Indoor Air 2003; 13: 212–222
www.blackwellpublishing.com/ina

INDOOR AIR
ISSN 0905-6947

Effectiveness of duct cleaning methods on newly installed duct surfaces

Abstract Two kinds of air duct cleaning methods, mechanical brushing with different brushes and compressed air cleaning, were compared in the laboratory and in newly built buildings. The ducts were contaminated either with test dust or with dust originated from a construction site. The amount of dust on the duct surface was measured with the vacuum test method and estimated visually before and after the cleaning. In addition, the cleaning times of the different techniques were compared and the amount of residual oil in the ducts was measured in the laboratory test. The brushing methods were more efficient in metal ducts, and compressed air cleaning was more efficient in plastic ducts. After the duct cleaning the mean amount of residual dust on the surface of the ducts was ≤ 0.1 g/m^2 in the laboratory test with ducts contaminated at construction site and ≤ 0.3 g/m^2 after cleaning in the field. The decrease in the dust deposits on the surface ranged from 86 to 99% and from 75 to 94% in the ducts cleaned in the laboratory or in the building site, respectively. The oil residues and the dust stuck onto the oil were difficult to scrape off and remove, and none of the cleaning methods were capable of cleaning the oily duct surfaces efficiently enough. Thus new installations should consist only of oil-free ducts.

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Key words: Brushing; Compressed air cleaning; Cleaning force; Duct; Dust; Oil residues.

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Received for review 9 September 2001. Accepted for publication 8 March 2002

Practical Implications
Mechanical brushing is a commonly used efficient method for cleaning of air ducts. Compressed air cleaning is also an efficient method, especially in plastic air ducts. However, it is slower and noisier compared with the brushing methods. Bends in ducts should be cleaned from both directions to ensure a good cleaning result. Oil residues were difficult to clean properly and therefore new installations should consist of oil-free ducts and components.

Introduction

Dust and residual oil in air ducts

Even in newly installed supply air ducts, the amount of dust on the inner surfaces of duct may be high if the ducts are not protected against impurities properly. In this case, ducts have to be cleaned after installation. In supply air ducts of buildings occupied less than a year, Pasanen (1998) found an average dust accumulation level of 5.1 g/m^2, which clearly exceeded the estimated annual accumulation rate of 1 g/m^2. The predominately (90%) inorganic fraction of the dust indicated that the dust originated from the transportation and storage of the ducts. Ducts can be exposed to dust during different phases of the ductwork installation. Finishing works, which produce a lot of dust, are the most critical periods during which dust accumulation ranging from 0.5 to 4.9 g/m^2 has been found (Luoma, 2000). With a proper protection programme the dust accumulation levels have been lower (0.4–2.9 g/m^2) compared with ducts installed without protection (1.2–4.9 g/m^2) (Holopainen et al., 2001). In addition, the inner surface of round ducts may be contaminated with residual oil originating from the manufacturing process (Pasanen et al., 1995, 1999). The mean amount of residual oil in spiral ducts manufactured by using three different techniques ranged from 7 to 196 mg/m^2 (Asikainen and Pasanen, 2000). Residual oil in an air duct affects the perceived air quality of the supply air (Björkroth and Asikainen, 2000).

Verification of cleanliness

Visual inspection is a primary and in some cases the only method to verify the cleanliness of the ductwork. According to the Finnish guideline for Indoor climate

(FiSIAQ, 2001), the limit value for dust accumulated in newly installed ducts is 1.0 g/m^2 in cleanliness category P1, and 2.5 g/m^2 in category P2. The corresponding values for air ducts in old buildings are 2.0 and 5.0 g/m^2, respectively. According to the guidelines published in Great Britain, the limit value of the surface dust level in supply and recirculation ducts is 1.0 g/m^2 and in extract ducts 6.0 g/m^2 (HVCA, 1998). According to the North American Duct Cleaners Association (NADCA), residual dust in cleaned air ducts should be $\leq$ 0.1 g/m^2. Besides this, if visible contaminants are present after the cleaning has been performed, the cleaning work is considered unacceptable (NADCA, 1992).

Air duct cleaning technology

Air duct cleaning contractors use several techniques to remove dust, debris and other contaminants from the duct surface. The air duct cleaning methods can be either dry or wet (HVCA, 1998). The most commonly used dry duct cleaning methods are mechanical brushing, compressed air cleaning and vacuuming manually. The main principles of these methods are the same; the dust is detached from the duct surfaces mechanically with a brush, a powerful air jet or a suction force, and the loose dust is carried out of the duct by airflow. Wet cleaning methods are seldom used to clean air ducts because the ductworks are not normally watertight.

The air velocity to transport the detached particles must be so high (above 10 m/s) that the particles will not redeposit onto the surface due to gravitational force. For particles <100 μm in diameter, gravitational deposition is minimal in duct lengths up to 30$\times$ the height of the duct when the transport air velocity is 22.9 m/s (Heinsohn, 1991). However, gravitational settling often occurs when particles exceed 100 μm in diameter. For some conditions, such as sticky materials on the surface, condensing conditions in presence of dust and strong electrostatic effects, velocity alone may not be sufficient to prevent settling (ACGIH, 1988).

Efficiency of the air duct cleaning methods

The efficiency of mechanical air duct cleaning methods in old air ducts has been reported by Ito et al. (1996), Kulp et al. (1997), and Holopainen et al. (1999). Their results show that mechanical air duct cleaning methods are effective in removing adhered dust and dirt from the inner surface of the ducts. Ito et al. (1996) measured the amount of dust on the duct surface with a wiping method before and after duct cleaning. Before cleaning, there was from 4–11 mg/m^2 of dust on the bottom surface of duct and 1–2 mg/m^2 after cleaning. Kulp et al. (1997) measured 0.2–3.6 g/m^2 amount of dust on the duct surface before cleaning using the NADCA vacuum test method. After cleaning, the amount of dust decreased to a level less than 0.2 g/m^2. Holopainen et al. (1999) measured the amount of dust on duct surfaces using an optical and a gravimetric tape method. The results of the optical method are expressed as a percentage of the reduction of the light extinction through a contaminated tape from that of a clean tape (Schneider et al., 1996). Before cleaning, the result of the optical method ranged from 23 to 53% and the results of the gravimetric tape method ranged from 3 to 10 g/m^2 of dust on the bottom surface of the duct. After cleaning, the values were 15–21% using the optical method, and 1–2 g/m^2 using the gravimetric tape method.

Jalonen (2000) compared the efficiency of mechanical air duct cleaning methods in new air ducts in laboratory and field conditions. He measured the amount of dust on the duct surface using the vacuum test method. The results showed that the material and the diameter of the brush affected the cleaning result. The best cleaning result was achieved using a micro-fibre cloth over a brush, the diameter of which was 100 mm bigger than that of the duct. The supply air ducts were manufactured without using oil lubricants. After duct cleaning, the amount of dust was lower than 0.5 g/m^2 at 96% of all the dust sampling points ($n = 24$).

Clean air ducts are an essential part of the good hygiene of HVAC systems (Sieber et al., 1996). Previous field studies have mainly investigated the efficiency of mechanical duct cleaning methods in old air ducts. Earlier studies have neither taken into account the material of the ducts and brushes nor the efficiency of different cleaning methods.

The aim of the study

This study focused on cleaning of newly installed air ducts. The aim of the study was to find out the efficiency of two dry air duct cleaning methods with different brushes and compressed air cleaning methods in new ducts. In addition, the influence of dust composition and residual oil on efficiency of the duct cleaning methods was studied.

Materials and methods

Dust measuring methods

The amount of dust was measured using the vacuum test method (Pasanen, 1999; Holopainen et al., 2001). The sampling device of the vacuum test method consisted of a suction hose, a pre-weighed membrane filter (0.8 μm pore size), a filter cassette, an air pump, and the templates (100 cm^2). The airflow of the pump was 10 dm^3 /min. Before and after sampling, the filter cassettes with the filters were weighed together 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

same method for measuring accumulated dust was used in all the experiments. Additionally, two researchers estimated visually the appearance and the amount of dust at each sampling point. During visual inspection the intensity and the direction of the illumination were taken into account by using the same torch and the results were recorded systematically.

Measuring methods of residual oil

Oil residues were measured using a filter contact method (Pasanen et al., 1999). The method is based on the pressing of an immersed glass fiber filter (Munktell filter MG 160, Grycksbo, Sweden) onto the surface with a constant pressure. The recovery and reproducibility of the sampling using the filter contact method with a constant pressure device was shown to be 96 ± 1% and the recovery and reproducibility of the extraction was shown to be 97 ± 2% for the tested lubricant Solvac 1535 GD. The detection limit for that oil is 12 mg/m^2.

Laboratory test with ASHRAE test dust

Test set-up. The cleaning methods were tested in three different types of round air ducts: a metal duct without residual oil (a cleanliness category P1 duct defined in FiSIAQ, 2001), a metal duct with residual oil (a cleanliness category P2 duct defined in FiSIAQ, 2001), and a plastic duct. The mean amount of residual oil was <12 mg/m^2 (all ducts below detection limit 12 mg/m^2) in the category P1 ducts. Category P2 ducts were prepared by spreading the oil on the inner surface of the duct (216–338 mg/m^2) which represent high level of oiliness in air duct. A small ductwork consisted of three straight ducts connected with two pieces of 90° bends (Figure 1). The diameter of the plastic ducts was 125 mm and of the metal ducts 160 mm. The length of the straight ducts was 7 m and of the bends 0.5 m (Ø 125: 2 × 0.25 m) and 0.7 m (Ø160: 2 × 0.35 m). The total lengths of the ductworks were 7.5 m (Ø 125) and 7.7 m (Ø 160). The ductworks were connected to a test equipment and they were contaminated using a dust feeding device (Kovanen, 2000). The amount of dust fed into each ductwork was 30 g, the dust feeding time was 15–18 min and the velocity of the airflow in the duct was 1.5 m/s during the dust feeding. ASHRAE (1992) standard test dust (Arizona dust) used for the test, consisted of 72% standardized air cleaner test dust, 23% molacco black, and 5% cotton linters. The particle size distribution by weight was 0–5 μm (39%), 5–10 μm (18%), 10–20 μ m (16%), 20–40 μm (18%), and 40–80 μm (9%). During the test, the temperature of the test room ranged from 17.7 to 21.3°C and RH from 46.6 to 51.4%.

After the amount of dust was measured, a cleaning company connected a low-pressure fan to the ductwork. The speed of the airflow, which carried the loosened dust out from the duct, was adjusted approximately to 10 m/s during mechanical brushing and to 23–24 m/s during compressed air cleaning. After the ductwork had been cleaned, the amount of dust was measured again at measuring points parallel to the measuring points before duct cleaning. Additionally, the cleaning result was estimated visually and the ducts were photographed with a digital camera. The cleaning times were also measured and recorded.

Sampling points. After the test dust had been fed into the ductworks, the amount of deposited dust was measured from pre-determined sampling points (Figure 1). In the plastic duct, the distances of the sampling points were 1.4, 1.7, 4.2, 4.6 and 5.6 m from the end of the duct. In the metal duct, the distances of the sampling points were 1.4, 1.7, 4.3, 4.8, and 5.8 m. The sizes of the openings were 180 × 300 mm^2 in the plastic

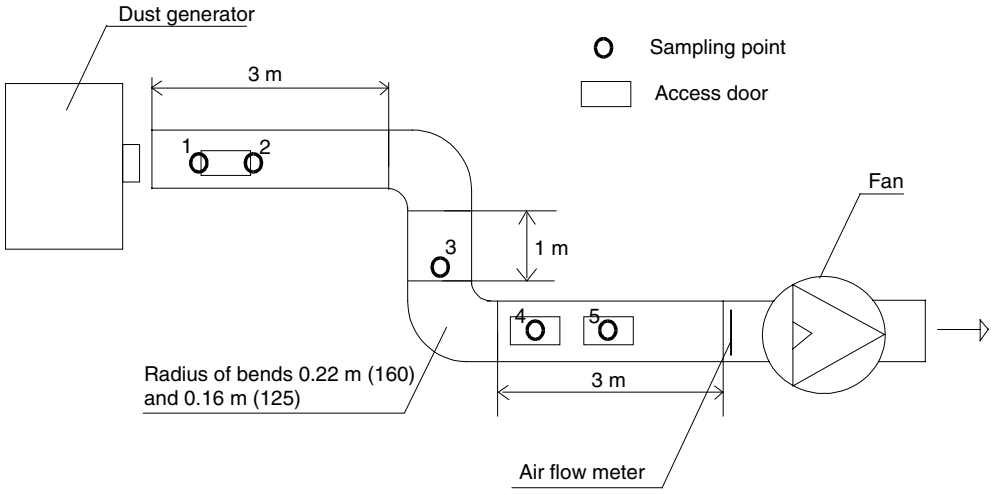

Fig. 1 The set-up of the laboratory test with ASHRAE test dust

duct and 180×430 mm^2 in the metal duct. The dust at sampling point number 3 was measured by detaching the duct and the 90° bend from each other. Additionally, the cleanliness of the ducts was evaluated visually after cleaning.

Cleaning methods. Two professional air duct cleaning companies cleaned the test ducts with rotating brushes and using brushes made of different materials. A third professional duct cleaning company cleaned the ducts with compressed air. In the mechanical brushing the experienced cleaners selected the bristles of the brushes made of nylon, polyester or polypropylene according to the type of the duct. The diameter of the brushes ranged from 180 to 250 mm and their length from 40 to 160 mm. The brushes were rotated at a speed of 570–2000 rpm. The brushes were connected to a flexible whirling arm of variable length and they were guided into the ducts (from the dust generator to the low-pressure fan) with flexible cleaning cables. The ducts were cleaned only once back and forth. In compressed air cleaning (CAC1) compressed air was let into the ducts from a compressor unit which was located outside of the test building. The air nozzle was guided into the ducts from the opposite end of the ductwork compared with brush cleaning (from the low-pressure fan to the dust generator). The ducts were cleaned by moving the air nozzle with the help of the hose to the end of the duct and then by pulling it back from the duct. According to the component manufacturer, the airflow through the air nozzle is approximately 50 dm^3/sec at an air pressure of 800 kPa. The cleaning method, diameter of the brush, rotating speed of the brush and material of the brush, are shown in Table 1.

Table 1 Cleaning methods and tested ducts

Laboratory test with ducts contaminated with test dust Cleaning methods	Tested ducts
MB1: Mechanical brushing with three brushes made of nylon (diameter of bristles $d = 0.5$–0.8 mm) and polypropylene ($d = 0.45$ mm). P1: diameter of nylon brush was 180 mm, P2: diameter of brush was 190 mm, PL: diameter of nylon brush was 150 mm. Rotation speed of brushes was 2000 rpm	P1-duct (Ø 160 mm) without residual oil (< 12 mg/m^2)
MB2: Mechanical brushing with two brushes made of nylon (d = 0.8 mm) and polyester ($d = 0.45$ mm), both were covered with polyester cloth. P1- and P2-ducts were cleaned with nylon brush whose diameter was 250 mm, PL-duct was cleaned with polyester brush whose diameter was 160 mm. Rotation speed of brushes was 570 rpm	P2-duct (Ø 160 mm) with residual oil (216–338 mg/m^2)
CAC1: Compressed air cleaning using an air nozzle. Airflow was about 50 dm^3 /sec and pressure 800 kPa	PL-duct (Ø 125 mm)
Laboratory test with ducts contaminated at construction site **Cleaning methods**	**Tested ducts**
MB3: Mechanical brushing with brush made of horsehair. Diameter of brush was 160 mm and rotation speed of brush was 2600 rpm.	P2 ducts (Ø 160 mm)
MB4: Mechanical brushing with brush made of nylon ($d = 0.8$ mm) and polypropylene (d = 0.45 mm). Diameter of brush was 160 mm and rotation speed of brush was 1200 rpm.	P2 ducts (Ø 160 mm)
MB5: Mechanical brushing with brush made of polypropylene ($d = 0.35$ mm). Diameter of brush was 190 mm and rotation speed of brush was 380 rpm.	P2 ducts (Ø 160 mm)
MB6: Mechanical brushing with brush made of nylon ($d = 0.5$ mm). Diameter of brush was 180 mm and rotation speed of brush was 2600 rpm.	P2 ducts (Ø 160 mm)
CAC2: Compressed air cleaning using a whipstream nozzle with rotation speed 10,000–20,000 rpm.	P1-duct (Ø 160 mm) without residual oil
Field test in five buildings **Cleaning methods**	**Tested ductworks**
MB7 (Building A): Mechanical brushing with brushes made of nylon ($d = 0.5$–1.0 mm). Brushes were 20–30 mm larger than the cleaned duct. Rotation speed of brushes was varied between 300–2000 rpm. The velocity of air carrying the dust out of the duct was varied between 5–10 m/sec	P1 ducts (Ø250–500 mm). Length of ductwork was 1090 m
MB8 (Building B): Mechanical brushing with brushes made of nylon ($d = 0.5$ mm). Brushes were 20–50 mm larger than the cleaned duct. Rotation speed of brushes was 570 rpm. The velocity of air carrying the dust out of the duct was about 5 m/sec	P1 ducts (Ø250–500 mm). Length of ductwork was 150 m
MB9 (Building C): Mechanical brushing with brushes made of nylon ($d = 0.3$–0.7 mm). Brushes were 20–50 mm larger than the cleaned duct. Rotation speed of brushes was varied between 500–800 rpm. The velocity of air carrying the dust out of the duct was varied between 4–25 m/sec	P1 ducts (Ø250–315 mm). Length of ductwork was 200 m
MB10 (Building D): Mechanical brushing with brushes made of nylon (d = 0.5–1.0 mm). Brushes were 20–65 mm larger than the cleaned duct. Rotation speed of brushes was varied between 300–800 rpm. The velocity of air carrying the dust out of the duct was varied between 4–20 m/sec	P1 ducts (Ø250–315 mm). Length of ductwork was 4000 m.
CAC3 (Building E): Compressed air cleaning using an air gun	P1 ducts (Ø250–315 mm). Length of ductwork was 20 m

P1 = Cleanliness category P1 duct, P2, cleanliness category P2 duct (FiSIAQ, 2001), PL, plastic duct, d, diameter of bristle.

Laboratory test with dust accumulated at construction site

Test set-up: The cleaning methods were tested in two different types of round air ducts (Ø 160 mm): a metal duct without residual oil (a cleanliness category P1 duct) and a metal duct with residual oil (a cleanliness category P2 duct). The mean amount of the oil residues was 8 mg/m^2 (3–20 mg/m^2) in the category P1 ducts and 56 mg/m^2 ($<$5–278 mg/m^2) in the category P2 ducts. Five separate ductworks consisted of three straight ducts which were connected with four pieces of 90° bends and two short pieces of duct (Figure 2). The total length of the straight ducts was 18 m and bends 2.0 m (Ø 160: 2×0.35 m + 2×0.7 m). The total length of each ductwork was approximately 20 m. The ducts were transported directly from the manufacturer to two different construction sites where they were kept unprotected with open ends for 2 or 3 weeks to get them contaminated. The ducts were stored with other ducts that were to be installed in the building under construction.

After the storage period, the ducts were sealed and transported to the laboratory to measure the dust accumulation in the ducts. After the amount of dust and residual oil were measured, the ducts were cleaned. A cleaning company connected a low-pressure fan to the ductwork. The speed of the airflow which carried the loose dust out of the duct was adjusted to approximately 15 m/sec during duct cleaning. Only the straight parts of the ductworks were cleaned. After the cleaning of the first duct at the bottom of the ductwork, the bend was detached and the next straight part of the ductwork was cleaned. After all the straight parts had been cleaned, the amount of dust and residual oil were measured again at the measuring points parallel to the measuring points before duct cleaning. Additionally, the cleaning result was estimated visually, and the cleaning time was recorded.

Sampling points: The dust accumulation was measured at pre-determined sampling points (Figure 2). The distance of the sampling points were 0.2, 5.6, 7, 12.6, 14 and 19.6 m from the beginning of the duct.

Cleaning methods: The principles of the cleaning methods were the same as with the laboratory test using ASHRAE test dust: in the mechanical brushing only category P2 ducts were cleaned with a brush, the bristles of which were made of horsehair, nylon, or polypropylene. The diameter of the brushes ranged from 160 to 190 mm and their length from 40 to 160 mm. The brushes were rotated at a speed of 380–2600 r/min. A duct cleaning company cleaned the category P1 ducts (without oil residues) using

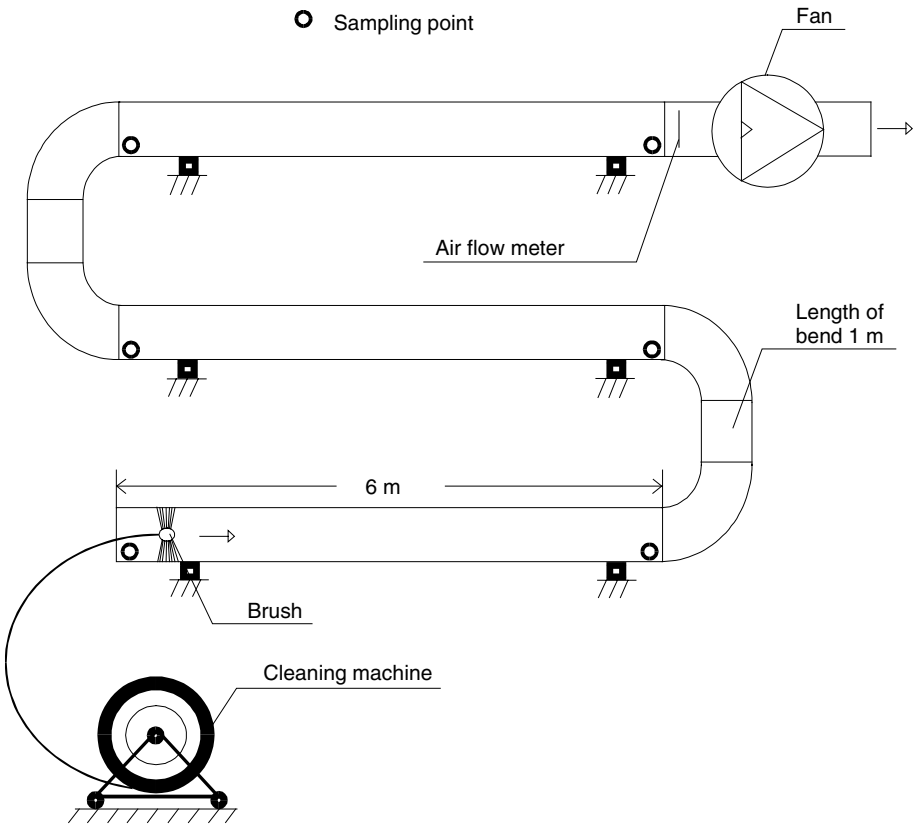

Fig. 2 The set-up of the laboratory test with dust accumulated at the construction sites

compressed air cleaning (CAC2). Compressed air was let into the ducts from the compressor unit, which was located outside of the test building. The rotating whipstream nozzle was guided into the ducts from the same direction as in brush cleaning. The ducts were cleaned by moving the nozzle with the help of a hose to the end of the duct and then by pulling it back from the duct. According to the component manufacturer, the whipstream rotates at 10000–12000 r/min when the compressor capacity is 5.2 m^3 /min and the air pressure is 800 kPa. The impact of the compressed airflow is then up to 1 m from the nozzle. The cleaning method, diameter of the brush, rotating speed of the brush, and material of the brush are shown in Table 1.

Field tests

Investigated buildings: Cleaning methods were also tested in the field in five buildings under construction. Three school buildings and two office buildings were selected for the study in the Helsinki metropolitan area. During the study the construction of the buildings was still under way. In four of the buildings, the air handling units were located on the top floor of the building. In one office building, the air handling units were located on the top as well as on the ground floor of the building. The cleaned ducts were mostly round air ducts, and they had no residual oil from the manufacturing process (cleanliness category P1 duct) on their surfaces.

Building (A) was a school building under renovation. This building had four floors and two of them were under renovation. The amount of dust was measured at five locations of the round ducts. Building (B) was a new two-storey school building. The amount of dust was measured at five locations of the ducts. Building (C) was an office building under renovation. It had six floors, five of which were being renovated. The amount of dust was measured at seven locations of the ducts. Building (D) was a new 11-storey office building. The amount of dust was measured at eight locations of the ducts. Building (E) consisted of an extension part of the main school building with four floors. The amount of dust was measured at four locations of the round ducts. The diameters and lengths of the studied ductworks are shown in Table 1.

Sampling points: The amount of dust was measured by taking four to eight samples before and after cleaning. The number of samples depended on the total length of the ductwork. All in all, three dust samples were taken from the rectangular supply air ducts whose size was 600×300 mm and 29 from the round ducts whose diameter was 200–800 mm. The samples were taken at three locations of the ductwork: close to the terminal units, at the middle of the ductwork, and close to the air handling units.

Cleaning methods: The principles of the cleaning methods were the same as with the laboratory tests: in the mechanical brushing, the bristles of brushes were made of nylon or polyester whose diameter ranged from 270 to 830 mm. The brushes were rotated at a speed of 300–2000 rpm. In the compressed air cleaning a professional duct cleaning company cleaned the ducts with a compressed air lance (CAC3). Compressed air was let into the air gun from a portable compressor unit and the air jet of the air gun was guided on the duct surfaces via the openings of the ductwork. Dust was blown out of the duct into the surrounding space by the air jet of the air gun without the help of a vacuuming unit. The cleaning method, velocity of the air, and rotating speeds of the brushes are shown in Table 1.

Results

Laboratory test with ASHRAE test dust

The amount of dust on the surface of the ducts exceeded 4 g/m^2 before mechanical brushing (MB1) and was below 1 g/m^2 after brushing. The lowest mean

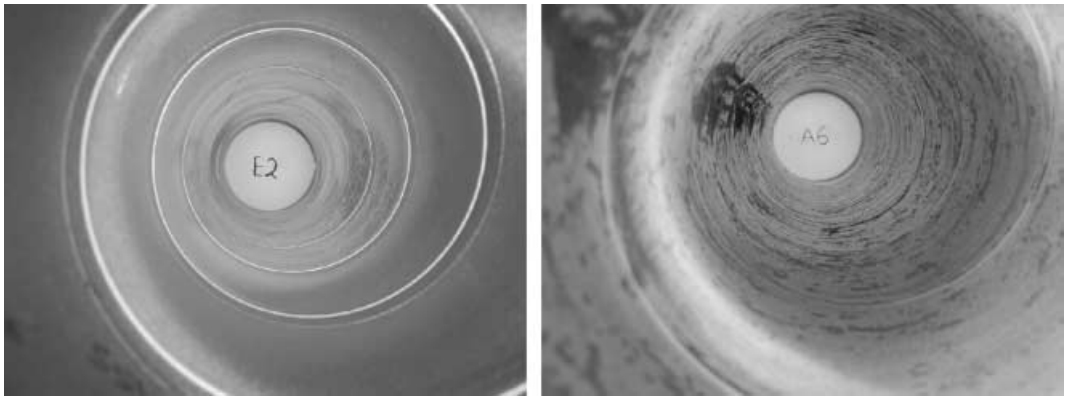

Fig. 3 Inner surface of category P1 duct (left) and category P2 duct (right) after brushing

amount of residual dust was in the category P1 duct (0.2 g/m^2) and the highest in the category P2 duct (0.6 g/m^2). The category P1 ducts looked visually clean (i.e. no residual dust) after brushing. The category P2 ducts had residual test dust which had adhered on the surface of the residual oil (Figure 3, category P2 duct). A thin layer (i.e. researchers were able to observe visually the smooth layer of residual dust on the duct surface) of residual test dust remained also on the inner surface of the plastic duct. In addition, the inner surface of duct after the 90° bend (at the distance 0.5 m) had more residual dust than any other surface of the duct.

Before compressed air cleaning (CAC1), the mean amount of dust on the surface of the ducts exceeded 5 g/m^2 and after cleaning it equalled or was < 1 g/m^2. The lowest mean amount of residual dust was measured in the plastic duct (0.1 g/m^2) and the highest in the category P1 duct (1.0 g/m^2). Visually, there was only a little (i.e. researchers were able to observe visually residual dust on some places of the duct surface) residual dust on the inner surface of the category P1 duct, which was contrary to the measured value (Table 2). The reason for the opposite result was that the dust sample was taken on the duct surface which had visually residual dust. The category P2 duct had a lot of residual dust, which had adhered on the surface of the residual oil. A thin layer of residual test dust remained on the inner surface of the plastic duct and the trajectory of the nozzle could be clearly observed. The duct cleaning time of compressed air cleaning was 1.6–4.7 times longer than the cleaning time of mechanical brushing. The results are summarized in Table 2.

Laboratory test with dust accumulated at construction site

Before mechanical brushing (MB3) the mean amount of dust was equal or higher than 1.0 g/m^2 and after cleaning ≤ 0.1 g/m^2. The P2 ducts looked visually clean after cleaning. Only some water stains or oil residues were observed after mechanical brushing (MB3) and (MB5). The mean amount of residual oil was higher before than after brushing except after mechanical brushing (MB5), in which case the mean amount of residual oil was lower before (33 mg/m^2) than after brushing (52 mg/m^2). However, the mean amount of the oil residue of P2 duct decreased to 44 mg/m^2, which means a 40% decrease from the initial value.

Table 2 Amount of dust before and after duct cleaning as well as cleaning time in laboratory test with ducts contaminated with test dust

	Type of duct and cleaning method								
	Category P1 duct (Ø 160 mm)			Category P2 duct (Ø 160 mm)			Plastic duct (Ø 125 mm)		
Measured parameter	MB1	MB2	CAC1	MB1	MB2	CAC1	MB1	MB2	CAC1
Amount of dust before (g/m^2)	8.6	4.9	7.2	5.8	4.8	5.3	8.7	6.0	6.9
Amount of RO before (mg/m^2)	<2	10	<2	338 (150–618)	216 (164–254)	272 (199–361)		–	–
Amount of dust after (g/m^2)	0.2	0.2	1.0	0.8	0.2	0.7	0.4	0.3	0.1
Cleaning speed (m/min)	3.7	2.3	1.1	4.0	3.1	1.9	5.2	–[a]	1.1
Visual inspection after cleaning	Very thin layer of dust			A lot of residual dust on duct surfaces			Very thin layer of dust		

[a] During the test the low-pressure fan stopped and therefore it was not possible to record the time.
P1 and P2 are the cleanliness categories of the duct (FiSIAQ, 2001).
MB, mechanical brushing; CAC1, compressed air cleaning with the air nozzle; RO, residual oil.

Table 3 Amount of dust and residual oil before and after duct cleaning as well as cleaning time in laboratory test with ducts contaminated at construction site

	Type of duct (Ø 160 mm) and cleaning method				
	Category P2 duct	Category P2 duct	Category P2 duct	Category P2 duct	Category P1 duct
Measured parameter	MB3	MB4	MB5	MB6	CAC2
Amount of dust before (g/m^2)	3.8 (0.1–10.4)	10.1 (8.6–11.2)	1.0 ($<$0.3–1.9)	2.1 (0.4–3.6)	3.5 ($<$0.1–10.1)
Amount of RO before (mg/m^2)	47 ($<$12–87)	102 (35–224)	33 (25–44)	119 (12–274)	9 ($<$12–16)
Amount of dust after (g/m^2)	<0.1	0.1 ($<$0.1–0.2)	<0.1	<0.1	<0.1
Amount of RO after (mg/m^2)	16 ($<$12–27)	23 (14–30)	52 (13–117)	33 (12–64)	15 (12–16)
Cleaning speed (m/min)	3–6	5–8	5–8	5–8	1–3
Visual inspection after cleaning	No residual dust, only some water and residual oil stain	Little residual dust on bottom of duct	No residual dust, only some water and residual oil stain	Little residual dust on bottom of duct	Little residual dust on bottom of duct

P1 and P2 are the cleanliness categories of the duct (FiSIAQ, 2001).
MB, mechanical brushing; CAC2, compressed air cleaning with whipstream nozzle; RO, residual oil.

Before compressed air cleaning (CAC2), the mean amount of dust on the surface of the ducts was 3.5 g/m^2 and after cleaning <0.1 g/m^2. Upon visual inspection, there was only a little residual dust on the inner surface of the category P1 ducts. The mean amount of residual oil was lower before (9 mg/m^2) than after cleaning (15 mg/m^2). However, the increase of the oil residues was insignificant (only 5 mg/m^2). The duct cleaning speed varied from 1 to 8 m/min. The results are summarized in Table 3.

Field tests

In the field tests, the cleaned supply air ducts had no oil residues (a cleanliness category P1 duct defined in FiSIAQ, 2001). Before mechanical brushing the mean amount of dust on the surface of the ducts was 0.8 g/m^2 and after cleaning 0.2 g/m^2. In three buildings, dust samples were also collected from rectangular ducts. The mean amount of dust in the rectangular ducts was 0.9 g/m^2 before duct cleaning and 0.1 g/m^2 after cleaning. Before compressed air cleaning, the mean amount of dust on the surface of the ducts was 5.4 g/m^2 and after cleaning 0.3 g/m^2. According to visual inspection and the measured value, the best results were achieved with mechanical brushing. The measured velocity of the air that carried the dust out from the duct was 3.5–25 m/sec depending on the measuring point and the diameter of the duct. The shape of the duct affected the cleaning time. It was more difficult and slower to clean a rectangular duct than a round duct because the corners of the rectangular duct were difficult to clean properly, especially when the rectangular duct was cleaned with a brush made for a round duct. The duct cleaning speed varied between 0.5 and 10 m/min. The cleaning results are presented in Table 4.

Discussion

The laboratory test facilities with test dust proved to be suitable for the comparison of various cleaning methods, although the composition of the dust differs from that of real dust accumulated at a construction site. Good cleaning results were obtained with all the methods because the test dust had not adhered firmly on the duct surface and, thus, it was easier to remove than impurities that have been for a long time in the duct. Thus the cleaning results may overestimate the efficiency of the methods if they are applied in real environment. After cleaning the ducts in the laboratory test, 1–14% of the accumulated test dust was left on the duct surfaces. In the category P1 and P2 metal ducts, the best cleaning result was achieved by mechanical brushing. The micro-fiber cloth together with the brush whose diameter was 90 mm bigger (36%) than the diameter of the air duct had the best capability to remove dust from the oily (category P2) duct surface. Additionally, the micro-fiber cloth together with the brush provided good cleaning results (0.2–0.3 g/m^2) in each tested duct. It should be noted that the amount of artificially increased oil on the duct surface was several times greater than that typically in the new ducts.

The inner surface of the duct after the 90° bend (at the distance 0.5 m) had more residual dust than the surfaces elsewhere in the duct. This was due to the fact that the whirling arm pushed the brush to the outer surface of the duct after the 90° bend. In order to obtain good cleaning results, the bends should be cleaned by approaching them from both directions.

Because dust did not stick on the category P1 duct and the plastic duct surfaces, compressed air cleaning, without the help of mechanical brushing, removed most of the dust from the duct surfaces. In the plastic air ducts, the least amount of residual dust was measured after compressed air cleaning but compared with the brushing methods it was somewhat slower. Depending on the type of the duct, brushing was 1.6–4.7 times faster than compressed air cleaning. Because the effective air jet of the air nozzle was very narrow, it was difficult to direct the air nozzle in the duct so that the air jet swept every point of the duct. After compressed air cleaning, a spiral track could be seen on the duct surface although the air nozzle was moved at a slower speed than the brush in the duct. In addition, the compressed airflow through the air nozzle generated high noise level which may be a problem in field applications.

Neither mechanical brushing nor compressed air cleaning were effective enough to remove residual oil

Table 4 Amount of dust before and after duct cleaning and cleaning time in field test

	Type of duct and cleaning method				
Measured parameter	MB7 (Ø250–500 mm)	MB8 (Ø250–500 mm)	MB9 (Ø250–315 mm)	MB10 (Ø250–315 mm)	CAC3 (Ø250–315 mm)
Amount of dust before (g/m^2)	0.6 (0.2–1.0)	0.9 (0.3–2.0)	0.8 (0.2–1.9)	0.7 (<0.1–4.0)	5.4 (0.8–17.7)
Amount of dust after (g/m^2)	0.2 (0.1–0.3)	0.2 (<0.1–0.6)	0.1 (<0.1–0.2)	0.1 (<0.1–0.2)	0.3 (0.1–0.5)
Cleaning speed (m/min)	2–10	1–5	2–8	2–8	0.5–1
Used transport velocity (m/sec)	6.5 (4.8–10.1)	5.1 (4.7–5.4)	16.7 (3.5–25)	10.1 (3.6–20.0)	–

MB, mechanical brushing; CAC3, compressed air cleaning with the air gun.

from the duct surface properly. Beside odor emissions (Björkroth and Asikainen, 2000), this is another reason why ducts and their components should be manufactured without oil lubricants. The negative effect of oil residues on the effectiveness of cleaning was noticed only upon visual inspection because not even the dust sampling method was capable of collecting all the dust from the oily surface.

In the laboratory test, in which ducts contaminated at a construction site were cleaned, dust adhered on the duct surfaces more firmly than the test dust had in the laboratory test. After cleaning the ducts, 1–10% of the accumulated dust was left on the duct surfaces. However, all the cleaning methods used decreased the amount of accumulated dust on the inner surface of the ducts to the acceptable cleanliness level of a P1 duct (1.0 g/m^2) (FiSIAQ, 2001). Mechanical brushing was effective enough to remove the settled dust from the duct surfaces. Only water stains and oil residues were observed after cleaning. Compressed air with whipstream nozzle removed dust from the duct surfaces that had no oil residues. Mechanical brushing [expect for mechanical brushing (MB5)] also decreased remarkably the level of oil residues in the P2 ducts manufactured with oil lubrication. On the other hand, the level of oil residues in the P1 ducts, which were manufactured without oil lubricants, increased a little after the compressed air cleaning using a whipstream nozzle. This slight increase in oil contamination may also be included in the variation of the analysis of oiliness of the duct surface (Asikainen and Pasanen, 2000). The whipstream nozzle spread the air in a different way from the air nozzle used in the laboratory test and no spiral track was found on the inner surfaces of the ducts. The whipstream nozzle was rather heavy and it was difficult to move in the horizontal ducts because it is primarily designed for vertical ducts.

After cleaning the ducts in the field tests, 6–25% of the accumulated dust was left on the duct surfaces. The amount of residual dust in the cleaned new air ducts was much less than that obtained in older air ducts (Holopainen et al., 1999). In other previous studies, the decreases in the amounts of residual dust in old ducts were 6–44% of the initial level before cleaning (Ito et al., 1996; Kulp et al., 1997). In this study, the ducts were normally brushed at least twice to achieve a good level of cleanliness. Visual inspection was the primary method for selecting a suitable brush type and for controlling the cleaning result after cleaning. The professional duct cleaners adjusted the air velocity in the ducts from experience to such a level that air transported the loosened dust out of the ducts before duct cleaning started. The measured air velocity was mostly below 10 m/sec, which is lower than the recommended level for industrial dust (ACGIH, 1988). On the other hand, the cleanliness level after duct cleaning was acceptable in spite of the low transport velocity of the air. As a matter of fact, the loosened dust particles were not only transported out of the air ducts with the airflow but also by means of the rotating brush or compressed air jet. One way to make sure that the transport air velocity is high enough is to install T connections to the ductwork so that the low-pressure unit can be connected tightly to the ductwork.

In building (E), the supply air ductwork (20 m) was cleaned with an air gun (Table 1). The air gun is suitable for cleaning the components of an air handling system, such as heat exchange coils, but not for cleaning large ductworks. However, it can be used for cleaning of small area of ductwork.

During the cleaning of rectangular ducts, the brush was rotated clockwise when cleaning the right side of the duct and anticlockwise when cleaning the left side of the duct when looking from the direction of cleaner. The interviewed (professional) air cleaners estimated that the cleaning of a rectangular duct usually takes approximately 1.5–2 times longer time than the cleaning of a round duct.

According to professional cleaners, the optimal rotating speed of the brush for centralizing the brush in the duct is over 500 rpm depending on the diameter and the material of the brush and bristles as well as on the weight of the whirling arm of the brush. However, it is difficult to direct and control the brush in the duct if the rotating speed of the brush is too high. On the other hand, the cleaning efficiency decreases if the speed of the brush is too low. It is easier to guide the brush to the corner of the duct, or in any needed direction, by changing the rotation direction of the brush and using a low enough speed for the brush. Thus, the rotating speed of the brush and the direction of rotation should be adjustable.

The bristles of the brush are normally connected to a spiral frame made of metal wire or in the holes of a frame made of plastic. In practice, the professional cleaning companies most often use a brush whose bristles are connected to the spiral frame. By using this kind of brush it is possible to clean ducts via small openings. The brush whose bristles are connected in the holes of a frame is stiffer than the brush whose bristles are connected to the spiral frame. The results show that the bristles of the spiral frame are efficient enough to remove fine and dry dusts.

The researchers noticed that particles from the building site were sucked into the ducts via the duct openings by the airflow caused by the low-pressure fan during duct cleaning. Air ducts should not be cleaned until all construction work that generates dust into the indoor air has been completed and the rooms of the building have been properly cleaned up. In addition, the duct and its components have to be designed and installed so that the ductwork can be cleaned easily even in completed buildings. It is possible to achieve a high level of cleanliness by mechanical brushing if care

is taken in selecting a suitable brush material for the removal of impurities, using high enough transport air velocities in the ducts during duct cleaning, using a fast enough rotating speed of the brush, brushing the ducts using a slow moving speed of the brush, and making sure that there are no visible contaminants after the cleaning has been performed.

Conclusion

Several methods can be used to remove debris and other surface contaminants from the surface of the ducts. The duct cleaning method should be chosen according to the material of the duct surface and quality of accumulated dust. The oil residues on the inner duct surface make duct cleaning difficult and dry cleaning methods are not efficient enough to remove sticky contaminants. By using mechanical dry cleaning methods it is possible to achieve a cleanliness level below 0.5 g/m^2 in newly installed ducts which have no residual oil from the manufacturing process on their inner surfaces and in which the dust is dry and mainly originates from the construction site. In the laboratory and field tests, the best cleaning result was achieved in the metal ducts with mechanical brushing. The results of compressed air cleaning were good in the new plastic air ducts with recently adhered dust but the cleaning method was slower and noisier compared with the brushing methods. In addition, when compressed air is used for duct cleaning, it must be produced with an oil-free compressor. A properly selected cleaning method is one of the most important factors for achieving a good level of cleanliness.

Acknowledgements

This study was carried out as a part of the Clean Ventilation Systems project funded by the National Technology Agency, Finnish industry and participating research organizations. The Clean Ventilation Systems project is a part of the Finnish Healthy Building Technology Program.

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