MODELING PARTICLE DEPOSITION IN VENTILATION DUCTS

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ABSTRACT
This paper describes predictions from two models of fractional particle loss in four typical HVAC duct runs. One model is a state-of-the-art Eulerian formulation; the second is based on empirical fits to experimental particle deposition data collected in a laboratory. The experiments are briefly described and sample results are presented. The Eulerian model only predicts deposition from fully developed turbulence, while the empirical model can be applied to duct bends and developing turbulence as well. The models predict almost no losses for particles smaller than 1 μm and nearly complete loss of particles larger than 40 μm in all duct runs. The empirical model suggests that particle loss in ventilation ducts is dominated by gravitational settling to the floor of horizontal ducts, and by deposition to zones where turbulent flow is undeveloped, such as in bends and in duct sections immediately after bends.

INDEX TERMS
HVAC, Particle deposition, Ventilation ducts, Modeling

INTRODUCTION
Particle deposition in heating, ventilating and air conditioning (HVAC) systems of buildings can affect system performance and influence the quality of indoor air. HVAC systems consist of louvers, filters, fans, heat exchangers, ducts and other equipment that provide conditioned air to interiors. Surfaces in ventilation systems can act as sinks, temporary storage reservoirs, and possibly sources, for pollutants such as particles, microorganisms and volatile organic compounds (VOCs).

Particles may deposit to and resuspend from duct surfaces. Predictions of exposure concentrations for building occupants are partially limited by an understanding of particle deposition in HVAC systems. Particle deposits have been observed to both sorb and emit VOCs to and from the passing air stream. Bacteria and fungi are known to deposit on HVAC surfaces and grow if sufficient water is present. Such growth produces VOCs and may amplify the concentration of microorganisms and certain VOCs in the air stream. Chemical interactions have been observed to occur between pollutants and HVAC surfaces (Morrison *et al.*, 1998) and particle deposits may alter the nature of these surface interactions. These sorts of pollutant transformations may be of considerable importance in overall HVAC hygiene.

This paper applies two particle deposition models to ventilation duct runs to explore the degree to which particles are lost to duct surfaces as air travels from outdoors to the interiors of commercial buildings. The models give information on the expected location of particle deposits within HVAC ducts and can also be used to predict accumulation rates of particle deposits on duct surfaces. Experiments of particle deposition in a lab HVAC duct used for testing the Eulerian model and developing the empirical model are also briefly summarized.

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METHODS

Results of particle deposition experiments have historically been presented as plots of dimensionless deposition velocity, V_d^+ versus dimensionless relaxation time, τ^+. The dimensionless deposition velocity of a particle to a duct surface is defined as

$$V_d^+ = \frac{J}{C_{ave} u^*} \tag{1}$$

where J is the time-averaged particle flux to the surface, C_{ave} is the time-averaged airborne particle concentration and u^* is the friction velocity. The dimensionless deposition velocity depends on a variety of factors including particle size, air speed and the roughness of the deposition surface. The dimensionless relaxation time is defined as

$$\tau^+ = \frac{C_c \rho_p d_p^2 u^{*2}}{18 \mu \nu} \tag{2}$$

where C_c is the slip correction factor, ρ_p is the particle density, d_p is the particle diameter, μ is the dynamic viscosity of air, and υ is the kinematic viscosity of air. The penetration, P, of particles through a vertical duct section may be calculated if V_d^+ is known:

$$P = \frac{C_{outlet}}{C_{inlet}} = \exp\left(\frac{-4LV_d^+ u^* P_{duct}}{U_{ave} A_{duct}} \right) \tag{3}$$

where C_{outlet} and C_{inlet} are the flow-weighted average particle concentrations at the outlet and inlet of the duct, respectively and L is the duct length, U_{ave} is the average velocity, A_{duct} is the duct cross sectional area and P_{duct} is the duct perimeter of a section through the duct normal to the flow direction. If the duct is oriented horizontally, differences in V_d^+ to the duct floor, wall and ceiling due to gravity must be taken into account and equation (3) is not valid. The fractional particle loss through a given section of duct is equal to 1 - P.

Experiments investigating the effect of air velocity and particle size on particle deposition rates from duct flow have been conducted in our laboratory. These experiments were carried out in a horizontal galvanized steel duct system with a 15 × 15 cm square cross section at air speeds of 2.2, 5.3 and 9.0 m/s and with monodisperse particles in the range 1-16 µm in diameter. Monodisperse, fluorescent particles were generated by a vibrating orifice aerosol generator (TSI Model 3450), neutralized by bipolar ions from a Kr-85 radioactive source (TSI Model 3054) and injected into the duct system through a mixing box. Fluorometric techniques were used to quantify the airborne particle concentration in the duct and the deposition flux to the galvanized steel duct surface. Particle deposition flux was measured at six locations for each experiment: two straight duct sections where turbulent flow was fully developed, two straight duct sections where turbulent flow was undeveloped and two 90° duct bends. The straight sections of duct where turbulent flow was fully developed were located at the end of long, straight sections of duct. The straight sections of duct where turbulent flow was undeveloped were located at the outlet of the mixing box and at the outlet of a 90° duct bend. In the straight duct sections, particle deposition fluxes to the upward facing duct floor, the vertical duct wall and the downward facing duct ceiling were measured independently to provide information on the location of particle deposits within the duct.

Data for particle deposition from fully developed turbulent flow generated by these experiments were compared to an Eulerian particle deposition model that accounts for Brownian and turbulent diffusion, turbophoresis, gravitational settling and surface roughness (Guha, 1997). This formulation represents the state-of-the-art in Eulerian deposition models and has shown good agreement with experiments conducted in small diameter tubes. This model can predict particle deposition to floor, wall and ceiling surfaces in ducts; however, it was developed to predict particle deposition only from fully developed turbulent flow.

Empirical correlations of the experimental data were developed to predict particle deposition in cases where the Eulerian model is not applicable or disagreed significantly with the current experimental data. In particular, the Eulerian model is not applicable in duct sections with developing turbulent flow or in duct bends. Furthermore, this model was found to disagree significantly with the experimental data for deposition to the duct wall and ceiling from fully developed turbulent flow. The only case where the Eulerian model agreed well with the experimental data was for particle deposition to the duct floor from fully developed turbulent flow. To address these limitations, we developed an empirical model that utilized our experimental data. An interpolation scheme was developed to enable the empirical correlations to be applied to the range of flow velocities and particle sizes of interest in ventilation ducts. The empirical model is in reasonable agreement with the limited data on particle deposition from flow in ducts with diameters similar to those found in HVAC systems. Furthermore, it allows for the calculation of particle deposition in duct bends and in straight sections of duct where turbulence is not fully developed. This is potentially important in HVAC systems where the turbulent flow is often not fully developed. However, this model is based on empirical fits to a limited set of experimental data and, as yet, has no means of accounting for the effect of duct surface roughness on particle deposition.

To explore the significance of particle deposition in typical HVAC ducts, these two particle deposition models were applied to the four duct runs described in Table 1. These duct runs were selected from a survey of 80 duct runs from four university buildings of 6- to 7-stories each. Duct runs were selected based on a random selection of duct endpoints and ranked in terms of length. In terms of total duct length, duct run A represents the 90th percentile, duct runs B and C are at the 50th percentile and duct run D corresponds to the 10th percentile. Each duct run begins at the HVAC supply fan, ends at a supply register in the building and consists of a series of successively smaller ducts with decreasing flow rates from beginning to end. Airflow rates were assumed to be constant at the design rates and duct dimensions were obtained from design drawings. In all modeling, the ducts were assumed to be smooth.

Table 1. Description of modeled duct runs

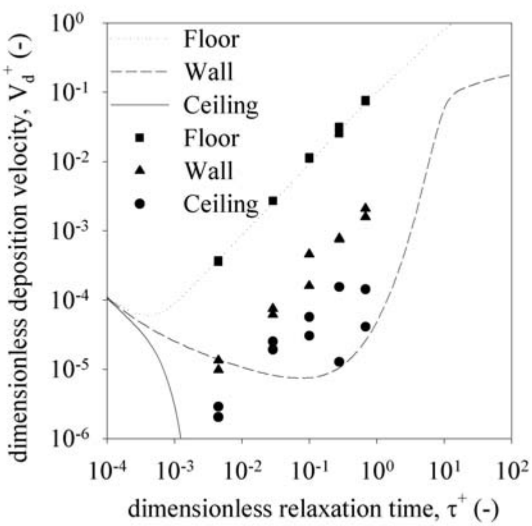
Duct run	*Total length (m)*	*Horizontal length (m)*	*% Undeveloped turbulent flow*	*Number of bends*
A	72	51	57	8
B	48	15	50	3
C	48	35	58	7
D	28	20	65	6

RESULTS

Figure 1 shows an example of the experimental particle deposition data collected in a duct section where turbulent flow was fully developed. The left and right sides of this figure show the same experimental data collected at an air speed of 2.2 m/s (u^* = 12 cm/s) with 1, 3, 5, 9 and 16 µm diameter particles. The experimentally measured deposition rates to the duct floor are greater than deposition to the duct wall, which, in turn, are greater than deposition to the duct ceiling. Similar experimental results were observed at higher air speeds. On the left side of Figure 1, the Eulerian model agrees with the experimental data in the case of deposition to the duct floor, but predicts deposition rates to the duct wall and ceiling that are drastically less than observed experimentally. The right side of Figure 1 shows the empirical model fits to the experimental data.

Experimental results not shown here suggest that particle deposition rates in duct bends and in straight sections immediately after duct bends where turbulent flow is undeveloped are significantly enhanced compared to deposition rates in straight ducts with fully developed flow. The Eulerian model is not applicable to deposition in duct bends or in sections with undeveloped turbulence. Empirical correlations similar to those displayed on the right side of Figure 1 were developed for use in the empirical model to estimate particle deposition in bends and straight sections with undeveloped turbulence.

Figure 2 displays the fractional particle loss versus particle size for particles traveling through the four duct runs predicted by the Eulerian model. In this model application, particle deposition in duct bends was ignored and the enhancing effect of undeveloped turbulence after bends on deposition was also neglected. For all duct runs, particle loss is predicted to be negligible for particles smaller than 1 µm and nearly complete for particles larger than 40 µm. Duct run A, the longest duct run, is predicted to have the greatest losses for a given particle size in the range of 1-40 µm. The shortest duct run, however, is not predicted to have the lowest particle losses. Duct B run, the duct with the shortest horizontal length is predicted to have the lowest losses, partially because deposition to the floor of horizontal ducts is what controls particle losses when bends are ignored.



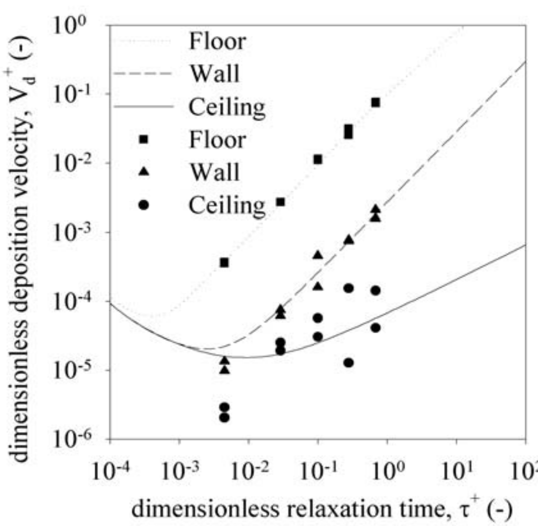


Figure 1. Comparison of the Eulerian model (left) and the empirical model (right) to experimental particle deposition data collected from fully developed turbulent flow at a velocity of 2.2 m/s.

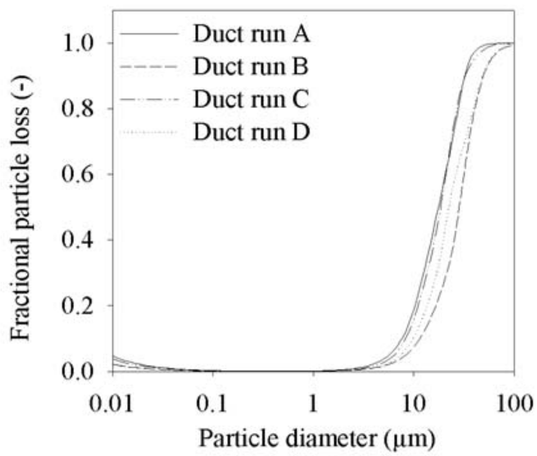


Figure 2. Fractional particle loss vs. d_p in modeled duct runs ignoring bends and undeveloped flow within Eulerian model.

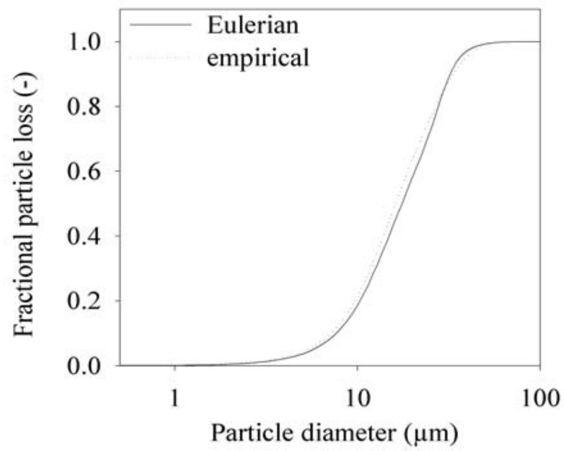


Figure 3. Fractional particle loss vs. d_p in duct run A ignoring bends and undeveloped flow with both models.

Further evidence that losses are controlled by deposition to the duct floor when deposition in and after duct bends is ignored is found in Figure 3. Here, the Eulerian and empirical models predict virtually identical particle losses in duct run A even though the empirical model predicts much higher deposition rates to the duct walls and ceiling.

Figure 4 compares predictions by the empirical model for losses in duct run C when bends are ignored to the case where the effects of bends and the associated undeveloped turbulent flow are taken into consideration. In this figure, particle losses are observed to increase significantly for particles in the size range of 1-40 µm when bends are taken into account. Figure 5 displays predictions of particle losses in the four duct runs by the empirical model while accounting for deposition in bends and the enhanced deposition from the undeveloped turbulence after bends. In this case, particles larger than 20 µm are expected to be completely lost in duct runs A, C and D. Duct run B, with only three 90° bends, is predicted to have lower losses for 1-40 µm particles than the other duct runs which have at least 6 bends.

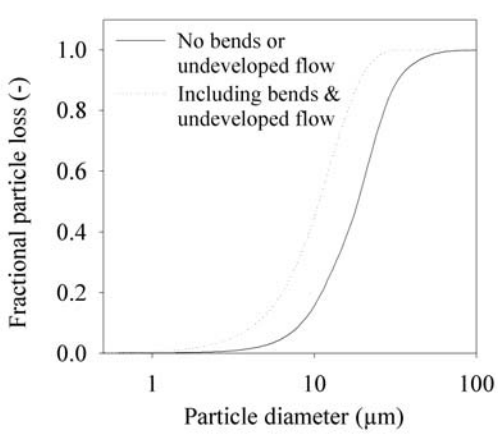


Figure 4. Difference in fractional particle loss in duct run C when including bends and undeveloped flow with empirical model.

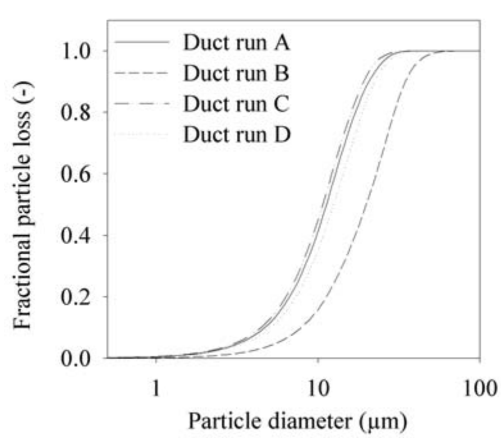


Figure 5. Fractional particle loss vs. d_p in modeled duct runs including bends and undeveloped flow with empirical model.

DISCUSSION

Experimental measurements suggest that, for particles larger than 1 μm, rates of deposition from fully developed turbulent flow to duct floors is significantly greater than to duct walls or ceilings over the range of air speeds of interest in HVAC systems. Experiments also indicate that particle deposition rates to duct surfaces are significantly enhanced in bends and in ducts immediately after bends compared to rates in duct with fully developed turbulence.

Even though the Eulerian and empirical models differ drastically in their estimates of particle deposition to duct walls and ceilings, predictions of fractional particle loss in sample ducts by the two models are nearly identical when bends are neglected. Both predict almost no particle loss in the modeled duct runs for particles smaller than 1 μm and complete loss for particles larger than 40 μm. Gravitational settling to the floor of horizontal ducts dominates particle losses in this case. When deposition in bends and enhanced deposition in sections after bends are considered using the empirical model, predicted particle loss rates for 1-40 μm particles are significantly increased compared to when bends are ignored. Our study results suggest that particle deposition in ducts primarily occurs in two zones: in and immediately after duct bends and to the floor of horizontal ducts.

CONCLUSIONS

A state-of-the-art Eulerian particle deposition model shows poor agreement with experimental data measuring deposition to the walls and ceiling of a horizontal ventilation duct. However, this poor agreement is inconsequential when predicting particle losses in straight HVAC duct runs because particle losses are dominated by gravitational deposition to the floor of horizontal sections, where the model performs well. The main deficiency of this Eulerian model in determining particle losses in HVAC ducts is its inability to account for deposition in bends and in straight duct sections with undeveloped turbulence.

The empirical model based on the collected experimental data is better able to deal with the bends and sections of undeveloped turbulence common to HVAC duct runs. Applications of this empirical model suggest that deposition in bends and in sections immediately after bends contributes significantly to fractional particle losses in typical HVAC ducts. Further experimental studies on particle deposition in duct bends and in sections following bends would help to reduce the uncertainties in this assertion. Additional experimental work is also warranted on particle deposition to rough duct surfaces, such as those covered with acoustic lining. The predictions that submicron particles are not significantly deposited in ducts should also be tested experimentally.

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REFERENCES

Guha A. 1997. A unified Eulerian theory of turbulent deposition to smooth and rough surfaces. *Journal of Aerosol Science.* Vol 28(8), pp 1517-1537.

Morrison GC, Nazaroff WW, Cano-Ruiz JA, *et al*. 1998. Indoor air quality impacts of ventilation ducts: Ozone removal and emissions of volatile organic compounds. *Journal of the Air and Waste Management Association*. Vol 48, pp 941-952.