Boundary Effect on Particle Motion in the Head Disk Interface

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ABSTRACT

Simulation of particle motion in the Head Disk Interface (HDI) aids in the understanding of the contamination process on a slider, which is critical for achieving higher areal data densities in hard disk drives. In this paper, the boundary effect—the presence of the slider and the disk—on particle motion in the HDI is investigated. A correction factor to account for this effect is incorporated into the drag force formula for particles in a flow. A contamination criterion is provided to determine when a particle will contaminate a slider. The contamination profile on a specific air bearing surface is obtained, which compares well with experiments.

Keywords: air bearings, particle contamination,

1. INTRODUCTION

To achieve higher areal densities in hard disk drives, the minimum flying height of the slider that carries the read/write transducer needs to be lower. The current goal of more than 1Tbit/in^2 requires that the minimum flying height to be less than 5nm. Among other problems this requirement poses, contamination on the air bearing surface (ABS) is also important. The contamination particles on a slider can cause the slider to loose its flying stability and crash, possibly causing damage to the disk and/or resulting in the loss of data. Specific designs used to reduce contamination can be seen on some contemporary commercial sliders, but the physical mechanism of contamination is still unclear, and it needs to be further investigated. The study of the contamination mechanism will be useful for designing specific slider features to reduce the contamination.

Due to the low volume fraction of particles in the HDI, which is less than 1%, the influence of the particles on the flow field is localized, i.e. their presence does not change the flow field near other particles. So the presence of other particles can be neglected when calculating the forces on a particle moving in this flow field. Likewise, the collision between particles is also negligible, and the trajectory of particles can be calculated separately. The general governing equation for a particle moving in a flow filed is quite complex [1, 2], but it can be simplified for the current problem based on the analysis of the order of different terms. It turns out that only the drag and lift forces as well as other microscale forces, if present, need to be considered. The effect of Brownian motion is also negligible due to the large Peclet number [3], which can be seen as a measure of the relative importance of Brownian motion compared with non-colloid motion. The larger the Peclet number the less important the Brownian motion.

Under the above assumption, Zhang and Bogy [4] studied the particle motion in a HDI. They found that for particles of radius less than 100nm, the lift force is unimportant and the particles move in a plane parallel to the disk. But for larger particles and particles crossing the transition region between a leading pad and the recess region, the lift force is important, and it induces the particle to move upward toward the slider and finally contact the slider. Shen *et al.* [5] noticed that the vertical (perpendicular to the disk) air velocity is not negligible for a particle moving in the transition region. They derived an approximate formula to calculate the corresponding drag forces. Their particle contamination results compared better with experiments.

In this report, we use essentially the same approach as Zhang and Bogy [4] and Shen and Bogy [2, 5]. The drag force formula is improved over those references by considering the influence of the slider and the disk. To be more specific, we incorporate the boundary effects, i.e. the influence of the slider and disk on particle motion in the HDI, and we propose a new contamination criterion.

2. KINETIC EQUATION FOR PARTICLE MOTION

The motion of each particle in the HDI is governed by Newton's equation:

$$m\frac{d^2\mathbf{r}}{dt^2} = \mathbf{F}_{saffman} + \mathbf{F}_{drag} + \mathbf{F}_{gravity} \tag{1}$$

where three forces are considered. The drag force is due to the velocity difference between the particle and the local flow field. The Saffman force is induced by the gradient of the air flow field around a particle and is perpendicular to the shear direction. Due to the low rotation velocity of the particle, and the Magnus force, which is due to particle rotation and is perpendicular to the axis of rotation, can be neglected [4].

The formula for each force is:

a) Drag force:

$$\mathbf{F}_{drag} = \frac{\pi}{2} C_d C_w \rho_g R^2 \left\| \mathbf{u_g} - \mathbf{u_p} \right\| (\mathbf{u_g} - \mathbf{u_p}) \tag{2}$$

where C_d is the drag coefficient for a particle moving in a rarified gas field extending to infinity [6], C_w is the correction factor due to the presence of the slider and/or the disk, R is the radius of the assumed spherical particle, ρ_g is the air density, $\mathbf{u_g}$ is the air velocity and $\mathbf{u_p}$ is the particle velocity. Previously the correction factor C_w used by Zhang and Bogy [7] was valid only for a sphere moving at some specific location between a slider and a disk. One of our goals in this paper is to get a more general correction factor C_w that is uniformly valid.

b) Saffman force: [8]

$$F_{saffman} = \frac{9}{\pi} J \mu R^2 \Delta U \sqrt{\frac{G \rho_g}{\mu}} \tag{3}$$

where μ is the air viscosity, ρ_g is the air density, ΔU is the magnitude of the particle velocity relative to the air flow, G is the velocity gradient of the air flow, and J is expressed as

$$J = \frac{\pi^2}{16} \left(\frac{1}{\varepsilon} + \frac{11}{6} l_w^* \right)$$

where $\varepsilon = \dfrac{\sqrt{G\mu / \rho_g}}{\Delta U}$ and $l_w^* = \sqrt{\dfrac{G\rho}{\mu}} l_w$

c) Gravity force:

$$F_{gravity} = \frac{4}{3} \pi R^3 (\rho_g - \rho_p) g \tag{4}$$

where ρ_p is the particle density and g is the acceleration of gravity.

3. BOUNDARY EFFECT ON PARTICLE MOTION

First we consider the case where a particle moves near a plane wall. Because of the extremely low Mach number, which is defined as the ratio of air speed to the local speed of sound and is about 0.03 for a slider flying over the outer track of a typical disk, the effect of compressible flow on the drag force can be neglected. The Reynolds number is the ratio of the inertia force to the viscous force, and it is defined as $\mathrm{Re}=UR\rho_g/\mu$. The air viscosity is not a function of air pressure and is about $2\times10^{-5}\mathrm{Nm/s^2}$ at room temperature. For a particle whose diameter is around 100nm and moves at a speed of 10m/s, which is of the same order as the disk speed, the Reynolds number is about 0.1. In view of the low Reynolds number, the flow is of Stokes type.

For a Stokes flow, where the inertia effect is unimportant compared with viscous effects, the nonlinear Navier-Stokes equation reduces to the linear Stokes equation. Due to the linearity of the equation, there is a linear relationship between the drag force and the velocity [9, 10]. Written in matrix form, this relation is

$$\mathbf{F}=\mathbf{AV} \tag{5}$$

where **F** is the drag force and **V** is the particle velocity. The matrix **A** connecting the force and velocity is called the "resistance matrix". Due to the symmetry of the current problem, Eq. (5) reduces to

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \begin{pmatrix} A_{xx} & & \\ & A_{yy} & \\ & & A_{zz} \end{pmatrix} \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} \tag{6}$$

where only the nonzero entries are shown.

To determine the nonzero entries appearing in the above matrix, we need to solve the

Stokes equation for different motions. An analytical formula has been derived for a spherical particle moving perpendicular to a plane, and this solution involves summation over an infinite number of terms. For a particle moving parallel to a plane, we instead need to solve a system of equations for the drag force. Either of them can be directly and efficiently used in Eq.(2) to get the drag force. But for limiting cases in which the particle moves far from or close to a plane, asymptotic results exist [11]. Here we propose to get a uniformly valid simple formula by combining the two limiting cases. The formula is

$$\mathbf{F}^{\mathbf{I}} = \mathbf{F}^{\mathbf{I}}_{far}(1-e^{-\beta_1\frac{\delta}{R}}) + \mathbf{F}^{\mathbf{I}}_{close}(e^{-\beta_2\frac{\delta}{R}}) \qquad (7)$$

where $\mathbf{F}^{I}_{far}$ is the drag force on a particle moving far from a wall, while $\mathbf{F}^{I}_{close}$ is that on a particle moving close to a wall, β_1 and β_2 are parameters to be determined by nonlinear regression to minimize the errors of this formula, δ is the gap between the particle and the wall and R is the radius of the particle, as shown in Fig. 1.

For different particle motions relative to a wall, the formulae are:

a) For a particle moving perpendicular to a wall:

$$\frac{F^I}{6\pi\mu UR} = \left[1-\frac{9}{8}\frac{R}{z}+\frac{1}{2}\left(\frac{R}{z}\right)^3\right]^{-1}(1-e^{-0.1\frac{\delta}{R}}) + \left\{\left[\frac{R/z}{1-R/z}\right]-\frac{1}{5}\ln\left[\frac{R/z}{1-R/z}\right]+0.9712\right\}e^{-0.08\frac{\delta}{R}} \qquad (8)$$

The two asymptotic results, F^I_{far} and F^I_{close} can be found in [10].

b) For a particle moving parallel to a wall:

$$\frac{F^I}{6\pi\mu UR} = \left[1-\frac{9}{16}\frac{R}{z}+\frac{1}{8}\left(\frac{R}{z}\right)^3-\frac{45}{256}\left(\frac{R}{z}\right)^4-\frac{1}{16}\left(\frac{R}{z}\right)^5\right]^{-1}(1-e^{-2.93\frac{\delta}{R}}) + \left\{\left[-\frac{8}{15}\ln\left(\frac{z}{R}-1\right)\right]+0.9588\right\}(e^{-2.68\frac{\delta}{R}}) \qquad (9)$$

Figure 2 compares Eq. (8) with the Brenner's exact results [9] for a particle moving perpendicular to a wall. As shown in the figure, the relative error is around 2%. Similar results are also available for Eq. (9).

The next step is to determine the effect of two walls–the slider and the disk–on a particle moving between them. Although this problem can be solved via boundary collocation or a boundary integral equation method, the result is not analytical and can not be efficiently incorporated in Eq. (2) as a correction factor. However, by using the method of reflection, an approximate formula was derived based on Eq. (7) [12][13]:

$$\mathbf{F}^{\mathbf{II}}(z) \approx \mathbf{F_0} + \sum_{n=0}^{\infty}[\mathbf{F}^{\mathbf{I}}(z+nd) - \mathbf{F}_0] + \sum_{n=0}^{\infty}[\mathbf{F}^{\mathbf{I}}(nd-z) - \mathbf{F_0}] - 2\sum_{n=1}^{\infty}[\mathbf{F}^{\mathbf{I}}(nd) - \mathbf{F_0}] \qquad (10)$$

where $\mathbf{F}^{\mathbf{II}}$ is the drag force on a particle moving between two walls, $\mathbf{F}^{\mathbf{I}}$ is the drag force derived from Eq.(8), $\mathbf{F}_0=6\pi\mu\mathbf{U}R$ is the Stokes drag force ($\mathbf{U}$ is the particle velocity), d is the distance between the two walls, and z is the distance from the center of the particle to the lower wall, as shown in Fig. 3.

Figure 4 shows a comparison between Eq. (10) and the numerical results obtained from the boundary collocation method [14] for a particle moving perpendicular to two parallel walls. The two results overlap and can not be distinguished from each other. Equation (10) involves a summation over an infinite number of terms and still can not be efficiently incorporated in Eq. (2). As shown in the next section, when a particle moves very close to a wall, a contamination criterion will be invoked. Thus, we only need to calculate the trajectory of particles that are not close to the wall. For these particles, the contributions from the higher order terms in the summation are negligible. Therefore, we only need to consider the first few terms in Eq. (10) in the following calculation.

As shown in Fig. 4, the drag force, predicted by Eq. (8) becomes unbounded when a particle moves very close to a wall. But the Saffman and gravity forces are both finite. Therefore, to make contamination possible, some other forces need to be considered.

4. CONTAMINATION CRITERION

Intermolecular forces exist for any two closely spaced bodies. According to Hamaker, the intermolecular force between a spherical particle and a wall is

$$F = \frac{A_H}{6}\left[\frac{R}{\delta^2} + \frac{R}{(\delta+2R)^2} + \frac{1}{\delta} - \frac{1}{\delta+2R}\right] \tag{11}$$

where A_H is the Hamaker constant, which can be determined via Lifshitz theory and is always around 10^{-19}-10^{-21}J [15]. In this formula, the retardation effect is neglected.

When a particle moves very close to a wall, i.e. the gap between the particle and the wall δ is much smaller than the particle radius R, the intermolecular force becomes important and increases as the particle moves closer. In this case, the asymptotic intermolecular force, derived from Eq. (11), is:

$$F_{IM} \sim \frac{A_H R}{6\delta^2} \tag{12}$$

while the asymptotic drag force derived from eq. (8) is

$$F_{drag} \sim \frac{2F_0 R^2}{\delta^2} \tag{13}$$

where $F_0=6\pi\mu UR$ is the Stokes drag force on a spherical particle in a free stream. Both the drag and intermolecular forces on a particle moving near a wall are inversely proportional to the square of the gap δ. Therefore, the unbounded drag force can be balanced by the intermolecular force when a particle approaches a wall. When the particle is far from the wall, the intermolecular force is negligible and the velocity decreases due to the increasing drag force. As the particle moves closer to a wall, the intermolecular force comes into play, but it is much smaller than the drag force. The total force is again dominated by the drag force and the velocity further decreases, which makes the ratio of the drag force to intermolecular force decrease also. The increase of the intermolecular force and the decrease of the drag force would make them balance each other at some location. Then there are no net forces applied on the particle and the particle moves with this velocity until it contacts the slider or disk. This velocity $u = \frac{A_H}{48\pi\mu R^2}$ is obtained by equating the forces in Eq. (12) and Eq. (13) under the condition that the particle approaches the slider or disk and $\delta << R$. So our contamination criterion is: when the particle approaches the slider or disk and the velocity perpendicular to the slider or disk is less than

$$u = \frac{A_H}{48\pi\mu R^2}, \tag{14}$$

the particle will move with this velocity and contact the slider or disk.

Although the particle trajectory can also be determined from Eq. (1) directly when the particle moves very close to a wall, the calculation involves subtraction of two large terms—the drag force and the intermolecular force. This introduces large errors and is unfavorable for calculations. This potential source of error is bypassed here by using the contamination criterion.

5. INTEGRATION SCHEME

Due to the low volume fraction of particles, the collision between particles is negligible. Then the trajectory of particles can be calculated separately without considering the interaction between them. To integrate Eq.(1), Zhang and Bogy [4] used a fourth-order Runge-Kutta method. In this method, an arbitrary time step needs to be supplied, and it is critical to the convergence of the integration. In order for the results to be correct, a very small time step needs to be chosen. But when the time step is too small, errors accumulate during the integration, and they can also lead to inaccuracies in the final results. Here, we use a fourth order Runge-Kutta method with a fifth-order correction to check the accuracy of the previous integration scheme. As shown in Fig. 5, a time step 10^{-5}s is small enough for convergence.

6. NUMERICAL RESULTS AND DICUSSION

To calculate the forces on a particle, the ambient flow field is needed. Here, the program CML Quick 4 [16], which is based on the finite volume method for solving the Reynolds equation, is used to get the air flow field in a HDI free of particles. The ABS design used in this paper is shown in Fig. 7.

Figure 6 shows the boundary effect on a particle's motion in the HDI. Initially, the particle experiences a lift force (Saffman force) and moves upward. If the boundary effect is not considered, the particle crosses the transition region and moves into the recess region. Then, near the trailing edge, there exists a downward air flow field and, accordingly, the particle moves downward and finally contacts the disk. However, when the boundary effect is included, due to the increasing drag force induced by the wall, the particle can not cross the transition region and instead contacts the leading pad.

Although a simplified correction factor was used in previous studies, the contamination profiles in those studies are not very different from the present results, as shown in Fig. 7. The reason is the same as that for only including the first few terms in Eq. (10): we only need to calculate the trajectory of particles which are not very close to either of the walls. At these locations, the difference between the previous C_w and the present C_w is not very large. Both of them are finite and of the same order. For particles moving close to a wall, however, the contamination criterion gets invoked. Due to the larger intermolecular force, the particles are always attracted to the slider or the disk. Therefore, the present contamination profile should be similar to that obtained previously. As shown in Fig. 7, the two profiles are only slightly different at some specific locations on the ABS, and there are more particles contaminating the slider when the new and more accurate C_w is used.

7. CONCLUSION

The boundary effect due to the presence of a slider and a disk is considered in the drag force formula for particles moving in between them. The effect is non-negligible on particle motion in the head disk interface. The drag force becomes unbounded as a particle approaches a slider or a disk. A contamination criterion is provided, which shows that a particle, when moving close to a wall, is attracted to the wall by an intermolecular force that grows at the same power of distance to the wall as the drag force. Although a less complete correction factor was used in previous studies, the present contamination profile is only a slightly different from that obtained previously. Both of them compare well with experimental results.

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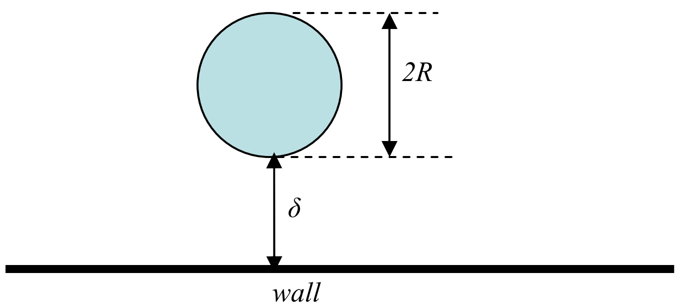

Figure 1 Sketch of a particle moving near a wall, where R is the particle radius and δ the gap between the particle and the wall.

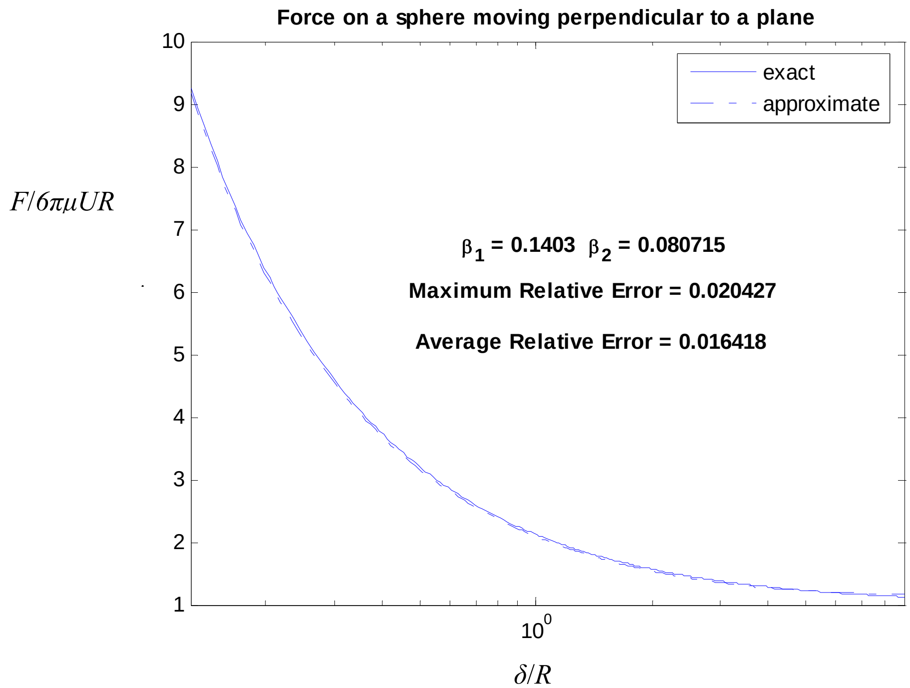

Figure 2 Comparison of eq. (8) with the exact results, where *F* is the drag force on a spherical particle moving perpendicular to a wall, and β_1 and β_2 are the parameters involved in eq. (8)

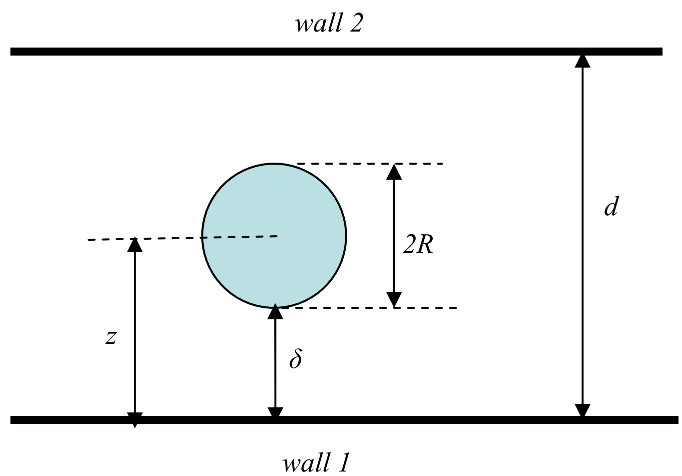

Figure 3 The geometry of a spherical particle moving between two walls, where *d* the distance between two walls

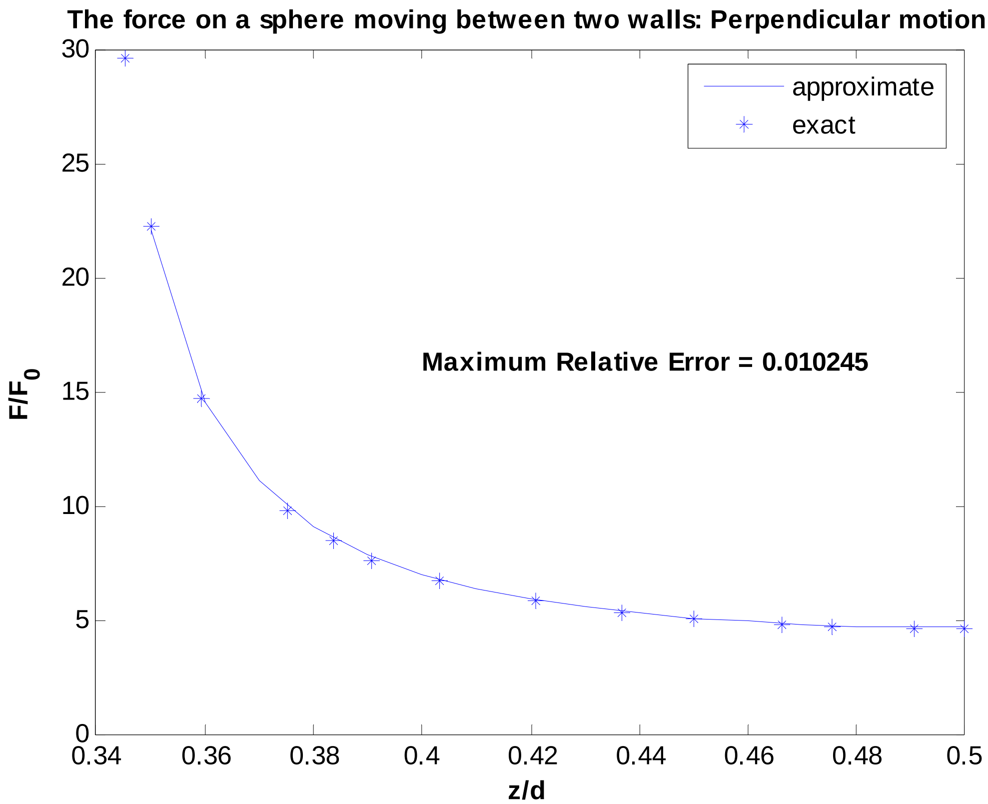

Figure 4 Comparison of eq. (10) and exact results obtained by boundary collocation method for a particle moving perpendicular to two parallel walls, where $F_0=6\pi\mu UR$ is the Stokes drag force.

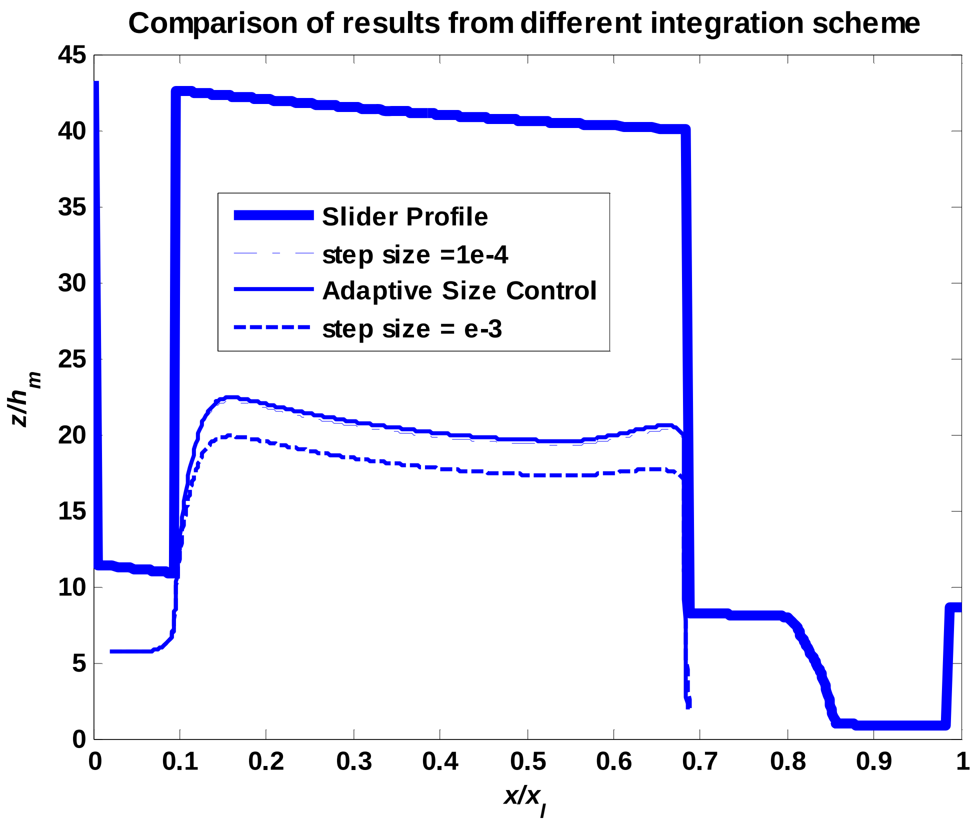

Figure 5 Effect of different time step for integration.

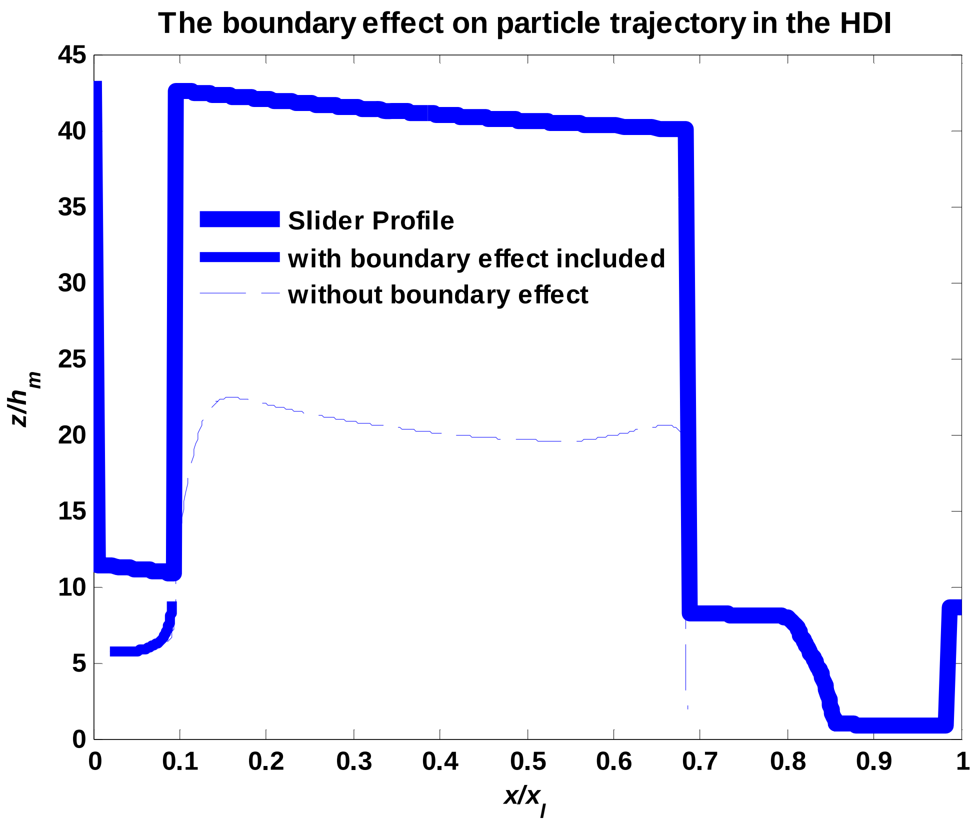

Figure 6 Boundary effect on particle moving in Head Disk Interface (HDI), where x_l is the slider length and h_m is the nominal flying height.

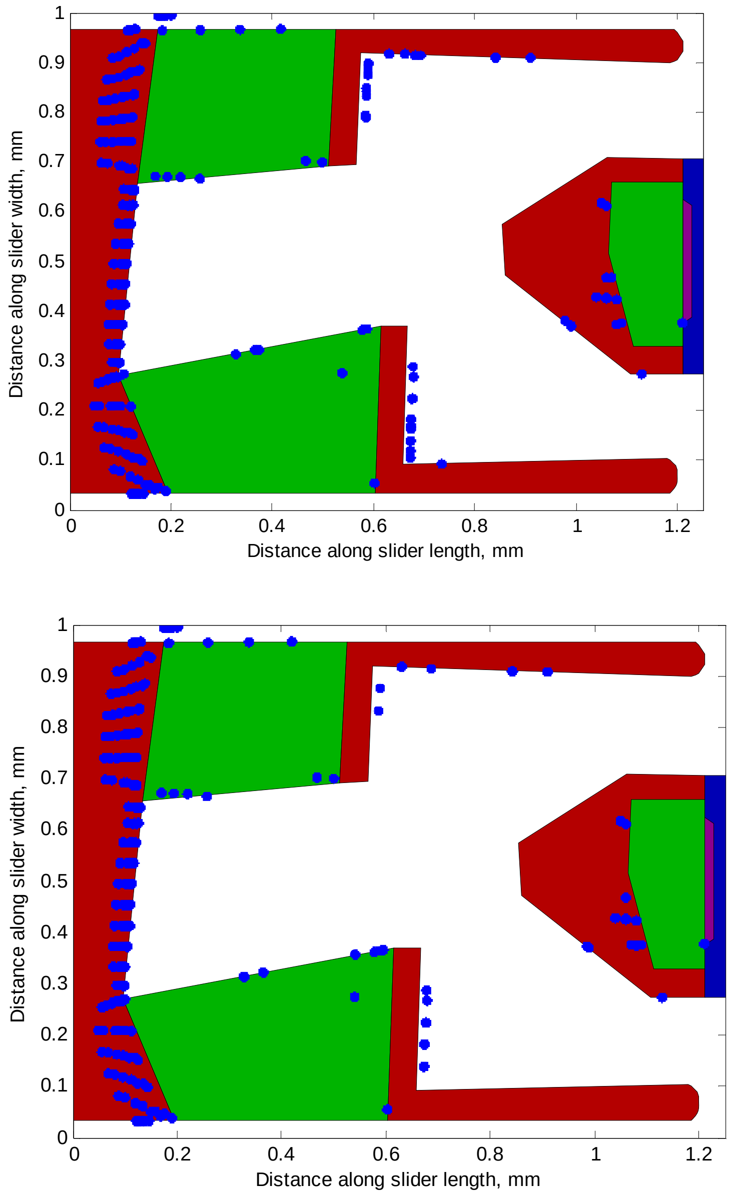

Figure 7 Comparison of the present contamination profile (Fig. 7a) and that obtained previously with a limited correction factor for the boundary effect