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計畫進度報告
氣膠微粒在管流中的熱泳沈降研究
Research on the thermophoretic deposition of aerosol particles in tube flow (2/3)

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Abstract

The project progress report up to this point involves investigating the thermophoreic deposition efficiency in turbulent tube flow and suppression of particle deposition by thermophoretic force in tube flow theoretically and experimentally. Particle deposition efficiencies due to other deposition mechanisms such as particle electrostatic charge for particles in Boltzmann charge equilibrium and turbulent diffusions were carefully assessed so that the deposition due to thermophoresis alone could be measured accurately in turbulent tube flow. As a result, the theoretical equation developed in this study for the turbulent flow regime are found to fit the experimental data of thermophoretic deposition efficiency very well with the difference being less than 1.0 %. In the aspect of suppressing of particle deposition by thermophoresis, it was found that deposition of particle due to convectional diffusion in the tube flow was suppressed completely by heating up the tube wall slightly higher than the air flow temperature. The experimental data agree well with theoretical predictions for particles at both Boltzmann charge equilibrium and charge neutral conditions.

Keywords: thermophoretic deposition; turbulent tube flow; suppression of particle deposition.

1. Introduction

Thermophoresis is a phenomenon in which a temperature gradient in a gas causes suspended particles to migrate in the direction of decreasing temperature. Experimental and theoretical knowledge of thermophoresis is of great interest as it has various industrial and laboratory applications. Extensive experimental and theoretical/numerical work have been published on thermophoresis (Waldmann [1]; Derjaguin et al. [2]; Talbot et al. [3]; Stratmann et al. [4]), thermophoretic particle deposition in turbulent tube flow (Nishio et al. [5]; Romay et al. [6]).

While most of the previous researches which focus on the thermophoretic deposition in the laminar flow regime seem to agree well with the experimental data, the study in the turbulent tube flow by Romay et al. [6] found that differences between their theoretical predictions and experimental data existed and increased with the flow Reynolds number. When the flow Reynolds number equaled 5517, the deviation was about 3 %, and it icreased to about 6 % when the Reynolds number was increased to 9656. Similar discrepancy was found when the theoretical predictions of Romay et al [6] were compared with the experimental data of Nishio et al. [5]. Therefore it is worthwhile for this study to obtain more accurate particle deposition efficiency data and find an appropriate formula for thermophoretic deposition efficiency in the turbulent tube flow.

Particulate contamination is a serious problem in the semiconductor industry. Particles carried by high temperature exhaust gas will deposit on the wall of pipelines exposed to ambient air. To prevent particle deposition in pipelines by thermophoresis, a common practice in the industry is to heat up the surface of the piping components such that the temperature is higher than that of the gas flow. To investigate the tube-wall temperature needed to suppress particle deposition in a tube is important. In this study, experimental study was verifed with theoretical results.

2. Theoretical method

In this study, a model for predicting the thermophoretic deposition efficiency in turbulent tube flow was developed using the critical trajectory method of Lin and Tsai [7]. A fully developed turbulent flow and fully developed turbulent temperature profiles were used. The particle thermophoretic deposition efficiency in the turbulent tube flow is a function of four parameters: the product of the Prandtl number and thermophoretic coefficient, $\Pr K_{th}$, the dimensionless temperature $(T_e-T_w)/T_e$, the Nusselt number Nu_D and the gas Peclet number Pe_g. The thermophoretic deposition efficiency depends on the thermophoretic parameter β_t, which can be written as

$$ {}_t = \frac{\Pr K_{th} Nu_D}{Pe_g} \frac{T_e - T_w}{T_w} \qquad (1)$$

The best-fit equation for the particle thermophoretic deposition efficiency in the turbulent tube flow is found to be

$$\eta_{tur} = 17.2 \; {}_t^{0.96}, \quad 0.02 < \; {}_t < 0.95 \qquad (2)$$

Fig. 1 shows that the predicted results of this equation fit the deposition efficiency of calculated data very well.

In the theoretical analysis for suppression of particle deposition, particle transport equations due to convection, diffusion and thermophoresis were considered and solved to obtain particle concentration profiles in a circular tube flow. The fully developed velocity field was used to simulate both temperature and particle concentration fields. The 2-D cylindrical energy equation and particle transport equations were discretized by means of the finite volume method and solved by the SIMPLE algorithm (Patankar [8]). The number of grid in computational domain is 12,000 (200 in the axial direction × 60 in radial direction). The outlet particle concentrations were calculated to obtain the particle deposition efficiency. Fig. 2 shows the resolution of the flow improves beyond 12,000, the deposition efficiency curves do not change appreciably. Therefore, 12,000 grids were used in the subsequent simulation. Moreover, the presented data agree well with the theoretical prediction of Hinds [9].

3. Experimental method

An experimental apparatus was set up to investigate particle deposition. Fig. 3 is the schematic dagram of the experimental apparatus. The experimental system includes two parts: (1) the aerosol generation and conditioning section, (2) experimental section. The aerosol was generated by a Collison atomizer and mixed with clean air in a tank. The aerosol was dried by a silica gel diffusion dryer, and then was neutralized by a TSI 3077 electrostatic charge neutralizer, the aerosol were brought to a state of Boltzmann charge equilibrium. After being neutralized, the aerosol was passed through a differential mobility analyzer (TSI 3081 Long DMA column) where a high-voltage was applied to select particles of a known electrical mobility. The extracted monodisperse aerosol was neutralized again, and then mixed with clean dilution air in another mixing tank To remove charged particles completely, an electrical condenser was used between the neutralizer and mixing tank so that the deposition efficiency of neutral particles could be measured. As the aerosol passed through the conditioning section, it was heated to a desired temperature by a heat exchanger where a thermostated silicon-oil bath was used. For the deposition experiment, the tube wall temperature of experimental section was kept at 296K by another heat exchanger where a thermostated water bath was used. For suppression experiment, the tube wall temperature of experimental section was heated to the desired temperature by the same method. Experiments were performed using particles from 0.038 to 0.498 μm size for turbulent deposition experiment and particle from 0.01 to 0.04 μm size for suppression experiment. The concentration of sodium chloride (NaCl) solution usually used was about 0.5 – 1.5 % w/vol. Similarly, 2%, v/v alcoholic solution of oleic acid was used in this experiment. The tube length of experimental section is 118 cm and the inner diameter is 0.43 cm.

4. Results and discussion

Particle deposition efficiency in turbulent tube flow

Particles deposition in turbulent tube flow may be due to eddy diffusion and turbulent inertial deposition. The particle deposition velocity towards the tube wall due to eddy diffusion is as follow (Friedlander, [10])

$$V_d = 0.0118\,\mathrm{Re}^{7/8}\,Sc^{1/3}(D/D_t) \qquad (3)$$

To compute penetration efficiency due to eddy diffusion, one can use the following equation, which is based on the mass conservation principle, as

$$P_{d,t} = \exp(-\pi D_t V_d L/Q) \qquad (4)$$

The dimensionless particle deposition velocity of turbulent deposition, developed by Friedlander and Johnstone [11] is

$$V_d^+ = V_d/u^* = \frac{1}{1883/(\tau^+)^2 - 50.6 + 1/\sqrt{f/2}}, \text{ for } 0.9\tau^+ \le 5$$

$$= \frac{1}{5\ln\dfrac{5.04}{0.9\tau^+/5 - 0.96} - 13.73 + 1/\sqrt{f/2}}, \text{ for } 5 < 0.9\tau^+ \le 30$$

$$= \sqrt{f/2}$$

$$\text{for } 0.9\tau^+ < 5 \qquad (5)$$

The penetration efficiency, P_{tur}, is computed using Eqs. (4) and (5). The particle deposition efficiency including both eddy diffusion and turbulent deposition in turbulent tube flow is calculated as

$$\eta_t = 1 - (P_{d,t} \times P_{tur}) \qquad (6)$$

Fig. 4 shows the comparison of theoretical results based on Eq. (6) with experimental deposition efficiencies (non-thermophoretic) with error bars indicated under turbulent flow (20 l min^{-1}) condition, for the particle diameter ranging 0.038 -0.498 μm. The graph illustrates that the experimental efficiencies are about 3.5% higher than the theoretical efficiencies for particles in Boltzmann charge equilibrium. But for neutral particles, particle deposition efficiencies are lower and agree very well with the theoretical predictions. The electrostatic deposition for particles in Boltzmann charge equilibrium is seen to be important and must be accounted for. It is best if one could use neutral particles for an accurate thermophoretic deposition experiment without the interference from electrostatic deposition.

In the turbulent flow regime, Fig. 5 shows that the experimental thermophoretic efficiencies (with error bars, at 343 K) are very close to the theoretical values based on the thermophoretic coefficient of Talbot et al. (1980) (both flow rate equals to 20 and 35 l min^{-1}). The theoretical coefficient of Derjaguin et al. [2] leads to the overestimation of the thermophoretic deposition efficiency in the range of particle sizes tested. Figure also shows that the thermophoretic deposition efficiency increases with an increasing inlet gas temperature.

Suppression of particle deposition

The results of suppression experiment show that for a given particle diameter, the particle deposition efficiency decreased with an increasing tube wall temperature and gas flow rate. The effect of Particle material on particle deposition efficiency isn’t important. The deposition efficiency for particles in Boltzmann charge equilibrium is slightly higher than that of charge neutral particles. It was observed (Fig. 6) that deposition of particle could be suppressed completely when the tube wall was heated to a temperature high enough so that a dust-free layer is formed near the tube wall. The theoretical results show that for a 0.04 μm NaCl particle at charge neutral condition, the particle deposition efficiencies are 0.97, 0.65 and 0.4% at the corresponding gas flow rate of 2, 3 and 5 slpm, respectively, when the tube wall temperature is kept at 296 K. Increasing the tube wall temperature to 308, 306 and 304 K for the gas flow rate of 2, 3 and 5 slpm, respectively, the particle deposition efficiency will drop to zero. The experimental data agree well with theoretical predictions for particles at both Boltzmann charge equilibrium and charge neutral conditions.

5. Conclusion

The thermophoretic particle deposition in turbulent tube flows was studied and compared with the theory developed in this study. For particles that are completely neutral, the non-thermophoretic deposition efficiencies agree very with the available theories in the literature, while the thermophoretic deposition efficiencies also agree very well with the present theory. The presented results show that particle deposition can be successfully suppressed by thermophoresis. The experimental data are also in a good agreement with theoretical predictions.

6. Reference

1. Waldmann, L. (1961) In *Rarefiled Gas Dynamics*, L. Talbot ed., Academic, New York, p.323.
2. Derjaguin, B. V., Rabinovich, Ya. I., Storozhilova, A. I., and Scherbina, G. I. (1976) Measurement of the coefficient of thermal slip of gases and the thermophoresis velocity of large-size aerosol Particles. *J. Colloid Interface Sci.* 57:451-461.
3. Talbot, L., Cheng, R. K., Schefer, R. W., and Willis, D. R. (1980) Thermophoresis of particles in a heated boundary layer. *J. Fluid Mech.* 101:737-758.
4. Stratmann, F., Otto, E., and Fissan, H. (1994) Thermophoretic and diffusional particle transport in cooled laminar tube flow. *J. Aerosol Sci.* 25:1305-1319.
5. Nishio, G., Kitani, S., and Takahashi, K. (1974) Thermophoretic deposition of aerosol particles in a heat-exchanger pipe. *Ind. Engng Chem, Process Des. Develop.* 13:408-415.
6. Romay, F. J., Takagaki, S. S., Pui, D. Y. H., and Liu, B. Y. H. (1998) Thermophoretic deposition of aerosol particles in turbulent pipe flow. *J. Aerosol Sci.* 29:943-959.
7. Lin, J.-S., and Tsai, C.-J. (2003) Thermophoretic deposition efficiency in a cylindrical tube taking into account developing flow at the entrance region. *J. Aerosol Sci.*. 34: 569- 583
8. Patankar S. V. (1980) *Numerical heat transfer and fluid flow*, McGraw-Hill, New York.
9. Hinds, W. C. (1999) *Aerosol technology*, 2nd Ed., Wiley, New York.
10. Friedlander, S. K. (2000) Smoke, Dust, and Haze, John Wiley & Sons, New York.
11. Friedlander, S. K., and Johnstone, H. F. (1957) Deposition of suspended particles from turbulent gas stream. *Ind. Engr. Chem.* 49:1151-1156.

NOMENCLATURE

D	particle diffusivity
D_t	tube diameter
f	fanning friction factor
K_{th}	thermophoretic coefficient

L	tube length
$P_{d,\ell}$	diffusional penetration efficiency in laminar tube flow
$P_{d,t}$	diffusional penetration efficiency in turbulent tube flow
Pe_g	gas Peclet number $(u_m \cdot r_0^2)/(\alpha \cdot L)$
Pr	gas Prandtl number
P_{tur}	inertial deposition efficiency in turbulent tube flow
Re	Reynolds number
r_0	Tube radius
Q	inlet gas flow rate
Sc	Schmidt number
T_e	gas temperature at inlet
T_w	wall temperature
u^*	friction velocity $u^* = u_m\sqrt{\frac{f}{2}}$
u_m	average gas velocity
V_d	particle deposition velocity

Greek letters

α	Particle diffusivity
β_t	thermophoretic parameter (in turbulent tube low) $\beta_t = PrK_{th}Nu_D(T_e-T_w)/(T_wPe_g)$
η_{tur}	thermophoretic deposition efficiency in turbulent tube flow
ν	air kinematic viscosity
τ^+	dimensionless particle relation time $\tau^+ = u^{*2}/\nu$

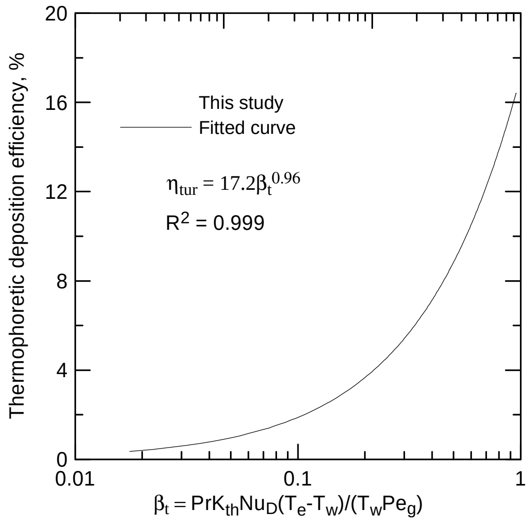

Figure 1. The thermophoretic deposition efficiency as a function of thermophoretic parameter â$_t$ in the turbulent tube flow.

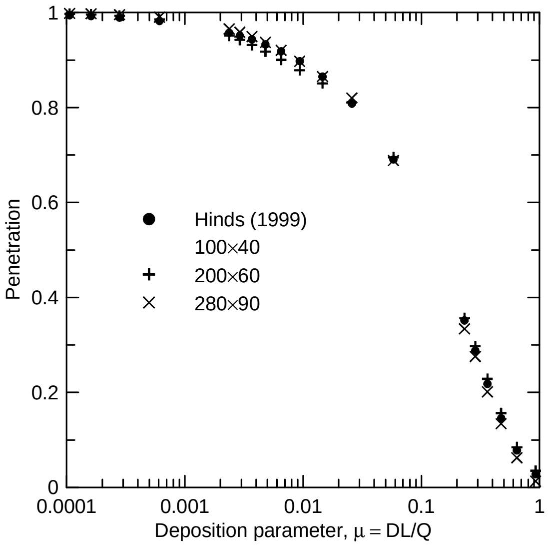

Figure 2. Diffusional penetration efficiency as a function of deposition efficiency μ.

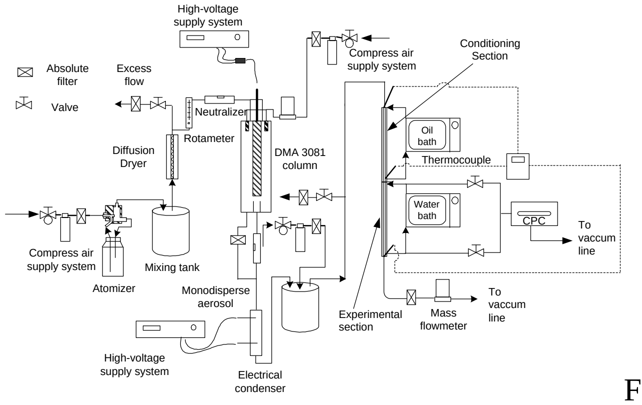

Figure 3. Experimental system.

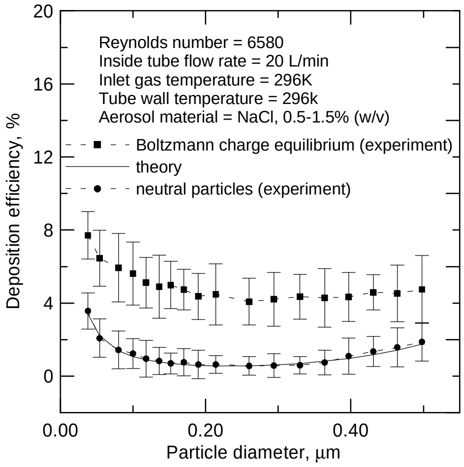

Figure 4. The comparison of experimental data (non-thermophoretic) and theoretical predictions of combined turbulent diffusion and inertial impaction under turbulent flow conditions (Re = 6580).

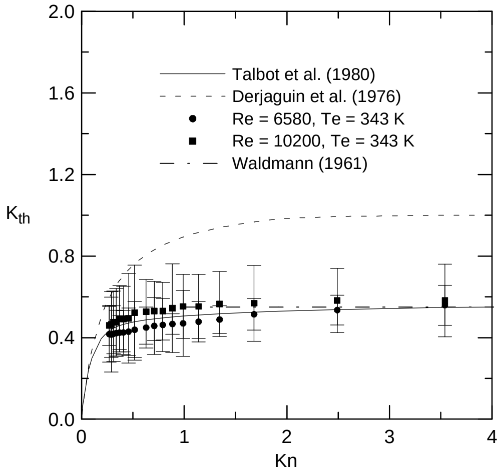

Figure 5. The comparison of experimental thermophoretic coefficients K_{th} with theoretical predictions.

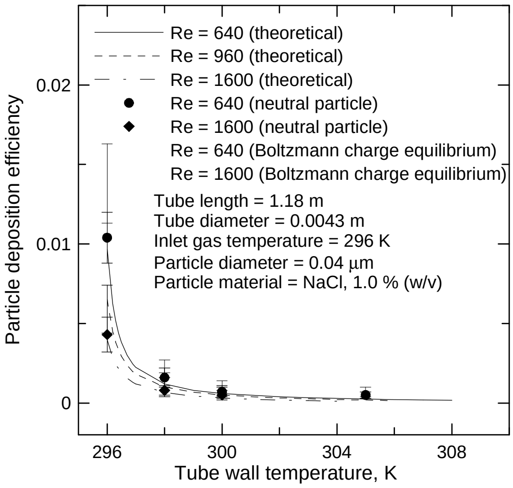

Figure 6. Particle deposition efficiency as a function of tube wall temperature.