinsic quantities for gas mixtures can be obtained from linear interpolation. For example, the heat capacity C_p of an air-helium gas mixture is $C_{pm} = \alpha C_{pH} + (1-\alpha) C_{pA}$ where α is the fraction of helium, and the subscripts H and A refer to the values for helium and air, respectively.

The intrinsic properties of the gas mixture can not be obtained simply from linear interpolation. Instead, we need to treat them separately. The mean free path of gas mixtures can be calculated from the following equation, which is derived theoretically from kinetic theory [14]

$$\begin{aligned}\lambda_m = & \frac{\alpha}{\sqrt{2}\pi d_H^2 n\alpha + \pi d_{HA}^2 n(1-\alpha)\sqrt{1+\frac{M_H}{M_A}}} \\ & + \frac{1-\alpha}{\sqrt{2}\pi d_A^2 n\alpha + \pi d_{HA}^2 n(1-\alpha)\sqrt{1+\frac{M_A}{M_H}}}\end{aligned} \tag{3}$$

where n is the number of molecules per unit volume, d is the molecular diameter, M is the molecular weight, the subscripts H and A refer to the corresponding values for helium and air, and $d_{HA} = (d_H + d_A)/2$.

The viscosity of the gas mixture can be obtained from the Reichenberg's method [18]

$$\mu_m = K_H(1 + H_{HA}^2 K_A^2) + K_A(1 + 2H_{HA}K_H + H_{HA}^2 K_H^2) \tag{4}$$

with

$$\begin{aligned}K_H &= \frac{\alpha\mu_H}{\alpha + (1-\alpha)\mu_H H_{HA}[3 + (2M_A/M_H)]} \\ K_A &= \frac{(1-\alpha)\mu_A}{(1-\alpha) + \alpha\mu_A H_{HA}[3 + (2M_H/M_A)]} \\ H_{HA} &= \frac{\sqrt{M_H M_A/32}}{(M_H + M_A)^{1.5}} Z_{HA} \left(\frac{M_H^{0.25}}{\sqrt{\mu_H Z_H}} + \frac{M_A^{0.25}}{\sqrt{\mu_A Z_A}}\right)^2 \\ Z_H &= \frac{[1 + 0.36T_{rH}(T_{rH} - 1)]^{1/6}}{\sqrt{T_{rH}}} \\ Z_A &= \frac{[1 + 0.36T_{rA}(T_{rA} - 1)]^{1/6}}{\sqrt{T_{rA}}} \\ Z_{HA} &= \frac{[1 + 0.36T_{rHA}(T_{rHA} - 1)]^{1/6}}{\sqrt{T_{rHA}}}\end{aligned}$$

where $T_{rH} = T/T_{cH}$, $T_{rA} = T/T_{cA}$, $T_{rHA} = T/\sqrt{T_{cA}T_{cH}}$, T is the gas temperature, and T_{cH} and T_{cA} are critical temperatures of helium and air, respectively.

The thermal conductivity of the gas mixture is obtained from the Wassiljewa equation [18].

$$k_m = \frac{\alpha k_H}{\alpha + (1-\alpha)A_{HA}} + \frac{(1-\alpha)k_A}{(1-\alpha) + \alpha A_{AH}} \tag{5}$$

with

$$A_{ij} = \frac{[1+\sqrt{k_{ij}}(M_i/M_j)^{0.25}]^2}{\sqrt{8[1+(M_i/M_j)]}}$$
$$k_{ij} = \frac{[\exp(0.04664T_{ri}) - \exp(-0.2412T_{ri})]\Gamma_j}{[\exp(0.04664T_{rj}) - \exp(-0.2412T_{rj})]\Gamma_i}$$

where $\Gamma_i = 210(T_{ci}M_i^3/P_{ci}^4)^{1/6}$, P_c is the critical pressure, and i and j can be either H or A. We note that the units used to calculate Γ_i are not all standard. Although the critical temperature T_{ci} is in Kelvin, the molecular weight M_i is in g/mol and the critical pressure P_{ci} is in bar.

Table I shows all of the relevant physical properties for different fractions of helium in the gas mixture as calculated from Eqs. (2), (3) and (4). The parameters required in this calculation are [19, 20]: d_H=0.366nm, d_A=0.215nm, M_H=28.966g/mol, M_A=4.003g/mol, T_{cH}=132.53K, T_{cA}=5.19K, P_{cH}=37.86bar and P_{cA}=2.27bar. As shown in Fig. 2, the mean free path of the gas mixture increases by 200% as the fraction of helium in the gas mixture α increases from 0 to 1, and the thermal conductivity of the gas mixture increases by 700%. This large increase underlies helium's ability to quickly dissipate heat generated in HDDs. The rates of change of the mean free path and the thermal conductivity also increase with α.

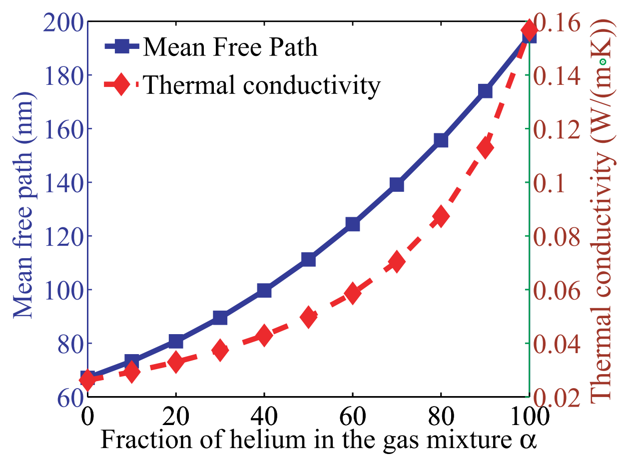

FIG. 2: Changes of the mean free path and thermal conductivity of air-helium gas mixtures with the fraction of helium in the mixture.

The viscosity of the air-helium gas mixture changes differently from the mean free path and the thermal conductivity. As shown in Fig. 3 and Table I, the viscosity increases until

TABLE I: Physical properties of air-helium gas mixtures.

α	λ_m (nm)	μ_m (μN·s/m^2)	k_m (W/(m·K))	C_{pm} (KJ/(kg·K))	C_{vm} (KJ/(kg·K))
0	67.10	18.60	0.0262	1.0064	0.7181
0.1	73.27	18.90	0.0293	1.4250	0.9591
0.2	80.72	19.21	0.033	1.8436	1.2001
0.3	89.50	19.53	0.0374	2.2622	1.4411
0.4	99.65	19.85	0.0429	2.6809	1.6821
0.5	111.25	20.17	0.0497	3.0995	1.9231
0.6	124.38	20.46	0.0586	3.5181	2.1641
0.7	139.13	20.68	0.0704	3.9367	2.4051
0.8	155.63	20.78	0.0873	4.3554	2.6461
0.9	174.02	20.63	0.1129	4.7740	2.8871
1	194.46	20.00	0.1567	5.1926	3.1282

α reaches about 0.7 after which it decreases. The results from Eq. (4) compare well with experimental results, which are excerpted from Ref. 21, with relative error less than 5% as shown in Fig. 3. We also note that the maximum change in viscosity is no larger than 10%. With all the physical properties obtained, we can now proceed to study the TFC sliders flying in air-helium gas mixtures.

IV. RESULTS AND DISCUSSION

The numerical results presented in what follows were obtained for a commercial TFC slider with a length of 0.85mm, a width of 0.7mm and a thickness of 0.23mm. Figure 4 shows a typical pressure distribution on the slider's ABS, which is similar, except in the neighborhood of the transducer, for all the cases no matter whether power is applied to the heater. The maximum pressure appears near the protruded area and approximately under the transducer. It acts like a high-stiffness spring helping to stablize the slider when the slider flies over rough surfaces or across tracks. The pressure is almost symmetric about the length centerline, resulting in a near-zero roll angle.

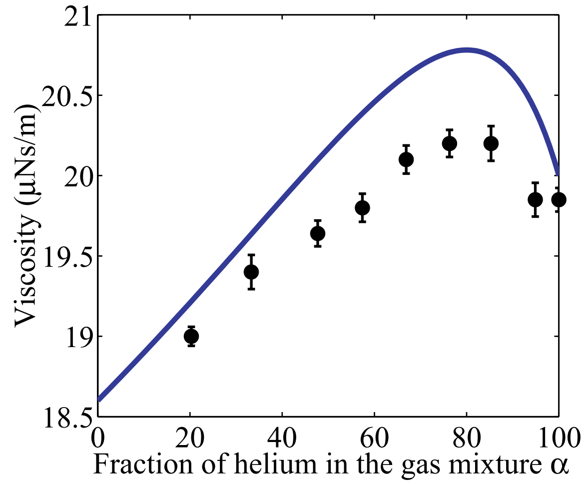

FIG. 3: Change of the viscosity of air-helium gas mixtures with the fraction of helium in the mixture. The results obtained from Eq. (4) are compared with experiments excerpted from Ref. 21. The relative error is generally within 5%.

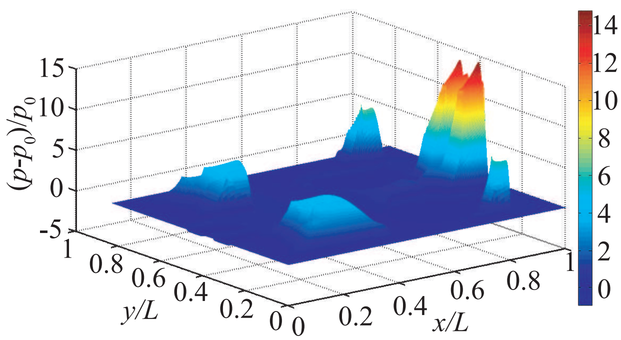

FIG. 4: Typical pressure distribution on the TFC slider's ABS. The maximum pressure appears near the transducer.

When no power is applied to the heater element, the slider's flying attitude and gas pressure on the ABS can be obtained from the generalized Reynolds equation given the force and torques on the slider applied by the suspension. Increasing the helium content in the gas mixture α increases the mean free path of the gas mixture, leading to fewer molecules in the HDI and less load carrying capability [22]. Thus, for a given load, the slider's flying height without heating decreases with α, as shown in Fig. 5, and the maximum pressure on the ABS also decreases with α, as shown in Fig. 6.

After power is applied to the heater element, a nonuniform temperature field is established

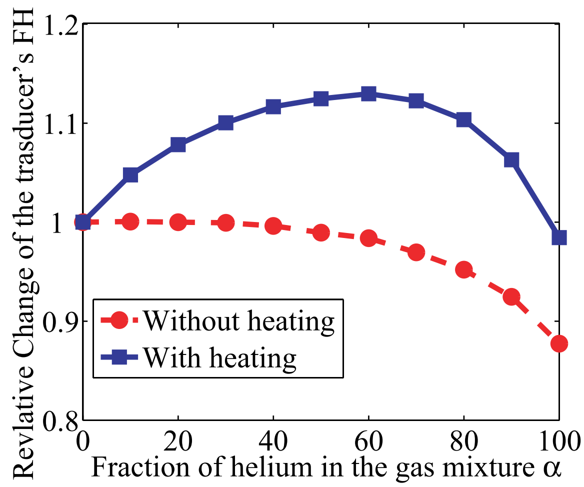

FIG. 5: Relative change of the gap spacing under the transducer with the fraction of helium in the gas mixture, normalized to the value at $\alpha = 0$. The gap spacing at $\alpha = 0$ without power applied to the heater element is 16.1nm, and that with power is 7.2nm.

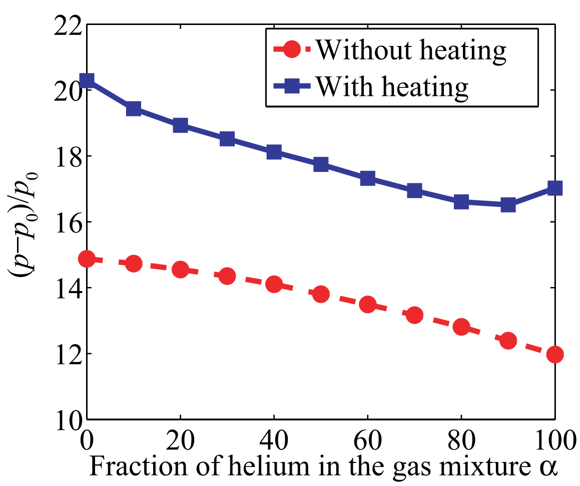

FIG. 6: Change of the maximum pressure with the fraction of helium in the gas mixture.

in the slider, and due to thermomechanical coupling, the slider deforms accordingly. Figure 7 shows the maximum temperature rise on the ABS at a given power for different values of α. The change of the maximum temperature rise is mainly affected by the heat flux on the ABS which serves as the boundary condition for solving the temperature field in the slider. As a simple estimation of the heat flux, we take in Eq. (2) $\sigma \sim 1$, $\gamma \sim 1.5$ and Pr~ 1, then

$$q \sim -k\frac{T_s - T_d}{h + 2\lambda} \tag{6}$$

Since the mean free path is inversely proportional to the local pressure, λ can be estimated to change by a factor of two given the maximum pressure shown in Fig. 6 and the mean free path in Table I. Since the gap spacing h changes by slightly more than 10% as seen from Fig. 5, the denominator of Eq. (6) then increases by 2 fold which is consistent with the numerical calculation of the denominator of Eq. (2) based on information from Figs. 5 and 6 and Table I. This increase, when combined with the 8-fold increase in the thermal conductivity as α increases from 0 to 1, results in the increase in the magnitude of the heat flux with α for the same difference in the temperatures of the slider and the disk, leading to more heat dissipated and a smaller maximum temperature rise as seen from the 2-fold decease of the maximum temperature rise with the gas content in Fig. 7.

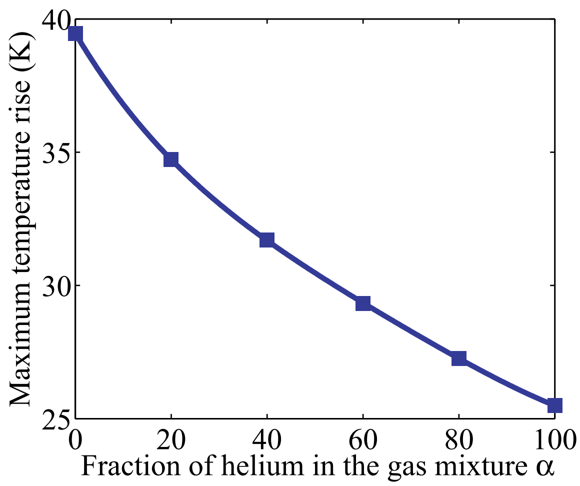

FIG. 7: Change of the maximum temperature rise with the fraction of helium in the gas mixture.

At a given power applied to the heater element, the change of the slider's deformation with α is mainly determined by the changes of the gas pressure and heat flux on the ABS. Since the pressure's effect on the protrusion is negligible, the change of heat flux dominates. As discussed above, the magnitude of the heat flux increases with α, causing the decrease of the slider's protrusion, as shown in Fig. 8. However, the maximum pressure, as seen from Fig. 6, first decreases and then increases with the helium content.

Figure 8 also shows the TFC slider's flying height loss, which is defined as the difference between the slider's flying height with a given power and that with no power. With the effect of its transducer protrusion, the slider adjusts its flying attitude such that the total pressure on the ABS balances the load applied by the suspension. As a result, the slider's

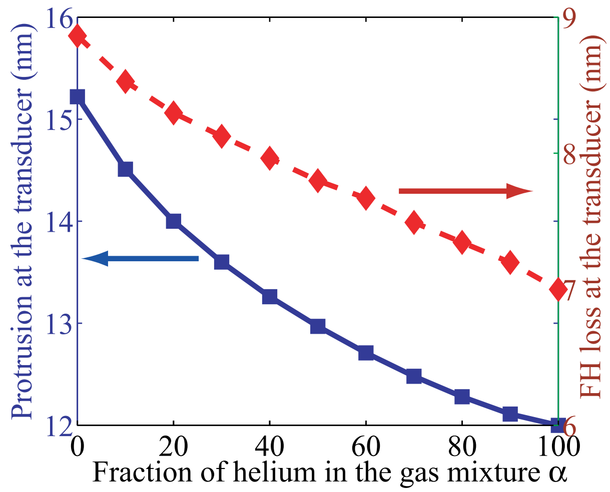

FIG. 8: Change of the slider's protrusion at the transducer with the fraction of helium in the gas mixture.

flying height loss is not equal to its protrusion, but it also decreases with the gas content. To quantitatively evaluate the effect of the thermal protrusion on the induced decrease in the slider's flying height, we plot in Fig. 9 the so called thermal actuation efficiency (TAE), defined as the ratio of the slider's flying height loss to its protrusion. Compared to that in air, the TAE is slightly higher in helium and, thus, slightly less power is required for a designated flying height loss. The maximum efficiency occurs when the gas mixture is composed of about 40% air and 60% helium, which increases the TAE by 2% compared with that in air. This finding brings out another advantage of using air-helium gas mixtures to fill the HDD: slightly less power is required for the same flying height loss.

V. SUMMARY AND CONCLUSION

This paper investigates the flying performance of thermal flying-height control (TFC) sliders in air-helium gas mixtures, and it studies the performance of a commercial TFC slider flying in gas mixtures with different gas contents. The slider's flying height loss and its protrusion are shown to decrease with the helium fraction, however, the ratio between the former and the latter quantities display a complex behavior: it first increases with α and finally decreases when α is greater than about 0.6, indicating that the gas mixture of 40% air and 60% helium is the most efficient from the view point of power cost for a designated

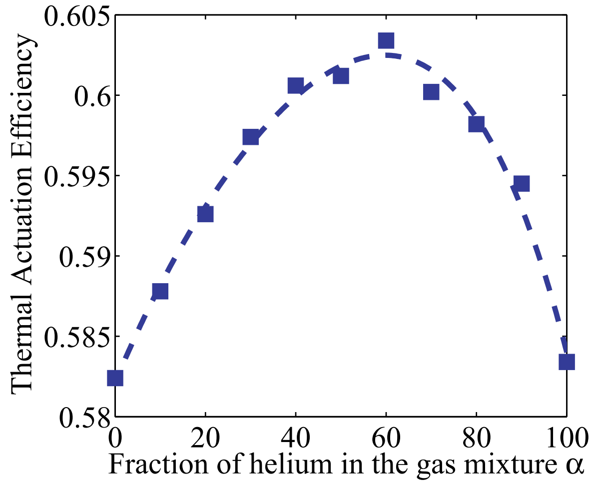

FIG. 9: Change of the thermal actuation efficiency with the fraction of helium in the gas mixture. The square points are numerical results and the dotted line is a smooth fit of the data with a fourth order polynomial.

flying height decrease. The approach proposed here may serve as the basis for designing TFC sliders flying in gas mixtures, and it can also be applied to investigate related problems such as, for example, when the mixture is air and water vapor. Such application is needed in order to investigate a slider's flying performance in a humid environment.

Acknowledgments

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