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The effect of cleanliness control during installation work on the amount of accumulated dust in ducts of new HVAC installations

Abstract The aim of this study was to evaluate the amount of dust in supply air ducts in recently installed ventilation systems. The samples for the determination of dust accumulation were collected from supply air ducts in 18 new buildings that have been constructed according to two different cleanliness control levels classified as category P1 (low oil residues and protected against contaminations) and category P2, as defined in the Classification of Indoor Climate, Construction and Building Materials. In the ducts installed according to the requirements of cleanliness category P1 the mean amount of accumulated dust was 0.9 g/m^2 (0.4–2.9 g/m^2), and in the ducts installed according to the cleanliness category P2 it was 2.3 g/m^2 (1.2–4.9 g/m^2). A significant difference was found in the mean amounts of dust between ducts of categories P1 and P2 ($P < 0.008$). The cleanliness control procedure in category P1 proved to be a useful and effective tool for preventing dust accumulation in new air ducts during the construction process. Additionally, the ducts without residual oil had lower amounts of accumulated dust indicating that the demand for oil free components in the cleanliness classification is reasonable.

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Practical implications
Protecting the ducts against dust during the construction process and using ducts without residual oil are the best ways to decrease dust accumulation on the air duct surfaces. Other than abrasive cutting methods are recommended to be used for the installation work of HVAC systems. The operational test and the cleaning of HVAC system should not be carried out until all construction work that produces dust ambient air has been completed. The Finnish guidelines (FiSIAQ, 2001) give useful instructions when aiming at the installation of a clean HVAC system. Additionally, instructions to install clean HVAC systems and for all workers at the construction site are needed.

Introduction

Over the past few years, the cleanliness of recently installed HVAC ducts (Luoma, 2000) and old ducts (Pasanen et al., 1992; Fitzner et al., 2000) has been taken into particular consideration. Dust and other impurities of new air ducts originate from manufacturing processes, transportation, storage and construction (Pasanen, 1998). A contaminated supply air system may have an adverse effect on indoor air quality. Laboratory measurements have shown that both new and old components of the air handling system are sources of sensory pollution of the air (Björkroth et al., 1997; Björkroth & Asikainen, 2000).

During the construction period, the contamination of the open-ended air ducts depends on the particle concentration and the time of exposure when dust is carried into the ductwork. Typically, the construction takes time from several months to 1 year and the particle concentration in the building spaces is high for several short periods during construction. For example, during floor grinding, the dust concentration may increase up to 90–2900 μg/m^3 (Luoma, 2000), which is much higher than the concentration in the ambient air. If duct endings are not protected against dust entrance, the ductwork may become so dirty that it should be cleaned before it is accepted for use (Holopainen et al., 2000). Besides particles originated from construction work, the particles formed during installation work easily spread into the duct.

Galvanized sheet metal is the most commonly used material for air ducts and other components of HVAC systems in many countries. Oily processing lubricants are used to decrease friction during the manufacturing process of round air ducts and other components (Pasanen et al., 1995). Sticky oil residuals on the duct surface provide a good adhesive for particles. Some Finnish manufacturers have improved their duct manufacturing processes so that the inner surface of a round duct is free of lubricants (Asikainen & Pasanen, 2000).

The Classification of Indoor Climate, Construction and Building Materials (FiSIAQ, 1995, 2001) is a tool for achieving healthy and comfortable indoor air quality in new buildings. It introduces good design and proper building construction practices as well as wise material selection to achieve good indoor air quality and climate. The classification includes three categories for the indoor climate, S1 to S3; the highest category S1 can be achieved by using M1 classified building materials and by following the instructions of cleanliness category P1. Indoor climate category S3 is in line with the official building codes in Finland. The guideline includes also the cleanliness classification of air-handling components and detailed instructions on how to construct a clean HVAC system. In cleanliness category P1, mostly classified air-handling components have to be used and the special requirements for design and installation of air-handling components should be followed. Cleanliness category P1 also demands the protection of duct endings during storage and transportation, and also after they have been installed. The components used in category P1 should fulfill the oiliness and dustiness values. The limit value for oiliness is ≤ 50 mg/m^2 and for dustiness ≤ 0.5 mg/m^2. In category P2, no specific requirements have been set for maintaining the cleanliness of the ducts and their components.

The aim of this study was to evaluate the effectiveness of different protective actions in achieving a clean supply air duct system in new buildings and to find out the location in the ductwork where most of the dust is accumulated. The amount of dust was measured in air-handling installations built according to category P1 procedures and in installations built according to category P2 without any stated cleanliness demands. The effect of oil residuals on the amount of deposited dust was also analyzed in some of these installations.

Buildings studied

The air-handling systems in 4 day-care centres, two cinema centres, five office buildings and seven schools were chosen for the study. In the construction specifications attention was paid to the cleanliness of the air-handling system. One day-care center, four office buildings and four schools were constructed according to cleanliness category P1. Ducts in category P1 were washed after the manufacturing process and protected against dust accumulation during the transportation, storage and construction phases. The air handling systems were installed in the rest of the buildings according to cleanliness category P2 with two specific instructions for installation: (1) ducts were to be protected with caps on the open ends during construction in three of the buildings, (2) ducts were to be cleaned after the construction phase in four of the buildings. In two of the buildings, no requirements were given on the cleanliness of the ducts. The air-handling systems were typical for new buildings in Finland consisting of a supply air intake grill, a filter unit, a heat recovery unit, a heating coil and a constant or variable air volume air-handling unit. Most of the supply air ducts were round spiral ducts, which were manufactured without oil lubricants. The air-handling units were mostly situated on the top floor of the buildings. In three renovated buildings, the air-handling units were installed on the ground level or basement floors. The supply air intakes were located 2–40 m from the ground. The buildings and their specifications are shown in Table 1.

Measurements

The amount of dust was measured by using the vacuum test method (Holopainen et al., 2001). In category P1 ducts, dust was sampled from 94 sampling sites of which 28 were located near the air-handling unit, 47 in the middle and 19 at the end of the ductwork. In category P2 ducts, dust was sampled from 45 sampling sites; nine of them located near the air-handling unit, 20 in the middle and 16 at the end of the ductwork. The total number of dust samples was 139. In each building, 3–28 samples were taken depending on the total length of the ductwork of the HVAC system. The results were compared between the category of the duct, sampling site in the duct, the shape of the duct and the combined effect of the category and oiliness of the duct. The significance of the results was calculated comparing means (*T*-test) and variances (*F*-test) from the results of Table 3.

Results

Amount of dust in the supply air ducts

Ducts in category P1. The mean amount of accumulated dust was 0.9 g/m^2 and the range 0.4–2.9 g/m^2 ($n_{\text{P1-buildings}} = 9$, $n_{\text{samples}} = 139$). In one case, the protection of the ducts was unsuccessful and the amount of dust was so high after the construction process that the ducts had to be cleaned after measuring. In this building, 28 dust samples were taken, the average dust accumulation was 2.9 g/m^2 and the standard deviation (s.d.) 3.6 g/m^2. When the samples of this building were not included in

Table 1 The type of buildings, the required cleanliness categories of the ducts and specifications for cleanliness of new supply air ducts

The type of building	Cleanliness category and protection	Specifications for the cleanliness of new supply air ducts	Construction site
Day-care center 1	P1	Inspector's control and ducts cleaning if he required	New building
Office 1	P1	Inspector's control and ducts cleaning if he required	New building
Office 2	P1	Inspector's control and ducts cleaning if he required	New building
Office 3	P1	Inspector's control and ducts cleaning if he required	New building
Office 4	P1	Inspector's control and ducts cleaning if he required	New building
School 1	P1	Inspector's control and ducts cleaning if he required	New building
School 2	P1	Inspector's control and ducts cleaning if he required	New building
School 3	P1	Inspector's control and ducts cleaning if he required	Extension part of the main building
School 4	P1	Inspector's control and ducts cleaning if he required	Extension part of the main building
Cinema center 1	P2, ducts were not protected	Ducts were specified to be cleaned after the construction phase	Renovated building
Cinema center 2	P2, ducts were not protected	Ducts were specified to be cleaned after the construction phase	Renovated building
Day-care center 2	P2, ducts were protected against dust with caps on the open ends during the whole construction phase	Inspector's control and ducts cleaning if he required	Renovated building
Day-care center 3	P2, ducts were protected against dust with caps on the open ends during the whole construction phase	Inspector's control and ducts cleaning if he required	New building
Day-care center 4	P2	No requirements were given for the cleanliness of the ducts	New building
Office 5	P2	No requirements were given for the cleanliness of the ducts	New building
School 5	P2, ducts were protected against dust with caps on the open ends during the whole construction phase	Inspector's control and ducts cleaning if he required	Extension part of the main building
School 6	P2, ducts were not protected	Ducts were specified to be cleaned after the construction phase	Renovated building
School 7	P2, Ducts were not protected	Ducts were specified to be cleaned after the construction phase	New building

P1 and P2 are cleanliness categories of the duct (FiSIAQ,1995, 2001)

the results ($n_{\text{samples}} = 111$), the mean amount of dust was 0.7 g/m^2 (0.4–0.9 g/m^2) in the category P1 ducts. The mean amount of dust was almost the same as the set limit value in category P1 (1.0 g/m^2) defined in the Classification of Indoor Climate, Construction and Building Materials (FiSIAQ, 2001).

Ducts in category P2. The mean amount of accumulated dust was 2.3 g/m^2 and the range 1.2–4.9 g/m^2 ($n_{\text{P2-buildings}} = 9$). The lowest dust load was 1.7 g/m^2 (1.3–1.9 g/m^2) in the ducts which were protected during construction work ($n_{\text{P2-buildings}} = 3$) ($T$-test: comparing means with other P2 ducts, $P < 0.186$), whereas the highest amount of dust was 2.8 g/m^2 (1.2–4.9 g/m^2) in the ducts that were specified to be cleaned after installation ($n_{\text{P2-buildings}} = 4$) ($P < 0.171$) compared with other P2 ducts. In the P2 ducts the mean amount of dust was significantly higher ($P_{n=17} < 0.002$; $P_{n=18} < 0.008$) than in the P1 ducts. However, the average of all P2 installations fulfilled the limit value in cleanliness category P2 (2.5 g/m^2). On the other hand, the mean amount of dust was higher than 1.0 g/m^2 in all category P2 ducts. The results are shown in Table 2.

Factors affecting dust accumulation

The amount of dust in the new air ducts was on average 1.3 g/m^2 ($n_{\text{samples}} = 111$; 1.6 g/m^2, $n_{\text{samples}} = 139$). A significant difference was found in the amount of dust between ducts of categories P1 and P2 ($P_{n=111} < 0.002$; $P_{n=139} < 0.051$) and ducts without residual oil (round P1 ducts) and ducts with residual oil (round P2 ducts), i.e. the combined effect of the cleanliness category and oiliness of the duct ($P_{n=62} < 0.0004$; $P_{n=88} < 0.007$). The amount of dust in the category P2 ducts which were protected against dust during the construction process was lower than in the other category P2 ducts but the difference was not, however, significant ($P < 0.263$).

Table 2 The type of buildings, required cleanliness categories of the ducts and measured amount of dust in supply air ducts

The type of the building (construction site)	Cleanliness category	Number of sampling points			The amount of dust in the duct (g/m^2)			
		B	M	E	Mean	s.d.	Min	Max
Day-care center 1 (NB)	P1	2	1	3	0.38	0.40	<0.01	1.10
Office 1 (NB)	P1	3	1	2	0.58	0.41	0.12	1.34
Office 2 (NB)	P1	4	5	4	0.75	0.46	0.20	1.80
Office 3 (NB)	P1	1	0	2	0.60	0.17	0.43	0.77
Office 4 (NB)[1]	P1	16	12	0	2.86	3.63	0.10	16.90
School 1 (NB)	P1	0	12	2	0.76	0.83	0.13	3.08
School 2 (NB)	P1	1	10	4	0.78	0.74	0.20	3.00
School 3 (EB)	P1	0	4	2	0.92	0.68	0.30	2.00
School 4 (EB)	P1	1	2	0	0.57	0.08	0.52	0.67
Mean P1					0.91 (0.67)[2]			
Cinema center 1 (RB)	P2	0	2	6	1.20	0.69	0.10	2.53
Cinema center 2 (RB)	P2	2	5	0	1.32	1.00	0.11	2.50
Day-care center 2 (RB)	P2	0	1	2	1.87	1.07	1.12	3.09
Day-care center 3 (NB)	P2	1	1	4	1.30	2.08	0.23	4.73
Day-care center 4 (NB)	P2	0	2	3	3.08	3.64	0.04	8.37
Office 5 (NB)	P2	0	2	1	1.30	1.09	0.08	2.18
School 5 (EB)	P2	0	3	0	1.91	2.36	0.50	4.63
School 6 (RB)	P2	4	2	0	3.76	7.65	0.42	19.38
School 7 (NB)	P2	2	2	0	4.92	8.19	0.19	17.14
Mean P2					2.30*,†			

EB = extension part of the main building, NB = new building, RB = renovated building.
B = located near the air-handling unit, M = located in the middle of the ductwork, E = located near the end of the ductwork.
[1] Protection against dust was unsuccessful.
[2] The mean that included the building which protection was unsuccessful are not included.
* *T*-test: Comparing means of cleanliness category P1 and P2; $P < 0.008$ ($P < 0.002$)[2].
† *F*-test: Comparing variances of cleanliness category P1 and P2; $P < 0.063$ ($P < 0.0001$)[2].

Ducts in category P1. The highest mean amount of dust (1.9 g/m^2) was found near the air handling unit, and the lowest (0.7 g/m^2) at the end of the ductwork ($P_{n=47} < 0.073$). Omitting the samples from the building where the protection against dust was unsuccessful (office 4 in Table 2), the highest mean amount of dust was 0.8 g/m^2 in the middle of the ducts and lowest (0.5 g/m^2) near the air handling units ($P_{n=47} < 0.105$). In category P1, the mean amount of dust was higher (1.5 g/m^2) in the round ducts than in the rectangular ducts (0.7 g/m^2) ($P_{n=94} < 0.090$). The amount of dust at different locations of category P1 and P2 ducts is shown in Figure 1.

Ducts in category P2. The highest mean amount of accumulated dust (3.3 g/m^2) was found in the middle of the ducts and lowest (0.6 g/m^2) near the air handling units ($P_{n=29} < 0.076$). In the round ducts, the mean amount of dust was 4.1 g/m^2, which was almost threefold the amount in the category P2 rectangular ducts (1.5 g/m^2) ($P_{n=45} < 0.020$). The results are summarized in Table 3.

Discussion

Dust accumulation in air ducts during the installation period leads commonly to accumulation levels of several grams per square meter of duct surface. The average levels in the systems with minor protection were about half of those found in the supply air ducts of recently built buildings (5.0 g/m^2) (Pasanen, 1998). The efficiency of the protection of duct endings with caps was documented by the low amount of dust in the P2 category ducts. Thus, dust accumulation into the duct can be partly avoided by duct protection during the whole of the construction phase. Especially, benefits are achieved during phases when the particle concentration is very high in the air at the building construction site (Luoma, 2000). However, the results showed that protection by capping the open ends during construction phases is not the only way to decrease dust accumulation during construction. The measured amount of dust in the air ducts installed according to the requirements of cleanliness category P1 was more than two times smaller compared with those installed according to category P2 requirements. The results obtained were similar to those of Björkroth et al. (2000). Their study showed that the amount of dust accumulated at the construction site on the category P2 duct (oily) surfaces was approximately twice as high as on the category P1 duct surfaces. They concluded that the mean amount of oil residuals was approximately eight times higher in the category P2 duct than in the category P1 duct.

Surprisingly, the amount of dust was highest in the category P2 ducts which were specified to be cleaned after the construction phase. In some cases, the large amount of dust indicated that the HVAC systems were

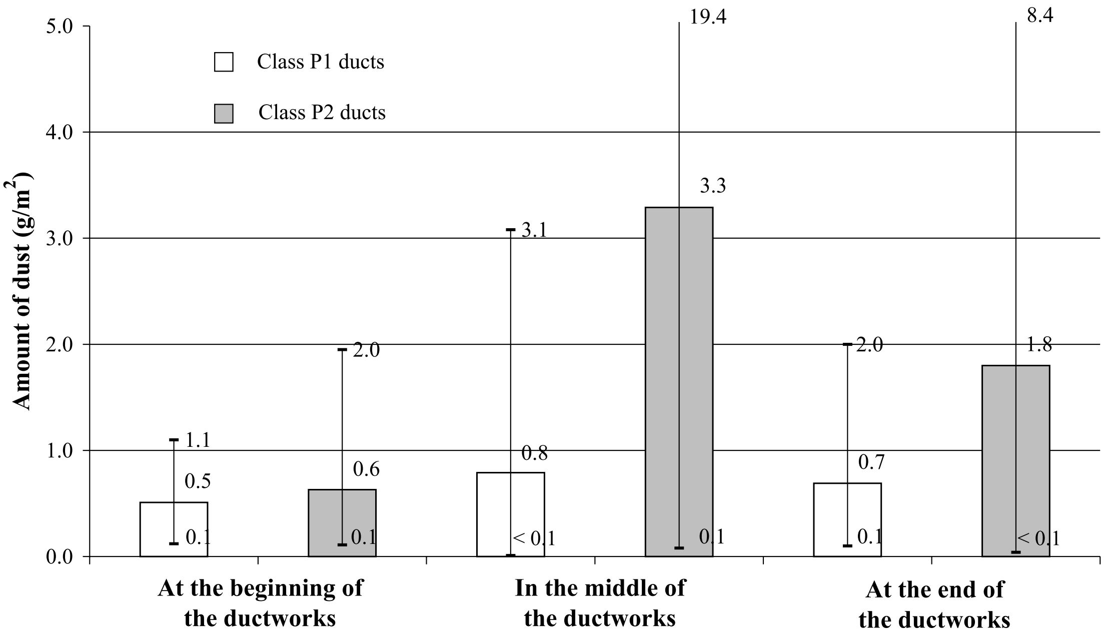

Fig. 1 The mean amount of dust and the range in cleanliness categroy p1 and p2 ductworks

Table 3 The results of average dust accumulation in the air ducts

Sampling sites	No of buildings/ Sample points		Average		s.d.		Min		Max	
Cleanliness category	P1	P2	P1 (g/m²)	P2 (g/m²)	P1 (g/m²)	P2 (g/m²)	P1 (g/m²)	P2 (g/m²)	P1 Max (g/m²)	P2 Max (g/m²)
All samples	9/94	9/45	1.35	2.21	2.25	3.86	< 0.01	0.04	16.90	19.38
All samples[1]	8/66	9/45	0.71	2.21*·†††	0.61	3.86	< 0.01	0.04	3.08	19.38
Beginning	7/28	4/9	1.92	0.63***·†††	3.56	0.53	0.10	0.11	16.90	1.95
Beginning[1]	6/12	4/9	0.51	0.63	0.29	0.53	0.12	0.11	1.10	1.95
Middle	8/47	9/20	1.28	3.29	1.53	5.33	< 0.01	0.08	7.90	19.38
Middle[1]	7/35	9/20	0.79	3.29*·†††	0.74	5.33	< 0.01	0.08	3.08	19.38
End	7/19	5/16	0.69	1.75	0.49	2.08	0.10	0.04	2.00	8.37
End[1]	6/19	5/16	0.69	1.75	0.49	2.08	0.10	0.04	2.00	8.37
O	9/77	6/13	1.50	4.05*·†††	2.46	6.76	< 0.01	0.10	16.90	19.38
O[1]	8/51	6/13	0.74	4.05**·†††	0.67	6.76	< 0.01	0.10	3.08	19.38
R	5/17	6/32	0.68	1.46	0.40	1.21	0.12	0.04	1.50	5.31
R[1]	4/15	6/32	0.63	1.46*·†††	0.38	1.21	0.12	0.04	1.50	5.31
NRO	9/94	6/32	1.35	1.46	2.25	1.21	< 0.01	0.04	16.90	5.31
NRO[1]	8/66	6/32	0.71	1.46***·†††	0.61	1.21	< 0.01	0.04	3.08	5.31
RO	–	6/13	–	4.05[2]	–	6.76	–	0.10	–	19.38

O = round duct, R = rectangular duct.
NRO = without residual oil, RO = with residual oil.
[1] The samples that included the building which protection was unsuccessful are not included.
[2] The samples were collected from the round ducts of the cleanliness category P2.
T-test: Comparing means of cleanliness category P1 and P2; *$P < 0.01$, **$P < 0.001$, ***$P < 0.0001$.
F-test: Comparing variances of cleanliness category P1 and P2; †††$P < 0.0001$.

cleaned too soon after installation and in other cases the systems were not cleaned at all. In the latter cases, more attention should be paid to the inspection of the HVAC systems which have been mentioned in the agreements.

In this study, 43% of the HVAC systems of the school buildings, 75% of the day-care centres and all the cinema centres were installed according to cleanliness category P2 whereas only 20% of the HVAC systems of the office buildings were installed according to cleanliness category P2. This indicates that companies with a good economy prefer to order good indoor air quality while most of the public buildings are built according to a lower standard.

Much dust may accumulate into the ducts if the operation test of the HVAC system has been carried out when the particle concentration is high at the building site. Based on visual inspection, it seemed that dust in some of the new supply air ducts originated from dust generating work after installation. The ducts should be protected during the whole of the construction process and the operation test as well as the cleaning of the HVAC system should not be carried out until all construction work that produces a lot of particles into ambient air has been completed (FiSIAQ, 2001).

At present, the abrasive cutting machine is commonly used for duct installation work. However, the cutter machine and plate shears, which do not produce much steel filings, should be used instead of the abrasive cutting machine. According to visual evaluation, some of the samples which were taken close to the inspection door in the middle of the ductworks contained a lot of steel filings because the ducts had been cut with an abrasive cutting machine. The density of steel is much higher than that of dust, and it increased the mass of the samples considerably. The cutting technique used for round air ducts may be one of the reasons why the dust accumulation is higher in round air ducts compared with rectangular air ducts.

The results showed that the limit value of 1.0 g/m^2 for accumulated dust, set as the criterion for cleanliness category P1, is realistic to achieve if the ducts are carefully protected against dust in all phases from the factory to the completion of the building. However, new methods are needed for cutting the ducts so that the steel filings are not spread into the ducts. The results also indicated that if no effort is made to protect the ducts, the amount of accumulated dust in the ducts is almost twice as high as in the protected ducts.

The results of this study showed that the Finnish guideline (FiSIAQ, 2001) gives useful instructions when aiming at the installation of a clean HVAC system. The results indicate that protection against dust during the construction process and using ducts without residual oil are the best ways to decrease dust accumulation on the air duct surfaces. Additionally, the clean installation method does not take much more time than the traditional installation method. When the clean installation method is used, more instructions and control for the mechanics installing the HVAC system and for all the employees at the construction site are needed. Before starting the construction work, a 1-day training should be arranged for all the employees in order to give them specific information and instructions on achieving the defined cleanliness category of the HVAC system.

Conclusion

The results of this study showed that the amount of dust was significantly lower in the category P1 ducts than in the category P2 ducts. The amount of dust in the category P2 ducts which were protected against dust during the construction process was lower than in the ducts that were not protected. The round category P2 ducts that had residual oil on the inner surfaces and were not protected against contamination collected approximately three times more dust than the round category P1 ducts without residual oil. Therefore, ducts should be manufactured using a method in which the inner surface of the duct has no residual oil. Furthermore, the ducts should be protected against impurities during transportation, storage and construction. Especially in the round ducts, steel filings were found close to the openings where ducts have been cut with an abrasive cutting machine.

The results indicate that guidelines on construction cleanliness are needed by the contractors to ensure the high quality of the HVAC system during construction process. All the participants at the construction site should pay more attention to the clean installation method of the HVAC system.

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