Analytical Investigation of Fine Particle Deposition in Automotive Exhaust Pipes

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Abstract

It has increasingly been recognized that both diesel and gasoline vehicles contribute substantially to fine airborne particulates, which have caused growing concern with regard to their effect on human health and the environment. The present study focuses on analytical investigation of particle deposition in the exhaust pipe and potential to capture and control exhaust particulate emissions prior to their release into the atmosphere. Analytical or empirical models of transport process of small particles in gaseous media from existing literature are employed, including diffusive, thermophoretic, electrostatic and gravitational effects. Representative engine conditions in exhaust pipes are simulated. Thermophoretic and electrical forces are dominant but found to be less influential as the exhaust gas flow rate is increased. Overall, it is the electrostatic effect that is more effective in capturing ultrafine particles and has potential for automotive particulate after-treatment system.

Keywords: Deposition, Particulates, Automotive Exhaust Pipes, Analytical Modeling

1. Introduction

Concerns over the adverse health effects of particulate matter have brought about increasingly stringent vehicle particulate emission legislation and the corresponding air quality standards. As a result, control and reduction of exhaust particulate mass and number concentration have become a main area of research in the automotive industry. Gasoline engines, as well as diesel engines, have been shown to be major sources of particulate emissions in terms of particle numbers, size and total mass especially in urban areas [1]. Fine particulates can penetrate the human respiratory system deep into the smallest airways and parts of the lungs. In this way, various chemical compounds and other potentially hazardous materials can be introduced into the human body. Automotive exhaust particulates consist mainly of a solid phase core surrounded by adsorbed low-volatility organic compounds and with an outer layer of highly volatile species [2]. The solid phase is made up primarily of small (10 – 80 nm) spherical carbonaceous particles and the liquid phase is composed of organic components, mainly hydrocarbon and sulfate. The solid carbon component of particulate matter is formed early in the combustion process and is relatively stable. The volatile organic component is in a gaseous phase at high temperatures. During cooling, as temperature drops, the organic component becomes increasingly adsorbed onto surfaces of the carbon particles. A typical size distribution of automotive exhaust particulates is shown in figure 1, similar to that in [3]. It is characteristically log-normal. The Majority of these particles is below 100 nm in which conventional techniques such as cyclones or filtration or other systems relying on inertial impaction of the particles to the trapping surfaces may not be efficient in capturing them, so alternative techniques should be investigated.

It is crucial to understand the behaviour of fine particles in order to control them. Transport of fine particles from fluid stream to exhaust pipe surfaces is important in predicting the rate of wall deposition and in understanding mechanisms that lead to particle removal. Removal or capture of particles between flat plates or in a pipe has been studied for a number of years. There is a large amount of literature concerning numerical and subject, investigations. The present study involves applying simple analytical models of particle transport mechanisms in gaseous media from existing literature to deposition of particles in exhaust pipes, evaluating the efficiency for capturing fine particles and investigating the potential to develop an exhaust after-treatment system that will contribute to the reduction of fine particle emissions from automotive vehicles. A typical exhaust pipe geometry is considered for the calculation. Exhaust gas flow rates, gas temperatures, particle size and charge distributions are chosen so that they closely resemble actual automotive vehicle exhaust pipe flow.

2. Particle Deposition Mechanisms and Modeling

Behaviour of particles depends upon their size range or size regimes. These size regimes can be classified into four categories, namely continuum, slip flow, transition and free molecular regimes ranging from large to small particles in order. When large particles can be treated as being submersed in a continuous gaseous medium or fluid, this is said to be in the continuum regime. When particles, especially those less than 100 nm diameter are affected by the motion of individual gas molecules, the flow is in the free molecular regime. Slip flow and transition regimes are in an intermediate range between the two. Equations governing the particle motion are based on the particle acceleration as a result of all forces acting upon it. A number of these forces depend on the nature of flow and particles that are being investigated. For the present study, the main mechanisms in turbulent pipe flows are turbulent diffusion, thermophoresis, gravitational settling and electrostatic effect. Deposition efficiency is defined as the ratio of the difference between inlet and outlet particle concentrations to the inlet particle concentration. Particles striking the wall will either adhere or, less frequently, bounce. Adhesion force is sensitive to surface roughness, particle shape and size. As new particles deposit, the already-attached particles are increasingly susceptible to detachment and subsequent re-entrainment off the wall. Particles re-entrain in an unpredictable manner. The unpredictability of re-entrainment contributes to variability in the modeling and measurement of particle emissions. It is known that mechanisms of particle detachment and re-entrainment from surfaces are complicated problems because of the great number of forces and parameters involved. Because particle bounce, adhesion and re-entrainment are beyond the scope of this study so no attempt has been made to include them in the current calculation.

2.1 Turbulent Diffusion

Particles not under the influence of external forces diffuse in a random fashion called Brownian motion. They travel in straight lines and collide with each other, and gas molecules, according to the kinetic molecular theory. Because particles have a much greater mass than gas molecules, the direction and speed of particles that collide with gas molecules are affected only slightly. But upon collision with other particles their velocity can be changed completely. Apart from the internal energy, diffusion can result because of the presence of concentration gradient. Diffusion becomes more important as particle size decreases. Particles too small to be significantly effected by external forces such as gravity can have a significant deposition rate because of diffusion. The rate of transport in a given direction is proportional to the coefficient of diffusion and the concentration gradient immediately outside the surface upon which the particles are deposited. A significant proportion of the deposition of the particles onto surfaces may be via turbulent diffusion process. Deposition of small particles from a turbulent flowing fluid to a solid boundary can be classified into three different regimes [4] for smooth pipes, namely turbulent particle diffusion regime, eddy diffusion-impaction regime and particle inertia-moderated regime, depending on their size range. The deposition rate is characterised by the deposition velocity which is the mass deposition rate per unit area per unit time divided by the mean concentration in the bulk flow.

For very small particles, Brownian diffusion becomes significant and deposition is effected by a combination of Brownian and eddy diffusion. The particles acquire momentum towards the wall which is induced by the turbulent eddies in the turbulent core and buffer layer, traversing the viscous sub-layer to the wall by means of downwards sweeps of fluid following the turbulent bursts [4]. There have also been numerous attempts to model deposition of particles from turbulent tube flows. As a result, various mathematical analysis methods have been developed and proposed. Despite the fact that these methods are largely based upon empirical assumptions, most of them can not be solved analytically and it is necessary to employ numerical computation. However, there exists a set of simple explicit formulae for the calculation of turbulent deposition which can be evaluated rapidly without recourse to a computer. This simple approximation method was shown to give good estimates in comparison with available experimental data [4, 5]. Following is the calculation method of turbulent deposition to smooth surfaces compiled in [5].

$$V_{+d} = \frac{(\nu/D)^{-2/3}}{14.5\left(\frac{1}{6}\ln\frac{(1+\phi)^2}{1-\phi+\phi^2}+\frac{1}{\sqrt{3}}\arctan\frac{2\phi-1}{\sqrt{3}}+\frac{\pi}{6\sqrt{3}}\right)}$$

where $V_{+d} = V_d/u_*$ dimensionless particle deposition velocity due to diffusion, V_d is deposition velocity, ν is kinematic viscosity, D is diffusion coefficient, $u_* = u\sqrt{f/2}$ is friction velocity, $f = 0.316/4\,\mathrm{Re}^{1/4}$ is fanning friction factor and $\phi = \sqrt[3]{\nu/D}/2.9$

Deposition efficiency due to turbulent diffusion can be found using the simple exponential equation that applies when the concentration near the surface is equal to zero,

$$\eta_d = 1-\exp\left(\frac{-4V_d L}{UH}\right)$$

where U is the mean gas velocity, L and H are the length and diameter of the pipe respectively.

2.2 Thermophoresis

Thermophoresis is of practical importance in many engineering applications such as thermal precipitators, the distribution of soot in combustion systems and thermophoretic deposition of particulate matter onto walls of piping systems. It is the phenomenon where very small aerosol particles experience a net thermophoretic force when suspended in a gas in which a temperature gradient is present. This force results from an imbalance in momentum transfer associated with molecular collisions between hot and cold sides of the particles. Therefore, this force tends to drive the particles in the direction of negative temperature gradient. The phenomenon occurs over the range of size regimes, from slip flow to free molecular flow regimes (particle size of a few tens of microns down to several nanometers). Particle deposition by thermophoresis is important when there is significant heat loss from the fluid stream to the surrounding e.g. in an engine exhaust pipe. When heat is lost to a cool surface, particles will be carried to that surface by thermophoresis.

A critical review of theories for thermophoretic coefficient which correlated well with experimental results was done by Talbot [6]. Using theory reviewed in [6], an expression for thermophoretic deposition velocity can be obtained. Particles near the wall that are subject to thermophoretic forces acquire thermophoretic velocities to reach the wall and deposit on it. Thermophoretic velocity is given by

$$V_T = -K_t \nu \frac{\nabla T}{T}$$

where

$$K_t = \frac{2C_s\left(\frac{k_g}{k_p}+C_t\frac{2\lambda}{d_{pt}}\right)\left[1+\frac{2\lambda}{d_{pt}}\left(A+B\exp\left(-C\frac{d_{pt}}{2\lambda}\right)\right)\right]}{\left(1+6C_m\frac{\lambda}{d_{pt}}\right)\left(1+2\frac{k_g}{k_p}+4C_t\frac{\lambda}{d_{pt}}\right)}$$

is dimensionless thermophoretic constant, ∇T is the temperature gradient in the gas, T is the average temperature of the gas near the particle, $C_s \sim 1.147$, $C_t \sim 2.18$, $C_m \sim 1.146$, A = 1.20, B = 0.41, C = 0.88, d_{pt} is the particle diameter, k_g and k_p are the thermal conductivities of gas and particle respectively.

In the development of an expression for the thermophoretic deposition efficiency, simplified assumptions are introduced. Johnson and Kittelson [7] predicted thermophoretic deposition in diesel oxidation catalyst channels by modeling the channel in terms of plug flow. It was assumed that particulate concentration and temperature everywhere within the tube cross section were constant, ignoring the effect of particle depletion near the tube walls. Walker and co-workers [8] considered the effect of thermal and concentration gradients in the radial direction and derived a theory to predict the thermophoretic deposition efficiency of particles from a hot stream of gas flowing through a cold tube. They found that the total efficiency depends on the total heat flux. The total heat flux only depends on the initial maximum temperature and the final minimum temperature to which the gas equilibrates and not on the shape of the wall temperature profile. According to [8], the deposition of aerosol particles flowing through a tube can be expressed as

$$\eta_t = \frac{\Pr K_t \phi_0}{\theta}$$

where

$$\phi_0 = \frac{\theta}{1+\theta} \quad and \quad \theta = \frac{T_w}{T_{bulk} - T_w}$$

T_w is wall temperature and T_{bulk} is bulk gas temperature. Thus, the degree of deposition is a function of temperatures, and is independent of the pipe geometry. The two expressions have differed in assumptions and approaches used. The former approach was more simplified than the latter. Both methods have been applied and suggested by Johnson and Kittelson [7] to be sufficiently accurate for the deposition calculation in a diesel oxidation catalyst. Preliminary tests using both expresions gave similar results for thermophoretic deposition in steady state flow in a representative engine exhaust pipe, considered here. However, because the latter is more easily evaluated and employs more realistic assumptions than the former expression, the one given by Walker et al. [8] is therefore used here for the subsequent calculations.

2.3 Gravitational Settling

Particles moving with the gas in horizontal flow will settle from the gas because of gravitational force. For motion of a small particle under gravity, the particle is accelerated by gravitational force until it reaches a terminal steady state velocity. Then gravitational force can be equated with Stokes drag. The flow within the exhaust pipe is in the turbulent regime throughout the range of engine operating conditions. For a system with turbulent flow in a horizontal cylindrical tube, the gravitational deposition efficiency is

$$\eta_s = 1 - \exp\left(\frac{-4V_s L}{UH}\right)$$

where $V_s = g\tau$ is the Stokes terminal settling velocity of the particles, g is the gravitational acceleration, τ is the particle relaxation time.

2.4 Electrostatic Attraction

For motion of a charged particle under an electric field, the particle is acted upon by an electric force. Most particles carry some electric charges and some may be highly charged. For highly charged particles, the electrostatic force can be a few orders of magnitude greater than the gravitational force. In this study, an electric field is applied to exert an electric force that will move the particles radially towards the pipe wall. The electric field is assumed to be produced by an electrode positioned at the centerline of the pipe and the pipe wall is grounded so that there would be an axisymmetric electric field pushing the particles towards the pipe wall, thus enhancing particle deposition. Automotive particles can usually be assumed to have a Boltzmann equilibrium charge distribution. For large particles, the Boltzmann charge distribution can be expressed by $|n| \cong 2.36\sqrt{d_p}$ (d_p in micrometer). This can be applied for $d_p > 50$ nm while below that the charge falls rapidly to 0.1 for $d_p = 20$ nm and 0.007 for $d_p = 10$ nm [9]. Particle motion resulting from electrical force can be determined in a manner similar to that for terminal settling velocity. For the turbulent flow within the exhaust pipe the deposition efficiency due to electrostatic effect can be estimated using

$$\eta_e = 1 - \exp\left(\frac{-4V_e L}{UH}\right)$$

where $V_e = ZE$ is the terminal settling velocity of the particles, Z is the electrical mobility of the particle, E is the electric field strength.

2.5 Overall Rate of Deposition

In this analytical calculation, the overall combined effect of deposition mechanisms for the net amount of particles deposited onto the wall, assuming complete independence of mechanisms, may be estimated by taking the fraction of particle penetrating the pipe as the product of the fractions penetrating due to each individual mechanism. To get a fair approximation for a given size particle, the total deposition efficiency which accounts for N different mechanisms of particle deposition may be calculated by

$$\eta_{tot} = 1 - (1-\eta_1)(1-\eta_2).....(1-\eta_N)$$
$$= 1 - \sum_{i=1}^{N}(1-\eta_i)$$

3. Particle Deposition in Exhaust Pipes

3.1 Operating Conditions

Calculations have been performed for typical gasoline vehicle exhaust conditions, similar to that in a real exhaust pipe, details in table 1. The pipe diameter of 50 mm and a total length of 1.25, 2.5 and 3.75 m have been considered. A middle sized passenger car engine, running steadily at stoichiometric air to fuel ratio at constant engine speed was assumed to produce representative engine exhaust condition that represents particle emission from a gasoline engine. The pressure in the exhaust pipe was approximated at atmospheric. The gas temperature was assumed to be constant at 500°C with the pipe wall temperature varying from 500°C for fully insulated pipe, to 127°C for cooled wall and 27°C for extreme condition of wall cooling to ambient temperature. The exhaust gases were assumed to behave like air, in which properties such as viscosity, gas density were taken from the relevant air property data. The exhaust gases' mass flow rate was estimated to be 0.035 kg/s for a maximum value and 0.01 kg/s for a mean value. Based on these given conditions, the resulting mean gas velocities in the pipe would then be about 40 and 11 m/s, corresponding to flow Reynolds numbers of 25000 and 7000 for the maximum and mean values of gas flow rate respectively. The flow in the pipe for the representative engine condition was therefore turbulent. Deposition of fine particles in exhaust pipes has been calculated for a large number of discrete sizes in the range of 10 nm to 1 μm under representative engine exhaust conditions. In this calculation and the following results, a number-weighted particle size distribution with number mean diameter of about 45 nm similar to typical gasoline particle size distributions has been estimated. The size distribution curve has been represented by a series of histograms divided into a large number of chosen particle discrete sizes of interest. Additionally, mass-weighted particle size distribution has also been derived using the expression "total particle mass is proportional to (particle number)(particle size)^3" from this number-weighted size distribution. Density of pure carbon or graphite is between 1800 and 2200 kg/m^3. Particles in nucleation mode could be considered as pure carbon while larger particles in accumulation mode were the result of agglomeration and therefore had a higher degree of porosity and lower density value. Particle density was therefore taken to be 1000 and 2000 kg/m^3 in this study. Particle thermal conductivity was taken to be that of graphite as well as an unrealistic value of 10 times larger in order to study its effect on themophoresis. For the particle sizes and conditions that were studied, the resulting Knudsen numbers, defined as a ratio between particle radius and gas mean free path, were in the range of 0.2 – 18.5, which effectively means that they were in free molecular and transition regimes where gas molecular collisions affect particle motion. This justifies the inclusion of the Cunningham correction factor for the diffusion coefficient.

Various assumptions have been introduced to simplify the calculation procedure so that estimates of particle deposition can be obtained. The validity of these assumptions will be discussed in the later section. These assumptions were spherical-shaped particles, uniform particle concentration distribution, smooth deposition surface, steady state flow condition, hydrodynamically and thermally fully developed flow and constant solid and fluid properties.

3.2 Parametric Investigation and Results

Deposition in exhaust pipes due to gravitational settling, turbulent diffusion, thermophoresis and electrostatic effect has been examined analytically. From the calculation for the case of fully insulated pipe and electrically neutral condition where there is no thermophoretic and electrostatic effects as shown in figure 2, it was found that for maximum and mean gas flow rates, particle deposition efficiency in exhaust pipes for steady state operation is very low. The overall efficiency corresponding to 10 nm to 1 μm particle size was well below 2 %. With reference to mass-weighted and number-weighted particle size distributions for gasoline-fuelled spark ignition engine exhaust emission, the models gave total cumulative deposition efficiency of 0.3 % by mass, 0.8 % by number. As a result, particle loss in the exhaust pipe due to deposition was negligible. It can be seen that difference in deposition efficiency is not significant for the whole size spectrum and only marginally different between the two gas flow rates considered. To a small degree, the reason for this may be due to the turbulence level. Because the high level of turbulence under the representative engine condition may tend to push the particles either away from the wall and cause the particles to be concentrated along the symmetry axis of the pipe as has been reported by Li and Ahmadi [10] or towards the wall promoting deposition as was the case here.

The sub-micron particles have a tendency to be deposited onto the wall due, mainly, to Brownian diffusion. With respect to the relationship between overall deposition efficiency and particle size, in turbulent flow, effect of diffusion is more pronounced on smaller particles than large ones because small particles have higher particle diffusivity than larger particles. These results are in reasonable agreement with that obtained by Schmidt et al. [11]. With a decrease in particle below 100 nm, the increasing ability of particles to diffuse caused an increase in the particle deposition rate. For an increase in particle size, the particle number concentration boundary layer shifts into the laminar layer. As a result, turbulent diffusion becomes less important to deposition. Deposition due to gravity has greater influence as particle size increases above sub-micron range. The clear difference in magnitude of deposition efficiency between the two mechanisms should become more evident for particle diameter at several μm and above. Gravitational settling is important for super-micron particles. Gravitational sedimentation is not an important deposition mechanism for sub-micron particles due to very low settling velocity.

Influence of the pipe length on particle deposition has also been studied. Three length chosen were nondimensionalized by the pipe diameter at x/D = 25, 50 and 75. It was found, as anticipated, that increase in the pipe length resulted in an increase in particle deposition. Limited parametric investigations of particle properties i.e. density and thermal conductivity, have also been carried out. It was clear that the effect of both the higher density and higher thermal conductivity were insignificant.

With application of thermophoretic forces by cooling wall to 127°C and 27°C, the calculated results are shown in figure 3. To achieve such wall temperatures in practice, a high degree of cooling is required. Nevertheless, the study is interesting in that a condition at cold start and an extreme case of attainable temperature gradient may be represented by these values of wall temperature. In this study, a transient effect was also considered. At cold start conditions, particles were deposited due to themophoresis when a cold pipe wall was flooded with hot exhaust gas. Thermophoretic deposition was predicted to be significant when a pipe wall initially at 127°C or 27°C was subject to a flow of exhaust which suddenly increased to 500°C. Deposition due to thermophoresis in this condition was effective within a short time and the instantaneous deposition efficiency was significant. It was proved that thermophoresis is by far the most important deposition mechanism under these conditions. Thermophoresis is strongly dependent on temperature gradient and flow condition and not so on particle size. For such a large temperature difference between the gas and the wall, heat transfer is large, hence, large temperature gradient. For the case of cooled wall (127°C), thermophoretic effect increased the total particle deposition from almost negligible to about 19 %. This was expected as the presence of the thermal force would add a radial acceleration to the particle, moving it towards the pipe wall. The increase in temperature gradient as the pipe wall was cooled down further to 27°C only increased the percentages of deposited particles from 19 to 23%, an increase of about 20%.

Application of electrical forces could be done by applying the voltage to the centerline electrode. The applied voltage was considered for 5, 10 and 20 kV which corresponded to electric field strength in the pipe of 200, 400 and 800 kV/m respectively. Figure 4 showed the percentage of particles that have deposited due to influence of electrical forces under mean flow conditions. By raising the applied voltage levels, electric field strength increased. This, in turn, resulted in greater deposition of particle. It can be seen that for applied voltage of 20 kV and particles below 100 nm, fraction of deposited particles due to electrical effect ranged from 30 to almost 95 %. It should be noted that the values of 10 – 20 kV applied voltage was practically feasible which can attain acceptable levels of electric field and space charge.

4. Discussion

From the results obtained, it can be seen that particle deposition in the exhaust pipe at steady state operation without thermophoretic and electrostatic effects can be neglected. Considering overall effects, an increase in particle diameter will lead to an increase in particle deposition, for sub-micron particles bigger than 0.2 μm in pipe flow. For particle below 0.2 μm, a decrease in particle size leads to an increase in particle deposition. At this particle size range, diffusion mechanism dominates. At particle size of above a few microns, gravitational settling becomes important. In the size range in between, there is no clear dominant mechanism. Regarding thermophoresis, in the cases of fully insulated pipe, thermally steady state was assumed, as a result, there was no heat transfer hence temperature gradient. Particle deposition by thermophoretic effect was therefore insignificant. An increase in heat transfer will increase deposition. It is likely that the more transient the mode of operation, the more particles will be deposited. Additionally, with wall cooling, greater deposition can be achieved. The degree of thermophoretic deposition depends directly on the level of cooling applied. With application of electric field, more particle deposition on the pipe wall is clearly evident. At sufficiently high electric field strength, 50 % or more of particles can be captured. It was clear from a comparison of the effects of the wall cooling and the applied electric field illustrated in figure 5 that electrostatic effect was more effective and had better potential to be developed into particulate capturing device than thermophoresis and other mechanisms.

The calculated results obtained predicted the deposition of particles in the simulated conditions considered. However, it should be borne in mind that this was just a qualitative estimate. Several limitations in this simple analytical models exist and are discussed below.

1) It is known that size distribution of particles emitted from a gasoline engine is typically of log-normal type. In this calculation, number-weighted particle size distribution has been estimated from typical particulate emissions. In comparison with the number-weighted size distribution obtained from Maricq et al. [12], it was found that the size distribution curves were similar and number mean and mode particle sizes were found to be within 10 %. The largest percent of particle number was found in the 10 to 100 nm range; above 0.5 μm, particle number was very small. With respect to the mass-weighted size distribution, more than 50 percent of the total particulate mass was in the region below 0.2 μm. Particles above 2 μm were responsible for about 25 percent of the total mass. When the calculated mass-weighted size distribution was compared with that obtained from Fanick et al. [13], it was found that they were slightly different. Fanick and co-workers found that particles below 0.2 μm were responsible for more than 65 % total mass and for the range of 0.4 – 2 μm, particle mass was small (less than three percent). The slight difference may be due to error in estimating particle number-weighted size distribution, use of different experimental tools, different engine and operating conditions.

2) All but very fine particles emitted are not spherical-shaped. They are more irregular-shaped, clustered- or chain-like. Because the mathematical models employed are usually applicable only to spherical particles, transport behaviour of real particles may not be well predicted. Particle shape factor significantly affects particle behaviour in various flow fields. For example, study by Gavze and Shapiro [14] showed that particle-wall interaction decreases with increasing particle non-sphericity. Effect of non-sphericity on dynamics of particle transport and deposition in gaseous media which have been studied extensively (for more details, see

e.g. 15) may be taken into consideration as an extension of the present work.

3) In this calculation, a smooth deposition surface was assumed. Generally, surfaces are, to some degree, rough. Roughness on the deposition surface is very influential in the capture of small particles and will encourage more deposition. As indicated by El-Shobokshy and Ismail [16], the surface roughness markedly affects the deposition velocity and deposition rate. The surface roughness also affects surface friction and friction or shear velocity. Nonetheless, if roughness height of 100 μm is assumed for the pipe surface, the resulting roughness Reynolds number will still be less than five, for which the surface can be considered as hydraulically smooth [4].

4) Because solid and fluid properties depend strongly upon temperature, for steady state condition, it is implied that there is no variation in temperature hence no variation in property. Constant solid and fluid properties are therefore justified. However, in real steady state engine operation, if the magnitude of exhaust gas temperature variation along exhaust pipe was assumed to be 50°C, the corresponding change in the gas property such as density would be about 10 % [17].

5) Since the flow in the exhaust pipe is usually highly turbulent, assumption of uniform particle concentration distribution is justified.

6) Particles from engines carry charges and their charge distribution has been observed to be closely similar to the Boltzmann distribution [18]. An electrode employed in the application of electrical forces to enhance particle deposition not only creates electric field but also charge the particles. The charging mechanisms from this corona-generating electrode additionally charge the particles to higher levels. However, no additional charging of particles has been considered in this study. The results from this study may be considered to be at a lower bound of the effect of electrostatic attraction.

5. Concluding Remarks

Investigation of particle deposition in automotive exhaust pipes has been analytically studied. The deposition is modeled, taking into account turbulent diffusion, thermophoresis, electrostatics and gravitational sedimentation. Factors influencing particle behaviors in the exhaust system such as temperatures of the gas and the wall, the flow conditions, particle size and applied electric field strength have been investigated. Empirical models describing physical nature such as particle transport can be used as preliminary analytical tools to offer some qualitative insight into deposition of particulate in the exhaust pipe. Prediction of particle deposition rate has been obtained using relatively simple models for particle transport behaviour in the exhaust system. For a steady state condition, it was found that the majority of particle loss occurs in the exhaust pipe in the size fraction below about 10 – 100 nm and the main mechanism responsible is the diffusion effect. For submicron particles, a decrease in particle size results in an increase in particle deposition efficiency. Gravitational effect does not play a significant part. Thermophoretic deposition is negligible for a well insulated system. Re-entrainment is difficult to predict quantitatively. The overall combined effect of deposition under steady state condition with no wall cooling was very small.

For a transient condition or a condition with a significant wall cooling, while the effects of gravity and inertial impaction on particle deposition are still weak, thermophoretic effect becomes strong and can compete with the diffusion effect. Deposition due to thermophoresis will dominate if large temperature gradient is available such as in the cold start condition. Application of electric field across the pipe cross section can also lead to more particle deposition and capture on the pipe wall as a result of electrostatic effect. Overall results indicated that thermophoretic forces may not be sufficiently strong to produce satisfactorily high particle capture efficiency. Electrical forces, however, can achieve particle capture efficiency of up to and above 50% under actual engine operating conditions. The use of electric fields has potential for exhaust after-treatment system.

6. References

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Exhaust pipe		
Length	(m)	1.25, 2.5, 3.75
Diameter	(mm)	50
Wall temperature	(°C)	500, 127, 27
Applied voltage	(kV)	0, 5, 10, 20
Exhaust gas flows		
Bulk gas temperature	(°C)	500
Pressure	(atm)	1
Exhaust gas mass flow rate	(g/s)	35, 10
Re		25000, 7000
Nature of flow		Turbulent
Particle system		
Size range	(nm)	10 – 1000
Density	(kg/m^3)	1000, 2000
Thermal conductivity	(W/mK)	100, 1000
Deposition mechanisms		Turbulent diffusion
		Thermophoresis
		Gravitational settling
		Electrostatic attraction

Table 1. Flow parameters and conditions in pipes for which calculations were performed

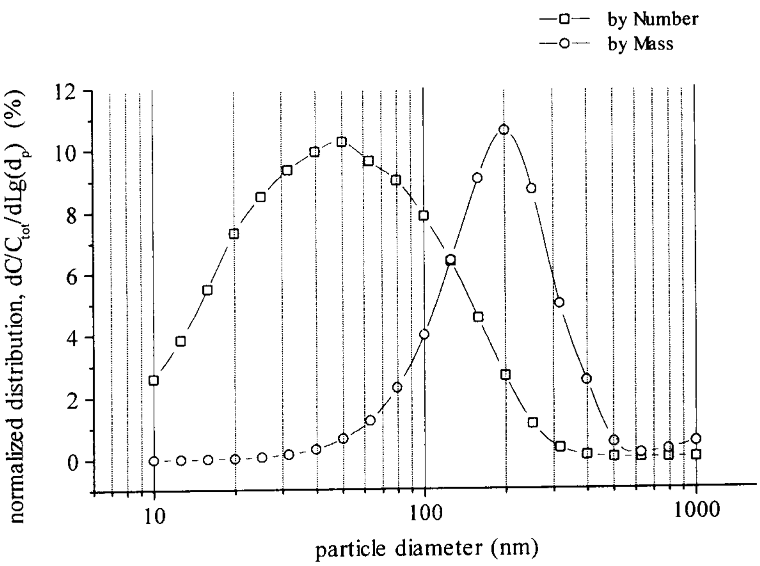

Figure 1. Typical size distribution of automotive exhaust particulates

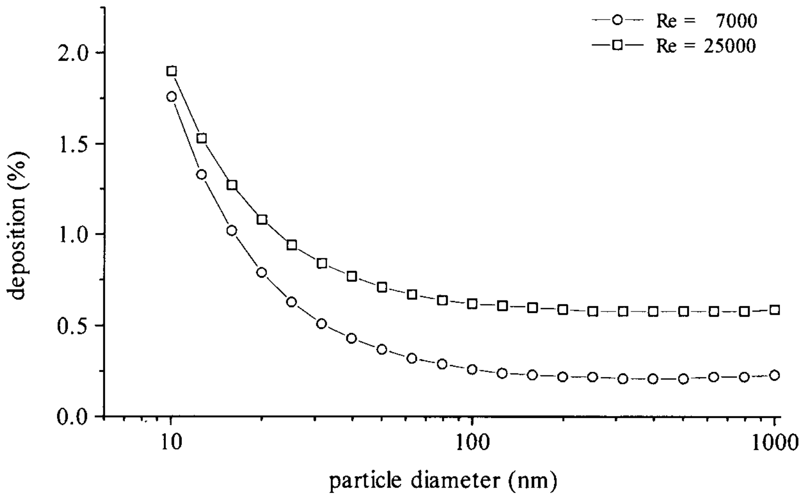

Figure 2. Percentage of fractional deposition as a function of particle size in a fully insulated, electrically neutral exhaust pipe flow, effect of Reynolds numbers corresponding to mean (0.01 kg/s) and maximum (0.035kg/s) gas flow rates

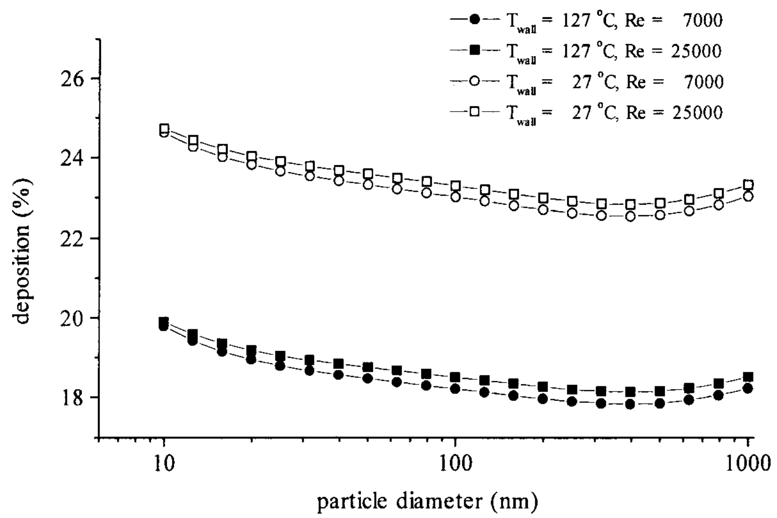

Figure 3. Percentage of fractional deposition as a function of particle size in an electrically neutral exhaust pipe flow for mean and maximum gas flow rates, effect of wall cooling to 127 and 27 °C

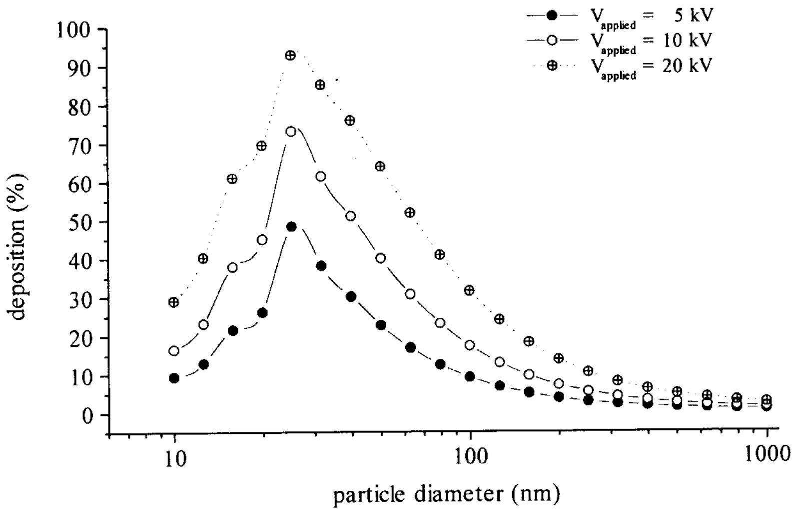

Figure 4. Percentage of fractional deposition as a function of particle size in an fully insulated exhaust pipe flow for mean gas flow rate (Re = 7000), effect of applied voltage (5, 10, 20 kV) on the centerline electrode

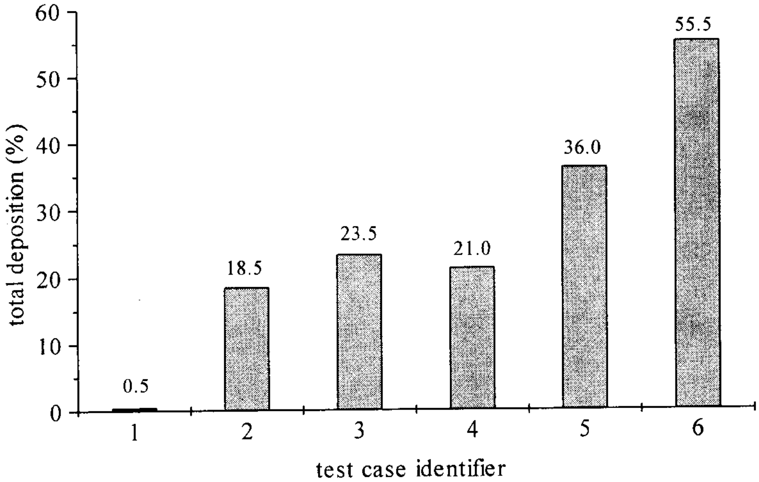

Figure 5. Prediction of total number deposition for typical automotive particulates in a representative exhaust pipe, mean flow rate (mid load), comparison between the effects of thermophoresis and electrostatic attraction, test case identifier (1) baseline case, fully insulated, no applied voltage, (2) with wall cooling to 127°C, no applied voltage, (3) with wall cooling to 27°C, no applied voltage, (4) fully insulated, applied voltage = 5 kV, (5) fully insulated, applied voltage = 10 kV, (6) fully insulated, applied voltage = 20 kV