DEPOSITION OF AEROSOL PARTICLES IN VENTILATION DUCTS

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ABSTRACT

In this work, experiments were carried out to estimate deposition rate of 5µm particles powder in large cylindrical straight ducts for different diameters. Two types of ducts were compared: rigid ducts and flexible ducts.

Results are compared to theoretical models of deposition in ducts to determinate real deposition rate appropriated to ventilation ducts. The flexible ducts have specific geometric surface and actual models are not able to predict good values.

Results indicate that deposition may significantly modify the particle concentrations in air flowing through ventilation ducts. More experimental data on deposition in flexible ventilation ducts are required for more complete model validation. A new simple model, more adapted to these specific ducts is developed.

KEYWORDS

Aerosol, deposition, ventilation, duct.

INTRODUCTION

Indoor air pollution has become a major subject over the past few decades. In the urban environment, outdoor air which is heavily polluted by industrial activities and vehicle emissions, penetrates through ventilation ducts and influences the indoor air quality. A correlation between outdoor PM_{10} concentrations and mortality in urban areas has been demonstrated. To evaluate the real exposure of building occupants to particle pollution, it's necessary to quantify particles lost in ducts.

In the literature, analysis of deposition of particles from a turbulent flow to smooth and rough surfaces was particularly well studied : Davies (1965), Schwendiman (1965), Wells (1967), Sehmel (1970), Liu and Agarwal (1974). Extensive reviews on particle deposition process were reported by Wood (1981) and Hinds (1982). El-Shobokshy (1983) measured particle deposition onto machinery-ground brass tubes with small mean roughness heights (7 and 20µm). More recently, Fan and Ahmadi (1993) developed a model for turbulent deposition. Adam (1993) reported a simple method to evaluate particle deposition in ducts which is adopted for our experiments. Lai (1999) measured the aerosol deposition velocity of 0.7-7.1µm particles on two-dimensional ribs in a turbulent duct flow and found that the deposition velocity increased by a factor of 2-3 relative to smooth surfaces. On a regular array of three dimensional roughness elements, Lai (2001) observed that compared with a smooth surface, the aerosol deposition increased by a factor 6 to 18. Abadie (2001) measured particle deposition velocity onto rough surfaces and introduced a caption coefficient which represented the increasing of the particle deposition velocity compared to smooth surfaces.

Experiments on flexible ducts were not well reported in the literature. The flexible ducts are widely used in ventilation, they have specific geometric surface and actual models of deposition are not able to predict good values.

THEORY

An aerosol particle that is settling in air due to the action of gravity reaches a terminal settling velocity V_s which is determined by a balance between gravitational force and fluid drag :

$$V_s = \frac{d_p^2 \rho_p C_c}{18\mu} g \quad (1)$$

where d_p is the particle diameter, ρ_p is the particle density, C_c is the slip correction factor, μ is the dynamic viscosity of air, and g is the gravitational acceleration.

The aerosol particle deposition velocity V_d is a useful concept for reporting theoretical and experimental rates of pollutant deposition, Friedlander (2000). It is defined as the pollutant flux density to a surface divided by the pollutant concentration at a large distance from the surface :

$$V_d = \frac{J}{C_\infty} \quad (2)$$

where J is the particle flux to the surface and C_∞ is the average concentration in the air stream.

When a turbulent gas carry particles with aerodynamic diameter larger than about 1µm flows parallel to a surface, particles deposit because of the fluctuating velocity components normal to the surface. In a turbulent flow, the fraction f_p of a given size particle flowing through a duct at a distance L from the inlet is a direct function of the deposition velocity, Baron and Willeke (1993), Sippola (1999) :

$$f_p = e^{-\frac{4 V_d L}{U D}} \quad (3)$$

where V_d is the aerosol particle deposition, L is the duct length, U is the average air velocity and D is the duct diameter.

The fraction of particles deposited in a duct f_d is given by : $f_d = 1 - f_p$ (4)

$$f_d = 1 - e^{-\frac{4 V_d L}{U D}} \quad (5)$$

METHODS

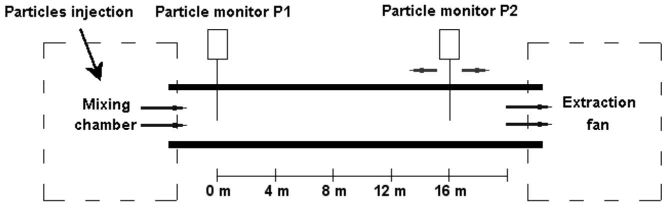

Figure 1: Schematic diagram of test rig and instrumentation

The experimental work was carried out using the duct system shown in Figure 1. The ducts were 16m long with a circular cross-sectional area (80mm, 100mm and 125mm diameter).

Two types of ducts were studied: rigid ducts (see Figure 2) and flexible ducts (see Figure 3).

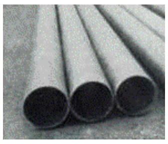

Figure 2: Rigid ducts

Figure 3 : Flexible ducts

The experimental procedure involved injecting 5µm particle powder into the mixing chamber. The fan was switched on to a predetermined speed. The dust monitors were switched on. The particle powder concentrations were measured continuously using infrared particle monitors. During experiments, only the second particle monitor was moved along the duct. The velocity was measured at several points along the duct. Two different air flows were used for each type of ducts. All experiments were reproduced approximately ten times.

The fraction of particles deposited was determined by comparing concentrations of aerosol particles.

$$f_d = \frac{C_1 - C_2}{C_1} \qquad (6)$$

where C_1 and C_2 are aerosol concentrations given by the particles monitors at points 1 and 2 in the duct.

RESULTS AND DISCUSSION

Figure 4 and 5 show the variation of the fraction deposited with the position in the duct. Only few experimental results are represented for more legibility.

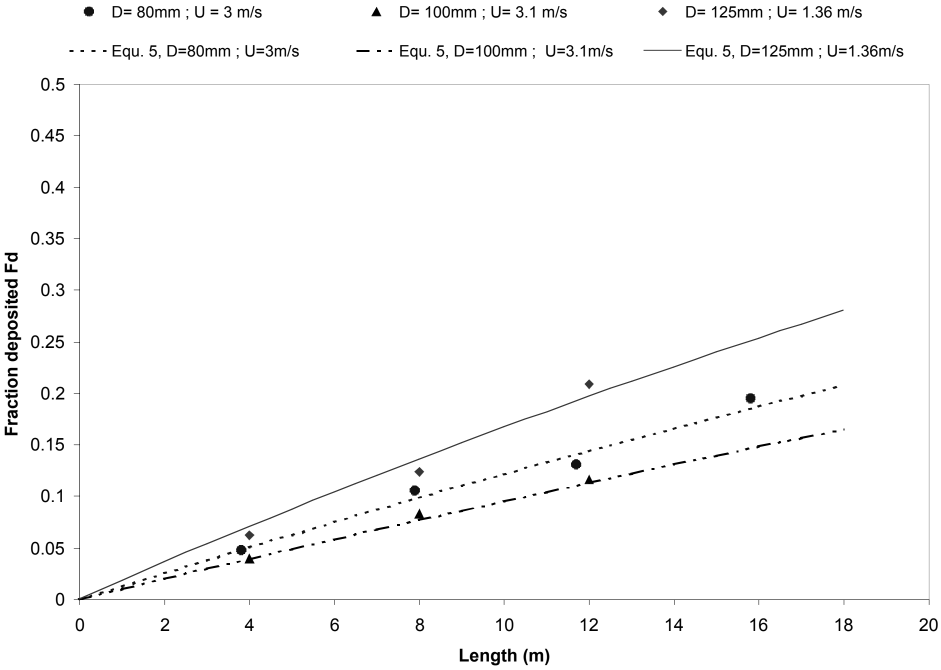

Figure 4: 5µm particle deposition in rigid ducts

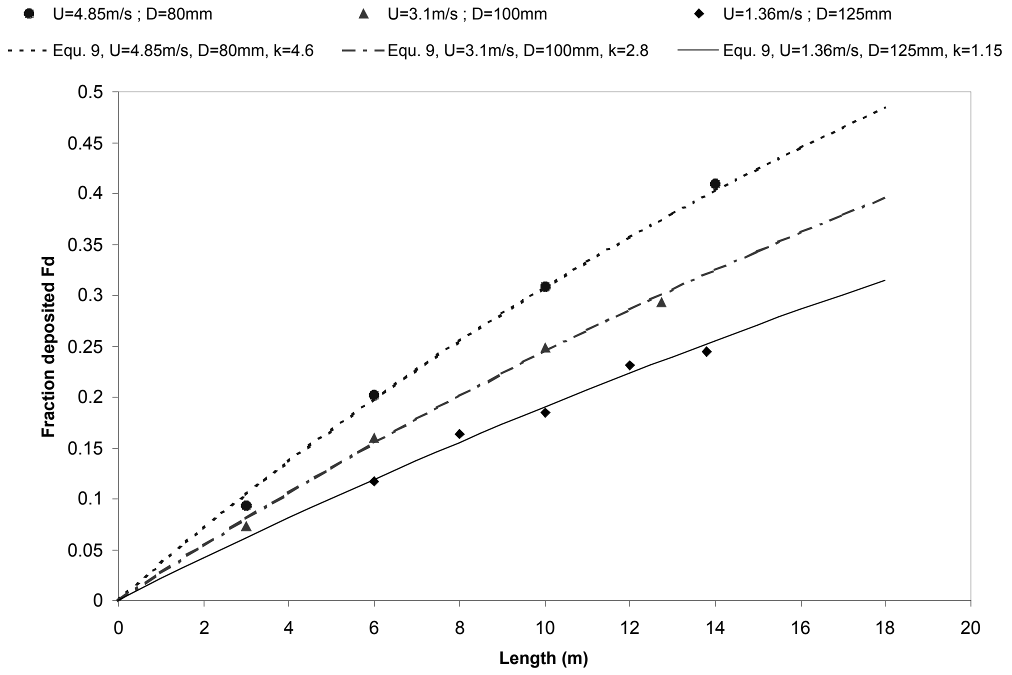

Figure 5: 5µm particle deposition in flexible ducts

Comparison of the predicted (equation 5) and experimental values shows good agreement for the rigid ducts, Figure 4. Rigid ducts are relatively smooth.

In flexible ducts, the aerosol particle deposition velocity is greater than smooth ducts. It depends on the specific roughness of the surface. Lai (2001) showed that the aerosol deposition increased by a factor 6 to 18 compared with a smooth surface when 3D roughness elements were added.

The impact of roughness on the aerosol particle deposition was demonstrated by Wells and Chamberlain (1967) and varies by a factor 1 to 1000 according to the roughness.

Our experiments showed that the aerosol particle deposition velocity V_d can be estimated from the equations 7 and 9, (see Figure 5). The aerosol particle deposition velocity increased by a factor k called caption coefficient. Table 1 shows that k varies from 1.15 to 4.6 for Reynolds number between 10^4 and 2.5×10^4.

$$V_d = k \times V_s \tag{7}$$

where V_s is the particle settling velocity and k the caption coefficient.

Duct diameter (mm)	80	80	100	100	125	125
Air velocity (m.s^{-1})	3.3	4.85	2.1	3.1	1.36	2
Reynolds	17600	25868	14000	20667	11333	16667
k	3.2	4.6	1.9	2.8	1.15	1.75
V_d, equation 7 (m.s^{-1})	2.49×10^{-3}	3.58×10^{-3}	1.48×10^{-3}	2.18×10^{-3}	8.96×10^{-4}	1.36×10^{-3}

Table 1: Aerosol deposition velocities, 5µm particles.

Lai (1999) measured aerosol deposition velocities and found 5×10^{-3} m.s^{-1} for 4.5 µm particles and 8.8×10^{-3} m.s^{-1} for 5.4 µm particles.

The caption coefficient, k seems to be a function of the air velocity. It can be estimated from equation 8, deduced from experimental values (Figure 6).

$$k = \kappa\ U \qquad (8)$$

where U is the average air velocity and κ is an empirical parameter equal to 0.93 s.m^{-1} in our experiments.

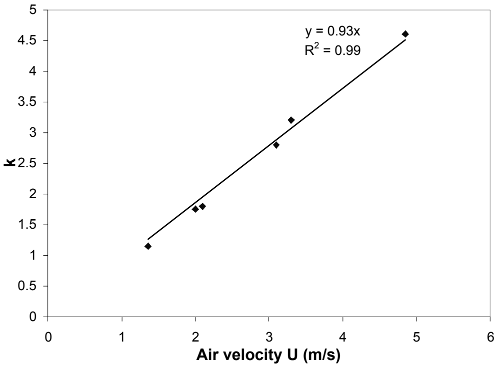

Figure 6: k function of air velocity in flexible ducts

Air velocity (m.s^{-1})	k	k=0.93*U	Absolute error	Relative error
1.36	1.15	1.26	0.115	10 %
2	1.75	1.86	0.110	6.3 %
2.1	1.9	1.95	0.053	2.8 %
3.1	2.8	2.88	0.083	3 %
3.3	3.2	3.07	0.131	4.1 %
4.85	4.6	4.51	0.090	1.9 %

Table 2: Uncertainty

The maximum relative error due to equation 8 is 10%.

Deposition in flexible ducts under turbulent flow can be estimated by a new model of deposition, using the following equation :

$$f_d = 1 - e^{-\frac{4\,k\,V_S\,L}{U\,D}} \qquad (9)$$

where k is the caption coefficient, V_s is the particle settling velocity, L is the duct length, U is the average air velocity and D is the duct diameter.

CONCLUSION

In the domain studied, for flexible ducts of diameter 80-125 mm and for air velocities between 1-5m.s^{-1} (typically encountered in ventilation ducts of individual houses), corresponding to values of Reynolds numbers 10^4 and $2.5\text{x}10^4$, for 5µm particles, a simple model of particle deposition in flexible ducts under turbulent flows was developed. A caption coefficient k was introduced to quantify the influence of the duct surfaces onto the particle deposition velocity.

More experiments on flexible ducts are necessary for a better validation of the deposition model. Interesting area which merits investigation is the influence of particle size especially $PM_{2.5}$ which are the most harmful for health.

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