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Simulation of Lubricant for Design of Magnetic Recording Systems under Laser Heating

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Simulation of Lubricant for Design of Magnetic Recording Systems under Laser Heating

Honors Project/Senior Design Project Report

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In Connection with Seagate Technology
Fremont, California

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ABSTRACT

Heat assisted magnetic recording is an advanced technology which can enable storage density increase in next generation hard disk drive. These drives are implemental in server (cloud) storage and the storage of large projects such as the Event Horizon Telescope which recently captured images of a black hole. The data is written on the magnetic surface by means of laser heating. The coercivity of magnetic medium is reduced by heating surface and within heating period data is written on disk. During the heating process, lubricant present on the disk might evaporate because of high temperature of laser and can accumulate on the slider which may reflow back to the dick after the end of heating process. This variation in the volume of lubricant on disk causes lubricant thickness variation, which may reduce efficiency of the process. Lubricant distribution and temperature distribution on disk & slider surface are evaluated with the help of lubricant film simulation.

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ABBREVIATIONS

HAMR	Heat Assisted Magnetic Recording
ABS	Air Bearing Surface
FEA	Finite Element Analysis

1. Introduction

In a today's fast-moving world, storing large amounts of data in a short volume is a challenge. Current technologies utilize a magnetic storage medium consisting of small magnetic grains, which are bitable with consistent magnetic capacity for almost a decade. An electromagnet is involved to write the data onto the storage medium, by passing over the rotating medium and generating a controlled magnetic field which manipulates the magnetic condition of these grains. Traditional disks have a minimum size for a magnetic field that is used to store data, making it difficult to write large amount of data in smaller regions.

HAMR is advance technique which temporarily heating the disk material during writing process, which reduces coercivity of magnetic material and allows writing to much smaller regions with large amount of data as shown in Figure-1.

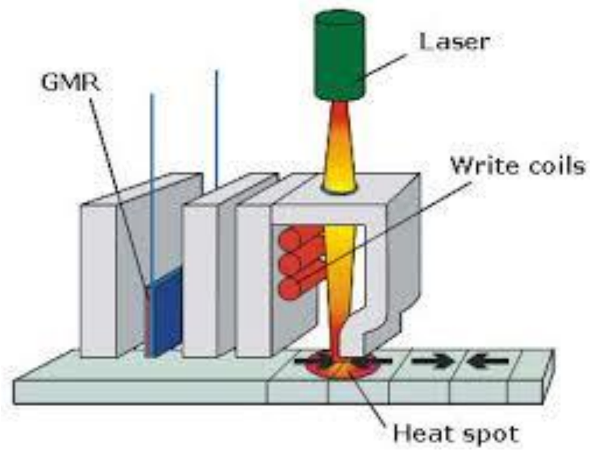


Figure 1: Heat Assisted Magnetic Recording

The coercivity defines ability of magnetic material to hold data and prevent it against any kind of external magnetic excitations. If coercivity is very high then it becomes difficult to write high amounts of data in small spaces. Coercivity of magnetic material needs to be reduced in order to fit high amounts of data in small spaces. The coercivity of the magnetic material is reduced by means of spot heating at thee location where data needs to be written. Laser heating process is used to spot heat location, because of which magnetic material losses its coercivity temporarily coils, and writes data in small space up to maximum capacity of magnetic material. Maximum data can be written as coercivity of material is not present temporarily. Once after data is written, within fraction of seconds, material is cooled down and regains its original coercivity, preventing written data from external magnetic excitations. During this heating process, the temperature of laser reaches up to 550°C which may cause lubricant to evaporate and accumulate on a slider changing in lubricant thickness. Lubricant accumulated on slider has bad effects on the performance. Apart from laser heating, there are other parameters which causes lubricant accumulation on slider surfaces. Air flow through the gap between slider & disk also carry out some of the lubricant from Air bearing surface. The effect of air flow and other design parameter on lubricant accumulation needs to be analyze.

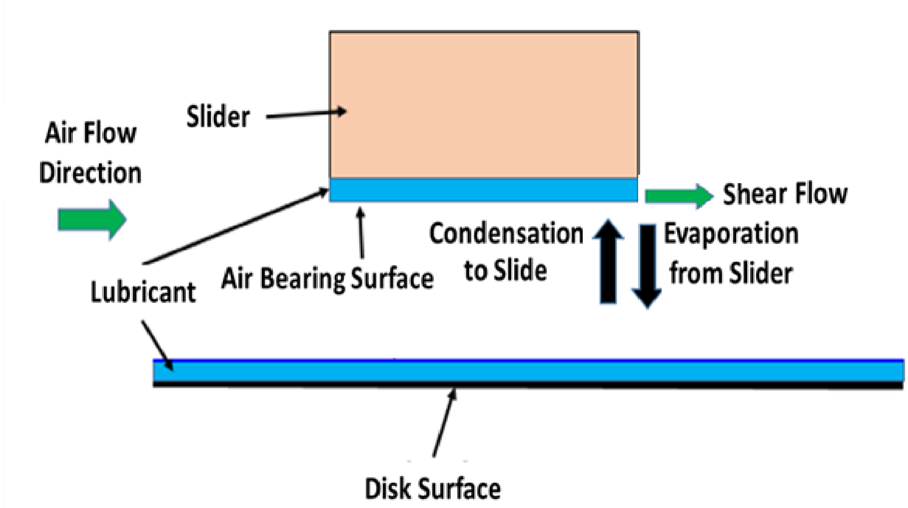


Figure 2: ABS Lubricant Accumulation on Slider

The lubricant which is moved by air flow gets accumulated on slider which is called as lubricant flow process. When air flow stops, lubricant accumulated on sliders may flow back to disk which is called as lubricant Reflow process. Both flow & reflow process needs to be analyzed to check effectiveness of air flow as well as design parameters on lubricant accumulation.

2. Project Definition

The scope of the project is to analyze effectiveness of air flow & ABS design parameters on lubricant accumulation. Experimental testing of ABS accumulation process is quite difficult and time consuming and hence, this process can be analyzed on multiphysics modeling tools. Simulation is a reliable tool to analyze physical problems on a various fundamental equation codes. Unsteady state/transient simulation will be carried out to check variation in Lubricant thickness with respect to time and two-dimensional simulations will be carried.

Necessity of Lubricant Film Simulation: multiphysics modeling is a tool that is being used extensively in industries to predict the flow behavior, acting forces, and pressure distribution. It also helps to know what kind of and what amount of forces are acting on the body. Flow behavior can be observed with simulation tools in initial design stage which helps to optimize design for better performances. The current problem involves liquid-air interface which needs multiphasic software for simulation. Flow of lubricant from ABS to slider is dependent on many factors (e.g. Air shear stress, Air pressure & disjoining pressure) of lubricant and air. These various factors need to be modeled with partial differential equations. This multiphase problem can be simulated in COMSOL Multiphase lubricant film modeling and simulation tool.

Software Overview: COMSOL Multiphysics is a cross-platform solver and multi-physics simulation software. It allows conventional physics-based user interfaces and coupled systems of partial differential equations (PDEs).

3. Partial Differential Equation for Simulations

In COMSOL, partial differential equation needs to be defined for simulation lubrication thickness problems. The first order partial differential equation is generated for simulating lubricant thickness and shear stress.

The following parameters affects lubricant thickness:

1. Pressure
2. Air Shear stress
3. Design Parameters

There are three types of pressure acting on lubricant; ambient pressure, disjoining pressure and surface tension pressure. Ambient pressure effect is captured in software in operating condition settings while disjoining pressure & surface tension pressure in lubricant needs to be consider for simulation. Disjoining pressure in lubricant can be calculated as,

$$P_\gamma = \gamma\left(\frac{\partial^2(h+h_s)}{\partial x_1^2} + \frac{\partial^2(h+h_s)}{\partial x_2^2}\right),$$

$$P_d = \frac{A}{(h+d_0)^3},$$

Where, Pa = Air Pressure

Pd = Disjoining Pressure

P_γ = Surface Tension Pressure

h = Lubricant thickness

d_0 = Molecular Cut off distance

$A=A_H=5\times10^{-20}$ J = HAMAKER Constant.

As disk has a flat surface and lubricant thickness is very small, surface tension developed in lubricant will be very small and hence surface tension pressure will be considered as zero in COMSOL setup.

$$P_\gamma=0$$

Now, $\frac{\partial P}{\partial x} = -\frac{\partial Pd}{\partial x} = -2\frac{\partial Pd}{\partial h}\frac{\partial h}{\partial x} = -(-3A(h+d0)^{-4})\frac{\partial h}{\partial x}$

This calculated pressure term can be used as function of x and y coordinates,

$$-(-3A(h+d0)^{-4})\frac{\partial h}{\partial x} \quad , -(-3A(h+d0)^{-4})\frac{\partial h}{\partial y}$$

Lubrication film thickness without condensation effect can be model with following equation with considering disjoining pressure effect,

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\tau_{xz}\,h^3}{2\mu}-\frac{3A}{3\mu}\,\frac{h^3}{(h+d_0)^4}\,\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\tau_{yz}\,h^3}{2\mu}-\frac{3A}{3\mu}\,\frac{h^3}{(h+d_0)^4}\,\frac{\partial h}{\partial y}\right)=0$$

y

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\tau_{xz}\,h^3}{2\mu}-\frac{A}{\mu}\,\frac{h^3}{(h+d_0)^4}\,\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\tau_{yz}\,h^3}{2\mu}-\frac{A}{\mu}\,\frac{h^3}{(h+d_0)^4}\,\frac{\partial h}{\partial y}\right)=0$$

……………………………………(1)

This equation is formed with shear stress and disjoining pressure effect on lubricant. τ_{xz} and τ_{yz} term defines shear stress for X & Y direction respectively. This lubricant film partial differential equation form will be used in COMSOL.

Initially, lubricant thickness, h is function of x, y and time t,

h=h(x,y,t)

At t=0

h=h(x, y, 0)=h0

At time t=0, lubricant thickness on disk is assumed as 4nm.

h0=4nm.

The governing equations involving the thickness of the lubricant film on the slider's surface (h) are given by equation (2), where **Γ** is the conservative flux, and f is the source term [2]–[6].

$$\frac{\partial h}{\partial t}+\boldsymbol{\nabla}\cdot\boldsymbol{\Gamma}=f \tag{2}$$

The conservative flux x and y components are given by equations (3) and (4) respectively, where τ(x,y) is the shear stress (equation (5)), μ is the effective viscosity, A_H is the Hamaker constant and d_0 is the Molecular cutoff distance [2]–[6].

$$\Gamma_x=\frac{1}{2\mu}\tau(x,y)h^2-\frac{A_H}{\mu}\frac{h^3}{(h+d_0)^4}\frac{\partial h}{\partial x} \tag{3}$$

$$\Gamma_y=-\frac{A_H}{\mu}\frac{h^3}{(h+d_0)^4}\frac{\partial h}{\partial y} \tag{4}$$

$$\tau(x,y)=\left\{\frac{\tau_{xz}\ \textit{in the lubricant domain}}{0\ \textit{otherwise}}\right\} \tag{5}$$

The source term f is given by equation (6), where R_{Cond} and R_{Evap} are respectively the condensation and evaporation rates and ρ is the lubricant density [2]–[6].

$$f=\frac{R_{Cond}(x,y)-R_{Evap}(h,x,y)}{\rho} \tag{6}$$

The evaporation/condensation rate $R_{Cond,Evap}$ is given by the expressions in equations (7) and (8), where P_0 is the bulk vapor pressure, M_n is the molecular weight, R is the gas constant, T is the absolute temperature, and $\Pi(t_d)$ is the disjoining pressure [7].

$$R_{Cond,Evap} = P_0\sqrt{\frac{M_n}{2\pi RT}}\cdot exp\left(-\frac{\prod(h)\,M_n}{-\rho RT}\right) \tag{7}$$

$$\Pi(h) = \frac{A_H}{6\pi(h+d_o)^3} \tag{8}$$

In summary, for any location (*x*, *y*), the lubricant thickness on the slider, *h*(*x*,*y*,*t*), is governed by the equation (9= (based on Ref. [1,2]),

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}\left[\frac{1}{2\mu}\tau_{xz}(x,y)h^2 - \frac{h^3}{3\mu}\frac{\partial \Pi(h)}{\partial x}\right] + \frac{\partial}{\partial y}\left[-\frac{h^3}{3\mu}\frac{\partial \Pi(h)}{\partial y}\right] = \frac{R_{cond}(h_d,T_d) - R_{evap}(h,T)}{\rho} \tag{9}$$

3. Model Description

As a conservative approach, lateral faces of slider are unfolded to locate them on same plane (XY plane) which makes model eligible for two-dimensional lubricant film simulation as shown in Figure 3. Now the model is resolved in two zone, inner rectangle & outer rectangle. Inner rectangle acts as a slider on a disk while outer rectangle acts as disk surface. Air flow coming from front end side of slider moves lubricant from ABS and accumulates it on deposit end of slider. Once after air flow stops, accumulated lubricant again flows back and spreads on disk surface which causes uneven distribution of lubricant and variable thickness.

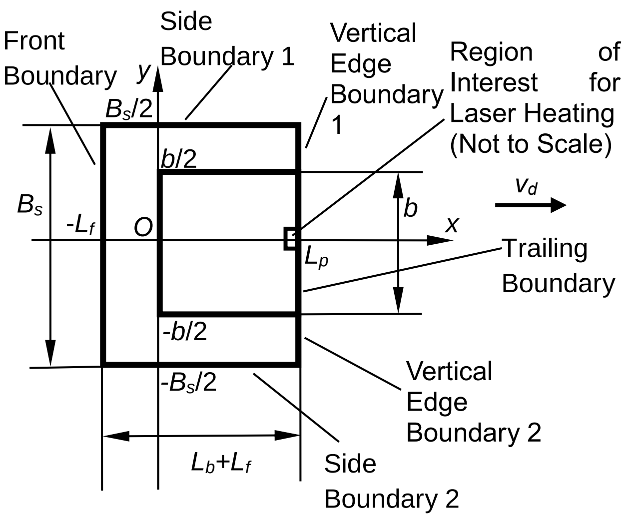


Figure 3: Domain model for ABS simulation

4. Lubricant Film Modeling and Simulation Strategy & Methodology

Two dimensional CFD model simulation of ABS model is carried out in COMSOL Multi-physics CFD tool. The initial case setup is done in order to set partial differential equations in COMSOL. The term which affects accumulation of lubricant are air shear stress, air pressure, disjoining pressure, air flow rate, slider skew angle and gap between slider & disk. The lubricant film simulation will be carried with all the variable parameters. Partial Differential Equation (PDE) is used to model air shear stress, air pressure, disjoining pressure effect with the help equation (1). PDE can be assigned in COMSOL.

COMSOL Model Setup:

1. 2D COMSOL Model is selected for PDE simulation.
2. Coefficient form of PDE is selected as a physics of model.
3. Parameters are imported in global definition setting by setting all values of dimensions and constants in notepad. Parameters referred for COMSOL PDE simulation is shown in figure below,

b	0.22[mm]	Base
Lp	.22[mm]	Length of pad
Tau_xz	(20/10.18)*(9.094E-9/Hf)*131.231[Pa]	Shear Stress XZ axis
mu	.144[Pa*s]	Viscosity of Lubricant
AH	5*10^-20[J]	Hamaker constant
d0	0.3[nm]	Molecular cutoff distance
h0	0.01[nm]	Initial lubricant height
Tau_yz	0	Shear Stress YZ axis
Bs	0.4[mm]	Outer rectangle base
Lf	.10[mm]	Outer rectangle position
Lb	.22001[mm]	rectangle length
P0	641.68*exp(-9.969*Mn)*133.322[Pa]	Bulk Vapor Pressure
T0	296.15[K]	Room Temp
R	8.314[J/(K*mol)]	R Gas Constant
Mn	2	Molecular Weight
rho	1.83E3[kg/(m^3)]	Lubricant Density
hd	1.5[nm]	Disk lubricant Thickness
PD_d	AH/(6*pi*(hd+d0)^3)	Disjoining Pressure
vd	Tau_xz*(9.094E-9/Hf)/eta_a	Velocity Disk
eta_a	1.8E-5[Pa*s]	Air Viscosity
Hf	2[nm]	Flying Height
Kf	(vd*eta_a)/(2*Hf*mu)	Flux coefficient
hes	h0	Lubricant Height Estimate
Tau	1.75[s]	Tau Time constant

Figure 4: Parameters in COMSOL

4. Coefficient form PDE from physics model is selected to define partial differential equation in COMSOL model. Partial differential equation form in COMSOL is given by Figure 5.

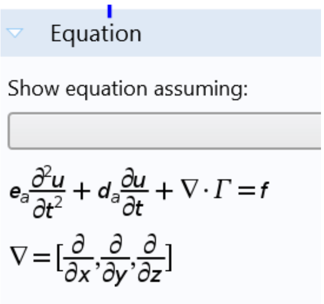


Figure 5: PDE Equation in COMSOL

5. Shear conditions on disk are defined by using analytic functions. Shear condition defines h0 and shear stress values on disk and sliders. Shear stress value on slider is zero (τ_{yz}=0). To define shear and h0 conditions on disk, 'if' loop is used in analytic, as shown in the expression text field shown in Figure 6.

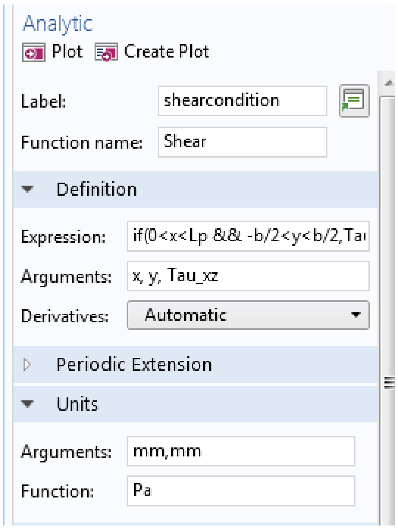


Figure 6: Shear condition in Analytic in COMSOL

If (0<x<Lp && -b/2<y<b/2,Tau_xz,0) Shear condition defines condition for region under small rectangle in Figure 3.

6. Dirichlet boundary conditions is applied on edges 1,2 and 3 of outer rectangle to define value of h.

7. Time dependent (unsteady) simulation type is selected in study to define simulation based on time and solution was solved for various time lengths. Figure 7 shows an example of 100 seconds with each 1 second time step. Solution is saved at every interval of a second (Figure 7).

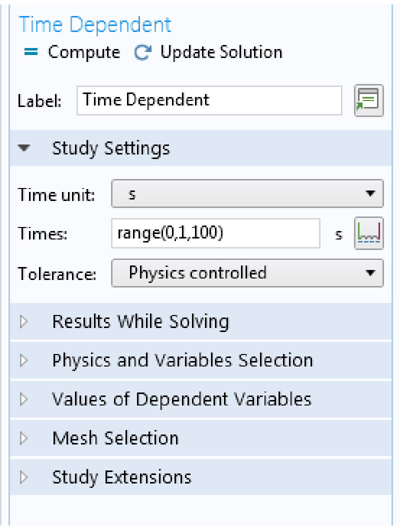


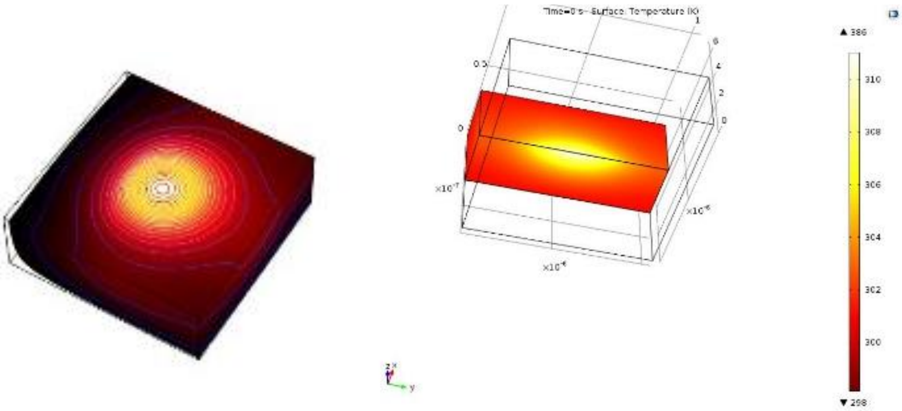
Figure 7: Solver Setting in COMSOL

5. Outcome of Lubricant Film Simulation

Outcomes of simulation in COMSOL Multiphysics are given below:

1. Lubrication thickness & distribution variation in three dimensions with lognormal approximation.
2. Temperature distribution in three dimensions with lognormal approximation.
3. Lubrication thickness at different time.
4. Graph of Lubricant volume with respect to time for various design parameters.
5. Velocity at different time.
6. Static & Total Pressure at different time.

The simulations were performed under the following conditions: v_d = 20 m/s, the lubricant is the perfluoropolyether (PFPE) lubricant Z-Dol 2000, with a molar mass M_n = 2 kg/mol and μ = 0.144 Pa-s [2], the air viscosity η_a =1.8 x 10^{-5} Pa-s, and parameters for disjoining pressure were based on Ref. [1]. The laser spot simulated has a full width at half maximum equal to 700 nm (free-space laser). The ambient temperature T_0 = 25°C.
The temperatures of the disk and slider due to laser heating were obtained from the finite element model (Figure 8). The temperature rise extends to a portion of the disk under the slider.



(a) (b)

FIGURE 8: Temperature distributions due to laser heating on (a) the disk surface, and (b) the slider surface.

As time advances, the average lubricant thickness on the trailing pad, h_{avs}, increases monotonically, approaching an asymptote (Figure 9). A decrease of flying height (9.1 to 2 nm) causes an increase in the shear stress at the air-lubricant interface, which enhances the lubricant flow off the trailing boundary, resulting in a reduced h_{avs}. The time needed to reach a steady state is reduced with increasing disk lubricant thickness.

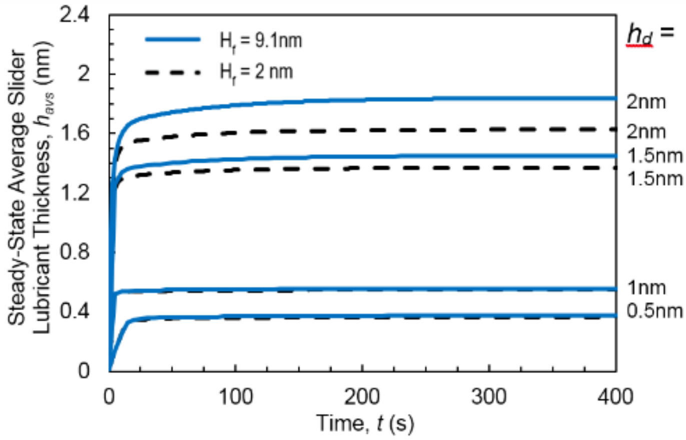


FIGURE 9: Average slider lubricant thickness versus time for different combinations of flying height, H_f, and disk lubricant thickness, h_d. (T = T_0)

The evolution of the lubricant distribution on the slider is shown in Figure 10. By 3.62s (see Fig. 10(a), the lubricant has already been deposited by condensation to the pad surface. A thicker deposition is observed at t = 10 s with some diffusion around the pad (see Fig. 10(b)). Diffusion to the front and side boundaries is obvious at 400 s, as shown in Fig. 10(c).

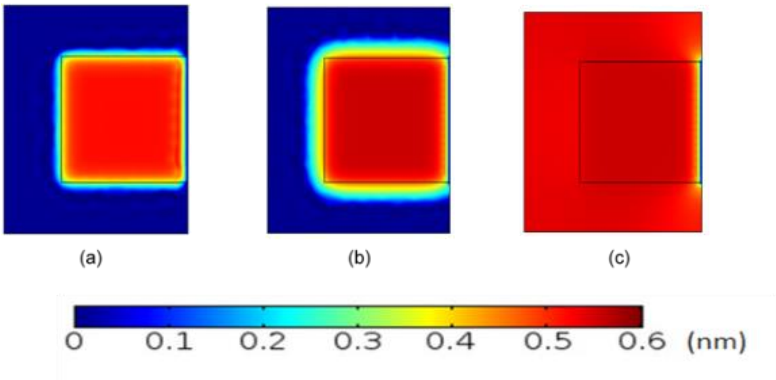


FIGURE 10: Lubricant distributions on the trailing pad of a slider at different elapsed times (h_d = 1 nm, H_f = 9.1 nm, T = T_0): (a) 3.62 s; (b) 10 s; (c) 400 s

With increasing disk lubricant thickness, h_d, the steady-state average slider lubricant thickness increases due to more evaporation from the disk (Figure 11). For larger disk lubricant thicknesses, this effect is significantly reduced with a decrease in flying height due to a greater loss of lubricant through shear.

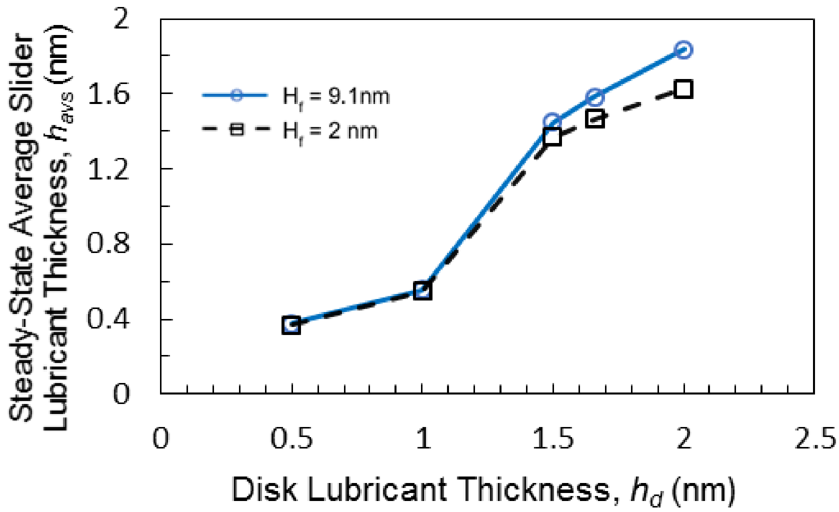


FIGURE 11: Steady-state average slider lubricant thickness, h_{avs}, versus the disk lubricant thickness for different values of flying height, H_f. (T = T_0)

6. Heating Effects and Considerations

The above simulation does not take into consideration how the heat generated from the laser affects the buildup of fluid on the disk or slider. Heating the lubricant may significantly affect the evaporation and condensation rate, therefore altering the fluid distributions. In an attempt to understand these effects, a model depicting the temperature distribution of the disk was created in COMSOL, using the heat transfer module.

7. COMSOL Heat Transfer Model

In order to understand the effects of the heat from the laser, a three dimensional model was developed using COMSOL. This was a time dependent model using the heat transfer in solids physics package. To represent the disk and the slider, two blocks were created and placed 2 nanometers apart with the block representing the slider sitting above the disk, as can be seen in figure 11.

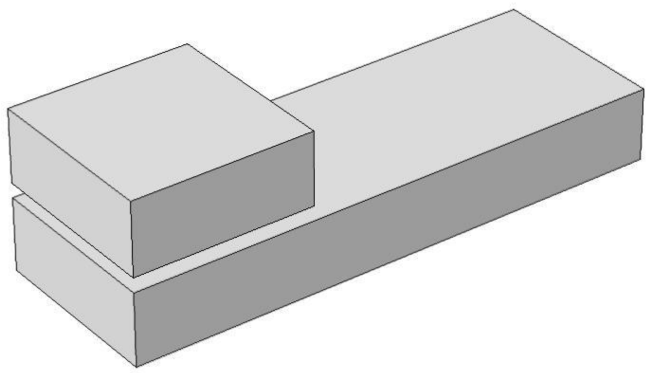


Figure 11: Disk and slider as blocks

This setup sets both the disk and the slider as a control volume upon which the laser will act. From there material properties were assigned to each block, with the slider being designated as aluminum from the standard material library, and the disk being designated as a custom material. The properties for this material can be seen in figure 12 below.

	Property	Name	Value	Unit	Property group
✓	Thermal conductivity	k	70	W/(m·K)	Basic
✓	Density	rho	7750	kg/m^3	Basic
✓	Heat capacity at constant pres...	Cp	3500	J/(kg·K)	Basic

Figure 12: Disk properties

These properties were selected based upon a previous study done by Drew Poling, Jeremy Huntington, Mohammed Al Mushref, and Jordan Solitro. Following this, boundary conditions and Initial values were established for heat transfer model. First a translational motion was applied to the disk in the positive X direction. From there the initial temperature of each domain was set to 298.15 degrees kelvin. Next a thermal insulation condition was applied to the side of the disk and slider as in figure 13.

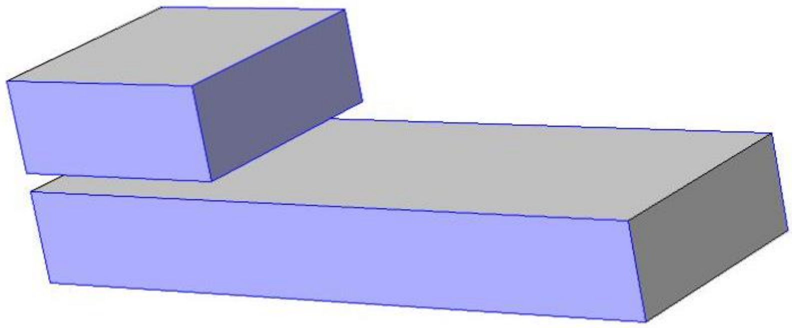


Figure 13: Insulation on disk and slider

After adding the insulation, the top surface of the disk, and the bottom surface of the slider were modeled as diffuse surfaces with an emissivity of 0.7. Then the bottom of the disk, the top of the slider, and the face in the negative X direction were set as thermal reservoirs with a temperature of 298.15 degrees kelvin as illustrated in figure 14.

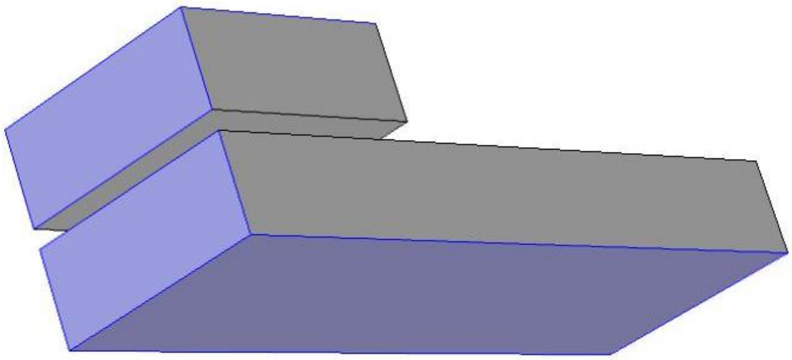


Figure 14: Thermal reservoirs

Finally came the setup for the heat from the laser. This was modeled as a general inward heat flux that followed a Gaussian pulse in the X and Y directions on the top surface of the disk. The standard deviation of the pulse was set as a third of the radius of the laser, and its maximum value was set equal to the laser's output power. The center was then shifted to position it in the correct place upon the disk. Later, the values for much of this setup was parameterized and can be seen in figure 15 below.

Name	Expression	Value	Description
v	5[m/s]	5 m/s	Translational velocity
P	30[mW]	0.03 W	Power
k1	70	70	Thermal conductivity of disk
c_p	3500	3500	Heat capacity of disk
r_spot	15[nm]	1.5000E-8 m	Radius of laser
T0	298.15 [K]	298.15 K	Initial Temperature

Figure 15: Model parameters

After the boundary conditions were selected, the mesh and solver were selected. For this model an iterative FGMRES solver was used. The mesh was designed as a custom sizing, with a maximum element size of 1.5E-9m and minimum of 7.5E-11m. These were the inputs used to model the temperature of the disk.

8. Heat Transfer Results.

The Heat transfer simulation yielded two useful plots, the first is a general temperature plot for the disk and slider system. The temperature contours of the simulated laser heating of the disk is shown in figure16 below.

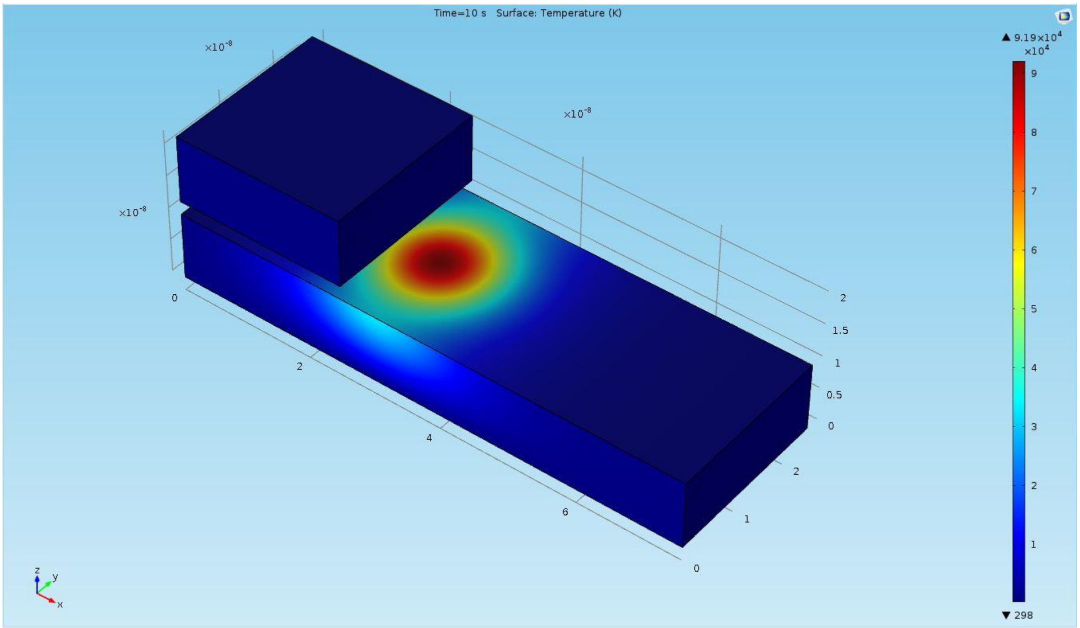


Figure 16: Temperature Contours.

The second useful plot show isothermal contours of the system, shown in figure 17.

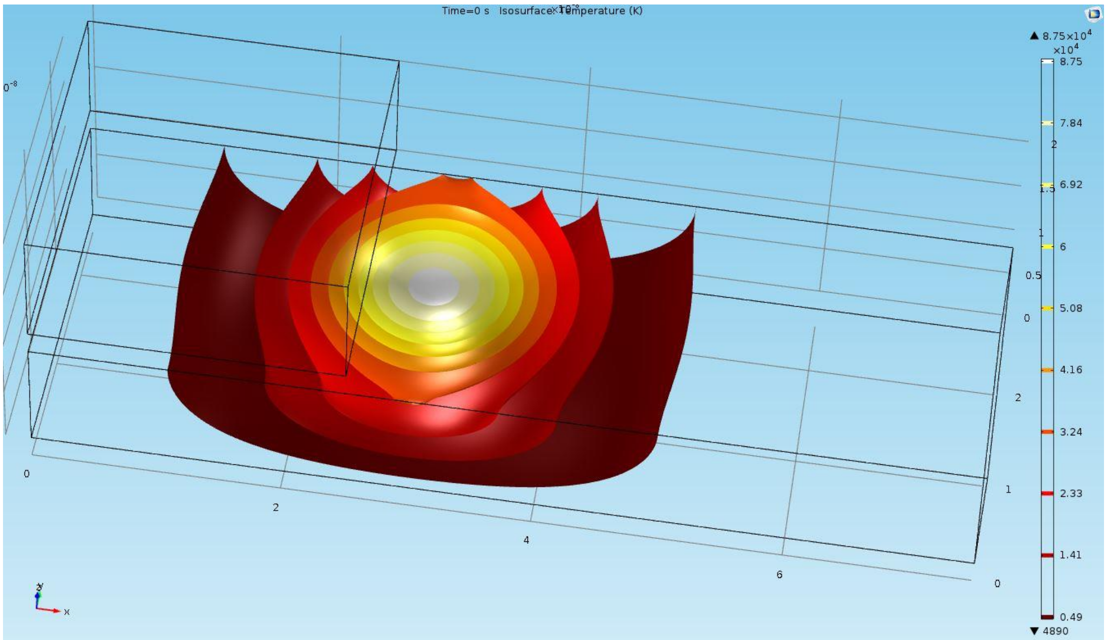


Figure 17: Isothermal Contours

These two plots show the effect of the laser's heating upon the disk. This information is quite useful as it may be used to influence the model. Current plans are being made to export the data from this model and import it into the COMSOL model to adjust the fluid transfer rates. However, the heat transfer model itself is incomplete as it does not take into consideration radiation from the disk to the slider. As such an improved model is being worked on to create a more accurate result.

9. Lubrication Results under Laser Heating and Disk Thickness Distribution

In a small region of interest for laser heating shown in Figure 3, specified by 218.6 μm ≤ x ≤ 220 μm (= L_p), -800 nm ≤ y ≤ 800 nm, the slider lubricant distributions are shown in Fig. 6 for different conditions. Compared to the reference case for the ambient conditions (Fig. 6(a)), the temperature rise due to laser heating near the trailing boundary caused a small "peninsula" region with raised lubricant thicknesses in addition to an overall rise of lubricant thickness (represented by the background color change) in this region (Fig. 6(b)). The shape of the lubricant "peninsula" seems to be a result of the combined effects of the diffusion and shear flow of the lubricant. Near the center-line (y = 0), the balance between the diffusion to the upstream and the shear flow to the down-stream would determine the length of the "peninsula" while the regions on the two sides (upper and lower areas in Fig. 6(b)) might not have sufficient lubricant to diffuse against the shear flow to the right, due to the relatively lower temperatures, thus resulting in no raised-lubricant region.

The influence of both the disk temperature distribution and changes in the local lubricant thickness on the disk is demonstrated in Figs. 6(c) and 6(d). A local decrease of the disk lubricant thickness in the form of an "indent," as the beginning part of a trough, is a physical phenomenon caused by lubricant evaporation from the disk and the thermal capillarity effect of the lubricant on the disk, as observed in the numerical solutions [3]. In the present study, this effect was explored by gradually increasing the maximum depth of an assumed spherical lubricant "indent," $(h_d)_{\max}$. When the maximum indent depth was set equal to 10% of the nominal disk lubricant thickness, i.e., $(h_d)_{\max}/h_d = 0.1$, the lubricant peninsula created by laser heating expanded slightly in the transverse (y) direction near the trailing boundary, as shown in Fig. 6(c). When the maximum indent depth reached 16%, or any percentage above it, the lubricant peninsula disappeared (Fig. 6(d)).

The disappearance of the lubricant peninsula can be explained by examining the influence of the disjoining pressure of the lubricant on the condensation term, R_{cond}, in Eq. (1). The disjoining pressure increases with a decrease of the disk lubricant thickness due to stronger intermolecular interactions of the lubricant molecules in a thinner film with the substrate [1]. Consequently, the raised disjoining pressure in the lubricant indent area will cause a significant decrease in the condensation term, thus reducing the original slider lubricant rise effect due to enhanced evaporation from the disk at elevated temperatures. These counteracting effects can eventually cause local cancellation of the disk temperature effect, thus eliminating the lubricant peninsula (Fig. 6(d)). Before the elimination, however, the effects of the lubricant indent might be to reduce the maximum lubricant rise at the peak of the raised peninsula and to make the lubricant thickness profile flatter, thus giving a slightly broadened transverse dimension of the lubricant peninsula near the trailing boundary (Fig. 6(c)).

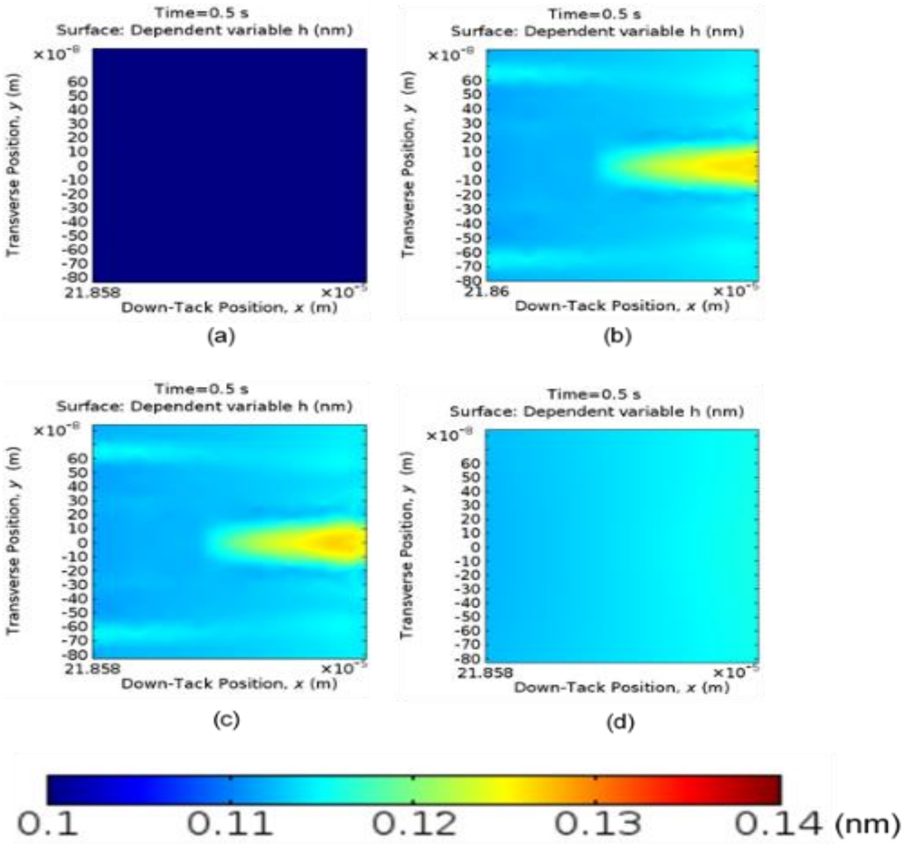


FIGURE 6: Local lubricant distribution on the slider affected by the local disk temperature rise and the local reduction of the disk lubricant thickness (h_d = 1 nm, H_f = 2 nm): (a) ambient conditions; (b) with the local disk temperature rise; (c) with the local disk temperature rise and a maximum local reduction of the disk lubricant thickness $(h_d)_{max}/h_d$ = 10%; (d) with the local disk temperature rise and $(h_d)_{max}/h_d$ = 16%

10. Conclusions

In conclusion Heat Assisted Magnetic recording is a complex process. In order to understand it more completely and improve upon current methods it is important to investigate the buildup of lubricant on both the disk and slider. To do so, two models were created using COMSOL Multiphysics. One model used lubricant film simulation predict how lubricant would move between the slider and disk, and another model used heat transfer to predict the temperature of the disk during this process. The disk slider system was simulated under various conditions to gain a better understanding of hard disk technology.

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