MEASUREMENT OF AIR FLOW RATES AND VENTILATION EFFICIENCY IN AIR HANDLING UNITS

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ABSTRACT

The use of tracer gas is of great help in measuring airflow rates and detecting shortcuts in air handling units, and is essential for ventilation efficiency measurement. However, the planning of experiments, that is choosing tracer gas injection locations and air sampling locations, is not straightforward. Moreover, the mathematics used for interpretation are quite complex, and require elaborate calculations. Therefore, a measurement protocol and the corresponding interpretation algorithms are being developed and implemented in a user-friendly computer program. This development is based on several years of practice in such measurements, and includes the solving of mundane but serious problems such as proper tracer gas mixing in air and representative sampling strategy.

The contribution presents the methods applied, the principles used in the test protocol, and an example of application to real air handling units.

KEYWORDS

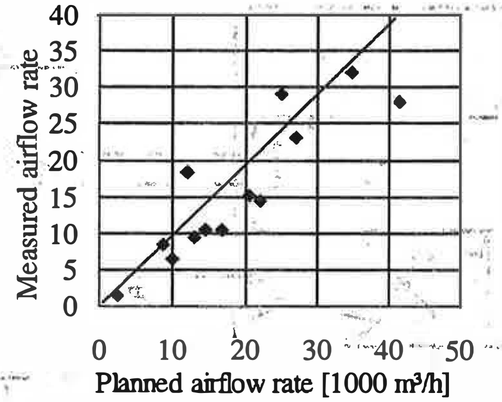
Ventilation, measurement, diagnostic, air handling units, tracer gas.

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].

Figure 1 shows a comparison between planned and measured airflow rates in 13 air handling units running in office buildings in Switzerland. Airflow rates ranging from 64% to 154% of the planned values were measured.

Recirculation rates deduced from CO_2 concentration measurements were compared to planned recirculation rates in 48 European office buildings equipped with mechanical ventilation. The recirculation rate differs from zero in 22 cases. Large discrepancies can be seen in Figure 2 for several of those buildings. Two buildings were found to have unexpected recirculation.



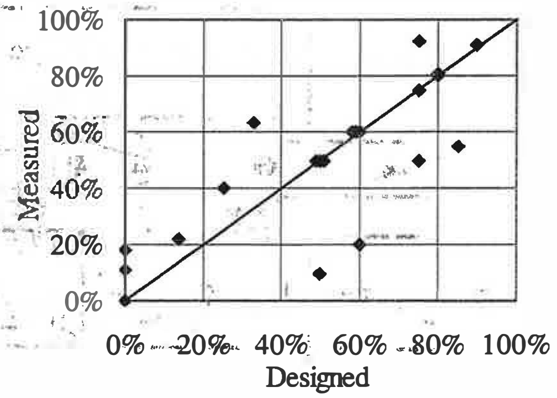


Figure 1: Measured airflow rates compared to design values [Roulet et al, 1994]

Figure 2: Measured recirculation rates compared to design values [Bluyssen et al, 1995].

Diagnosis tools would therefore be useful to detect dysfunction, preferably before or when commissioning the air handling unit. 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 are measured that way, while many other airflow paths may be found in an air handling unit, as shown on Figure 3.

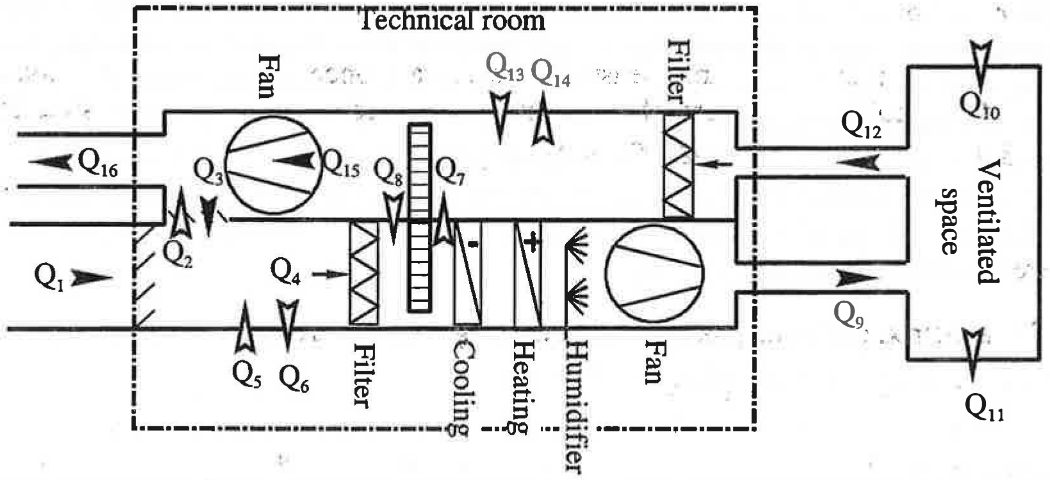


Figure 3: Schematics of an air handling unit showing main and secondary airflow paths.

METHOD

Measurement technique

Tracer gases are injected, most often at a constant flow rate, at carefully chosen locations in the air handling unit. Experience has shown that most practical and efficient injection locations are as indicated in Figure 4. 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
- Tracer three injected in the main return air duct

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.

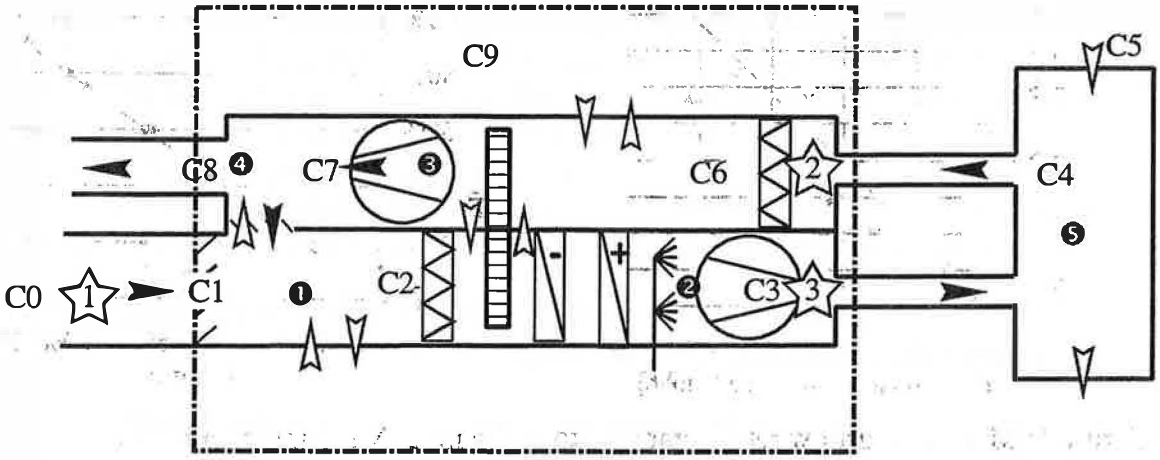


Figure 4: Locations of nodes (circled numbers), tracer gas injection (stars),and sampling points for concentration measurements (C_i).

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 the wanted airflow rates.

Interpretation

Using all three tracer gases and measuring tracer gas concentration at all locations shown in Figure 4, the following system of equations is obtained, assuming steady state and perfect mixing of tracer gas at sampling locations:

$$\vec{I} = C \cdot \vec{Q} \qquad 1$$

where:

C is a matrix, containing the measured tracer gas concentrations:

$$C=\begin{pmatrix}
1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & -1 & -1 & -1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 1 & 1 & -1 & -1 & 0\\
0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0\\
C_{11}-C_{10} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & C_{12} & C_{19} & -C_{12} & -C_{12} & C_{16} & -C_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{13} & C_{15} & -C_{14} & -C_{16} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & C_{12} & -C_{16} & 0 & 0 & 0 & C_{16} & C_{19} & -C_{16} & -C_{17} & 0\\
0 & C_{11} & -C_{17} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{17} & -C_{18}\\
C_{11} & -C_{11} & C_{17} & -C_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{26}-C_{24} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & C_{22} & C_{29} & -C_{22} & -C_{22} & C_{26} & -C_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{23} & C_{25} & -C_{24} & -C_{26} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & C_{22} & -C_{26} & 0 & 0 & 0 & C_{26} & C_{29} & -C_{26} & -C_{27} & 0\\
0 & C_{21} & -C_{27} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{27} & -C_{28}\\
C_{21} & -C_{21} & C_{27} & -C_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{33} & C_{35} & -C_{34} & -C_{36} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & C_{32} & C_{39} & -C_{32} & -C_{32} & C_{36} & -C_{33} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & C_{32} & -C_{36} & 0 & 0 & 0 & C_{36} & C_{39} & -C_{36} & -C_{37} & 0\\
0 & C_{31} & -C_{37} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{37} & -C_{38}\\
C_{31} & -C_{31} & C_{37} & -C_{32} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

In this matrix, the first subscript of C_{ij} denotes the tracer, while the second one refers to the sampling point. The first five lines of this matrix contain the coefficient of the conservation equations of air at the five nodes marked in Figure 4. The next line gives the coefficient of the conservation equation of tracer one in the outdoor air duct. The next five lines result from the conservation equations of tracer one at the five nodes. A second set of six lines relates to tracer two, the first line resulting from conservation in the main return duct. The last five lines relate to tracer 3, conservation laws being written at the five marked nodes.

$\bar{I}$ = (0, 0, 0, 0, 0, I_1, 0, 0, 0, 0, 0, I_2, 0, 0, 0, 0, 0, I_3, 0, 0, 0, 0) is the vector containing the tracer gas injection rates, the subscript denoting the tracer gas;

$\bar{Q} = \left(Q_1 \quad Q_2 \quad \ldots \quad Q_{16}\right)$ is the vector of the airflow rates to be determined.

This system contains 22 equations for only 16 unknowns. This opens several possibilities:

1. The over-determined system can be solved using least square analysis:

$$\bar{Q} = \left(C^T C\right)^{-1} C^T \bar{I} \tag{2}$$

2. Combining some of the equations of system (1) allows to avoid the measurement of certain concentrations. For example, adding equations 9, 10 and 11, 15, 16 and 17, and 20, 21 and 22 eliminates C_{17}, respectively C_{27} and C_{37}. The system is reduced to 16 equations and no measurement is required at location C7. There are other such possibilities to avoid measurements at C3, and, under some conditions, at C2, C4, C5, and C6.

3. A set of 16 equations can be selected to give the best accuracy. This can be done by calculating the condition number[1] of all the 26334 sets of 16 equations extracted from the full system, and taking the set with the smallest number.

If some of the 16 airflow rates are known to be zero, the system can be greatly simplified, since:

It there is:	That is if:	Then:
no inverse recirculation	$Q_2 = 0$	$C_{i7} = C_{i8}$ for $i = 1, 2,$ and 3
no recirculation (intended or not)	$Q_3 = 0$	$C_{i2} = C_{i1}$ for $i = 1, 2,$ and 3
no leaks to supply air handling unit	$Q_5 = Q_8 = 0$	$C_{i3} = C_{i2}$ for $i = 1, 2,$ and 3
no leaks to return air handling unit	$Q_7 = Q_{13} = 0$	$C_{i7} = C_{i6}$ for $i = 1, 2,$ and 3
an over-pressurised ventilated space	$Q_{10} = 0$	$C_{i6} = C_{i4}$ (for $i = 1$ and 3 only) $C_{i4} = C_{i3}$ (for $i = 1$ and 2 only)

In this case, the columns corresponding to non existent airflow paths, as well as the lines filled with zeros are deleted, which reduces the order of the systems of equations.

If less than three tracer gases are used, the corresponding equations should be deleted. In this case, some of the airflow ratess cannot be determined.

A special case is when only tracer 3 is used. This could be the carbon gas emitted in the ventilated space by occupants. That tracer gas is of great practical interest, since it does not need any injection system. In this case, equation 1 can easily be solved assuming that there is no inverse recirculation, and no leaks in the air handling unit. The recirculation rate is then:

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[1] The condition number is defined by $\left\|C\right\| \cdot \left\|C^{-1}\right\|$, where $\left\|C\right\|$ is the norm of C. A good norm is $\left\|C\right\| = \sqrt{\mu_1}$, where μ_1 is the largest eigenvalue of $C^T C$. (for more information, see [Bevinton, 1969])

$$R = \frac{Q_3}{Q_4} = \frac{C_{32} - C_{30}}{C_{36} - C_{30}} \qquad 3$$

And the outdoor airflow rate per occupant is:

$$\frac{Q_1 + Q_{10}}{N_{persons}} = \frac{0{,}017[\mathrm{m}^3/\mathrm{h}]}{C_{36} - C_{30}} \qquad 4$$

assuming that a person exhales 17 l/h carbon gas. Airflow rates are then in [m³/(h person)] if concentrations are in volumetric ratios. It is not possible, with only one tracer injected into the ventilated space, to differentiate between outdoor air from mechanical ventilation and from infiltration.

PLANNING TOOL

There are many types of air handling units, and each new measurement poses new problems. It is hence impossible to write a detailed measurement protocol valid for all types. Therefore, we developed a computer program that performs the following tasks:

1. Request input data:
   - Characterisation of the air handling unit (type , location, design airflow rates, heat exchanger, position of fans with respect to heat exchanger, etc.);
   - Tracer gas(es) used, injection location(s) and design concentration(s);
   - Characterisation of building (approximate volume, number of occupants, overpressurised or not, etc.;
   - Non existing airflows.
2. Evaluate the risk of poor tracer gas mixing from the distance between injection and sampling locations and from the devices (fans, bends, filters, dampers) placed in-between.
3. Evaluate the feasibility of the measurement, in particular whether there are enough equations to determine all remaining airflow rates. If not, request new input.
4. Prepare a printed measurement protocol containing injection and sampling locations, injection rates of tracer gases and system of equation (1).
5. Request measured concentrations or read them in a file.
6. Solve system (1) and prepare a measurement report.

EXAMPLE

Sulphur hexafluoride was injected as tracer one, and nitrogen protoxyde as tracer two in an air handling unit without planned recirculation, but equipped with a rotating heat exchanger. Resulting concentrations are shown in Figure 6, and measurement results in Figure 5.

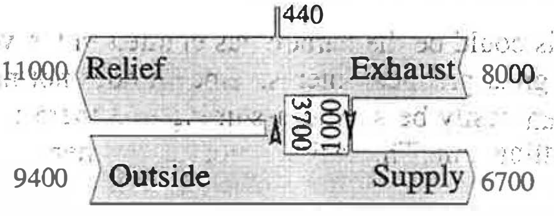

Figure 5: Measured airflow rates in a leaky air handling unit. Design airflow rates were 13'000 m³/h for both supply and return, and zero for recirculation.

Leaks in the heat exchanger, as well as in the return air channel were detected with this measurement. Measurement in three other identical units in the same office did not show any shortcut. However, measured outdoor airflow rates were between 55% and 66% of the design value.

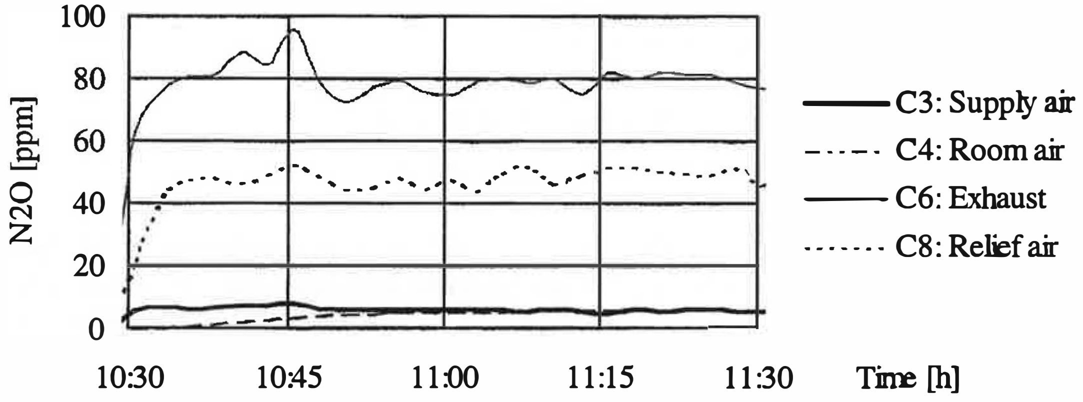

Figure 6: Concentrations at locations shown in Figure 4 resulting from injection of SF_6 as tracer 1 and N_2O as tracer 2, in a leaky air handling unit. Shortcut through the heat exchanger dilutes exhaust air, thus decreasing the relief air concentration. Presence of this tracer gas in supply air results from parasitic recirculation.

CONCLUSIONS

Diagnosis of airflow rates in air handling units often detects unexpected leakage and main airflow rates differing from design values. Therefore, methods that make commissioning easier will allow early detection of such dysfunction, thus improving both indoor air quality and efficiency of air handling units.

Main airflow rates as well as leaks and unexpected shortcuts can be easily measured in air handling units using the tracer gas technique, provided that the experiment is well designed and that computer tools help in interpreting the measurement data.

Note that such measurement may easily include a step-up or step-down experiment which allows to assess the mean age of air in the ventilated space [Sandberg and Sjöberg, 1984]. If the ventilated volume is known, the nominal time constant and hence the air change efficiency can be determined, allowing the detection of shortcuts and dead zones in the ventilated space.

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