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A comparison of tracer-gas techniques for measuring air flow in a duct

S B RIFFAT*

A description of the use of tracer-gas techniques for measuring air flow in ducts is presented. Experimental procedures for the use of the constant-injection, pulse-injection and concentration-decay techniques are discussed. This paper also describes a new tracer-gas system with variable sampling speed, which was used to measure the decay of tracer-gas concentration. Measurements of air flow made with each of the three tracer-gas techniques are compared with measurements made with a pitot tube. The closest agreement is observed for measurements made with the constant-injection technique.

1 List of symbols

C	concentration of tracer gas, ppm
C_0	concentration of tracer gas at $t = 0$, ppm
F	volumetric flow rate, m^3/s
V	effective volume of the duct, m^3
q	injection flow rate of tracer gas, m^3/s
G	volume generation rate of tracer gas, m^3/s
I	air exchange rate, h^{-1}
t	time, s
X	distance from the duct inlet in the direction of flow, m
D_h	hydraulic diameter of duct, m
W	width of duct, m
H	height of duct, m
α	an instant in time within a given interval, s

2 Introduction

Air flow in ducts is of considerable engineering importance in the design of HVAC systems, nuclear reactors and gas turbines. Measurements of air flow in ducts are usually carried out using hot-wire anemometers, pitot tubes or laser doppler velocimeters. Tracer-gas techniques offer an alternative approach, and although they have been widely used for measuring ventilation in buildings[1–4], only limited work has been published regarding their use for measuring air flow in ducts[5–6]. The present study investigates the application of these techniques, and compares the results obtained with tracer-gas methods with those obtained with a pitot tube.

3 Application of tracer-gas techniques for measuring air flow in ducts

3.1 Constant-injection technique

The constant-injection tracer-gas technique can be used to measure air flow in ducts. Assuming that the air and tracer gas are perfectly mixed within the duct, and that the concentration of tracer gas in the outside air is zero, the mass balance equation is:

$$V\,dC_{(t)}/dt + F_{(t)}\,C_{(t)} = q_{(t)} \qquad (1)$$

The duct air-exchange rate I is given by:

$$I_{(t)} = F_{(t)}/V \qquad (2)$$

Assuming that both the injection rate of tracer gas into the duct and the air exchange rate are constant during the measurement, the solution of equation (1) is:

$$C_{(t)} = q/F + (C - q/F)\exp(-It) \qquad (3)$$

If the system were close to equilibrium, the concentration of tracer gas would change slowly and the rate of change of concentration of tracer gas would be small. After a sufficiently long period, the transient term in equation (3) would die out and the flow rate through the duct would simply be given by:

$$C = q/F \qquad (4)$$

Hence, if measurements of tracer-gas flow rate and concentration can be made, F can be evaluated.

3.2 Pulse-injection technique

This technique is based on the injection into the duct inlet of a short-duration pulse of tracer gas, at a rate $G_{(t)}$. The variation of concentration with time is measured at the duct exit. The amount of injected tracer gas is small, so it does not contribute significantly to the volume flow rate of air in the duct.

If we assume that the tracer gas is well mixed across the section of the duct, then the volume flow rate of tracer gas leaving the duct is equal to the product of the flow rate and the exit concentration—ie $F_{(t)}C_{(t)}$. If the tracer gas is assumed to be purged from the duct after a time interval (t_1 to t_2) then the volume of tracer gas leaving the duct must equal the amount injected. Applying the integral volume balance of tracer gas, we have:

$$\int_{t_1}^{t_2} F_{(t)}\,C_{(t)}\,dt = \int_{t_1}^{t_2} G_{(t)}\,dt \qquad (\text{for } F_{(t)} \geqslant 0) \qquad (5)$$

The integral mean value theorem can be applied to equation (5) as follows:

$$F_{(\alpha)} = \left[\int_{t_1}^{t_2} C_{(t)}\,dt\right]^{-1} \int_{t_1}^{t_2} G_{(t)}\,dt \qquad (\text{for } t_1 \leqslant \alpha \leqslant t_2) \qquad (6)$$

3.3 Concentration-decay technique

This method involves an initial injection of tracer gas into the duct. The gas is allowed to mix with the internal air while the duct fan is switched off. Then the fan is switched on and the concentration of tracer gas is monitored over

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*S B Riffat, BSc Dipl Tech MSc DPhil CEng MIMechE MInstE MASHRAE, Lecturer in Building Services Engineering, Department of Civil Engineering, Loughborough University of Technology, Leicestershire, LE11 3TU.

given time interval. Assuming that the concentration of tracer gas in the outdoor air is negligible, and that there is no source of tracer gas within the duct (ie $q_{(t)} = 0$), equation (1) becomes:

$$V\, dC_{(t)}/dt = -F_{(t)}\, C_{(t)} \tag{7}$$

This can be rearranged to give:

$$dC_{(t)}/C_{(t)} = -(F_{(t)}/V)\, dt \tag{8}$$

Equation (8) can be solved by integration (assuming that F is constant) as follows:

$$\int_{C_{(0)}}^{C_{(t)}} dC_{(t)}/C_{(t)} = -(F/V) \int_{t=0}^{t=t} dt \tag{9}$$

Hence:

$$\ln(C_{(t)}/C_{(0)}) = -(F/V)t \tag{10}$$

Equation (10) can be rewritten as follows:

$$C_{(t)} = C_{(0)} \exp(-It) \tag{11}$$

This technique does not require the absolute concentration of tracer gas to be measured. If the logarithm of the tracer-gas concentration is plotted against elapsed time, the slope of the line is equal to I. The volumetric flow rate F can be determined by multiplying the air-change rate I by the internal volume of the duct.

4 Experimental

The duct shown in Fig. 1 was constructed from plywood 12 mm thick. The entrance to the duct consisted of a bell-mouth made from wooden bars, and the duct itself was 3 m long with an internal cross-section of 250 mm x 40 mm. The downstream end was connected to the suction side of a centrifugal fan by means of a diffuser, and the flow rate through the duct was varied by means of a slide gate at the discharge end of the fan. The centrifugal fan was driven by an AC motor of 335 W.

Static and velocity pressure tappings were positioned along the duct, as shown in Fig. 1. The velocity tappings allowed the insertion of a pitot tube which could be traversed across the duct cross-section in order to measure velocity at various distances from the wall. A single-tube inclined manometer, manufactured by Air Flow Development Ltd, was used to measure the static and velocity heads.

The following techniques were used to measure air flow rate in the duct:

a) Constant-injection technique

Fig. 2 shows the instrumentation used with the constant-injection technique. N_2O tracer gas was injected at a constant rate into the duct inlet, through a number of small injection tappings distributed around the perimeter of the duct inlet. These tappings were connected to a manifold by flexible tubing. N_2O was supplied to the manifold via a type F-100/200 mass-flow controller, which had a maximum flow capability of 1 L/min and was manufactured by Bronkhorst High-Tech BV, Holland.

The measurement accuracy of the mass-flow controller was ±1%; the flow rate was controlled by means of a variable power supply, and the rate of tracer gas injected was displayed on a digital unit. A steady flow rate was achieved by means of a reservoir between the N_20 cylinder and the mass-flow controller. Initial tests of tracer-gas concentration (as measured by the gas analyser) showed fluctuations because of poor mixing of tracer gas and air. This difficulty was overcome by the installation of a honeycomb disperser at the inlet of the duct.

Tracer gas/air samples were collected in a sampling tube that could be positioned at different points along the duct. The tube was mounted on a traversing mechanism that allowed samples to be taken at various distances from the duct wall. The concentration of N_2O tracer gas was measured by an IRGA 120 Infra-red Gas Analyser manufactured by J and S Sieger Ltd.

b) Pulse-injection technique

Use of this technique involved the injection by syringe (Fig. 3) of a known amount of tracer gas at the inlet of the duct. The amount was large enough to allow detection by the gas analyser, but sufficiently small that its effect on the duct flow rate was insignificant. Multi-point injection was necessary for the approximation of a uniform concentration across the cross-section of the duct at the measurement point.

The concentration of tracer gas had to be measured at the downstream point, to determine the integral of the concentration. It was important to collect samples at different heights from the duct wall, to obtain an average concentration of tracer gas across the duct. The concentration was determined by filling an air sample bag by means of a small pump. Sampling was begun one minute before the pulse was injected, and continued until the pulse was completely purged from the duct. The concentration integral was

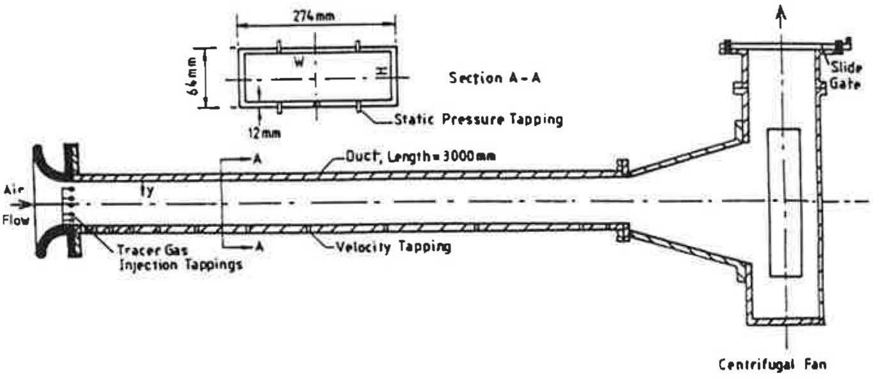

Fig. 1 Schematic diagram of the duct system.

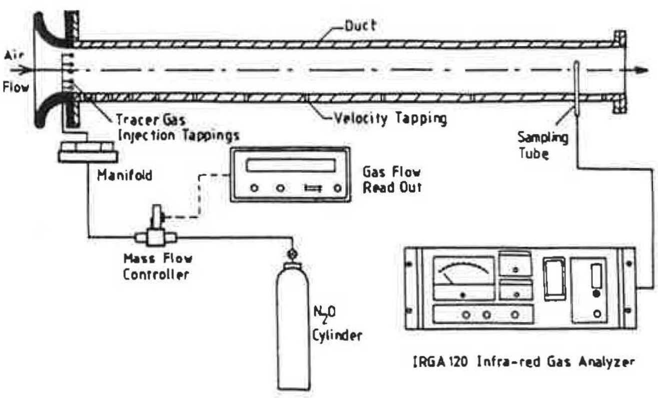

Fig. 2 Instrumentation for the constant-injection technique.

determined by multiplying the average concentration by the time over which the sample bag had been filled.

c) Concentration-decay technique
Air-flow measurements were carried out by means of a variable-speed microprocessor tracer-gas system, Fig. 4. This incorporated solenoid valves, tracer-gas sample bags, a pulse pump, a microprocessor-based controller, a manifold and a by-pass valve. The sampling period of the tracer-gas system could be adjusted over a wide range (seconds, minutes, hours, weeks or months). The sampling periods (eg minutes to months) are normally used to measure averages of infiltration rates in buildings. The decay of tracer gas in the duct was very rapid, so short sampling periods (ie seconds) were required to measure the concentration in these experiments.

The system was designed to take up to 40 samples at short or long intervals, and its sampling period could be different during the transient and dominant periods of an experiment. In a typical experiment, a large number of samples were taken during the transient period, and a small number during the dominant period. Use of a large number of data points for the transient period minimised the error in the term dC/dt (see tracer-gas equation 1) and hence allowed air flow in the duct to be calculated more accurately.

Samples of air and tracer gas were collected from several points along the duct and injected automatically into a portable gas chromatograph/analyser. This allowed the concentration of tracer gas in each sample to be determined.

5 Results and discussion

Measurements of air-flow rate in the duct were carried out by means of the constant-injection, the pulse-injection and the tracer-gas decay techniques. The first set of experiments was carried out using the constant-injection technique. Tracer gas was injected into the duct inlet by means of the mass-flow controller, as described in Section 4. For small air flows the rate of injection was approximately 0.35 L/min; for high air flows, it was approximately 0.75 L/min.

The concentration of tracer gas at different heights from the duct wall was measured at the fully developed region of the duct ($X/D_h = 100$); it was found to be smallest near the duct wall, and reached a maximum at the centre of the duct. The concentration profile across the duct cross-section was similar in shape to the velocity profile obtained with the pitot tube. We also carried out measurements of the centre-line concentration along the duct, at various flow rates. The concentration of the tracer gas was found to decrease as X/D_h increased, until it reached a constant value at the fully developed region of the duct.

For the second set of experiments the pulse-injection technique was employed. A plastic bag and small pump were used to collect air samples at the fully developed region of the duct. The pump was switched on one minute before the injection of tracer gas was begun, and switched off several minutes after the injection was completed. The concentration of tracer gas was found to be slightly higher at measurement points furthest away from the duct wall.

The microprocessor tracer-gas system was used in the third set of experiments, which were conducted with the decay technique. With the sampling period set to one second, it was only with low air flows in the duct that we were able to determine the concentration of tracer gas. For flow rates greater than 0.05 m^3/s the decay of tracer gas was too rapid to allow measurements of concentration.

Fig. 5 compares measurements of duct air-flow rate made with the tracer-gas techniques, and those with a pitot tube. For small flow rates (ie below 0.02 m^3/s) the results obtained from the tracer-gas techniques were found to be in a good agreement with those obtained with the pitot tube. For high flow rates (ie above 0.02 m^3/s) the results obtained from the constant-injection technique were found to be in closer agreement with the pitot-tube results than those obtained with the pulse-injection technique and the decay method.

Note, however, that there are uncertainties in the measurements made with the pitot tube, which is sensitive both to alignment with the flow and to turbulence level. Additional

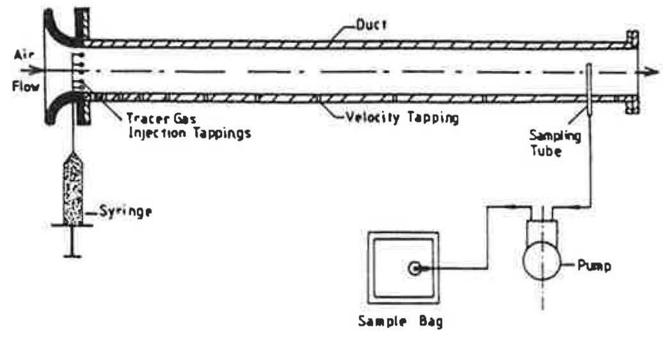

Fig. 3 Instrumentation for the pulse-injection technique.

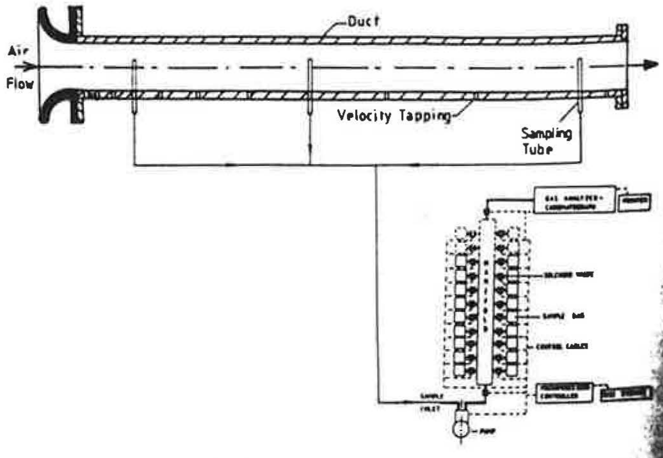

Fig. 4 Instrumentation for the concentration-decay technique.

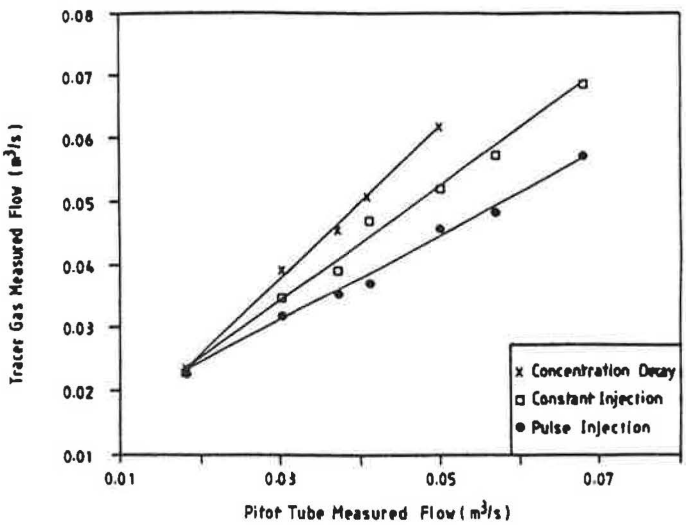

Fig. 5 Comparison of measurements of tracer-gas air flow and those made with a pitot tube.

errors arise from the difficulty of measuring the velocity close to the duct wall, and measuring the internal cross-sectional area of the duct.

Use of the pulse injection technique incorporates errors arising from uncertainty in estimating the integral of the concentration. The error can be minimised if a large number of tracer-gas samples are taken across the duct, so that the concentration obtained represents the real average value. The accuracy of this technique can be further improved if the tests are repeated several times and an estimate of the repeatability of the experiments is thereby obtained.

Use of the decay technique produced the largest error, as the decay of tracer-gas concentration was rapid and it was difficult to obtain a large number of data points at high flow rate. Modification of the present measuring equipment to allow a high sampling frequency (for example 0.1 s) would improve experimental accuracy. A further source of error arises in the difficulty of measuring the effective volume of the duct.

6 Conclusions

Tracer-gas techniques were found to offer a simple and useful approach for measuring air flow in ducts. The comparison of measurements made with the tracer-gas techniques and those made with a pitot tube showed that the closest agreement was observed in measurements made with the constant-injection technique. The accuracy of the measurements made with the decay technique could be improved by more frequent sampling. More complete mixing of the tracer gas with air would improve the measurement accuracy of the pulse injection technique.

Tracer-gas techniques require further laboratory trials and field-testing on ducts with a range of aspect ratios, in order to establish their viability on a wider scale.

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