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Research on Thermophoresis Deposition of Aerosol Particles

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Abstract. An aerosol is a system of liquid or solid particles in suspension in a gas, which includes both the particles and the suspended gas. The aim of this paper is to study the thermophoretic forces in aerosol systems. We introduce the concepts of particle size distribution, DLVO theory and multiphase flow models, followed by four case studies of thermophoretic deposition. This study has some limitations that need further investigation for a number of specific reasons. Firstly, the impact of thermophoresis is often overlooked in discussions about aerosols and their walls. Additionally, the focus has only been on solid walls, while the same problem applies to soft walls such as the human respiratory tract. The complexity of fluid models that involve multiple particles and forces also presents challenges. The task of examining the effects of temperature fields and temperature variations will be even more daunting. There is a pressing need for further research in this area.

Keywords: particle deposition, thermophoresis, aerosol, wall.

1. Introduction

The definition of a phase is that it is a region of space (a thermodynamic system) where all the physical properties of a material are similar or at least similar to each other. Some people use phase as a synonym for state of matter, as a phase is a data which describes the state of matter of a substance. However, there are compounds that form different phases that are in the same state of matter. It is very common for us to observe four different states of matter in our daily lives: solids, liquids, gases and plasmas.

In some mixtures, the substances distributed in the liquid material are not dissolved. They are simply dispersed and settle out once the mixture stops being shaken. Such heterogeneous mixtures are known as suspensions.

In chemistry, a colloid is known as a colloidal dispersion and is a homogeneous mixture which contains two substances in different phases. Part of this dispersion can be interfacial particles consisting of many atoms or molecules (103-106) with a diameter size of between 1 nm and 100 nm, or it can be large molecules or micelles with no phase interface. The former are referred to as sols and the latter as polymer solutions or associated colloids.

The difference between a suspension and a colloid is that the particles in a suspension separate when the mixture settles, which makes it easy to distinguish a colloid from a suspension.

Table 1. Different Suspensions in Different Dispersions.

Medium/phase		Dispersed phase		
		Solid	Liquid	Gas
Dispersion medium	Solid	Solid sol	Gel	Solid foam
	Liquid	Sol	Emulsion or liquid crystal	Foam
	Gas	Solid aerosol	Liquid aerosol	Undefined

Solid-liquid suspensions consist of solid particles in different size ranges, such as nanoscale, micron and millimetre particles, as well as particles with different densities. If the particles are too small or if their density is approximately the same as that of the liquid forming the suspension, they will not settle. Non-settling suspensions can be considered as pseudo-fluids with effective rheological properties and their flow in circular and non-circular pipes can be assessed as single-phase flow.

An aerosol is a gaseous dispersion system consisting of solid or liquid particles. The density of these solid or liquid particles can vary considerably, from new nuclei containing a few molecules to cloud droplets and dust particles in the earth's crust with a size of a few tens of microns [1].

Aerosol particles are usually between 0.01 and 10 microns in size, while plant aerosols vary in size from 5 to 100 microns for pollen, and 0.01 to 1000 microns for wood and tobacco burning aerosols. The shape of the particles varies and can be nearly spherical, such as liquid mist beads, or flaky, needle-like and other irregular shapes.

The most classical model in this field is the DLVO theory on the stability of colloids. It is believed that the stability of a solute under certain conditions depends on the potential energy of interaction between colloidal particles, which can be described by calculating the interaction forces to describe the adhesion of the particles.

A mathematical limit can be used in the DLVO theory which is about the relationship between extended particles and particles and between particles and walls.

The decomposition method can also be used for temperature gradients and velocity gradients. The phenomenon of particles suspended in a liquid being trapped by a solid surface is known as particle deposition [2]. The presence of a wall can cause a change in the velocity of the aerosol (faster or slower), depending on the relative separation of the instance from the wall, the surface properties and the temperature of the surrounding environment. Particle deposition can therefore be considered and the specific case calculated.

There are several ways of modelling multiphase flows. Using a basic set of equations, we can calculate the pressure, speed, temperature, apparent density, volume fraction, and size of the suspended matter in each phase. In addition, we can calculate the distribution of pressure, velocity, and temperature. The effect can be calculated for a variety of situations.

A commonly used model is the two-fluid model. As is the case with two-phase proportions, separate sets of mathematical and physical equations are developed. These equations take into consideration a number of physical factors such as drag, relative displacement, momentum, and heat exchange (transfer) between the phases, as well as the physicochemical properties of the phases themselves.

In addition, a homogeneous phase model is introduced. For two-phase mixed homogeneous flows, the homogeneous phase (continuous medium) model and the diffusion model can be extended and analysed according to classical hydrodynamic methods.

In addition, statistical group models can also be used. We propose the statistical group (particle group) model as an alternative to the multi-phase flow model, where the flow is composed of bubbles, droplets and solid particles. The statistical group (particle group) model is based on stochastic analysis which is particularly suitable for two-phase flow systems.

The physical model is used to make experimental measurements, and as a result, measurement technology plays a very prominent role in the experiment. There have been many advances in instruments and technologies that have been applied to the measurement of multiphase flows in recent years, such as the observation of flow pattern and flow state with high-speed photography, holographic photography, flow display technology, the measurement of velocity with Laser Doppler Velocimetry (LDV), particle image velocimetry (PIV), etc., the detection of bubble concentration in the liquid flow with fiber optic sensors (probes), the measurement of solid particle concentration in the flow with Bp neural network system, and the measurement of the average concentration of the section with radioisotope method, etc.(solid liquid two phase flow).

2. Definition of Thermophoresis

There is a phenomenon known as thermophoresis, which is the movement of particles as a result of a temperature gradient [3]. It is a phenomenon of mass transfer in a temperature gradient. The temperature gradient is greater near the heated surface compared to the temperature gradient away from the surface. Therefore, the thermoelectric effect is mainly present in the near-wall region. The phenomenon of thermophoresis has been extensively studied in aerosol systems in recent decades [4]. Four case studies will be presented in the following paragraphs.

3. Applications of Thermophoresis

In the article "The effect of thermophoresis on dust accumulation on solar panels", the accumulation of dust was studied depending on the temperature gradient between the solar cell and the surrounding air. Particles were moved from the hot zone to the cold zone (solar cell to air) and tested using a non-isothermal laminar airflow through the boundary layer approximation of the solar cell. The researchers calculated the generated thermophoretic force from the temperature profile. It was found that a strong thermophoretic force was generated at the entrance to the solar panel.

There are a number of ways to verify the inhomogeneity of the thermal resistance along a solar panel. The authors simulated the trajectories of Lagrangian particles to understand the effects of thermophoresis and demonstrated that thermophoretic forces would form a free layer of dust accumulation, for particle sizes, less than 1 micron. The temperature difference between a solar cell and the air around it is huge. Typically, in a desert environment, the temperature difference is 35◦ C; by using the PVlib code, it is shown that temperatures can even reach 50◦ C. The results of these measurements and simulations show that the thermoelectric effect plays an important role in dust deposition during the day.

The authors show that for micron or submicron diameter particles, the deposition rate due to pyroelectric forces should be taken into account. Given the wind speed, dust density and particle size distribution, the amount of dust accumulated in one hour can be calculated. In order to gain further insight into dust deposition on PV panels, various dust transport processes and environmental conditions should be considered. The implication of the results is that for submicron sized particles during the day, the thermal grid effect may affect dust deposition on solar cells.

In the article “Thermophoresis deposition studies for NaCl and diesel exhaust particulate matter under laminar flow”, the fine particle deposition is considered a problem in numerous processes.

The regulation particle emissions from engine exhaust is a crucial area of research, as it is closely related to health and the environment. This problem has been solved by developing better engines and exhaust gases treatment. A better understanding of the transport system in the exhaust particulate matter of a diesel engine (PM) is needed in order to discover highly efficient control approaches.

The focus of this study was twofold. Firstly, a model was established to anticipate the thermophoresis deposition under laminar flow in the tube with the wall temperature reducing along the axial direction. Using a thermal conductivity (kp) value of 0.5 W/mK for exhaust particles in order to simulate experimental observations was determined to be a satisfactory correlation between the model and the experimental results.

Next, thermophoretic deposition of NaCl test aerosols and diesel exhaust particles was carried out at temperatures (gas inlet) of 170, 260 and 360 ° C and $400 < Re < 2000$. They found that the model results for NaCl test aerosols were within 14-17% prediction error in the parameter space range, while the prediction error for engine exhaust particles was within 10-18%. This difference was considered comparable to that reported in the literature. The exploratory results suggest that the expression of the thermophoresis coefficient proposed in 1980 is relevant to a wide range of exhaust particulate matter over a wide range of gas temperature particle sizes.

Previous studies have reported on the morphology of particulate matter in diesel exhaust gases and further consideration of the effect of these on thermophoresis may be important.

The article "Transport of submicron particles from leaks to vertical surfaces in chambers under reduced pressure" explains that in modern semiconductor production many manufacturing processes use specially designed equipment that can generate high temperatures and reduced pressures. Particles may be generated within this system due to changes in the thermodynamic state of the technical process itself or during ventilation. In addition, particles can be transported into the system due to leakage.

Models that are simplified and idealised experiments conducted in static conditions are useful for offering insight into how particles behave in real equipment based on simplified models and idealized experiments.

Their study was carried out to investigate particle transport and deposition using different pressures, surface temperatures, and distances between the particle inlet and the surface. This was done at different pressures, surface temperatures, and particle distances. As a means of modelling these particle transport processes, analogies are drawn between the governing equations for momentum, energy and mass. These analogies are applied to the extended diffusion equations in order to attain a more accurate representation. It is clear from the numerical calculations that the results of the particle concentration boundary layer calculations can provide us with detailed information about the velocity, temperature, and thickness of the particle concentration boundary layer, as well as their distribution in a non-dimensional manner. Specifically, the researchers explore how external forces are able to influence the particle concentration field at the surface and how that relates to external forces.

A comparison of theoretical and experimental results shows the need to use Schlichting's flow field model behind the injector to investigate how particles are transported to a vertical surface located far behind the leak point.

The article "Suppression of particle deposition in a tube flow by heat transfer" investigates how particle deposition is suppressed when the temperature of the tube wall exceeds the temperature of the internal gas. This was investigated both theoretically and practically.

This study carried out a numerical analysis to quantify the particle concentration distribution and particle deposition efficiency under laminar tube flow conditions using different tube wall temperatures above the inlet gas stream temperature. A study found that particle deposition efficiency was significantly reduced when the tube wall was heated to a temperature slightly above that of the gas stream, which may be linked to the effect of heat on particle deposition efficiency. It was necessary to validate the numerical results by measuring the deposition efficiency of monodisperse particles in order to establish their validity. The greatest inhibition of particle deposition occurred near the front end of the tube, as there was a temperature difference between the airflow and the tube wall. Further in, once the flow reaches temperature, the thermal conductivity of the particles is less than the diffusion force and the particles start depositing again.

An empirical expression has been developed that can be applied to the case of a given dimensionless deposition parameter. This expression can be used to identify the temperature difference required within a laminar flow tube for zero deposition efficiency, as well as to predict how best to suppress the deposition of thermally diffused particles by controlling the tube wall temperature.

4. Discussion

One concern with the results of the study is that the phenomenon of thermophoresis is often neglected in the discussion of aerosols and aerosol walls. Another is that only solid walls have been discussed above and the same issue is involved in the case of soft walls (e.g. human respiratory tract etc.). Furthermore, fluid models involving multiple particles and multiple forces are inherently complex. Considering the effects of temperature fields and temperature variations will be even more difficult. A great deal of work needs to be done in this area.

5. Conclusion

There are some similarities between these four articles. Firstly, they study the deposition of particles through a tube with a circular cross section. The flow rates are very low and the normal mass flow is shown to be more pronounced. They fit well with the numerical and experimental data on thermal diffusion deposition efficiency. Secondly, all the articles deal with the problem of surface dust in microelectromechanical systems (MEMS) or other industrial products in a general way. Thirdly, the application scenarios are similar. The solid walls are very hot and cannot be cooled at will. Because the wall is particularly sensitive to interfacial properties thermophoresis in the presence of thermal gradients, it provides unique data on the structural properties of colloids or macromolecular fluids and particle/solvent interactions at the nanoscale. Finally, the transport properties of an aerosol depend largely on its size and how the surrounding gas molecules interact with it. The particle distribution under the previously mentioned study conditions is inevitable and the distribution sizes are similar.

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