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Thermophoresis deposition studies for NaCl and diesel exhaust particulate matter under laminar flow

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ABSTRACT

Deposition of fine particles is acknowledged as a concern in various processes. Previous studies have investigated thermophoretic transport for various flow regimes (~30 < Re < 1400), particle sizes (0.01 to 8 µm), and temperature ranges of 25 to 145 °C and 425 to 580 °C. An experimental setup was developed to study thermophoretic deposition for particles near ~1 µm size, in the 170 < T_{gas} < 360 °C temperature range, similar to the conditions of exhaust from the diesel engine used in the present study. NaCl test aerosols (Mass mean diameter (MMD) 0.32 and 0.61 µm), and diesel exhaust particles (MMD 0.44, 0.35 and 0.29 µm) were used at gas inlet temperatures of 170, 260 and 360 °C, and 400 < Re < 2000. A model was developed to predict thermophoretic deposition under laminar flow in a pipe with an axially decreasing wall temperature. Use of a thermal conductivity (k_p) value of 0.5 W m^{-1} K^{-1} for engine exhaust particles in the model, was found to best match with the experimental observations. For both kinds of particles, the model developed in the present work performed as well as other existing models in the literature.

1. Introduction

Control of engine exhaust particle emissions remains an important research area for reasons of health (Donaldson, Stone, Gilmour, Brown, & MacNee, 2000; Kagawa, 2002) and environment (Lloyd & Cackette, 2001). This has been addressed by development of better engines and treatment of exhaust gases (Suzuki, Kuwana, & Dobashi, 2009; Strom & Sasic, 2012). There is a need to better understand the transport behaviour of diesel engine exhaust particulate matter (PM) for design towards more efficient control approaches. Besides this, deposition of fine particles is acknowledged as a concern in various processes such as fouling in heat exchangers, contamination in microelectronics, sample collection of atmospheric particles, losses in nanopowder production and deposition in turbines. Most such gas streams have particles in the sub-micrometer size range, which are subject several transport mechanisms including diffusion, turbulent impaction, thermophoresis, and electrophoresis. Particle laden gas streams that are at a temperature higher than the downstream equipment have the potential of utilising thermophoresis for particle removal. Such an understanding could also be utilised for prevention of deposition in situations such as sampling, fouling and contamination. Efforts towards development of a thermophoretic precipitator have been reported by Messerer, Niessner and Poschl (2004), Chien, Huang and Tsai (2009).

Several studies reported in literature have addressed theoretical and experimental aspects of thermophoretic (TP) deposition

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Nomenclature

A_i	Pipe inside area (m^2)
A_o	Pipe outside area (m^2)
C_m	Momentum exchange coefficient = 1.14
C_p	Specific heat of the gas (kJ kg^{-1} K^{-1})
C_s	Thermal slip coefficient = 1.17
C_t	Temperature jump coefficient = 2.18
C_u	Slip correction factor
d_p	Particle diameter (µm)
d_t	Pipe diameter (m)
dA	Elementalarea = $\pi d_t dx$ (m^2)
dn	Change in concentration (g m^{-3})
dx	Elemental length (m)
FEG-SEM	Field Emission Gun - Scanning Electron Microscopy
h_i	Convective heat transfer coefficient of gas on the pipe inner surface (W m^{-2} K^{-1})
h_o	Convective heat transfer coefficient of air on the pipe outer surface (W m^{-2} K^{-1})
$\bar{h}$	Average convective heat transfer coefficient (W m^{-2} K^{-1})
k_g	Thermal conductivity of gas (W m^{-1} K^{-1})
k_p	Thermal conductivity of particle (W m^{-1} K^{-1})
k_t	Thermal conductivity of pipe (W m^{-1} K^{-1})
K_{th}	Thermophoretic coefficient
Kn	Knudsen number
L	Pipe length (m)
MMD	Mass Mean Diameter (µm)
MOUD	Micro Orifice Uniform Deposition Impactor
$\dot{m}$	Mass flow rate (kg s^{-1})
n	Particle concentration (g m^{-3})
n_i	Particle concentration at inlet (g m^{-3})
n_o	Particle concentration at outlet (g m^{-3})
Nu	Nusselt number
p	Perimeter of the pipe (m)
PM	Particulate Matter
Pr	Prandtl number
PSD	Particle Size Distribution
Q	Volumetric flow rate (m^3 s^{-1})
r_i	Pipe inner radius (m)
r_o	Pipe outer radius (m)
Re	Reynolds number
SSI	Single Stage Impactor
T_a	Ambient temperature (°C)
T_{ag}	Mean film temperature (°C)
T_{gas}	Exhaust gas temperature (°C)
$T_{m(i)}$	Gas mean temperature inlet to the pipe (°C)
$T_{m(o)}$	Gas mean temperature outlet of the pipe (°C)
$T_{m(x)}$	Gas mean temperature at axial position x (°C)
$T_{w(x)}$	Pipe wall temperature at axial psotion x (°C)
TP	Thermophoretic
V_{th}	Thermophoretic velocity (m s^{-1})
x	Distance from the entrance (m)

Greek Symbols

$(\nabla T) = dT/dr$	Radial temperature gradient (K m^{-1})
Δx	Elemental length (m)
η_{th}	Thermophoretic deposition efficiency
λ	Mean free path
μ_g	Dynamic viscosity of the gas (N s m^{-2})
μ_w	Dynamic viscosity of the fluid near the wall (N s m^{-2})
ρ_g	Density of the gas (kg m^{-3})

(Montassier, Boulaud, & Renoux, 1991; Stratmann, Otto, & Fissan, 1994; Tsai, Lin, Aggarwal, & Chen, 2004). Assessment of relative dominance of various transport mechanisms, such as thermophoresis and diffusion, under laminar and turbulent flow conditions, is the first step while considering such studies for a specific application. Thermophoresis is more dominant than diffusion in the 0.01–1 µm size ranges by 1 to 3 orders of magnitude under laminar flow (He & Ahmadi, 1998; Walker, Homsy, & Geyling, 1979; Tsai & Lu, 2004; Messerer, Niessner, & Poschl, 2004).

Previous studies have investigated thermophoretic transport for various flow regimes (~30 < Re < 1400) (Stratmann, Otto, & Fissan, 1994; Tsai, Lin, Aggarwal, & Chen, 2004; Munoz-Bueno, Hontañón, & Rucandio, 2005) and particle sizes (0.01–8 µm) (Montassier, Boulaud, & Renoux, 1991; Tsai, Lin, Aggarwal, & Chen, 2004; Munoz-Bueno, Hontañón, & Rucandio, 2005). The temperature ranges of these studies broadly fall into two ranges, namely ~25–145 °C (Stratmann, Otto, & Fissan, 1994; Romay, Takagaki, Pui, & Liu, 1998), and 425–580 °C (Munoz-Bueno, Hontañón, & Rucandio, 2005). Studies in the 150–450 °C temperature range, which is the typical range for engine exhaust (Hwang, Han, Yun, Kim, & Kim, 2005; Lee, Byun, Bae, & Lee, 2006; Messerer, Niessner, & Poschl, 2003), are limited. Further, the approach of most of the previous studies has been to use a constant wall temperature for the entire length of the pipe. In actual processes, such as soot laden flow in an engine exhaust, this constraint would need to be relaxed.

The focus of the present study was twofold. First, to develop a model for thermophoretic deposition in laminar flow in a pipe with an axially decreasing wall temperature condition based on reported literature; and second, to develop an experimental setup to study thermophoretic deposition for particles with dp < 1.0 µm size, in the 170 < T_{gas} < 360 °C temperature range, as conditions of particle size and temperatures in an engine exhaust respectively.

2. Materials and methods

The design of the experimental setup was intended such that it could be utilised to study thermophoretic deposition of particles with different properties and different sources. Further, it was also intended to fulfil on the requirements of experimental validation of the model simulations for thermophoretic deposition with reasonable accuracy. The focus was to first use the well studied NaCl test aerosols, followed by diesel particulate matter from an engine with sizes and concentrations matched by the test aerosols.

The bench scale particle deposition setup was developed with a pipe for laminar flow (400 < Re < 2000) with two kinds of