Simulation of Static Flying Attitude with Different Heat Transfer Models for a Flying Height Control Slider with Thermal Protrusion

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Abstract

The air bearing cooling effect and viscous heating effect are considered in the numerical simulation of an air bearing slider with its flying height controlled by thermal protrusion, which is conventionally called thermal flying height control (TFC) or dynamic flying height (DFH). The simulation results show that the air bearing cooling is dominant compared with the viscous heating. Different models for the air bearing cooling, i.e. the heat conduction on the slider's air bearing surface (ABS), are also used and compared in the numerical simulations. It is found that all of these models, including a recent one considering the dependence of the air molecule mean free path on the ambient temperature, give very close simulation results of the slider's static flying attitude. The difference is less than 10% of the result obtained with Chen's model [1], which is used in current CML program.

Introduction

The Thermal flying height control (TFC) - dynamic flying height (DFH) - technique is widely used in current hard drives to lower the slider's flying height as presented in the patent by Meyer et al [2]. This advantageous technique makes use of a resistance heating element near the read/write transducer. When a current is applied through the heating element, it undergoes local thermal expansion and forms a localized thermal protrusion near the trailing edge center close to the read/write transducer. The thermal protrusion reduces the flying height very locally at the transducer. In this way the transducer flying height becomes adjustable. This technique provides control that can compensate for the static flying height (FH) loss and reduce the likelihood of head-disk contact for an air bearing slider. Additionally, this technique has the potential of achieving a partial contact head disk interface (HDI). The controllable contact area created by the thermal protrusion at the transducer helps maintain a very light contact between the slider and the disk, while the rest of the air bearing surface (ABS) remains undeformed and flies at a safe distance from the disk.

For a slider with thermal protrusion, the cooling effect of the air bearing was first analyzed by Juang, Chen and Bogy [3]. The coupling problem between the thermal protrusion and the air bearing was numerically solved using a loop composed of a static Reynolds equation solver for the air bearing and a finite element analysis for the thermal protrusion. It was shown that the heat transfer from the slider to the disk through the air bearing film has a considerable effect on the flying height reduction efficiency. The work in that paper used a HDI heat transfer model developed by Chen and Bogy [1]. The viscous dissipation was neglected in that simulation, since Chen's model concluded that on the ABS the viscous dissipation is about 1-2 orders of magnitude less than the heat conduction. An independent work done by Ju [4] produced another heat transfer model with different viscous dissipation. Recently Zhou et. al. [6] and Shen et. al. [7] proposed two different new HDI heat transfer models. As different heat transfer models for head disk interface are proposed, however, a question arises as to how much difference is caused in the static flying attitude with the different heat transfer models applied in the simulation. In this report, this question is addressed using a pico and a femto air bearing sliders. The simulation results show that the viscous dissipation does not affect the static flying attitude even when the FH is less than 2 nm. It is also found that the different models for heat conduction on the ABS give very close simulation results for the slider's static flying attitude. The relative difference is less than 10% in the static transducer flying height and less than 1% in the pitch angle, when compared with Chen's model [1].

Heat transfer models for the head-disk interface

In the numerical flying attitude analysis for a slider with thermal protrusion carried out by Juang, Chen and Bogy [3], the HDI heat transfer model developed by Chen and Bogy [1] is used for the heat conduction on the ABS. In fact, Chen's model originates from the HDI heat transfer model by Zhang and Bogy [5]. Zhang's model and Chen's model both use the velocity slip and temperature jump theory at the boundary of the air bearing. Both models have shown that the heat flux on the ABS has two contributions. One is the heat conduction, which transfers heat from the slider to the air bearing when the ABS has a higher temperature than the disk surface; the other is the viscous dissipation due to the air flow within the HDI. Both models have the same expression for the heat conduction, the same expression for the viscous dissipation due to the Couette flow, but different expressions for viscous dissipation contributed by the Poiseuille flow. For a simplified situation with disk velocity U in the slider length direction (i.e. x-direction) and zero disk velocity in the slider width direction (i.e. y-direction), the expression for heat flux on the ABS is,

$$q_{ABS} = q_{conduction} + q_{viscous} = q_{conduction} + q_{Couette} + q_{Poiseuille},$$

where $q_{conduction} = -k\dfrac{T_s - T_d}{h + 2b\lambda}$ and $q_{Couette} = \dfrac{\mu U^2 h}{2(h+2b\lambda)^2}$.

Zhang's model has

$$q_{Poiseuille} = -\frac{Uh^3}{6(h+2b\lambda)(h+2a\lambda)}\frac{\partial p}{\partial x} + \frac{h^3}{24\mu}\left[\left(\frac{\partial p}{\partial x}\right)^2 + \left(\frac{\partial p}{\partial y}\right)^2\right],$$

Chen's model has

$$q_{Poiseuille} = -\frac{Uh(ah\lambda + bh\lambda + 2ab\lambda^2)}{6(h+2b\lambda)(h+2a\lambda)}\frac{\partial p}{\partial x} + \frac{ah^2\lambda}{4\mu}\left[\left(\frac{\partial p}{\partial x}\right)^2 + \left(\frac{\partial p}{\partial y}\right)^2\right].$$

In the above heat flux expressions, k is the thermal conductivity of air; μ is the viscosity of air; T_s and T_d are the temperatures of the slider and the disk, respectively; h is the local slider-disk gap; λ is the mean free path of air; p is the local air bearing pressure; $b = 2\dfrac{(2-\sigma_T)}{\sigma_T}\dfrac{\gamma}{(\gamma+1)}\dfrac{1}{P_r}$, where σ_T is the thermal accommodation coefficient; P_r is the Prandtl number of air, γ is the ratio of the specific heat; $a = \dfrac{2-\alpha}{\alpha}$, where α is the momentum accommodation coefficient. In fact the first term in the expression of $q_{\text{Poiseuille}}$ represents the coupling of Poiseuille flow and Couette flow. That term is included in the heat flux contributed by the Poiseuille flow for a notation simplification in this report.

Zhang's model and Chen's model both show that the heat flux on the ABS is dominated by the heat conduction while viscous dissipation is only a second order effect. Because of this, only the heat conduction on the ABS, i.e. the cooling effect of the air bearing, is considered in the static flying height simulation by Juang, Chen and Bogy [3].

Ju [4] proposed another heat transfer model for the HDI. The heat conduction part is also based on the temperature jump theory, which makes it have a similar expression to those shown in Zhang's and Chen's models. In fact the heat flux due to conduction in Ju's model is just the corresponding term in Zhang's and Chen's models with surface thermal accommodation coefficient σ_T equal to 1. However, the viscous dissipation due to the Couette flow in Ju's model is based on an approximate solution of the Boltzmann transport equation and the expression is different from the term in Zhang's and Chen's models. Also the viscous dissipation contributed by the Poiseuille flow is not included in Ju's model. The complete expression of heat flux on the ABS by Ju's model is,

$$q_{ABS} = q_{conduction} + q_{viscous} = -k\frac{T_s - T_d}{h + 2b\lambda} + \frac{1}{8}\rho U^2 \sqrt{\frac{8RT}{\pi}}\frac{2\lambda}{h + 2\lambda},$$

where ρ is the air density and T is the air temperature.

Based on Zhang's and Chen's models, Zhou et. al. [6] took the change of air molecule mean free path caused by temperature rise into consideration and proposed a generalized heat transfer model. This model shows that the heat flux due to conduction varies significantly when the mean free path of the air molecules changes, giving

$$q_{ABS} = q_{conduction} + q_{viscous} = -k\frac{T_s - T_d}{h + 2b\lambda} + q_{viscous},$$

where $\lambda = \xi(\frac{T}{T_0})^{\omega+0.5}\frac{p_0}{p}\lambda_0$ with parameters ξ and ω determined by the model used for the mean free path of air. For example, $\xi=1$ and $\omega=0.5$ for the hard sphere model; $\xi=0.8244$ and $\omega=0.75$ for the variable soft sphere model; $\xi=0.75$ and $\omega=1$ for the variable hard sphere model. Experimental data provide $\xi= 0.80\sim0.85$ and $\omega=0.75$ for an air film [6], which indicates that the variable soft sphere model is applicable to air films.

Different from these models based the velocity slip and temperature jump theory, Shen and Chen [7] recently proposed a HDI heat transfer model based on the linearized Boltzmann equation. This model gives a heat conduction flux close to those obtained in Zhang's model, Chen's model and Ju's model, but it has different viscous dissipations. In this model the relation between the viscous heating due to the Couette flow and the inverse Knudsen number is quite different from that in Zhang's and Chen's models, but close to that obtained from Ju's model. In both Ju's model and Shen's model the viscous dissipation due to the Couette flow asymptotically approaches a constant as the inverse Knudsen number decreases to 0.01, while in Zhang's and Chen's models the Couette-flow-caused viscous dissipation reduces almost to zero as the inverse Knudsen number goes to 0.01. Also the viscous dissipation contributed by the Poiseuille flow obtained from Shen's model and from Zhang's and Chen's models are different. Presumably Shen's model is more accurate for the heat transfer with small inverse Knudsen number, since it is directly derived from the linearized Boltzmann equation. However, the expression for heat flux given by this model has complex integrations with respect to molecule velocities. It is not applicable to the engineering simulation of the slider's flying attitude with adjustable thermal protrusion.

Simulation of air bearing sliders with thermal protrusion

This report is focused on the numerical analysis of the air bearing cooling effect and the viscous heating effect on the slider's static flying attitude, and numerical comparisons of different static flying attitudes obtained when different HDI heat transfer models are applied. First, Ju's model is used for analysis of the effect of viscous heating on the slider's static attitude, since the heat conduction term and the viscous heating term in Ju's model are both validated by Shen's model based on the linearized Boltzmann equation. Second, the slider's static simulation results obtained with Zhang's and Chen's models, Ju's model and Zhou's model are compared to analyze the difference caused by different heat conduction models, which are applied for the air bearing cooling.

In the numerical analysis, an INSIC pico slider [3] and a commercial femto slider are used. The pico slider's ABS is shown in Figure 1 and its heating-power-off static flying attitude is shown in Table 1. The static flying height of a slider with thermal protrusion is obtained using the loop shown in [3]. This loop contains a Reynolds equation solver for the steady state of an air bearing slider and a finite element analysis program to calculate the thermal protrusion with inside heating, heat convection on non-air-bearing surfaces and complex heat transfer at the ABS. In this report the CML static air bearing program is used to solve the generalized Reynolds lubrication equation for the slider's static flying attitude. In the iteration the ABS with updated thermal protrusion is input into the CML program. The finite element model for a pico slider with a GMR head and a micro heater developed in [3] is used here for the protrusion calculation by an ANSYS program. The heat conduction at the ABS, i.e. air bearing cooling, can be treated as heat convection at the ABS with given convection coefficients in ANSYS. Since the boundary conditions of heat flux and convection can not be applied to the same boundary in ANSYS, the viscous dissipation flux is treated as surface heating on the ABS, which has a heat generation rate twice the viscous heating flux.

The commercial femto slider's ABS is shown in Figure 2. Due to the lack of an accurate ANSYS model for the read/write transducer, heater and other components in this femto slider, the structures of read/write transducer and micro heater used in [3] are scaled and adopted in the simulation of this femto slider. The same loop is used to obtain the femto slider's static flying attitude with different HDI heat transfer models.

Simulation results for static flying attitudes

1. Pico slider

a) Viscous heating versus air bearing cooling

Ju's model is applied in the loop to analyze the effect of viscous dissipation on the slider's static flying attitude. Table 2 shows the simulation results for 40 mW, 80 mW and 120 mW heating power using Ju's model with and without the consideration of viscous dissipation contributed by the Couette flow. It is obvious that the effect is negligible, even when the flying height is below 2 nm. Figure 3 shows the corresponding temperature and heat flux at the ABS, and it is seen that the largest difference is less than 1%. So the viscous dissipation contributed by the Couette flow has negligible effect on the slider's static flying attitude and the heat transfer on the ABS for this INSIC pico slider.

b) Heat conduction in Ju's model versus Zhang's and Chen's models

The only difference between the heat conduction part in Ju's model and that in Zhang's and Chen's models is that the surface thermal accommodation coefficient is 1.0 in Ju's model, while it is a parameter in Zhang's and Chen's models. For the slider and disk surface, the thermal accommodation coefficient is chosen as 0.9 in Zhang's and Chen's models. Here simulations are carried out with three values of heating powers, 40 mW, 80 mW and 120 mW. Table 2 lists the slider's static flying attitude obtained with Ju's model and with Zhang's and Chen's models. Figure 4 graphically shows the comparison of static flying attitudes obtained through these two types of models neglecting the viscous heating. The biggest relative difference in static transducer FH and pitch angle is less than 10%. The difference in static roll angle is less than 1μrad and thus negligible, although the difference is large compared with 1 micron radian level roll angle. Figure 5 shows the temperature and heat flux on the ABS. The largest relative difference is also less than 10%. This difference is larger than the difference between the flying attitude results with and without considering the Couette-flow-caused viscous heating in Ju's model. It indicates that the surface thermal accommodation coefficient has a larger effect than the Couette-flow-caused viscous heating in the HDI heat transfer.

c) Heat conduction in Zhou's model versus Zhang's and Chen's models

The only difference between Zhou's model and Zhang's and Chen's models is that the dependence of mean free path of the air molecules on the ambient temperature is considered in Zhou's model. Here simulations are carried out with different ambient temperatures. The air parameters used in the models, including the ratio of the specific heat, Prandtl number and thermal conductivity, change as the air temperature changes. Table 3 lists those parameter values for the air temperatures of $0^{o}C$, $25^{o}C$, $50^{o}C$ to $75^{o}C$. Using those values in Zhou's model or Zhang's and Chen's models, the slider's static flying attitudes are obtained and listed in Table 4 at the ambient temperatures of $0^{o}C$, $25^{o}C$, $50^{o}C$ to $75^{o}C$, when the heat power is 40 mW and 80 mW, respectively. It is obvious that as the ambient temperature increases, the air cooling effect on the slider surface, including the ABS and non-ABS, decreases if the convection and conduction coefficient do not change. This leads to an increase in the slider's temperature and thermal protrusion at the trailing edge center. Increased thermal protrusion causes more flying height loss. Figures 6 and 7 graphically show the difference between the simulation results obtained from Zhou's model and from Zhang's and Chen's models when the heating power is 40 mW and 80 mW, respectively. The largest relative differences in static transducer FH and pitch angle are less than 10%. Although the relative difference in static roll angle is larger than 10%, the absolute difference is still less than 1μrad and is negligible.

It was shown in [6] that the mean free path of air increases as the air temperature increases. So for the HDI a large difference in heat transfer between Zhou's model and Zhang's and Chen's models is expected to occur at high temperatures. Figure 8 shows the temperature and heat conduction on the ABS at the slider's static state for the cases at 75^{o}C ambient temperature, obtained using Zhou's model and Zhang's and Chen's models, respectively. The maximum relative difference is less than 5%.

2. Femto slider

A heating power of 200 mW is used in the simulation of the commercial femto slider, whose ABS is shown in Figure 2. Usually its working power is less than 200 mW. Table 5 lists the static flying attitudes of the femto slider with different heat transfer models. It is obvious that the flying attitudes obtained with Ju's model with and without considering Couette-flow-caused viscous heating, and Zhang's and Chen's models are almost the same. At the ambient temperature of 75^{o}C, the static flying attitudes obtained with Zhou's model and Zhang's and Chen's model are also very close. The largest difference is no more than 2% when compared with the results obtained with Zhang's and Chen's models.

Conclusions

Numerical simulations for the static flying attitudes of sliders with thermal protrusion are carried out using different head-disk-interface heat transfer models. The air bearing cooling effect is dominant at the air bearing surface compared with the viscous heating due to the Couette flow. Since the viscous heating contributed by the Poiseuille flow is no larger than the viscous dissipation contributed by the Couette flow [7], it is expected that the entire viscous dissipation has a negligible effect on the slider's static flying attitude.

The change of surface thermal accommodation coefficient from 1.0 (used in Ju's model [4]) to 0.9 (recommend in Zhang's and Ju's models [1, 5] for the slider and disk surfaces) causes less than a 10% change in static transducer flying height and pitch angle. The consideration of the dependence of the air molecule's mean free path on ambient temperature in Zhou's model gives a relative difference less than 10% in static transducer flying height and pitch angle when compared with Zhang's and Chen's models. Considering the dynamic flying height modulation of approximately 10% of the flying height, Zhang's model (or Chen's model), which is used in the current CML program for the air bearing cooling effect, is accurate enough for the static flying attitude simulation of an air bearing slider with thermal protrusion.

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Table 1 Specification of the suspension used in the numerical analysis and corresponding static flying attitude of the pico slider (shown in Figure 1) with heating power off

Suspension	Suspension load: 1.5 gf Pitch torque: -6.4 μN.m Roll torque: 0.0 μN.m Pitch static attitude: 0.0 rad Roll static attitude: 0.0 rad
Static flying attitude	Transducer FH: 14.37 nm Pitch: 154.57 μrad Roll: 0.36 μrad

Table 2 Static flying attitudes of the pico slider (shown in Figure 1) obtained with and without the viscous heating contributed by the Couette flow

		Ju's Model		Zhang's and Chen's Models
Heating power		With viscous heating	Without viscous heating	
40mW	Transducer FH (nm)	8.51	8.51	8.35
	Pitch (μrad)	149.56	149.56	149.18
	Roll(μrad)	0.0679	0.0678	0.10
80 mW	Transducer FH (nm)	4.21	4.23	4.00
	Pitch (μrad)	143.94	144.00	143.30
	Roll (μrad)	-0.327	-0.244	-0.23
120 mW	Transducer FH (nm)	1.77	1.75	1.60
	Pitch (μrad)	137.18	137.19	136.07
	Roll (μrad)	-0.80	-0.83	-0.84

Table 3 Air parameters at different temperatures

Temperature	ratio of the specific heat γ	Prandtl number *Pr*	thermal conductivity k (W/m·K)
0 ^{o}C	1.401	0.713	0.02428
25 ^{o}C	1.400	0.707	0.02624
50 ^{o}C	1.399	0.701	0.02816
75 ^{o}C	1.398	0.697	0.03003

Table 4 Static flying attitudes of the pico slider (shown in Figure 1) obtained with Zhou's model and with Zhang's and Chen's models

Heating power	Ambient temperature	Flying attitude	Zhou's model	Zhang's and Chen's models
40 mW	0^oC	Transducer FH (nm)	9.47	9.20
		Pitch (µrad)	148.91	148.41
		Roll (µrad)	0.079	-0.014
	25^oC	Transducer FH (nm)	8.44	8.36
		Pitch (µrad)	149.49	149.21
		Roll (µrad)	0.036	0.011
	50^oC	Transducer FH (nm)	7.31	7.22
		Pitch (µrad)	149.47	149.45
		Roll (µrad)	0.096	0.066
	75^oC	Transducer FH (nm)	5.87	5.87
		Pitch (µrad)	148.48	148.60
		Roll (µrad)	0.011	0.096
80 mW	0^oC	Transducer FH (nm)	5.08	4.76
		Pitch (µrad)	143.35	142.39
		Roll (µrad)	-0.26	-0.34
	25^oC	Transducer FH (nm)	4.16	4.01
		Pitch (µrad)	143.85	143.39
		Roll (µrad)	-0.27	-0.23
	50^oC	Transducer FH (nm)	3.36	3.28
		Pitch (µrad)	144.35	144.15
		Roll (µrad)	-0.36	-0.26
	75^oC	Transducer FH (nm)	2.29	2.33
		Pitch (µrad)	143.18	143.21
		Roll (µrad)	-0.43	-0.34

Table 5 Static flying attitudes of the Femto slider (shown in Figure 8) obtained with different HDI heat transfer models

		Ju's Model		Zhang's and Chen's Models	Zhou's model with 75°C	Zhang's and Chen's Models with 75°C
Heating power	Flying attitude	With viscous heating	Without viscous heating	Without viscous heating	Without viscous heating	Without viscous heating
200mW	Transducer FH (nm)	9.15	9.11	8.99	7.68	7.71
	Pitch (μrad)	103.65	103.81	103.26	103.45	103.70
	Roll(μrad)	-25.76	-25.58	-25.71	-26.15	-26.08

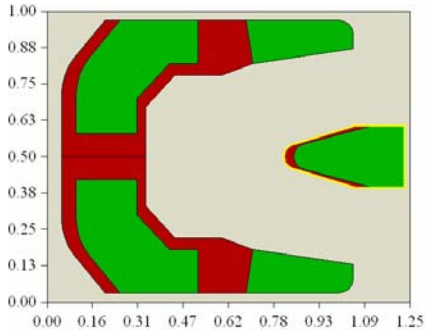


Fig. 1 Air bearing surface of an INSIC pico slider (unit: mm)

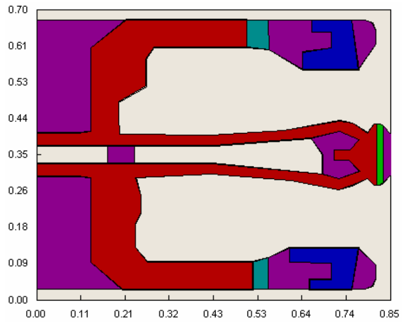
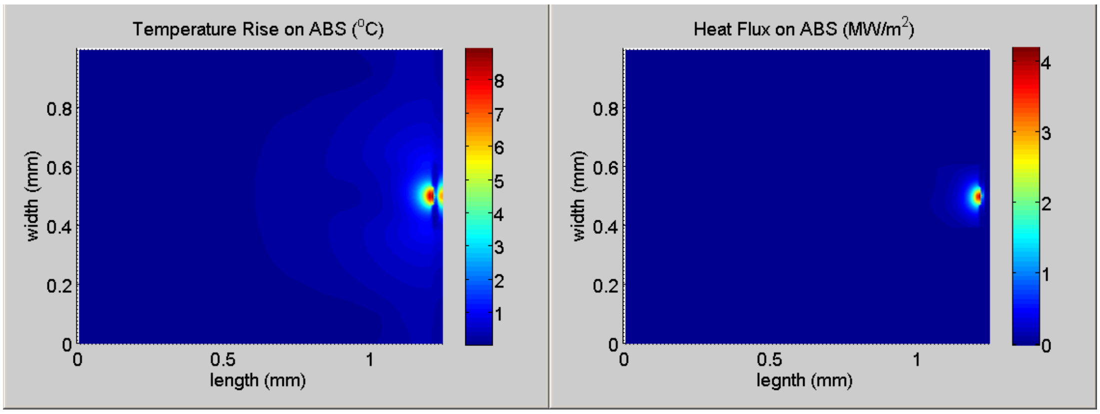
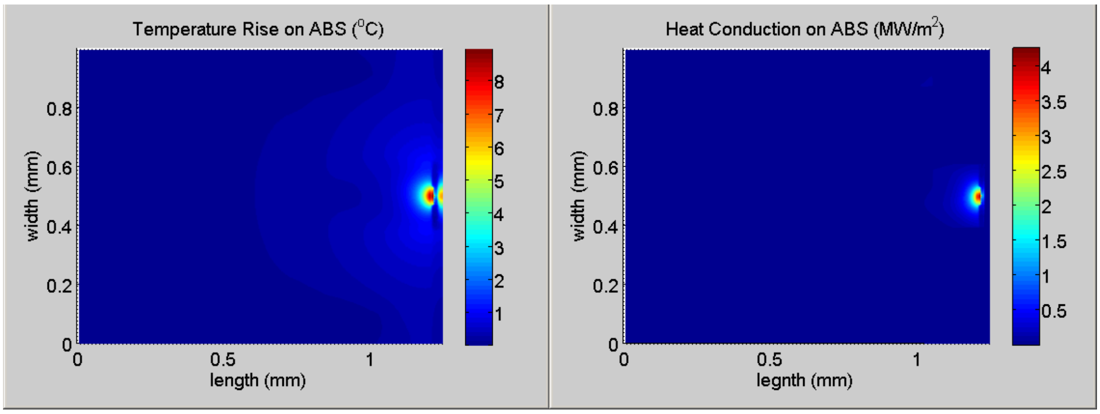


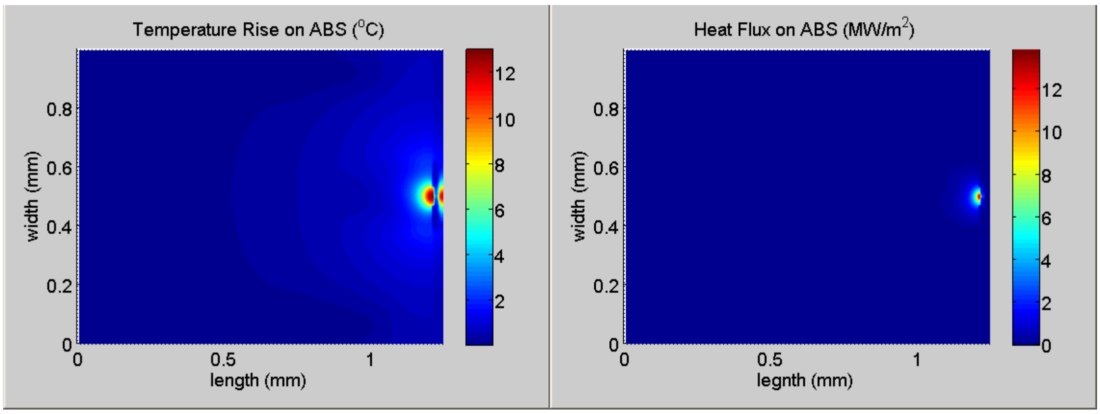
Fig. 2 Air Bearing Surface of a commercial femto slider (unit: mm)



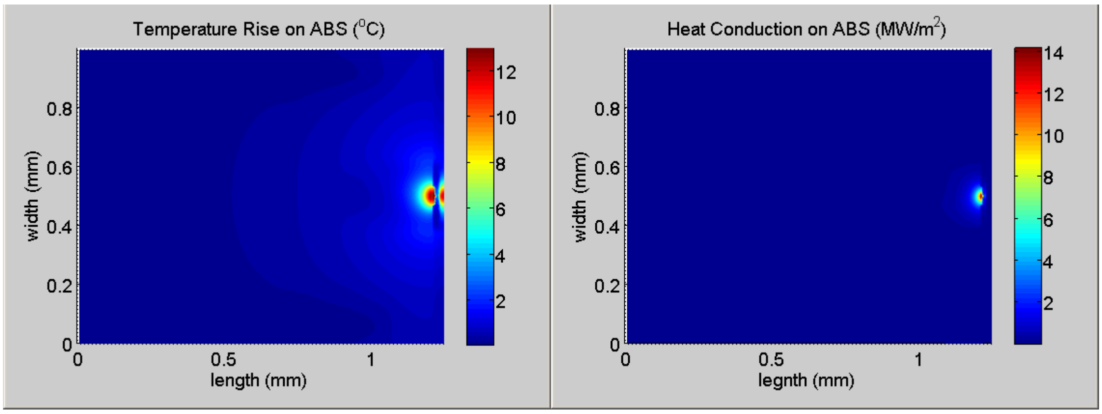
(a) 40 mW power considering the viscous heating contributed by the Couette flow



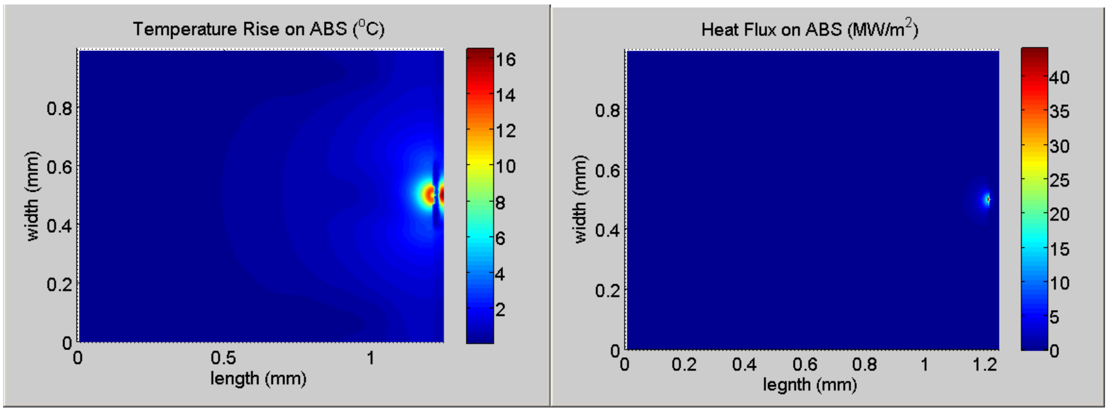
(b) 40 mW power without considering the viscous heating contributed by the Couette flow



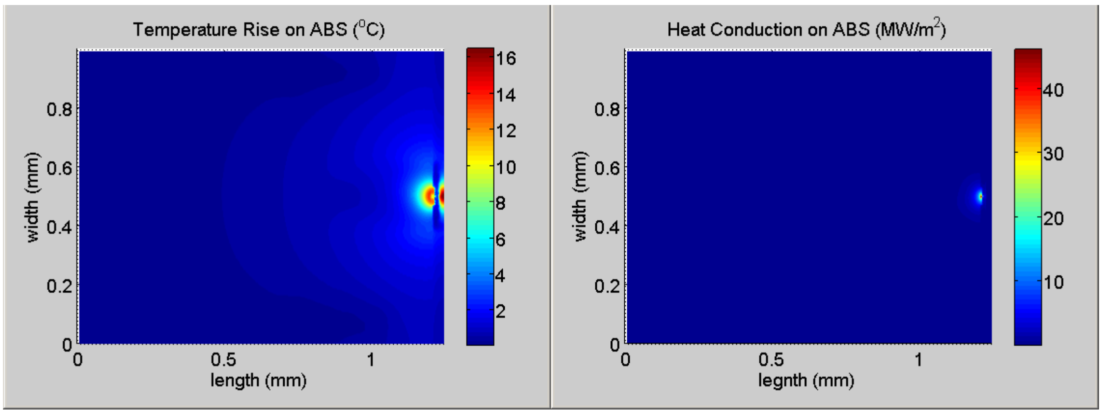
(c) 80 mW power considering the viscous heating contributed by the Couette flow



(d) 80 mW power without considering the viscous heating contributed by the Couette flow



(e) 120 mW power considering the viscous heating contributed by the Couette flow



(f) 120 mW power without considering the viscous heating contributed by the Couette flow

Fig. 3 Temperature and heat flux on the ABS at the static state flying attitude with and without considering the viscous heating for a heating power of 40 mW, 80 mW and 120 mW

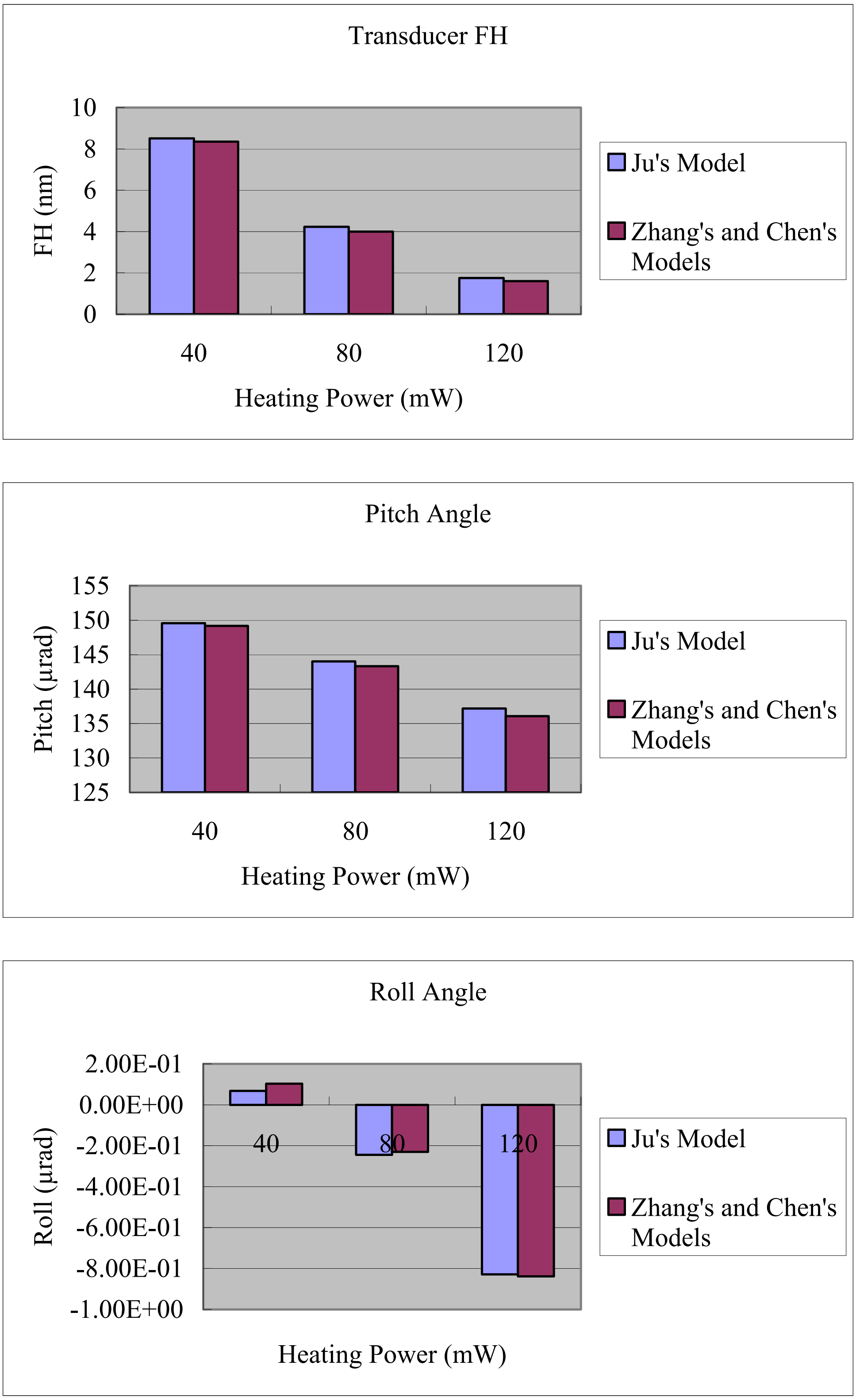
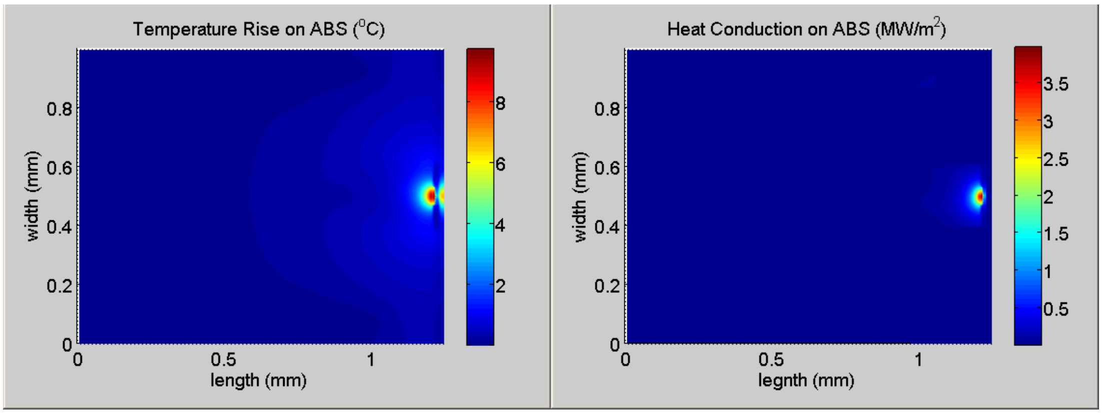
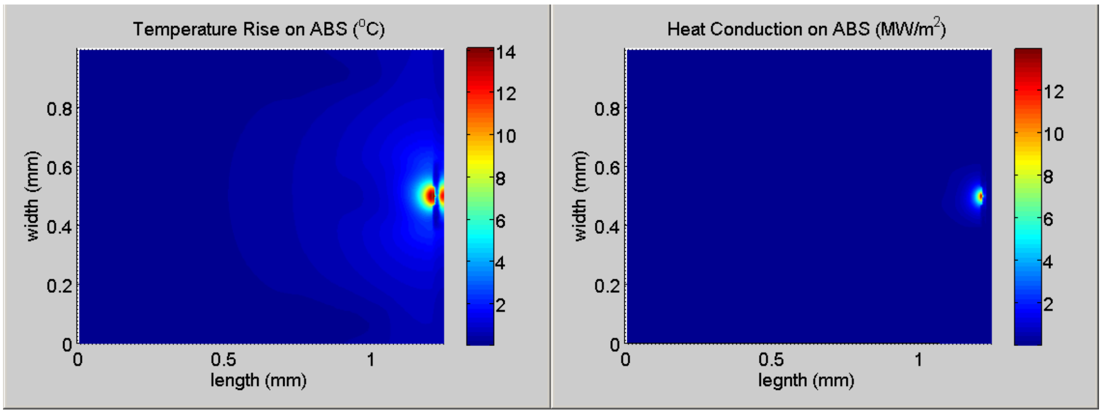


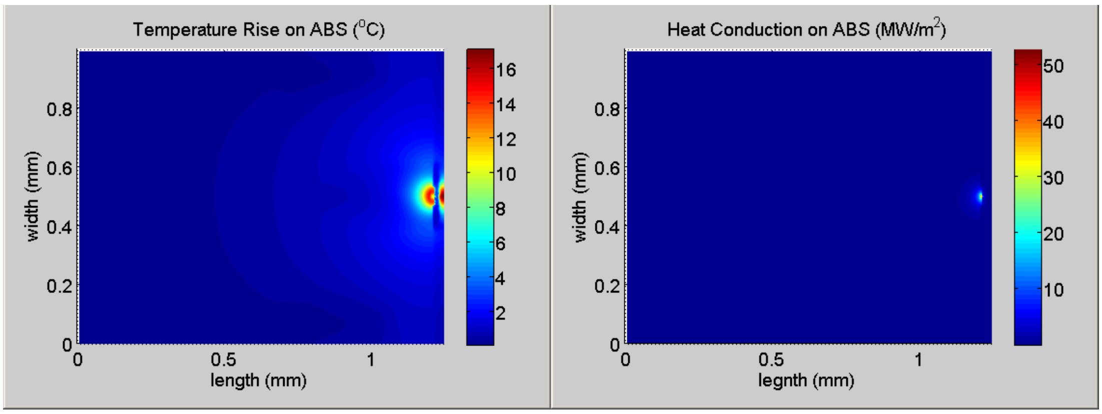
Fig. 4 Static transducer flying height, pitch and roll angles of the slider obtained with Ju’s model versus with Zhang’s and Chen’s models



(a) 40 mW heating power

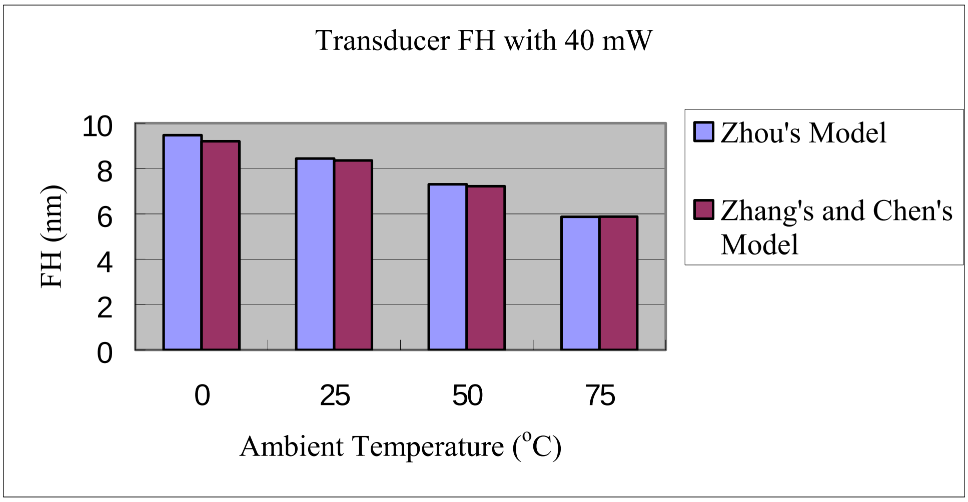


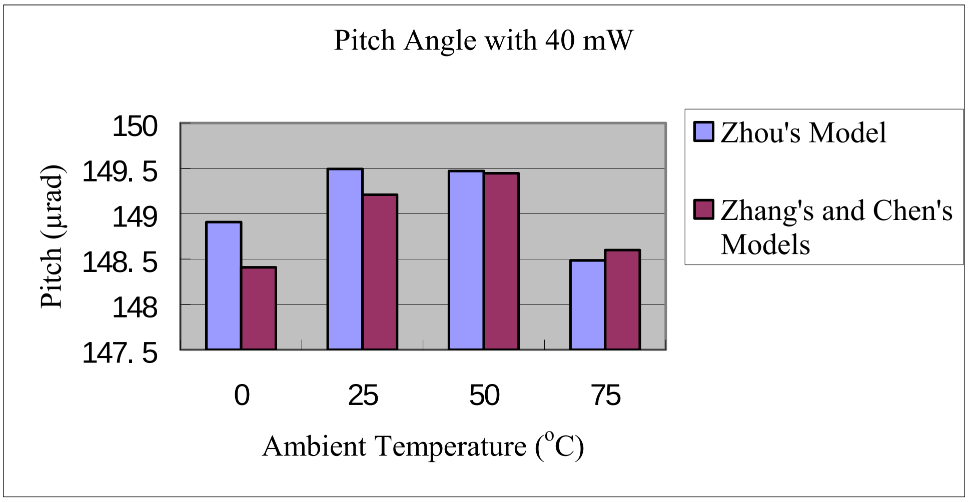
(c) 80mW heating power



(d) 120mW heating power

Fig. 5 Temperature and heat conduction flux on the ABS at the static state flying attitude obtained with Zhang's and Chen's models (the viscous dissipation is neglected)





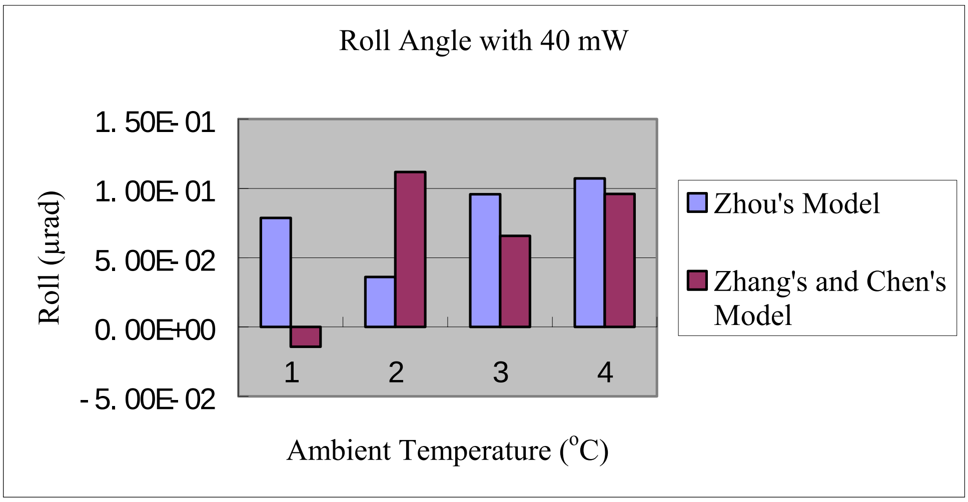


Fig. 6 Static transducer flying height, pitch and roll angle of the slider obtained with Zhou's model versus Zhang's and Chen's models with the heating power of 40 mW

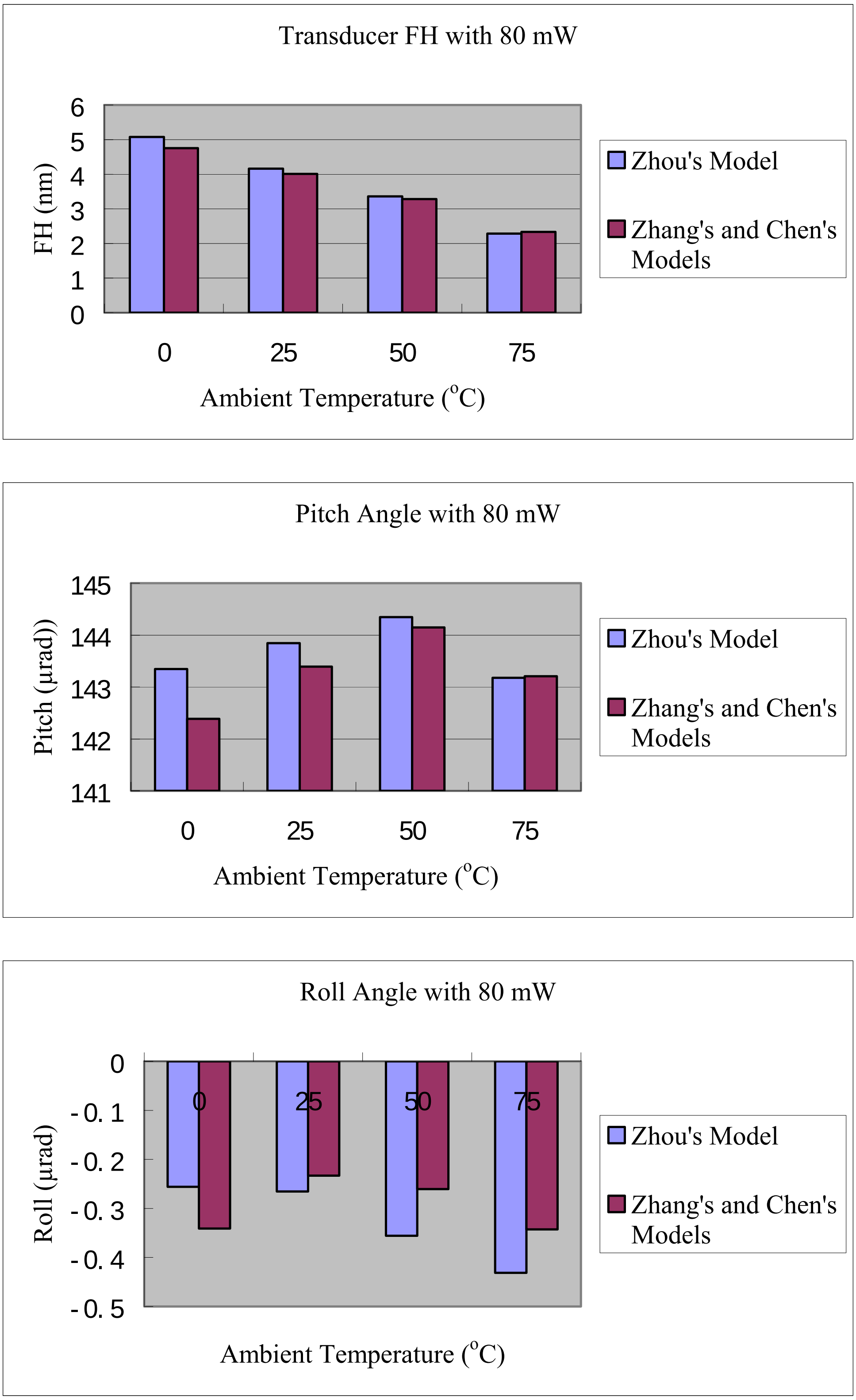
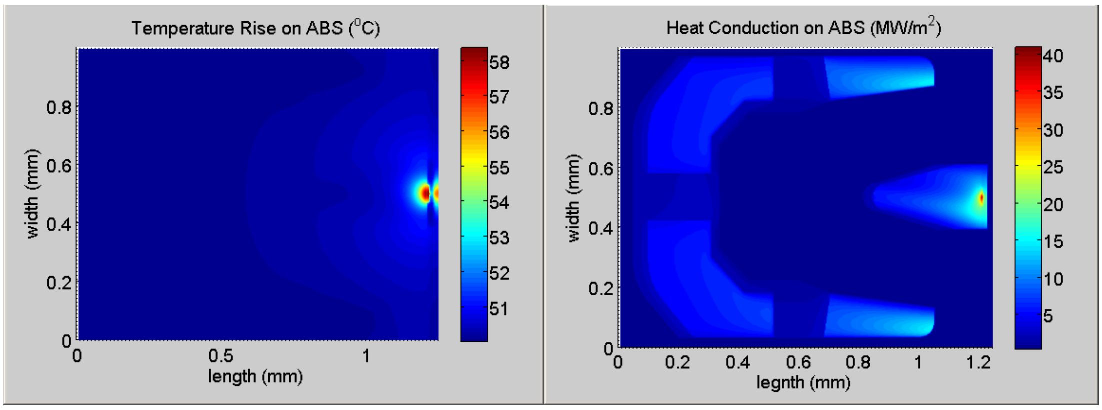
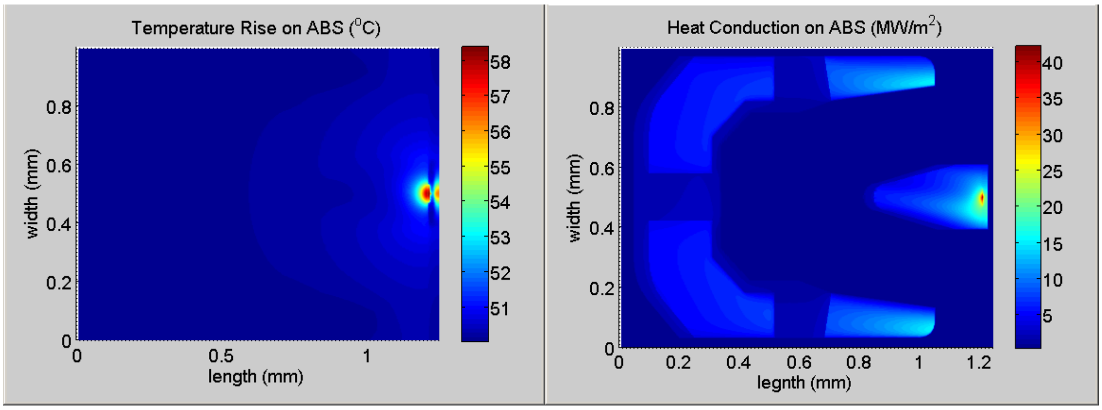


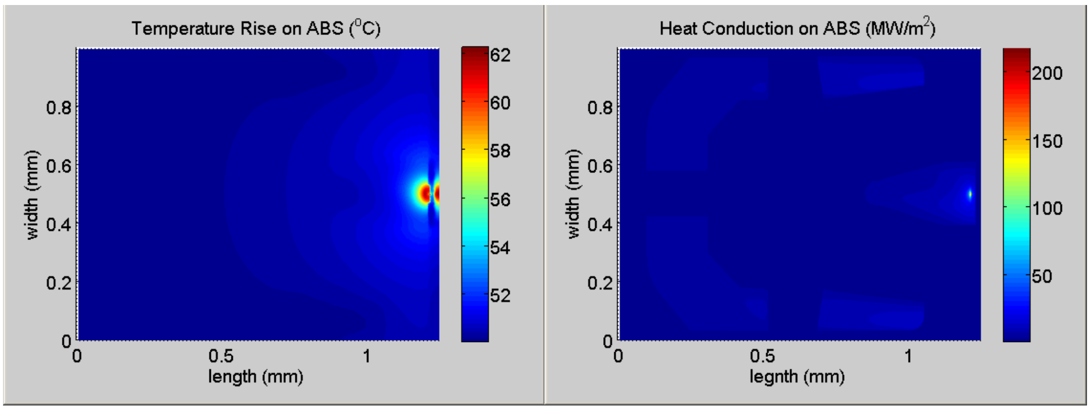
Fig. 7 Static transducer flying height, pitch and roll angle of the slider obtained with Zhou's model versus Zhang's and Chen's models with the heating power of 80 mW



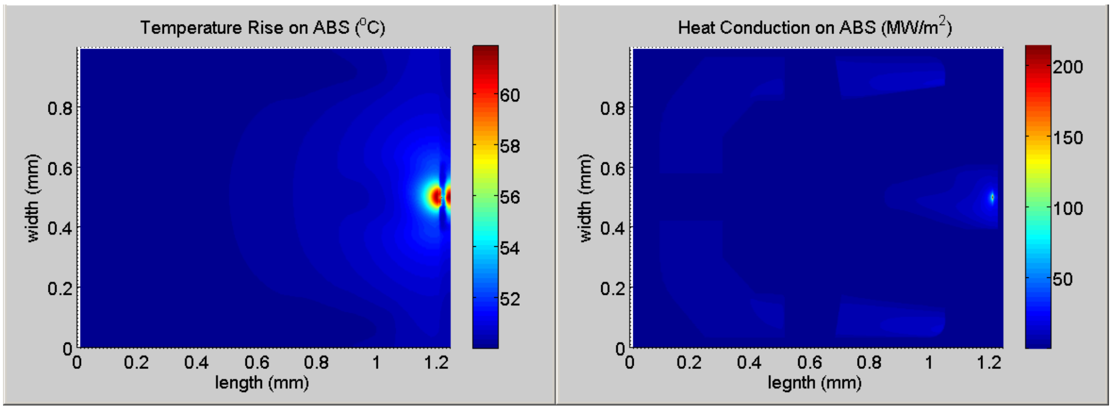
(a) 75 ^{o}C ambient temperature and 40 mW heating power with Zhou's model



(b) 75 ^{o}C ambient temperature and 40 mW heating power with Zhang's and Chen's models



(c) 75^{o}C ambient temperature and 80 mW heating power with Zhou's model



(d) 70°C ambient temperature and 80 mW heating power with Zhang's and Chen's models

Fig. 8 Temperature and heat conduction flux on the ABS at the static state obtained with Zhou's mdoel versus Zhang's and Chen's models (the viscous dissipation is neglected) at the ambient temperature of 70°C