A cleaning concept for HVAC system

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ABSTRACT
A cleaning concept consists of an evaluation procedure for estimating the need of cleaning, a theoretical model to design a rotating duct cleaning brush, cleaning methods and a verification method of the cleaning result of HVAC system. The visual evaluation method with a video camera and a display has been developed for a primary method to evaluate cleanliness before and after the cleaning work. The results obtained with the theoretical model of the brush were in good agreement with those obtained in the laboratory tests. A cleaning brush with a special Y-gear for rectangular ducts was developed and tested in the laboratory. Additionally, a brush cleaning machine with high torque and adjustable brush speed was developed.

INDEX TERMS
Cleaning; Cleanliness; Dust; Inspection; Modelling

INTRODUCTION
Dust and other contamination accumulate on the surfaces of HVAC system during its construction and operation. Dusty surfaces may increase energy consumption, decrease air flow rate (Wallin, 1994) and may cause malfunction problems to the HVAC system. Additionally, contamination into supply air duct may cause negative health impacts to occupants. Thus, the HVAC systems, which convey very dusty or fire hazard contamination, have to be cleaned frequently.

National regulations and guidelines give regular time periods to inspect cleanliness of the HVAC system (SNBH, 1994; VDI, 1998; ACR, 2001; FiSIAQ, 2001), limit value for dust accumulation (SNBH, 1994; HVCA, 1998; FiSIAQ, 2001; VDI, 2002) and to clean the HVAC system (HVCA, 1998; MI, 2001). Some organizations have presented the limit values for acceptable dust accumulation to verify the cleaning results of the HVAC system (NADCA, 1992; Juell *et al.*, 1994; JADCA-01, 1997; HVCA, 1998). Sweden (SNBH, 1994) and later Germany (VDI, 1999) have been pioneers requiring specific qualification and experience for inspectors before they are authorized to inspection work.

Although visual inspection is a subjective method, it is used to estimate the need for cleaning (VDI, 1998; NADCA, 2003) and to verify the results of the cleaning work of the HVAC system with other objective measuring methods (Juell *et al.*, 1994; HVCA, 1998; ACR, 2001). A trained and experienced inspector could estimate the amount of dust accumulation quite accurately in relatively clean new air ducts visually (Holopainen *et al.*, 2002a). A consistent visual inspection procedure helps an inspector to evaluate the cleanliness of the HVAC system systematically.

Several cleaning methods are used to remove debris and other surface contaminants from the air ducts (Luoma *et al.*, 1993; NADCA, 1995; HVCA, 1998; NAIMA, 2003). One commonly used and efficient method is mechanical brushing (Holopainen *et al.*, 2001). The main principle of the brushing method is to detach accumulated dust from the duct surfaces with the mechanical contact without causing damage to the surfaces or the components of the

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ductwork. A vacuum collector conveys the loosened dust from the ductwork to a filter unit using the movement of airflow. The vacuum collection device might be a significant source of pollutants in the building (Puhakka *et al.*, 1992; NADCA, 1995), especially when the exhaust air is supplied back into occupant space during duct cleaning work. Ductwork may consist of various surface materials and shapes of duct. Especially the corners of the rectangular duct are difficult to clean properly. There are no standards to define the effects of different types of brushes and bristles on various surfaces (NADCA, 1995). To date the manufactures of the brushes have used mostly empirical methods to design the cleaning brushes. Mathematical modelling can offer faster and scientific progress in development work of the brushes for different purposes.

PRINCIPLES OF THE CLEANING CONCEPT

The visual inspection method is based on the notion that an inspector is able to evaluate quite accurately the average weight of dust accumulation on the new air duct surface (Holopainen *et al.*, 2002a). After the inspector had evaluated the cleanliness of HVAC system he had to make a clear conclusion if the system is clean enough or not. However, an objective sampling method (NADCA, 1992; JADCA-01, 1997; Pasanen, 1999; VDI, 2002; Asikainen *et al.*, 2003) is needed if the inspector cannot decide if the system is clean enough. In case the HVAC system needs to be cleaned a cleaning plan for the HVAC system will be prepared. The plan consists of the cleaning methods, health and safety requirements and verification of the cleaning result (NADCA, 1995; HVCA, 1998; ACR, 2001; Asikainen *et al.*, 2003). The inspection and cleaning results of the HVAC system are reported (HVCA, 1998; ACR, 2001) and recorded (Holopainen *et al.*, 2002b) on the maintenance manual of the building for the next periodic inspection. Figure 1 presents a simplified diagram of the cleanliness maintenance of HVAC system.

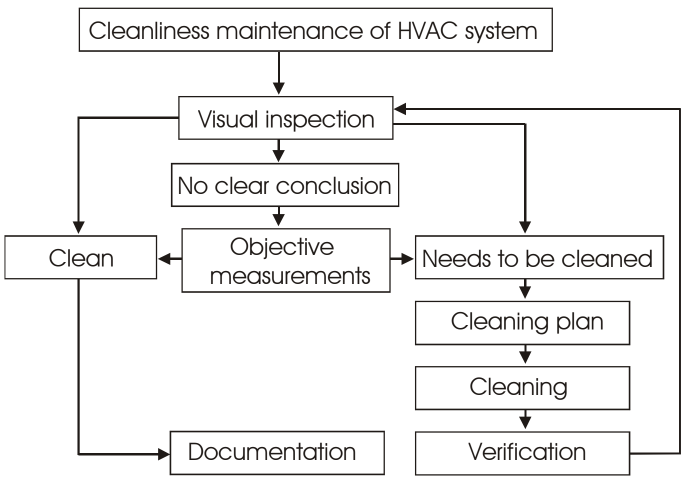


Figure 1 The elements of HVAC cleaning concept.

EVALUATION AND VERIFICATION OF THE CLEANLINESS OF THE HVAC SYSTEM

The visual evaluation method is designed for use as a primary method to evaluate the cleanliness of the HVAC system. The visual method is based on the systematic inspection of the cleanliness by comparing the amount of dust and debris to those of the visual scale and recording the inspection results on an inspection form (Holopainen *et al.*, 2002a). The visual cleanliness scale consists of six photographs, which display six different dust accumulation levels from clean duct to dust accumulation of over 10 g/m^2. The reference amount of dust was measured with the vacuum test method with a template of 100 cm^2 (Pasanen *et al.*, 1999).

A video camera and its display are used in order to inspect all parts of the ductwork. Additionally, a simple thickness measuring method (a comb) is developed to use it with the help of visual inspection (Asikainen *et al.*, 2003).

MODELLING OF THE ROTATING BRUSH

A simple model for a rotating cleaning brush in round ducts was developed using large deformation elastic theory (Holopainen and Salonen, 2002). The main interest was to determine the value of the unknown normal force N acting on the bristle tip and the contact angle β (see Figure 2) in terms of the parameters of the problem such as the angular speed of the brush ω and the ratio L/R, etc. The contact angle β is defined as the angle between the duct surface normal and the bristle axis tangent at the bristle tip. Authors recognized that other factors such as the surface pressure and the sweeping speed may also have significant influence on the cleaning efficiency.

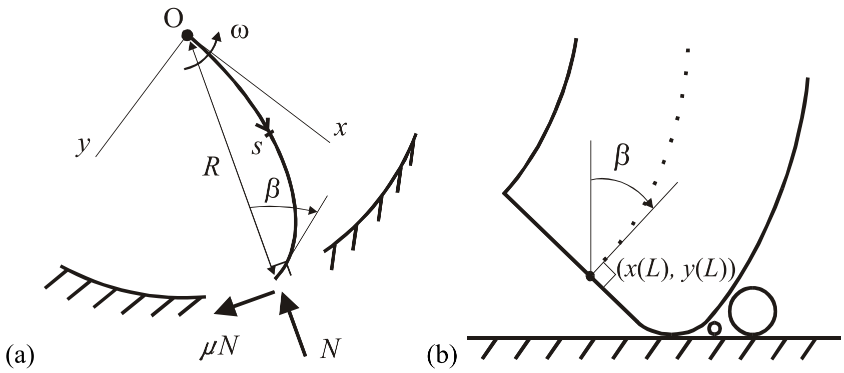


Figure 2 (a) Deformed bristle and the used approximation for the contact forces at the bristle tip. (b) Bristle tip.

The point collocation method was applied to determine the undetermined parameters in connection with the method of weighted residuals. The detailed final equations are developed and solved with the Mathcad (2003) software. The results of the model were satisfactory compared to those obtained in laboratory tests. Holopainen and Salonen (2002) describe in more detail the rotating cleaning brush modelling. Holopainen and Salonen (2003) present more details of the laboratory test.

BEHAVIOUR OF BRISTLES OF ROTATING BRUSH

Two different types of the rotating duct cleaning brushes were studied in the laboratory. The bristles of the brush designed for cleaning round duct were made of nylon (thickness of bristles $d = 0.8$ mm) and the diameter of the brush was 600 mm (Figure 3). A developed brush designed for cleaning a rectangular duct consists of two brushes, which were located approximately at 45° angles (by a special Y-gear) from each other (Figure 4). The bristles of the brush were made of nylon ($d = 0.5$–0.8 mm) and polypropylene ($d = 0.45$ mm) and the diameter of the brush was 700 mm. The brushes were rotated at the same rotation speed in the plastic rectangular duct (410 mm × 250 mm). The behaviour of the brushes was recorded by taking photographs with a digital camera. The cleaning efficiency of the brushes was estimated visually.

It was found that the brush designed for round duct had vibration (bounce up and down) at a certain rotation speed. During rotation the shape of the brush varied from more symmetric (Figure 3a) to S-shape (Figure 3b) in a rectangular duct.

(a)  (b) 

Figure 3 Rotating brush designed for the round duct (a) 'more symmetric' period, (b) 'S-shape' period.

The bristles of the developed brush contacted the corner of the bottom and ceiling of the rectangular duct. Figure 4 presents the behaviour of the developed brush in a rectangular duct.

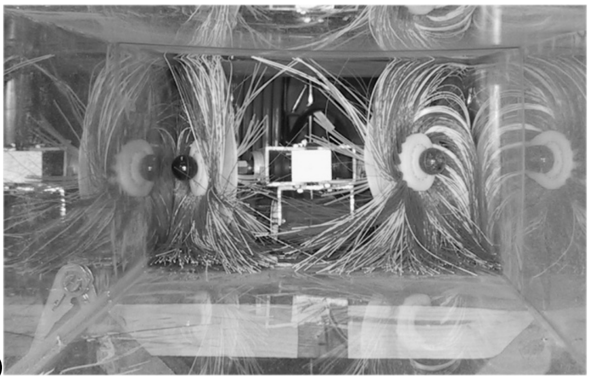
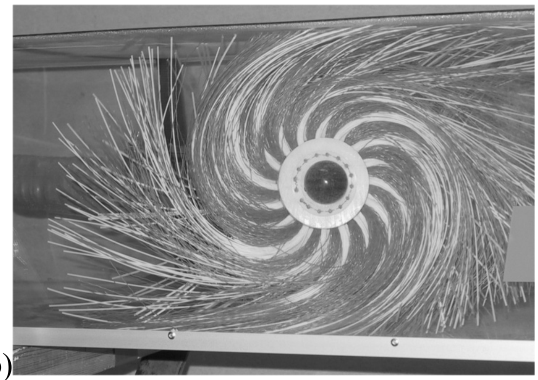
(a)  (b) 

Figure 4 Developed brush for the rectangular duct (a) in the front of the duct, (b) from the side of the rectangular duct.

Based on visual inspection and increment of noise caused by brushing, the cleaning efficiency of the brushes increased as a function of the rotation speed. However, it was difficult to direct and control both brushes in the duct when the rotating speed of the brush increased too high.

CLEANING DEVICES

According to practical experience, the availability of the power supply is one of the critical point in duct cleaning. Therefore, the advanced brush cleaning machine is powered by a hydraulic system using one phase (120/230 V, 50/60 Hz) with a variable motor speed. The centring device of the remote-controlled brush makes it possible to clean large ducts and the corners of the rectangular duct quite properly. The flexible shaft of the cleaning machine can be reached up to 40 m in the ducts.

Ductwork is normally cleaned the same direction as airflow into ducts during the operation of the HVAC system (NAIMA, 2003). The small diameter of the branch ducts (100–400 mm) are cleaned by using a smaller electric driven brushing machine and the main ducts (diameter of 400 mm and up) using the hydraulically, electrically or pneumatically powered cleaning machine with high power. The components of the ductwork, such as bends and dampers, are cleaned from both directions to ensure good cleaning results and without causing damage to the components. During duct cleaning the vacuum collection device with appropriate filters is connected to the access openings of the ductwork using a flexible vacuum hose. The airflow speed in the duct is adjusted over 10 m/s (ACGIH, 1988) by using dampers and covering other accesses of the ductwork. For high airflow rate or pressure drop two or more vacuum collectors are connected in parallel or series, respectively.

INSPECTION TOOLS

The remote-controlled video camera robot is applied to inspect the need for duct cleaning. The camera robot enables the evaluation of the amount of dust accumulation and other contaminants such as condensation and moisture damage in the ducts. The camera unit is equipped with a long cable (25–30 m), which ensures accessibility to remote places in the duct where access openings do not exist, or where the accesses are in difficult places. The camera robot is equipped with a remote-controlled lifting arm for sampling by wiping, scratching with the thickness measuring comb (Asikainen *et al.*, 2003) or gel-lifting (Schneider *et al.*, 1996). Illumination is taken into account with a halogen lamp. The results of inspection are recorded and documented by the camera for next periodic inspection.

DISCUSSION

The developed visual inspection scale was made to support the subjective evaluation of inspectors, constructors and building owners. It can be observed that wiping the surface of the duct with a finger or the thickness measuring comb from the side of the duct to the bottom helps the evaluation of the cleanliness. The inspection procedure proved as a tool for evaluation of cleanliness of the HVAC system before and after cleaning systematically.

The deflected shape of the bristle changes as a function of the rotation speed of the bristle. The increase of the thickness of the bristle increases significantly the normal force (N) and decreases slightly the contact angle (β). A higher bristle length than the duct radius ratio (L/R) strongly increases the deflection of the bristle and the contact angle, but relatively weakly the normal force (Holopainen and Salonen, 2002).

Based on visual inspection, both tested brushes can be used for cleaning fine and dry dusts on the rectangular duct surfaces. However, the brush designed for the round duct could not clean 'the dead corner' of the rectangular duct properly (Figure 3). It seems that the angle between the brushes by the special Y-gear (Figure 4) and the parameters of the brushes, such as length and thickness (stiffness) of bristles, have a significantly better effect on the cleaning results of the corner of the rectangular duct. Additionally, the built-in video camera system of the cleaning machine helps the operator to steer the brushing head to the corners of the ducts and to inspect the result of the cleaning work immediately.

CONCLUSION

Using the elements developed in the project it is possible to construct a cleaning concept of the HVAC system. The cleaning concept consists of suitable tools for evaluation procedures for estimating the need of cleaning, a tool for designing and selecting the cleaning brush in round ducts, the cleaning methods of the HVAC system and verification of the cleaning result.

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REFERENCES

ACGIH (1988). *Industrial Ventilation: a Manual of Recommended Practice*. American Conference of Governmental Industrial Hygienists, Inc.

ACR (2001). *Assessment, Cleaning, & Restoration of HVAC Systems*. An Industry Standard Developed by the National Air Duct Cleaners Association, ACR 2002, 30 pp.

Asikainen, V., Holopainen, R., Majanen, A. *et al*. (2003). The verifying concept for the cleanliness of HVAC systems. *The 7th International Conference on Healthy Building 2003*.

FiSIAQ (2001). *The Classification of Indoor Climate 2000*. FISIAQ publication 5E, The Finnish Society of Indoor Air Quality and Climate (FiSIAQ), Espoo, Finland, 40 pp.

Holopainen, R., Asikainen, V., Tuomainen, M. *et al*. (2001). Effectiveness of duct cleaning methods on dusty and oily duct surfaces. Accepted for publication by *Indoor Air*.

Holopainen, R., Narvanne, J., Pasanen, P. *et al.* (2002a). Visual method for evaluation of cleanliness of air duct. *Proceedings of Indoor Air 2002 Conference*, Vol. 1, pp. 682–687.

Holopainen, R., Asikainen, V., Pasanen, P. *et al*. (2002b). *Uuden ilmanvaihtojärjestelmän puhdistus* (Cleaning of new HVAC system). Helsinki University of Technology. Department of Mechanical Engineering, Laboratory of Heating, Ventilating and Air Conditioning, 5 pp. (in Finnish).

Holopainen, R. and Salonen, E.-M. (2002). A simple model for analyzing bristle contact force and contact angle in rotating brush duct cleaning. Helsinki University of Technology. Department of Mechanical Engineering, Laboratory of Heating, Ventilating and Air Conditioning, B72, Espoo, 39 pp.

Holopainen, R. and Salonen, E.-M. (2003). Modelling bristle behaviour in rotating brush duct cleaning. Helsinki University of Technology, Department of Mechanical Engineering, Laboratory of Heating, Ventilating and Air Conditioning, B75, Espoo, 58 pp.

HVCA (1998). *Cleanliness of Ventilation Systems, Guide to Good Practice Cleanliness of Ventilation Systems*. London: Heating and Ventilating Contractors' Association HVCA Publications (TR/17), 24 pp.

Juell, M., Mosland, T.B. and Andersen, A. (1994). *Rene ventilasjonssystem*. Teknologisk Institutt, Bygg og innemiljø, Oslo, 9 pp. (in Norwegian).

Luoma, M., Pasanen, A.-L. and Pasanen, P. (1993). *Ilmastointilaitosten puhdistustekniikka* (Cleaning of air conditioning systems). Technical Research Centre of Finland (VTT), Research Notes 1492, Espoo, Finland, 59 pp. + appendices (in Finnish).

Mathcad (2003). http://www.mathcad.com/, accessed 4 April 2003.

Ministry of the Interior (MI) (2001) *Sisäasianministeriön asetus ilmanvaihtokanavien ja—laitteistojen puhdistamisesta* (The regulation of cleaning of HVAC systems). Pelastusosasto, Helsinki, 802/2001 (in Finnish).

NADCA (1992). *Mechanical Cleaning of Non-Porous Air Conveyance System Components*. An Industry Standard Developed by the National Air Duct Cleaners Association. Washington, DC, NADCA, 1992-01, 12 pp.

NADCA (1995). *Introduction to HVAC System Cleaning Services*. *A Guideline for Commercial Consumers*. An Industry Standard Developed by the National Air Duct Cleaners Association, Washington, DC, NADCA, 21 pp.

NADCA (2003). *HVCA Inspection Manual, Procedures for Assessing the Cleanliness of Commercial HVAC System*. Developed by the National Air Duct Cleaners Association, Washington, DC, NADCA, 69 pp. + appendices.

NAIMA (2003). http://www.naima.org/pages/stewardship/ieq/issues.html, accessed on 1 July, 2003.

Pasanen, P. (1999). Verification of cleanliness of HVAC systems. In: Loyd, S. (ed.), *Proceedings of VHExCo99*, Birmingham, UK.

Puhakka, E., Kärkkäinen, J. and Jyrkiäinen, J. (1992). *Tuloilmakanaviston puhdistustyön seuranta esimerkkitapauksen avulla* (A case study of cleaning of HVAC system). LVIS 2000, Report 14, Espoo, pp. 82–88 (in Finnish).

Schneider, T., Kildesø, J., Petersen, O.H., Kloch, N.P. and Løbner, T. (1996). Design and calibration of a simple instrument for measuring dust on surfaces in the indoor environment. *Indoor Air* **6**, 204–210.

The Swedish National Board of Housing, Building and Planning (SNBH) (1994). *Checking the performance of ventilation systems*. General Guidelines 1992:3E, 30 pp.

VDI 6022 (1998). *Hygienic standards for ventilation and conditioning systems, Office and assembly rooms*. Part 1, 44 pp.

VDI 6022 (1999). *Hygienic standards for ventilation and conditioning systems, Standards for hygiene training*. Part 2, 8 pp.

VDI 6022 (2002). *Hygienic standards for ventilation and conditioning systems in production facilities and business enterprises*. Part 3, Düsseldorf, Germany, 28 pp.

Wallin, O. (1994). Computer simulation of particle deposition in ventilating duct system. Doctoral dissertation, Building Service Engineering, Royal Institute of Technology, Stockholm, Sweden, 162 pp.

Yoshizawa, S., Ito, H., Kumagai, K., Shizawa, K., Shimizu, S., Abe, S. and Ichiki, T. (JADCA-01) (1997). Methods to evaluate the duct cleaning efficiency. Research Report of the Japan Air Duct Cleaners Association, Tokyo, Japan, JADCA, 8 pp.