VENTILATION SYSTEM PERFORMANCE

11th AIVC Conference, Belgirate, Italy
18-21 September, 1990

Paper 11

MEASUREMENT OF AIRFLOW IN HVAC SYSTEMS USING TRACER-GAS TECHNIQUES

S B RIFFAT[1] and M HOLMES[2]

1. Building Services Group,
Department of Civil Engineering,
Loughborough,
Leicestershire, LE11 3TU,
United Kingdom.

2. Arup Research and Development,
13 Fitzroy Street,
London, W1P 6BQ,
United Kingdom.

SYNOPSIS

This paper describes the use of tracer-gas techniques to measure airflow in a rectangular duct and a HVAC system. Experimental procedures are discussed for the application of the constant injection, pulse injection and decay techniques using N_2O and SF_6 as tracer gases. This paper also describes a new tracer-gas system with variable sampling speed which was used to measure the decay of tracer-gas concentration. A comparison is presented between tracer-gas measurements and those made with a pitot tube and a hot wire anemometer.

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)
W	duct width (m)
H	duct height (m)
α	an instant in time within a given interval (s)

1. INTRODUCTION

Indoor air quality, thermal comfort and energy use in buildings are largely dependent on the performance of HVAC systems. Incorrect ventilation rate is a common cause of poor indoor climate in office buildings and this can have detrimental effects on the occupants. If these problems are to be avoided, frequent checks on the performance of HVAC systems must be carried out. Measurement of air flow in HVAC systems is usually carried out using traditional instrumentation such as, hot-wire anemometers, vane anemometers and pitot tubes. This type of instrumentation is difficult to employ in practice as a long measuring duct is required for the establishment of fully developed flow profiles. In addition, traditional instrumentation fails to give an accurate picture of the performance of the HVAC system as a whole.

Tracer-gas techniques such as constant injection, constant concentration, concentration decay and pulse injection offer an alternative approach for measuring air flow in HVAC systems and unlike traditional instrumentation, are not limited by the complexity of duct configurations. Tracer-gas techniques can be used to measure flow rates over a wide range of values (i.e. laminar and turbulent flow) as very low concentrations of tracer gas can easily be detected using gas chromatographs. Moreover, tracer-gas techniques can be used to measure flow rates directly and do not require determination of the cross-sectional area of the duct or the flow profile at the duct wall. One further application, in which the use of tracer-gas techniques offers considerable advantages over the deployment of traditional instrumentation, is the determination of the air tightness of air ductwork. Control of air leakage is important if energy losses and leakage noise are to be minimised.

The literature contains only limited data on the use of tracer-gas techniques for measuring airflow in ducts[1-3]. The present study investigates the application of these techniques for the measurement of airflow in a duct and a HVAC system. Measurements of airflow made with tracer-gas techniques are compared with those made with a pitot tube and a hot wire anemometer.

2. FUNDAMENTALS OF TRACER-GAS TECHNIQUES

There are three fundamental ways to make use of tracer gases in air flow rate measurements:

Constant injection - The dilution of a tracer gas injected into the duct system at a fixed rate is used to infer the main flow rate.

Pulse injection - Uses the dilution of a short duration injection of a tracer gas.

Concentration decay - The rate of dilution of a known concentration is used to indicate the airflow rate.

The theoretical basis of each of these will now be discussed.

2.1 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, steady state conditions should be achieved. This means that the transient term in equation (3) would be close to zero and so the airflow can be calculated from:

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

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:

$$F_{(\alpha)} = \left[\int_{t1}^{t2} C_{(t)}\, dt\right]^{-1} \int_{t1}^{t2} G_{(t)}\, dt \qquad (\text{for } t_{1} \leq \alpha \leq t_{2}) \qquad (6)$$

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:

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

This can be rearranged to give:

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

Equation (8) can be solved by integration (assuming 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:

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

Equation (10) can be rewritten as follows:

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

This technique does not require the measurement of the absolute concentration of the tracer gas. 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 effective volume of the duct.

3. MEASUREMENT OF AIRFLOW IN A DUCT

This section describes the equipment and techniques used to compare the methods outlined in section 2, and presents results obtained.

3.1 Experimental

The duct shown in Figure 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 250mm x 40mm. 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 as shown in Figure 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, 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

Figure 2 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 maximum flow capability of 1 Litre/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 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 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_20 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 (Figure 3) of a known amount of tracer gas at the inlet of the duct. 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

Air flow measurements were carried out using a microprocessor tracer gas system, Figure 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). 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 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.

3.2 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 air flows, the rate of injection was approximately 0.35 Litre/min; for high air flows, it was approximately 0.75 Litre/min.

The concentration of tracer gas at different heights from the duct wall was measured at the fully developed region of the duct, i.e. $X/D_h = 100$; it was found to be smallest near the duct wall and reached a maximum value at the centre of the duct. The concentration profile across the duct cross-section was similar in shape to the velocity profile obtained using the pitot tube. Measurements of the centre-line concentration along the duct were carried out for 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.

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 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 tracer gas concentration.

Figure 5 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 oils) would improve experimental accuracy. A further source of error arises from to the difficulty of measuring the effective volume of the duct.

4. MEASUREMENT OF AIRFLOW IN A HVAC SYSTEM

Comparison of measurements of duct airflow made with tracer gas techniques and a pitot tube showed that the constant injection technique was the most accurate. Further tests were carried out to establish the viability of this technique for measurement of airflow in a HVAC system. Experiments were performed in a room-sized environmental chamber connected to a HVAC system, see Figure 6; SF_6 rather than N_2O, was used as the tracer gas for safety reasons. An SF_6 gas analyser (type Binos 1) made by Leybold-Heraeus GMBH, was employed.

Measurements were carried out in the fresh-air supply and recirculated-air ducts of the HVAC system. Fresh air was drawn into the system from outside the building by means of a centrifugal fan which was driven by a variable speed DC motor and had maximum speed of 1400 rpm. The fresh-air supply was passed through a filter before being mixed with the recirculated-air at the Air-Conditioning Bench. The first set of measurements were carried out at various flow rates in the fresh-air supply duct. The equipment used to measure flow rates in the fresh-air supply duct is shown in Figure 7. SF_6 tracer gas was injected at a constant rate at a number of points in the inlet region of the duct and concentration of tracer gas was measured at positions upstream from the Air-Conditioning Bench.

Figure 7 shows a comparison of measurements of duct airflow made with the tracer gas technique and a hot-wire anemometer. A hot-wire anemometer was used in preference to a pitot tube as it allows more accurate measurement of flow rate at low air-velocity. The flow rate correlation between the tracer gas measurements and hot-wire measurements is given by:

$$F_{\text{tracer gas}} = 0.769 \ F_{\text{hot-wire}} + 2.46 \times 10^{-3} \qquad (12)$$

General agreement was found between the tracer gas results and those obtained with the hot-wire anemometer; the average difference between the two sets of measurements was approximately 16%. Uncertainties arise in measurements made with the hot-wire anemometer as this instrument is sensitive to turbulence level. Additional errors arise as a result of the difficulty of measuring the velocity close to the duct wall and measuring the internal cross-sectional area of the duct.

The second set of measurements were carried out in the recirculated-air supply duct and the equipment used to make these measurements is shown in Figure 9. Tracer gas was injected at the merger point of the two return-ducts from the environmental chamber and the tracer concentration was monitored downstream from the bend in order to obtain good mixing, Figure 9. Measurements of the background concentration of tracer gas were also made as some tracer gas was contained in the recirculated flow from the environmental chamber.

Figure 10 shows a comparison of airflow measurements made in the recirculated-air supply duct with the constant injection technique and the hot-wire anemometer. The flow rate correlation between the tracer gas measurements and hot-wire measurements is:

$$F_{\text{tracer gas}} = 0.675\, F_{\text{hot-wire}} + 4.93 \times 10^{-2} \qquad (13)$$

The agreement between measurements made with the tracer-gas technique and those made with the hot-wire anemometer was not as good as was the case for measurements made in the fresh-air duct. This could be due to incomplete mixing of tracer gas and experimental error arising from the delay in measuring the background concentration of tracer gas. Use of a second gas analyser situated close to the sampling position would reduce this delay.

CONCLUSIONS

1. Tracer-gas techniques were found to be a simple and useful approach for measuring airflow in ducts.

2. 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.

3. The accuracy of airflow measurements in HVAC systems could be improved by sampling at a point immediately downstream of a filter, bend or heat exchanger coil to achieve good mixing of tracer gas.

4. 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.

ACKNOWLEDGEMENTS

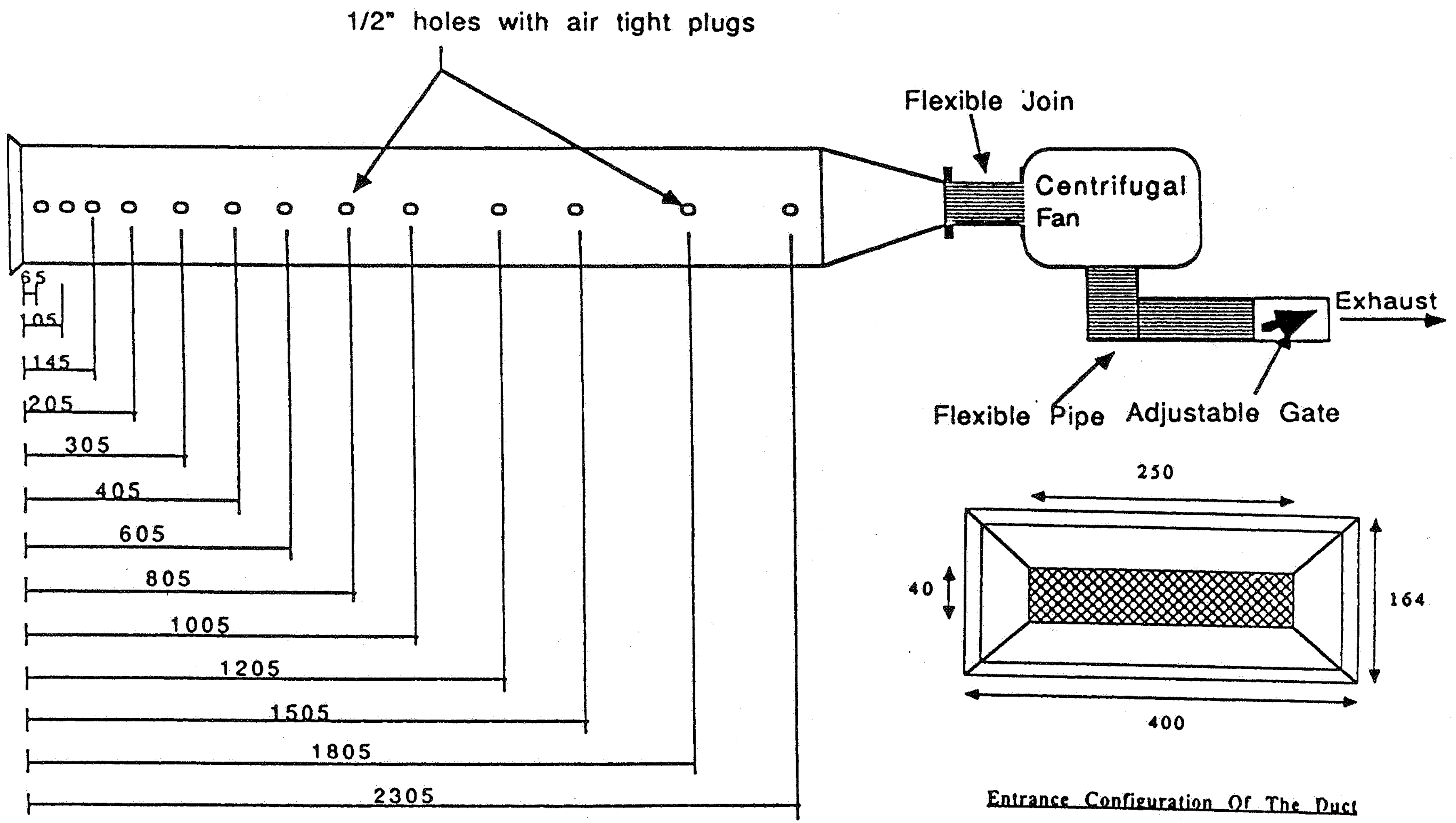
We gratefully acknowledge the contribution of M. Goh and the financial support of the Science and Engineering Research Council.

REFERENCES

1. LUNDIN, L.
"Air leakage in industrial buildings-preliminary results".
Proceedings of the 4th AIVC Conference 'Air Infiltration Reduction in Existing Buildings' Elm, Switzerland, September 1983, pp.6, 1-6, 8.

2. AXLEY, J. and PERSILY, A.
"Integral mass balances and pulse injection tracer gas techniques".
Proceedings of the 9th AIVC Conference 'Effective Ventilation', Gent, Belgium, Paper No.7, September 1987.

3. RIFFAT, S.B. and LEE, S.F.
"Turbulent flow in a duct: Measurement by a tracer gas technique".
Building Services Engineering Research and Technology, 11(1), pp.21-26, 1990.



Entrance Configuration Of The Duct

Figure 1 Schematic diagram of the duct system

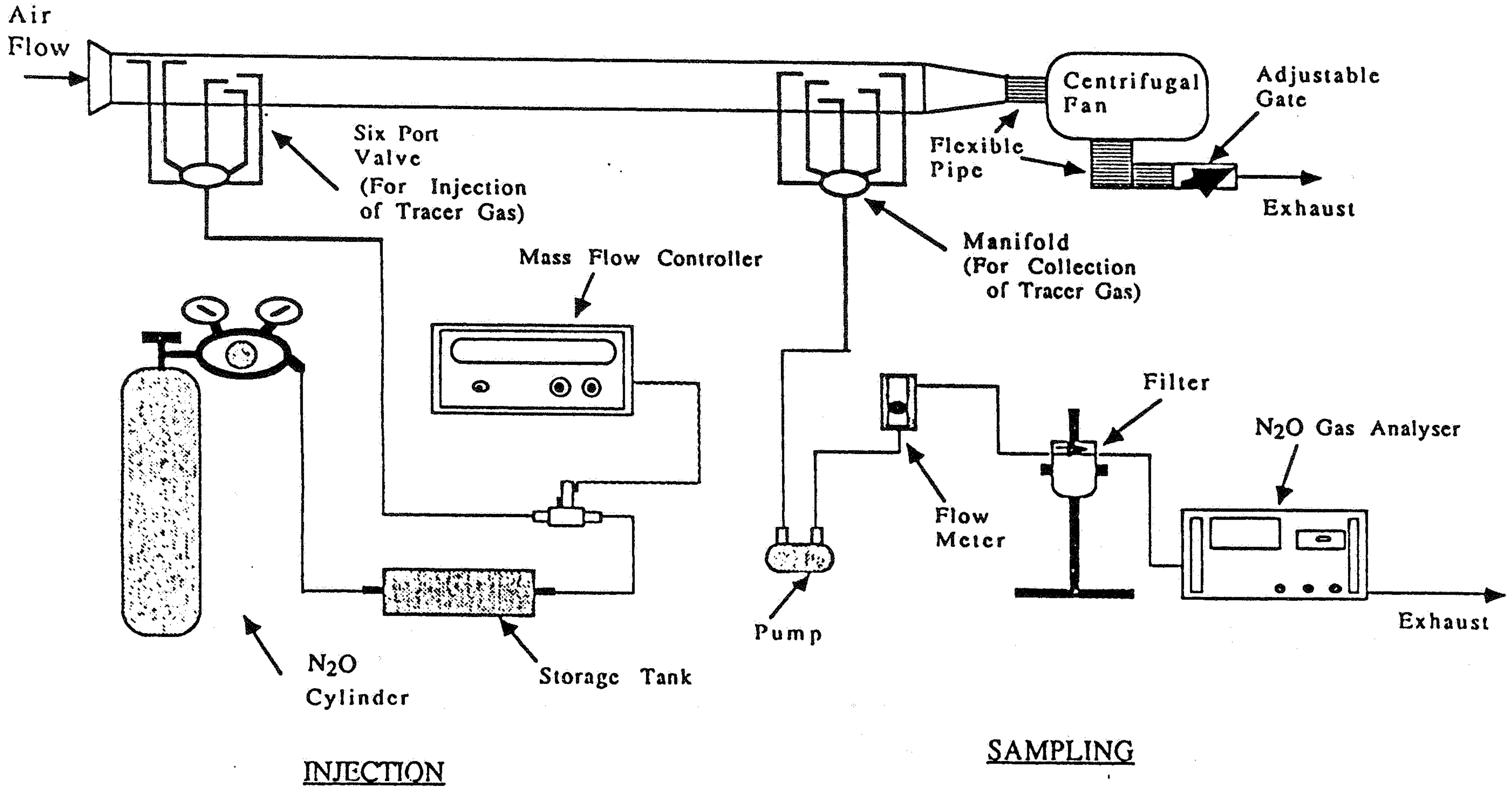


Figure 2 Instrumentation for the constant injection technique

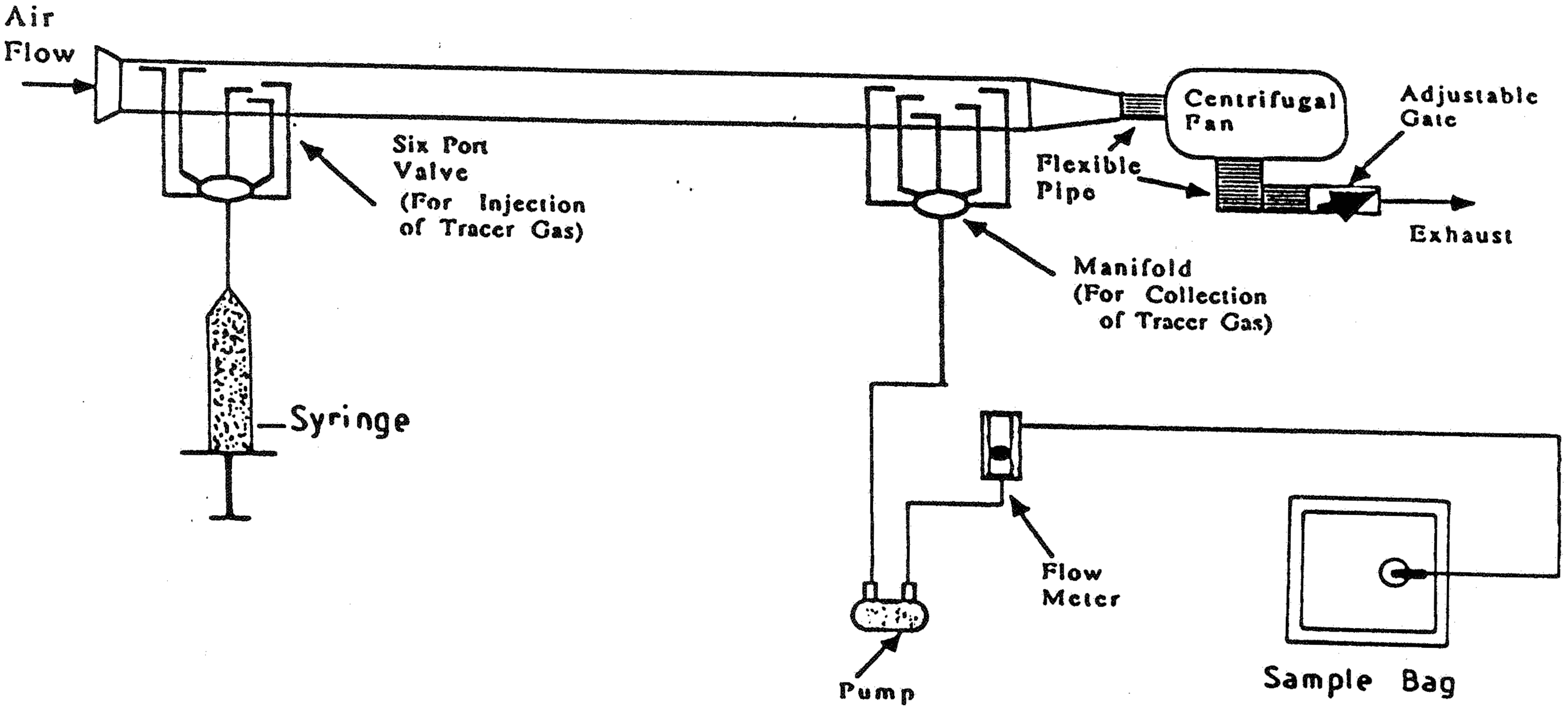


Figure 3 Instrumentation for the pulse injection technique

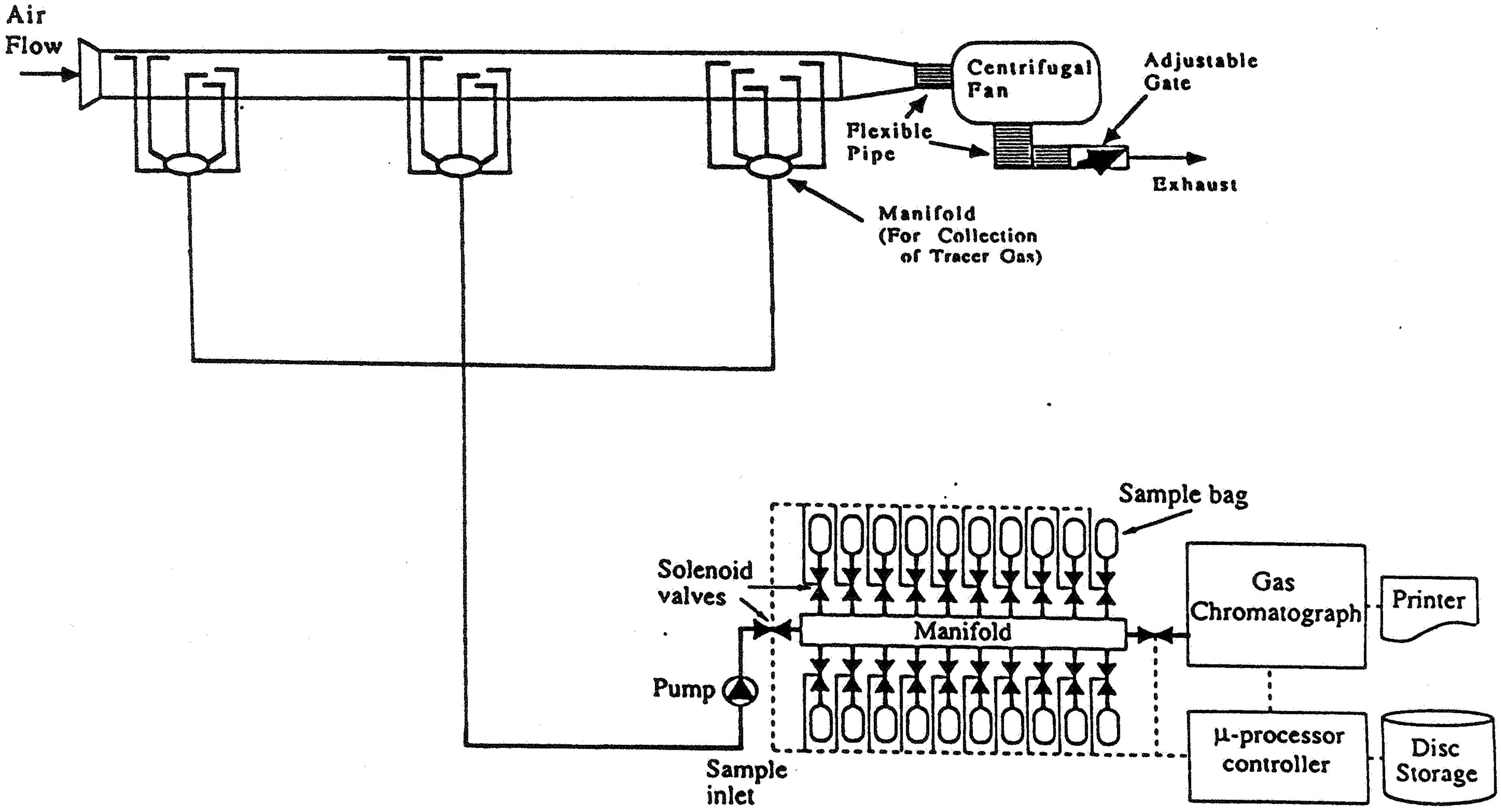


Figure 4 Instrumentation for the concentration decay technique

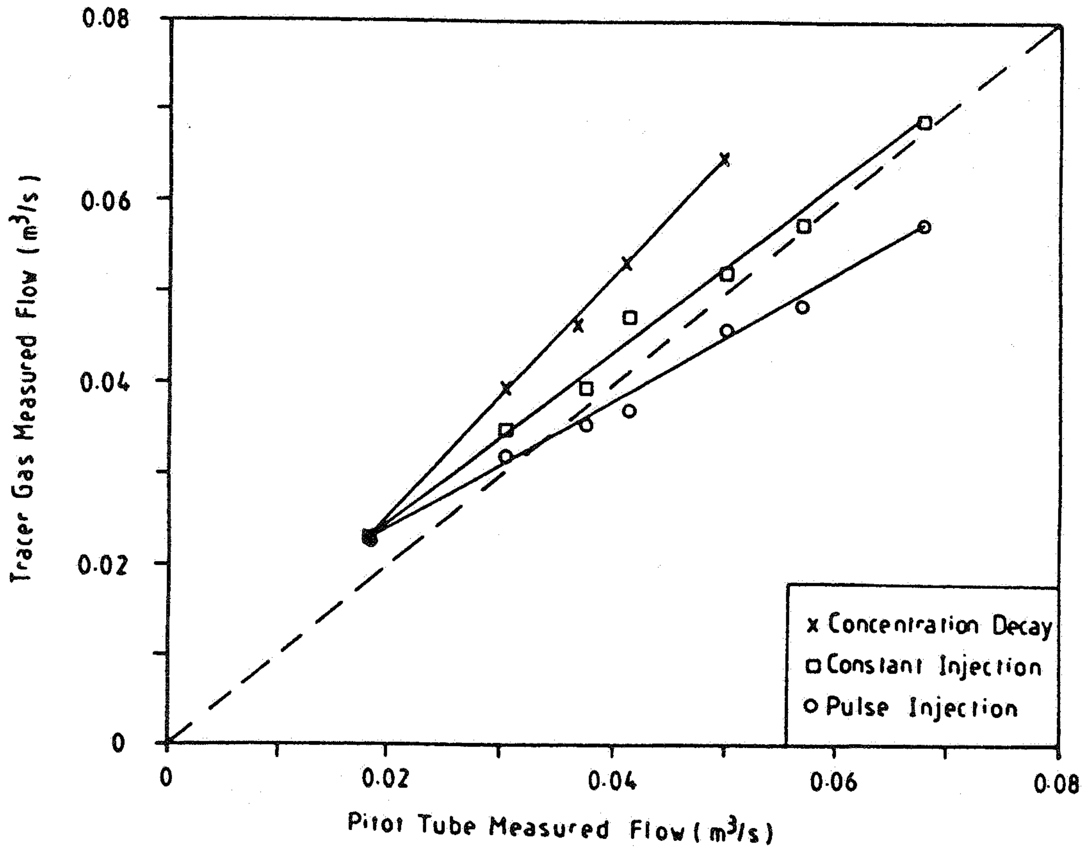


Figure 5 Comparison of tracer gas air flow measurements and measurements made with a pitot tube.

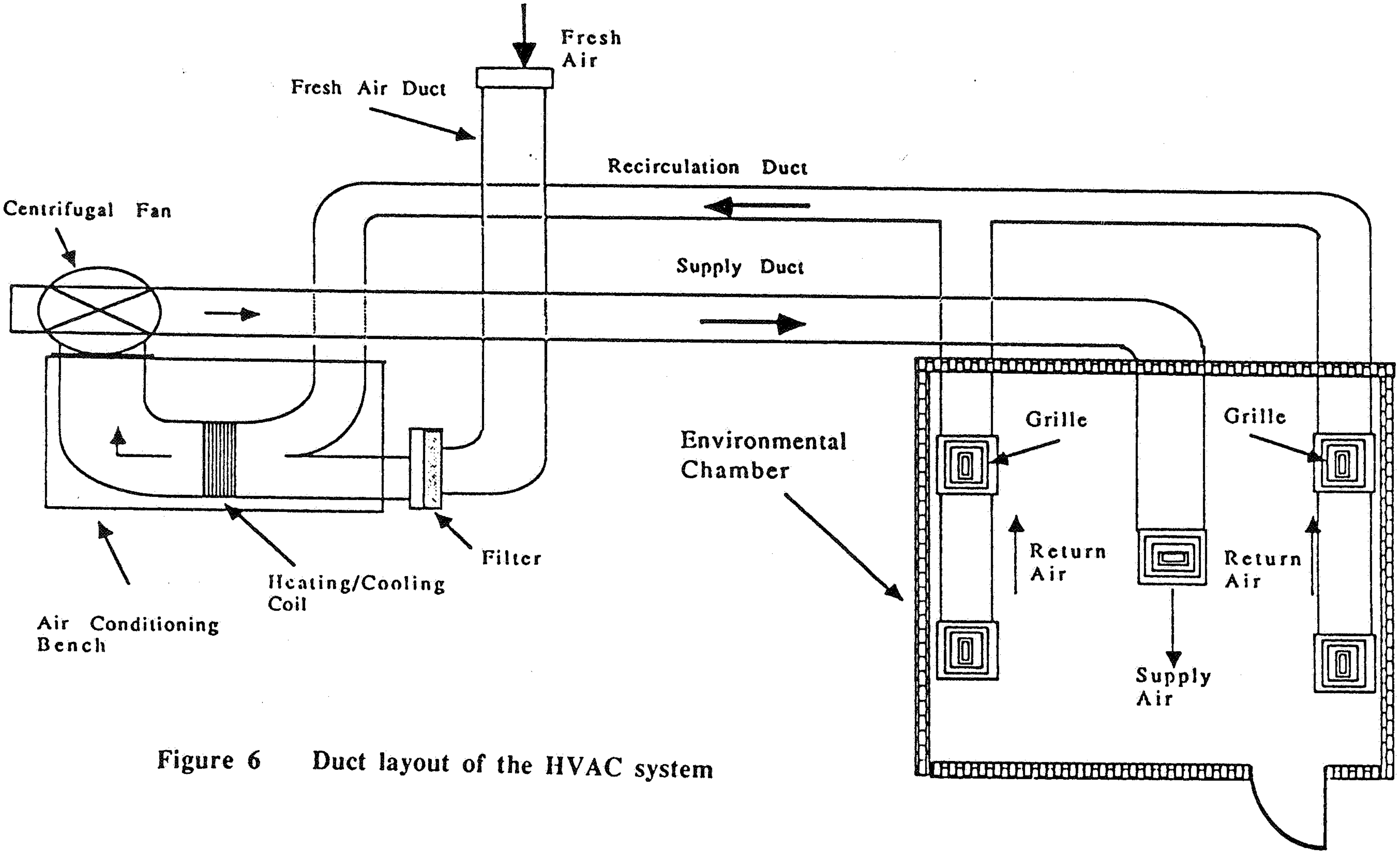


Figure 6 Duct layout of the HVAC system

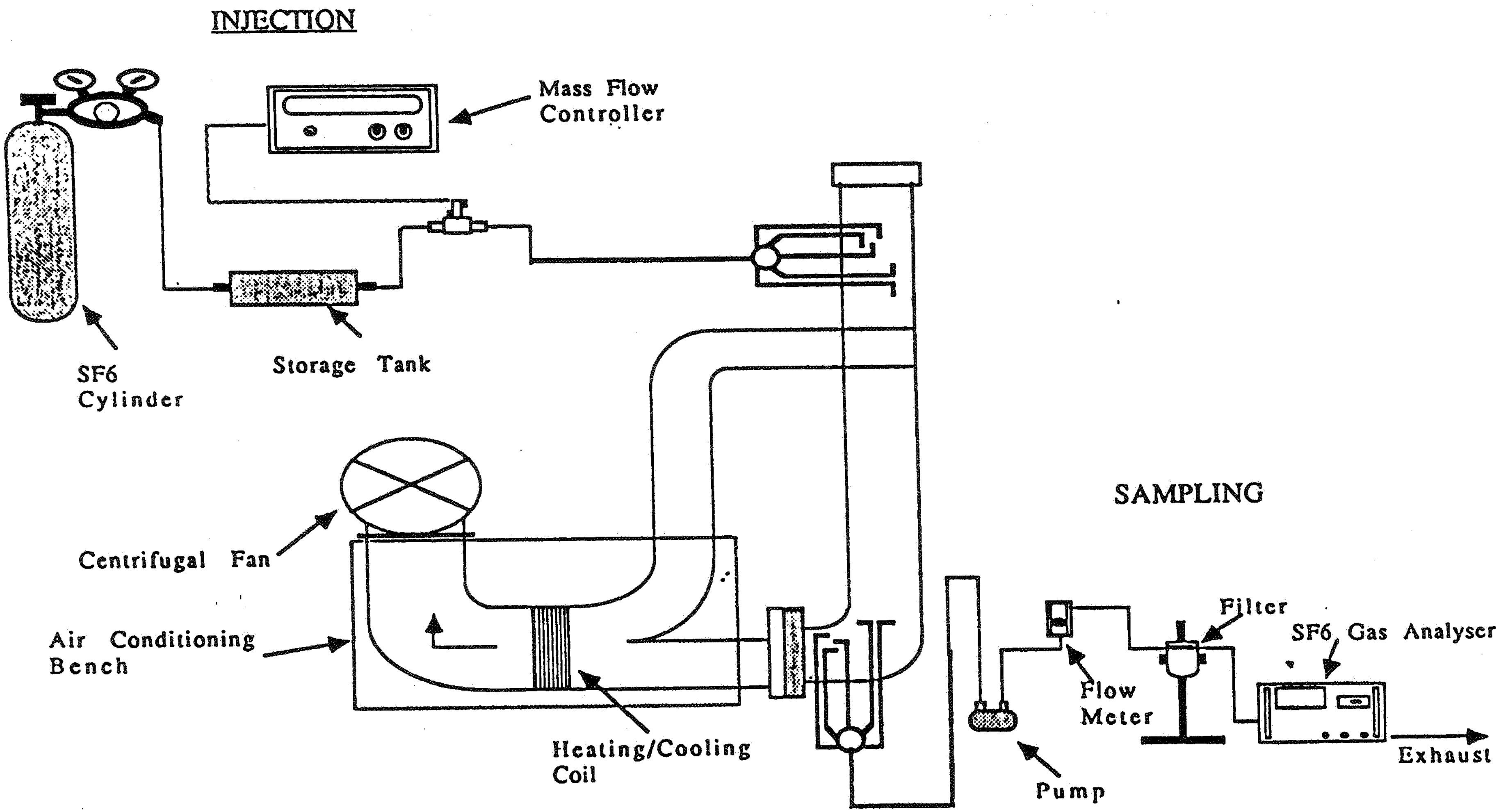


Figure 7 Equipment used to measure flow rate in the fresh-air supply duct

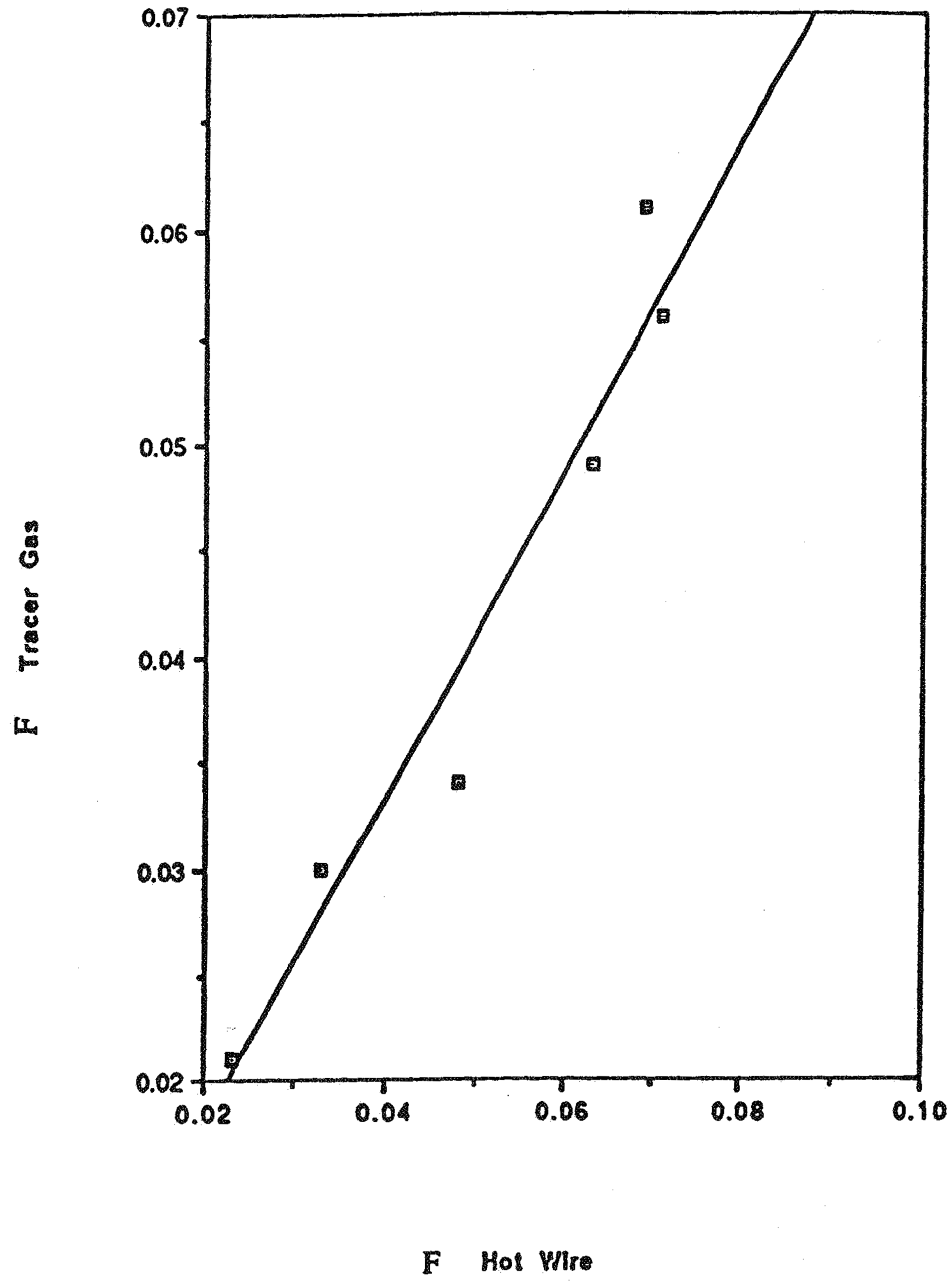


Figure 8 Comparison of airflow rate in the fresh-air supply duct measured with the constant injection technique and a hot-wire anemometer

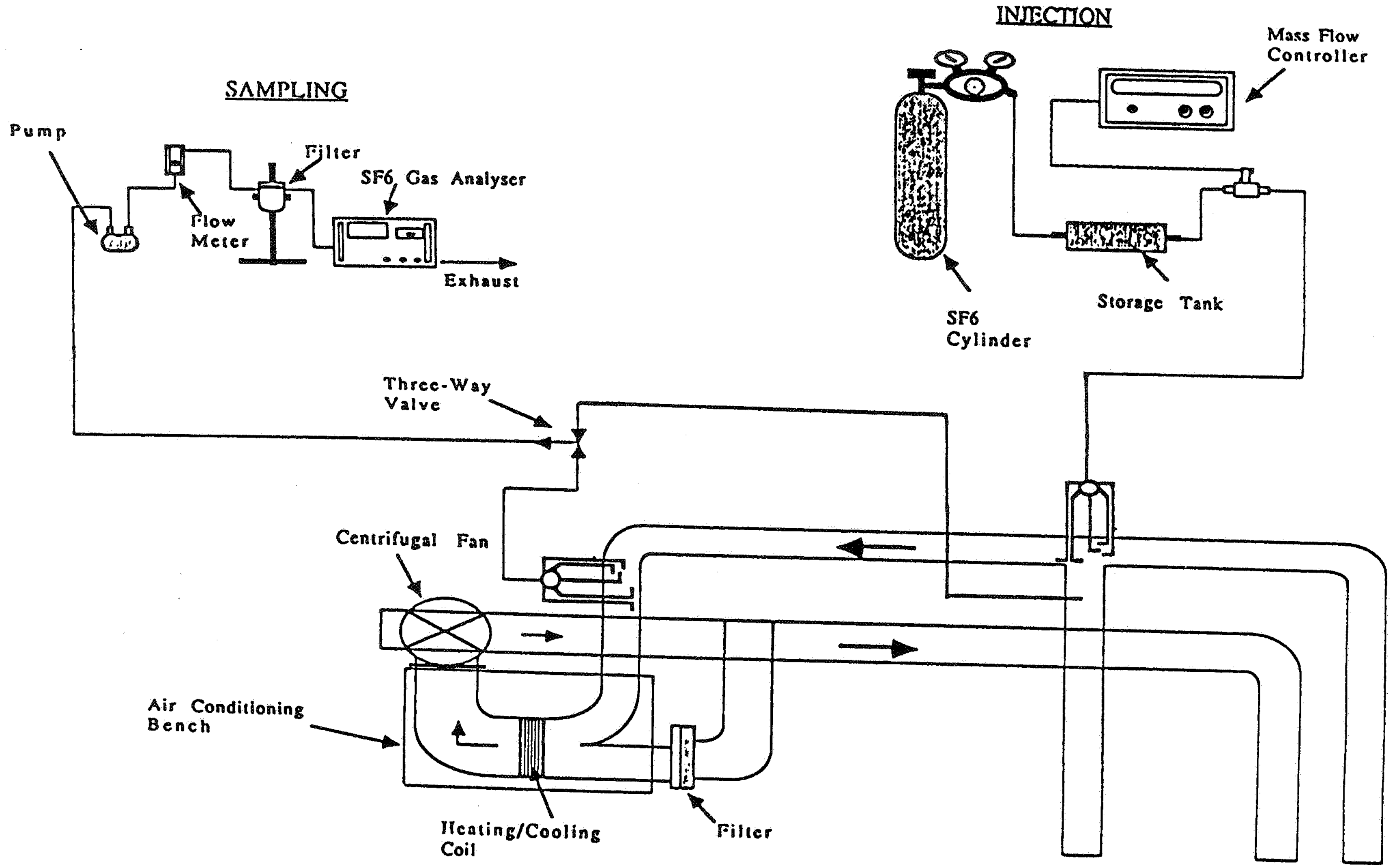


Figure 9 Equipment used to measure airflow in the recirculated-air supply duct

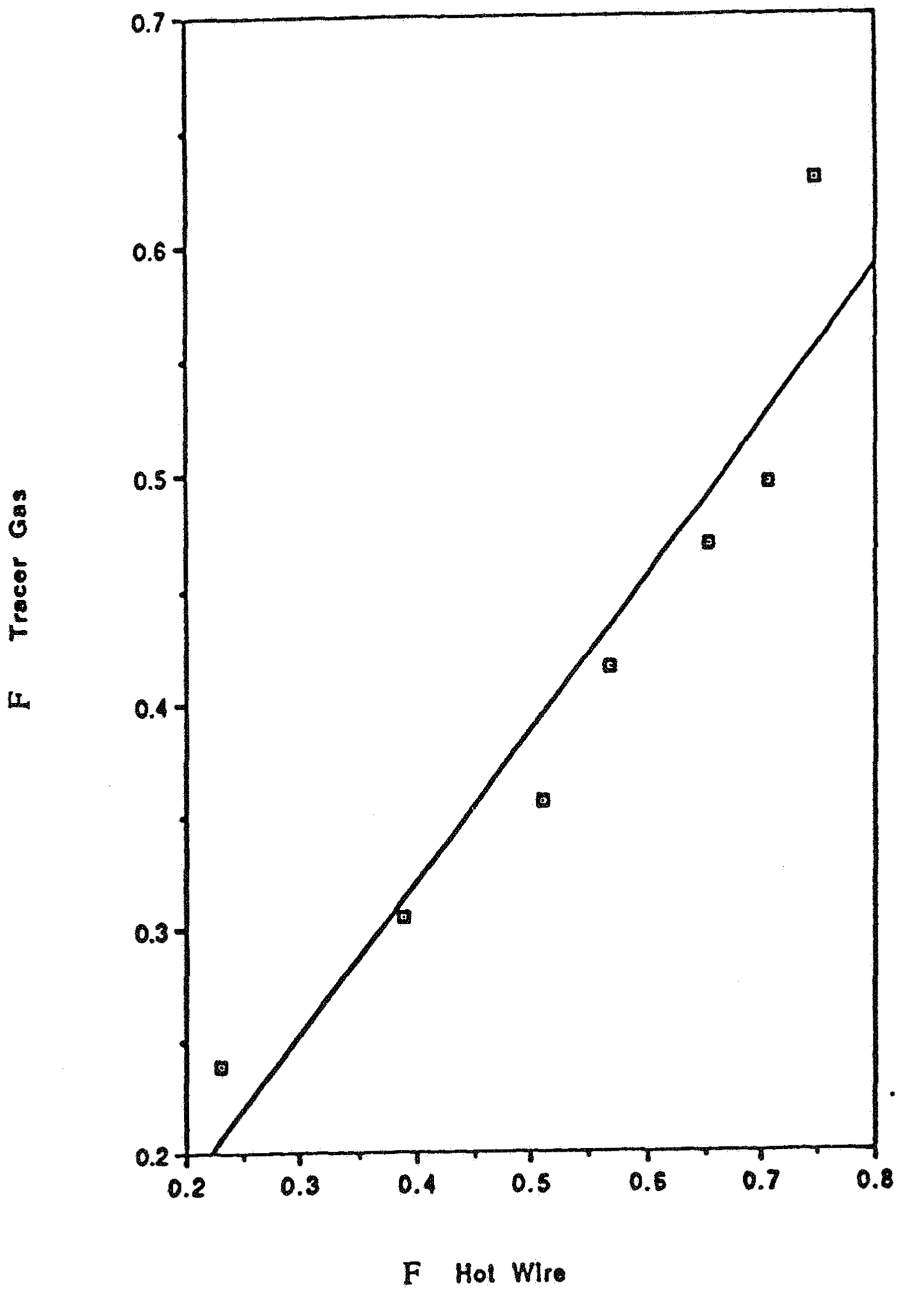


Figure 10 Comparison of flow rate in the recirculated-air supply duct measured with the constant injection technique and a hot-wire anemometer.