Applying tracer gas technique for measurements in air handling units with large recirculation ratio

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ABSTRACT

Tracer gases are often used to assess airflow rates in air handling units. Published methods are mostly designed for units with recirculation ratios lower than those commonly found in Singapore and other tropical countries. Large recirculation ratio homogenize the concentrations, so that concentrations in supply and extract ducts are close to each other. In addition, such units often present a large time constant, so the time needed to reach equilibrium is very large. A procedure for tracer gas dilution technique adapted to such air-handling units is presented.

INDEX TERMS

Commissioning; Measurement technique; Recirculation; Tracer gas; Ventilation rate

INTRODUCTION

Methods to measure airflow rates using tracer gas are used since several decades (ASTM 1988; Roulet and Vandaele, 1991). They are, among other uses, applied for measuring outdoor airflow rates or all the airflow rates in air-handling units (Presser and Becker, 1988; Roulet *et al.*, 1994). The principle is to inject tracer gases in the inlet, supply and/or extract ducts at a known rate, I_k, to measure their equilibrium (steady state) concentrations, C_{ik}, at several carefully chosen locations, and to use the air and tracer gas conservation equation to interpret the measurements and get all required airflow rates Q_{ij}.

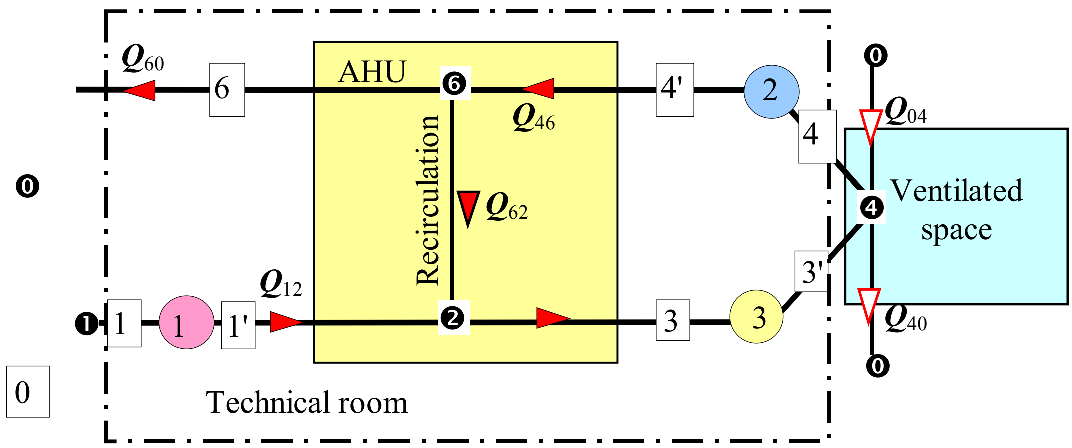

Figure 1 The simplified network representing the air handling unit and ducts. Numbers into black circles represent the nodes of the network. Circles are tracer gas injection locations, and

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numbered rectangles are air sampling locations. Arrows represent possible airflow rates Q_{ij} from node *i* to note *j*.

Most methods are designed to measure units with recirculation ratios below 50%. This is the case of the method proposed 2 years ago (Roulet *et al.*, 2000), together with an interpretation software. However, air-handling units designed to condition (heat or cool) spaces with large loads such as those found in cold or tropical climates often present large recirculation ratios that homogenize the concentrations, and large nominal time constant (ratio of the ventilated volume to the outdoor airflow rate) that strongly increase the time needed to get steady state. Among the several possible methods to assess airflow rates, some are better adapted to large recirculation ratios than others.

UNSTEADY STATE AND ASSESSMENT OF CONCENTRATIONS

Steady state is quickly reached within ducts, where the air velocity is 1 m/s or more. The concentration difference between air sampled downwind (far enough to get complete mixing) and upwind the tracer gas injection port becomes quickly constant. It, however, takes several hours in the ventilated volume to get the steady state concentration C_{6k} or C_{3k} (notations according to Figure 1).

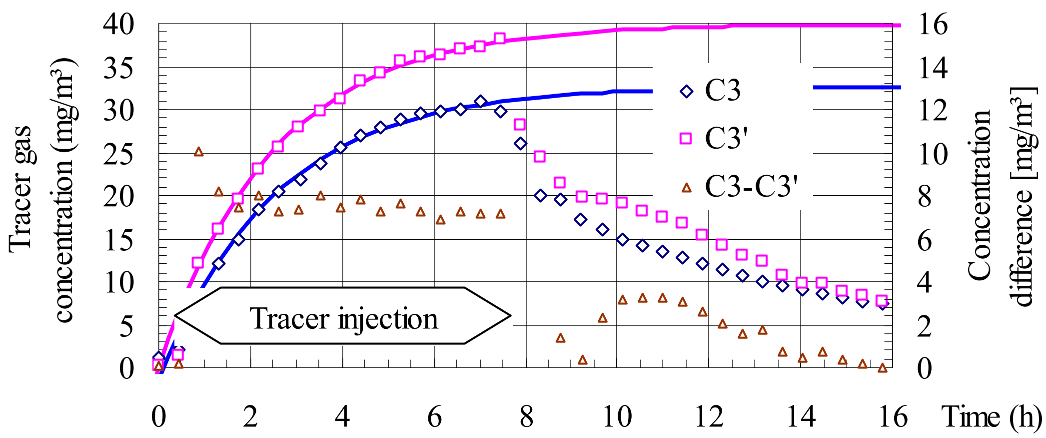

Figure 2 Tracer gas concentrations in supply duct, upwind (3) and downwind (3′) the tracer gas injection port. Dots are measured concentrations, while lines are exponential fits.

Writing the conservation equation of tracer gas 3 at node 4, in the ventilated space, gives:

$$V\frac{\partial C_{43}}{\partial t} = I_3 + Q_{24}C_{23} + Q_{04}C_{03} - (Q_{46} + Q_{40})C_{43} \tag{1}$$

Because of the large recirculation ratio, it can be assumed that the concentration is homogeneous in the ventilated space. Dividing this equation by the supply airflow rate Q_{24} gives:

$$\frac{V}{Q_{24}}\frac{\partial C_{43}}{\partial t} = \frac{I_3}{Q_{24}} + C_{23} + \gamma_i C_{03} - (1+\gamma_i)C_{43} \tag{2}$$

where γ_i is the infiltration ratio Q_{04}/Q_{24}. Using the definition of the nominal time constant ι_n, of the recirculation ratio R, and using the tracer gas conservation at node 2:

$$\frac{V}{Q_{24}} = \frac{V}{Q_{01}}\frac{Q_{01}}{Q_{24}} = \tau_n(1-R) \qquad \text{and} \qquad C_{23} = RC_{43} + (1-R)C_{03} \tag{3}$$

we get

$$\tau_n(1-R)\frac{\partial C_{43}}{\partial t} = \frac{I_3}{Q_{24}} - (1-R+\gamma_i)(C_{43} - C_{03}) \tag{4}$$

The steady state concentration is:

$$C_{43}^{\infty} = \frac{I_3}{Q_{34}\left(1 - R + \gamma_i\right)} + C_{03} \tag{5}$$

and $$C_{43}(t) = C_{43}^{\infty}\left(1 - e^{-\frac{t}{\tau}}\right) \quad \text{with} \quad \tau = \frac{\tau_n\left(1 - R\right)}{1 - R + \gamma_i} \tag{6}$$

The theoretical exponential can be fitted on the experimental points, allowing the determination of the steady state concentration and time constant (Figure 2) without waiting for the equilibrium. In this example of actual measurement, the effective time constant $\tau = 2{,}5$ hours. The measurement time should be however large enough to get sufficient accuracy. A minimum is one nominal time constant, but two is preferred.

AIRFLOW RATES

Assessment of Airflow Rates from Measurements

In the method shortly presented in Roulet and Vandaele (1991), it is recommended to inject the tracer gases in the outdoor and extract air ducts (locations 1 and 2 in Figure 1). Air sampling for tracer gas analysis concentration should be taken where complete mixing is achieved, i.e. up to 25 diameters in straight ducts, but less than 3 diameters downwind bends, fans, heat exchangers, etc. In case of mixing problems, tracer could be injected at several places in the same duct section. Supply and extract airflow rates are determined by the following relations (notations according to Figure 1).

The airflow rates, calculated from air and tracer gas mass conservation equations are (I_k is the injection rate of tracer k, and C_{jk} is the steady state concentration of tracer k at location j):

Intake airflow rate $$Q_{12} = \frac{I_1}{C_{1'1} - C_{11}} \tag{7}$$

Supply airflow rate, assuming that the air-handling unit is airtight (tracer k = 2 recommended):

$$Q_{24} = Q_{12}\frac{C_{6k} - C_{1k}}{C_{6k} - C_{3k}} \tag{8}$$

Extract airflow rate $$Q_{46} = \frac{I_2}{C_{62} - C_{42}} \tag{9}$$

Recirculation flow rate $$Q_{62} = Q_{12}\frac{C_{3k} - C_{1k}}{C_{6k} - C_{3k}} \tag{10}$$

Or, alternatively $$Q_{62} = Q_{24}\frac{C_{3k} - C_{1k}}{C_{6k} - C_{1k}} \tag{11}$$

Another alternative is to calculate Q_{62} from the recirculation ratio R, if R is assessed using Eqn (33):

$$Q_{62} = R\,Q_{24} \tag{12}$$

Infiltration flow rate (with $k \neq 3$, recommended value: $k = 1$):

$$Q_{04} \cong Q_{24}\frac{\left(C_{3'k} - C_{4k}\right)}{\left(C_{4k} - C_{0k}\right)} = Q_{12}\frac{\left(C_{6k} - C_{1k}\right)\left(C_{3'k} - C_{4k}\right)}{\left(C_{6k} - C_{3k}\right)\left(C_{4k} - C_{0k}\right)} \tag{13}$$

Exfiltration flow rate $$Q_{40} = Q_{04} + Q_{24} - Q_{46} \tag{14}$$

Exhaust airflow rate $$Q_{60} = Q_{04} - Q_{40} + Q_{01} \tag{15}$$

Error Analysis

The error analysis is based on the assumption that random and independent errors soil the measurements of tracer gas concentration and injection rates. In this case, the confidence interval of any result, for example, an airflow rate, is:

$$[Q-\delta Q; Q+\delta Q] \quad \text{with} \quad \delta Q(x_i) = T(P,\infty)\sqrt{\sum_i \left(\frac{\partial Q}{\partial x_i}\right)^2 \delta x_i^2} \tag{16}$$

where:

T(P, ∞) is the Student coefficient for having the actual value within the confidence interval with probability $1 - P$

x_i is any variable on which the airflow rate Q depends.

δx_i is the standard deviation of the variable x_i, assumed to be a random variable of mean x_i. and normal distribution.

The confidence intervals of the airflow rates are then:

Intake airflow rate $$\delta Q_{12} = T(P,\infty)\sqrt{\frac{\left(C_{1'1}-C_{11}\right)^2 \delta I_1^2 + I_1^2\left(\delta C_{1'1}^2 + \delta C_{11}^2\right)}{\left(C_{1'1}-C_{11}\right)^4}} \tag{17}$$

Supply airflow rate $$\delta Q_{24} = \sqrt{\delta Q_{12}^2 + \delta Q_{62}^2} = \frac{T(P,\infty)}{\left(C_{6k}-C_{3k}\right)^2}\sqrt{f_{24}} \tag{18}$$

where: $$\begin{aligned} f_{24} &= \left(C_{6k}-C_{1k}\right)^2\left(C_{6k}-C_{3k}\right)^2 \delta Q_{12}^2 + \\ &+ Q_{12}^2\left[\left(C_{6k}-C_{3k}\right)^2 \delta C_{1k}^2 + \left(C_{6k}-C_{1k}\right)^2 \delta C_{3k}^2 + \left(C_{1k}-C_{3k}\right)^2 \delta C_{6k}^2\right] \end{aligned} \tag{19}$$

Extract airflow rate $$\delta Q_{46} = T(P,\infty)\sqrt{\frac{\left(C_{62}-C_{42}\right)^2 \delta I_2^2 + I_2^2\left(\delta C_{62}^2 + \delta C_{42}^2\right)}{\left(C_{62}-C_{42}\right)^4}} \tag{20}$$

Recirculation flow rate $$\delta Q_{62} = \frac{T(P,\infty)}{\left(C_{6k}-C_{3k}\right)^2}\sqrt{\left(C_{6k}-C_{3k}\right)^2\left(C_{3k}-C_{1k}\right)^2 \delta Q_{12}^2 + Q_{12}^2 f_{62}} \tag{21}$$

where: $$f_{62} = \left(C_{6k}-C_{3k}\right)^2 \delta C_{1k}^2 + \left(C_{6k}-C_{1k}\right)^2 \delta C_{3k}^2 + \left(C_{3k}-C_{1k}\right)^2 \delta C_{6k}^2$$

alternatively $$\delta Q_{62} = \frac{T(P,\infty)}{\left(C_{6k}-C_{1k}\right)^2}\sqrt{\left(C_{6k}-C_{1k}\right)^2\left(C_{3k}-C_{1k}\right)^2 \delta Q_{24}^2 + Q_{24}^2 f'_{62}} \tag{22}$$

where: $$f'_{62} = \left(C_{6k}-C_{3k}\right)^2 \delta C_{1k}^2 + \left(C_{6k}-C_{1k}\right)^2 \delta C_{3k}^2 + \left(C_{3k}-C_{1k}\right)^2 \delta C_{6k}^2$$

or if calculated from Eqn (12): $$\delta Q_{62} = T(P,\infty)\sqrt{R^2 \delta Q_{24}^2 + Q_{24}^2 \delta R^2} \tag{23}$$

Infiltration: $$\delta Q_{04} = \frac{T(P,\infty)}{\left(C_{4k}-C_{0k}\right)^2}\sqrt{\left(C_{3'k}-C_{4k}\right)^2\left(C_{4k}-C_{0k}\right)^2 \delta Q_{24}^2 + Q_{24}^2 f_{04}} \tag{24}$$

with $$f_{04} = \left(C_{3'k}-C_{4k}\right)^2 \delta C_{0k}^2 + \left(C_{4k}-C_{0k}\right)^2 \delta C_{3'k}^2 + \left(C_{3'k}+C_{0k}\right)^2 \delta C_{4k}^2 \tag{25}$$

Exfiltration $$\delta Q_{40} = \sqrt{\delta Q_{04}^2 + \delta Q_{24}^2 + \delta Q_{46}^2} \tag{26}$$

Exhaust $$\delta Q_{60} = \sqrt{\delta Q_{04}^2 + \delta Q_{40}^2 + \delta Q_{01}^2} \tag{27}$$

Effect of Large Recirculation Ratio

In Eqns (8), (10) and (13) the concentrations difference $C_{6k} - C_{3k}$ is at the denominator, and these two concentrations are close to each other at steady state when the recirculation ratio is high. This leads to a large confidence interval of the calculated airflow rates. In this case, it is better to inject the tracer gas at location 3 instead of location 2. The supply airflow rate can then be determined with a better accuracy, using:

$$Q_{24} = \frac{I_3}{C_{3'3} - C_{33}} \tag{28}$$

The confidence interval being calculated, *mutatis mutandis*, using Eqn (17) or, assuming that the confidence interval is the same for both concentrations:

$$\frac{\delta Q}{Q} \cong T(P,\infty)\sqrt{\left(\frac{\delta I}{I}\right)^2 + 2\left(\frac{\delta C}{C'-C}\right)^2} \tag{29}$$

The recirculation airflow rate can then be calculated using:

$$Q_{62} = Q_{24} - Q_{12} \tag{30}$$

with:
$$\delta Q_{62} = T(P,\infty)\sqrt{\delta Q_{24}^2 + \delta Q_{12}^2} \cong T(P,\infty)\sqrt{1+(1-R)^2}\ \delta Q \tag{31}$$

assuming that the relative error $\delta Q/Q$ is the same for both airflow rates, and taking into account that $Q_{12} = (1 - R)\ Q_{24}$. Note that, in this case, δQ_{62} decreases when R increases.

The extract airflow rate Q_{46} cannot be assessed without injecting a tracer gas in the extract duct. However, in air handling units having no exhaust duct (such as most units in Singapore and other topical countries), $Q_{60} = 0$, hence $Q_{46} = Q_{62}$, and $Q_{40} = Q_{01} + Q_{04}$.

Recirculation Ratio

The recirculation ratio is defined by:

$$R = \frac{Q_{62}}{Q_{24}} = \frac{Q_{62}}{Q_{62} + Q_{12}} \tag{32}$$

Assuming that there is no leak in the air-handling unit, it can be assessed using:

Method **A**
$$R = \frac{C_{3k} - C_{1'k}}{C_{6k} - C_{1'k}} \tag{33}$$

the subscript k being for any tracer gas except the one injected in inlet duct. The confidence interval is:

$$\delta R = \frac{T(P,\infty)}{\left(C_{6k} - C_{1'k}\right)^2}\sqrt{f_R} \tag{34}$$

where:
$$f_R = \left(C_{3k} - C_{6k}\right)^2 \delta C_{1'k}^2 + \left(C_{6k} - C_{1'k}\right)^2 \delta C_{3k}^2 + \left(C_{3k} - C_{1'k}\right)^2 \delta C_{6k}^2 \tag{35}$$

If we assume that the relative error is the same for all concentrations, and taking into account that, for tracers injected at locations 2 and 3, $C_{1'k} \cong 0$ and therefore $C_{3k} \cong RC_{6k}$, we can get a simpler expression for the confidence interval of the recirculation ratio:

$$\delta R \cong \frac{T(P,\infty)\ \delta C}{C}\sqrt{2(R^2 - R + 1)} \tag{36}$$

The recirculation ratio can also be calculated using:

Method **B** $\quad R = \dfrac{Q_{62}}{Q_{24}} \quad$ with $\quad \delta R = \dfrac{\delta Q}{Q}\sqrt{(1+R)} \quad (37)$

or method **C** $\quad R = 1 - \dfrac{Q_{12}}{Q_{24}} \quad$ with $\quad \delta R = \sqrt{2}\,\dfrac{\delta Q}{Q}(1-R) \quad (38)$

assuming that the relative error $\delta Q/Q$ is the same for both airflow rates, and taking into account that $Q_{12} = (1 - R)\ Q_{24}$.

DISCUSSION

The three methods for determining *R* are compared in Figure 3. Method A (Eqn 33) should be preferred at low recirculation ratio, while method C is best at large recirculation ratio. Method B could be applied at low recirculation if method A cannot be applied.

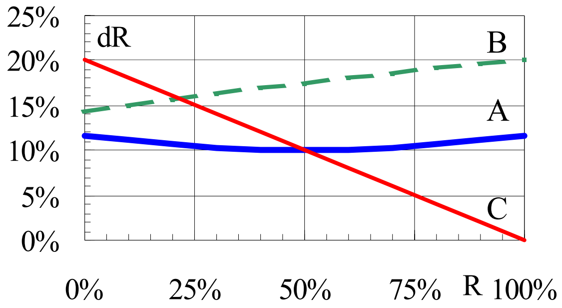

Figure 3 Confidence interval of the recirculation ratio as a function of the recirculation ratio itself, for three assessment methods. For this figure, the relative confidence interval (at 90%) of injection rate and concentrations is 5%.

CONCLUSIONS AND IMPLICATIONS

An error analysis shows that some ways of interpreting the measurement provide more accurate results than others, and that the best way depends on the unit measured. Therefore, care should be taken to select the most appropriate method. Measurement time could be shortened by fitting the dynamic expression of concentration on the experimental points to assess the steady state concentration without reaching it.

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