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Computational fluid dynamics

An advanced active tool in environmental management and education

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Abstract *The improvement in the quality of life together with thermal comfort, air quality, health, workplace security and energy conservation measures justify the integral education of environmental (outdoor and/or indoor) phenomena. Environmental education, through the appropriate tool, can play an important and vital role in this domain. Computational fluid dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as distribution of pollutants by means of computer-based simulation. This technique, allowing the simulation and the visualization of environmental problems, represents a powerful tool to motivate, guide and educate on the environment. The main objective of this paper is to introduce this new advanced active tool in environmental education, directed to indoor-environment quality, that permits the prediction and visualization of air movement, air temperature and air contaminant (such as tobacco smoke) distribution in rooms. With suitable mathematical models and boundary conditions, a computational code has been developed to predict and visualize these phenomena. In order to demonstrate its applicability, the simulation of air contamination distribution in an office room with a smoker was performed.*

Introduction

In today's technological society about 90 percent of our lifetime is spent in an indoor environment. The main objective of buildings has always been to provide shelter from sun, wind, cold and rain. In the past designs were relatively simple and took into consideration the local environmental conditions. The buildings were designed to be naturally ventilated. Often "builder" and "occupant" were one and the same. The buildings had high ceilings and the location and size of windows was in such a way as to avoid excess heat entering from sun radiation and to supply enough air coming in. However, nowadays due to current energy saving procedures indoor-environment quality has tended to decrease. In fact, in the last decade the drive to produce more energy efficient buildings has led to the design of highly insulated buildings that are airtight.

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Artificial lighting and ventilation created an indoor climate largely independent of outdoor climate conditions. Other factors which have increased indoor-air pollution are the many new materials used in the construction and furnishing of buildings. Tobacco smoke is frequently identified as the main indoor-air pollutant. There are, however, many other important indoor-air pollutants: combustion products and moisture from heating and cooking, volatile organic compounds, bio effluents, microorganisms, allergens and fibres. Radon, a radioactive gas present in many naturally-occurring rocks and soils, is a more recently recognized indoor-air pollutant problem, which represents a serious risk for human health (Awbi, 1995).

Therefore, it is normal that complaints about indoor air quality in non-industrial buildings have increased over the years. Parameters such as ventilation and pollution sources are documented as being of major importance. A healthy and pleasant climate is defined as a fairly low air velocity, small velocity and temperature gradients throughout the room, and also a low concentration of pollutants. A satisfactory distribution of ventilation-air in a room is essential to reach this aim. An unsatisfactory airflow pattern (air ventilation) may be due to the air supply, temperature gradients within the room, type and positioning of supply and extract air-ducts, machines, furniture and other objects within a room. There are many configurations of ventilation air distribution systems and a wide range of potential conditions within residential or office buildings (Loomans, 1998). The prediction of ventilation performance (and so indoor-environment quality) for any specific situation is difficult. In fact, the required ventilation in a space depends on the total pollution source strength, the perceived air quality of the outdoor air, the desired perceived air quality and the ventilation efficiency in that space. The traditional way to determine the air quality in existing buildings is to ask people at their working place how they perceive the air (Fanger, 1988). The use of independent people who visit the investigated buildings is another approach. This procedure, as well as the experimental studies, is very time consuming and expensive. Computational fluid dynamics (CFD) makes it possible to simulate airflow patterns, thermal comfort and concentration distributions of pollutants in a space at much less cost (Ramos, 1998). This technique, allowing the simulation and the visualization of environmental problems, represents a powerful tool to motivate, guide and educate about the environment. For this purpose, a theoretical model is described first, and then the simulation of the air contamination distribution in an office room with a smoker is presented.

Indoor-environment quality vs environmental education

The occupant appreciates the indoor environment mainly by its air quality and thermal conditions. Fanger (1972) presented two units of measurement used in assessing the thermal comfort. The two units (PMV, predicted mean vote and PPD, predicted percentage of dissatisfied) were used to predict the thermal comfort as a function of the two individual parameters (clothing insulation and metabolic rate) and four environmental parameters (air velocity, air temperature, mean radiant temperature and humidity). International standard ISO 7730 (1994) uses this methodology. The air quality in a room, as perceived by the occupant, is a function of the indoor air pollution. The perceived air quality cannot be determined objectively. It is defined as the immediate impression of the indoor air quality experienced by people entering a space. In this methodology, developed by Fanger (1988), the perceived air quality is determined by a sensory panel. The air quality is assessed in decipol or in the percentage of dissatisfied, the air pollution load is given in olf. To obtain minimum acceptable indoor air quality levels, a room must be ventilated with fresh air. In recent years a number of new ventilation systems and strategies have been introduced to improve indoor environment quality (air quality/thermal comfort) and energy efficiency. Before ventilation rate can be specified it is necessary to identify those contaminants and their sources within the buildings as well as to establish acceptable concentrations in indoor air. There are comprehensive standards (ASHRAE, ISO, DIN, etc.) that give each contaminant and the health risk for short, medium and long term exposure. There are four pollutants of special concern to indoor air quality (Awbi, 1995); these are tobacco smoke, formaldehyde, radon and biogenic particles. In addition we have odours, carbon dioxide and moisture, which have significant effects on IAQ. A serious risk for human health is given by radioactive gas radon, which is a more recently recognized indoor air pollutant problem. Due to current energy saving procedures the buildings are highly insulated and air quality has tended to decrease. In certain cases the indoor pollution can even reach levels ten times higher than the external pollution. So, it appears the "sick building syndrome", which is a situation that is verified in buildings in that a significant number of occupants (more than 20 percent) presents health problems related to the indoor air quality (World Health Organization, 1983). Sick buildings can be derived from insufficient ventilation or a very high load of pollutants. Studies are being conducted to predict the correct flow rates and air distribution to create an internal clean, comfortable and healthy environment in order to promote appropriate human respiration, dilution of pollutants below maximum permissible concentrations, control of internal humidity, thermal comfort and productivity (Brohus and Nielsen, 1996; Loomans, 1998; Nielsen, 2000; Ramos *et al.*, 2002). The improvement of life quality and people's productivity needs development, teaching and implementation of new rules and a new attitude towards the use and ventilation of indoor spaces. This domain is a new and fundamental challenge for environmental education.

Insufficient ventilation or a very high load of pollutants promotes a sick indoor environment. There are many means to ventilate a room. In fact, the number of indoor airflow configurations is very large. They may be classified according to their flow conditions or according to the way they ventilate a room (Awbi, 1995; Loomans, 1998). Two main principles are available for mechanical ventilation of an office room: mixing ventilation; and displacement ventilation. Mixing ventilation means that the air is supplied to the room at relatively high velocity (Figure 1). The entry of room air in the supply jet causes a high degree of mixing to take place. As a result the temperature and contaminant concentration tend to remain uniform. In fact, the aim is to use supply air to dilute the concentration of contaminants in the room. This is the most important ventilation principle since the introduction of mechanical ventilation. With displacement ventilation, relatively cool and clean air is supplied at floor level at a low velocity (Figure 1). Air from the lower part of the room is induced upward by rising convection flows from heat sources in the room and then is removed at ceiling level. Displacement ventilation is only applicable in cooling situations, and is used in buildings with large occupancy and large thermal loads. The CFD technique permits prediction and visualization of the indoor environment provided by these ventilation systems. Therefore, it represents a powerful new tool to teach and sensitize about indoor-environment problems.

CFD: a new study methodology

In recent years CFD has taken a prominent position for the simulation of airflow and indoor-environment problems. Information on indoor-environment quality can be derived from the calculated indoor airflow pattern, temperature and contaminant distributions. CFD opened a route to numerically predict the indoor environment on a detailed level with high flexibility in terms of configurations and boundary conditions. In fact, one of its main advantages over other tools is its

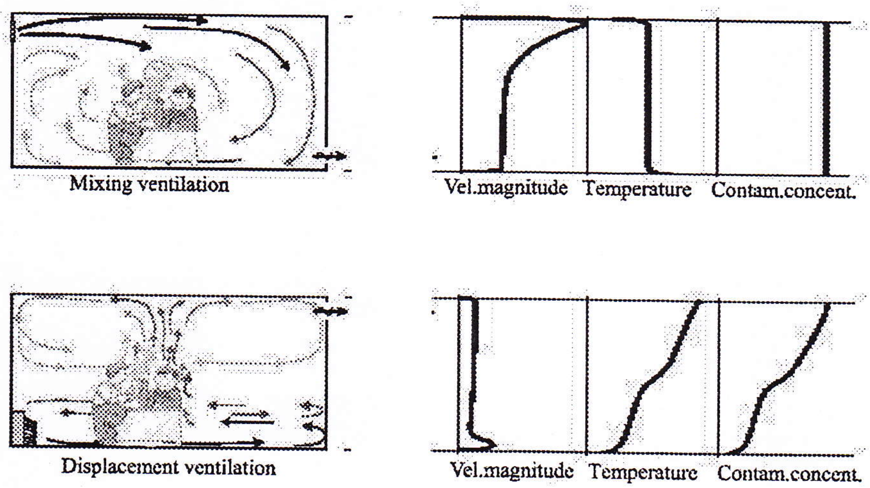

Figure 1. Schematic representation of ventilation systems

ability to simulate a wide range of configurations. Encouraging results have been obtained from simulations of several configurations of the indoor-environment problems. Developments in turbulence modelling and solver techniques for calculating the flow problem have improved the simulations process considerably. The ever-increasing processing speed and memory now available on today's computers make it easier to use CFD for handling environment-engineering problems. Since the first application to room air distribution by Nielsen (1976), there has been great interest in developing CFD computer codes for predicting the airflow and transportation of pollutants in rooms (Yaghoubi *et al.*, 1995; Hadidi, 1998; Carvalho *et al.*, 1999; Pitarma *et al.*, 2003). The use of CFD is now maturing in this field. Nowadays, the development of commercial versions of the CFD-code with extensive data handling possibilities and a pleasant interface with the programmer, combined with the rapid increase in computer power over recent years, have further enhanced its practical application (Gaspar *et al.*, 2003). Therefore, CFD studies can provide services for the community in general, in areas of thermal comfort, indoor environment quality and energy saving measures, constituting a powerful tool for environmental education. With the CFD, the teacher has the capability to simulate and to show to the students several situations of indoor/outdoor environmental problems at a very low price compared to experimentation. For instance, we can simulate and visualize, in an office room with natural/mechanical ventilation, who receives the "youngest" air and who is submitted to the "oldest" (i.e. contaminated) air (Figure 2). Thus, with this tool it is possible to predict and to visualize the effect on the other occupants of the pollution produced by a certain person.

Airflow and the transport of pollutants within a room is very complex, normally three-dimensional, recirculating, and turbulent. The computer code CLIMA3d was developed at the Polytechnic Institute of Guarda and the Polytechnic Institute of Leiria, with the collaboration of the Technical University of Lisbon, to predict flow patterns, temperatures and pollutant concentrations in a space with a certain ventilation system. The programme is based on the finite-volume discretization method, employing a staggered grid for mean-velocity components relative to scalar properties, and uses non-linearly spaced grids to take into consideration the high gradients near room walls. The time-averaged equations of momentum, heat and mass transfer are solved with air as an incompressible fluid. The Boussinesq

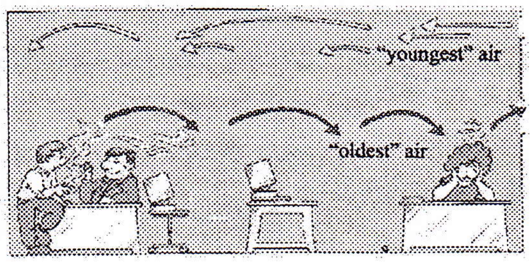

Figure 2.
Contaminant transport principle

approximation is applied to include density variations as a result of temperature differences. Turbulence is modelled with the well-known k-ε turbulence model (Rodi, 1982), resulting in extra transport equations for the turbulent kinetic energy (k) and the dissipation rate of turbulent kinetic energy (ε). A turbulent viscosity determined by k and ε is added to the dynamic viscosity of air. The flow near walls is modelled with standard logarithmic wall functions. The transportation of pollutants is based on convection and diffusion. To account for turbulent mixing a turbulent diffusion coefficient is added to the molecular diffusion coefficient, assuming a turbulent Schmidt number of 1. A numerical integration procedure based on the SIMPLE/SIMPLER algorithm is applied to iterate towards a converged solution. The numerical solution procedure is basically as described by Patankar (1980). The program code is written in Fortran 90. PCs and workstations are used for pre- and post- processing of data.

Case study: indoor-environment quality in an office room with a smoker

The investigation has been carried out by means of numerical prediction of the environment in a mechanically ventilated office room with a smoker. Indoor-environment quality obtained with the conventional ventilation system (mixing flow) is evaluated. The office space has a surface area of $6.0 \times 3.0\text{m}^2$ and 3.58m high. A schematic drawing of the office room is shown in Figure 3. The room dimensions and the applied coordinate system are also shown in Figure 3. The room parameters and obstacle features are also shown. One work place, with an office table ($1.2 \times 1.2\text{m}^2$) and a person seated in a chair to operate a computer and to smoke, is located in the center of the room. The air flows into the room through a supply square opening placed close to the ceiling and leaves the room through another square hole placed in the opposite wall close to the floor. Table I shows the relevant operation parameters. The room walls have a global coefficient of heat transfer of $2.0\text{Wm}^{2\circ}\text{C}$, and the ceiling and the floor are supposed adiabatic. The internal thermal load is 340W, corresponding to the occupant's metabolism and the computer power.

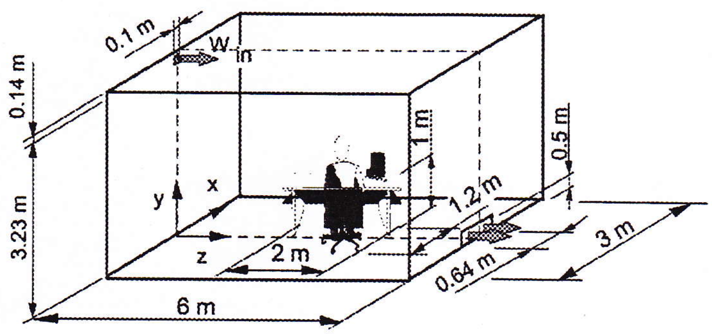

Figure 3.
Office room model

Results and discussion

A simulation was done to determine the airflow pattern, temperature and contaminant distributions, perceived air quality distribution, the occupied zone's average concentration, the maximum concentration in the room, the room mean occupied ventilation effectiveness and any local ventilation effectiveness. The results presented here is for a grid of $12 \times 20 \times 15$ control volumes (points). The computed results agree well with that observed in the experiments. The airflow within the room is essentially three-dimensional. Typical results of line contours of air velocity magnitude, air temperature and pollutant concentration on an X-Y plane at the room in the symmetry plane are shown in Figures 4-6, respectively. These plots represent distribution of those parameters for steady-state conditions. The results show that contaminant dispersion depends on the location of the source and local velocity. In fact, the concentration is low at the inlet, where the fresh air is supplied, and concentration is high near the source location. In the regions with low velocity, pollutants are not rapidly removed and, consequently, the average concentration becomes higher. For instance, smokers are usually placed in locations of stagnant flow that will increase the smoke level in that zone;

Table I.
Operation parameters

Inlet air velocity (m/s)	Air temperature (°C)	Air flow rate (l/s)	Thermal cool load (W)	Contaminant source (olf)
2.0	14.0	28.0	240.0	6.0

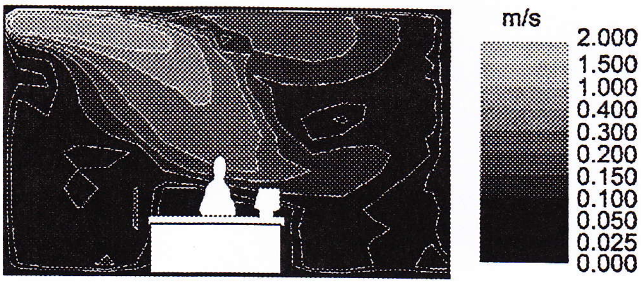

Figure 4.
Predicted mean air velocity

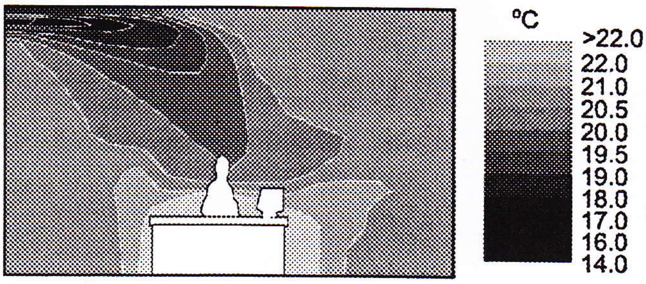

Figure 5.
Predicted air temperature

however, if they were placed in the mixing zone, the whole space will be contaminated by smoke. It was shown that changing the location of contaminant may change the concentration levels and distribution within a certain space, and the location must be placed wisely. It may be concluded that the best place for contaminant location is either as close as possible to outlet position, or in the main flow stream feeding the exit flow current. The ventilation rate also affects the pollutant concentration within the room. In this study, all the supply air was pure outside air. In most applications recirculated air that worsens the problem of the indoor air quality is used. It could be demonstrated that, in general, displacement ventilation provides a better air quality in the occupation zone if compared with the mixing ventilation system. However, displacement ventilation is only applicable in cooling situations and it uses higher volume flow of outside air. This gives a decided advantage to the displacement system but, naturally, with higher costs. Finally, it should be noted that room obstacles also influence room air quality.

Conclusion

The applicability of CFD for the simulation of indoor-environment quality is confirmed. Indoor-environment quality is influenced by room air distribution that depends on several parameters (boundary conditions): airflow rate, thermal load, location of obstacles, ventilation systems and pollutants load. To achieve a good indoor climate and air quality, it is necessary to supply the thermal load and fresh air either by opening windows or by installing a suitable ventilation system for the introduction of fresh air. A new way of thinking and therefore a new approach to education is necessary. But, little information is available on indoor-environment quality. A concentrated effort to provide educational material to all levels of society should be undertaken. Formal education for design professionals is needed. Informal and formal education should be developed for building owners and operators, for occupants and the general public. CFD models can provide an effective tool for the sensitization of these problems. Certainly this use of CFD will take an increasingly important and prominent position in the promotion of a more positive attitude towards issues of energy consciousness and the environment.

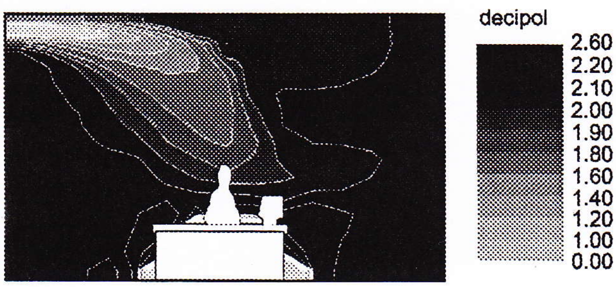

Figure 6.
Predicted air-quality perception

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