Proc. CIBSE A : Building Serv. Eng. Res. Technol. 17(4) 167–176 (1996) Printed in Great Britain

Case study

Summary The aim of this study is to assess the performance of the mechanical ventilation system and air quality in an office building. The perfluorocarbon tracer (PFT) technique was used to measure air flow in an air handling unit and to estimate flow rates supplied to the office. In order to validate the PFT technique as a viable means of measuring air flow in the mechanical ventilation system, the PFT measurements were compared with measurements made using a pitot-static tube. Air exchange range, ventilation effectiveness and age of air were examined. The concentrations of carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO) and dust particles were monitored. In addition, a questionnaire was completed by the staff in order to provide a subjective assessment of indoor air quality.

Ventilation and air quality in an office building

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Received 22 January 1996, in final form 2 May 1996

1 Introduction

Since the oil-crisis in the early 1970s, many new insulation techniques have been implemented to increase the air-tightness of buildings. Improved fabric insulation and 'tight' doors and windows cut down heat losses to the outside and reduces the building's energy consumption. However, insufficient ventilation provided by the mechanical ventilation system will result in poor indoor air quality and under extreme conditions, can be harmful to the occupants of the building. This leads to problems associated with 'sick building syndrome' (SBS). The ventilation system also assists in the removal of pollutants originating in the air-space. In addition, the performance of the mechanical ventilation system influences thermal comfort; for example, cold draughts can produce an unpleasant living or working environment for the occupants. Studies have shown that ventilation systems in buildings are largely responsible for 'sick building syndrome'[1,2]. Complaints of sickness among people in 'tight buildings', especially those housing equipment and machines, have become a significant problem over recent years[3,4].

In this case study, complaints about indoor air quality in the office building under consideration have been made by the staff. These include reference to stale air, overheating and physical discomfort such as headaches, nose and respiratory problems. In order to determine how these complaints were related to the performance of the ventilation system in the building, an evaluation of the building's ventilation and indoor air quality was carried out. This evaluation is a typical indoor air quality (IAQ) audit which includes both objective measurements and subjective assessment. Objective measurements involve the measurement of building ventilation rates, effectiveness of the ventilation system, and concentrations of selected indoor air pollutants. In the case of subjective assessment, a questionnaire was completed by the office staff.

2 Description of the office and its ventilation system

This two-storey building was built in 1990 to an energy efficient design and was first occupied in 1991. The office space takes up about 40% of the building space while the remaining 60% is for workshops. The workshops are demonstration areas for processes like spray-painting and electro-plating. A separate mechanical exhaust system with extractor hoods is provided for all processes to remove any pollutants emitted by them. For this paper, the office was studied because of its denser population and because the space is mechanically ventilated. It it an open-plan office which has a total floor area of 126 m^2 and is located on the ground floor of the building.

Air conditioning of the office is provided by a heat pump system through an air handling unit located in the plant room. Figure 1 is a schematic of the distribution system. The ventilation air from the air handling unit is delivered to the office through three air diffusers in the suspended ceiling. The air extracted from the office via two grilles is vented to the outside. In summer, this system operates with 100% fresh-air intake and no humidification. This is possible because the outdoor temperature is within the human thermal comfort conditions. In addition, this gives a cost-saving.

3 Measurement of airflow in air handling units

Airflow measurements were made in the air handling units of an office building using the pitot-static traverse method and PFT technique using sampling tubes[5].

3.1 Pitot-static traverse method

Velocity pressure and tracer gap tappings were positioned along the ducts at the air handling units. The velocity tappings allowed insertion of a pitot-static tube which could be traversed across the duct cross-section in order to measure velocity at various distances from the duct wall. Velocity pressures were measured using an EMD 2500 micromanometer made by Airflow Development, UK.

3.2 PFT technique

The PFT system includes the following components:

(*a*) *Tracer injection system.* Figure 2 shows the PFT tracer injection system, which consists of a cylindrical aluminium block with a heating element inserted into the base. The block is bored to allow insertion of a small glass vessel containing the PFT liquid. The

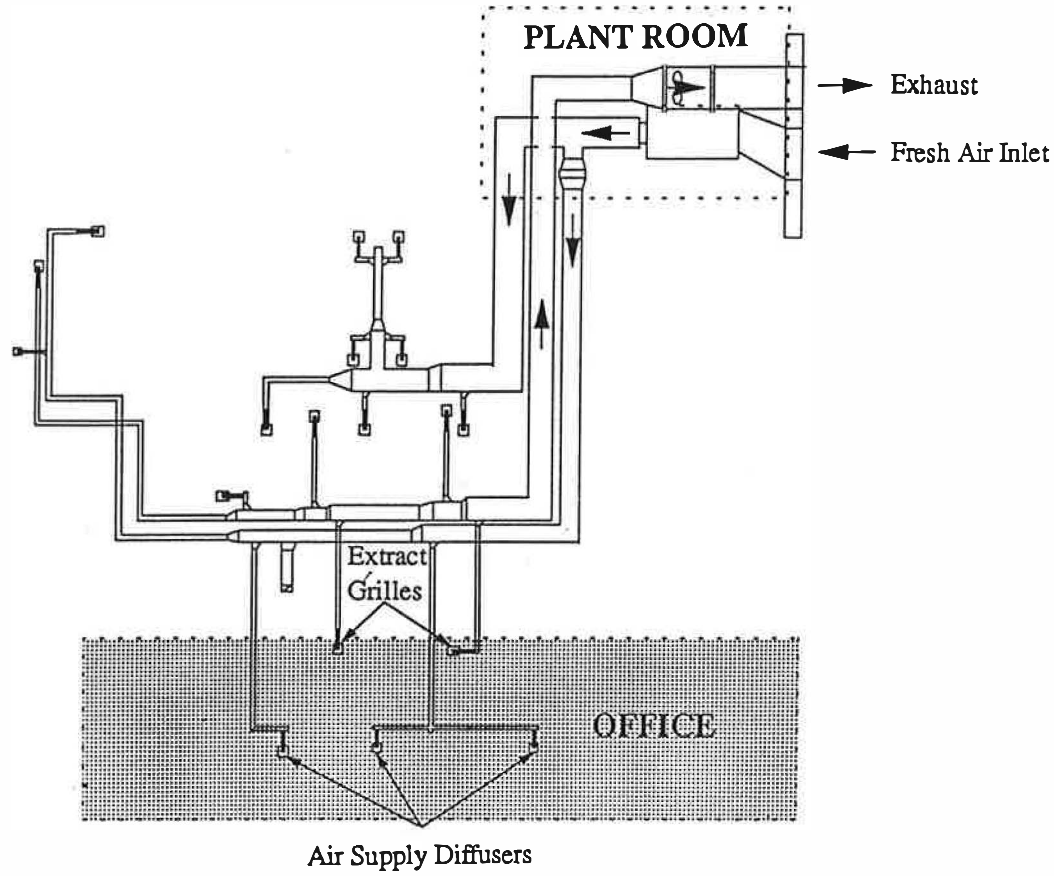


Figure 1 Schematic of the air distribution system

vessel is of $3\,cm^3$ capacity and has a neck 3 mm in diameter and 15 mm long. 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. The aluminium block is insulated to prevent excessive heat loss when it is heated.

(*b*) *Tracer sampling system.* The sampling system shown in Figure 3 consists of solenoid valves, tracer gas

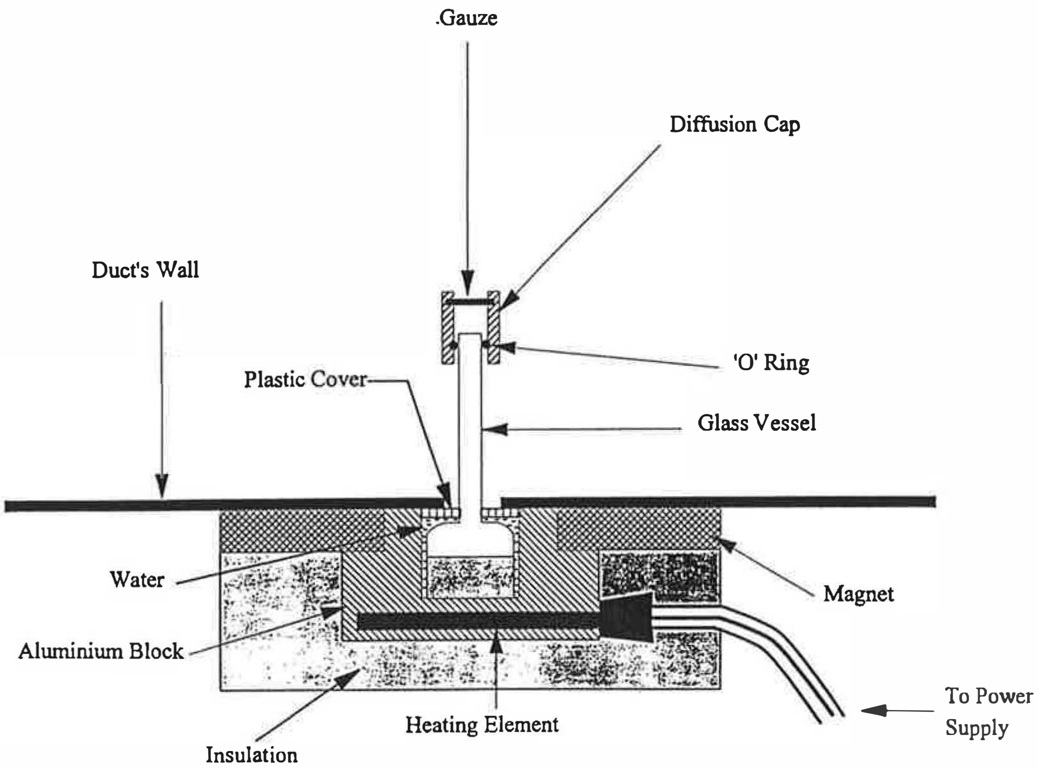


Figure 2 PFT tracer injection system

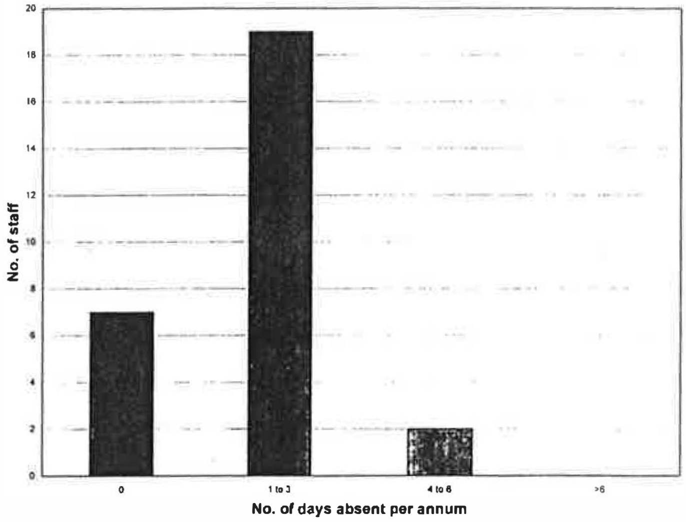


Figure 3 Tracer gas sampling system

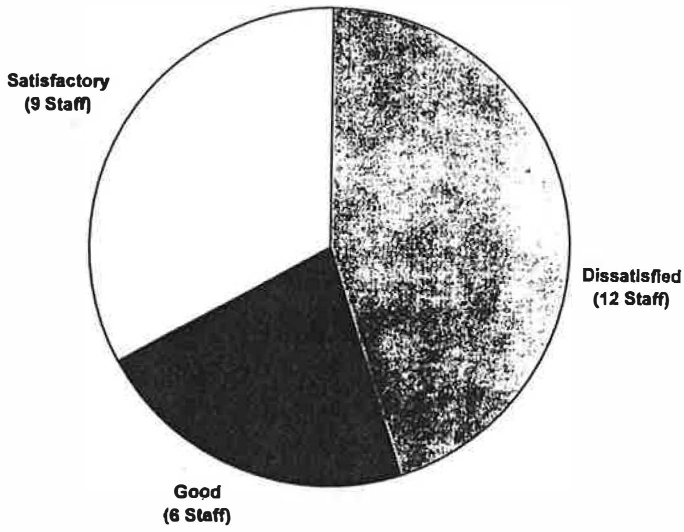


Figure 4 Schematic of the thermal desorber/gas analysis system

sampling tubes, 'programmable logic controller', manifold and flowmeter. The sampling interval of the programmable controller can be set as frequently as one second. The manifold of the sampling system was designed with a minimum 'dead' air volume, and as the tracer gas in the manifold was purged between samples, the effect of this volume was negligible. Air may be drawn at a constant rate into each sampling tube using a small gas-tight pump. The sampling tubes are made of stainless steel and packed with the adsorbent Chromosorb 102, 60–80 mesh, supplied by Chrompack Ltd (see Figure 3). The system operates 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 the samples have been collected. If preferred, the sampling system could be connected to a group of sampling bags rather than to the adsorbent sampling tubes.

(*c*) *Tracer gas analysis*. A multi-gas analyser, type 1302, manufactured by Bruel & Kjaer, Denmark, together with a thermal desorption system, type SBK 1355, manufactured by CBISS Ltd, UK, were used to separate and analyse the samples in the adsorbent mesh (see Figure 4). The analyser had a detection limit of parts per billion (PPB) and an accuracy of $\pm 1\%$.

Analysis of these tubes consists of placing the tube in the thermal desorption system, which 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 automatic and controlled by the thermal desorption system. The results are displayed on the multi-gas analyser.

The PFT technique determining the airflow rate in the duct F ($m^3 s^{-1}$) is based on the theory of the constant-injection technique as shown below:

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

The tracer gas released into the duct from the PFT injection system is at a constant rate q ($m^3 s^{-1}$) and the resulting concentration C (ppm) is measured using the multi-gas analyser. This assumes that a steady-state condition exists in tracer injection and sampling and the air and tracer gas are perfectly mixed within the duct with the outside air free of tracer gas.

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. Additional airflow measurements were conducted at the exhaust duct system (not shown in Figure 5).

4 Measurement of air exchange rates

The air exchange rate in the office was measured using the tracer-gas decay technique. The technique involved an initial injection of SF_6 tracer gas into the air space through the fan section of the air handling unit to provide a better tracer and air mixing in the office. The tracer gas was allowed to mix for 10 minutes with the aid of mixing fans to establish a uniform concentration in the air space. The decay of SF_6 tracer gas was monitored

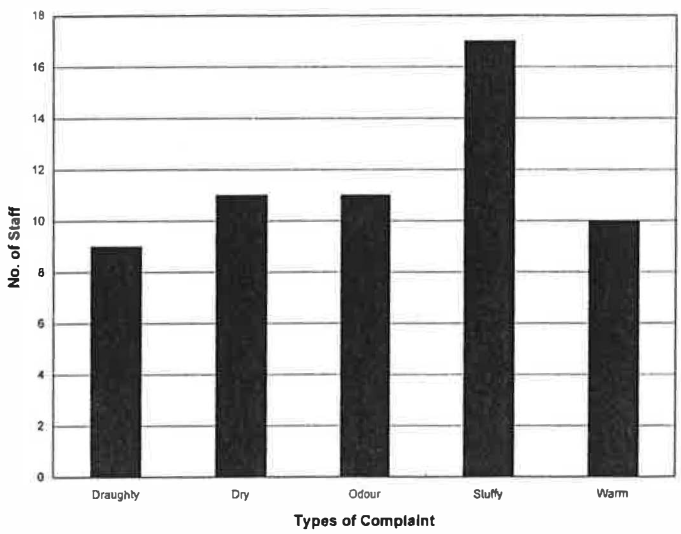


Figure 5 Instrumentation for airflow measurements at the air handling unit

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.

5 Age of air and ventilation effectiveness

Evaluation of the ventilation effectiveness 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 air distribution are believed to be responsible for some complaints about air quality.

Ventilation effectiveness 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 five minutes with the aid of mixing fans 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 effectiveness 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.

6 Monitoring concentrations of CO_2, CO, HCHO and aerosol particles

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

The concentrations of CO_2, CO and HCHO were measured using the MIRAN portable ambient air analyser. The accuracy of this analyser is estimated as ±15%. The concentration of aerosol particles was measured using the dust monitor, type 1.12, made by Grimm Ltd, Germany. The monitor was capable of measuring particles of diameter 0.1–10 μm with an accuracy of ±5%.

7 Results and discussion

7.1 Evaluation of air flow rates in air handling units

Airflow rates were measured in the air handling unit of an office building using the pitot-static traverse method and PFT technique using sampling tubes. Table 1 compares the measurements of airflow rate made with pitot-tube and PFT technique (using sampling tubes) at the air handling unit and exhaust duct system.

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 4.7%. In the case of airflow rate measurements at the exhaust system made using the PFT technique and pitot-static traverse method, the difference was −10.0%.

Table 1 Measurements of airflow rate in the air handling unit

Type	Airflow rates $m^3 s^{-1}$		Percentage difference $(F_t - F_p)/F_p$
	Pitot tube (F_p)	Sampling tubes (F_t)	
Air handling unit	1.49	1.56	4.7
Exhaust system	1.50	1.35	−10.0

7.2 Evaluation of air exchange rates

Measurements were carried out on a calm day with a south westerly wind at a speed of $0.5\,m\,s^{-1}$. Air infiltration could be neglected as the external wind pressure was low and it is a very 'air-tight' building. The air exchange rate in the office was 3 air changes per hour (ach^{-1}). This is below the recommended value of 4 to $6\,ach^{-1}$ given in the *CIBSE Guide, Installation and Equipment Data*[6].

In this study, the air temperatures were measured using a hot-wire anemometer, type TA2, made by Airflow Development Limited, UK. The indoor and outdoor air temperatures 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].

7.3 Evaluation of the age of air and ventilation effectiveness

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 effectiveness $\varepsilon = 1$. However, when there is a non-uniform distribution of air over the office air-space, values of ε are significantly less than 1. The ventilation effectiveness of the system was found to be $\varepsilon = 0.75$. The ineffectiveness of the system was partly due to the limited number and positions of air-supply diffusers and extract grilles in the office.

7.4 Evaluation of concentrations of indoor air pollutants

The concentration of carbon dioxide in the office varied between locations. The measured concentration of carbon dioxide ranged from 610–690 ppm. These values are well below the ASHRAE standards[8] recommended value of 1000 ppm for continuous exposure. This indicates that there is relatively good distribution of fresh air over the conditioned air-space and that the ventilation rate is sufficient.

Measurements of carbon monoxide level showed that its concentration was 0.2 ppm. This value is well below the acceptable indoor concentration of 9 ppm as indicated by Raatschen[9].

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

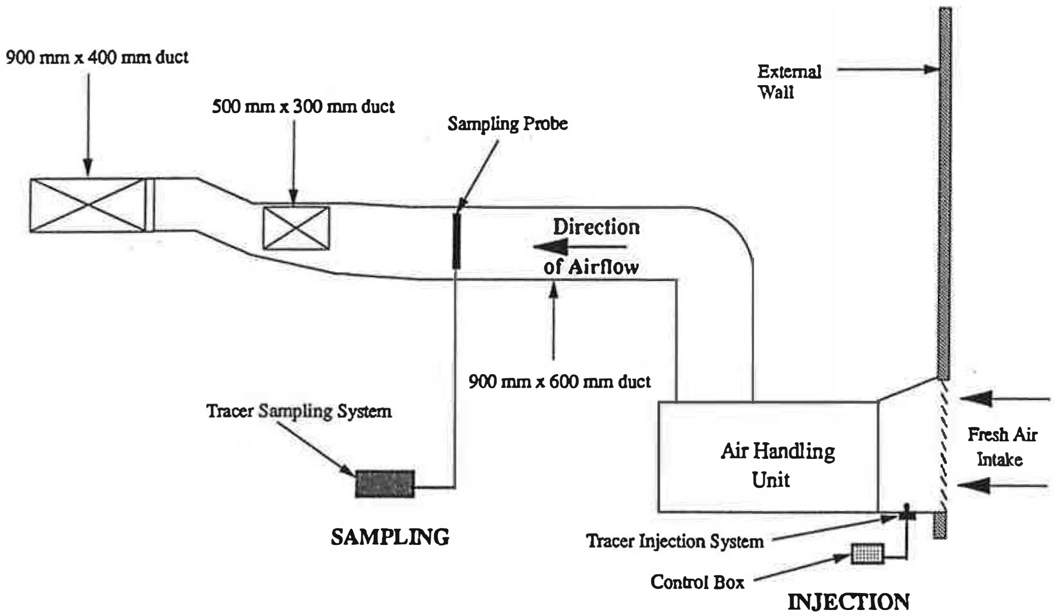


Figure 6 General complaints from staff

0.1 ppm[9]. However, the location with concentration above this value may be responsible for the eye irritation experienced by the staff. This contaminant is emitted mainly from particle board and various insulation materials.

The concentration of dust particles less than 5 μm in diameter was found to be 0.0122 mg m^{-3}. The maximum concentration of dust particles was 0.095mg m^{-3}. For long-term exposure, the recommended maximum level of particulates in the diameter range 0.1 to 100 μm is 0.075 mg m^{-3} as given by the National Primary Ambient Air Quality Standards[8]. On the whole, the level of dust particles was acceptable, apart from the area near the photocopying machines.

8 Office survey: Methodology

In addition to the objective measurements conducted in the office, the effects of air quality on the health of the

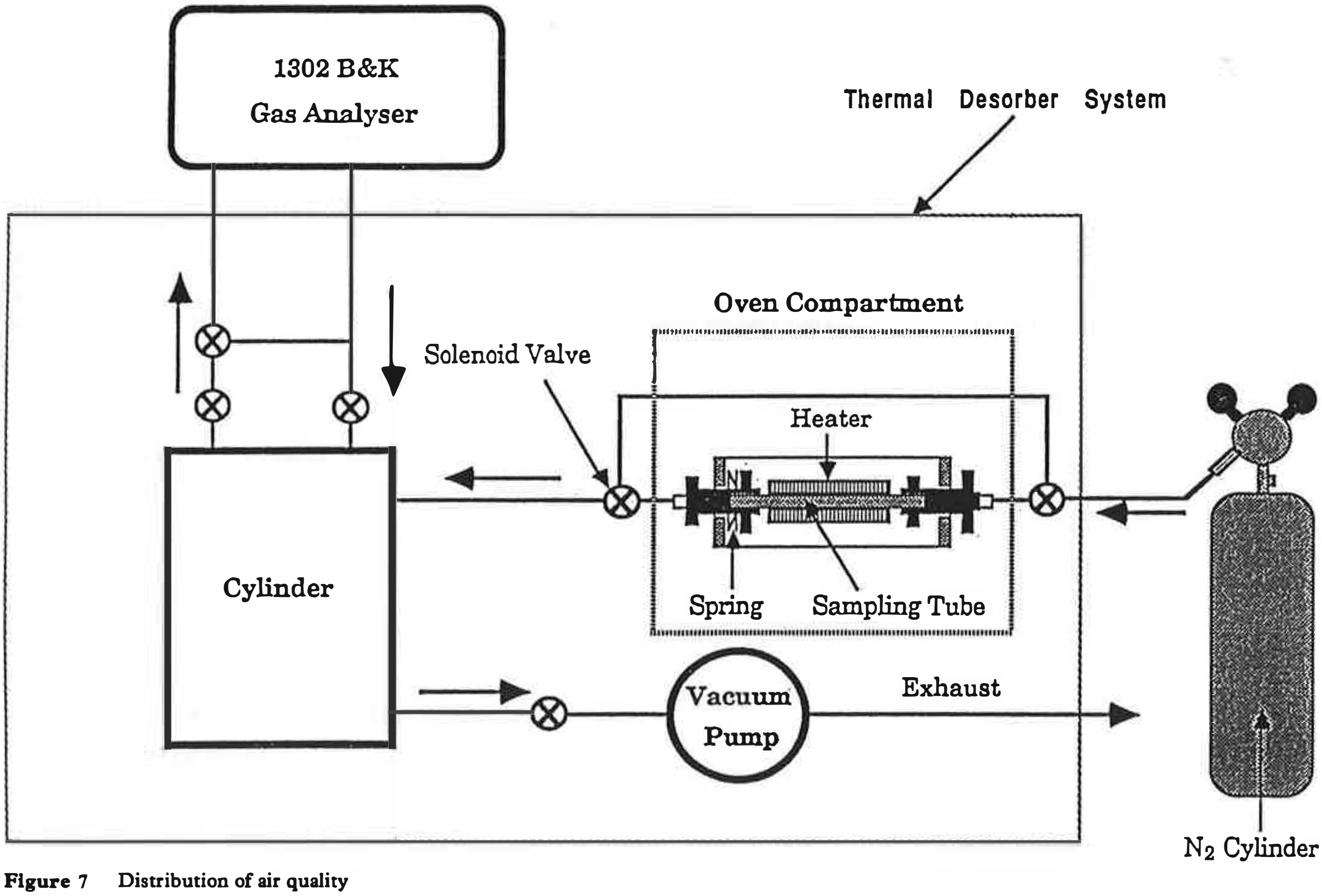


Figure 7 Distribution of air quality

office's staff were assessed subjectively. A questionnaire was distributed to the office's staff while the objective measurements were being taken. A sample of the questionnaire is shown in the Appendix.

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

8.1 *Assessment of quesionnaires*

The main types of complaints from the staff are shown in Figure 6. The majority of the complaints were about the stuffy atmosphere. About 11 staff found that the air in the office had an odour and was draughty, dry and warm. Figure 7 reflects the opinions of the staff on the air quality in the office. Six and nine staff felt that the air quality was good and satisfactory, respectively. The remaining staff were dissatisfied with the air quality.

Figure 8 shows the distribution of length of staff absence in days. The majority of the staff were absent for an average of one to three days per annum; two of them were absent for four to six days and seven staff were not absent from work at all. Figure 9 shows that most of the days lost from work were due to influenza, followed by nose problems, respiratory problems and migraine, in order of decreasing incidence. 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 acceptable range.

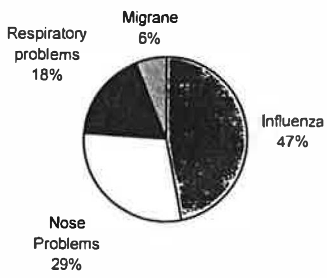
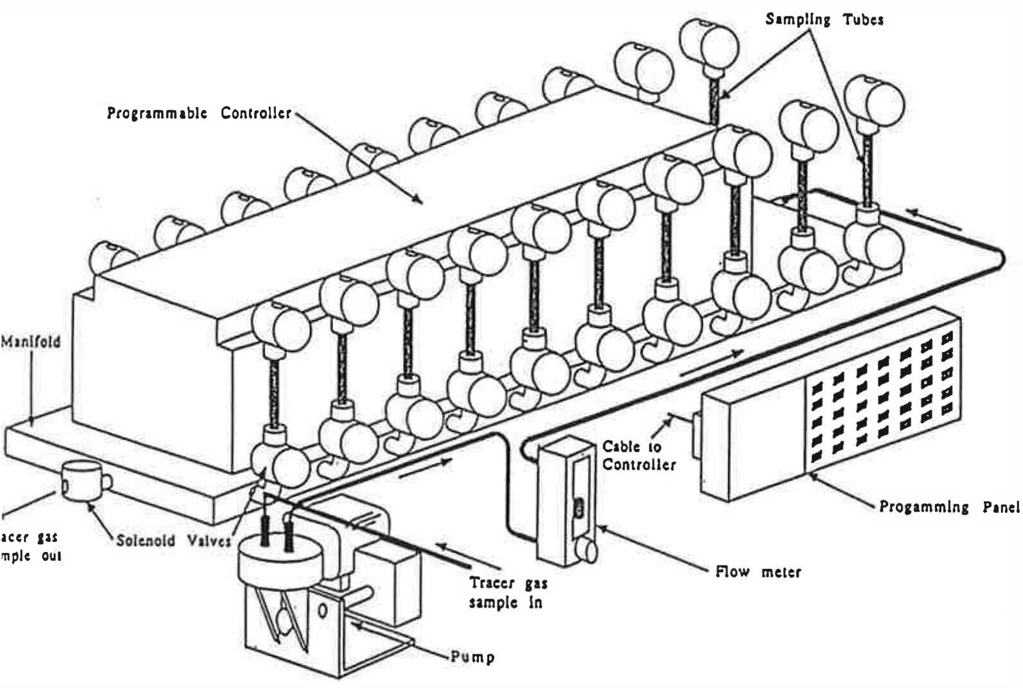
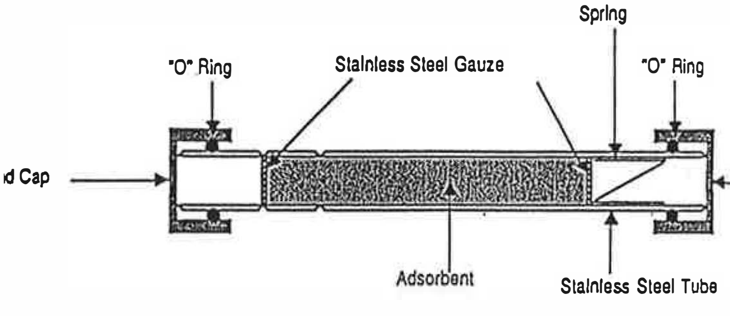


Figure 9 Types of illness

9 Office survey: comments on ventilation and air quality

The information obtained from the measurements and questionnaires shows that the office does have some ventilation and air quality problems. Some of these problems are the likely cause of the complaints.





Sampling tube with end caps

Figure 8 Distribution of length of staff absence from work

9.1 Comments on ventilation

The result obtained from air exchange rate measurements showed that the office was not well ventilated. Poor ventilation of spaces will lead to a build-up of CO_2 and airborne contaminants such as water vapour and body odour. In summer, the ventilation system operates with the fresh air intake damper fully opened at the air handling unit. The amount of fresh air supplied into the office space was $57.81\,l\,s^{-1}$ per person or $12.41\,m^{-2}$ with the airflow rate of $1.56\,m^3\,s^{-1}$ measured at the air handling unit using the PFT technique (see Table 1). The fresh air provided to this office is more than sufficient because the recommended values for offices are $10\,l\,s^{-1}$ per person or $0.7\,l\,s^{-1}\,m^{-2}$ as given by ASHRAE Standard 62-1989[8].

The above results indicated that there is sufficient fresh air supplied to the office but there is still a build-up of pollutants in certain locations of the office space. This shows that the distribution of air over the conditioned space is more important than the quantity of fresh air supply to it. Results for the evaluation of the age of air and ventilation effectiveness indicated that there was non-uniformity in the distribution at the office. The complaints of air stuffiness may be due to this poor air distribution to dilute the CO_2 in some parts of the office. The dense population ($4.67\,m^2$/person) in the office space may be partly responsible for the complaints of air stuffiness.

As a whole, the air temperatures in the office were within the thermal comfort conditions. However, some occupants complained that the air was warm because they were sitting close to the window with maximum exposure to direct solar radiation. As for the complaint of dryness, the air humidity may be quite low even though it is summer. In addition, the humidifier was not in operation during that period. The complaint of odour was mainly due to the newly-laid carpets and this will deteriorate with time.

9.2 Comments on air quality

In this study, only selected indoor air pollutants were monitored. The concentration of CO_2 varied between locations. On the whole, the CO_2 level was acceptable. The average concentration of HCHO merely satisfied the acceptable level. Higher concentration of HCHO can be found in areas with newly-laid carpets and ceiling tiles, and occupants will experience health problems such as eye irritation. Generally, the concentration of dust particles in the office was under control except near the photocopying machine. High concentrations of dust particles can result in respiratory problems such as mucous membrane irritation and respiratory impairment. On the whole, the average number of symptoms experienced by the each occupant is about 0.7 and this is still acceptable.

10 Remedial measures

Some remedial measures to overcome the ventilation and air quality problems are suggested as follows.

10.1 Ventilation

The air exchange rate needs to be increased to the recommended value of 4–6 air changes per hour. This could be achieved by increasing the speed of the centrifugal fan (provided that sufficient motor power is available).

Non-uniformity of air distribution can be rectified by relocating the supply diffusers and exhaust grilles or increasing their number.

10.2 Indoor air quality

The concentration of HCHO could be best reduced by controlling the emission rate at the source rather than by increasing the ventilation rate.

The high concentration of dust particles encountered in the photocopying room would be avoided if it had an additional local extract or fan.

11 Conclusions

The PFT technique has been used to measure air flow in an air handling unit and exhaust system at the plant room. The differences between air flow rates estimated using the PFT technique and those determined using a pitot-static tube at the air handling unit and exhaust system were 4.7% and −10.0%, respectively. PFT technique was found to be a relatively simple and useful method for measuring airflow in the air handling unit and exhaust system.

The 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 was below the recommended value and the air distribution system into office was not well designed. These faults tended to produce an environment considered overwarm and stuffy by many office staff.

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Appendix: Questionnaire on the analysis of the internal environment in an office building

***All information that you have given in this questionnaire will be Anonymous and Confidential**

I. GENERAL INFORMATION

1. Sex : ____________ 2. Age : ____________

3. Do you smoke?
( ) a. Yes ( ) b. No
If yes, do you smoke in the office?
( ) a. Yes ( ) b. No

II. NATURE OF WORK

1. What type of occupation?
( ) a. Managerial ( ) b. Professional
( ) b. Clerical ( ) d. Secretarial
( ) e. Others (Please specify : ________________)

2. How often so you handle these jobs daily? Please rank in the order of frequency (1 - most frequent & 8 - least frequent).
( ) a. Professional work ( ) e. Typewriter
( ) b. VDU ( ) f. Writing
( ) c. Telephone ( ) g. Photocopier
( ) d. Meeting ( ) h. Paper work

3. On average, how many hours per day do you spend in the office?
( ) a. 1 - 2 hours ( ) c. 5 - 6 hours
( ) b. 3 - 4 hours ( ) d. 7 - 8 hours

4. Do you need to sit in the same area during office hours?
( ) a. Yes ( ) b. No

5. How many years have you been working in the present location?
____

6. What would you rate your stress level in work?
( ) a. Very high ( ) c. Average
( ) b. High ( ) d. Low ( ) e. Very low

7. How do you rate your work?
( ) a. Satisfied ( ) c. Interesting ( ) e. Boring
( ) b. Stimulating ( ) d. OK

III. THERMAL COMFORT

1. How do you feel about the ambient air temperature?
   ( ) a. Very cold ( ) c. Cool ( ) e. Warm
   ( ) b. Cold ( ) d. Satisfactory ( ) f. Hot ( ) g. Very hot

2. Do you experience draughts?
   ( ) a. Yes ( ) b. No
   If yes, how is it? (Please tick two boxes)
   ( ) a. Hot ( ) b. Cold ( ) c. High ( ) d. Low

3. How do you feel about the room air?
   ( ) a. Too dry ( ) b. Satisfactory ( ) c. Too wet

4. Do you have control over the air temperature for your working area?
   ( ) a. Yes ( ) b. No

5. Do you sit near the window?
   ( ) a. Yes ( ) b. No
   If yes, how often do you open them?
   ( ) a. Opened frequently ( ) b. Opened occasionally ( ) c. Never opened

IV. AIR QUALITY

1. What is your feelings towards the ambient air?
   ( ) a. Very stuffy ( ) b. Stuffy ( ) c. Fresh ( ) d. Very fresh

2. Do you sense the presence of any odour?
   ( ) a. Yes ( ) b. No

3. Where do you think the odour may have come from if it exists? (more than one answer is possible)
   ( ) a. Cigarettes ( ) e. Ceiling tiles
   ( ) b. Papers or books ( ) f. Furniture
   ( ) c. Other occupants ( ) g. Wall finishes
   ( ) d. Carpet ( ) h. Others (Please specify : ______)

4. How do you consider the odour?
   ( ) a. Unacceptable ( ) b. Acceptable

5. What is your overall rating for the indoor air quality?
   ( ) a. Very good ( ) c. Satisfactory ( ) e. Very bad
   ( ) b. Good ( ) d. Bad

V. HEALTH

1. What is the average number of days per year that you are absent because of illness?
   ( ) a. 0 ( ) b. 1 - 3 ( ) c. 4 - 6 ( ) d. >6

2. What type(s) of illness did you suffer in those absent days? (more than answer is possible)
   ( ) a. Respiratory problems ( ) c. Problems with nose
   ( ) b. Allergic problems ( ) d. Problems with eyes
   ( ) e. Others (Please specify : ______________________________)

3. Have you experienced the following symptom(s) during office hours only and they disappear or alleviate quickly after leaving the office? (more than one answer is possible)
   3.1 Problems with nose
   ( ) a. Dryness ( ) c. Stuffy nose
   ( ) b. Itching, stinging sensation ( ) d. Running nose
   3.2 Problems with eyes
   ( ) a. Dryness ( ) c. Watering eyes
   ( ) b. Itching, stinging sensation ( ) d. Reddening of skin
   3.3 Problem with skin
   ( ) a. Dryness ( ) c. Reddening of skin
   ( ) b. Itching, stinging sensation
   3.4 Neurotoxic symptoms
   ( ) a. Reduced memory ( ) d. Headache
   ( ) b. Tired or sleepy feeling ( ) e. Dizziness, Intoxication
   ( ) c. Reduced power of concentration ( ) f. Nausea or feeling of vomiting

VI. OVERALL SUBJECTIVE RATING FOR THE WORKING AREA

1. What do you think of your working environment?
   ( ) a. Very comfortable ( ) c. Acceptable
   ( ) b. Comfortable ( ) d. Uncomfortable ( ) e. Very Comfortable

2. Was the office decoration satisfactory?
   ( ) a. Yes ( ) b. No

3. Do you find that some/all of the symptoms you experienced as stated in V. (3) above also occurred in the past during office hours?
   ( ) a. Very often ( ) c. Seldom
   ( ) b. Sometimes ( ) d. Never

4. Do you find that these symptoms are more obvious at the beginning of a week e.g. on Mondays and Tuesday?
   ( ) a. Yes ( ) b. No

5. Do you have any other comments on the internal environment e.g. air temperature, air quality, lighting, noise etc?

   ____

Thank you for completing this questionnaire.

Proc. CIBSE A: Building Serv. Eng. Res. Technol. 18(1) 63–66 (1997) Printed in Great Britain B426

Erratum

Ventilation and air quality in an office building

In the above case study by K W Cheong[1] the figures should have been captioned as follows.

Reference

1 Cheong K W Ventilation and air quality in an office building *Proc. CIBSE A: Building Serv. Eng. Res. Technol.* 17(4) 167–176 (1996)

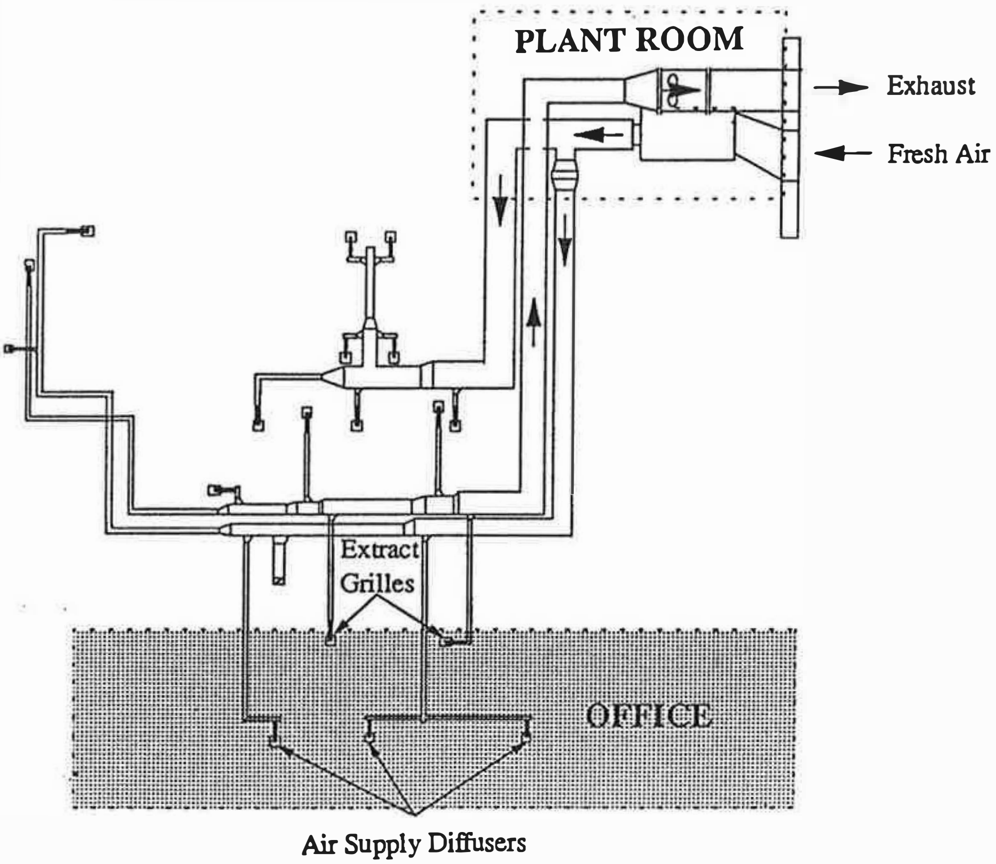

Figure 1 Schematic of air distribution system

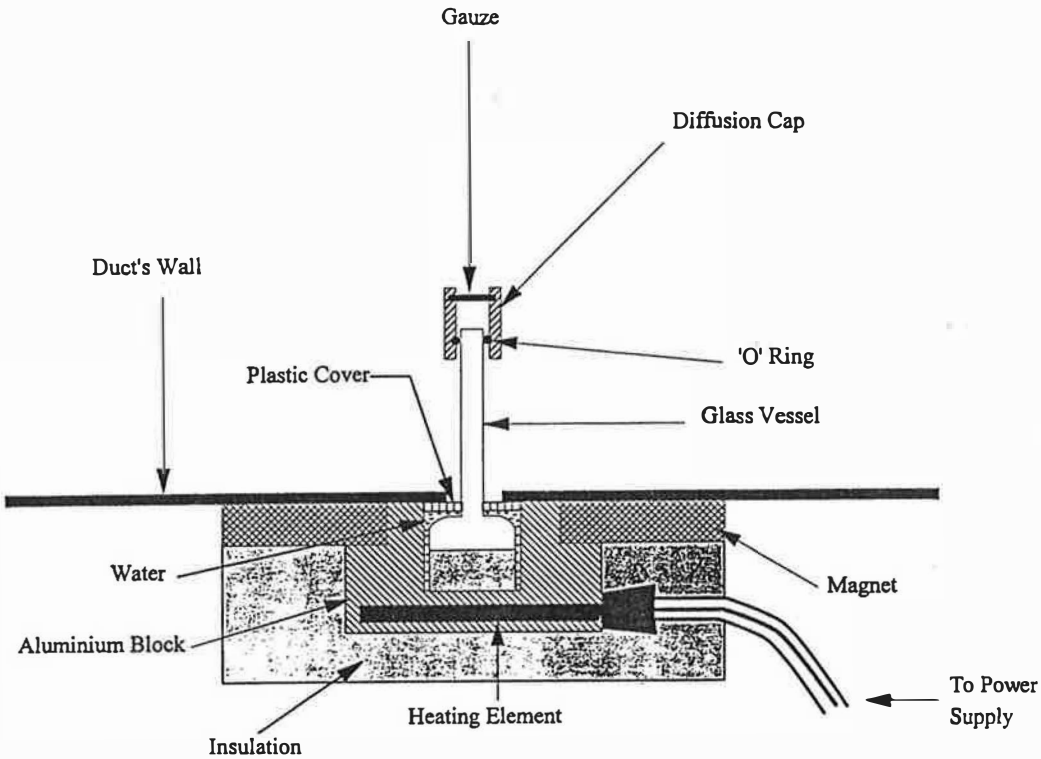

Figure 2 PFT tracer injection system

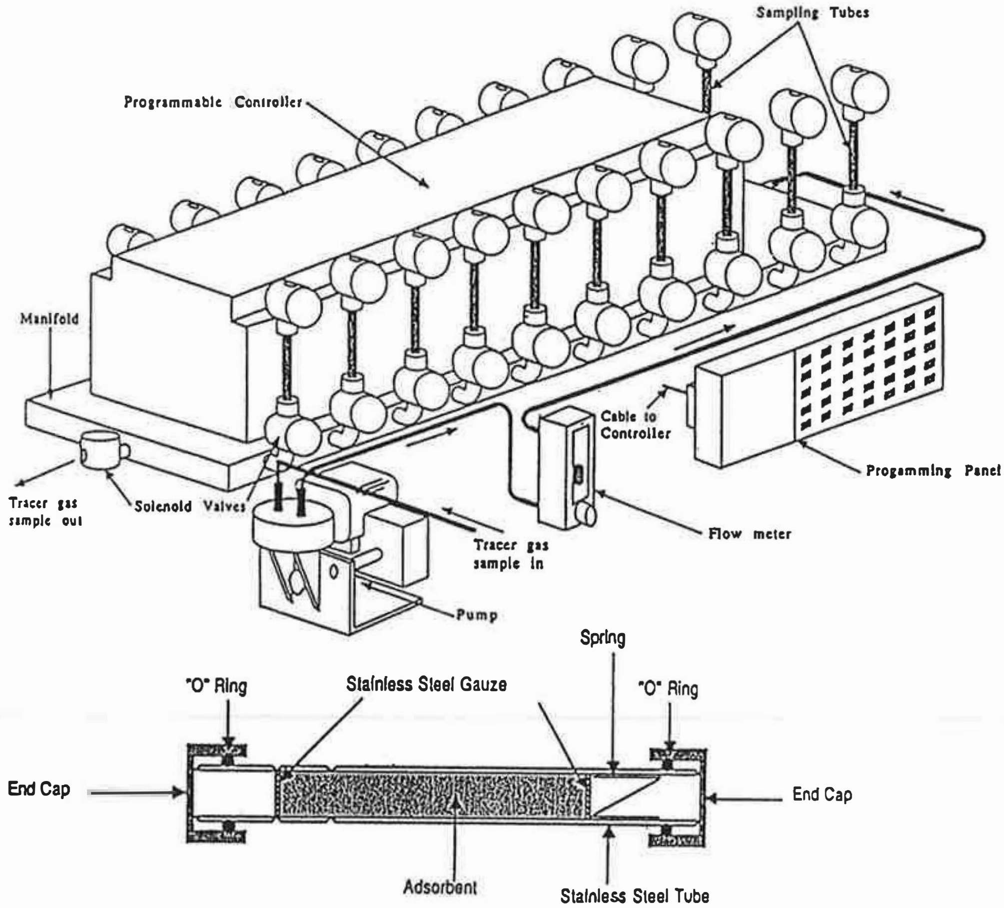

Figure 3 Tracer gas sampling system

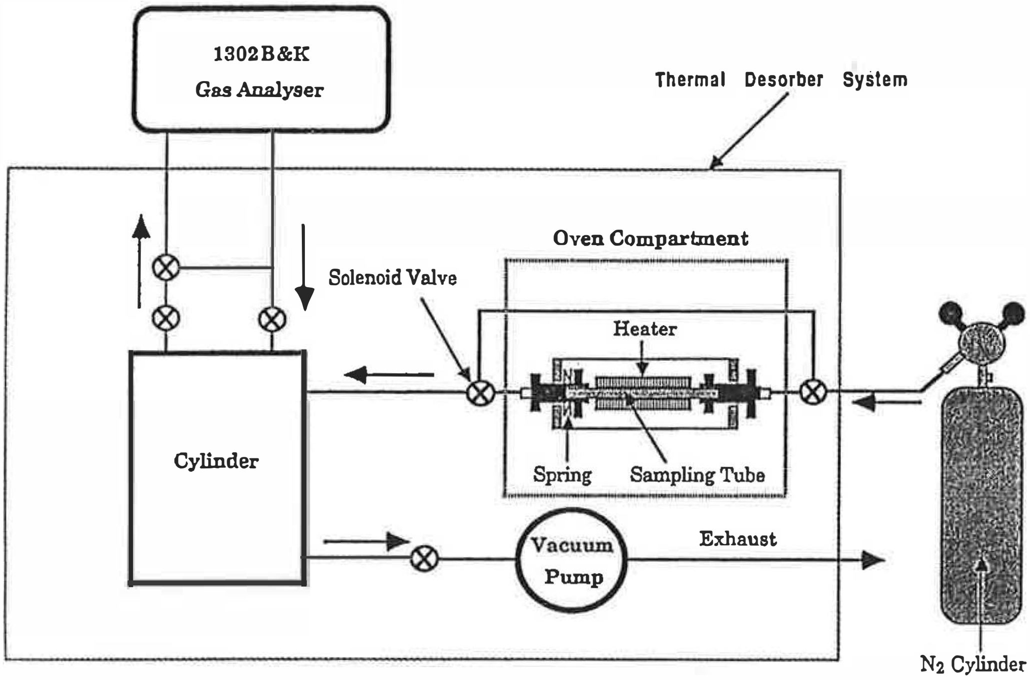

Figure 4 Schematic of thermal desorber/gas analysis system

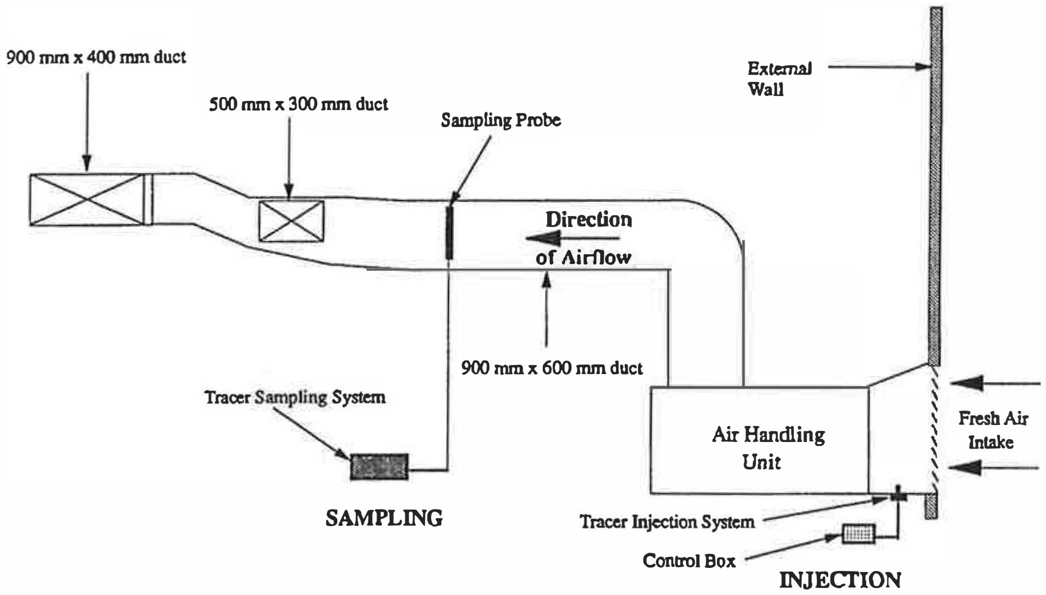

Figure 5 Instrumentation for air-flow measurements at the air handling unit

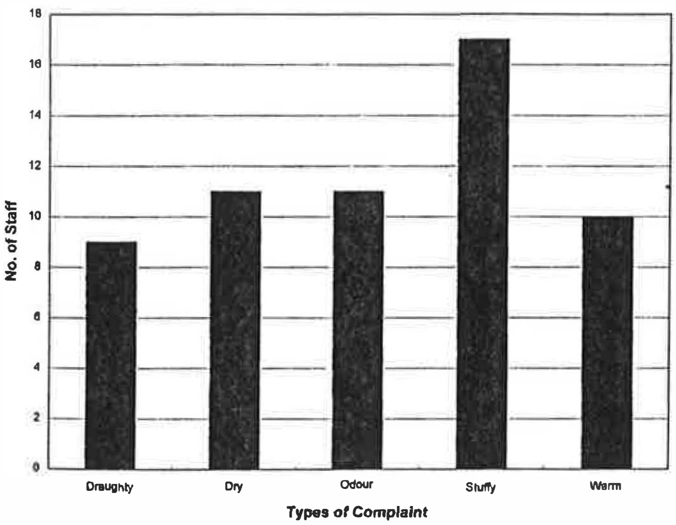

Figure 6 General complaints from staff

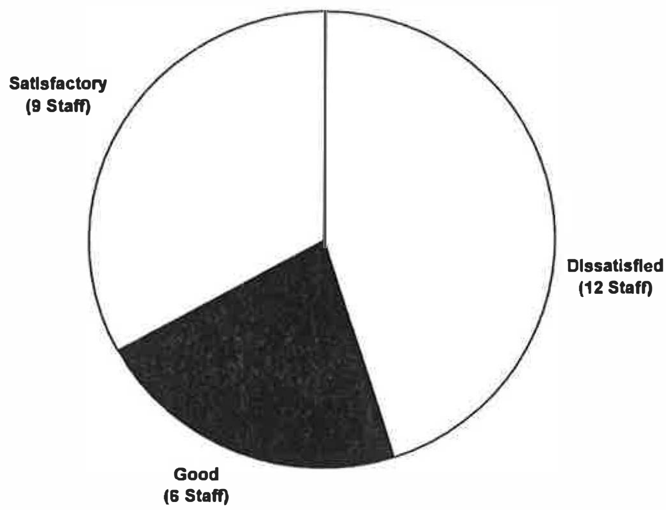

Figure 7 Distribution of air quality

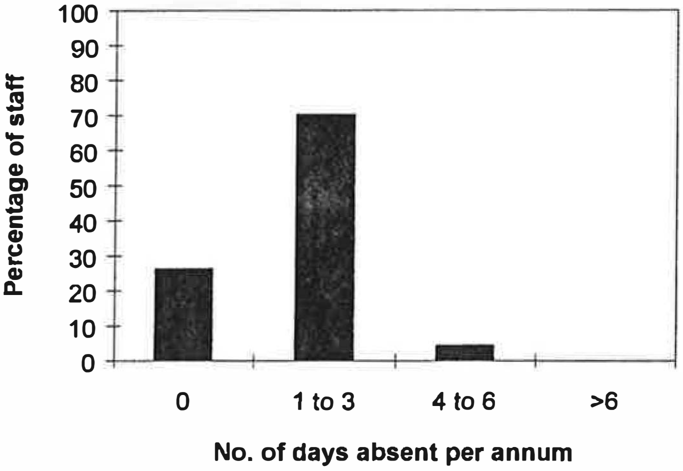

Figure 8 Distribution of length of staff absence from work

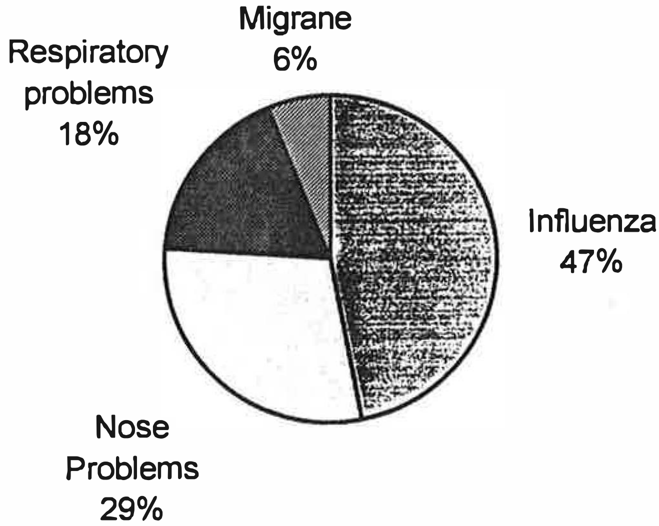

Figure 9 Types of illness