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The Field Comparison of Three Measuring Techniques for Evaluation of the Surface Dust Level in Ventilation Ducts

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Abstract This paper reports the comparison of three measuring methods for quantifying the amount of dust on the inner surface of ventilation ducts: 1) a vacuum test method; 2) a gravimetric tape method; and 3) an optical method. Thirteen recently constructed buildings were selected for the field test in the Helsinki metropolitan area. The dust samples in each method were all taken from the same location in the duct. Most of the ducts sampled had no residual oil originating from the manufacturing process. The mean amount of dust measured with the vacuum test method was 1.3 g/m^2 and the range was $<$0.1–8.4 g/m^2. The mean surface dust level measured using the gravimetric tape method was slightly lower, i.e. 1.2 g/m^2 ($<$0.1–5.0 g/m^2). The mean cleanliness level of the ducts was 15% (2–41%) using the optical method. The wide variations and differences in the results of the different methods were caused by the unequal distribution of dust on the duct surfaces.

Key words HVAC system; Duct; Dust; Field test; Measuring methods; Cleanliness

Practical Implications
Surface dust sampling methods are necessary to evaluate the need for cleaning and also to control the quality of the cleaning work. The vacuum test is the most effective method of collecting dust from the duct surface and it is suitable for the objective determination of the surface dust level, especially in research work. The gravimetric tape method can be applied particularly to duct surfaces with low amounts of dust and it is easy to set up in the field. The optical method is also convenient for field applications but it is less accurate than the gravimetrical methods. All of the methods can be used to check the cleanliness of new air ducts when the surface dust level is relatively low.

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Introduction

Many methods have been used to evaluate the cleanliness of heating, ventilating and air-conditioning (HVAC) systems. The principles and purposes of the methods vary and therefore they may give different results (Fransson et al., 1995; Müller et al., 1999). Some of the methods have been developed to check the cleanliness level after the cleaning work (NADCA, 1992), while others have been developed to evaluate the need for cleaning (Winttest, 1997; HVCA, 1998) or to be used to achieve quantitative data for research purposes (Pasanen, 1998).

The most commonly used methods for evaluating the amount of dust on the inner surface of the air ducts are based on the gravimetric analysis of the mass on a given area (Table 1). In the gravimetrical vacuum test method the dust is sucked from a standardized area on a pre-weighed filter with the aid of a vacuum pump (Valbjørn et al., 1990; NADCA, 1992). This method allows the analysis of the elemental composition of the dust (Fransson et al., 1995) and the microbial composition (Valbjørn et al., 1990; Laatikainen et al., 1991). Various techniques for loosening the dust from the duct surface have been developed (Valbjørn et al., 1990; NADCA, 1992; Winttest, 1997; Pasanen, 1998; Alfano et al., 2000). The gravimetrical vacuum test method is commonly used in research work.

In the gravimetric tape method the sample is collected on a pre-weighed tape from a known area (Fransson et al., 1995). The sample is taken by pressing the tape against the dusty surface. The gravimetric tape method is easy and and can be set up rapidly in the field. The surface dust level (g/m^2) is available immediately after the sampling and weighing of the samples. In addition to the tape method, dust can be collected for gravimetric analysis with, for example,

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Table 1 The characteristics of dust sampling methods

Measuring method	Place of preparation	Detection limit	Purpose	Unit	Reference
Vacuum test (NADCA)	Laboratory	[1)] 0.001 g/m^2	Evaluation of cleaning work	g/m^2	NADCA, 1992
Winttest	Laboratory	[1)] 0.001 g/m^2	Evaluation of need for cleaning	g/m^2	Winttest, 1997
Gravimetric tape	Field	[2)] 0.1 g/m^2	Evaluation of need for cleaning	g/m^2	Fransson et al., 1995
Wiping (JADCA)	Laboratory	[1)] 0.001 g/m^2	Evaluation of need for cleaning	g/m^2	Ito et al., 1997
Wiping with solvent	Laboratory	[1)] 0.001 g/m^2	Evaluation of need for cleaning	g/m^2	Fitzner et al., 2000
Optical method	Field	0.1%	Cleanliness level	%	Schneider et al., 1996
Thickness test	Field	[3)] –	Evaluation of need for cleaning	µm	HVCA, 1998

[1)] When the resolution of the laboratory balance is 0.01 mg and the sampling area 100 cm^2
[2)] When the resolution of the field balance is 1.0 mg and the sampling area 100 cm^2
[3)] Not mentioned (HVCA, 1998)

the wiping technique. Ito et al. (1996) used the method and wiped the dust from a 100 cm^2 area of the duct with a pre-weighed non-woven (polypropylene) cloth. The method was proved to be reproducible and the recovery of the method was more than 70% (Ito et al., 1996). The authors concluded that the wiping technique could be applied to quantitative dust sampling from duct surfaces. The method has been developed further and at present 70% propanol is used as a solvent added to the cloth to increase the dust removal efficiency (Fitzner et al., 2000).

The optical method can also be used to determine the cleanliness of air ducts. The operating principle of the method is based on the change in the light extinction through a transparent sampling tape. A special device is used for measuring the change in light extinction of the gelatine-coated tape before and after sampling. The amount of dust on the surface is expressed as a percentage of the reduction of the light extinction through the contaminated tape from that of a clean tape (Schneider et al., 1996). The method is useful for field applications.

One way to express the cleanliness of the duct surface is to measure the thickness of the dust layer. An instrument developed for this purpose is based on the electromagnetic measurements of the distance from the dust surface to the sheet metal surface. The deposited thickness test (D.T.T.) method has been introduced as an alternative method to the vacuum test method in guidelines published in Great Britain (HVCA, 1998). The guidelines recommend employing the D.T.T. method, especially when grease or adhered deposits are clearly present. The properties of the various measuring methods are summarized in Table 1.

Various methods have been used to measure the surface dust level, which makes the comparison of the results difficult. In previous studies some of the methods have been compared in the air ducts of old existing buildings. In a study by Fransson et al. (1995), three parallel sets of dust samples were taken from air ducts that had been in use for several years using five different methods. NADCA's vacuum test method resulted the lowest surface dust level (0.01 g/m^2). The highest level (4.2 g/m^2) was obtained with the vacuum test method when the dust was loosened from the sheet metal duct surface with the aid of a blade. The authors recommend the use of the gravimetric tape and the optical method for measuring the amount of dust in air ducts (Fransson et al., 1995).

Fitzner et al. (2000) studied six sampling methods (Table 2). Four of the methods were applications of the vacuum test method. Dust was loosened with a blade,

Table 2 The amount of dust defined with the different measuring techniques

Measuring technique	Fransson et al. (1995)			Fitzner et al. (2000)
	RCE[1)]	(g/m^2)	SD	RCE
Vacuum test (NADCA)	0.002	0.01	0.003	0.02
Vacuum test with blade	0.90	4.18	1.36	0.90
Gravimetric tape	0.34	1.57	0.84	0.35
Wiping method (JADCA)	0.43	2.00	0.74	0.50
Wiping method with 70% propanol	–	–	–	1.00
Winttest method	–	–	–	0.10
Optical method	–	20%[2)]	5.00	–

[1)] The relative collection efficiency (RCE) is calculated assuming that the vacuum test method with the blade is 0.9
[2)] The optical method measures the change in light extinction
SD=the standard deviation of the samples

a brush, the filter cassette (Winttest method) or without touching the sampling area (NADCA). The other methods employed were the wiping method developed by the Japanese Air Duct Cleaners Association (JADCA) and the gravimetric tape method. The highest amount of total dust (relative number 1.0) was measured using the modified wiping method in which a solvent (70% propanol in water) was added to the wiping cloth to increase the relative collection efficiency (RCE) of the dust. The vacuum test method without the mechanical loosening of the dust had the lowest efficiency (NADCA). However, the RCE of NADCA's vacuum test method was ten times higher than that measured by Fransson (Table 2).

The studies of Fransson et al. (1995) and Fitzner et al. (2000) showed great variations between the methods applied in old, used ventilation ducts. Only a small number of studies were carried out, and thus, more field comparison studies are needed to evaluate the effectiveness of the methods. Additionally, there is also the need to evaluate the measuring methods with newly installed ducts because a recent study by Holopainen et al. (2000) has shown that they are not clean either. In the study by Holopainent et al., three commonly used dust sampling methods were evaluated in the field. In addition to the compatibility of the results obtained with different methods, the usefulness and reliability of the methods in field applications were also evaluated. Other objectives were to find out whether the method could be used to evaluate the need for cleaning or whether it is suitable for verifying the cleanliness level after the cleaning work. In addition, the distribution of dust on the duct surface was analysed using the results of parallel samples from the new air ducts.

Material and Methods

Ducts

Thirteen recently built buildings with mechanical ventilation systems were randomly selected for the study. Air ducts were installed either by using the current manufacturing, storage and installation practice, or the ducts were manufactured using a new process without processing oils, and they were protected against dust deposition during the construction process. The dust samples were collected via the inspection openings in the ducts. Fifty-eight % of the sampling sites were located in rectangular ducts. Some of the round ducts (18%) had residual oil from the manufacturing process on the interior surfaces.

Measuring Strategy and Methods

In one of the buildings, a larger amount of parallel samples were taken from the sampling sites for the analysis of the dust distribution on the duct surface. A commercial tape (3M Scotch™Plus) was used for the tape sampling. Ten sampling sites were chosen for the vacuum test method and four for the gravimetric tape and the optical methods.

The parallel dust samples were taken from the bottom of the duct surface, at intervals of approximately 5 mm. The samples were taken from locations where the dust layer seemed to be equal for all the methods upon visual inspection. In each building, the mean value of the surface dust level was measured by taking 3–6 samples. The number of samples depended upon the total length of ductwork. A total of 26 dust samples were taken from the rectangular supply air ducts and 20 from the round ducts. Scotch™ Double Sided 665 tape was used for the tape method in the 12 buildings. Additionally, two researchers visually estimated the quality and the amount of dust at each sampling point and the results were recorded systematically.

Vacuum Sampling Method

The sampling device used for the vacuum test method consisted of a suction hose, a pre-weighed membrane filter (0.22- or 0.8-µm pore size), a filter cassette, an air pump and the templates (100 cm^2). A polyvinyl chloride (PVC) suction hose was connected to the filter cassette. The airflow of the pump was 10 dm^3/min and the air velocity in the suction hose 8.5 m/s. Before and after the sampling, the filters (37-mm diameter) and their cassettes were stored at 20 °C in a desiccator for three days. After this, the filter cassettes with the filters were weighed together. In the round ducts, the samples were collected from one of the lower quarters of the duct, between the lowest and broadest line of the duct (Pasanen, 1998). All of the samples were taken carefully from the duct surface by scraping the surface with the suction hose crosswise over the area of the template. During sampling the ventilation was turned off. Additionally, a blank sample was used for quality control in each building. After the samples had been stabilized in the desiccator for three days, the filter cassettes with filters in them were weighed using a laboratory balance (METTLER AE 240 Dual Range Balance) with a resolution of 0.00001 g. The theoretical detection limit of the method was 0.001 g/m^2.

The dust was sampled at parallel sampling sites of the new supply air duct using three different measuring methods. Three parallel samples were taken with the vacuum test and the tape method and four with the optical method. The field balance was used to weigh the whole sampling set, consisting of a filter, it's cassette and a suction hose, before and immediately after the sampling. The filter and it's cassette were then placed in the desiccator again and, after three days, weighed with the laboratory balance. The field balance (Sartorious Basic^{lite} Series BL 150 S) had a resolution of 0.001 g. The theoretical detection limit of the method was 0.1 g/m^2.

Gravimetric Tape Method

The gravimetric tape method used Scotch™ Double Sided 665 tape covered with transparent sheets for sampling. The surface area of the hand-cut sampling tape was 46 cm^2. The pre-weighed tape was pressed against the surface with a constant force roller (10 N). Three samples were taken at 5-mm intervals. The sampling tapes were weighed before and after sampling as in the vacuum test method. The theoretical detection limit of the method was 0.0022 g/m^2 (the resolution of the balance was 0.00001 g).

The surface dust level was measured in one building with the 3M Scotch™Plus tape. This tape was selected after laboratory tests and it's properties (dust collection efficiency and hygroscopic properties) are quite similar to than of the Scotch™ Double Sided 665 tape. Some tape materials (paper based) are hygroscopic, and the water adsorbed to the tape may cause a significant error. The size of the tape was 85×85 mm, resulting in an area of 72 cm^2. The sampling procedure was the same as the Scotch™ Double Sided 665 tape. The theoretical detection limit of the method was 0.14 g/m^2 (the resolution of the balance was of 0.001 g).

Optical Method

The optical method (BM-Dustdetector) was originally developed for quality control of space cleaning and it has later been applied to the evaluation of the cleanliness of air ducts. The device measures the light extinction, which is the removal of light from a beam of light either by absorption or change of direction (reflection/refraction), and displays the light extinction as a percentage (Schneider et al., 1996). The device is calibrated so that the display indicates the projection area of the dust particles on the tape as a percentage of the sampled area. The measuring procedure was as follows. First, the light extinction of an unused tape was measured. Then, the gelatine-coated adhesive tape was placed on the duct surface and pressed with a roller (F=10 N). The roller was run over the tape three times in transverse directions. After the tape was contaminated, the amount of the sampled particles was quantified by measuring their extinction. Four parallel samples were taken at 5-mm intervals. The average of the percentage readings was used as the result. Because of particle overlap, the results of the optical methods were corrected using Equation 1 (Schneider et al., 1996).

$$A_t = -\ln\left(1-\frac{A}{100}\right)\times 100 \qquad (1)$$

where A_t is the true value (%) and A the measured value (%).

Results

Amount of Dust in the Supply Air Ducts

The average surface dust level determined by the vacuum test method (n=45) was 1.3 g/m^2 (range <0.1–8.4 g/m^2). The tape method provided slightly lower mean results 1.2 g/m^2 (<0.1–5.0 g/m^2) than the vacuum test method. The optical method gave cleanliness results of 15% (2–41%). The relative standard deviations (RSDs) of the parallel samples were higher in the tape method than in the optical method. The quality of the dust affected the performance of the methods. The results are shown in Table 3.

In the ducts without residual oil (n=37) the average surface dust level determined using the vacuum test method was 1.1 g/m^2 (<0.1–5.3 g/m^2) and slightly higher, with the tape method, on average 1.2 g/m^2 (<0.1–4.6 g/m^2). The result of the optical method was 15% (2–41%). The RSDs of the parallel samples were higher in the tape method than in the optical method. In the ducts with residual oil (n=8) the average surface dust level determined by the vacuum test method was 1.8 g/m^2 (0.1–8.4 g/m^2). The average amount of dust was 1.2 g/m^2 (0.1–5.0 g/m^2) with the tape method. The result of the optical method was 14% (5–33%). The RSDs of the parallel samples were slightly lower in the tape method than in the optical method.

Distribution of Dust on Duct Surface

The homogeneity of the dust distribution on the duct surface was studied in a building under construction. Three parallel dust samples were taken from ten sampling sites using the vacuum test method. Each sampling site seemed to have the same amount of dust-upon visual inspection. The whole sampling set (including a suction hose measuring 40 mm in length) was weighed before and immediately after the dust sampling using the field balance. Only the filter and it's cassette were weighed with the laboratory balance. The mean amount of dust was 0.4 g/m^2 and the RSDs of the vacuum test method were 12–129% using the laboratory balance. The mean amount of dust was 0.5 g/m^2 and the RSDs of the vacuum test method were 0–125% using the field balance. The result shows that 22% of dust remained on the inner surface of the suction hose.

The highest mean amount of dust collected with the vacuum test method was 0.6 g/m^2 (weighed with the

Table 3 The average amount of dust in the air ducts (n=45)

Sampling site	Vacuum test		Gravimetric tape method[1)]			Optical tape method		
	Average (g/m^2)	Median (g/m^2)	Average (g/m^2)	Median (g/m^2)	RSD min–max	Average (%)	Median (%)	RSD min–max
NRO (n=37)	1.1	0.7	1.2	0.8	2–298	15	13	3–177
RO (n=8)	1.8	0.4	1.2	0.5	1–95	14	9	7–222
All samples	1.3	0.5	1.2	0.7	1–298	15	13	3–222

1) The gravimetric tape was Scotch™ Double Sided 665 tape
NRO=without residual oil, RO=with residual oil

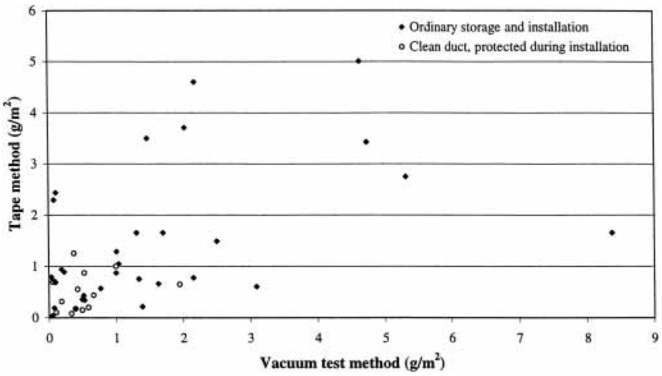

Fig. 1 A scatter plot of the data obtained using the tape and the vacuum test method (n=45)

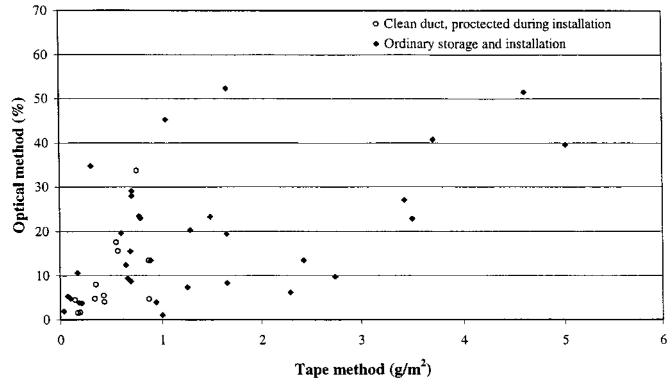

Fig. 2 A scatter plot of the data obtained using the optical and the tape method (n=45)

field balance) and 0.5 g/m^2 (weighed with the laboratory balance). The mean amount of dust with the tape method was 0.5 g/m^2 (weighted with the field balance). The result of the optical method was, on average, 9%. The results are shown in Table 4. The RCE for the tape method was 0.8 compared with the vacuum test method using the 3M Scotch^{TM}Plus.

Correlation between the Results of Different Measuring Methods

The tape method and the optical method were compared with the vacuum test method. For the vacuum test method, each data point in Figures 1 and 2 represents one sample, while for the results of the tape method and the optical method the data points are presented as averages of three and four samples, respectively. The linear multiple correlation coefficient (R^2) between the tape method and the vacuum test method was 0.3. No linear correlation existed between the optical method and the vacuum test method (R^2=<0.1).

The tape method and the optical method are compared in Figure 2. The multiple linear correlation coefficient between the tape method and the optical method was 0.3. The result is expressed in Equation 2.

$$A = 6.49 \times \text{Tape} + 9.41 \qquad (2)$$

When the surface dust level was less than 6 g/m^2 measured with the vacuum test method (n=44), the multiple linear correlation coefficient between the tape method and the vacuum test method was 0.4. Additionally, the tape and the optical method were compared using the results of the dust samples that were collected from the surfaces without residual oil (n=37) and, in this case, the resulting multiple linear correlation coefficient was 0.4.

Discussion

The vacuum test is considered to be an effective and reliable method for determining the amount of dust in air ducts (Fransson et al., 1995). The effectiveness of the method was demonstrated in this study, as the highest amount of dust was collected with the vacuum test method. The residual oil on the round duct surface seemed to decrease the sampling efficiency. Dust

Table 4 The average amount of dust measured with four different methods in recently installed air ducts

Sampling site	Vacuum test method				Tape method[3]		Optical method	
	Laboratory scales[1]		Field scales[2]		Field scales[2]			
	(g/m^2)	RSD (%)	(g/m^2)	RSD (%)	(g/m^2)	RSD (%)	A_t (%)	RSD (%)
1	0.2	102	0.2	50	0.4	43	7	64
2	0.4	22	0.7	31	0.5	42	5	26
3	0.6	136	0.6	54	0.6	74	16	31
4	1.0	120	1.0	135	0.5	31	9	40
Average	0.5		0.6		0.5		9	

1) Resolution of the laboratory balance was 0.01 mg
2) Resolution of the field balance was 1.0 mg
3) The tape was 3M Scotch^{TM}Plus
A_t=percentage covered by particles corrected for particle – particle overlap

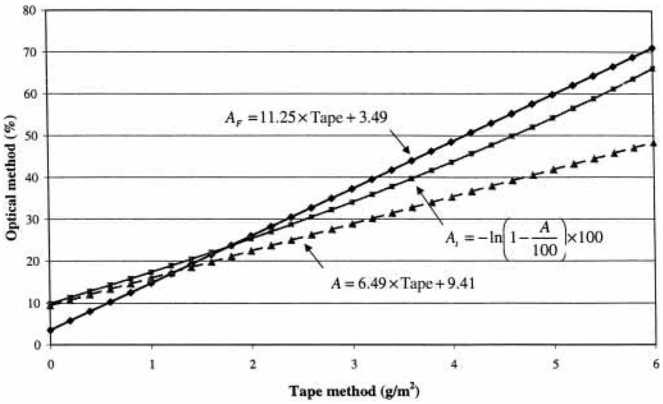

Fig. 3 Result of tape method (g/m^2) and calculated cleanliness level of optical method (%) using equations 1–3

adheres quite strongly onto residual oil and, therefore, the airflow and scraping with the plastic suction hose cannot remove all of the dust and residual oil from the duct surface. Because dust collects on the surface of the suction hose and the wall of the filter cassette, the most reliable result can be achieved by weighing the filter cassette with the filter and the hose together (Pasanen, 1999). One-fifth (22%) of the dust sample adhered onto the inner surface of the straight suction hose (5 mm in diameter and 40 mm in length) when the air velocity in the hose was 8.5 m/s. During the sampling, the average wall loss of the suction hose was 0.5 g/m^2. Therefore, the suction hose should be short and straight to minimize the wall loss.

The surface dust level measured with the gravimetric tape method was only slightly lower than that measured with the vacuum test method, especially in the ducts containing some residual oil. The results indicate that the tapes used in the study are effective and reliable for dust sampling when the dust layer is thin. Similar findings have been reported in a previous laboratory study where an upper limit of 4 g/m^2 was suggested for the tape method (Pasanen, 1999). This field study was carried out in duct systems where dust was recently deposited on the surfaces. In new supply air ducts, the amount of dust is normally low enough for the tape to collect most of the dust from the surface. The RCE of the tape method compared with the vacuum test method was 0.9 using Scotch™ Double Sided 665 tape (n=46) and 0.8 using 3M Scotch™Plus (n=4) calculated from the result of the mean value. Both of the tapes were made of plastic, which is a non-hygroscopic material. When using the gravimetric tape method, it is important to press the sampling tape evenly with a constant force against the surface under examination. Dust saturation of the adhesive tape restricts the sampling efficiency for high dust levels. It seems that the tape collects only the top layer of dust from a very dusty surface, which leads to an incorrect result. However, the tape method is useful, at least in places where the dust lies loosely on the surface and where the amount of dust is fairly small.

The readings of the optical device were between 2–41%. The operating range of the optical instrument was 0–52% (the maximum value of 52% corresponding to black tape used as a reference). Out of 180 samples, the optical measuring device gave 12 zero readings. In some of these cases the device gave a zero reading although dust spots were visually observed on the tape. On the other hand, in a few cases the dust level was very low on the surface, indicating that the instrument was very close to the detection limit. The optical method measures a projected area, not the mass. Therefore, the relation between the optical and gravimetric methods depends on particle density and size distribution. However, the projected area as measured with the optical method is nearly independent of the optical properties of the particles (Schneider et al., 1996). The gelatine-coated adhesive tape is only 30 mm wide and, therefore, it enables dust sampling even from narrow openings. The optical method is the most convenient method to use in the field.

Fransson et al. (1995) compared the different dust sampling methods.

$$A_F = 11.25 \times \text{Tape} + 3.49 \quad (3)$$

Equation 3 expresses the relationship between the optical method and the tape method. The equation gives higher results than Equation 2 when the amount of dust is more than 1.2 g/m^2. In Figure 3, the overlap is taken into account with Equation 1.

The results of the gravimetric tape and the optical methods were the same order of magnitude in both oil-free and oily duct surfaces. They gave higher readings in the ducts without residual oil than in the ducts

Table 5 The results of the optical method as a function of the tape method using various equations

Tape (g/m^2)	A_F (%)	A (%)	A_t (%)	Ratio $\frac{A}{A_F}$	Ratio $\frac{A_t}{A_F}$	Difference $\frac{A_F - A}{A_F}$ (%)	Difference $\frac{A_F - A_t}{A_F}$ (%)
0	3.5	9.4	9.9	2.7	2.8	−169	−182
1	14.8	15.9	17.3	1.1	1.2	−8	−17
2	26.0	22.4	25.4	0.9	1.0	14	2
3	37.3	28.9	34.1	0.8	0.9	22	8
4	48.5	35.4	43.7	0.7	0.9	27	10
5	59.8	41.9	54.3	0.7	0.9	30	9

A_F=11.25×tape+3.49, equation (3); A=6.49×tape+9.41, equation (2); A_t=percentage covered by particles corrected for particle – particle overlap which had residual oil, whereas the vacuum test method gave the opposite results. The dust adhered more strongly to the ducts that had residual oil than to the ducts without residual oil, and the tape could not collect dust as effectively from the oily surface as the vacuum test method could.

In Table 5, the results of the tape method are compared with the optical method. Equation 3 of Fransson et al. gave approximately the same result as Equation 2 when the amount of dust was in the range of 1.0–1.6 g/m^2 (difference −8%–+8%). When the results were corrected using Equation 1, they were approximately in the same range (1.4–2.6 g/m^2 (difference −6%–+7%)).

The correspondence between the methods can be estimated using Equations 2 and 3. For example, Equation 2, based on the results of this study, gives 1.6 g/m^2 for the 20% reading of the optical method and Fransson et al.'s Equation 3 gives 1.5 g/m^2 for the same 20% reading.

The results given by the investigated dust measuring methods did not correlate well with each other. One reason might be that the amount of dust was not equally distributed on the duct surface in the sampling locations (the large RSDs) even though the distribution seemed uniform upon visual inspection. The quality and the density of the dust might also be different at the bottom and the top of the dust layer at each sampling site, which could therefore bias the results of the correlation. The samples were collected carefully but the dust samples had to be taken via small or narrow openings without the possibility of always seeing the sampling area, and this might have also affected the results. The standard deviations of each measuring method were large, which may also indicate non-uniform distribution of dust on the duct surface and may affect the comparability of the methods. The total mass of the dust samples was very small and even a small amount of steel filings in the sample would bias the parallel results of the gravimetric methods.

The amount of dust in the new air ducts is normally low, in this study the mean amount was 1.3 g/m^2 (median 0.5 g/m^2). When the amount of dust was under 6 g/m^2, the multiple correlation coefficient between the tape method and the vacuum test method (n=44) was 0.4. No correlation between the optical method and the vacuum test method was found. In our previous study, the linear multiple correlation coefficient was 0.6 between the tape method and the vacuum test method, and 0.4 between the optical method and the vacuum test method when the amount of dust was under 3 g/m^2 (Holopainen et al., 2000).

Usually, the duct surface was visually estimated to be clean when the surface dust level was less than 0.1 g/m^2. The duct is clearly unclean when the surface dust level is higher than 5.0 g/m^2 measured with the vacuum test method. Thus, the professional inspector needs to apply measuring methods when the amount of dust is in the range of 0.1–5.0 g/m^2.

Conclusion

The vacuum test is the most effective method of collecting dust from duct surface and it is suitable for the objective determination of the dust level, especially for research work. Due to its good collection efficiency it can also be applied in old air ducts. The surface dust level on the inner surface of the suction hose of the sampler may be significant. In this study, 22% of the mass of dust accumulated in the suction hose. The tape method can be applied particularly to duct surfaces with low amounts of dust. The tape material must be able to collect dust well and it should not be hygroscopic. The tape method gave 7% lower results than the vacuum test method. Some results of the optical method and visual observation did not correspond with each other. The results calculated from Fransson et al.'s equation and Equation 2 developed in this study gave approximately the same result when the amount of dust was 1.4–2.6 g/m^2 as measured with the tape method. The RSDs of the surface dust level at the parallel sampling sites of the duct was large, in ten sampling sites 12–129% measured with the vacuum test method even though the surface dust level seemed to be similar according to visual inspection and affected the correlation of the methods.

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