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Definition of cleanliness: Ducts

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Contents

1. Abstract

The result of the first report the literature review about maintenance guidelines [25] was that it is very important to define a new maintenance guideline for HVAC systems.
The existing guidelines typically do not address the full spectrum of critical factors. Some of them lack precise specifications about cleanliness and precise working procedures.
Thus, the new maintenance guideline should be a mix of existing guidelines and results from the investigations about cleanliness and related working procedures. Therefore in this report the definition of cleanliness for ducts and humidifiers will be found.

2. Ducts

2.1. Introduction

Nowadays humans spend up to 90% of their time indoors. Thus, the quality of indoor air has become an important factor for their well-being and comfort. In the 1970's work related symptoms of employees became recognized, the so-called sick-building-sydrom (SBS). The World Health Organization stated that, besides other factors such as harmful contaminants from building construction, peoples activities and outdoor sources, the hygiene of heating, ventilation and air conditioning (HVAC) systems is an important factor in maintaining good indoor air quality (IAQ), particularly when it is considered that the energy crisis in the early 1970's forced building owners to operate HVAC-systems with reduced airflow rates in order to save energy costs (WHO, 1984).

The two types of HVAC-system components that have mainly been suspected as sources of indoor air pollution are either those components where sufficient moisture for microbial activity and growth is present, such as humidifiers (Baur, 1989; Roßkamp, 1994) or those where particles and microorganisms deposit and may accumulate during operation, mainly filters (Möritz, 1996; Elixmann, 1989; Bottlinger and Nagel, 1993).

Similar to their behavior on filters particles and microorganisms deposit and accumulate in ventilation ducts of HVAC-systems, though to a much lesser extend (Küchen, 1998). However, due to the long installation time (up to several decades) and the large inner surface (about 10 % of the floor area in office buildings, Pasanen, 1998) of ventilation ducts, a significant amount of dust may accumulate mainly on the bottom surface of ventilation ducts and may promote the survival and growth of microorganisms for the following reasons:

- the dust layer reduces the contact of microorganisms to the sheet metal surface of the ducts which is known to have an adverse affect on their survival (Müller, H., 1995).
- it may act as a source of nutrients (Möritz and Rüden, 1996; Sugawara, 1998).

As a consequence of enhanced conditions of growth and survival, metabolitic products, spores or even viable cells can be released into the supply air and cause health problems to occupants of the buildings. Another aspect is the release of lysisproducts from the decay of dead microorgansims, mainly endotoxins from gramnegative bacteria which are reported to be responsible for allergic reactions during inhalation (Möritz and Rüden, 1995).

In the following chapters, this report gives an overview on the mechanisms of deposition of particles in air ducts (**chapter 2.2**), the existing level of pollution in and from ducts and the current guidelines on the cleanliness of ventilation ducts required to maintain acceptable IAQ based on the literature on air duct research (**chapter 2.3**). Afterwards (**chapter 2.4 and 2.5**) methods and results of the research of TUB are provided. **Chapter 2.6** contains a definition of cleanliness concluded from own research activities, the literature review and the current guidelines. Finally proposals are made on how to maintain an acceptable level of cleanliness in ventilation ducts (**chapter 2.7**).

2.2. Deposition Mechanisms of Particles in ventilation ducts

Apart soil debris from construction and oil residues from duct manufacture as sources of impurities that can be avoided prior to operation of a HVAC-system, microorganisms and non-viable particles suspended in the supply air deposit on the duct surface and accumulate during operation. This deposition requires the particles to be transported from the air stream sufficiently close to the duct surface in order for adhesive forces between surface and particles to take effect. The key mechanisms of transport of particles to the duct surface have been under intensive investigation, particularly with regard to clean room issues. These major mechanisms shall be briefly discussed below.
Depending on the size of the particles and the characteristics of the air flow (degree of turbulence) transport to the duct surface is driven by the following four mechanisms (Kvasnak et al. 1993):

(1) gravitational sedimentation

(2) turbulent impaction

(3) Brownian diffusion

(4) turbulent diffusion

Whereas large (micron-sized-) particles are mainly affected by the mechanisms (1) and (2), small particles are mostly influenced by mechanisms (3) and (4) (Baron and Willeke, 1993). At low flow regimes large (micron-sized-) particles settle on the bottom surface of the duct mainly due to gravitational sedimentation (1), whereas the transport of smaller (submicron-sized-) particles is mainly driven by Brownian diffusion. The orientation of the duct surface is less important with increasing degree of turbulence where turbulant impaction (2) and diffusion (4) processes dominate the deposition of large and small particles, respectively (Kvasnak et al., 1993).
The latter two mechanisms explain, why with increasing air velocity (Lengweiler et al, 1997; Fransson, 1996), surface roughness or in flow obstacles (bends, diffusers, dampers etc.) (Wallin, 1993) the dust load on walls and ceiling of the duct increases, which has been shown through dust measurements by Ito et al. (1996). On the other hand, particles require a sufficient time for transport to the duct wall, depending on their size and subsequently their terminal settling velocity, so that increasing velocity decreases the overall deposition rate, as the particles will have penetrated the duct prior to being transported to the surface (Adam et al., 1996).
In general, as existing calculation models (Wallin, 1993; Kvasnak et al. 1993) and laboratory studies (Adam et al., 1996) show, the particle concentration in the air (either gravimetric or number related) is the basic parameter influencing the dust surface concentration, whereas other parameters (flow velocity, degree of turbulence, surface roughness, duct geometrie) merely affect the deposition rate, i.e. the fraction of airborne particles that settles on the duct surface. As a consequence it is obvious that if more particles pass the ventilation filters and enter the duct system the surface dust concentration can expected to be higher.

2.3. Literature Review

Since the late 1980’s an increasing number of authors have been publishing reports on the hygiene of ventilation ducts. In the various studies quite a large spectrum of parameters have been determined, mainly the surface concentration of dust and microorganisms (fungi and bacteria) on the bottom of the duct, but also the quality of the supply air (particles, microorganisms, TVOC, Odour a.o.).

Surface dust has been quantified by a various measurement methods and most of the target values for dust in ventilation ducts in existing guidelines refer to a certain specified dust sampling method (**chapter 2.7**). A short description of the existing methods was already given by Müller, B. (1998a). A more comprehensive description can by found in Gresens (1998). This chapter gives an overview of the pollution level of ventilation duct surfaces based on the studies examined and summarizes some of the basic findings of the existing reports regarding the impact of accumulated debris in ducts on supply air quality.

2.3.1 Existing levels of pollution of ventilation duct surfaces

2.3.1.1. Existing levels of dust

In the studies published on surface dust concentration in ventilation ducts, various methods with different detection efficiencies were used. In an early study of Nielsen et al. (1990) the dust was removed with a rasor blade and collected on a filter by means of a vacuum pump. Other scandinavian researchers used plastic blades to loosen the dust (Laatikainen et al., 1991; Pasanen, 1994), whereas in the USA and Canada only the suction from a vacuum pump alone serves to remove the dust from the duct surface (Auger, 1994; Fortmann et al., 1997). Dust is also removed by wiping with a cloth (Ito et al., 1996) or by adhesive tape (Fransson et al., 1995).

With all the methods mentioned above the dust is removed from a defined area of the duct surface and the concentration is determined gravimetrically as weight per surface area in [g/m²]. Other methods include the measurement of dust thickness (HVCA, 1998) or the percentage reduction of light transmission through a transparent adhesive tape contamimated with dust compared to its clean state (Fransson et al., 1995; Yoshizawa et al., 1997; Holopainen et al. 1999).

The following table summarizes the results of the existing studies (Table 1). It can be seen that dust surface concentration can be as high as 158 g/m² and efficiencies of detection of the different methods vary greatly between < 1% to 100%. Apart from factors as filter class, age, location, operation time and particle deposition mechanisms, factors that are quite specific for each duct under investigation, it is important to point out that different measurement methods will as well yield entirely different results even in the same ventilation duct. Therefore, if a definition of cleanliness is to be defined with regard to the surface dust concentration in ventilation ducts, the different detection efficiencies of the various methods have to be taken into account. A further obstacle is the poor correlation between most of the methods (Yoshizawa et al, 1997; Fransson, 1995; Holopainen, 1999), which is due to the little reproducibility of many of the methods and to differences in rigidness of the dust layer (Gresens, 1998; Küchen, 1998).

Table 1: Summary of dust surface concentration levels from various studies

Type of building	n	Age	Filter class range	mean	range	Annual deposition rate	Method	Efficiency(3) of detection	Source
		[Jahre]	[EU]	[g/m²]	[g/m²]	[g/(m²xa)]		[%]	
school, office	13	3 to 29	n.r.	6,8	1,1 to 50,9	0,7(2)	vacuum, rasor blade	100	Nielsen et. al. (1990)
school, office	6	5 to 11	2 to 7	18,2	3,6 to 140	2,3	vacuum, plastic blade	n.r.	Laatikainen et. al. (1991)
publ. Buildings	6	7 to 51	5 to 7	10,6	1,2 to 58,3	3,5	vacuum, plastic blade	n.r.	Pasanen et. al. (1992)
Residential	33	0 to 45	n.r.	0,2	<DL to 2,7	<0,1	vacuum (NADCA)	< 1 (47 bis 92)	Auger (1994)
Office	14	3 to 34	2 to 7	13,2	1,2 to 158	1,0	vacuum, plastic blade	n.r.	Pasanen (1995)
Residential	23	2 to 16	3 to 5	1,2(1)	0,2 to 3,9	n.r.	vacuum, brush	n.r.	Kalliokoski et. al. (1995)
n.r.	5	19 to 37	2 to 6	2,6	1,9 to 3,0	0,2 bis 0,3	Tape	38	Fransson et. al. (1995)
n.r.	4	22 to 32	n.r.	7,5	n.r.	n.r.	Wiping with cloth (JADCA)	90	Ito et. al. (1996)
Residential	9	9 to 35	n.r.	6,4	1,5 to 26,0	n.r.	vacuum (MVDS)	(94)	Fortmann et. al. (1997)
day-care centers	3	< 1	n.r.	n.r.	0,04 to 8,4	n.a.	vacuum	n.r.	Holopainen et al. (1999)
publ. Buildings	13	3 to 30	3 to 9	18,8	4,0 to 131	1,1	New method with solvent	100	Küchen (1998)
publ. Buildings	17	3 to 30	3 to 9	7,0	0,2 to 82	0,5	Wiping (JADCA)	41	Küchen (1998)
publ. Buildings	12	3 to 30	3 to 9	1,9	<DL to 21	0,2	vacuum	12	Küchen (1998)

Notes:
(1) dust concentration calculated based on whole duct area
(2) refers to a operation time of one year
(3) Values in parenthesis for loose (soft) dust layer (Fortmann et al.,1997)
Values without parenthesis reported by Fransson et al. (1995)
Values for JADCA-wiping method reported by Yoshizawa et al. (1997)

n.r. not reported
DL Detection Limit
JADCA Japanese Air Duct Cleaners Association method (Ito et al., 1996)
NADCA National Air Duct Cleaners Association method (NADCA, 1992)
MVDS Medium Volume Dust Sampler by US EPA (Fortmann et. al. 1997)

2.3.1.2. Existing Levels of Microorganisms

Similar to the preceding part of this report, this section intends to provide a short overview on the surface concentration of microorganisms in ventilation ducts as reported in the literature. The quantification of microorganisms is undertaken by one of the following three methods:

- **Contact plate method**: An agar plate is pushed directly onto the duct surface which causes microorganisms to adhere to the agar; the plates are then incubated and the colony forming units (CFU) are counted (Laatikainen et al., 1991; Auger, 1994).
- **Swab method**: A cloth (Tarvainen et al., 1994, Fortmann et al, 1997) or other material [e.g. a Q-Tip (Sverdrup and Nyman, 1990)], usually wetted with a sterile saline solution, is used to remove microorganisms from the surface by wiping; afterwards the microorganisms are eluted into the same solution (e.g. physiological Sodiumchloride-solution) and plated onto agar for analysis.
- **Cultivation of dust directly:** A sufficient amount (e.g. 0,5 g) of dust is taken from the duct surface and directly suspended in solution (Kalliokoski et al, 1995; Pasanen, 1995; Nielsen et al., 1990), which is later plated on agar.

Although there are only three different basic methods, it has to be stressed that comparable to the dust sampling, the analysis of microorganisms in ventilation ducts are in detail quite different with regard to other factors such as incubation time, incubation conditions (rel. humidity, temperature) and composition of agar media. Table 2 summarises the quantities of molds and bacteria as reported in various studies. Note that, depending on the basic method applied in the studies, the concentrations refer either to the dust mass (CFU/g → direct cultivation from dust) or to a unit area of the duct surface (CFU/m² → swab and contact agar methods).

Table 2: Summary of surface concentration levels of viable moulds and bacteria from various studies

Type of building	n	Age	Filter class range	dust conc. range	moulds range	bacteria range	Method	Source
		[years]	[EU]	[g/m²]	x 1000	x 1000		
offices, day-care	6	n.r.	2 to 7	n.r.	0,001 to 0,015 CFU/m²	0,001 to 0,022 CFU/m²	Swab	Nyman + Sandström (1990)
school, office	6	5 to 11	2 to 7	3,6 to 140	0,2 to 23 CFU/m²	0,5 to 36 CFU/m²	contact plates	Laatikainen et. al. (1991)
Operation theatres	6	n.r.	n.r.	n.r.	0,8 to 60 CFU/m²	1,2 to 320 CFU/m²	Swab	Tarvainen et al. (1994)
Residential	33	0 to 45	n.r.	<DL to 2,7	<DL to 80 CFU/m²	<DL to 320 CFU/m²	contact plates	Auger (1994)
Residential	9	9 to 35	n.r.	1,5 to 26,0	13 to 250 CFU/m²	0,005 to 1,5 CFU/m²	Swab	Fortmann et. al. (1997)
Public buildings	16	3 to 9	3 to 9	<DL to 131	<DL to 44 CFU/m²	<DL to 44 CFU/m²	contact plates	Küchen (1998)
school, office	13	3 to 29	n.r.	1,1 to 50,9	0,07 to 6,2 CFU/g	0,05 to 5 CFU/g	direct cultivation	Nielsen et. al. (1990)
Office	8	4 to 31	5 to 7	1,2 to 58,3	0,2 to 2,3 CFU/g	<DL to 10 CFU/g	direct cultivation	Pasanen (1992)
Office	14	3 to 34	2 to 7	1,2 to 158	0,3 to 24 CFU/g	n.r.	direct cultivation	Pasanen (1995)
n.r.	12	n.r.	n.r.	n.r.	0,2 to 1500 CFU/g	10 to 100 CFU/g	direct cultivation	Sugawara (1996)
Office	7	n.r.	n.r.	n.r.	2 to 6 CFU/g	n.r.	direct cultivation	Kumagai et al. (1997)
Residential	23	2 to 16	3 to 5	0,2 to 4,3	20 to 2,7x 10^4 CFU/g	n.r.	direct cultivation	Kalliokoski et. al. (1995)*
Residential	24	2 to 16	3 to 5	0,2 to 4,3	4 x 10^4 to 3.3 x 10^5 CFU/g	n.r.	two-phase system	Pasanen et al. (1997)*

Table 2 shows great differences in the concentrations of fungi and bacteria in ventilation ducts in an overall range between the detection limit and 2,7 x 10^2 CFU/g from direct cultivation and 3,2 x 10^5 CFU/m^2 from the methods referring to unit surface area. Some factors generally increasing concentrations of microorganisms include moist conditions and air recirculation Nielsen et. al. (1990). Dust surface concentrations appear to have little influence on concentrations of viable microorganisms indicating that the survival time of bioaerosols after deposition on the duct surface is generally short, but further study is required on this aspect (Küchen, 1998).

Bacterial contamination in ducts is generally lower than in other components such as rotating heat exchangers (10^7 CFU/m^2, Nyman and Sandström, 1991), cooling coils (10^7 CFU/m^2) or humidifiers, and it appears to decrease with increasing height of the air intake. Moist or wet insulation material was also found much higher contaminated with both bacteria and moulds (10^7 to 10^9 CFU/m^2). The main fungal species in dust from air ducts are *Penicillium, Cladosporium, Aspergillus, Aureobasidium and Alternaria,* originating basically from the outdoor environment (Pasanen, 1998).

Another aspect is the comparison of viable and total concentrations of microorganisms as investigated by Pasanen et al. (1997) for moulds (shaded area in Table 2). It has been shown that the viable proportion of moulds was less than 5 % in dust accumulated in ventilation ducts, indicating that conventional cultivation methods may not reveal the full allergenic potential of dust settled in air ducts (Pasanen et al., 1997).

2.3.1.3. Factors influencing the concentration of dust and microorganisms on the surface of ventilation ducts

Some studies aimed to investigate the factors which influence the level of pollution in ventilation ducts regarding dust and microorganisms (Laatikainen et al., 1991; Pasanen, 1995; Küchen, 1998), others focused on the conditions supporting survival and growth of microorganisms (Pasanen et al., 1993; Pasanen et al., 1995; Chang et al., 1996; Jantunen et al., 1998).

As a short summary of the results of these studies, **Table 3** shows the factors of influence in the first column and the impact of an increase of these factors on the surface concentrations of dust and microorganisms in the second and third column. It has to be emphasized that the table serves only as an orientation to show qualitative trends rather than correlation’s of statistical significance.

Table 3: Factors influencing the concentration of dust and microorganisms on the surface of ventilation ducts as derived from various studies

Factors: Increase of:	Influence on the Concentration of:	
	dust	Mikroorganisms
outdoor air concentration of particles and microorganisms	↑	↑
filtration efficiency*	↓	↓
operation times / age of duct	↑	--
availability of water (rel. humidity, water condensation)	--	↑
air velocity	--	↓
nutrients	--	↑

Notes:
* = Number of Filter units, Filter class
↑ **= Increase**
↓ **= Decrease**

2.3.4 Impact on Air Quality and effects of duct cleaning

Some of the studies reviewed deal with the impact of dirty air ducts on supply air quality (Fransson et al. 1995; Björkroth et al., 1997; Foarde et al., 1998), while others identified the effect of duct cleaning, i.e. the values of selected parameters before and after cleaning of ducts were compared (Auger, 1994; Fortmann et al., 1997; Kumagai, K. et al., 1997; Ishikawa, 1996; Yoshizawa et al., 1997).

For filters it is reported that odour emission increases with dust load, is higher for the coarse fraction (dp $\geq$ 10 µm) of particles and variates seasonally (Pasanen et al., 1994). In air ducts, odour emissions have been reported to stem from both oil residues from fabrication and dust deposit (Björkroth, 1997) as well as metabolism of deposited fungi (Kumagai et al., 1996). Laboratory studies conducted at TUB and BJÖRKROTH indicated that the odour of air ducts generally decreases with air flow rate, increases with length, and, more importantly, that ducts without oil residues smelled less than ducts with oil residues. Furthermore glass ducts were found to be less odour intensive than spiral wound or flexible aluminum ducts (Müller, B., 1998a; Björkroth, 1999).

Duct cleaning has been reported to reduce odour (Ishikawa et al., 1996, Björkroth et al., 1997, Karpen, 1996) and the concentration of volatile organic compounds (VOC’s) (Kumagai et al., 1996). On the other hand, air ducts can be a sink of odour (Finke and Fitzner, 1993), which is confirmed in part by the laboratory studies at TUB and BJÖRKROTH where those ducts which had no oil residues showed a decrease of odour with length. Besides, odour emission from HVAC-systems is mainly caused by filters, rotary heat exchangers, humidifiers and air recirculation (Finke and Fitzner, 1993; Pejtersen et al., 1989).

Another aspect to be considered is the resuspension of particles and microorganisms from the duct surface back into the supply air stream. An interesting finding from a laboratory-study of Foarde et al. (1998) was that high flow velocity and low relative humidity of the air increased the rate of resuspension of spores of a test fungus (*Penicillium chrysogenum*) into the air flow.[1]

The same effect was studied in supply ducts in Tokio during disturbed conditions, i.e. when the fan is turned on and off intermittently. It was shown that the number of particles at the air outlet increased by about an order of magnitude within a period of five minutes after the fan was turned on because of resuspension. After duct cleaning, this effect was greatly reduced, particularly for the large size fractions (dp $\geq$ 2 µm) (Yoshizawa et al., 1997).

Auger et al. (1994) and Fortmann et al. (1997) did research on the effect of duct cleaning on the concentrations of particles and microorganisms in the supply air and on the duct surfaces under normal operation. The results from the studies are not in good agreement. Whereas Auger (1994) found no significant decrease of dust concentration on the duct surfaces by cleaning, in the study of Fortmann et al. (1997) a significant decrease, as would be expected, could be shown. Concentrations of microrganisms on the duct surface decreased only insignificant, except for moulds in the study of Fortmann et al. (1997). A decrease of mould concentrations through cleaning was also reported by Morey (1995). The concentrations of particles and microorganisms in the air decreased only insignificant after cleaning, this time with exemption of total CFU/m^3 (Sum of moulds and bacteria) in the study of Auger (1994). It was not mentioned in any of the three reports what time interval lay between duct cleaning and the measurement of surface microorganisms.

2.3.5. Existing Guidelines

A comprehensive review of the existing guidelines on maintenance was given by Müller, B. (1998b). In this section, only those guidelines and recommendations in the literature are shortly summarized, were values on the hygienic aspects of air ducts are mentioned, together with some recommendations on the hygienic quality of room air. The values are shown in Table 4 and discussed below.

[1] In theory, a significant external energy is required for resuspension to occur because of the adhesion forces between particle and duct surface. The higher the air velocity, and consequently turbulent energy and aerodynamic drag, and the rougher the surface (further increasing drag forces) the more likely resuspension of deposited particles is to occur. On the other hand, adhesion forces are significantly increased if the surface is wet with oil or water or if an interstitial water film has formed under high humidity conditions (Foarde et al., 1998).

Table 4: Current target values on the hygiene of air ducts and room air.

Surface Dust					
Country	**Duct used for**	**Dust-Values**		**Method**	**Remarks (Source-No.)**
		after Cleaning	**prior to Cleaning**		
USA	(1)	0.1 g/m²		Vacuum Method NADCA	Guideline (1)
Great Britain	Supply Air Recirculating Air Exhaust Air	0.1 g/m²	1 g/m² 60 µm 1 g/m² 60 µm 6 g/m² 180 µm	Vacuum Method HVCA(3) Vacuum Method HVCA(3) Vacuum Method HVCA(3)	Guideline (2)
Sweden	Supply Air		1 g/m²	not mentioned	Ordinance (4)
Japan	Supply Air	1 g/m²		Wiping Method JADCA	Guideline (5)
Finland	Supply Air		2 g/m² 5 g/m²	Scrape-/Vacuum Method	Guideline (6)
Germany	general	broom-clean		Scrape -/Vacuum method	Guideline (7)

Surface Microorganisms					
Country	**type of dust**	**MO-type (category)**	**MO-Value**	**Method**	**Remarks (Source-No.)**
Scandinavia	floor dust!	Moulds (low risk) (medium risk) (high risk)	 < 1.000 CFU/g 1-3.000 CFU/g > 3.000 CFU/g	direct cultivation	Proposal (8)
Scandinavia	floor dust!	bacteria (low risk) (medium risk) (high risk)	 < 6.000 CFU/g 6-10.000 CFU/g > 10.000 CFU/g	direct cultivation	Proposal (8)
USA	dust in air duct	moulds bacteria	< 15.000 CFU/g < 30.000 CFU/g	direct cultivation	Proposal (9)

Surface Residual Oil, man-made mineral fibres, dust and PAQ of new(!) ducts					
Country	**description**	**parameter**	**Value**	**Method**	**Remarks (Source-No.)**
Finland	duct surface	residual oil fibres	10 g/m² 0,01 f/cm²	not mentioned	Proposal (10)
Finland	duct surface	dust dust	0,5 g/m² 5 %	vacuum-method Tape	Proposal (10)
Finland	odour from duct	odour intensity odour acceptability	4 decipol 0,05	scale 0...20 decipol (trained panel) scale -1...+1 (untrained panel)	Proposal (10)

Air Quality					
Country	**air-type**	**type**	**Value**	**Method**	**Remarks (Source-No.)**
WHO	room air	aerbourne fungi	< 150 CFU/m³	RCS centrifugal impactor	Guideline (11)
USA	room air	total aerbourne MO aerbourne fungi aerbourne fungi	< 1.000 CFU/m³	not mentioned	Guideline (12)
Finland	room air	fungi in air	< 200 CFU/ m³	one-stage Andersen-Sampler	Proposal (13)

References:
(1) National Air Duct Cleaners Association (NADCA, 1992)
(2) Heating and Ventilation Contractors Association (HVCA, 1998)
(3) Mikrometer-Values refer to measurement of dust thickness
(4) The Swedish National Board of Housing, Building and Planning (BFS, 1992)
(5) Yoshizawa et al. (1997)
(6) 2 g/m² = "excellent maintenance", 5 g/m² = "good maintenance", Finnish Society of Indoor Air Quality and Climate, (FiSIAQ, 1995)
(7) Verein Deutscher Ingenieure, Guideline VDI 6022 (VDI, 1998)
(8) Nordic Ventilation Group as cited in Luoma et al. (1993)
(9) Mechanical Hygiene Industries (no year)
(10) Säteri (1998)
(11) WHO (1990)
(12) Annual American Conference of Governmental Industrial Hygienists (ACGIH, 1985)
(13) Sandholm and Wirtanen (1993)

As can be seen from **Table 4**, most target values on the cleanliness of air ducts refer to acceptable surface dust levels which vary significantly between 1 to 10 g/m² prior to and 0,1 to 1 g/m² after duct cleaning, depending on the determination method. Furthermore, there different values are recommended for supply, recirculating and exhaust ducts as well as values on dust thickness (HVCA, 1998). The German standard VDI 6022 prescribes the inner duct surfaces to be broom-clean, a description which was quantified in own investigations by TUB as discussed below in chapters 4 and 5. There are only two target values recommended for surface microorganisms (< 15.000 [moulds] and < 30.000 [bacteria] CFU/m²)(MHI, 1993) which are 3 times higher than those for floor dust, shown here as comparison (Luoma et al., 1993). Comparing the values of existing surface concentration of dust (means 1,2 to 18,8 g/m²) and microorganisms (up to $2{,}5\times10^5$ CFU/m² and $1{,}5\times10^6$ CFU/g) as shown above in Tables 1 and 2, it appears that quite a number of ducts would require cleaning. However, little information is available in the sources as to the rationale of the particular values regarding the impact on air quality or even occupant perception.
More helpful for the definition of cleanliness appear the values for new ducts provided by Säteri (1998), particularly with respect to preventive measures during manufacture and construction. They can serve as an orientation for „starting values“ prior to operation, whereas maintenance measures may later be acquired to keep ducts for as long as possible in an acceptable state of cleanliness (e.g. through high filtration efficiency or reduction of recirculated air volumes). Little information is available on the resuspension of microorganisms from the duct surface back into the supply air apart from the study of Foarde et al. (1998) which is briefly discussed above (**Chapter 2.3.4**). Nevertheless **Table 4** also contains a few target values on the concentration of microorganisms in room air as an orientation.

2.4 Material and Methods

As the German guideline VDI 6022 provides no quantitative target values for dust and microorganisms but requires interior surfaces of HVAC-systems to be 'broom-clean', an investigation was undertaken to quantify which the level of cleanliness this description actually means. Several factors might affect this quantification, e.g. the following:

- the type of broom or brush used for cleaning
- the degree of rigidness depending on particle characteristics and level of oil residues which commingle to a crusty layer in the process of particle deposition during operation
- the level of dust surface concentration and type of surface

For the purpose of this investigation initially two sampling points within the same duct on a sheet metal surface were selected which had a similar dust level [app. 10 g/m²]. As Küchen (1998) reported, the rigidness of dust within the same duct may vary, depending on the location of the sampling points (beginning or end of duct), as shown in (Figure 1).

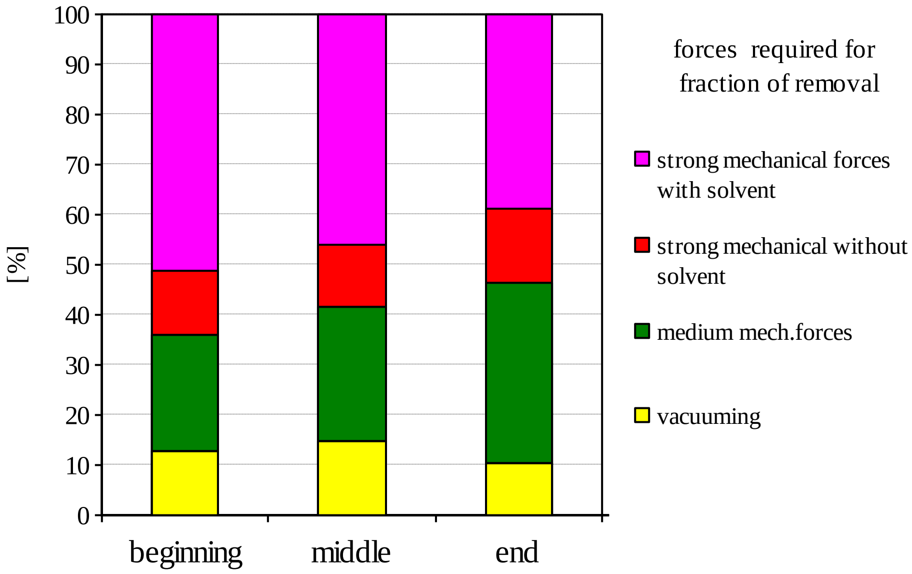

Figure 1: Forces required to loosen dust from duct surface [%] at different locations of ventilation ducts (mean of 11 ducts), (Küchen, 1998).

It can be seen from **Figure 1** that the percentage fraction of dust which can be removed without solvent increases from 49 % at the beginning of the duct to 61 % at the end; i.e. significant fractions of the dust (39 to 51 %) require usage of solvent or extreme mechanical forces to be loosened. As a consequence, two locations for sampling were selected - one at the beginning of the chosen duct (harder dust layer) and the other at its end (softer dust layer); apart from the data from Küchen (1998) the characteristics of the dust layer at these locations were also confirmed visually.

At the two sampling locations the investigation was undertaken as follows:

- determination of dust concentration by means of the method as described by the Japanese Air Duct Cleaners Association (wiping of a 100 cm² area with a pre-weighed polpropylene cloth [Kimtex, Kimberly Clark Co.]), without use of solvent (Kumagai et al., 1997); additionally as an own variation the same method with solvent (propanol, 70 %), 3 parallel samples, respectively:
    1. Prior to cleaning
    2. After cleaning with a 'soft' broom
    3. After cleaning with a 'hard' scrubber
- transport of the dusted samples to the laboratory, where the samples were weighed to determine the level of dust per unit area [g/m²] (the samples with solvent were stored 24 hours at a temperature of 20 ± 2 °C and rel. humidity of 40 ± 5 % to ensure that the solvent to be completely evaporated.

The weighing was undertaken with a Satorius Balance with a resolution of 0,1 mg. Each sample was packaged into aluminum foil which is rigid enough to ensure a calm weighing procedure on the one hand and to avoid electrostatic influences between balance wind shield and the cloth on the other.

2.5 Results

The following figures show the results of the measurement separately for the beginning (**Figure2**) and end (**Figure 3**) of the duct.

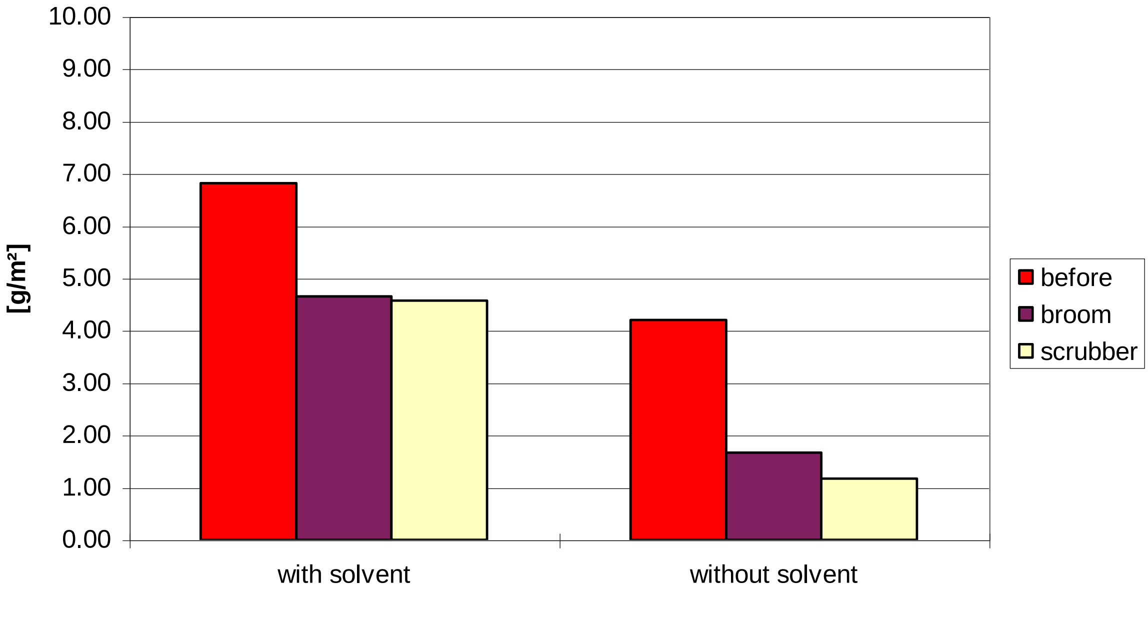

Figure 2: Dust surface concentration at beginning of duct before and after cleaning with broom and scrubber

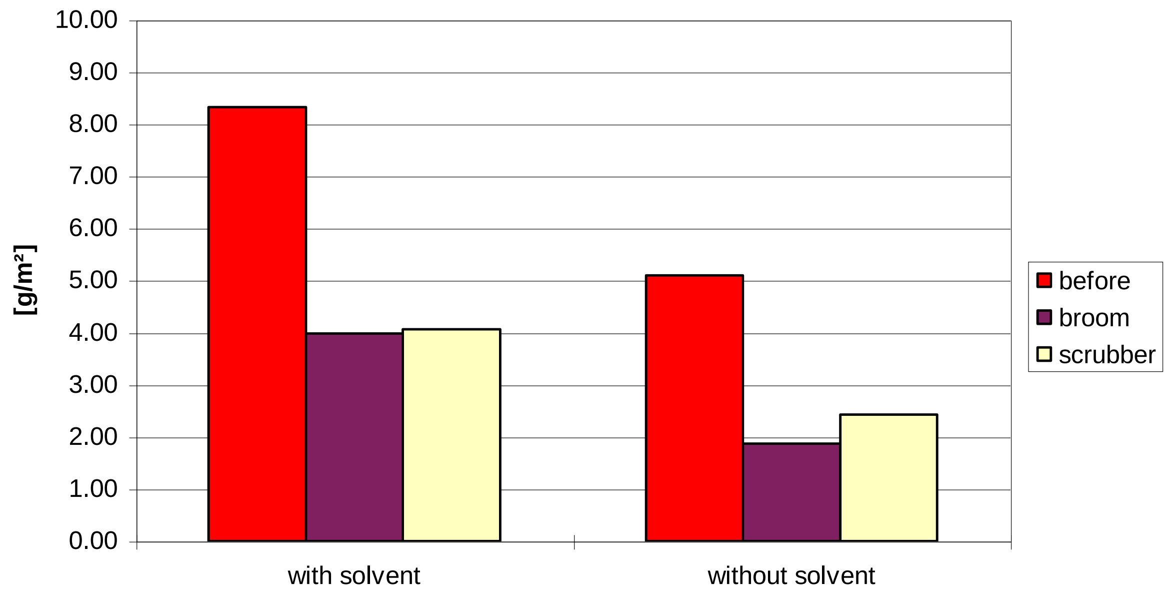

Figure 3: Dust surface concentration at <u>end of duct</u> before and after cleaning with broom and scrubber

It can be seen from the figures that there is little difference in the effectiveness of cleaning between broom and scrubber, particularly if the dust is determined with use of solvent, where a layer of between 4 (end of duct) and nearly 5 g/m² (beginning of duct) remained at the surface after cleaning. The corresponding values for measurement without solvent are between 1,5 and 2,5 g/m², with the broom more effective in cleaning at the beginning of the duct and the scrubber at the end. It has been shown that a significant amount of dust remains on the duct surface after mechanical cleaning, particularly when solvent is applied for measurement. Obviously is mechanical cleaning little effective in the removal of that fraction of dust which is commingled with oil residues to a crusty layer. To clarify this issue, **Figure 4** shows the ratio between the dust concentrations measured without solvent and those with solvent in percent, shown as the mean of both sampling locations.

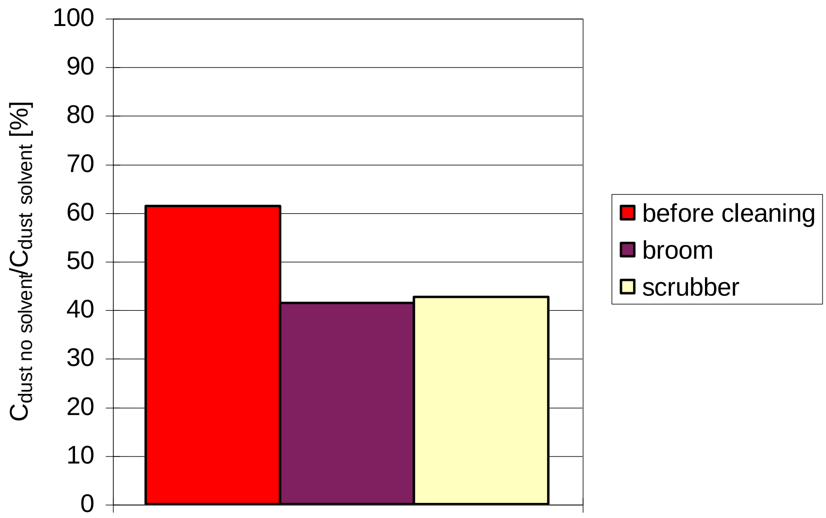

Figure 4: Ratio of the dust concentrations determined without solvent and with solvent [%]

It can be seen, that the fraction of dust that can be removed without solvent, i.e. the one that is less crusty or looser, decreases after cleaning with either type of brush (from app. 60 % to app.

40 %). This means that cleaning removes a larger amount of loose dust and only little of the crusty fraction. However, this is only the overall tendency as averaged over both sampling locations. As shown in the following figures, the percentage reduction of dust through cleaning is different depending on the sampling location.

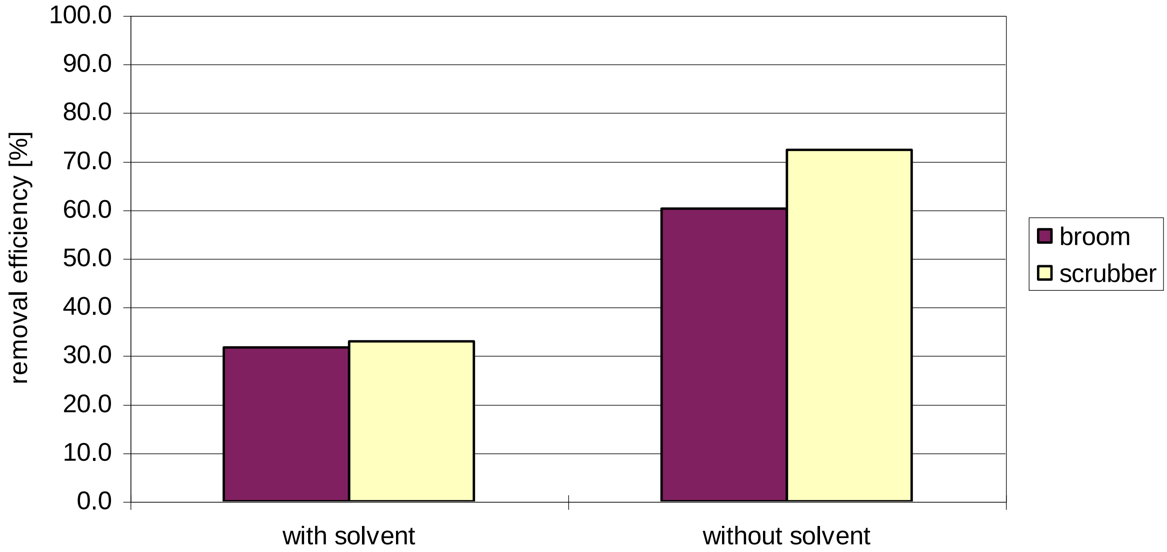

Figure 5: Reduction of the dust concentrations by mechanical cleaning determined without solvent and with solvent [%] at <u>beginning of duct</u>

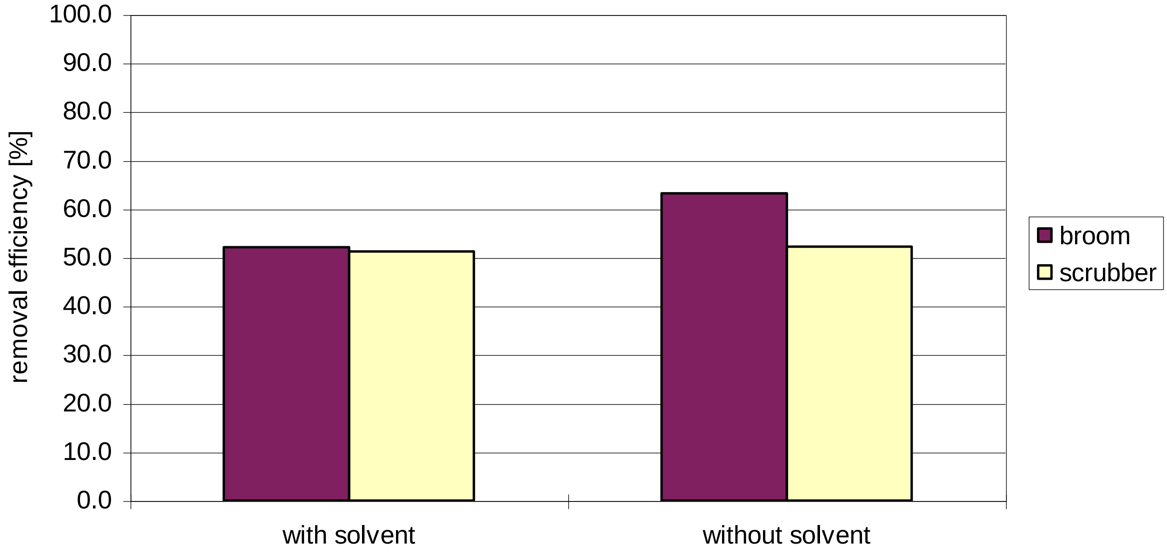

Figure 6: Reduction of the dust concentrations by mechanical cleaning determined without solvent and with solvent [%] at <u>end of duct</u>

Figures 5 and 6 indicate that dust removal efficiency by cleaning is similar for both sampling locations when the dust is measured without solvent (around 60 %). However at the beginning of the duct the removal efficiency measured with solvent is only 30 %, compared to 50 % at the end of the duct. This indicates that at the beginning of the duct a large fraction of dust is crusty and therefore difficult to remove by mechanical cleaning, so that this fraction can still be detected with use of solvent after cleaning resulting in a low percentage removal values. As a comparison, in the Japanese Guideline on cleaning a removal efficiency of > 75 % is prescribed (SHACSEJ, 1996).

2.6 Definition of Cleanliness

In practice, HVAC-systems are aimed to improve air quality compared to outdoor concentrations which is usually (under normal operation and proper maintenance) the case with regard to airborne microorganisms and particles due to filtration (Müller, B., 1998; Küchen, 1998). However, as discussed in Chapter 2.3.4, the following three major contaminants from ducts may deteriorate IAQ and should be limited:

1. residues of lubricant oils from duct manufacture
2. dust accumulated during operation or debris from construction
3. deposited microorganisms, particularly when toxigenic species are present and conditions are favourable for their survival and growth

In the context of this recommendations it might initially be sufficient, for preventive considerations, to limit the surface dust concentration in ducts. With other standard values for dust between 1 and 10 g/m² and VDI 6022 as orientation (broom-clean = 5 g/m², wiping with solvent and 2 g/m² wiping without solvent), the following three levels of cleanliness are recommended:

low standard	20 g/m²
medium standard	10 g/m²
high standard	5 g/m²

These values refer to dust measurement methods which use solvents or mechanical forces sufficient to remove the dust layer completely from the sampling area. As an example **Picture 1** shows a picture taken from Küchen (1998), to illustrate the dust removal requirements to which the above values refer.

Picture 1: Example for completely blank sampling area compared with two other methods

The picture shows the sampling areas from a vacuum method (oval), the JADCA-wiping method without solvent (quadrangle) and the areas of a new method (circle), used without and with solvent (solvent rings around sampling area). The above values refer to methods that leave the sampling area as blank as can be seen on the picture in the foreground at the right (circle with solvent ring).

To be able to apply other methods **Table 5** shows the above mentioned values calculated for other methods of measurement using the detection efficiencies listed in **Table 1** as guiding values.

Table 5: Approximate corresponding target values for duct cleanliness referring to various existing dust measurement methods

Method	description	Detection efficiency (Faktor)	Dust surface concentration [g/m²]		
			low standard	**medium standard**	**High standard**
Total dust	solvent	1	20.0	10.0	5.0
Vacuum	with blade	0.9	18.0	9.0	4.5
Wiping	JADCA	0.5	10.0	5.0	2.5
Tape	gravimetric	0.35	7.0	3.5	1.8
Vacuum	with brush	0.15	3.0	1.5	0.8
Vacuum	Wintest	0.1	2.0	1.0	0.5
Vacuum	NADCA/HVCA	0.02	0.4	0.2	0.1

It should be highlighted at this point that the detection efficiency-factors stated in Table 5 are only indicative and do not reflect linear correlations of high significance between the values determined by the different methods in the field. However, the approach in this report is a first attempt to define the cleanliness of air ducts in terms of concrete dust values without descriminating sampling methods and procedures that have proven to function well elsewhere so that a refinement of the above used calculation factors might be a useful and worthwhile future research task.

In order to provide a simple definition of cleanliness, a visual impression is given in the following pictures to show various levels of dust surface concentration. In general, it can be used as a first approximation during duct inspection that when the metal duct surface can not be seen anymore through the layer of dust, a value of 20 g/m² is likely to be exceeded and one of the above methods shall be chosen to quantify the dust concentration. This effect can be seen in the following figures **(Picture 2-4)**

Picture 2: Duct with a dust layer of 5 g/m² (high standard)

Picture 3: Duct with a dust layer of 10 g/m² (medium standard)

Picture 4: Duct with a dust layer of 25 g/m² (low standard)

The aspects of microorganisms shall not quantitatively deal with here because only two values on the concentrations of fungi and bacteria on ventilation duct surfaces, based on industry internal recommendations, are available (Table 4). There is a general hesitation to provide recommendations on acceptable levels of duct surface microorganisms despite the fact that many values of acceptable dust concentrations are published. The reasons for this lack of standards goes beyond the mere absence of any established interactions between duct surface concentration and indoor air quality parameters such as odour, MVOC's or Endotoxins (mechanisms that are not much more scientifically investigated yet with regard to dust) but may be caused by one of the following further obstacles:

- there is a great number of species involved which vary significantly in their allergenic potential, requirement of nutrients, moisture or temperature
- the existence of a vast variety of analytical methods covering different groups of microbes (bacteria, fungi [moulds, yeasts, mildewes]) and of these either sum-parameter or even subgroups (e.g. gram-negative, various trophic groups) or families (Legionella, Pseudomonas)
- the difficulty of interpretation of sum-parameters (e.g. total bacteria) stemming from the importance to be aware of the specific mixture of species within the sample, particularly

with respect to certain toxigenic or pathogenic species (e.g. Stachybotrys, Myrothecium, Fusarium, Aspergillus fumigatus, Legionella pneumophila etc.).

Therefore this recommendation shall be limited to the consideration of dust, as discussed above, and residuol oil and odour from new ducts.
Based on the recommendations of Säteri (1998) it is recommended that a value of <u>10 g/m² residual oil</u> from duct manufacture and a value of <u>4 decipol in perceived air quality</u> is not exceeded for new ducts prior to operation. The reasons for the limitation of oil residues are as follows:

- the relation of oil residues and odour emissions is fairly established in laboratory studies and in the field (Björkroth et al., 1997, Müller, B., 1998a)
- oil residuas promote the deposition and adhesion process of particles on surfaces and result in the developement of a crusty and rigid dust layer which is not only difficult to clean (Chapter 2.3.5) but further enhances deposition through increased surface roughness (Wallin, 1993)
- oil residues may act as a nutrient source and therefore promote microbial (and possibly pathenogenic) growth in areas with moisture problems (Pasanen et al., 1995)

2.7 Measures to ensure/maintain acceptable Air Quality

Measures to avoid deterioration of indoor air quality from ducts include a proper maintenance but acually start before the beginning of operation, i.e. in the phase of planning, manufacture and installation.

<u>Planning, Manufacture and Installation</u>

VDI 6022 (1998), FiSIAQ (1995) and other guidelines provide some recommendations on these issues as follows:

- flexible air ducts are to be limited because of the difficulty of cleaning
- ducts shall be cleaned after the manufacturing to limit oil residues to the extend mentioned above
- tapes or tags shall not be attached and sealants with high emission shall be avoided
- the interior surfaces shall be smooth, sharp-edged curves and transition pieces or self-tapping screws in the walls should be avoided
- stiffeners and other fittings shall be installed in such a way that deposits of dirt are prevented and cleaning can be carried out
- insulation is necessary where temperatures may fall short of the dew point
- service opening for inspection and cleaning have to be installed
- ducts and accessories shall be protected from moisture and dirt during storage at the factory or the construction site and during transport; the ends of the ducts shall be closed and accessories packed in closed boxes
- during installation, dirt shall not accumulate in the ducts, packages have to be removed just before installation
- prior to the first operation, all parts in contact with the airflow shall be checked for complete cleanliness and recleaned if necessary

The folowing point, maintenance aspects is also described in detail in various guidelines (Müller, B., 1998b) so that again, only the main issues shall be summarised here.

Maintenance

Maintenance cycles and measures:

a) 12 monthly: inspection of accessible sections of the duct for damage, rectify if necessary

b) 12 monthly: inspection of interior surface for contamination and corrosion at two to three representative points, clean if required

c) not specified: check the hygiene conditions in the air duct at a representive point, clean if required

Picture 5: Duct section behind a humidifier

2. Further specifications by TUB:

point b) and c):

- inspection intervals may take into account certain system specific aspects such as level of outdoor air pollution, type of system (supply, recirculating), filtration efficiency, height of outdoor air intake
- inspection points are to be chosen in areas within the duct system which offer particularly favourable conditions for the survival of microorganisms (behind humidifiers [see **Picture 5** below], in areas of dew point conditions such as cold deck surfaces) and where the highest dust load can be expected (beginning of duct, particularly where filters of low class are installed or in systems older than 20 years)
- inspection procedures shall start with a visual check on dust deposit thickness, i.e. is metal duct surface visible; if not, then quantitative measurement of dust required; the visual check should include an spots of possible microbial contamination
- measurement areas at the inspection points shall be chosen as follows:
    - in rectangular ducts on the bottom surface at half width
    - in circular ducts on the bottom around the lowest point

- is a distance of the inspection point to obstacles (e.g. elbows) or fittings of > 5 HD not possible, generally those areas of visibly highest dust concentration should be investigated
- ducts smaller than 71 mm in diameter (circular) or 120 mm in width (rectangular), where no service openings can be installed may be visually inspected with an endoscope inserted through a hole in the size of those drilled for measurement of air flow

Therefore the following investigations with regard to these aspects have already been commenced or are in the planning phase:

- PAQ of air ducts with different dust levels in the field.
- Effect of cleaning with broom and scrubber on MO’s (swab and contact plate methods).

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