Evaluation of Thermal Comfort and Indoor Air Quality

D J Croome, FCIBSE, FInstHospEng, FRSA, MInstP, MInstE, MASHRAE
G Gan
H B Awbi, MIMechE, MCIBSE, MRAeS

Department of Construction Management & Engineering
University of Reading
PO Box 219, Whiteknights, Reading, RG6 2BU, UK

1. INTRODUCTION

A comfortable indoor environment is a necessity for occupants' good health and high productivity. Thermal comfort and indoor air quality depend on several environmental parameters including fresh air flow rate, air movement, air temperature, mean radiant temperature, humidity and contaminant sources in the air supply system or in the space. Their optimum values depend on the occupant conditions such as metabolic rate, clothing and personal hygiene. Improved thermal comfort is achieved at home or in workplaces through proper thermal mass and insulation together with appropriate heating, ventilation or airconditioning systems. The design and maintenance of ventilation systems has a decisive effect on the quality of indoor air. Poor indoor air quality is a principal cause of "sick building syndrome". An effective ventilation system enables indoor air quality to be controlled with minimum energy consumption and occupant dissatisfaction. In designing such a system a knowledge of airflow pattern, temperature and contaminant distributions in spaces is needed.

This paper presents some results of an investigation into the air movement, thermal comfort and indoor air quality in a naturally ventilated classroom. The investigation has been carried out both experimentally and numerically.

2. EXPERIMENTAL METHOD

Zainal and Croome (1990a, 1990b) investigated the indoor environment of a naturally ventilated classroom at Reading University for various arrangements of window and door openings. Air velocities and temperatures were measured at a horizontal level 0.9 m above the floor with omnidirectional hot wire anemometers. Air flow rates were determined using the concentration decay method with iso-butane as the tracer gas.

Thermal comfort was measured using a comfort meter; indoor air quality was assessed on the basis of the carbon dioxide levels during the occupancy periods. A subjective evaluation of thermal comfort and indoor air quality was also undertaken using a questionnaire comprising seven point scales on warmth and freshness. It was found that in summer when all the windows and doors were closed indoor air was unacceptable for comfort both in terms of thermal environment and odour intensity or freshness due to insufficient supply of fresh air. However when some windows were opened the indoor environment was improved (Zainal and Croome, 1990b); door openings have added a significant effect. Another test in which the thermal environment was monitored in the occupancy period for one week showed that on average the thermal comfort was acceptable when all the windows were closed whilst the door was occasionally opened (Zainal and Croome, 1990a).

3. NUMERICAL METHOD

The principle for the numerical evaluation of thermal comfort and indoor air quality is the incorporation of airflow model with the comfort model. The airflow model is based on the continuity equation, Navier-Stokes equation, thermal energy equation and the diffusion equation for transport of gases or particles as well as the equations representing the effects of turbulence. The solution of these equations is coded in a computer program called ARIA-R and the verifications of the CFD program have been presented by the present authors (Gan, et al. 1991a, 1991b & 1991c).

Thermal comfort is evaluated in terms of the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) proposed by Fanger (1982), which are related to air temperature, velocity, mean radiant temperature and vapour pressure of air for given values of metabolic rate, work and thermal resistance of clothing. Indoor air quality evaluation is based on the concentration of CO_2. In the present evaluation the air velocity, temperature and contaminant distribution are given by the flow equations. The mean radiant temperature for any point in the space is taken as a function of the temperature and thermal properties of room surfaces and the shape factors between the surfaces. Other parameters are taken as fixed values for the whole space. A number of numerical predictions have been made for the thermal comfort and distribution of CO_2 in the classroom, one of which is discussed below.

4. DISCUSSION

In the prediction presented here, six windows were half open. Air flowed into the room through four windows on one wall and flowed out from two windows on the opposite wall (cross-ventilation, see Figure 1). The measured air change rate is 3.62 per hour, and the calculated air velocity at the windows for air supply is 0.356 m/s at 19.9°C. The room was occupied by twenty-two people. The occupants were simulated as obstacles. It is assumed that each occupant produces 100 W heat and 4.7×10^{-3} l/s CO_2. The supply air is assumed to have a CO_2 concentration of 350 ppm. Heat gains due to solar penetration through windows and artificial lighting were also included.

The predicted air flow pattern in the room space, distributions of temperature, predicted percentage of dissatisfied and CO_2 concentration on the level 0.9 m above the floor are shown in Figure 1. The predicted airflow pattern was complicated due to the presence of obstacles and the effect of thermal buoyancy (Fig. 1 (a)). The air temperature is high close to the occupants due to the body heat (Fig. 1 (b)). The predicted velocity and temperature distributions have been compared with experimental results (Gan, et al. 1991a & 1991b).

Figure 1 (c) shows that a comfortable thermal environment is attained for this case. The average PPD in the occupied zone (floor to 1.8 m high) is about 8%, (between neutral and slightly warm). The test for this prediction was, however, conducted under a mild outdoor environment (about 20°C). According to this result, if the outdoor air temperature is much higher the indoor environment will be beyond the acceptable level for thermal comfort unless it is compensated for by a higher air flow rate. Therefore, in a hot climate some measure may have to be taken to provide sufficient and preferably cool fresh air without causing excessive draught if discomfort in the space is to be avoided. In a cold season, heat needs to be provided to maintain indoor thermal comfort which conforms with normal practice.

The predicted concentration of CO_2 is relatively high in zones away from the air supply openings compared to that in the areas close to the windows used for the air supply (Fig. 1 (d)). However, the average concentration of CO_2 in the room is low (670 ppm) due mainly to the high air flow rate; based on 3.62 air changes per hour this is about 15 l/s per person.

Previous investigations (see Gan, et al. 1991b & 1991c) indicate that thermal comfort and contaminant distribution are affected by the density and distribution of occupants and by locations of the supply and extract openings. The optimum arrangement of window and door openings for comfort will therefore vary for different combinations of these factors. Effects of turbulence, standard deviation around the mean air velocity are being investigated at head and foot levels.

5. CONCLUSIONS

This investigation has shown that a reasonably comfortable indoor environment in naturally ventilated rooms can be achieved by appropriate arrangement of window/door openings in a mild climate. However, this may be difficult to maintain during a hot summer. It has also been shown that the 3-D CFD program ARIA-R can be used to evaluate the thermal comfort and indoor air quality in ventilated rooms.

Further experimental and numerical investigations of these indoor environment criteria in offices are currently under way for a variety of systems in different buildings. Measurements will be undertaken at head and foot levels.

REFERENCES

1. Fanger, P.O. (1982): "Thermal Comfort — Analysis and Applications in Environmental Engineering", Robert E. Krieger Publishing Company, Florida.

2. Gan, G.; Awbi, H.B. & Croome, D.J. (1991a): "Simulation of air flow in naturally ventilated buildings", Building Simulation '91, Nice, Sophia-antipolis, France.

3. Gan, G.; Awbi, H.B. & Croome, D.J. (1991b): "Air flow and thermal comfort in naturally ventilated classrooms", 12th AIVC Conference, Ottawa, Canada.

4. Gan, G.; Croome, D.J. & Awbi, H.B. (1991c): "Numerical prediction of contaminant distribution in ventilated rooms", Ventilation '91, Cincinnati, Ohio, USA.

5. Zainal, M. and Croome, D.J. (1990a): "Building planning and ventilation: The effects of natural ventilation via windows and doors linked by corridor/ passage-way", Roomvent '90 — Proceedings of the Second International Conference on Engineering Aero- and Thermodynamics of Ventilated Room, Oslo, Norway (13-15 June, 1990), pp.D2 (67).

6. Zainal, M. and Croome, D.J. (1990b): "Ventilation characteristics of selected type of buildings and indoor climate", Ventilation System Performance — Proceedings of the 11th AIVC Conference, Belgirate, Italy (18-21 September, 1990), Vol. 2, pp.195-210.