

Improving an IR Tracer Gas Analyser by Digital Filtering

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An algorithm is described by which the time between samples can be greatly reduced in a multipoint measuring system with an infrared gas analyser. Normally such a system is rather slow due to the large cuvette volume of the analyser. By using a simple correctional algorithm the sample period can be reduced from approximately 30-45 s to 10-15 s without substantial loss of precision. It is required that the air flow through the analyser is maintained constant. The algorithm is derived using a digital filter designing technique.

1. INTRODUCTION

IN RECENT years the performance of ventilation systems often has been evaluated on models derived from age distribution theory [1], and two common models are the mean age of air and the air exchange efficiency [1-3]. Tracer gas techniques have been used for evaluating a ventilation system. Multipoint measuring systems with one infrared (IR) gas analyser have been used in several tracer gas studies [3-5]. The maximum frequency with which the air from the sampling points can be analysed sequentially is determined by the time constant of the system. The purpose of this study was to develop a general method for speeding up the performance of an IR analyser. Methods for improved performance of a gas chromatograph, another common tracer analyser, is discussed elsewhere [6, 7].

A diagram of a multipoint measuring system is shown in Fig. 1. To minimize any delay of the tracer gas analysis caused by long sample tubing all tubes of the system are continuously flushed using gas-tight pumps. The tracer-air mixture from points being sampled by the system is delivered sequentially from the channel selector to the gas analyser. Previous studies have emphasized that the gas analyser must be stabilized before the tracer concentration is recorded [5]. An IR analyser cannot respond instantaneously to rapid variations in concentrations of the sampled airflow due to the inherent time constant caused by the rather large cuvette volume of the analyser. Consequently the recorded concentration signal may be distorted compared to the true concentration value of the sampled airflow. The distortion may be decreased by increasing the sampling flow rate [4]. The distortion may, however, be eliminated by calculating the true concentration values from the measured and distorted signal by means of a simple algorithm (a digital filter). The theory on which the present study is based—digital signal

processing—is summarized first, and subsequently the performance of the developed algorithm is validated on data obtained from extreme experimental conditions in the laboratory.

2. THEORY

Let the cuvette volume of an IR analyser be denoted V , and the constant sampling flow rate denoted Q . A nominal time constant of the cuvette is denoted τ , and $\tau = V/Q$. At any time the true tracer concentration of the sampled air is $G(t)$ and the cuvette concentration is $C(t)$. A spatial homogeneous cuvette concentration is assumed, and $C(t)$ may be estimated from a tracer mass balance of the cuvette:

$$dC(t)/dt = 1/\tau(G(t) - C(t)). \quad (1)$$

The time period required for an IR analyser to perform a single tracer analysis is denoted δ . The analyser delivers the time-weighted average of the absorbance and the concentration obtained from the calibration function is denoted $M(t)$. Now, as an approximation, it is assumed that $M(t)$ is the true time-weighted average of $C(t)$:

$$M(t) = 1/\delta \int_{t-\delta}^t C(t') dt'. \quad (2)$$

Consider a sequential sampling technique as shown in

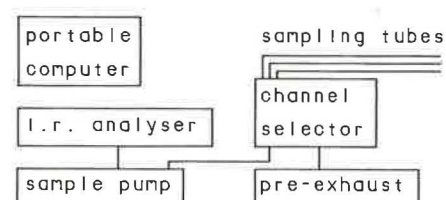


Fig. 1. Multipoint measuring unit.

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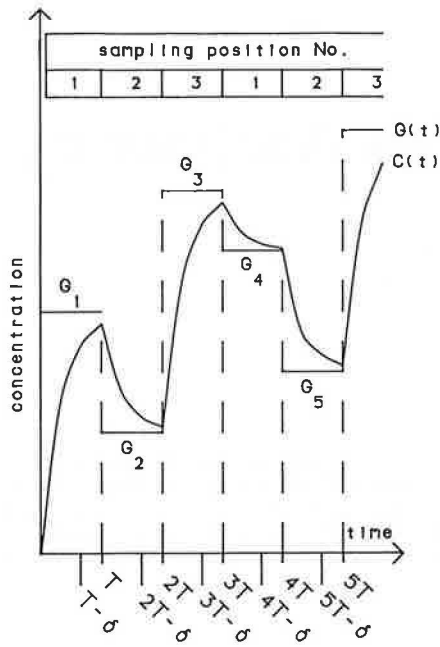


Fig. 2. Sequential sampling of the tracer concentration at 3 different positions.

Fig. 2. In succession each location is allowed a constant sampling period T for sucking the tracer-air mixture through the IR analyser and to perform the analysis. At $t = (n-1)T$ ($n = 1, 2, \dots$) the channel selector connects a new sampling line to the IR analyser and the cuvette is flushed for the time period $(n-1)T - nT$. The analyser commences the analysis at $t = (n-1)T + (T - \delta)$, and the analysis is completed at $t = (n-1)T + (T - \delta) + \delta = nT$. The concentration $M(nT)$ obtained at $t = nT$ is given by equations (1) and (2). As an approximation it is now assumed that $G(t)$ of the sampled location is constant throughout the sampling period $(n-1)T - nT$. Let this constant concentration be denoted $G(nT)$, and from Fig. 2 is observed that $G(0) = 0$ is assumed. By digital filtering the true concentration $G(nT)$ may now be calculated from the distorted concentrations $M(nT)$, $M((n-1)T), \dots$. In the discipline of digital signal processing the calculation is performed by constructing a digital filter D (Fig. 3) with the true concentration $G(nT)$ as the output.

As shown in Fig. 2 $G(nT)$ is assumed to change in a stepwise manner, and the digital filter is designed so the system in Fig. 3 responds correctly upon the step-function $H(t)$:

$$G(t) = H(t) = \begin{cases} 1 & \text{for } t \geq 0 \\ 0 & \text{for } t < 0. \end{cases} \quad (3)$$

From equations (1)–(3):

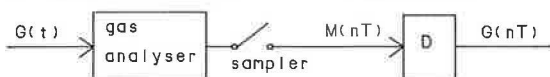


Fig. 3. A model of the gas analyser and the digital filter signals. $G(t)$ is the continuous input, and discretely (at $t = nT$) the sampler delivers a signal to the filter D . The discrete output from the filter is $G(nT)$.

$$C(t) = 1 - \exp(-t/\tau), \quad t \geq 0, \quad (4)$$

$$M(t) = 1 - \tau/\delta(\exp(\delta/\tau) - 1) \times \exp(-t/\tau), \quad \text{for } t = T, 2T, \dots \quad (5)$$

By introducing the constant a , equation (5) can be rewritten as:

$$M(t) = 1 - a \exp(-t/\tau), \quad \text{for } t = 0, T, 2T, \dots \quad (6)$$

where the constant a is given by:

$$a = \tau/\delta(\exp(\delta/\tau) - 1) \exp(-T/\tau). \quad (7)$$

In digital signal processing a transformation called the z -transformation is a useful remedy [8, 9]. For a sequence X_1, X_2, \dots, X_n , the z -transform is defined by:

$$X(z) = \sum_n X_n z^{-n}, \quad (8)$$

where z is a complex variable and plays a role similar to that of the variable s in the Laplace transform. From tables on z -transforms [9]:

$$G(z) = \frac{z}{(z-1)} \quad \text{and} \quad M(z) = \frac{z}{(z-1)} - \frac{az}{(z-A)}, \quad (9)$$

where $A = \exp(-T/\tau)$.

From Fig. 3 is seen that $D(z) = G(z)/M(z)$. Using equation (9) yields:

$$D(z) = \frac{1 - Az^{-1}}{1 - a + (a-A)z^{-1}}. \quad (10)$$

It can be shown that equation (10) translates to:

$$G_n = \frac{1}{1-a} (M_n - AM_{n-1} - (a-A)G_{n-1}), \quad (11)$$

where $G_n = G(nT)$ and $M_n = M(nT)$.

Consider as a special case a gas analyser with an averaging time much less than the sample period, i.e. $\delta \ll T$. As $a \rightarrow A$ for $\delta \rightarrow 0$ the algorithm of equation (11) simplifies to:

$$G_n = \frac{1}{1-A} (M_n - AM_{n-1}). \quad (12)$$

In a well-mixed chamber with an initial concentration $C(0) = 0$, and with a constant inlet concentration $G(T) = C(\infty)$ equation (12) reduces to the well-known form:

$$C(\infty) = G(T) = \frac{C(T)}{(1 - \exp(-T/\tau))}. \quad (13)$$

3. EXPERIMENTAL CONDITIONS

The performance of the developed algorithm [equation (11)] was validated in the laboratory using a previous reported multipoint measuring system [10]. A diagram of the system is shown in Fig. 1. The algorithm was programmed and installed as a real time procedure in the data acquisition programme of the system. Using gas-tight pumps the constant sampling flow rate of the system was $33 \text{ dm}^3 \text{ m}^{-1}$, and the cuvette volume of the IR analyser (Foxboro Analytical Miran 80) was 5.6 dm^3 , i.e. $\tau = V/Q = 10.2 \text{ s}$. Commencing an analysis the analyser performed an initial stability-check followed by the ana-

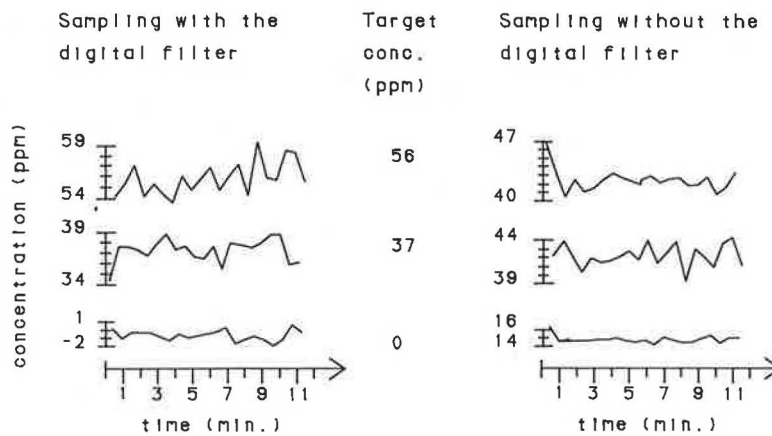


Fig. 4. Measured tracer gas concentrations of the exposure chambers.

lytical procedure at the selected analytical wavelength (10.829 μm). The time period allowed for the stability-check was adjustable and in this study fixed at the minimum (approximately 5 s). The analyser had an adjustable time period, δ , to perform the analytical procedure, and in the study δ was fixed at the minimum (approximately 5 s). From simulation on previous data (unpublished) the algorithm had shown an optimal performance with the parameters $\tau = 8.7$ s and $\delta = 4.6$ s, and it is noted that these were used for the algorithm throughout the study. The IR was calibrated for SF_6 concentrations ranging 0–60 ppm, and the accuracy of the analysis was estimated to be $\pm 5\%$ [10].

In the laboratory 7 separate experiments were performed for validating the performance of the algorithm as a function of the allowed sampling period T . In an experiment a sampling period T was selected and the tracer concentrations at the centre of three separate bench-top exposure chambers were sequentially measured for a 30 min period. Each chamber (volume 25 dm^3) was ventilated at constant temperature with clean air (no tracer) at a constant air flow rate (50 $\text{dm}^3 \text{min}^{-1}$) controlled by a calibrated rotameter at an estimated accuracy of $\pm 5\%$. The outlet from the chambers was vented outside the laboratory. A constant chamber tracer concentration was generated by labelling the supply air with tracer gas (SF_6). From a pressurized bottle the tracer gas was introduced into the air supply at a constant flow rate controlled by a calibrated rotameter at an estimated accuracy of $\pm 3\%$. The three selected constant target tracer concentration levels were: 32 ppm (chamber 1), 0 ppm (chamber 2) and 44 ppm (chamber 3).

4. RESULTS

All the tracer gas test results were collected on the hard disk of the computer for subsequent analysis. The condensed results of all the experiments are listed in Table 1. Due to an insufficient algorithm some of the estimated mean concentrations in chamber 2 came out to be negative values. Though without any physical reality these concentrations have been listed in Table 1 with the negative sign. A one-way analysis of variance showed a statistically significant ($\alpha = 0.05$) influence of the sampling

period T on the concentration levels obtained from the exposure chambers 1 and 2, but not on the concentrations obtained from chamber 3. No systematic influence, however, was observed from the sampling period T .

To illustrate the performance of the algorithm the measured concentrations from an experiment ($T = 11$ s) plotted against time are shown in Fig. 4. It is noted that the plotted data originate from an experiment where the three selected tracer gas concentration levels were: 56 ppm (chamber 1), 0 ppm (chamber 2) and, 37 ppm (chamber 3). For comparison Fig. 4 also shows the concentrations obtained from an identical experiment without using the digital filter.

5. DISCUSSION

Tracer gas techniques have been used to measure interzonal air flows and the performance of ventilation systems in buildings. For these applications tracer gas-air samples have to be taken at various locations in the building. The sampling interval has to be as short as possible, so that an adequate number of samples can be collected from each sampling location in a reasonable length of time. This may be achieved by using multiple intercalibrated tracer analysers [11]. A convenient alternative may, however, be a multipoint measuring unit with a single tracer analyser having an adequate response in the time domain. An improved performance of a gas chromatograph has been achieved by various multi-

Table 1. The dynamic performance in the time domain of an IR analyser with a digital filter

Sampling period T (s)	Measured chamber tracer concentration levels* (ppm)		
	Chamber 1	Chamber 2	Chamber 3
11	31.3 \pm 1.2	-1.1 \pm 0.5	43.0 \pm 0.9
15	31.8 \pm 1.2	-0.4 \pm 0.2	43.5 \pm 0.8
20	31.2 \pm 0.9	0.0 \pm 0.1	43.6 \pm 0.9
25	30.2 \pm 0.8	0.1 \pm 0.1	44.2 \pm 0.7
30	30.3 \pm 0.7	0.1 \pm 0.1	43.8 \pm 0.9
35	32.1 \pm 0.6	0.2 \pm 0.0	43.5 \pm 1.0
55	31.9 \pm 0.6	0.0 \pm 0.0	43.9 \pm 0.9

* Arithmetic mean \pm standard deviation.

column techniques [6, 7]. Previously increasing the sampling rate has been recommended for improving the performance of an IR analyser [4], and the digital filter described in this study is a further improvement.

The digital filter was validated from extreme experimental conditions using a maximum step-change of 42 ppm. The algorithm assumes $G(0) = 0$, and as a further challenge of the digital filter this assumption was violated deliberately by selecting $G(0) = 32$ ppm. The IR analyser delivered a time-weighted average of the absorbance, and a tracer concentration was obtained from a non-linear calibration function. The digital filter was developed assuming $C(nT)$ to be a time weighted average [equation (2)]. Further data analysis (unpublished) showed, however, an insignificant error ($1\% <$) due to the non-linear calibration function. The nominal cuvette time constant was $\tau = 10.2$ s but the optimal algorithm performance was achieved for $\tau = 8.7$ s indicating a slightly incomplete mixing process of the cuvette volume. As may be observed from equation (13) the algorithm is sensitive to the time constant τ : putting $T = 11$ s in equation (13) and using $\tau = 10.2$ s instead of $\tau = 8.7$ s causes a 9% error of the concentration obtained.

From Table 1 the sampling period T had a statistical significant ($\alpha = 0.05$) influence on the obtained tracer concentration levels from exposure chambers 1 and 2,

but not on the concentrations obtained from chamber 3. No systematic influence of the sampling period T on the obtained concentration levels was observed. Assuming the target concentration of chamber 1 (32 ppm) to be the true concentration the maximum error from the digital filter was less than 6%. Accepting this minor error a sampling period of 11 s can be used, and as may be observed from Fig. 4 heavily distorted tracer concentrations would be obtained using a sampling period of 11 s without the digital filter. Studies using IR analysers previously have reported sampling periods ranging 30–45 s [3–5, 12].

The algorithm was programmed and installed as a real time procedure of a data acquisition programme. The algorithm may, however, also be applied for computing on raw data sampled in the field by a data logger.

6. CONCLUSION

By the derived algorithm the sampling period of a multipoint measuring system using an IR gas analyser may be reduced from approximately 30–45 s to 10–15 s, the lower limit set by the time period required to perform the analysis. The improved performance is obtained without substantial loss of precision. It is required that the sampling flow rate through the analyser is kept constant.

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