Proceeding of the 15th ME-NETT Conference

Thermal model of Ultra-Thin Film Head Slider in Magnetic Storage Devices

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Abstract

This paper investigates heat generation in ultra-thin film slider/disk air bearing of magnetic storage systems due to viscous dissipation, which transfers heat from the air bearing to the slider. From heat transfer model with discontinuous boundary conditions and solve it numerically. In this study, the shape of magnetic head sliders are tapered-flat, truncated cycloidal-flat and exponential-flat are investigated. Temperature distribution and heat flux are obtained. Simulation results shows that temperature distribution and heat flux in the case of only viscous dissipation (Temperature of the slider surface equals to temperature of disk surface $T_s = T_d$) decrease with decrease in the flying height. In other words, "warming effect" decreases with decrease in the flying height.

1.Introduction

Thermal effects in slider/disk air bearing have previously investigated, Tian et al (1997)[1], Zhang and Bogy (1999)[2] reported temperature variation phenomena in the air bearing. A phenomena called thermal asperities due to flash temperature that rise when a slider contacts a disk near the MR transducer (a data reading device in magnetic head slider working on the principle of the resistance varies with the variation of surrounding magnetic field). And similar phenomena occurs when the slider flies close to the disk without contact[1]. Thus experiment results shown when the slider with MR transducer flying over an asperity which disturbs the steady flying condition. Readout signal of MR transducer varies with the flying height of the slider. They conclude that the air bearing has a cooling effect with MR transducer which is the major contribution to readout signal variation of MR transducer. Then Zhang and Bogy[2], they introduce a thermal model using discontinuous boundary conditions in a thin slider/disk air bearing and solve it numerically. They find that heat flux occurs by heat conduction mainly which transfers heat from the slider to the air bearing when the slider has higher surface temperature than the disk and viscous dissipation which transfer heat from the air bearing to the slider. Whether the air bearing acts as "coolant" or "heater" depends on which part of the heat conduction or viscous dissipation is relatively small. Generally, viscous dissipation plays a weaker role unless temperature difference between slider and disk close to zero. Simulation results shown that the conduction effect increases with decrease in the flying height but viscous dissipation effect decreases with decrease in the flying height. In other words, cooling effect increases with decrease in the flying height.

This paper introduces theoretical investigations in heat transfer between the slider and the air bearing to study mechanism of " warming effect " of the air bearing. Solving heat transfer problem between the slider and the air bearing from Reynolds equation, Navier Stokes equation and energy equation using discontinuous boundary condition[2]. Assuming physical properties of the air are constant if temperature changes small. So we can evaluate the properties at a certain reference temperature eg. Average temperature of the two surfaces. With such an approximation, the momentum and energy equations can be solved separately. Since temperature difference between slider and disk surfaces is expected to be very small, it is reasonable to apply a constant property assumption in an air bearing. Thus we can solve the momentum and energy equations seperately. In the beginning, we solve Navier Stoke equations (reduced form) and energy equation respectively by slip boundary conditions to obtain temperature distribution in the air bearing. From Fourier's law we obtain an expression for heat flux between the slider and the air bearing. A computer program was implemented to obtain temperature distribution and heat flux for several cases. In the simulation, we use three types of sliders which have differences in shape are tapered-flat type slider, truncated cycloidal-flat type slider and exponential-flat type slider.

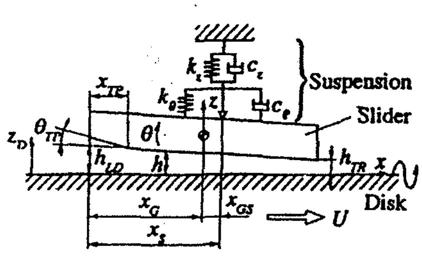

Fig .1 Magnetic head slider.

2.Governing equations in the air bearing

In the following analysis we focus only at static condition so the time dependent terms in the governing equations are not included.

2.1.Reynolds equation

At present, high performance magnetic head/disk requires only sub-micro flying height. Fig.1 shows magnetic head slider system for this study. Reynolds equation with the effect of molecular slip can be expressed as

$$\frac{\partial}{\partial x}\left[ph^3\left(1+\frac{6a_0KnP_0h_m}{ph}\right)\frac{\partial p}{\partial x}\right]+\frac{\partial}{\partial y}\left[ph^3\left(1+\frac{6a_0KnP_0h_m}{ph}\right)\frac{\partial p}{\partial y}\right]$$
$$=6\eta_a\frac{\partial(Uph)}{\partial x} \qquad (1)$$

which h_m is reference air film thickness p is air pressure P_0 is ambient air pressure, η_a is air viscosity at ambient air pressure, a_0 is surface factor.

2.2.Navier Stokes equations

The simplification of Navier Stokes equations for bearing has been performed by many researchers[2], we only list the simplified results and do not present the detailed derivation

$$\frac{\partial p}{\partial x}=\mu\frac{\partial^2 u}{\partial z^2} \qquad (2a)$$
$$\frac{\partial p}{\partial y}=\mu\frac{\partial^2 v}{\partial z^2} \qquad (2b)$$
$$\frac{\partial p}{\partial z}=0 \qquad (2c)$$

where u,v are velocities in x and y directions. p is the pressure and μ is the viscosity of air. For simplification, we assume μ is uniform in the air bearing. The velocity component w in the z direction is approximated to be zero. Clearly, the pressure p is constant across the thickness of the air bearing.

2.3.Energy equation

Since the magnitudes $|\partial/\partial x|\approx|\partial/\partial y|<<|\partial/\partial z|$ and the velocity of air in z direction is approximately zero in a lubrication problem. We neglect the small terms and rewrite the energy equation as

$$k\frac{\partial^2 T}{\partial z^2}+\mu\left(\frac{\partial u}{\partial z}\right)^2+\mu\left(\frac{\partial v}{\partial z}\right)^2=0 \qquad (3)$$

Normally, the viscous dissipation term is smaller in magnitude than the conduction term in equation (3) but when temperature difference between slider and disk surface is close or equal to zero " warming effect " of viscous dissipation can not be neglected. Therefore, we interest this term in equation (3) for analysis.

2.4.Boundary condition

We assume disk velocity U does not equal zero in x direction and velocity V equals zero in y direction that is the case which slider flying at mid-radius of the disk. For temperature, considering that the disk is larger than the air bearing much and rotating with high speed. We assume that the disk has constant speed and uniform temperature. Introducing slip condition for the velocity and jump condition for temperature at the boundaries of the air bearing [2,3]. We can write boundary conditions for velocity and temperature as

$$u(0)=U+\frac{2-\sigma_M}{\sigma_M}\lambda\left.\frac{\partial u}{\partial z}\right|_{z=0} \qquad (4a)$$
$$u(h)=-\frac{2-\sigma_M}{\sigma_M}\lambda\left.\frac{\partial u}{\partial z}\right|_{z=h} \qquad (4b)$$
$$v(0)=-\frac{2-\sigma_M}{\sigma_M}\lambda\left.\frac{\partial v}{\partial z}\right|_{z=0} \qquad (4c)$$
$$v(h)=-\frac{2-\sigma_M}{\sigma_M}\lambda\left.\frac{\partial v}{\partial z}\right|_{z=h} \qquad (4d)$$
$$T(0)=T_d+2\frac{2-\sigma_T}{\sigma_T}\frac{\gamma}{\gamma+1}\frac{\lambda}{\Pr}\left.\frac{\partial T}{\partial z}\right|_{z=0} \qquad (4e)$$
$$T(h)=T_s+2\frac{2-\sigma_T}{\sigma_T}\frac{\gamma}{\gamma+1}\frac{\lambda}{\Pr}\left.\frac{\partial T}{\partial z}\right|_{z=h} \qquad (4f)$$

Where σ_M is momentum accommodation coefficient and σ_T is thermal accommodation coefficient γ is ratio of C_p to C_v which are specific heats at constant pressure and constant volume respectively. T_s and T_d is the slider surface temperature and the disk surface temperature, respectively. For convenience, we write $a=(2-\sigma_M)/\sigma_M$ and $b=2(2-\sigma_T)\gamma/\sigma_T(\gamma+1)\Pr$ in the following analysis.

2.5.Air film thickness expressions

2.5.1.Tapered-flat type slider

$$h=h_{TR}+(L-L_{TP})\tan\theta+(L_{TP}-x)\tan\theta_{TP} \quad ;0\le x\le L_{TP} \qquad (5a)$$
$$h=h_{TR}+(L-x)\tan\theta \quad ;L_{TP}\le x\le L \qquad (5b)$$

2.5.2.Truncated cycloidal-flat type slider

$$h=h_{TR}+(L-L_{TP})\tan\theta+(L_{TP}-x)\tan\theta_{TP} -\frac{L_{TP}}{\pi}\tan\theta_{TP}\sin\left(\frac{\pi(L_{TP}-x)}{L_{TP}}\right);0\le x\le L_{TP} \qquad (6a)$$
$$h=h_{TR}+(L-x)\tan\theta \quad ;L_{TP}\le x\le L \qquad (6b)$$

2.5.3.Exponential-flat type slider

$$h=h_{TR}+(L-L_{TP})\tan\theta+h_{TR}\left(e^{m(L_{TP}-x)}-1\right)$$
$$m=\frac{1}{L_{TP}}\ln\left(\frac{h_{TR}+\tan\theta_{TP}L_{TP}}{h_{TR}}\right);0\le x\le L_{TP} \qquad (7a)$$
$$h=h_{TR}+(L-x)\tan\theta \quad ;L_{TP}\le x\le L \qquad (7b)$$

The air film thickness distributions are calculated from equations (5), (6), (7) for tapered-flat, truncated cycloidal-flat and exponential-flat type sliders respectively as shown in Fig.2.

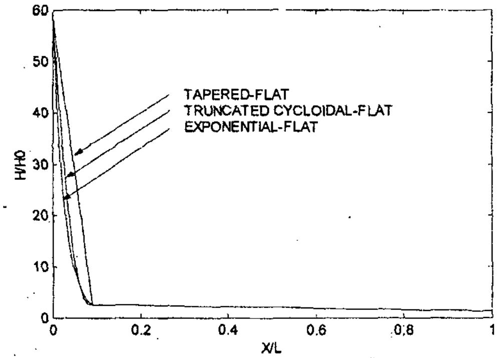

Fig. 2 Air film thickness.

3.Heat transfer between magnetic head slider and air bearing

To obtain heat transfer in the air bearing, we need to know temperature distribution by solving Navier Stoke equation and energy equation. Since the constant property approximation, Navier Stoke equation and energy equation can be solved seperately.

3.1.velocity distribution

Velocity distribution can be obtained by integrating Navier Stoke equation (reduced form) (2a)-(2b) using boundary condition (4a)-(4d). With straight forward procedure, the results are as follow :

$$u=-\frac{1}{2\mu}\frac{\partial p}{\partial x}\left(a\lambda h+hz-z^2\right)+U\left(1-\frac{z+a\lambda}{h+2a\lambda}\right) \tag{8a}$$

$$v=-\frac{1}{2\mu}\frac{\partial p}{\partial y}\left(a\lambda h+hz-z^2\right) \tag{8b}$$

Right terms of equation(8a), the first term is the Poiseulle flow term(see Fig. 4) and second term is Couette flow (see Fig. 3). While (8b) has only Poiseulle flow because we let the disk velocity in y direction $V=0$. From above equation found that these results have not known pressure gradient terms in x and y direction yet. To complete the results, we need to solve Reynolds equation to obtain pressure distribution. For solving this problem, numerical method needed[2,4].

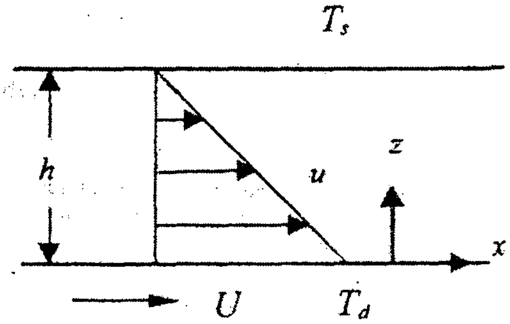

Fig. 3 Couette flow.

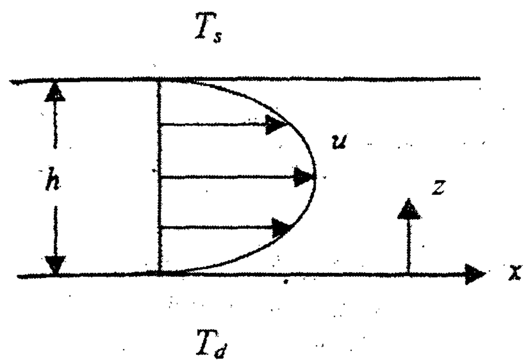

Fig. 4 Poiseulle flow.

3.2.Temperature distribution

We fill velocity result(8a) and (8b) into energy equation (3) then integrate it for temperature distribution in the air bearing.

$$T=T_d-\frac{1}{k}\left\{\frac{1}{12\mu}\left[\left(\frac{\partial p}{\partial x}\right)^2+\left(\frac{\partial p}{\partial y}\right)^2\right]z^4-\frac{1}{3}\left\{\frac{h}{2\mu}\left[\left(\frac{\partial p}{\partial x}\right)^2+\left(\frac{\partial p}{\partial y}\right)^2\right]+\frac{\partial p}{\partial x}\frac{U}{h+2a\lambda}\right\}z^3\right.$$
$$\left.+\frac{\mu}{2}\left[\left(\frac{h}{2\mu}\frac{\partial p}{\partial x}+\frac{U}{h+2a\lambda}\right)^2+\frac{h^2}{4\mu^2}\left(\frac{\partial p}{\partial y}\right)^2\right]z^2\right\}$$
$$+\left\{\frac{T_s-T_d}{h+2b\lambda}+\frac{1}{k}\left[\frac{h^3}{24\mu}\left\{\left(\frac{\partial p}{\partial x}\right)^2+\left(\frac{\partial p}{\partial y}\right)^2\right\}+\frac{\mu U^2 h}{2(h+2a\lambda)^2}\right.\right.$$
$$\left.\left.+\frac{Uh^3}{6(h+2a\lambda)(h+2b\lambda)}\frac{\partial p}{\partial x}\right]\right\}(z+b\lambda) \tag{9a}$$

we can write temperature distribution in non-dimensional form is

$$(T_0)T^*=T_d-\frac{1}{k}\left\{\frac{1}{12\mu}\left[\frac{P_0^2}{L^2}\left(\frac{\partial p^*}{\partial x^*}\right)^2+\frac{P_0^2}{B^2}\left(\frac{\partial p^*}{\partial y^*}\right)^2\right]h^4(z^*)^4\right.$$
$$-\frac{1}{3}\left\{\frac{h}{2\mu}\left[\frac{P_0^2}{L^2}\left(\frac{\partial p^*}{\partial x^*}\right)^2+\frac{P_0^2}{B^2}\left(\frac{\partial p^*}{\partial y^*}\right)^2\right]+\frac{U}{(h+2a\lambda)}\frac{P_0}{L}\left(\frac{\partial p^*}{\partial x^*}\right)\right\}h^3(z^*)^3$$
$$\left.+\frac{\mu}{2}\left\{\left(\frac{h}{2\mu}\frac{P_0}{L}\left(\frac{\partial p^*}{\partial x^*}\right)+\frac{U}{(h+2a\lambda)}\right)^2+\frac{h^2}{4\mu^2}\frac{P_0^2}{B^2}\left(\frac{\partial p^*}{\partial y^*}\right)^2\right\}h^2(z^*)^2\right\}$$
$$+\left\{\frac{(T_s-T_d)}{(h+2b\lambda)}+\frac{1}{k}\left\{\frac{1}{24\mu}h^3\left[\frac{P_0^2}{L^2}\left(\frac{\partial p^*}{\partial x^*}\right)^2+\frac{P_0^2}{B^2}\left(\frac{\partial p^*}{\partial y^*}\right)^2\right]+\frac{\mu U^2 h}{2(h+2a\lambda)^2}\right.\right.$$
$$\left.\left.+\frac{Uh^3}{6(h+2a\lambda)(h+2b\lambda)}\frac{P_0}{L}\frac{\partial p^*}{\partial x^*}\right\}\right\}(hz^*+b\lambda) \tag{9b}$$

Similarly, equation of temperature consists both Poiseulle flow and Couette flow and the term are combined.

3.3. Heat transfer

From Fourier's law $q=-k\partial T/\partial z$ at $z=h$ and temperature distribution (9a) we obtain heat transfer through the slider as follow

$$q=-k\frac{T_s-T_d}{h+2b\lambda}+\frac{h^3}{24\mu}\left\{\left(\frac{\partial p}{\partial x}\right)^2+\left(\frac{\partial p}{\partial y}\right)^2\right\}+\frac{\mu U^2 h}{2(h+2a\lambda)^2}-\frac{Uh^3}{6(h+2a\lambda)(h+2b\lambda)}\frac{\partial p}{\partial x} \tag{10a}$$

Heat transfer equation(10a) can be written in non-dimensional form as

$$\frac{qh}{\mu U^2}=-\frac{T_s-T_d}{\left(\frac{\gamma-1}{2}\right)\Pr M^2 T_0\left(1+2b\frac{\lambda}{h}\right)}+\frac{1}{2\left(1+2a\frac{\lambda}{h}\right)^2}+\frac{1}{24}\mathrm{Re}^2\left(\frac{h}{L}\right)^2\left(\frac{P_0}{\rho U^2}\right)^2\left(\frac{\partial p^*}{\partial x^*}\right)^2$$
$$+\frac{1}{24}\mathrm{Re}^2\left(\frac{h}{B}\right)^2\left(\frac{P_0}{\rho U^2}\right)^2\left(\frac{\partial p^*}{\partial y^*}\right)^2-\frac{1}{6}\mathrm{Re}\frac{h}{L}\frac{P_0}{\rho U^2}\frac{1}{\left(1+2b\frac{\lambda}{h}\right)\left(1+2a\frac{\lambda}{h}\right)}\frac{\partial p^*}{\partial x^*} \tag{10b}$$

4.Simulation results

We simulate in case of the disk running with linear velocity 20 m/s. Using the program to obtain pressure, temperature and heat flux of the three types of the sliders. As shown in Fig.5, Fig.6, Fig.7, Fig.8, Fig.9, Fig.10, Fig.11, Fig.12 ,Fig.13, Fig.14, Fig.15, Fig.16, Fig.17and Fig.18.

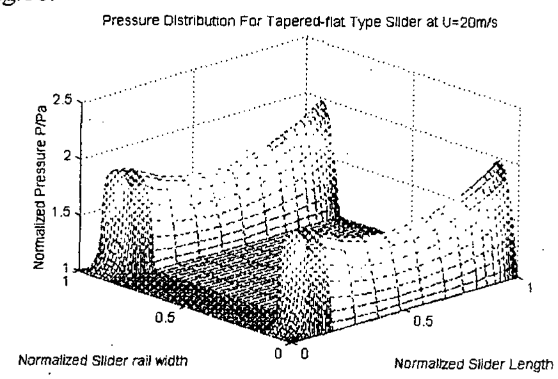

Fig. 5 Pressure profile in air bearing of tapered-flat type slider.

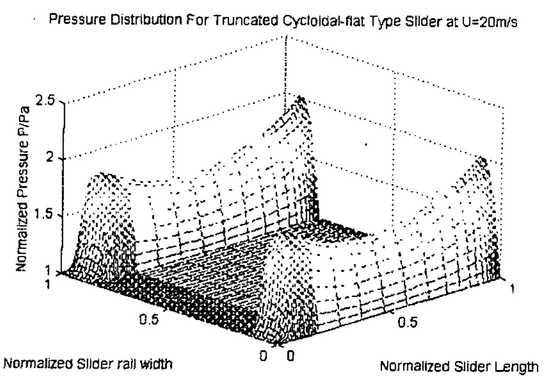

Fig. 6 Pressure profile in air bearing of truncated cycloidal-flat type slider.

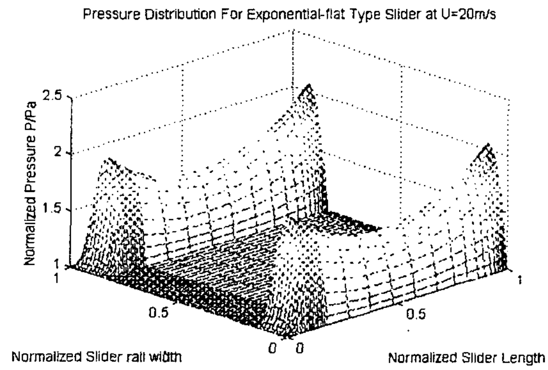

Fig. 7 Pressure profile in air bearing of exponential-flat type slider.

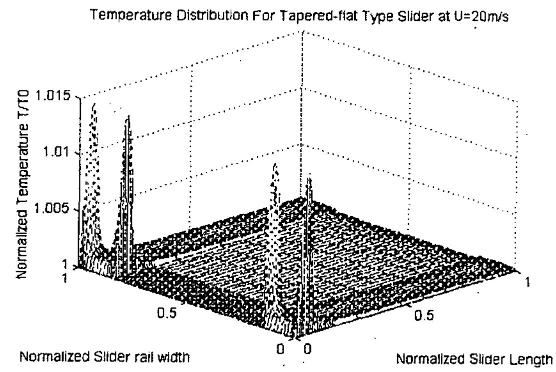

Fig. 8 Temperature profile in air bearing of tapered-flat type slider.

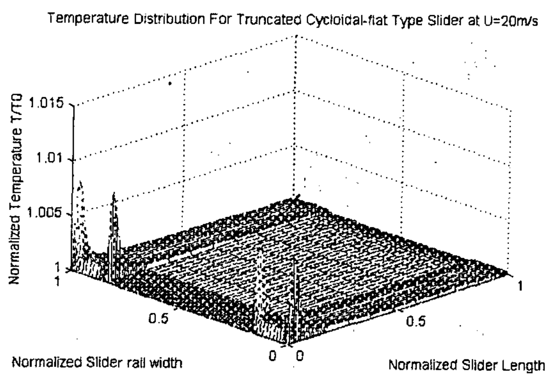

Fig. 9 Temperature profile in air bearing of truncated cycloidal-flat type slider.

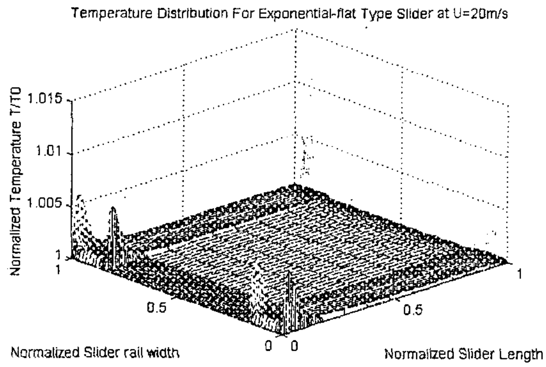

Fig. 10 Temperature profile in air bearing of exponential-flat type slider.

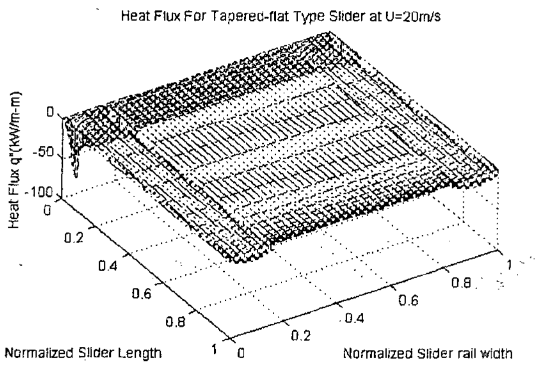

Fig. 11 Heat flux between slider and air bearing of tapered-flat type slider $(T_s - T_d = 0\,K)$.

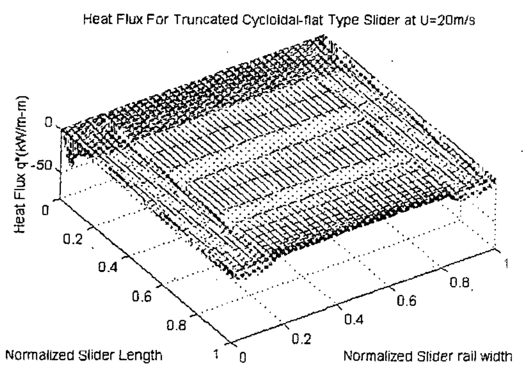

Fig. 12 Heat flux between slider and air bearing of truncated cycloidal-flat type slider $(T_s - T_d = 0\,K)$.

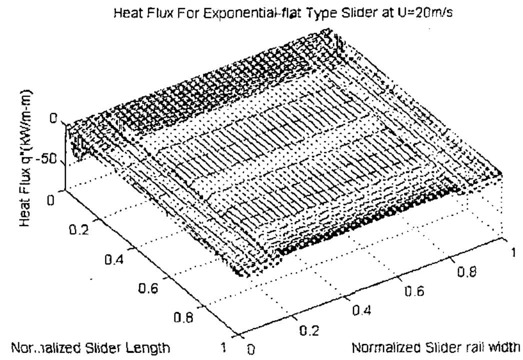

Fig. 13 Heat flux between slider and air bearing of exponential-flat type slider $(T_s - T_d = 0\,K)$.

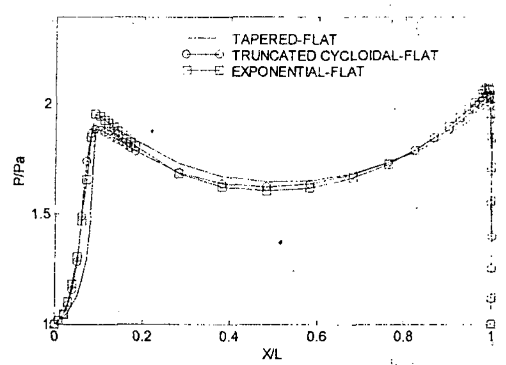

Fig. 14 Mid rail width pressure vs slider-rail length.

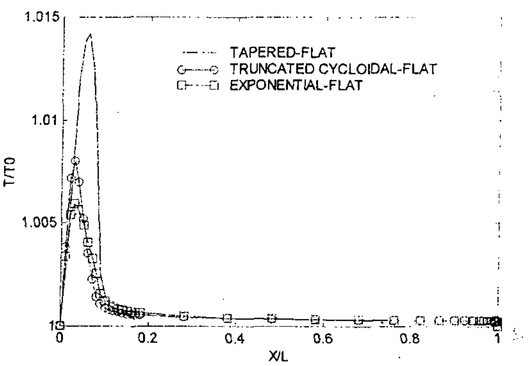

Fig. 15 Side rail width temperature vs slider-rail length.

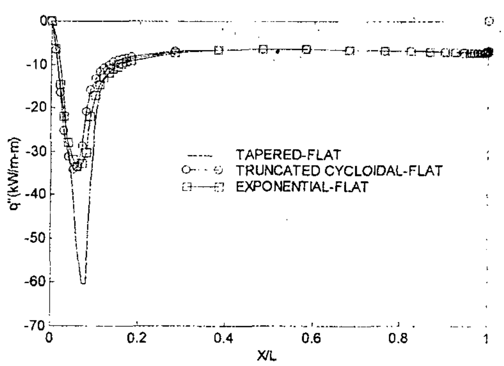

Fig. 16 Side rail width heat flux at film thickness z=h vs slider-rail length.

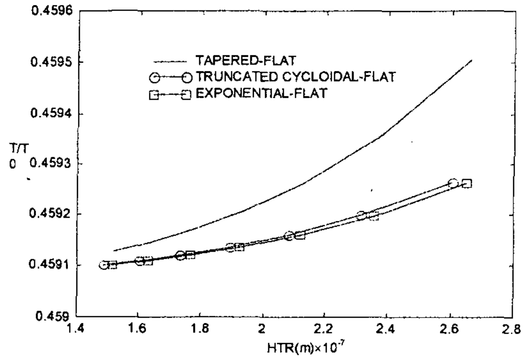

Fig. 17 Average temperature vs flying height of slider trailing edge $(T_s - T_d = 0\,K)$.

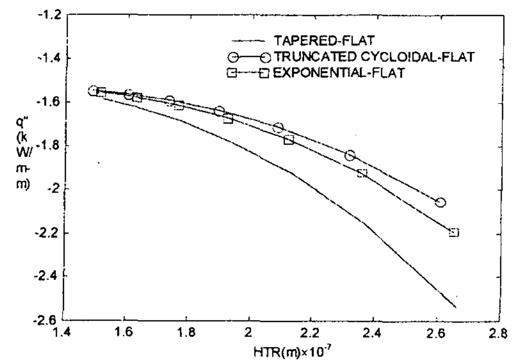

Fig. 18 Average heat flux vs flying height of slider trailing edge at $(T_s - T_d = 0\,K)$.

5.Conclusion

In this study, the following conclusion can be drawn as:

1. Solve Navier Stokes' equations and energy equation separately to obtain temperature distribution. Maximum temperature occurs at the taper length range of the head sliders.
2. From Fourier's law $(q = -k\partial T/\partial z)$ heat flux can be calculated and maximum heat flux occurs at the taper length range of the sliders head.
3. When temperature difference between slider/disk is close or equal to zero, the effect of viscous dissipation make heat transfer from the air bearing to the slider, may be called " warming effect ".
4. Heat transfer to the slider decreases with decrease in the flying height of the slider or "warming effect" decrease with decrease in the flying height.
5. Average temperature comparing among three types of the sliders from high to low value are tapered-flat type slider, truncated cycloidal-flat type slider and exponential-flat type slider respectively.
6. Average heat flux comparing among three types of the sliders from high to low value are tapered-flat type slider, exponential-flat type slider and truncated cycloidal-flat type slider respectively.

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Nomenclature

C_p	specific heat at constant pressure
C_v	specific heat at constant volume
h	air bearing space
k	thermal conductivity of the air
Kn	Knudsen number
B	width of the slider
L	length of the slider
M	Mach number
p	air bearing pressure
P_0	ambient air pressure
p^*	non-dimensional air bearing pressure $p^* = p/P_0$
Pr	Prandtl number
q	heat flux between the slider surface and the air bearing
R	gas constant
Re	Reynolds number
T	air bearing temperature
T_s	temperature of the slider surface
T_d	temperature of the disk surface
T_0	ambient air temperature
ΔT_0	temperature difference between the slider and disk surface
T^*	non-dimensional temperature $T^* = T/T_0$
u, v, w	velocity component of the air bearing
U	linear velocity of the disk at the slider location
u^*, v^*, w^*	non-dimensional velocity components $u^* = u/U, v^* = v/U, w^* = w/U$
x, y, z	coordinates in the air bearing
x^*, y^*, z^*	non-dimensional coordinates in the air bearing $x^* = x/L, y^* = y/L, z^* = z/h$
a_0	surface coefficient

Greek symbols

α thermal diffusivity of the air
γ ratio of the specific heats $\gamma = C_p/C_v$
λ mean free path of the air
μ viscosity of the air
ν dynamic viscosity of the air
σ_M momentum accommodation coefficient
σ_T thermal accommodation coefficient
η_a viscosity at the ambient air pressure