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DAHU : Diagnosis of Air Handling Units

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DAHU: DIAGNOSIS OF AIR HANDLING UNITS

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ABSTRACT

A measurement protocol for diagnosis of air handling units and the corresponding interpretation algorithms were developed and implemented in a user-friendly computer program. This development is based on several years of practice in such measurements, and includes the solution of mundane but serious problems such as proper tracer gas mixing in air, representative sampling strategy, and interpretation using the most robust system of equations.

The diagnosis protocol includes methods to determine the main and parasitic airflow rates, the mean age of air and global ventilation efficiency in the ventilated space, the efficiency of heat exchangers, the contaminant transfer from exhaust to supply duct, and the power efficiency of fans. The contribution presents the principles and the methods applied in the test protocols.

KEYWORDS

Ventilation, diagnosis, measurement, leakage, airflow rate, pressure, efficiency

INTRODUCTION

It was found that air handling units seldom function as planned: airflow rates are not those required, that recirculation rate is not at its set-point value and parasitic shortcuts sometimes dramatically decrease the ventilation efficiency *[Bluyssen et al, 1995, Roulet et al, 1994]*. Diagnosis tools would therefore be useful to detect dysfunction, preferably when commissioning the air-handling unit.

AIRFLOW RATE MEASUREMENTS

Velocity measurements using Pitot tubes are often used for that purpose. Such techniques, however, can be applied only in long straight ducts, seldom found in technical rooms. In addition, only main airflow rates can be measured that way, while many other airflow paths may be found in an air-handling unit, as shown on Figure 1.

Tracer gas dilution technique is very efficient to assess airflow rates in air handling units *[Roulet and Vandaele, 1991]*. Tracer gases are injected, most often at a constant flow rate or as a pulse, at carefully

chosen locations in the air ducts close to the handling unit. Experience has shown that most practical and efficient injection locations are as indicated in Figure 1. Three tracer gases suffice in most cases to determine all primary and secondary airflow rates: Tracer one injected in the outside air duct; tracer two injected in the main supply air duct; and tracer three injected in the main return air duct.
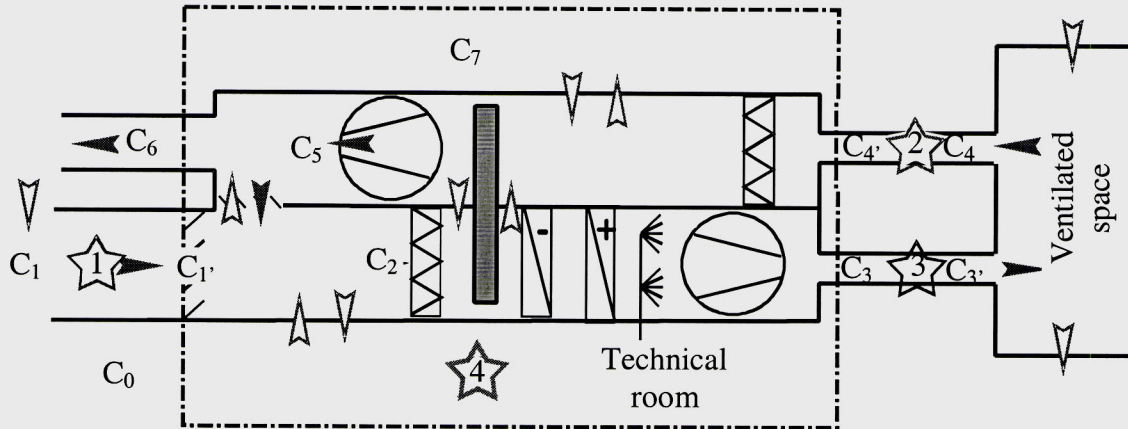

Figure 1: Schematics of an air handling unit showing main (plain arrows) and secondary (empty arrows) airflow paths. Locations of tracer gas injection (stars), and sampling points for concentration measurements (C_i) are also shown in this figure.

One or two tracer gases are enough in many cases; in particular when secondary airflow rates are not quantified. If several tracer gases are needed but not available, it is possible to use the same tracer gas in several experiments, injecting the tracer successively at different locations. The tracer gas injection flow rate, I, should be adjusted on the basis of the design outdoor airflow rate Q_{01}. If C_k is the expected tracer gas concentration of tracer k:

$$I_k = C_k Q_{01} \tag{1}$$

The ducts, leakage and shortcut network in the air handling system seen from outside, like a black box, are represented schematically as shown in Figure 2. Recirculation may be intentional, and occurs between nodes 6 and 2, or could pass through a leak such as those sometimes found in heat exchangers, through nodes 5 and 3. From the indoor air quality point of view however, there is not much difference whether the recirculated air passes through a leak between extract and supply parts of the AHU or through purpose installed duct. Therefore, the simplified network, as shown in Figure 2, is adapted for most investigations.
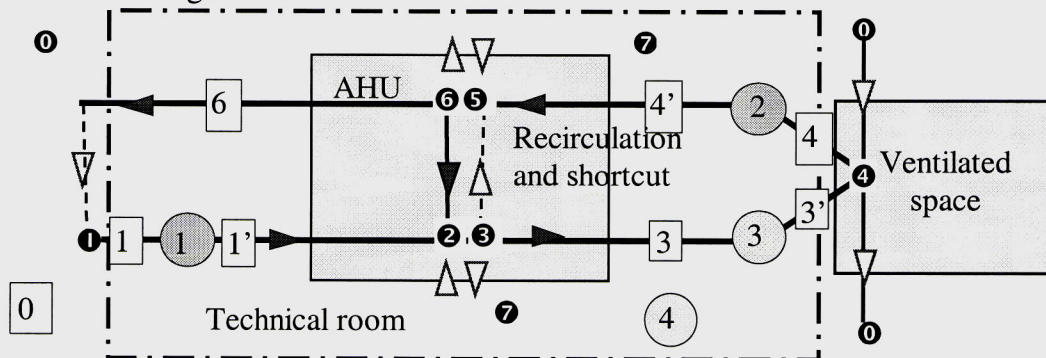

Figure 2: The simplified network representing the air handling unit and ducts. Numbers into black circles represent the nodes of the network. Circles are tracer gas injection locations, and numbered rectangles are air sampling locations. Arrows represent possible airflow rates.

Tracer gas concentrations are measured at various locations, in order to obtain enough equations from conservation of airflow and tracer gas flows to determine all airflow rates. Important is that good

mixing of tracer gas in the measured airflow be ensured. Tracer gas and air mass conservation equations can be written in various ways, leading to different interpretation methods. We tested several methods *[Roulet et al, 1998]*, and have found that the node-by-node method, developed by Roulet and Compagnon *[1989]* for multizone tracer measurements in buildings is well suited to measurements in ductwork and air handling units. Air flow and tracer gas conservation equations at each node can be rearranged so as to obtain one system of equation per node, giving all airflow rates entering in this node:

$$-I = \sum_{=0} \left[C - C \right] Q \tag{2}$$

where:

I_{ik} is the injection rate of tracer gas k in (or just upwind) node i
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Q_{ji} is the airflow rate from node j to node i

"Just upwind" and "just downwind" mean far enough from the node to ensure a good mixing, but close enough to have no branching between the injection port or sampling location and the node. Airflow rates leaving the zones are determined by mass conservation equations:

$$Q_0 = \sum_{=0} \left[1 - \delta \right] Q - \sum_{=1} \left[1 - \delta \right] Q \tag{3}$$

The system of equations 2 and 3 is solved to obtain all main airflow rates and recirculation flow rates shown in Figure 2 using only two tracers injected at locations 1 and 2, or all airflow rates, including leakage, using an additional tracer at location 4. Tracer 3 can be used to improve accuracy for supply airflow rate.

MEASUREMENT OF VENTILATION EFFICIENCY

This quantity is deduced from the measurement of the room mean age of the air. The basic principle is to mark the air to be traced with a gas (the tracer gas), according to a known schedule, and to follow the concentration of that tracer gas at the exhaust *[Sandberg and Sjoberg, 1984]*. This measurement can be performed at the same time and together with airflow rate measurement. Three injection schedules can be used. In the **decay** strategy, injection is stopped and measurement begins after a uniform concentration of tracer is achieved. For **step-up,** the tracer is injected at air inlet at a constant rate from the starting time throughout the test. Alternatively, a short pulse of tracer can be released in the air inlet at the starting time. It was shown however that, for rooms with a single air inlet and a single air outlet, the step up method should be preferred, since it is the easiest to perform in that case and gives the best accuracy *[Roulet and Cretton, 1992]*. This is the case when measurement is performed at the air handling unit, assessing the mean age of air and ventilation efficiency for the whole space ventilated by the measured unit.

Tracer gas is injected into the supply air in the outside air duct at a constant rate, starting at a known time t_0. It is assumed that the tracer and the air are fully mixed in the supply duct. Tracer gas concentration in the extract duct (location C_4) is recorded. The sampling time interval should be much shorter than the expected age of air, to record the transient evolution of the concentration.

This measurement provides both the nominal time constant and the mean age of air in the ventilated space. Injection rate is maintained constant until a steady state is obtained. An example of such a record is given in Figure 3. When the concentration stabilises, the step-up experiment is ended. However, it is recommended to perform a decay experiment, i.e. to continue recording the

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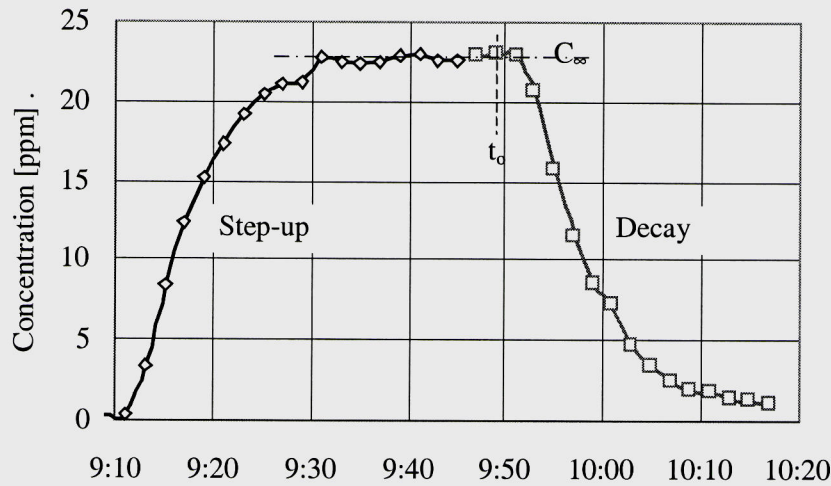

Figure 3: Record of tracer gas concentration in extract duct during a measurement of the age of air.

To interpret the recorded tracer gas concentrations and obtain the age of air, the background (or supply) concentration should first be subtracted from all measurements, and the elapsed time should be calculated by subtracting the starting time from all time values. Then the nominal time constant, τ_n, the mean age of air in the ventilated space, $\langle t \rangle$, and the ventilation efficiency:

$$\eta_a = \frac{\tau_n}{2\langle t \rangle}$$

(4)

are calculated form the moments of the concentration of tracer gas in the exhaust duct *[Sandberg and Sjoberg, 1984]*.

MEASUREMENT OF FAN POWER EFFICIENCY

The mechanical power delivered by a fan is the product of the volume air flow rate Q_v delivered by the fan, by the pressure differential Δp, across the fan. Airflow rate is measured by tracer gas dilution technique, and pressure differential is easily measured with a differential manometer. The electrical power consumed by the fan motor, Φ_e, is measured with a wattmeter, and the fan efficiency is:

$$\eta = \frac{\Phi}{\Phi} = \frac{Q\,\Delta p}{\Phi}$$

(5)

EFFICIENCY OF HEAT EXCHANGERS

The energy (or enthalpy) efficiency is the ratio of the enthalpy flow delivered to the supply air by the enthalpy flow available in exhaust air:

$$\eta = \frac{H_{i\,s} - H_{i\,s}}{H_{i\,s} - H_{i\,s}}$$

6

Since airflow rates are known from previous measurements, assessment of temperature and moisture content of air at three locations only allows the determination of the enthalpy efficiency.

Also interesting, and much simpler to assess, is the temperature, or exergy efficiency, telling how well the temperature is recovered. This efficiency is simply calculated from temperature measurements upwind and downwind the heat exchanger in both supply and exhaust channels:

$$\eta_\theta = \frac{\theta_{downwind,\ supply} - \theta_{upwind,\ supply}}{\theta_{upwind,\ exhaut} - \theta_{upwind,\ supply}} \qquad 7$$

Care should be taken to measure temperature and air humidity in well mixed zones, especially downwind the exchanger, and to check that that the air is neither heated, cooled, dried or humidified between the heat recovery exchanger and the measurement location.

CONTAMINANT TRANSPORT IN ROTATING HEAT EXCHANGERS

Contaminates can be transferred from exhaust to supply ducts by rotating heat exchangers, not only though possible leaks, but also by adsorption-desorption*[Andersson, 1993, Pejtersen, 1996]*. To measure this transfer, concentrations of various volatile organic compounds upwind and downwind both sides of the heat exchanger should be measured. The VOC's may be those present in the air extracted from the ventilated space, or a mix of compounds injected in the extract duct. Experiments performed with VOC from the ventilated space may be inaccurate, since VOC concentrations are - or at least should be - low! Therefore, it is recommended to inject a VOC mix in the exhaust duct, in such a way that the VOC's are well evaporated and mixed to the air at location C_4. Sampling locations C_6 and C_3 should be far enough from the rotating heat exchanger, to ensure a good mixing to the air.

For such measurements, pulse injection was found most practical. The VOC's are evaporated rather quickly so that the necessary mass, M_i, of each component is totally injected in a time much smaller than the nominal time constant of the ventilation system. Air sampling should start before the beginning of the injection pulse, and ends only when VOC's concentrations are back to their background level, that is after at least five nominal time constants. Air at the four locations is sampled with a pump through small tubes filled with an adsorbing medium. Sampling rate Q_s is about 0,1 litre of air per minute. VOC's accumulate in the compound by absorption. The sampling tube is then hermetically sealed and mailed to the laboratory for further analysis by gas chromatography. The method used in these experiments is the one developed by the Swiss Federal Office of Health for the European Indoor Air quality Audit project *[Mogl et al, 1995]*.

For each compound, the VOC mass M_i passing at location i can be calculated from the sampled mass m_i, which is the direct result of the analysis of the sampler:

$$M_i = m_i \frac{Q_i}{Q_s} \qquad (8)$$

If there is no transfer at all, $M_3 = M_1 = M_0$, the outdoor concentration of each compound, and $M_6 = M_4$. If some VOC's are transferred, the transfer rate can be calculated as the ratio of the mass of VOC delivered into supply air, and the mass of VOC in extract air:

$$R = \frac{M_3 - M_1}{M_4} \qquad (9)$$

Note that the above relations are exact only when air flow rates in the AHU are constant. If this is not the case, they provide nevertheless a useful information, as Persily and Axley *[1989]* showed it.

CONCLUSIONS

Experiments on more than 20 units have shown that dysfunction of air handling units, often not suspected when using classical commissioning methods, can easily be detected and quantified using this methodology. With the equipment now available at the LESO, the time required for a full diagnosis of a unit is less than a day work for two persons. Further developments should reduce the weight of the material and instruments required on site and also reduce the diagnosis time. More information on the method presented here, including detailed experimental planning, interpretation methods and error analysis can be found in a comprehensive report *[Roulet et al, 1999]*. Diagnosis results are presented at the Indoor Air conference *[Roulet et al, 1999]*, at Healthy buildings 2000 *[Roulet et al, 2000]*, and in a report for the EU Joule AIRLESS project *[Roulet et al, 1999]*.

REFERENCES

Andersson B.; Andersson K.; Sundell J.; Zingmark P.-E. [1993]: Mass transfer of Contaminants in Rotary Enthalpy Exchangers. *Indoor Air* **3** 143-148.

Bluyssen P. M.; de Oliveira Fernandes E.; Fanger P.O.; Groes L.; Clausen G.; Roulet C.-A.; Bernhard C.-A.; Valbjorn O.[1995]: European Audit Project to Optimise Indoor Air Quality and Energy Consumption in Office Buildings. *Final report of Contract Jou2-CT92-022*, TNO Bouw, Delft (NL).

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Persily A. and Axley J.[1990]: Measuring Airflow Rates with Pulse Tracer Techniques. In *Airchange Rates and Air Tightness in Buildings*, ASTM STP 1067, M. H. Sherman, Ed. ASTM, Philadelphia.

Roulet C.-A.; Compagnon R.[1989]: Multizone Tracer Gas Infiltration Measurements - Interpretation Algorithms for Non-Isothermal Cases. *Energy and Environment*, **24**, 221-227.

Roulet C.-A.; Vandaele L [1991]: *Air Flow Patterns within Buildings – Measurement Techniques.* Technical note 34, AIVC, Coventry.

Roulet C.-A.; Cretton P.[1992]: Field Comparison of Age of Air Measurement Techniques. *Proc. of Roomvent'92, Aalborg, ,3 213-22*

Roulet C.-A; Foradini F and Cretton P. [1994]. Use of tracer gas for diagnostic of ventilation systems. *Proc. of Healthy Buildings '94 conference, Budapest*, **2**, 521-526.

Roulet C.-A.; Foradini F and Deschamps L. [1998]: Measurement of Air Flow Rates and Ventilation Efficiency in Air Handling Units. *EPIC'98 conference, Lyon*, **3**, 970-975

Roulet C.-A.; Foradini F and Deschamps L. [1999]: Measurement of Air Flow Rates and Ventilation Efficiency in Air Handling Units. *Indoor Air '99 conference, Edinburgh,* **5**, 1-6

Roulet C.-A; Deschamps L.; Pibiri M.-C.; Foradini F. [1999]: *DAHU: Diagnosis of air Handling Units.* Joule Thermie AIRLESS report, 38 p, LESO-EPFL, Lausanne.

Roulet C.-A.; Foradini F and Pibiri M.-C [2000]: Accepted at Healthy Buildings 2000 conference (No 277)

Sandberg M. and Sjöberg M. [1984]: The Use of Moments for Assessing Air Quality in Ventilated Rooms. *Building and Environment* **18**, 181-197.

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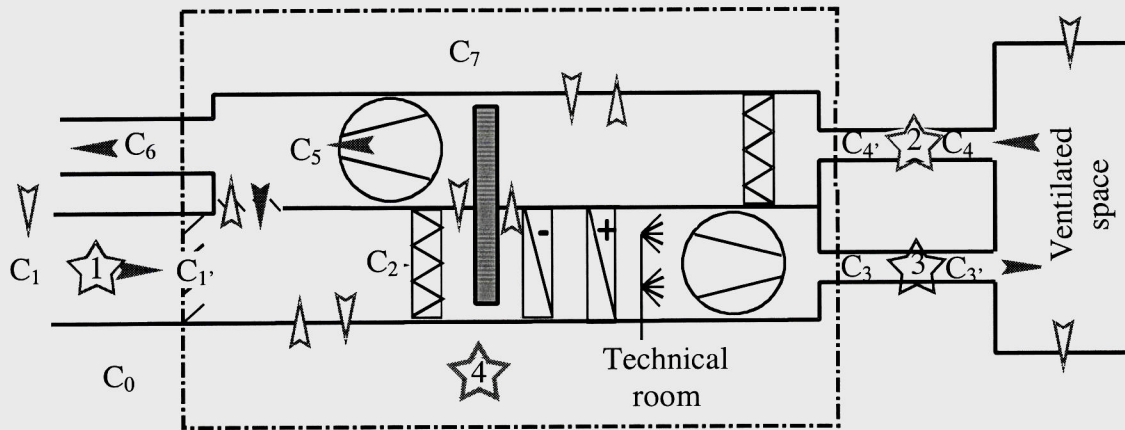

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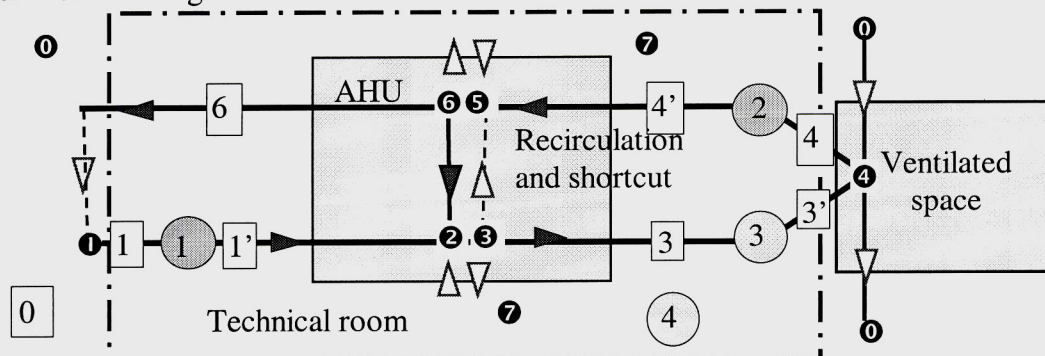

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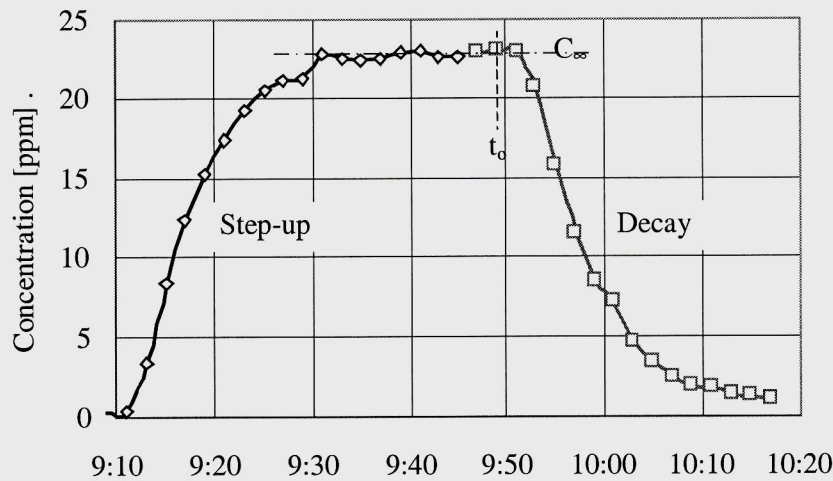

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are calculated form the moments of the concentration of tracer gas in the exhaust duct *[Sandberg and Sjoberg, 1984]*.

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Note that the above relations are exact only when air flow rates in the AHU are constant. If this is not the case, they provide nevertheless a useful information, as Persily and Axley [1989] showed it.

CONCLUSIONS

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REFERENCES

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Pejtersen J. [1996]: Sensory Air Pollution Caused by Rotary Heat Exchangers. *Proc. of Indoor Air 96, Nagoya.* **3**, 459-464.

Persily A. and Axley J.[1990]: Measuring Airflow Rates with Pulse Tracer Techniques. In *Airchange Rates and Air Tightness in Buildings*, ASTM STP 1067, M. H. Sherman, Ed. ASTM, Philadelphia.

Roulet C.-A.; Compagnon R.[1989]: Multizone Tracer Gas Infiltration Measurements - Interpretation Algorithms for Non-Isothermal Cases. *Energy and Environment*, **24**, 221-227.

Roulet C.-A.; Vandaele L [1991]: *Air Flow Patterns within Buildings – Measurement Techniques.* Technical note 34, AIVC, Coventry.

Roulet C.-A.; Cretton P.[1992]: Field Comparison of Age of Air Measurement Techniques. *Proc. of Roomvent'92, Aalborg,* ,*3 213-22*

Roulet C.-A; Foradini F and Cretton P. [1994]. Use of tracer gas for diagnostic of ventilation systems. *Proc. of Healthy Buildings '94 conference, Budapest*, **2**, 521-526.

Roulet C.-A.; Foradini F and Deschamps L. [1998]: Measurement of Air Flow Rates and Ventilation Efficiency in Air Handling Units. *EPIC'98 conference, Lyon*, **3**, 970-975

Roulet C.-A.; Foradini F and Deschamps L. [1999]: Measurement of Air Flow Rates and Ventilation Efficiency in Air Handling Units. *Indoor Air '99 conference, Edinburgh*, **5**, 1-6

Roulet C.-A; Deschamps L.; Pibiri M.-C.; Foradini F. [1999]: *DAHU: Diagnosis of air Handling Units.* Joule Thermie AIRLESS report, 38 p, LESO-EPFL, Lausanne.

Roulet C.-A.; Foradini F and Pibiri M.-C [2000]: Accepted at Healthy Buildings 2000 conference (No 277)

Sandberg M. and Sjöberg M. [1984]: The Use of Moments for Assessing Air Quality in Ventilated Rooms. *Building and Environment* **18**, 181-197.