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THE APPLICATION OF TRACER-GAS TECHNIQUES FOR MEASURING AIRFLOW IN A DUCT

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A description of the use of tracer-gas techniques for measurement of airflow 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 airflow made using 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. INTRODUCTION

Airflow in ducts has considerable engineering importance in the design of HVAC systems, atomic power reactors and gas turbines. Measurements of airflow 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, only limited work has been published on the use of these techniques for measuring airflow in ducts (1-2). The present study investigates the application of these techniques, and compares the results obtained using tracer-gas methods and those obtained with a pitot tube is made.

2. FUNDAMENTALS OF TRACER-GAS TECHNIQUES

2.1 Constant-Injection Technique

The constant injection tracer-gas technique can be used to measure airflow 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.

2.2 Pulse-Injection Technique

This technique is based upon the injection into the duct inlet of a short-duration pulse of tracer-gas at a rate $G_{(t)}$. The variation of tracer 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, i.e. $F_{(t)}\, C_{(t)}$. If the tracer gas is assumed to be purged from the duct after some time interval, (t_1 to t_2) then the volume of tracer gas leaving the duct must equal to the amount injected. Applying the integral volume balance of tracer gas, we have:

$$\int_{t1}^{t2} F_{(t)}\, C_{(t)}\, dt = \int_{t1}^{t2} G_{(t)}\, dt \qquad (\text{for } F_{(t)} \geq 0) \qquad (5)$$

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

$$F_{(\alpha)} = \left[\int_{t1}^{t2} C_{(t)}\, dt\right]^{-1} \int_{t1}^{t2} G_{(t)}\, dt \qquad (\text{for } t_{t1} \leq \alpha \leq t_2) \qquad (6)$$

2.3 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. The fan is then switched on and the concentration of tracer gas is monitored over a 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 (i.e. $q_{(t)} = 0$), equation (1) becomes:

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

This can be rearranged to give:

$$dC(t)/C_{(t)} = -(F_{(t)}/V)dt \qquad (8)$$

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

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

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

Equation (10) can be rewritten as follows:

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

The volumetric flow rate, F, can be determined by multiplying the air change rate, I, by the effective volume of the duct.

3. MATERIALS AND METHODS

The duct shown in Fig. 1 was constructed from plywood 12 mm thick and had a bellmouth made from wooden bars. The duct was 2.43m long and had an internal cross-section of 0.25mm x 0.04mm. The downstream end of the duct was connected to the suction side of a centrifugal fan by means of a diffuser and the flow rate through the duct was varied using a slide gate located at the discharge end of the fan. The centrifugal fan was driven by an AC motor of 335W.

Static and velocity pressure tappings were positioned along the duct. 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, made by Airflow Development Ltd, UK, was used to measure the static and velocity heads.

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

i) Constant-Injection Technique

Fig. 1 shows the instrumentation used with the constant injection technique. Nitrous oxide tracer gas was injected at a constant rate into the duct inlet, through a number of small injection tappings located around the perimeter of the duct inlet. These tappings were connected to a manifold by flexible tubing. Nitrous oxide 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 B V, Holland. The measurement accuracy of the mass flow controller was ± 1%; the flow rate was controlled using a variable power supply. The rate of tracer gas injection was displayed on a digital unit. A steady flow rate was achieved by means of a reservoir between the N_2O 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 using a honeycomb disperser at the inlet of the duct.

Samples of air and tracer gas 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, UK.

ii) Pulse-Injection Technique

Use of this technique involved the injection by syringe 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 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 determined by multiplying the average concentration by the time over which the sample bag was filled.

iii) Concentration Decay Technique

Airflow measurements were carried out using a microprocessor tracer gas system. 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). Sampling periods of minutes to months are normally used to measure averages of infiltration rate in buildings. As the decay of tracer gas in the duct was very rapid, short sampling periods (i.e. seconds) were required to measure 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 the airflow 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.

4 RESULTS AND DISCUSSION

Measurements of airflow rate in the duct were carried out by means of the constant injection, the pulse injection and the decay tracer gas techniques. The first set of experiments was carried out using the constant injection technique. Tracer gas was injected into the duct inlet using the mass flow controller, as described in the experimental section. For small duct airflows, the rate of injection was approximately 0.35 L/min; for high airflows, it was approximately 0.75 L/min. The second set of experiments was performed using the pulse injection technique. A plastic bag and a 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-controlled tracer gas system was used in the third set of experiments which were conducted using the decay technique. With the sampling period set to one second, it was only with low airflows 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 tracer gas concentration.

Fig. 2 shows a comparison between measurements of duct airflow rate made with the tracer gas techniques and those with a pitot tube. For small flow rates (i.e. 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 (i.e. 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 using 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 to alignment with the flow and to turbulence level. Additional 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 the uncertainty in estimating the concentration integral. 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 using 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 very 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 0.1s) would improve experimental accuracy.

5. CONCLUSIONS

The use of tracer-gas techniques were found to be a simple and useful approach for measuring airflow in ducts. Comparison of measurements made with a pitot tube and those made with different tracer-gas techniques showed that closest agreement was obtained for measurements made using the constant-injection technique. The accuracy of measurements made with the decay and pulse injection techniques could be improved by more frequent sampling and better mixing of tracer gas.

LIST OF SYMBOLS

C tracer gas concentration (ppm), C_0 concentration of tracer gas at $t = 0$ (ppm)
F volumetric flow rate (m^3s^{-1}), V effective volume of the duct (m^3)
q injection flow rate of tracer gas (m^3s^{-1}) G tracer volume generation rate (m^3s^{-1})
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 the duct (m) α an instant in time within a given interval (s)

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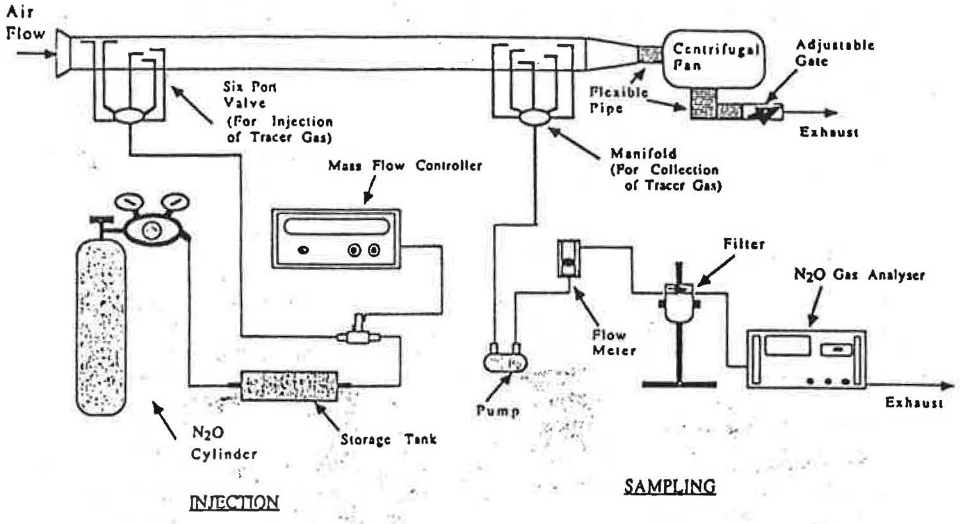

Figure 1 Instrumentation for the constant injection technique

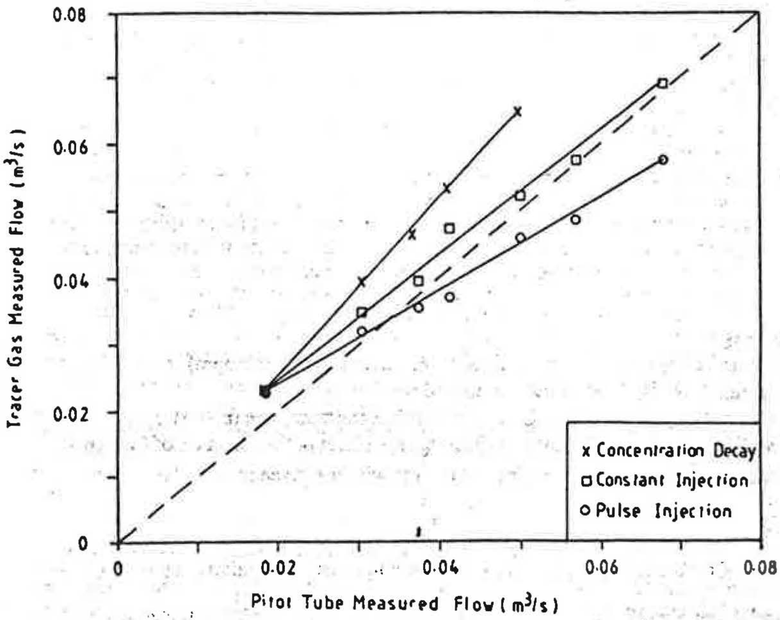

Figure 2 Comparison of flow rate in the recirculated-air supply duct with the constant injection technique and a hot-wire anemometer.