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Development of a New Tracer-Gas Sampling System For Measuring Airflow in Ducts

K W Cheong, S B Riffat

School of Architecture, University of Nottingham,
University Park Nottingham, NG7 2RD, UK

SYNOPSIS
This paper is concerned with measurement of airflow in ducts using an active (pumped) sampling system. The system is capable of sampling tracer gases using either tubes packed with adsorbent or sample bags. A perfluorocarbon tracer (PFT) was injected into the ducts using thermostatically-controlled heating blocks. The samples were collected and analysed using a thermal desorber/gas analyser system. Laboratory and field testing of airflow in ducts was carried out. A large office building was studied for measurements of ventilation rate, ventilation efficiency and air quality. A questionnaire was also completed by office staff in order to assess air quality and thermal comfort.

1. INTRODUCTION

Indoor air quality, thermal comfort and energy use in buildings are largely dependent on accurate balancing of air distribution systems. Airflows are usually balanced using traditional instrumentation such as pitot tubes but these measurements can be inaccurate and time consuming as the velocity profile across the duct must be determined. Tracer-gas techniques offer alternative approach for measuring airflow in ducts and have several advantages [1].

Several investigations have been made of the application of the constant-injection and pulse-injection techniques for measuring of airflow in ducts [2-4]. These involved the injection of tracer gases such as SF_6 and N_2O into the duct via either a mass-flow controller or a syringe followed by downstream sampling using a gas analyser. The passive tracer-gas technique using perfluorocarbons (PFTs) has also been examined [5]. In this case small tubes filled with PFT liquid, known as sources, are placed at the inlet of the duct and tubes packed with adsorbent, known as samplers, are placed downstream. The emission rate of the sources is dependent on the air temperature while the uptake rate of the samplers is significantly influenced by the air velocity and turbulence in the duct. The orientation of sample tube with respect to the flow also affects the uptake rate. As a result measurement errors using the passive PFT techniques are large.

This work examines the accuracy of an active (pumped) sampling technique. A perfluorocarbon tracer was injected at a constant rate into the duct using a thermostatically-controlled heating block and gas samples were collected using an automated sampling system. This system was used for airflow measurements in laboratory and field tests.

Field tests were carried out in a large building and this involved measurement of ventilation rates, ventilation efficiency and concentration of specific air pollutants. In addition, a questionnaire was completed by the office staff in order to assess air quality and thermal comfort.

2. DESCRIPTION OF THE SYSTEM

The PFT system consists of the following:

2.1 Tracer Injection System

Figure 1 shows the PFT tracer injection system. This simple system consists of a cylindrical aluminium block with a heating element inserted into the base. The block was bored to allow insertion of a small glass vessel containing the PFT liquid. The vessel is 3ml capacity and has a neck of 3mm diameter and 15mm length. Water is placed in the bore hole to ensure uniform heating throughout the glass vessel. A plastic cap is placed over the hole to prevent water from spilling over the aluminium block. A diffusion cap is placed at the outlet of the vessel to allow uniform dispersion of tracer gas into the duct.

A magnet is fixed to the heating block so that the injection unit can be attached to the duct wall during airflow measurements.

2.2 Tracer Sampling System

The sampling system is shown in Figure 2. This consists of solenoid valves, tracer gas sampling tubes, a programmable logic controller, a manifold and a flowmeter. The system is capable of taking samples as frequently as once per second. Air at a constant rate may be drawn into each sampling tube using a a small pump. The sampling tubes are made of stainless steel and packed with adsorbent Chromosorb 102, 60-80 mesh, supplied by Chrompack Ltd (see Figure 2).

The operation procedure of the system is as follows. At the beginning of each experiment the first solenoid valve opens and the pump is turned on. At the end of the desired sampling time, set by the programmable controller, the pump is turned off. The procedure is repeated until all samples have been collected.

If preferred, the sampling system could be connected to a group of sampling bags instead of the adsorbent sampling tubes (see Figure 3).

2.3 Tracer Gas Analysis

Multi-Gas Analyser, type 1302, manufactured by Bruel & Kjaer, Denmark together with a Thermal Desorption System, type SBK 1355, manufactured by CBISS Ltd, UK was used for separation and analysis of the samples in the adsorbent (see Figure 3). The accuracy of the analyser was estimated to be within ±1%.

Analysis of these tubes consists of placing the tube in the thermal desorption system. The system desorbs the collected sample by heating the tube and flushing the desorbed material into a loop which is automatically connected to the multi-gas analyser. The analysis is completely automated and controlled by the thermal desorption system. The results are displayed on the multi-gas analyser.

The gas sample in the sampling bags are analysed by using the type 1302 multi-gas analyser.

3. THEORY

Tracer gas is injected into the duct at a constant rate, q, (m^3/s) and the resulting concentration (ppm) response, C, is measured. Assuming that the air and tracer gas are perfectly mixed within the duct, and concentration of tracer gas in the outside air is zero, the following equation can be used to determine airflow rate, F, (m^3/s)

$$F = \left(\frac{q}{C}\right) x\ 10^6 \qquad (1)$$

4. MEASUREMENT AND RESULTS

Airflow measurements in duct systems were conducted in the laboratory and an air distribution system of a large office building located at Nottingham. The PFT system was used for different air flow rates and results were compared with measurements made by the pitot-static traverse method.

The ventilation efficiency of the mechanical ventilation system and air quality in this office building were studied. In addition, a questionnaire was completed by the office staff in order to provide a subjective assessment of the indoor air quality.

4.1 Laboratory Tests

The experimental work was carried out using the duct system and instrument as shown in Figure 4. The duct system was constructed using a galvanised mild steel duct 6m long with a cross-section of 0.3 x 0.3m. The downstream end was connected to an axial fan by means of a diffuser. The flow rate through the duct was varied using a speed controller made by ABB Stromberg Drives, Finland. The fan was driven by an AC motor of 4 kW and with a maximum speed of 2880 rpm. The fan was manufactured by Elta Fans Ltd, UK.

Background contaminants in the adsorbent tubes can give rise to interference and inaccuracies in air flow measurements. To prevent this, all sampling tubes were cleaned before and after each use. The thermal desorption system is set to cleaning mode to remove contaminants contained in the adsorbent.

Airflow measurements commenced by filling the vessel with perfluoro-n-hexane (PP1) and then weighing it. Tracer gas was injected into the duct by placing the tracer injection system at a point upstream of the duct system. Samples were collected in clean tubes fitted into the sampling system via the sampling probes inserted into the duct downstream of the injection point. After 6 minutes, the injection and sampling process was stopped and the vessel was reweighed. The injection rate of tracer into the duct was determined by taking the difference in weight of the vessel and dividing by the duration of injection (i.e. 6 minutes). Analysis of the sampling tubes were performed by setting the thermal desorption system to analytical mode. A calibration graph [units against concentration (in mg/m^3)] was required to determine the actual concentration of tracer-gas in tubes as the direct readout values from the multi-gas analyser required a factor adjustment. Once the injection rate and concentration of tracer-gas in the sampling tube are known, the airflow rate in the duct can be evaluated by using equation (1).

Additional air flow measurements were obtained by collecting samples in bags using sampling system and analysing them using the multi-gas analyser. The pitot-static traverse method was employed in the same experiment to provide a comparison between air flow measurements made using different techniques.

Tables 1 and 2 compare measurements of air flow rate made with a pitot tube and the PFT technique using sampling tubes and bags.

No.	Airflow Rates, (m^3/s)		Percentage Difference $(F_t - F_p)/F_p$
	Pitot-Tube, (F_p)	Sampling Tubes, (F_t)	
1	0.495	0.530	7.1
2	1.038	1.070	3.1
3	1.455	1.394	-4.2

Table 1 Comparison of airflow measurements in a duct using a pitot tube and PFT technique, sampling tubes

No.	Airflow Rates, (m^3/s)		Percentage Difference $(F_b - F_p)/F_p$
	Pitot-Tube, (F_p)	Sampling Bags, (F_b)	
1	0.453	0.432	-4.6
2	0.750	0.734	- 2.1
3	1.206	1.191	-1.2

Table 2 Comparison of airflow measurements in a duct using a pitot tube and PFT technique, sampling bags

Measurement of airflow rate obtained using the pitot-static traverse method and PFT technique using sampling tubes and bags were in close agreement. The difference between airflow rates estimating using the PFT technique (using tubes) and measurements made using a pitot-tube was in the range -4.2 to 7.1%. In the case of airflow rate measurements made using the PFT technique (using bags) and pitot-static traverse method, the difference was in the range -4.6 to -1.2%.

4.2 Field Tests

Airflow measurements were made in the air handling units of an office building using the pitot-static traverse method and PFT technique using both sampling tubes and bags. Figure 5 shows the instrumentation set-up for airflow measurement at the air handling unit. The tracer injection system was inserted into the duct close to the fresh air inlet and sampling was carried out downstream of the air handling unit. Samples were collected in tubes via the manifold. The airflow rate in the air handling unit was also measured by using the pitot-static traverse method and additional airflow measurements were conducted at the exhaust duct system (not shown in Figure 5).

Table 3 compares the measurements of airflow rate made with pitot-tube and PFT technique (using sampling tubes and bags) at the air handling unit and exhaust duct system.

Type	Airflow Rates (m^3/s)		Percentage Difference $(F_t - F_p)/F_p$
	Pitot Tube (F_p)	Sampling Tubes (F_t)	
Air Handling Unit	1.494	1.567	4.9
Exhaust System	1.502	1.349	-10.2

Table 3 Measurements of airflow rate in the air handling unit

Measurements of airflow rate obtained from the pitot-static traverse method and PFT technique using sampling tubes were in close agreement. The difference between airflow rates estimated using the PFT technique and measurements made using a pitot-tube at the air handling unit was 4.9%. In the case of airflow rate measurements at the exhaust system made using the PFT technique and pitot-static traverse method, the difference was -10.2%.

4.3 Assessment of the Ventilation and Air Quality in an Office Building

4.3.1 Description of the Office Building and its Ventilation System

This office building was constructed in 1990 to an energy efficient design and was first occupied in 1991. It is a two-storey building and measurement were carried out in the general office located on the ground floor. The office is an open-plan office and has a floor area of 126 m^2.

Air conditioning of the office is provided by a heat pump system through an air-handling unit. Figure 6 shows schematic of the air distribution system. The ventilation air from the air handling unit is delivered to the office through three air diffusers at the suspended ceiling. The air extracted from the office via two grilles is completely purged to the outside.

4.3.2 Description of Measurement

4.3.2.1 Measurement of Air Exchange Rate

The air exchange rate in the office was measured using the tracer-gas decay technique. This technique involved an initial injection of SF_6 tracer gas into the air space through the air handling unit. The tracer gas was allowed to mix for 10 minutes to establish a uniform concentration in the air space. The decay of SF_6 tracer gas was monitored every 40 seconds over a period of 35 minutes, using the Binos 1000 Infra-red Gas Analyser, made by Rosemount GmbH, Hanau, Germany. The accuracy of the analyser was estimated to be within ±2%. The tracer gas concentration data was analysed to determine the air-exchange rate for the office.

4.3.2.2 Age of Air and Ventilation Efficiency

Evaluation of the ventilation efficiency of the mechanical ventilation system in a building is crucial as it provides information about the ability of the system to supply and extract air from the conditioned space. Information on the ventilation rate of the building is adequate if the air distribution in the building is uniform. Non-uniformities in an air distribution are believed to be responsible for some complaints about air quality.

Ventilation efficiency, ε, was evaluated in the office. This evaluation consisted of measurements of local age of air in the office and average age of air at the system exhaust. The age of air was measured using the tracer-gas decay technique. This technique involved an initial injection of SF_6 tracer gas into the office through the air handling unit. The tracer gas was allowed to mix for 5 minutes to establish a uniform concentration in the air space. The decay of the tracer gas was monitored in the office and at the exhaust duct once every 40 seconds, using the Binos 1000 Infra-red analyser and Miran Portable Ambient Air Analyser, type 1B2, (made by Foxboro Company, USA), respectively, over a period of 40 minutes. The tracer-gas concentration data in the office and at the exhaust were analysed to determine the age of air, τ, (min.). The ventilation efficiency of the mechanical ventilation system was determined by dividing the age of air at the exhaust, τ_E, by the age of air in the office, τ_O.

4.3.2.3 Monitoring Concentrations of CO_2, CO and HCHO

Monitoring of indoor air pollutants such as CO_2, CO and HCHO was carried out at the office. Measurements were conducted at locations with the highest concentration of pollutants.

The concentration of CO_2, CO and HCHO were measured using the Miran Portable Ambient Air Analyser. The accuracy of this analyser is estimated to be ±15%.

4.3.3 Results and Discussion

4.3.3.1 Evaluation of Air Exchange Rate

Measurements were carried out on a calm day with a south-westerly wind at a speed of 0.5 m/s. Air infiltration could be neglected as the external wind pressure was low and it has a very tight building. The air exchange rate in the office was 3 ach. This is below the recommended value of 4 to 6 air changes given in the CIBSE Guide "Installation and Equipment Data"[6].

The air temperatures for both indoors and outdoors were 23.5°C and 22°C, respectively. The recommended air temperature in an office is in the range of 23.3 to 25.6°C for summer[7] . Thus we concluded that the indoor air temperature was within the recommended value.

4.3.3.2 Evaluation of the Age of Air and Ventilation Efficiency

The measurements showed that the age of air in the office was about 25 minutes (i.e. the length of time for fresh air to remain in the office is 25 minutes).

When there is a uniform distribution of air over the office air-space, the ventilation efficiency, $\varepsilon = 1$. However, when there is a non-uniform distribution of air over the office air-space or in another words, some stagnant zones within office air-space, values of ε are significantly less than 1. The ventilation efficiency of the system was found to be $\varepsilon = 0.75$. The inefficiency of the system was partly due to the limited number and position of the air-supply diffusers and extract grilles in the office.

4.3.3.3 Evaluation of Concentrations of Indoor Air Pollutants

The concentration of carbon dioxide in the office ranged from 610 to 690 ppm. These values are well below the ASHRAE standards[8] recommended value of 1000 ppm for continuous exposure.

Measurements showed that the concentration of carbon monoxide was 0.2 ppm. This is well below the acceptable indoor concentration of 9 ppm[9].

The average concentration of formaldehyde in the office was found to be 0.1 ppm. This coincides with the acceptable indoor concentration of 0.1 ppm[9].

4.3.4 Survey at the Office Building

A subjective assessment of the effect of air quality on the health of the office staff was carried out. This was achieved by distributing a questionniare to the staff immediately after the objective measurement has been completed.

For this assessment, a total of 27 questionnaires were printed and distributed to the staff. The office staff comprised 19 males and 8 females. The average age of the staff was 33 years old.

4.3.4.1 Assessment of the Questionnaires

The main types of complaint from the staff are shown in Figure 7. The majority of the complaints were about the stuffy atmosphere. About 40% of the staff found that the air in the office had an odour, was draughty, warm and dry. For the overall air quality rating, 55% of them were pleased with the air quality and the remaining 45% were dissatisfied.

The majority of the staff were absent for an average of 1 to 3 days per annum; 12.5% of them were absent for 4 to 6 days and 25% of the staff were not absent from work at all.

This subjective assessment showed that air quality at the office building is within tolerable limits and that the number of days lost due to illness is also within an acceptable range.

5. CONCLUSIONS

A fast-response sampling system using a perfluorocarbon tracer (PFT) has been used for measurement of airflow in ducts. Measurements of airflow obtained using the PFT technique and pitot static traverse were in close agreement.

Results obtained from objective measurements and the subjective assessment revealed that the office building has some ventilation and air quality problems. The air exchange rate is below the recommended value and the air distribution system into the office is not well designed. This faults tended to produce an environment felt to be overwarm and stuffy by many office staff.

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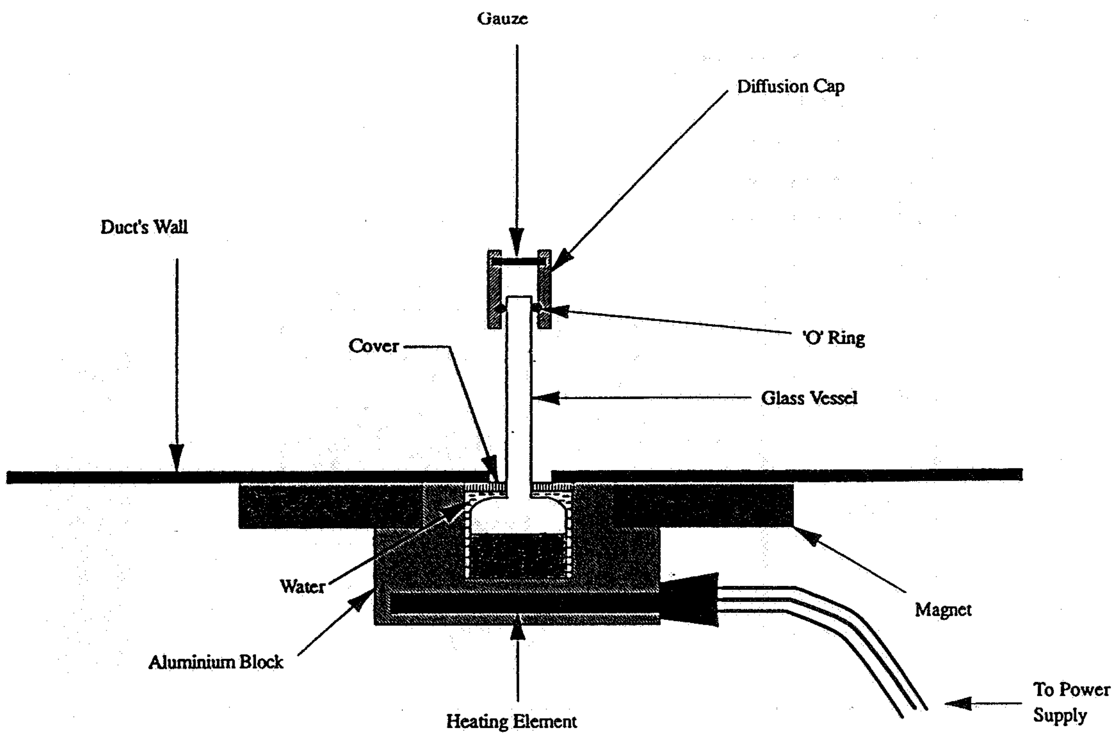
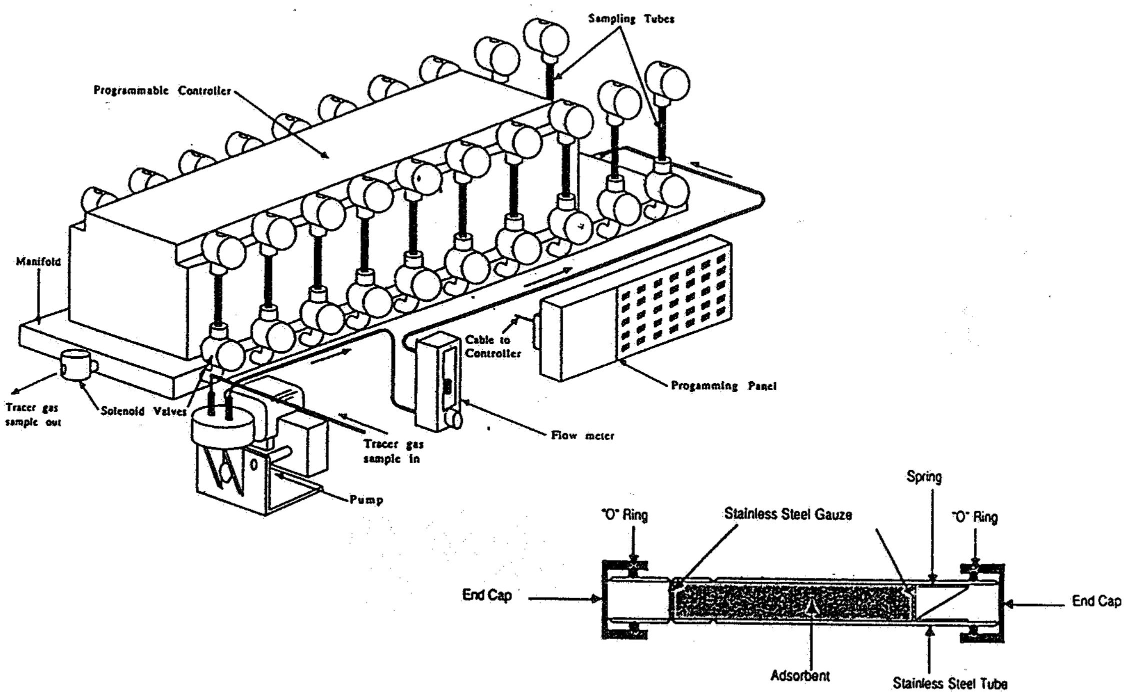


Figure 1 PFT tracer injection system



Sampling tube with end caps

Figure 2 Tracer gas sampling system

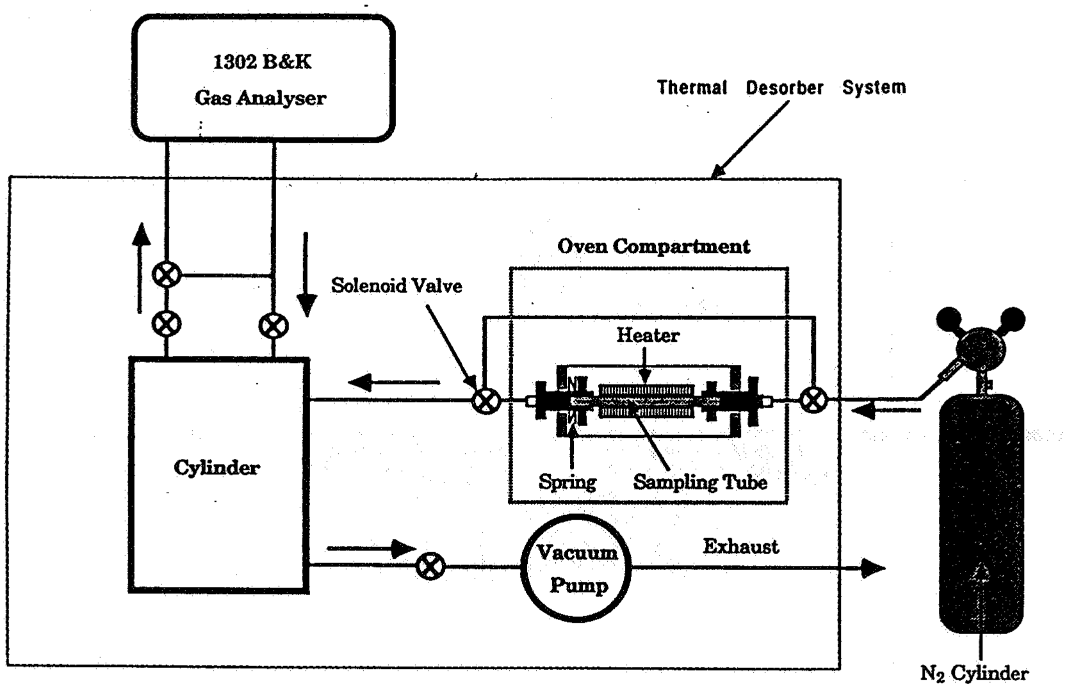


Figure 3 Schematic of the thermal desorber/gas analysis system

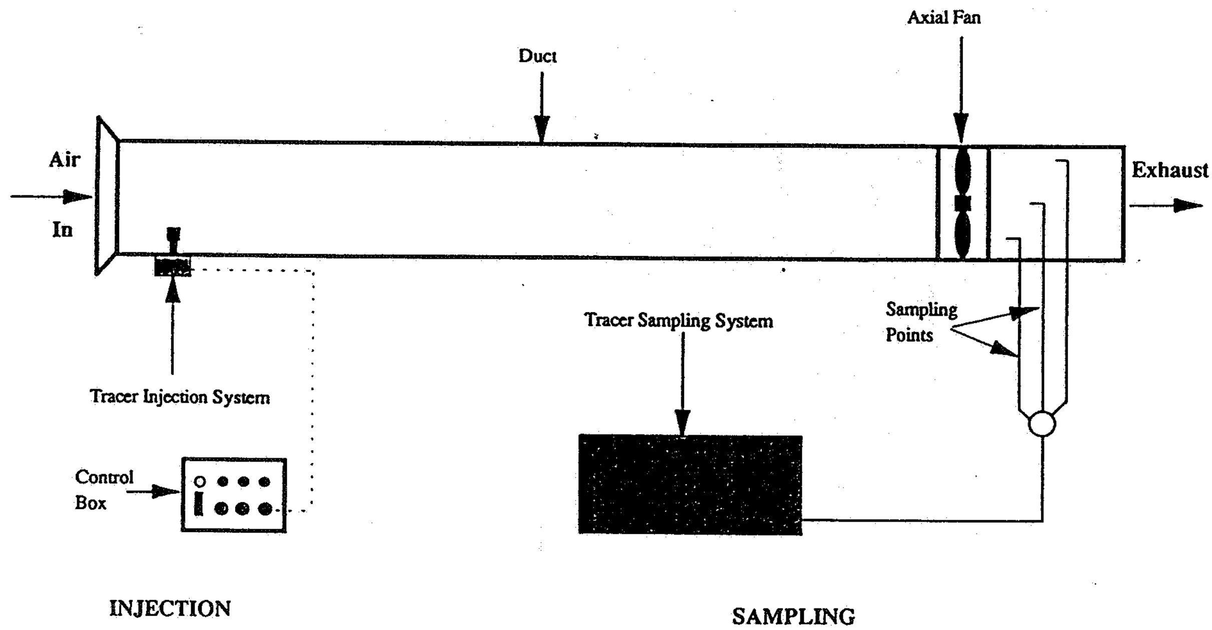


Figure 4 Instrumentation for PFT technique

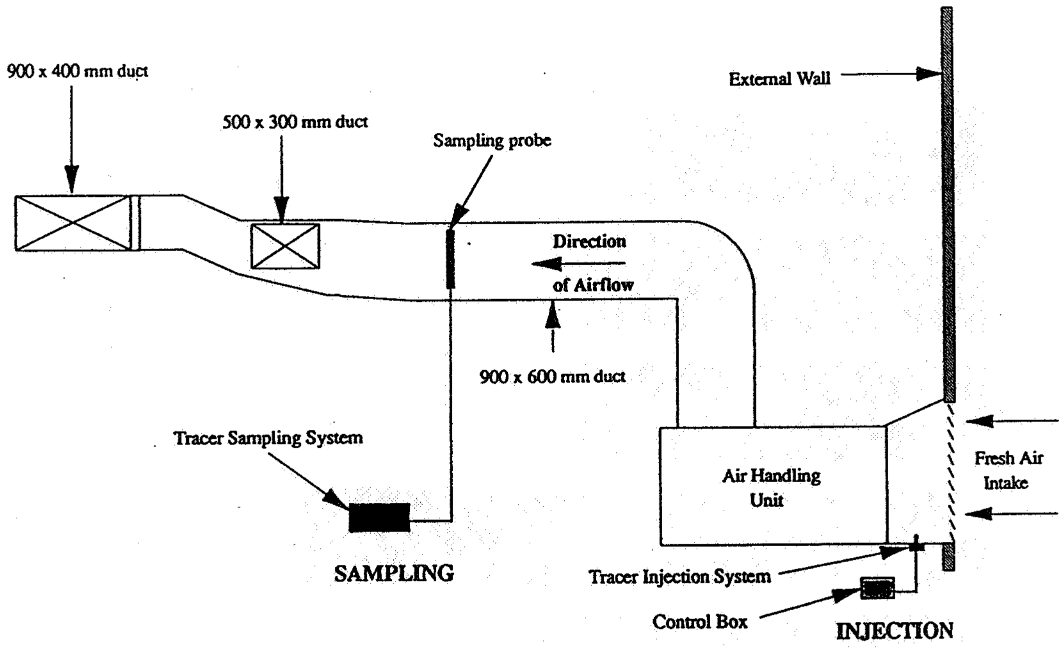


Figure 5 **Instrumentation for airflow measurements at the air handling unit**

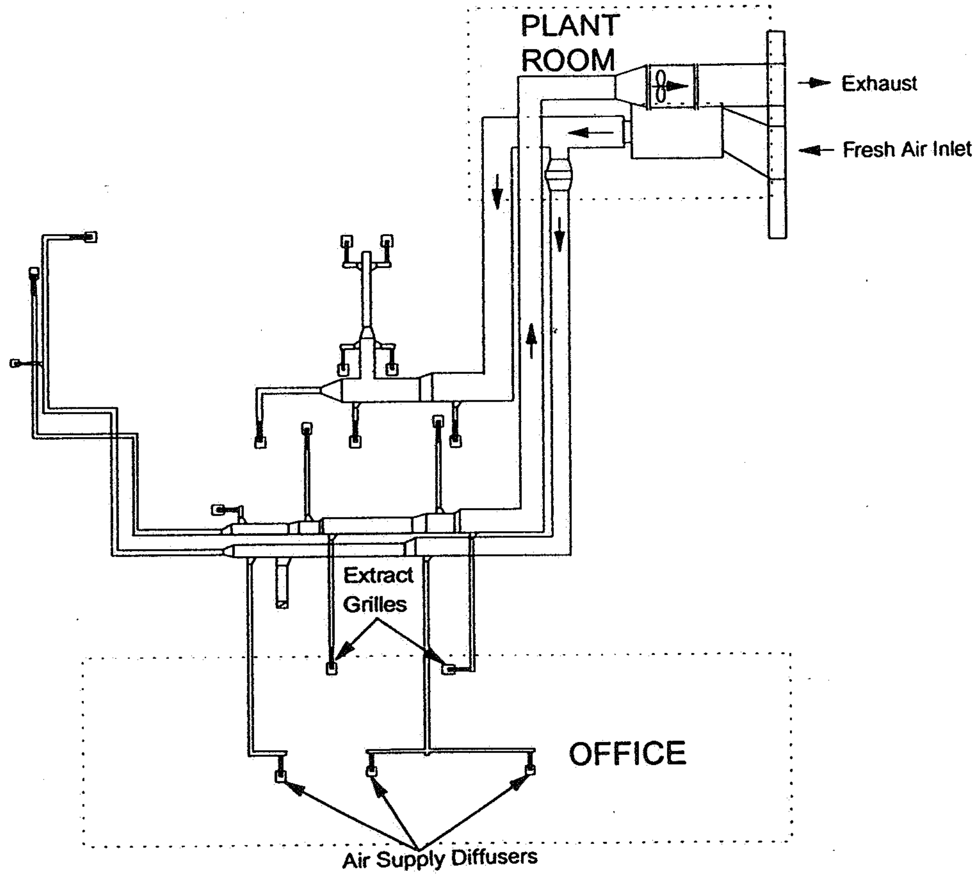


Figure 6 **Schematic of the air distribution system**

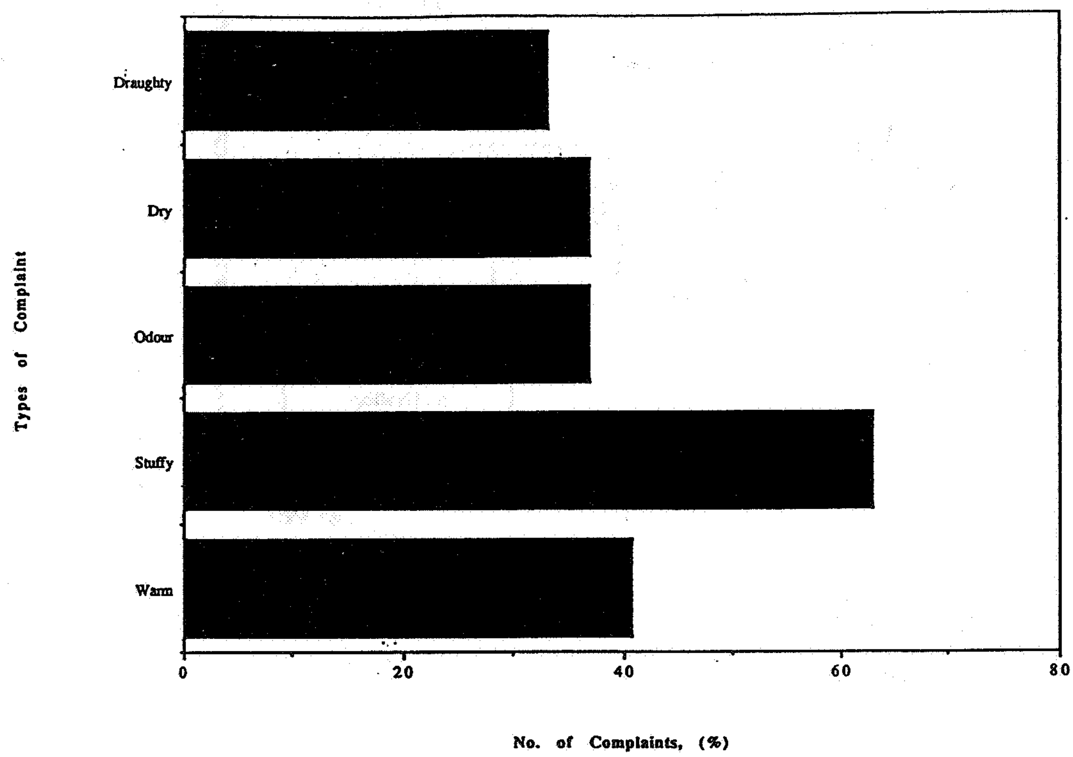


Figure 7 General complaints from staff