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Phenomenological Model of Heat Transfer in Hard-Disk Air Bearing Based on Nonlocal Behavior in Air

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Abstract-- In this paper, a new phenomenological model of heat transfer in hard-disk air bearing based on nonlocal behavior in air molecule is developed. Analysis of the model shows that it is a more accurate to simulate the behavior of heat transfer due to heat conduction and the viscous dissipation for Couette flow case. Since, assumption of the nonlocal behavior (in space) in air molecular, due to its scattering from the boundaries of the domain through which air flow is moved, allows us to eliminate deficiencies of continuum model, in particular, based on the temperature jump theory.

Index Terms-- lagging, molecular scattering, nonlocal, slide/disk air bearing.

I. INTRODUCTION

Heat transfer processes between a slider and disk surface in hard disk drives (HDD) is important issue. Indeed, to achieve higher areal density, the significant reducing the flying heights of air bearing to a few nanometers is required. In particular, to support areal density 10 Tbit/in², the flying height has to be less than 4 nm. Recently, the Thermal Fly-height Control (TFC) technology has been designed to provide such a nano-scale flying height [1, 2]. In TFC technology, a microheater embedded in-situ slider is used to control the protrusion and gap by means of measuring Joule heating current. Moreover, a nano-level slider-disk gap leads to a thermal deformation of the slider's air bearing surface as well as air bearing cooling affect which have a great influence on a performance of HDD [3-4]. Thus, it becomes a very important to accurately describe heat transfer in hard-disk air bearing, in order to provide further HDD improvement.

To solve this issue, S. Zhang and D.B. Bogy proposed the analytical heat transfer model in a thin slider/disk air bearing based on the reduced Navier-Stokes equation with velocity slip and

temperature jump boundary conditions [5]. Then Chen et al. extended result of Zhang's work by accounting for the pressure gradient and their model agreed well with experiment for the flying heights of air bearing between 80 and 100 nm [6]. In works [7-9] the mean free path of air's molecular was modified and applied to the conduction heat flux model proposed by S. Zhang and D.B. Bogy. It is important to note that, in mentioned above studies, bulk values of thermal conductivity and viscosity are assumed to be constant. However, this fact is at variance with reality and required the further analysis.

Other approach to study of heat transfer in the slider/disk interface is to use the direct simulation Monte Carlo method, which was shown in [10]. This method allowed analyzing numerically to study the heat conduction as well viscous dissipation induced by plane Couette flow. Author showed that the heat conduction model proposed by S. Zhang and D.B. Bogy is held.

In work [11] the authors developed a model based on the linearized Boltzmann equation. However, from the point of view of the contribution of viscous dissipation in heat transfer in the slider/disk interface, there is no consistency between continuum Zhang's model and model based on the linearized Boltzmann equation.

To fill this gap, in this study we propose continuum model based on the assumption of the nonlocal behavior [12] in air molecule heat transport in the slider/disk interface.

II. NONLOCAL BEHAVIOR IN AIR MOLECULE. GOVERNING EQUATION IN AIR BEARING

In this analysis, a slider/disk interface can be represented as a channel between two boundary plates in which air flow moves along these plates. The top plate is movable. We consider in this analysis a steady state; hence, the time dependent terms in the related equations disappear. Assuming the nonlocal behavior (in space) in air molecular due to its scattering from the boundaries of the domain through which air flow is moved, we can write the following equation similar form to Fourier's law along the x axis:

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$$q''(s+l_q, x) = -k \frac{\partial T}{\partial x} \quad (1)$$

and Newton's law of viscosity :

$$\varphi(s+l_\varphi, x) = \mu \frac{\partial u}{\partial x}, \quad (2)$$

where q'' is the heat flux, T is the temperature, l_q is the length measuring the nonlocality of the heat flux, k is the bulk value of the thermal conductivity of air, φ is the shearing stress, u is the y axis component of air flow velocity, μ is the bulk value of the dynamic viscosity of air, l_φ is the length measuring the nonlocality of the shearing stress, s is the size of the domain along the x axis through which air flow is moved. Equations (1) and (2) are the basic assumption of this study.

The net heat transfer between the two bounding surfaces of Couette flows can be computed by subtracting the viscous heating term from the heat conduction term:

$$q_n'' = \frac{k(1-e^{-s/l_q})}{s}(T_s - T_d) - \frac{\mu(1-e^{-s/l_\varphi})}{s}U^2. \quad (3)$$

where U is the disk velocity, T_s and T_d are surface temperatures of the slider and disk, respectively, $l_q = 3l$, $l_\varphi = 3\text{Pr} \cdot l$, Pr is the Prandtl number, l is the mean free path of air molecule. Thus, Eq (3) is phenomenological model of heat transfer in hard disk air bearing based on nonlocal behavior in air molecule.

III. RESULTS

Proposed model (3) is compared with known models, namely, based on temperature jump theory by Zngang and Bogy [5], kinematic theory by Shen and Chen [11], Monte Carlo simulation by Ju [10]. For comparing, the following non-dimensional form is used

$$Q_n = \frac{lq_n''}{k(T_s - T_d)} = Q'' - Q_v''\tilde{U}^2, \quad (4)$$

where $D = s/l$ is the inverse Knudsen number, $\tilde{U}^2 = \left(U / \sqrt{R(T_s - T_d)} \right)^2$, R is the gas constant.

$$Q'' = \left(1 - e^{-\frac{D}{3}} \right) / D, \quad Q_v'' = \frac{4}{15} \left(1 - e^{-\frac{D}{3\text{Pr}}} \right) / D.$$

Results are shown in Fig. 1 and Fig. 2. We show that the new model prediction for heat conduction agrees well with known models namely based on Boltzmann equation and the temperature jump theory. For the viscous dissipation due to Couette flow, the new model prediction qualitatively agrees with models base on Boltzmann equation and Monte Carlo simulation. The new model prediction agrees quantitatively well with model based on Monte Carlo simulation, the difference is

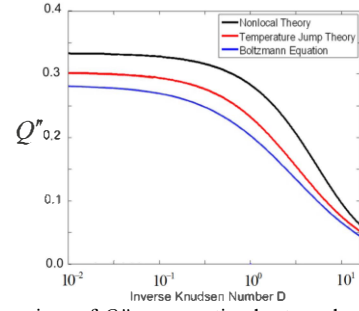


Fig. 1. Comparison of Q'' , representing heat conduction between two parallel plate obtained from nonlocal theory with other existing solutions.

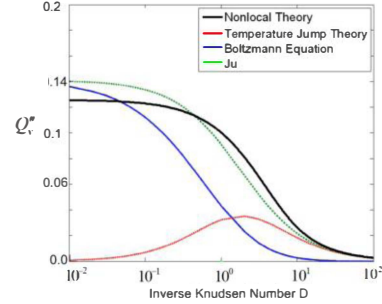


Fig. 2. Comparison of Q_v'' , representing viscous dissipation due to Couette flow between two parallel plate obtained from nonlocal theory with other existing solutions.

less the 7%.

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