

Development for Thermophoresis Experimental Under Microgravity Condition

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Abstract. In the temperature field, a small particle will move towards the lower temperature side. This phenomenon is called thermophoresis, which influences the movement of soot particles in exhaust gas from combustors. It is important to understand the behavior of soot particles in the combustion field for emission control. The main problem for measuring the thermophoretic velocity is the natural convection. The velocity of such natural convection is usually comparable to the thermophoretic velocity and cannot be measured directly. To avoid this problem, experiments should be conducted under microgravity conditions. . In the present work, device has been developed for conducting experiments repeatedly under a microgravity environment in a very short period time, i.e. 0.3 s, by means of the free-fall method, to accumulate data of the thermophoretic velocity. Experiments have been conducted to measure the movement of particles in the microgravity environment with and without temperature gradient. For the former experiment, it is seen that the particles has almost no movement in the horizontal and the vertical directions. Results confirmed that there is negligible effect of blowing and gravitational on the particles movement. For the later one, experiments have been done in a surrounding of a pure gas of argon. The thermophoretic velocity is measured at 313 ± 2 K for various pressure conditions from 20 kPa to 100 kPa. The thermophoretic velocity for each particle is individually measured, and the mean value and its 95% confidence interval for each experimental condition are statistically obtained. Result from experiments are compared with the theory and satisfactorily agreement is found for tested gas.



1. Introduction

The improvement in technology produces development in transportation and industrial. However this improvement requires increment in the energy consumption. Since 1970, the world energy consumption growth is about 2.3% per year [1]. It is estimated about 86% of the energy source is produced from fossil fuels such as coal, petroleum, and natural gas. Fossil fuels are of great importance since it can produce significant amount of energy per unit weight. Consumptions of all these three sources have been increased such that the reserves of these sources have been used up quickly. Some developments have been done to produce alternative energy from the non-fossil sources such as nuclear and biomass energies. Some of these developments have reached the practical stage but only 16% of the global final energy consumption comes from these sources. Currently, fossil fuels are still considered as valuable energy sources; which is important to be used efficiently.

Significant amount of heat energy is released due to the combustion of fossil fuels. However, the use of fossil fuels raises the environmental concerns. Burning of fossil fuels produces carbon dioxide, which is one of the greenhouse's gases that enhances radiative forcing, which contributes to global warming. It is important to understand the combustion phenomenon in a combustion chamber since improvement of the energy efficiency will produce undesirable gas emissions and environmental pollution.

Soot is one of the main pollutants emitted from the combustion devices. It is important to understand the behavior of soot particles in the combustion field for emission control. Dobashi et al. [2] have conducted experiments to examine smoke generation process in a flickering pool fire and have found the residence time of soot particle in the soot production is increased by the flickering motion of the flame. It is noted that the thermophoretic force might increase the residence time in the soot production region. Thus, quantitative understanding of the phenomenon is indispensable for controlling the movement of particles in this system.

There have been some direct measurements on the thermophoretic phenomenon of such an aggregate particle. Zheng and Davis [3] have measured the thermophoretic force acting on an aggregate of polystyrene latex spheres, and found that the force is affected by the number of primary spheres in the aggregate. Suzuki and Dobashi [4] have conducted direct measurements on the thermophoretic velocity of the soot particles, and have revealed that the velocity is dependent not only on the macroscopic size of the soot particle but also on the aggregation condition; experimental results suggest that this phenomenon is dominated by the size of primary spheres when the aggregation is coarse. Thus, prior understanding for an aggregate, well knowledge about the phenomenon for a single sphere is important.

Several experiments have been performed to measure the thermophoretic force or the thermophoretic velocity [5-17]. Above experimental methods are complex in practical implementation, and as a consequence, involve numerous errors. Among those, errors caused by buoyancy are the largest problem; in a field with a temperature gradient, buoyancy induces natural convection, which influences the movement of particles and disturbs the measurement. The velocity of such natural convection is usually comparable to the thermophoretic velocity and cannot be measured directly. To avoid this problem, some experiments have been conducted under microgravity conditions. Toda et al. [18, 19] performed experiments in a drop tower facility and demonstrated that the microgravity environment satisfactorily suppresses the disturbance. Prodi et al. [20, 21] also conducted microgravity experiments by means of a drop tower facility and/or parabolic flights. However, those data are not sufficient enough owing to limited trial numbers of experiments.

In this research, a device has been developed for conducting experiments repeatedly under a microgravity environment in a very short period of time, i.e. 0.3 s, by means of the free-fall method, to accumulate data of the thermophoretic velocity. Statistical treatment is done in order to attain satisfactory accuracy. Then, results will be compared with the existing theory by Hoshino et al [22].

2. Experimental Setup

Experimental apparatus is divided into three main units: drop tower, measuring unit and a damping cushion. Figure 1 shows the overview and the schematic of the apparatus. The measuring unit is hung at the top of the drop tower by an electric magnet. The unit starts falling when the electric magnet is deactivated. The falling distance is 0.6 m, which corresponds to the duration time of the microgravity condition at 0.3 s. In this research, the drop tower with the height about 2 m is chosen based on consideration of the drop distance, the height of the measuring unit, and height of the damping cushion.

The framework of the drop tower is $W1\text{ m} \times L0.7\text{ m} \times H2\text{ m}$ and is manufactured from angle frames. The base of the tower is fixed to the floor by bolts for preventing the movement of the tower during experiments. The electric magnet is attached to the center of the upper of the drop tower to hang the measuring unit 1 m height from the floor. When the magnet is deactivated, the drop unit falls before it hits the damping cushion. The damping cushion is chosen from the commercial comforter and is placed inside the cardboard box with the size of $W0.9\text{ m} \times L0.6\text{ m} \times H0.4\text{ m}$.

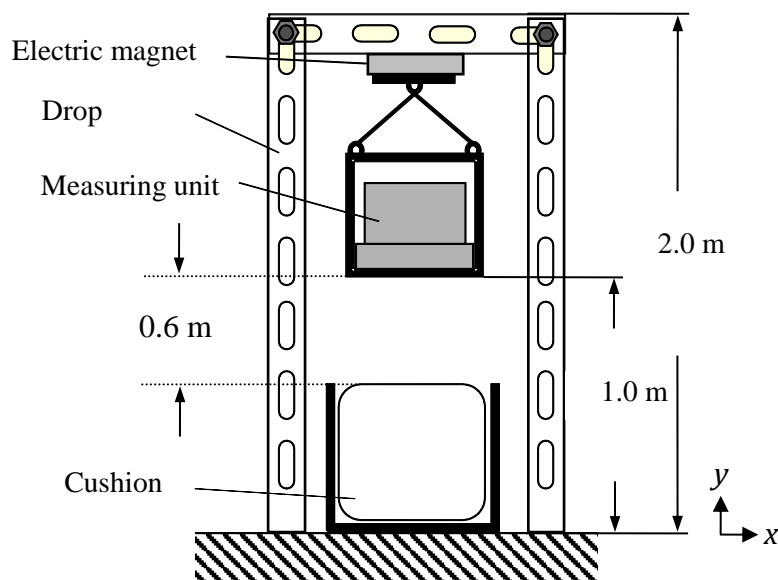


Fig. 1 Schematic of apparatus.

Figure 2 shows a variation of the gravity level during an experiment. The gravity level is measured by the G-sensor attached on the measuring unit. The duration time of the free-fall is about 0.3 s as seen in the figure. When the electric magnet is deactivated at $t = 0$, the gravity level in z-axis changes from -1.0 G to $+0.4\text{ G}$ once, possibly owing to the vibrational motion of the frame of the unit, and then decays as time passes until the unit reaches the cushion. The range between $\pm 0.1\text{ G}$ in gravity level is regarded as the microgravity condition in this work, the duration time of which is about 0.25 s.

It is noted that the measurement accuracy of thermophoretic velocity is influenced by variation of the size and the shape of particles. In the present work, particles having a small variation of the size and the shape are chosen in order to increase the measurement accuracy.

Sample particles used in this research are PMMA (polymethylmethacrylate) sphere particle from Sekisui Plastics Co., Ltd. The density and the thermal conductivity of the particles are 1200 kg/m^3 and 0.21 W/(m K) , respectively. These particles are chosen since the size is quite uniform. Figures 3 and 4 show the SEM image and the probability density distribution of the particles diameter measured from the images, respectively. The mean diameter of these particles is $2.91\text{ }\mu\text{m}$ as shown in Table 1.

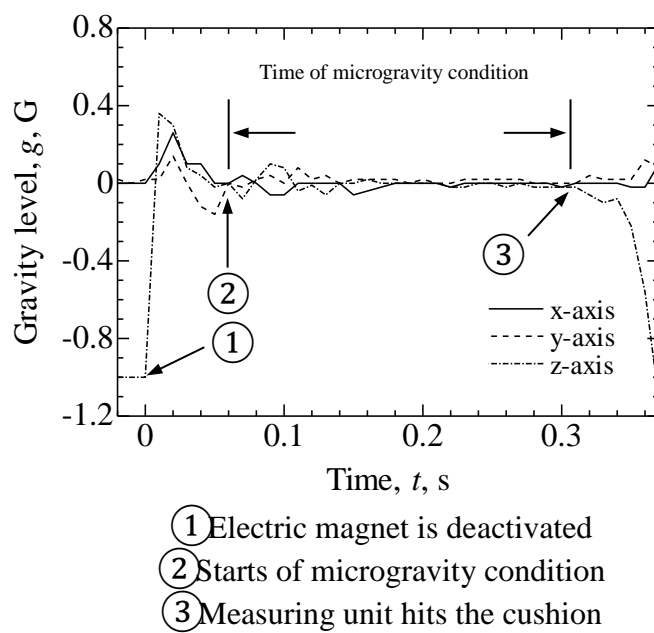


Fig. 2 Gravity level during experiment.

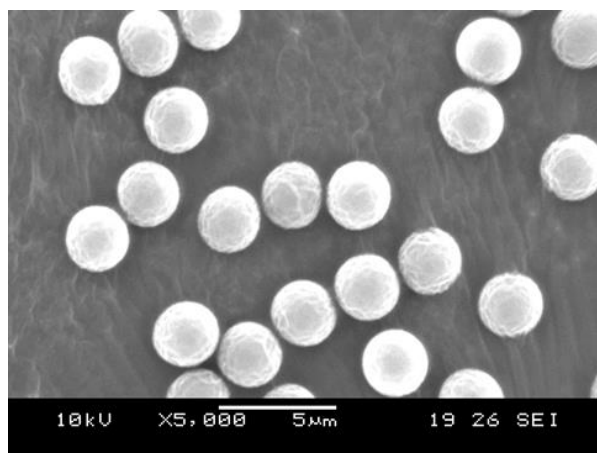


Fig.3 SEM image of PMMA particles.

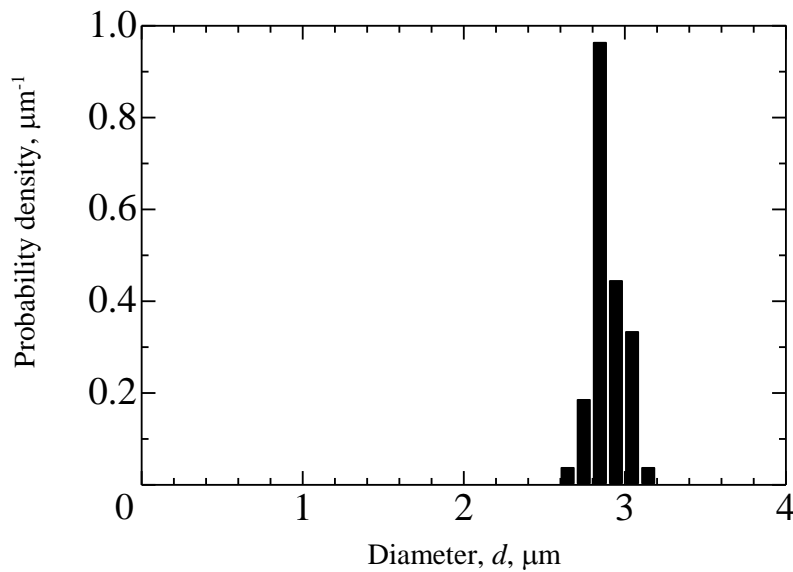


Fig. 4 Diameter distribution of particles.

Table 1 Diameters of PMMA particles.

Mean, μm	Standard deviation, μm	Confidence interval (95%) for the mean, μm
2.91	0.09	0.03

The thermophoresis is a phenomenon due to the momentum exchange from the collision between of gas molecules and the particle. The mean velocity of gas molecules increases as the temperature increases, such that the momentum of gas molecules increases accordingly. The measurement of the thermophoretic velocity should be taken at a fixed temperature since the velocity is dependent on not only the temperature gradient but also the temperature itself.

In this research, experiments have been done in a surrounding of a pure gas of argon. Figure 5 shows the position of the reference temperature; which is 1.0 mm from the hot surface. The thermophoretic velocity is measured at 313 ± 2 K. The position is related to the measurement area. The position is determined in order to easily capture the image of particles during the experiment.

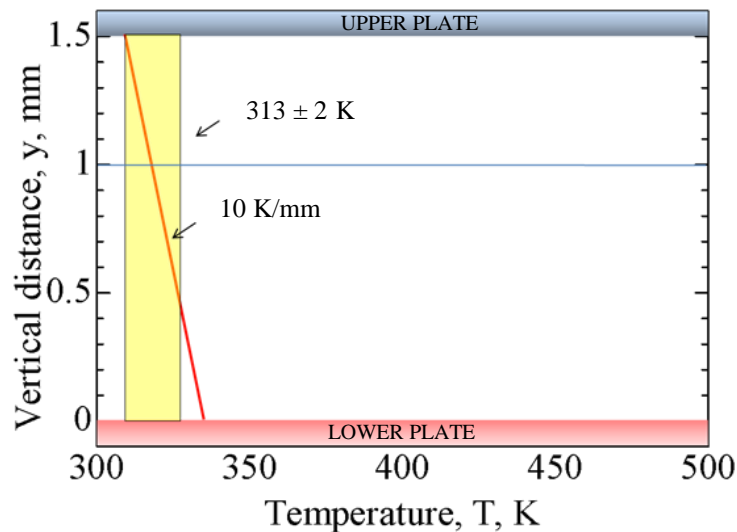


Fig. 5 Determination of temperature gradient and temperature reference for each experiment.

The temperature field is created by using the temperature control unit. The lower plate is heated via a plate heater while the upper plate is kept cold in order to perform the temperature gradient. When the bottom plate reaches its pointed temperature, the upper plate is put in the place where the distance between the plates is 1.5 mm. It should be kept in mind that the target temperature of cold plate should be higher than environmental temperature. The measuring unit is dropped when the temperature of upper plate becomes the target temperature. Efficiency of the experiment is increased by preparing two upper plates; which are changing after every experiment.

The temperature field during the experiment is monitored by measuring temperatures at two points in the vessel: one is in the upper plate and the other in the bottom one. The temperature field is controlled based on these measured temperatures. Before making experiments, the preparatory measurement for the temperature field is conducted by inserting two more thermocouples suspended in the chamber at different heights. Measuring two points is sufficient because the linearity of the temperature field has already been confirmed by the Mach-Zehnder interferometry. The relation between these temperatures at monitoring points and the actual temperature field in the chamber is examined from this preparatory measurement. When conducting thermophoresis experiments, additional two thermocouples are removed; the temperature field is controlled based on the temperatures at those two monitoring points.

Figure 6 shows the temperature variation for both plates during the experiment. Blue and red lines represent the temperature for bottom and upper plates, respectively. For example, the temperature of bottom plate is set at 210°C and the distance between plates is 1.5 mm. It is seen that the temperature of bottom plate becomes constant after the plate reaches its target temperature while the temperature of upper plate increases as time increases.

Experiments are conducted with the test gas of argon. The target temperature and the temperature gradient are 313 K and 10 K/mm, respectively. Various pressure conditions are chosen from 20 kPa to 100 kPa. The thermophoretic velocity for each particle is individually measured, and the mean value and its 95% confidence interval for each experimental condition are statistically obtained.

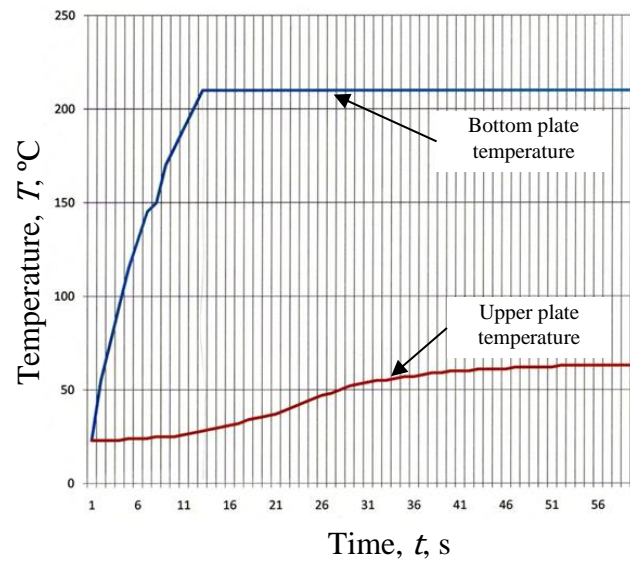


Fig. 6 Relation between time and temperature.

3. Experimental Result

The movement of particles in the microgravity environment has been confirmed by conducting the experiment without temperature gradient. The movement of particles is captured via a high-speed camera. The image is analyzed by using two-dimensional image measurement software. This software analyzes the position for each selected particle from the image. The position is measured based on two-dimensional coordinate. The setting of the brightness and the contrast can be adjusted in order to make the image more clearly. Figures 7 and 8 show the movement of particles in the vertical and horizontal directions, respectively. It is seen that the particles has almost no movement in the horizontal and the vertical directions. Results confirmed that there is negligible effect of blowing and gravitational.

Figure 9 shows examples of the movement of particles during a free-fall in the surrounding gas of argon at 20 kPa. The measurement of the velocity should be taken at a fixed temperature since the thermophoretic velocity is dependent on not only the temperature gradient but also the temperature itself. The velocity of each particle is measured by tracing its movement while it travels within the range of the temperature between 313 ± 2 K. It is seen from the figure that the velocity of each particle can be considered as constant in the range.

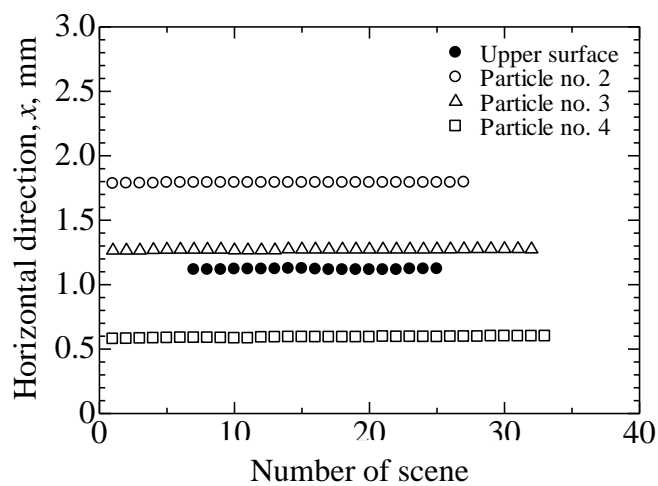


Fig. 7 Movement of particles in vertical direction.

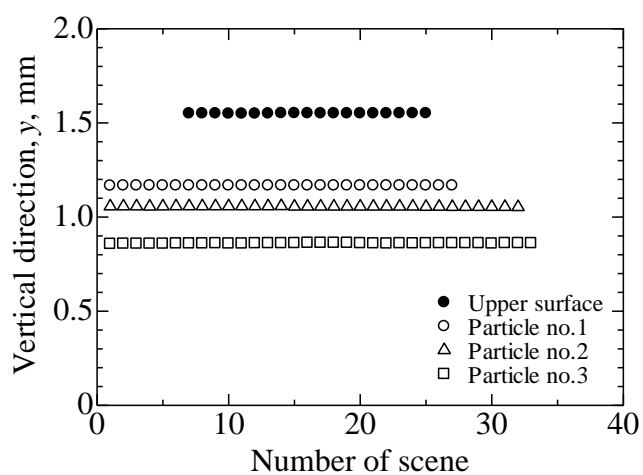


Fig. 8 Movement of particles in horizontal direction.

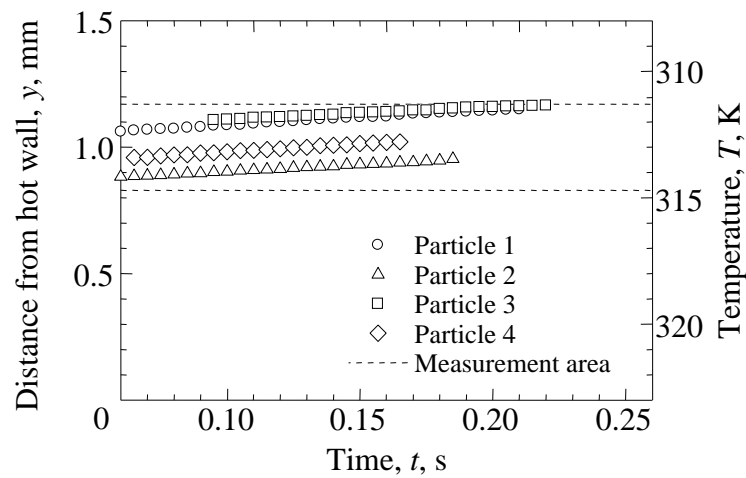


Fig. 9 Movement of particles in surrounding gas of argon.

Table 2 shows the statistical data for the tested pressure conditions with the argon gas. It is noted that the 95% confidence interval indicates not the range of data scattering but the range of expected mean value of the population. It is seen that the confidence interval is roughly estimated at around 0.01 mm/s to 0.02 mm/s. The ratio of the confidence interval to the mean value is only 3% for the pressure at 20 kPa. As the pressure increases, the velocity decreases, and as a consequence, the ratio tends to increase.

Table 2 Statistical data of thermophoretic velocity in surrounding gas of argon.

Pressure, P , kPa	20	40	60	80	100
Sampling number, n , –	39	35	37	33	47
Mean thermophoretic velocity, \overline{V}_T , mm/s	0.538	0.183	0.111	0.075	0.066
Standard deviation, σ , mm/s	0.053	0.044	0.026	0.030	0.036
Confidence interval (95%), mm/s	0.017	0.015	0.009	0.011	0.011
Ratio of confidence interval to mean thermophoretic velocity, –	0.03	0.08	0.08	0.15	0.17

Figure 10 shows the thermophoretic velocity for each gas. The white rectangle (\square) represents experimental values for argon, respectively. Error bars in the figure indicate the 95% confidence interval for the mean. The solid line is the prediction calculated by assuming constants to be identical to those in the previous work [23], namely, C_M , C_T , C_S , and C_H to be 1.000, 1.875, 0.750, and 1.000, respectively. Hoshino et al. [22] have derived an improved theoretical solution of the thermophoretic velocity by applying the boundary condition proposed by Lockerby et al. [24], which includes the thermal stress slip and the higher order isothermal slip. The equation is given as follows:

$$V_T = \frac{3\mu C_c}{2\rho T_{F0}} \frac{\left[(k + C_T Kn) + \frac{4}{3} (C_M C_T Kn^2 + C_M Kn[k-1]) \right]}{\left[1 + 3C_M Kn + \frac{9}{2\pi} Pr Kn^2 (1 - \gamma^{-1}) \right] (1 + 2k + 2C_T Kn)} |\nabla T|, \quad (1-1)$$

where μ , $|\nabla T|$, ρ , T_{F0} , k , Kn , C_M , C_T , Pr , and γ are the viscosity, the temperature gradient, the density of the surrounding gas, the reference temperature, the gas-to-particle thermal conductivity ratio, Knudsen number, constants for slip flow, temperature jump, Prandtl number and the specific heat ratio, respectively. Here, the reference temperature T_{F0} is defined as the supposed gas temperature at the center of the particle in the given temperature field without the existence of the particle, and Knudsen number Kn is the ratio of the mean-free-path l to the particle radius. The mean-free-path is calculated from the following equation [25]:

$$l = \frac{\mu}{0.499P} \sqrt{\frac{\pi R T_{F0}}{8}}, \quad (1-2)$$

where P and R are the pressure and the gas constant, respectively.

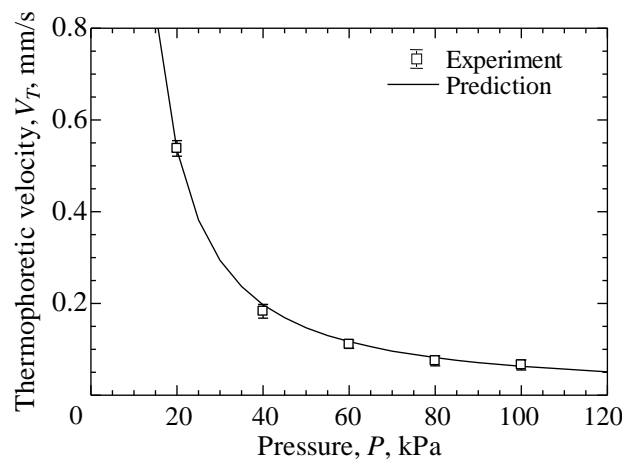


Fig. 10 Pressure dependence of thermophoretic velocity in surrounding gas of argon.

Result shows the prediction is in a good agreement with experiments throughout all the tested pressure conditions; the solid line runs through the range of the confidence interval at every tested pressure. It is also proved that the satisfactory accuracy can be attained by using the statistical treatment to experiments data.

4. Conclusion

In this study, development apparatus for conducting thermophoresis experiment under microgravity condition is done and following results are obtained:

1. A device has been developed for conducting experiments repeatedly under a microgravity environment in a very short period of time, i.e. 0.3 s, by means of the free-fall method, to accumulate data of the thermophoretic velocity.
2. The experiment without temperature gradient is conducted to confirm movement of particles in the microgravity environment. Results show the particles have almost no movement in the horizontal and the vertical.
3. It is seen that the prediction is in a good agreement with experiments throughout all the tested pressure conditions. The solid line runs through the range of the confidence interval at every tested pressure.

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References

- [1] Statistical Review of World Energy, London.
- [2] Dobashi, R., Kong, Z.W., Toda, A., Takahashi, N., Suzuki, M., and Hirano, T. (1999). Mechanism of smoke generation in a flickering pool flame. *Proceeding of the 6th International Symposium on Fire Safety Science*, 255-264.
- [3] Zheng, F., and Davis, E.J. (2001). Thermophoretic force measurements of aggregates of microspheres. *Journal of Aerosol Science*, 32, 1421-1435.
- [4] Suzuki, S., and Dobashi, R. (2007). Thermophoretic effect on soot particle behavior –influence of particle morphology. *21st ICDERS*, 239.
- [5] Fredlund, E. (1938). Absolute measurements of radiometric action in gases. *Philosophical Magazine*, 26, 987-1000.
- [6] Jacobsen, S., and Brock, J.R. (1965). The thermal force on spherical sodium chloride aerosols. *Journal of Colloid Science*, 20, 544-554.
- [7] Rosenblatt, P., and La Mer, V.K. (1946). Motion of a particle in a temperature gradient; thermal repulsion as a radiometer phenomenon. *Physical Review*, 70, 385-395.
- [8] Saxton, R.L., and Ranz, W.E. (1952). Thermal force on an aerosol particle in a temperature gradient. *Journal of Applied Physics*, 23, 917-923.
- [9] Schadt, C.F., and Cadle, R.D. (1961). Thermal forces on aerosol particles. *Journal of Physical Chemistry*, 65, 1689-1694.
- [10] Li, W., and Davis, E.J. (1995). Measurement of the thermophoretic force by electrodynamic levitation: microspheres in air. *Journal of Aerosol Science*, 26, 1063-1083.
- [11] Li, W., and Davis, E.J. (1995). The effects of gas and particle properties on thermophoresis. *Journal of Aerosol Science*, 26, 1085-1099.
- [12] Keng, E., and Orr, C. (1966). Thermal precipitation and particle conductivity. *Journal of Colloid and Interface Science*, 22, 107-116.
- [13] Schadt, C.F., and Cadle, R.D. (1957). Thermal forces on aerosol particles in a thermal precipitator. *Journal of Colloid Science*, 12, 356-362.
- [14] Kousaka, Y., Okuyama, K., Nishio, S., and Yoshida, T. (1976). Experimental study of thermophoresis of aerosol particles. *Journal of Chemical Engineering of Japan*, 9, 147-150.

- [15] Prodi, F., Santachiara, G., and Prodi, V. (1979). Measurements of thermophoretic velocities of aerosol particles in the transition region. *Journal of Aerosol Science*, 10, 421-425.
- [16] Davis, L.A., and Adair, T.W.III. (1975). Thermal force on a sphere. *Journal of Chemical Physics*, 62, 2278-2285.
- [17] Tong, N.T. (1975). Experiments on photophoresis and thermophoresis. *Journal of Colloid and Interface Science*, 51, 143-151.
- [18] Toda, A., Ohi, Y., Dobashi, R., Hirano, T., and Sakuraya, T. (1996). Accurate measurement of thermophoretic effect in microgravity. *Journal of Chemical Physics*, 105, 7083-7087.
- [19] Toda, A., Ohnishi, H., Dobashi, R., Hirano, T., and Sakuraya, T. (1998). Experimental study on the relation between thermophoresis and size of aerosol particles. *International Journal of Heat and Mass Transfer*, 41, 2710-2713.
- [20] Prodi, F., Santachiara, G., Travaini, S., Vedernikov, A., Dubois, F., Minetti, C., and Legros, J.C. (2006). Measurements of phoretic velocities of aerosol particles in microgravity conditions. *Atmospheric Research*, 82, 183-189.
- [21] Prodi, F., Santachiara, G., Di Matteo, L., Vedernikov, A., Beresnev, S.A., and Chernyak, V.G. (2007). Measurements of thermophoretic velocities of aerosol particles in microgravity conditions in different carrier gases. *Journal of Aerosol Science*, 38, 645-655.
- [22] Hoshino, A., Suzuki, M., and Masuda, W. (2010). Influence of particle size distribution on measurement accuracy of thermophoretic velocity. *Proceeding of the 48th Symposium (Japanese) on Combustion*, 464-465.
- [23] Hoshino, A., Suzuki, M., and Masuda, W. (2010). Numerical analysis on thermophoretic phenomenon in slip flow regime considering thermal stress effect. *The 21st International Symposium on Transport Phenomena*.
- [24] Lockerby, D.A., Reese, J.M., Emerson, D.R., and Barber, R.W. (2004). Velocity boundary condition at solid walls in rarefied gas calculations. *Physical Review E*, 70, 017303-1-017303-4.
- [25] Kennard, E.H. (1938). *Kinetic Theory*. McGraw-Hill: New York.