THERMOPHORESIS OF PARTICLES IN GAS-PARTICLE TWO-PHASE FLOW WITH RADIATION EFFECT

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The radiation effect on the thermophoresis of particles is analyzed for a gas-particle two-phase laminar flow. Two-phase radiation by both gas and particles is considered; in addition, the thermal nonequilibrium between gas and particle is taken into account. It is concluded that the particle diffusion velocity as well as particle concentration depends strongly on the optical radius of gas or particle. In general, the radiation was found to decrease the particle diffusion. In case that gas as well as particle radiation exists, the deposition of particle is mainly influenced by the gas. The effects of parameters such as the optical radius, conduction to radiation parameter, thermal loading ratio, and wall emissivity on the cumulative collection efficiency $E(x)$ are also considered. As the optical radius and tube wall emissivity increase, $E(x)$ decreases. The increase in conduction to radiation parameter $N$ and thermal loading ratio $C_L$ leads to an increase in $E(x)$.

INTRODUCTION

Prediction of particle transport in nonisothermal gas flow is important in studying the erosion process in combustors and heat exchangers, the particle behavior in dust collectors, and the fabrication of optical waveguide and semiconductor devices, and so on. Environmental regulations on small particles have also become more stringent due to concerns about atmospheric pollution.

When a temperature gradient is established in gas, small particles suspended in the gas migrate in the direction of decreasing temperature. This phenomenon, called thermophoresis, occurs because gas molecules colliding on one side of a particle have different average velocities from those on the other side due to the temperature gradient. Hence, when a cold wall is placed in the hot particle-laden gas flow, the thermophoretic force may cause particles to be deposited on it. The magnitude of this force depends on gas and particle properties as well as on temperature gradient. Aside from the thermophoresis, the particle behavior is also affected by such mechanisms as Brownian diffusion, inertial impaction, and electrostatic force. But there are many instances in which these effects are negligible so that the thermophoresis is the only one playing an important role.
There have been many experimental and numerical studies on thermophoresis. Derjaguin et al. [1] performed various experiments on the thermophoresis of aerosol particles and measured the thermal slip coefficient to calculate thermophoretic velocity, and then compared it with a theoretical one. Using the results above, Walker et al. [2] calculated the deposition efficiency of small particles due to thermophoresis in a laminar tube flow. While thermophoretic deposition in a turbulent pipe flow was measured by Calvert and Byers [3], Thakurta et al. [4] numerically computed the deposition rate of small particles on the wall of a turbulent channel flow using the direct numerical simulation (DNS). Besides, assuming that the particle temperature was always equal to the gas temperature in a laminar tube flow, Yoa and colleagues [5] numerically investigated the thermophoresis phenomenon by taking into account the particle radiation.

Based on a paper review of these papers, we concluded that most of these previous studies on the thermophoresis neglected the effects of thermal radiation, and only a few have taken only one of two phases into consideration assuming the thermal equilibrium between gas and particle phases. In fact, there are various kinds of high temperature systems such as a heat exchanger and an internal combustor, in which the radiation may not be negligible in comparison with the conductive and convective heat transfer mode. Usually, the gas like CO₂ and H₂O generated during combustion of a hydrocarbon fuel and the particles such as soot and coal suspended

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>( C_L )</td>
<td>thermal loading ratio ( (= \rho_p c_{pp} / \rho_g c_{pg}) )</td>
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<tr>
<td>( c_p )</td>
<td>specific heat</td>
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<td>( n )</td>
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<td>( n_p )</td>
<td>number of particles per unit volume</td>
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<td>( \text{Stk} )</td>
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<td>( \bar{s} )</td>
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<td>( v )</td>
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<td>( p )</td>
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<tr>
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<td>wall</td>
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in a hot gas flow absorb, emit, and scatter the radiation. There also exists the temperature difference between gas and particle phases. As a matter of fact, it was experimentally reported that the gas and particles in a high temperature combustion system are in a thermal nonequilibrium [6]. Consequently, the radiation effect by gas as well as particles must be simultaneously considered, which is the case in this study.

The goal of this study is thus to investigate the radiation effects by both gas and particles on particle transport due to thermophoresis in an axisymmetric tube while considering the thermal nonequilibrium between gas and particle phases. Thus, in this study the two-phase radiative transfer equation is to be introduced to deal with gas and particle radiation at the same time, which then can be solved using the discrete ordinates method (DOM).

GOVERNING EQUATIONS

As schematically drawn in Figure 1, a two-phase flow (gas and particle) at 1000 K enters a tube, where the wall is maintained at 300 K. The flow is considered to be laminar and fully developed. The gas and particle are then gradually cooled down as they flow downstream due to conduction and radiation heat transfer. Since the temperature gradient is generated, the small particles suspended in the gas begin to move in the transverse direction of decreasing temperature by thermophoresis. The particles, which reach the cold wall, are assumed to be deposited therein.

In order to analyze this phenomenon, a simplified mathematical model would be introduced below while retaining the essential physical features of the problem based on the following assumptions:

1. The system is axisymmetric and steady state.
2. The volume fraction of the particles is small enough that the collision between the particles is negligible.
3. Gas and particle properties are independent of temperature.
4. Particles are spherical in shape and of uniform size.
5. There is no viscous energy dissipation and internal heat source.
6. The radiative properties of gas and particles are gray.
7. No scattering is considered in radiation.

\[ y \quad T_w = 300 \text{K}, \quad \epsilon_w = 1.0 \]

\[ u_g = 2U_{\infty} (1 - \eta) \quad T_{g,\infty} = T_{p,\infty} = 1000 \text{K} \]

Figure 1. Schematic of thermophoresis of particles in gas-particle two-phase flow.
(8) The wall surface diffusely emits and reflects radiation.
(9) The gas and particle phases are in thermal nonequilibrium.

As the gas is assumed to be fully developed, it is not necessary to solve the continuity and momentum equation of gas. Therefore, only the energy equation is solved here for the gas phase while the continuity, momentum, and energy equations are solved for the particle phase. The governing equations based on the two-fluid model are then as follows:

The continuity equation of particle

$$\frac{\partial}{\partial \xi}(\phi u_p) + \frac{1}{\eta} \frac{\partial}{\partial \eta}(\eta \phi v_p) = 0 \tag{1}$$

The \( u \) momentum equation of particle

$$u_p \frac{\partial u_p}{\partial \xi} + v_p \frac{\partial u_p}{\partial \eta} = \frac{1}{Stk} (u_p - u_g) - \frac{K}{Stk \, Re_R} \frac{1}{\theta_g} \frac{\partial \theta_g}{\partial \xi} \tag{2}$$

The \( v \) momentum equation of particle

$$u_p \frac{\partial v_p}{\partial \xi} + v_p \frac{\partial v_p}{\partial \eta} = \frac{1}{Stk} (v_p - v_g) - \frac{K}{Stk \, Re_R} \frac{1}{\theta_g} \frac{\partial \theta_g}{\partial \eta} \tag{3}$$

where

$$\xi = \frac{x}{R} \quad \eta = \frac{y}{R} \quad \phi = \frac{\rho_p}{\rho_{p,in}}$$

$$Re_R = \frac{U_{avg} R}{\nu} \quad \text{and} \quad Stk = \frac{\rho_{pm} d_p^2 U_{avg}}{18 \mu R} \tag{4}$$

In the above the gas and particle velocity components are normalized by \( U_{avg} \), \( \rho_p \) represents the apparent particle concentration in gas flow, defined as \( \rho_p = \rho_{pn} n_p \). \( Stk \) denotes the Stokes number that is the ratio of momentum relaxation time \( \tau_{mom} \) to the characteristic flow time \( \tau_{flow} \). Other symbols are listed in the nomenclature. The last term in Eqs. (2) and (3) actually represents the thermophoretic velocity, \( V_T \), of a particle that can be theoretically derived as follows [2]:

$$V_T = -K \frac{\nabla T}{T}$$ \tag{5}

where \( K \) is the thermophoretic coefficient that depends mainly on the Knudsen number \( Kn = \lambda / (d_p / 2) \). For the flow regime where the molecular mean-free path, \( \lambda \), is on the order of the particle radius, \( R_p (= d_p / 2) \), the following formula proposed by Derjaguin et al. [1] can be used.

$$K = k_T \frac{1 + c_1(\lambda / R_p)(k_p / k_g)}{1 + (k_p / 2k_g) + c_1(\lambda / R_p)(k_p / k_g)} \tag{6}$$
Here, $c_1$ is constant ($=2.17$) and $k_T$ is the thermal slip coefficient whose value is about 1.1. $k_p$ and $k_g$ are the thermal conductivities for particle and gas, respectively. The energy equation of gas

\[
\frac{1}{Pe_R} \frac{\partial^2 \theta_g}{\partial \xi^2} + \frac{1}{Pe_R \eta \partial \eta} \left( \eta \frac{\partial \theta_g}{\partial \eta} \right) + \frac{C_L \tau_{\text{flow}}}{\tau_T} (\theta_p - \theta_g) - \frac{\tau_g}{Pe_R N} (\theta_g^4 - G_o)
\]  

(7)

The energy equation of particle

\[
\frac{u_p}{Pe_R} \frac{\partial \theta_p}{\partial \xi} + v_p \frac{\partial \theta_p}{\partial \eta} = - \frac{\tau_{\text{flow}}}{\tau_T} (\theta_p - \theta_g) - \frac{\tau_p}{C_L Pe_R N} (\theta_p^4 - G_o)
\]  

(8)

where

\[
C_L = \frac{\rho_p c_{pp}}{\rho_g c_{pg}} \quad \theta_g = \frac{T_g}{T_{in}} \quad \theta_p = \frac{T_p}{T_{in}} \quad Pe_R = \text{Re}_R \text{Pr}
\]

\[
\tau_{\text{flow}} = \frac{R}{U_{\text{avg}}} \quad \tau_T = \frac{3}{2} \text{Pr} \left( \frac{c_{pp}}{c_{pg}} \right) \tau_{\text{mom}}
\]

\[
\tau_{\text{mom}} = \frac{\rho_m C(d_p) \rho p^2}{18 \mu} \quad \text{(If slip between particle and gas is neglected, } C(d_p) = 1)
\]

\[
\tau_g = \kappa_g R \quad \tau_p = \kappa_p R \quad N = \frac{\kappa_g}{4 R \sigma n^2 T_{in}^3}
\]  

(9)

The boundary conditions for the governing equations can be expressed as follows:

At inlet, $\xi = 0$

\[
u_p = u_g \quad v_p = 0 \quad \phi = 1 \quad \text{and} \quad \theta_p = \theta_g = 1
\]  

(10a)

At exit

\[
\frac{\partial \theta_g}{\partial \xi} = 0
\]  

(10b)

at $\eta = 0$

\[
\frac{\partial u_p}{\partial \eta} = 0 \quad v_p = 0 \quad \frac{\partial \phi}{\partial \eta} = 0 \quad \text{and} \quad \frac{\partial \theta_g}{\partial \eta} = \frac{\partial \theta_p}{\partial \eta} = 0
\]  

(10c)

at $\eta = 1$

\[
\theta_g = \theta_w
\]  

(10d)

The last terms in the energy equations (7) and (8) for gas and particle denote the nondimensionalized divergence of radiative heat flux for gas and particle, respectively. $G_o$ stands for incident radiation, whereas $N$, $\tau_g$, and $\tau_p$ are the dimensionless variables that represent a ratio of conduction to radiation and the optical radius for gas and particle, respectively.
Radiative Heat Transfer of Gas and Particle

To obtain the incident radiation, $G_o$, denoted in the energy equations, the radiative transfer equation (RTE) should be solved. For a gray, emitting, absorbing, and scattering gas-particle two-phase medium in a thermal nonequilibrium state, the RTE can be written as follows [8, 9]:

$$\frac{dI(\vec{s})}{ds} + (\kappa_g + \kappa_p + \sigma_s)I(\vec{s}) = \kappa_g I_{bg} + \kappa_p I_{bp} + \frac{\sigma_s}{4\pi} \int_{4\pi} I(\vec{s}')\Phi(\vec{s}, \vec{s}')d\Omega'$$ \hspace{1cm} (11)

In the above equation, while the absorption, emission, and scattering are all considered for the particle phase, the scattering for the gas phase is neglected. In this study, the gas absorption coefficient is assumed to be constant, whereas the particle absorption coefficient is assumed to be dependent on the particle concentration as follows:

$$\kappa_p = \phi \kappa_{p, in}$$

where $\kappa_{p, in}$ is the particle absorption coefficient at inlet.

Together with Eq. (11), if the particle as well as gas temperature and the boundary conditions for the radiative intensity are known, the intensity of medium can be obtained. For the opaque, emitting, and diffusely reflecting wall, the outgoing intensity from the wall consists of emission from the wall and reflection of incoming intensities such that [7]

$$I(\vec{r}_w, \vec{s}) = \varepsilon_w I_b(\vec{r}_w) + \frac{1 - \varepsilon_w}{\pi} \int_{\vec{s} \cdot \vec{a}_{w} < 0} I(\vec{r}_w, \vec{s}')|\vec{s}' \cdot \vec{n}_w|d\Omega'$$ \hspace{1cm} (12)

The divergence of radiative heat flux in energy equations is then defined to be

$$\nabla \cdot \vec{q}^R = \int_{4\pi} (\vec{s} \cdot \nabla I) d\Omega = \int_{4\pi} \frac{dI}{ds} d\Omega$$ \hspace{1cm} (13)

If Eq. (11) is substituted into Eq. (13) and the integration is performed, the following equation can be obtained:

$$\nabla \cdot \vec{q}^R = \kappa_g \left( 4\pi I_{bg} - \int_{4\pi} I d\Omega \right) + \kappa_p \left( 4\pi I_{bp} - \int_{4\pi} I d\Omega \right)$$ \hspace{1cm} (14)

Here, $\nabla \cdot \vec{q}_g^R$ and $\nabla \cdot \vec{q}_p^R$ are the divergences of radiative heat flux for gas and particle, respectively, which physically mean the net radiative energy of each phase out of control volume.

The RTE is here solved using the DOM, in which the solid angle is discretized by selecting a discrete set of directions spanning the total solid angle of $4\pi$ steradians with predetermined weights ($w_m$). The number of directions $M$ depends upon the order of discrete ordinates through the relationship $M = N(N+2)/2$, where $N$ represents the order of the approximation. Preliminary evaluations revealed that the $S_4$ approximation is quite adequate, while the $S_2$ approximation is less accurate. The $S_6$ and $S_8$ approximations did not produce enough improvement in accuracy compared with the increase in computational cost so that the $S_6$ approximation is used in this study [8, 9, 10, 11].
NUMERICAL ANALYSIS

A nonuniform grid has been adopted in both axial and radial directions. When the grid size is increased from \((41 \times 81)\) to \((51 \times 101)\), the solution change is only less than 2\% so that the grid size of \((51 \times 101)\) is used here.

In this work, all the governing equations are solved in the fully coupled manner. First, the energy equation for gas, (7), and the energy equation for particle, (8), are solved using the power law scheme [12] to obtain the new temperature field for gas and particle. Then the momentum and continuity equations for particle are computed with the upwind scheme [12] to obtain the particle velocity and concentration at each point. All the governing equations are then computed iteratively until the following convergence criterion is satisfied:

\[
\sum_j \sum_i \left( A_{ij}^{n+1} - A_{ij}^n \right) < 10^{-6}
\]

Here, \(A\) denotes \(T_g, T_p, u_p, v_p, \) or \(\phi\). The \(i\) and \(j\) represent the grid number for the \(x\) and \(y\) directions, respectively, while \(n\) denotes the iteration step. Also, the computational conditions used in this study are listed in Table 1.

RESULTS AND DISCUSSIONS

In the following, unless otherwise specified, the tube wall emissivity is 1.0; the inlet temperature of both gas and particle is 1000 K; and the tube wall temperature is maintained at 300 K. The results on the effect of two-phase radiation on thermophoresis are to be presented in terms of the cumulative collection efficiency, which is defined as the percentage of particles that are deposited on the wall within a distance \(x\) from the tube inlet such that

\[
E(x) = \frac{\int_0^x J_p(s) 2\pi R ds}{\phi m U_{avg} \pi R^2}
\]

where \(J_p = \phi v_p \mid_w\) is the particle deposition flux at the wall.

First, to validate the accuracy of the present program and numerical method, we compare, the current results with the solutions by Walker et al. [2] in Figure 2. It shows that the present cumulative deposition efficiency is in agreement with Walker’s results for the case without radiation. Also, Figure 3 shows that the present solutions

| Table 1. Computational conditions for gas-particle two-phase flow |
| --- | --- |
| Conditions | Quantities |
| Tube length \((L)\) | 5 m |
| Tube radius \((R)\) | 0.1 m |
| Inlet temperature \((T_{in})\) | 1000 K |
| Wall temperature \((T_w)\) | 300 K |
| Prandtl number \((Pr)\) | 2/3 |
| Reynolds number \((Re_R)\) | 300 |
| Particle diameter \((d_p)\) | 0.5 \(\mu\)m |
| Wall emissivity \((\varepsilon_w)\) | 1 |
agree very well with Pearce and Emery's results [13] in which \( \tau_o \) and \( N \) denote the optical thickness and the conduction-to-radiation parameter, respectively.

Based on this validation, further calculation on the effects of radiation on thermophoresis is done and presented below. First, since the particle deposition phenomenon is mainly due to the gas temperature variation, the effect of optical radius of gas and particle and conduction to radiation parameter \( N \) on the mean
temperature of gas is examined. Figure 4 displays the mean temperature variation of gas along the axial direction with $\tau_g$ at $\tau_{p,\text{in}} = 0$, $T_w/T_{\text{in}} = 0.3$, and $N = 0.01$. The mean gas temperature is the physical quantity of interest in the heat transfer study and is defined by

$$\Theta_m(\xi) = \frac{\int_0^1 \theta_g(\xi, \eta) u(\eta) \eta d\eta}{\int_0^1 u(\eta) \eta d\eta}$$

As shown in Figure 4, with the increase in the optical radius of gas, the mean gas temperature more rapidly approaches the wall temperature. This is because the emission of radiant energy by gas is much stronger for the larger value of the optical radius. Hence, the thermal entry length becomes the longest for the case without radiation. Figure 5 describes the variation of mean temperature of gas with the change of $\tau_{p,\text{in}}$ for $\tau_g = 0$. The results are qualitatively similar to those in Figure 4. In Figure 6, the results are given in terms of the conduction-to-radiation parameter $N$ for $\tau_g = 0.2$ and $\tau_{p,\text{in}} = 0.3$. For smaller $N$, the radiation becomes dominant so that the medium cools down to wall temperature faster.

To enhance the basic understanding of thermal behavior of gas–particle flow when two-phase radiation is taken into account, the gas and particle temperature profiles are plotted in Figure 7 along the radial direction at various axial locations ($x/R = 10$, 25, and 40) for various optical radii of particle with $\tau_g = 0.1$, $T_w/T_{\text{in}} = 0.3$, and $N = 0.01$. As $\tau_{p,\text{in}}$ increases, the particle temperature decreases faster, while the temperature difference between the gas and the particle increases. This results from the fact that an increase in $\tau_{p,\text{in}}$ results in more radiative heat loss by particle due to higher emission. The gas and particle temperatures going downstream are observed to become the same in the figure. In particular, it is also noted that the particle temperature becomes higher than the gas temperature near the wall since

![Figure 4](image-url)  
*Figure 4. Gas mean temperature along the axial direction for various optical radii of gas for $\tau_{p,\text{in}} = 0$.*
there occurs a conductive heat loss to the constant temperature wall of 300 K. Figure 7 further illustrates that the particles are cooling faster than gas, although the optical radius of the gas and the particle is the same before they reach thermal equilibrium. That is because the heat capacity of particles is smaller than that of gas in this study since the particle concentration is much smaller.

Figure 5. Gas mean temperature along the axial direction for various optical radii of particles for $\tau_g = 0$.

Figure 6. Gas mean temperature along the axial direction for various conduction-to-radiation parameters for $\tau_g = 0.2$ and $\tau_{p,n} = 0.3$. 
Usually, the amount of particle deposition on the wall depends entirely on particle diffusion velocity as well as particle concentration in the flow field. To examine the influence of gas as well as particle radiation on the diffusion velocity and the particle concentration, we plot Figures 8–11. Figure 8 describes the effect of $\tau_{p,\text{in}}$ on the particle diffusion velocity for $\tau_g = 0$ at various axial locations. As shown in Eqs. (2) and (3), the particle diffusion velocity is affected by the gas temperature gradient with the thermophoretic coefficient depending on particle size. In general the particle diffusion velocity decreases downstream since the gas temperature gradient diminishes as it cools down. It is also observed that as $\tau_{p,\text{in}}$ decreases, the particle diffusion velocity is higher at each $x$. This is because the gas temperature

Figure 7. Nondimensional temperature profiles for gas and particles for various $x/R$ with constant optical radius of gas $\tau_g = 0.1$, and various optical radii of particle $\tau_{p,\text{in}} = 0.1, 0.2, \text{and } 0.3$.

Figure 8. Particle diffusion velocity variation at various axial distances for various optical radii of particles with $\tau_g = 0$. 
gradient is higher as $\tau_{p,\text{in}}$ decreases as shown in Figure 7. Figure 9 represents the effect of $\tau_{p,\text{in}}$ on the particle concentration for $\tau_g = 0$ at various axial locations. In the figure it is noted that the particle concentration at tube center is higher while it is lower near tube wall. But as it goes downstream, the particle concentration at tube center decreases while it increases near the tube wall.

Figures 10 and 11 depict the effects of $\tau_g$ on the particle diffusion velocity and particle concentration for $\tau_{p,\text{in}} = 0$. Their variations along the axial direction are very similar to those in Figures 8 and 9. Therefore, regardless of gas or particle radiation, it is concluded that its effect on the particle diffusion is the same.
In the above, a detailed variation of particle diffusion at each location was considered, which is not, however, good for figuring out total efficiency of particle diffusion. Consequently, the cumulative collection efficiency $E(x)$ is not examined. In Figures 12 and 13, the effects of gas or particle radiation on $E(x)$ are presented. Regardless of phase dependency, the cumulative collection efficiency becomes higher as the optical radius decreases. The highest cumulative collection efficiency is obtained when there is no radiation. This is in agreement with the results in Figures 8 and 10, in which the particle diffusion velocity is higher for lower optical radius.

![Figure 11](image1.png)

**Figure 11.** Particle concentration variation at various axial distances for various optical radii of gases with $\tau_{p,\text{in}} = 0$.

![Figure 12](image2.png)

**Figure 12.** Cumulative collection efficiency for various optical radii of gases with $\tau_{p,\text{in}} = 0$. 

The influence of a combination of gas and particle optical radii on $E(x)$ is observed in Figure 14 when their total optical radius is constant, i.e., $\tau_t = 1.0$ for three cases such that $\tau_g = 0.2$, $\tau_{p,in} = 0.8$; $\tau_g = 0.5$, $\tau_{p,in} = 0.5$; and $\tau_g = 0.8$, $\tau_{p,in} = 0.2$. As shown in Figure 14, $E(x)$ is seen to decrease with an increase in optical radius of gas, regardless of a counterbalancing decrease in $\tau_{p,in}$. Based on this, the
cumulative collection efficiency is more dependent on the gas optical radius for the conditions given here.

Figure 15 shows the effects of the conduction-to-radiation parameter $N$ on $E(x)$. As $N$ increases, i.e., the conduction becomes more dominant, $E(x)$ increases. Again the radiation diminishes the particle diffusion.

Figure 16. Cumulative collection efficiency for various thermal loading ratios for $\tau_g = 0.2$ and $\tau_{p,\infty} = 0.3$. 
The effect of the thermal loading ratio $C_L$ on $E(x)$ is seen in Figure 16. The higher $C_L$, the higher $E(x)$ becomes. Therefore, as the particle heat capacity is higher relative to the gas heat capacity, more particles are diffused toward the cold wall.

In Figure 17, the effect of tube wall emissivity on $E(x)$ is examined. As the wall emissivity increases, the cumulative collection efficiency decreases. This is because the higher wall emissivity results in a decrease in the temperature gradient near the wall.

CONCLUSIONS

A numerical simulation was performed to investigate the radiation effects on the thermophoresis of particles in the gas-particle two-phase flow. Unlike previous studies, the two-phase radiation by both gas and particles were not only considered, but the thermal nonequilibrium between two phase was also taken into consideration in this study. When the optical radius of gas or particle, conduction-to-radiation parameter, tube wall emissivity, and thermal loading ratio were varied, their effects on the particle diffusion velocity, particle concentration, and cumulative collection efficiency were examined and discussed. Based on the final results, the following conclusions have been drawn:

1. Regardless of gas or particle radiation, as the optical radius decreases, the particle diffusion velocity becomes higher as it goes downstream.
2. As the optical radius increases, the medium cools down more rapidly so that the temperature gradient along the radial direction is smaller. Hence, the cumulative collection efficiency $E(x)$ decreases.
3. The increase in the conduction-to-radiation parameter results in an increase in the cumulative collection efficiency owing to a reduction of radiation.
4. When the thermal loading ratio increases, the cumulative collection efficiency increases. That is, the higher particle heat capacity enhances the particle diffusion.

5. As the wall emissivity rises, $E(\lambda)$ diminishes because the gas temperature gradient at the wall is reduced near the wall.

REFERENCES


