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Influence of Brownian Motion on Nanoparticle Deposition in a Microchannel Heat Sink

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ABSTRACT

With the increasing demand for cooling systems for electronic devices, nanofluid-microchannel heat sinks (MCHSs) have emerged as a hot topic. However, solving the problem of nanoparticle deposition is key to bringing this technology to an industrial scale. Traditional research focuses on the chemical characters of stationary nanofluids. However, thermophysical factors also affect the deposition of flowing fluid. In order to analyse thermophysical characteristics of an Al_2O_3-water nanofluid in a straight microchannel, Brownian force was simulated using a discrete phase model (DPM). The results indicate that Brownian motion has a great impact on particle deposition. However, the influence of temperature on the mean free path could be ignored for nanofluids in the MCHS. The deposition rate decreased with increasing particle diameter, but the deposition rate reduced as the velocity increased. These results have a guiding significance when designing new microchannel structures and inform the best conditions to reduce deposition.

Keywords: Nanofluids, MCHS, DPM, Deposition

NONMENCLATURE

Abbreviations	
MCHS	Microchannel Heat Sink
DPM	Discrete Phase Model
Symbols	
ζ_i	Gaussian white noise function
S_0	Spectral intensity
v	Kinematic viscosity
k_B	Boltzmann constant
D_B	Brownian diffusion coefficient
C_c	Cunningham correction
Kn	Knudsen number

1. INTRODUCTION

Modern microelectronic devices place the highest demands on cooling systems. So, to improve the heat transfer of cooling systems, modern coolant fluids and heat exchanger structures have been researched [1]. Pure liquid, high latent heat capacity fluids, was a major research topic before the 1980s [2]. However, traditional coolants were unable to meet the heat flux requirements of modern applications, so nanofluids became an essential topic of research in recent decades.

Nanofluids have many advantages, such as having adjustable properties, high thermal conductivity and high specific surface area while needing low pumping power. Researchers have attempted to understand nanofluids by studying their physical properties, heat transfer performance and environmental friendliness [3]. However, very few nanofluid systems are available in the market at present. The main problem is that nanoparticles are easily deposited out of their base fluids [4]. In a parallel line of research, Tuckerman and Pease first put forward the concept of MCHS at Stanford University in the early eighties [5]. MCHS can improve the compactness of cooling devices with their smaller geometry and low coolant flow making devices cheaper [6]. However, due

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to their compact structure, clogging can be a problem that reduces their performance and lifespan, hindering the development of new MCHS. Combining nanofluids with MCHS can improve the efficiency of cooling devices for microelectronics. However, this makes deposition and clogging problems more serious.

Therefore, solving the deposition problem in nanofluid-MCHS is key to making this technology reach an industrial scale. However, published papers are very limited in this area. Traditional studies on nanofluid stability only analyse chemical aspects. Therefore, this paper studies the influence of thermophysical factors on nanofluid (water base fluid) deposition in MCHS. Specifically, Brownian force was analysed by DPM simulation to investigate deposition influence factors.

2. RESULT AND DISCUSSION

2.1 *Numerical method*

A straight, rectangular cross-section 3D model with width of 0.2 mm, a height of 0.067 mm and length of 20 mm was studied. The nanoparticles were Al_2O_3, and the base fluid was water. Continuity, momentum, and energy equations were simultaneously solved by computational fluid dynamics (CFD), ANSYS Fluent 2020 Ra, coupled with user-defined field (UDF). The SIMPLE algorithm in a pressure-based solver was used. The second-order central difference scheme was applied to diffusion and convective terms. The convergence criteria were that all the relative errors needed to be lower than 10^{-6}. Particle trace was calculated using the following formulas [7]:

$$m_p \frac{d\overrightarrow{u_p}}{dt} = \sum \vec{F} \tag{1}$$

$$D_B = \frac{k_B T C_c}{3\pi\mu d_p} \tag{2}$$

$$F_{B_i} = m_p \zeta_i \sqrt{\frac{\pi S_o}{\Delta t}} \tag{3}$$

$$S_0 = \frac{216 \upsilon k_B T}{\pi^2 \rho d_p^5 \left(\frac{\rho_p}{\rho}\right)^2 C_c} \tag{4}$$

$$C_c = 1 + Kn\left(1.257 + 0.4\exp\left(-\frac{1.1}{Kn}\right)\right) \tag{5}$$

$$\eta = \frac{N_d}{N_{total}} \times 100\% \tag{6}$$

Brownian motion refers to the random movement of particles suspended in a medium. In Eqs. (3) and (4), the main influence factors include nanofluid temperature, viscosity, particle diameter and mean free path. The mean distance travelled by a molecule between two successive collations is the mean free path, and it is the most important factor in Brownian motion. Due to this, the mean free path was considered to indicate the influence of Brownian force on particle deposition. Mean free path is a temperature dependant (TD) value, however, DPM in Ansys regards it as temperature independent (TI). Therefore, the difference between the solutions was compared to improve accuracy. In order to compare the difference between TD and TI, Ansys coupled UDF was used to calculate the TD value. A heat flux of 100 kW/m^2 was added to the bottom face of the straight channel, with the remaining faces kept adiabatic.

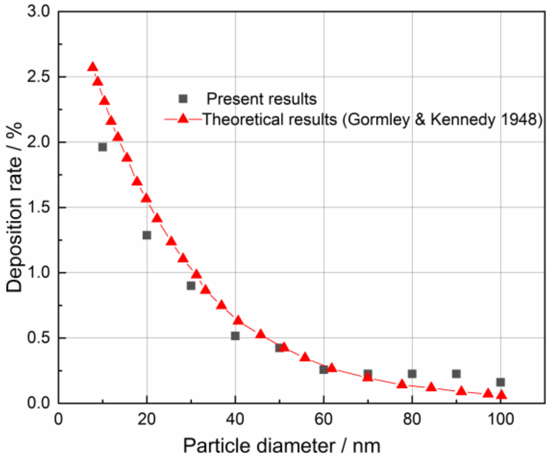

Fig. 1. Deposition rate changes with particle diameter

2.2 *Grid Sensitivity Test and Solution Verification*

A grid sensitivity test was performed on deposition rate. Five different grid combinations such as 15*50*1200, 20*65*1200, 25*75*1200, 25*75*1500 and 25*75*1800 were used. Deviation from the deposition efficiency was less than 1% for grid numbers between 25*75*1200 and 25*75*1500. Therefore, the grid

25*75*1200 (nodes number 2373176) was deemed sufficient for the simulation. The simulation validation was performed based on particle deposition, as shown in Fig. 1. The changing trend agreed with the theoretical results of Gormley and Kennedy [8].

2.3 Results

As shown in Fig. 2, the changing trends and values of deposition rate for different particle diameters were almost the same. Therefore, the influence of temperature on the mean free path could be ignored for nanofluids in the MCHS. The reason was that in nanofluids, the Kn << 1, so that $C_c \approx 1$. The drag force near the wall was the same as the main fluid due to small particles, which is different from gas base fluids. Therefore, the default option of DPM could be used to set the mean free path for nanofluids in the microchannel.

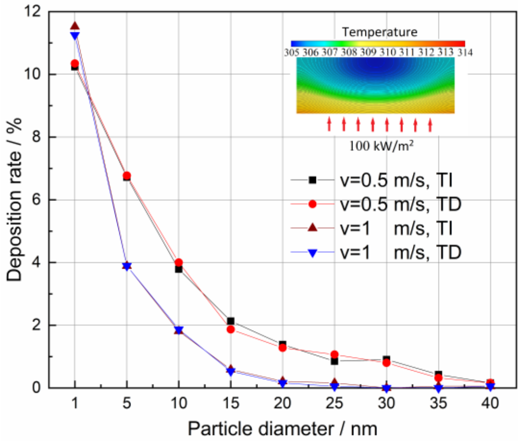

Fig. 2. Deposition rate changes with particle diameter both TI and TD of the mean free path

According to Eq. (5), the Cunningham value was calculated from the mean free path. As shown in Fig. 3, deposition rates varied with fluid velocity in different Cunningham values. With a heat flux at the bottom face of 100 kW/m^2, and a nanoparticle diameter of 10 nm, the deposition rate changed with the Cunningham values at the same velocity, implying that Brownian motion influenced particle deposition. What's more, the deposition rate increased with the increase of Cunningham values. As the Cunningham value is proportional to the Brownian diffusion coefficient in Eq. (2), the Brownian force must have increased. However, the growth rate of deposition rate decreased with the increase of Cunningham value. The increasing trend of deposition rate fell when the Cunningham value was higher than 0.8, indicating the influence of Brownian motion was also limited. It is worth noting that the deposition rate was almost 0 when the Cunningham value was 0.2 and the velocity was higher than 0.5 m/s. It was shown that Brownian motion had a greater influence on particle deposition than other forces.

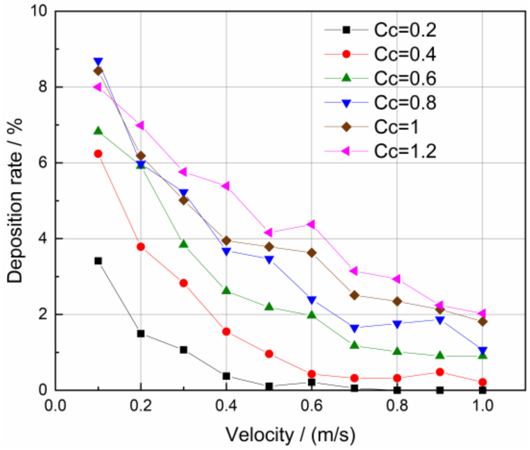

Fig. 3. Deposition rate varies with velocity in different Cunningham values

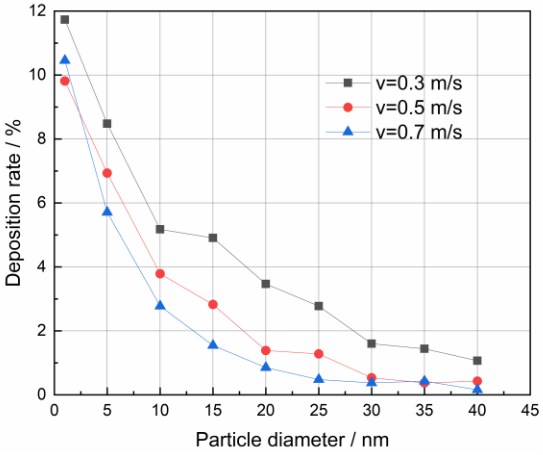

Fig. 4. Deposition rate changes with particle diameter

In order to further research the influence of Brownian motion on particle deposition, only Brownian motion was applied to the nanoparticles in the following simulation. Fig. 4 shows the relationships among particle diameter, velocity and deposition rate. The heat flux of 100 kW/m^2 remained on the bottom face of the straight channel, and the rest of the faces were adiabatic. It can be seen that the deposition rate decreased with increasing particle diameter at the same velocity, with the axial-directional residence time remaining almost same. According to Eq. (2), the Brownian diffusion coefficient decreased as the particle diameter increased. Therefore, the radial-directional residence time increased with an increase of diameter, decreasing deposition on the walls.

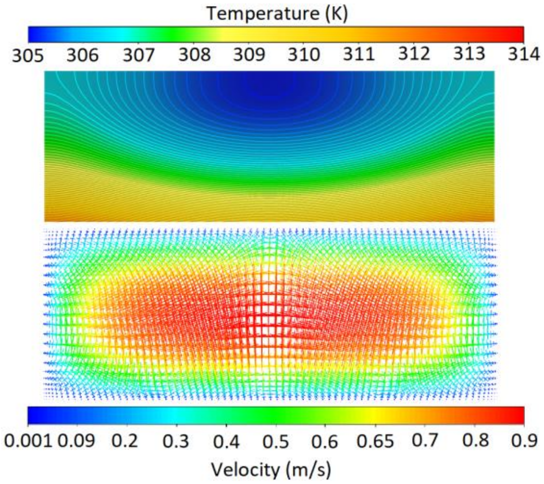

Fig. 5. Contour of the temperature and velocity at the fully development position

At the same time, Fig. 4 shows that the deposition rate reduced with the increase of the velocity for the same particle diameter. Velocity had no influence on the Brownian motion. The Brownian diffusion coefficient remained the same if the particle diameter did not change and the radial-directional residence time was same. However, the velocity did change the axial-directional residence time, decreasing the deposition rate. The velocity near the wall was lower than in the vicinity of the centreline, as shown in the Fig. 5. This was the main reason of particle migration. It is also worth noting that due to the bottom heat flux position, the fluid's bottom temperature was higher than top, but the velocity contour was symmetric, shown in Fig. 5. This is due the microstructure of the channel and high flow velocity (0.5 m/s).

2.4 Conclusion

Brownian motion has the greatest influence on particle deposition. Although the mean free path is a TD value, the influence of temperature could be ignored for nanofluids in the microchannel. This was because the Kn << 1, so that Cc ≈ 1, which is different than with gas base fluids. The deposition rate decreased with increasing particle diameter at the same velocity. At the same time, the deposition rate reduced with the increase of the velocity at the same particle diameter.

In summary, Brownian motion had a great impact on deposition for nanofluids in the MCHS, so nanofluid temperature, viscosity, particle diameter, mean free path and fluid velocity were the main affecting factors. This paper did not consider particle rotation and particle collision, so the corresponding forces should be studied as a next step.

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