# COMPUTATION OF AIRFLOW IN A DISPLACEMENT VENTILATION/CHILLED CEILING ENVIRONMENT

L. Jalil [1*], A.H.Taki [1] and D.L. Loveday [2]

[1] School of Architecture, De Montfort University, Leicester LE1 9BH UK
[2] Department of Civil and Building Engineering, Loughborough University, Loughborough, LE11 3TU UK

## ABSTRACT
Displacement ventilation combined with a chilled ceiling system have been investigated by (Kofoed, 1994), (Almadari and Eagles, 1996), (Fitzner, 1996), (Taki et al., 1996), (Loveday, et al 1998) and (Rees, 2001). However, characterisation tests in such a combination system revealed that the use of a chilled ceiling with displacement ventilation could have a detrimental effect upon the displacement flow. This paper presents an assessment of the ability to model airflow and temperature distributions in such combination environments with a standard Computational Fluid Dynamics (CFD) code. Modelling is carried out over a range of typical office conditions for a range of heat loads and ceiling surface temperatures. It was found that the CFD code could be used to successfully predict the airflow in these environments by showing good agreement with those of earlier studies. The implications for the future design of displacement ventilation and chilled ceiling environment are discussed.

## INDEX TERMS
Computation Fluid Dynamics, Displacement Ventilation, Chilled Ceiling, Airflow.

## INTRODUCTION
Over the last few decades the office environment has changed rapidly and is continuing to do so. One such change is the fact that office space has expanded with open-plan office environments taking the place of the traditional segregated office units. With the large open-open office space came the problem of providing adequate air ventilation to the whole office. One method used was displacement ventilation, where air is introduced at one part of the room and is allowed to sweep in one direction across the space taking the pollutants and exhausting them at the opposite part of the room. Displacement ventilation is mainly characterized by buoyancy-driven airflow. In this system, low velocity air is supplied from a low level supply device in the occupied zone at a temperature slightly cooler than the design room temperature, in order to obtain the displacement effects. As a result of thermal comfort limitations given in BS EN ISO Standard 7730 (ISO 1995) (namely that the vertical air temperature gradient should be less than 3$^{o}$C/m), a displacement ventilation system is limited to removing a convective load of up to 25W/m$^2$ of floor area. A typical office might exceed 60W/m$^2$ of heating load. Therefore, an additional cooling mechanism was required to meet this load, frequently a chilled ceiling. The chilled ceiling system provides an additional heat removal mechanism from the space. In this system the ceiling temperature is maintained by circulating cool water through pipes. In principle, the combined system of displacement ventilation and chilled ceiling has the potential to remove the convective heat gains generated

[*] Contact author email: ljalil@dmu.ac.uk

by peoples and equipment with chilled ceiling providing radiant cooling and reducing the overall temperature gradient by cooling air in the upper part of the room.

It is understood that chilled ceilings can remove heat loads of up to 100W/m$^2$ mainly by radiation, and can also enhance the thermal comfort sensation of the occupants (Loveday et al., 1998). This paper aims to assess the use of CFD code for predicting airflow and temperature distributions in such combination environments and to highlight the implications on air quality.

## COMPUTATIONAL FLUID DYNAMICS (CFD) MODELLING

CFD modeling is the process of representing a fluid flow problem by mathematical equations based on the fundamental conservation laws of physics, and solving those equations to predict the variation of the relevant parameters within the flow field. Usually these could be velocity, pressure and temperature, and also concentrations of chemical species. These conservation laws can be expressed in terms of non-linear "elliptic" partial differential equations, the solutions of which provide the basis for the CFD model. The CFD model solves numerically the equations and produces field values for the temperature, velocity and the chemical species. The CFD code used in this study, has the ability to simulate advanced computation of three-dimensional airflow and temperature in and around enclosures (Wittles, 1986, 1992). The accuracy of the CFD code used has been compared with other CFD codes, and also with laboratory results for environments that employs displacement ventilation systems. The results showed good agreement with these codes (Taki et al. 2002).

## THE SITUATION BEING MODELLED

The Environmental Test Room facility based at the Department of Civil and Building Engineering, Loughborough University is 5.4m long 3m wide and 2.8m high, was used in this study and was modeled with adiabatic walls.

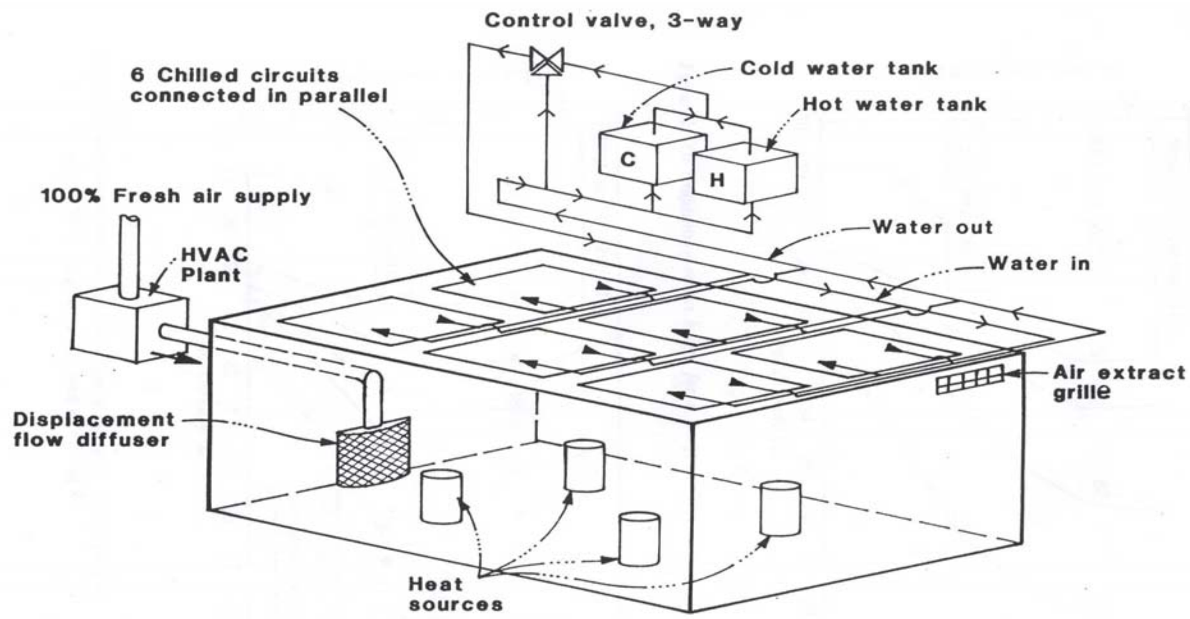


**Figure 1.** Schematic diagram of the room being modelled

The room employed a chilled ceiling and displacement ventilation system. The displacement ventilation system was set to operate at a supply temperature of 19°C and 3.9 air changes per hour. A heat load of 60W/m$^2$ of floor area was achieved by placing within the room four thermal dummies to represent human occupants and office equipment. The ceiling surface temperatures were set to the following values 14, 16, 18 and 21°C (Figure 1). A Cartesian mesh consisting of 22680 cells was used to model the room, 27 cells in length (x) direction, 56 cells in height (y) direction and 15 cells in width (z) directions, κ-ε turbulence model was adopted for the simulation.

**RESULTS AND DISCUSSIONS**

Using the CFD simulation, Figure 2 shows vertical temperature profiles in the room, (that is, plots of room air temperature versus height) for a range of ceiling temperatures (14, 16, 18 and 21°C) at a fixed heat load of 60W/m$^2$. Figure 2 also shows the predictions of temperature profile for the case of displacement ventilation only (where there was no chilled ceiling). The results show that at low ceiling temperatures of 14°C the stratified boundary layer is strongly suppressed, and that there is some destruction of displacement flow pattern. At higher ceiling temperatures of 16 -21°C, some displacement flow is present. This agrees with work carried out by (Taki et al., 1996).

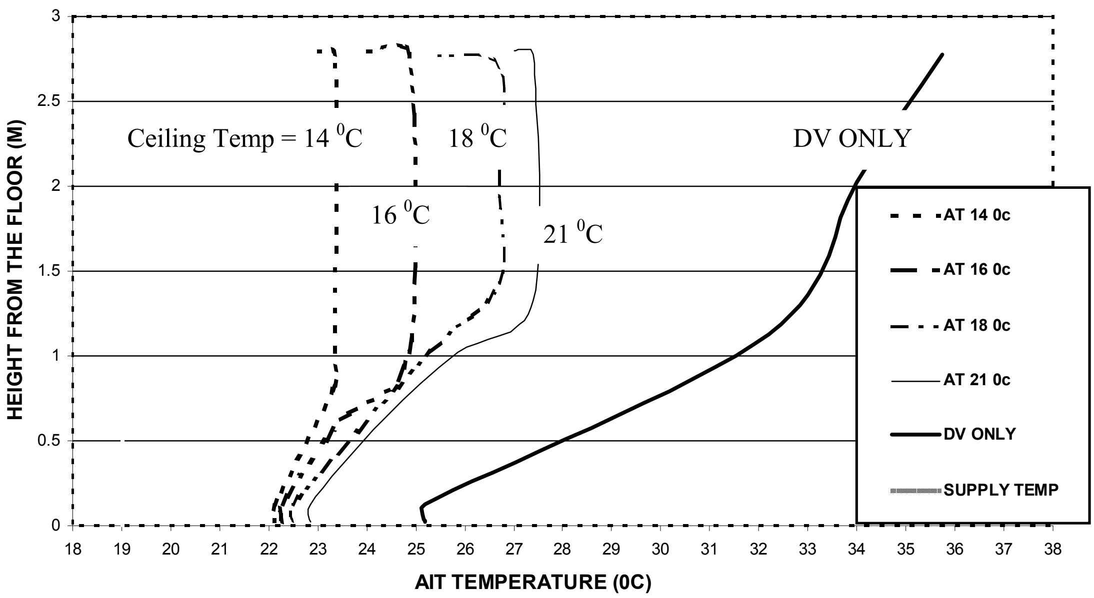


**Figure 2.** Air temperature versus height for a range of ceiling surface temperature at a heat load of 60W/m$^2$.

The CFD simulation also showed that the wall temperatures were lower than the room temperatures. This could have been caused mainly through the radiative heat exchange between the room walls and cooled ceiling, where the air is then driven downwards by the negative buoyancy thus, the walls tend to have a lower temperature than room air temperature. This agrees with the findings of (Kruhne, 1996), (Alamdari, 1996), (Brohus, 1998) and (Fitzner, 1996). Because the air begins to flow downward and out of the mixing zone below the ceiling, the contaminated air reaches the zone of fresh air and increases contamination near the floor and at the breathing level. Therefore it can be concluded that the use of a chilled ceiling with displacement ventilation can have an adverse effect on the air quality in the zone of fresh air.

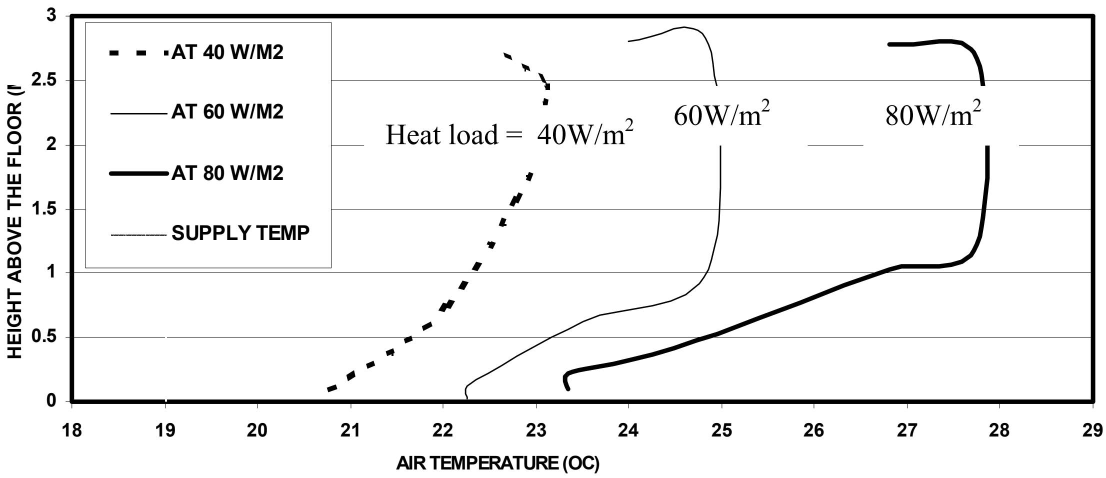


**Figure 3.** Air temperature versus height for a range of heat loads at a ceiling temperature of 16 °C

Figure 3 shows the air temperature profiles for a range of heat loads, 40, 60 and 80 W/m$^2$ at ceiling temperature of 16°C. It shows that air temperatures are almost constant above the height of 1.1m from the floor. The results also show that the vertical temperature gradient increases with the heat load and it exceeds 3°C/m for the heat load of 80W/m$^2$. To meet the criteria given in the ISO 7730, the ceiling temperature should be lowered to remove such heat loads. Figure 4 shows the results of (Alamdari and Eagles, 1996) who also used a CFD code to investigate the effects that a chilled ceiling has on the temperature profile. The results show good agreement with regards to the temperature profile and agree as regards the height of the stratified boundary layer.

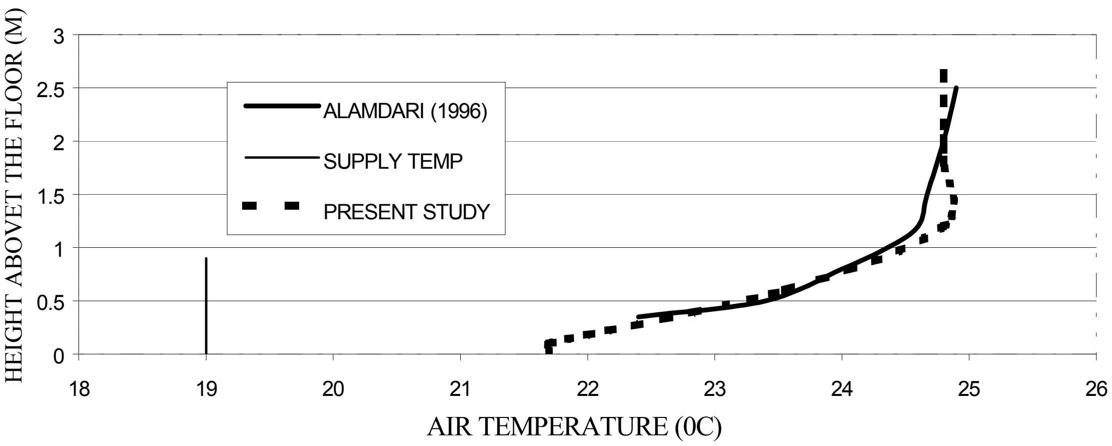


**Figure 4.** Air temperature versus height above the floor, for ceiling temperature 16°C, 3.5ACH and 60W/m$^2$: comparison of this with (Alamdari and Eagles, 1997)

The results presented by (Taki et al., 1996) did not satisfy the room heat balance equation due to heat losses through the room surfaces. These heat losses were estimated from the knowledge of surfaces U-values, internal and external air temperatures, and were found to be approximately 40% of the total heat load within the room. For the aim of comparison, the room was modelled with a heat load of 40 W/m$^2$ of floor area and the results are presented in Figure 5; the predictions are in agreement with the experimental data for ceiling temperatures of 14,16 and 18 $^o$C. The CFD findings prove that the combined operation of displacement ventilation and chilled ceiling systems could cause deterioration in air quality as a result of flow pattern.

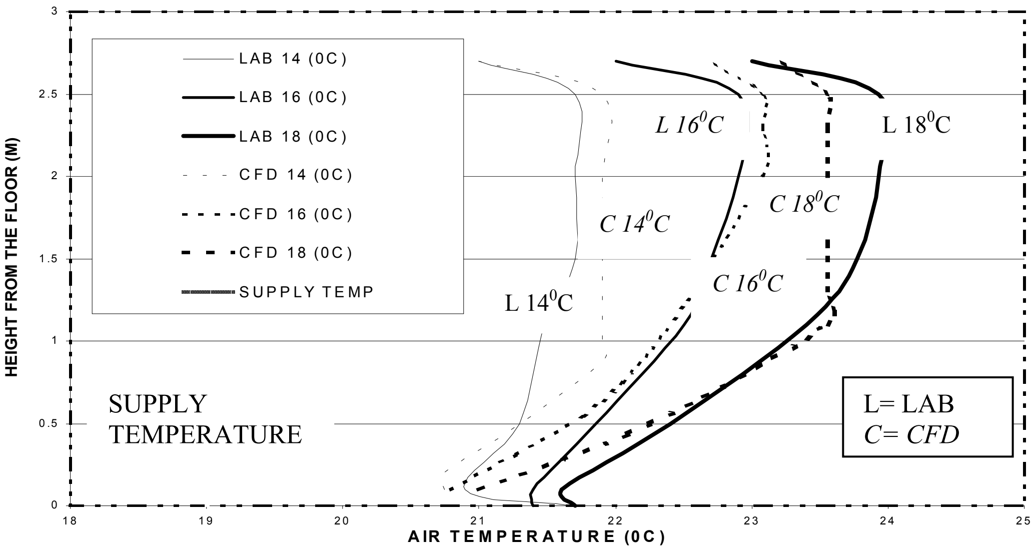


**Figure 5.** Air temperature versus height above the floor for a range of ceiling temperatures, and at fixed heat load of 40W/m$^2$ and 3.9 ACH.

## CONCLUSIONS

Using CFD, computational predictions have been produced for a chilled ceiling and displacement ventilation environment. The CFD predictions agreed with those reported by (Taki et al, 1996), (Kruhne, 1993), (Alamdari and Eagles, 1996), and (Fitzner, 1996). This proves that the CFD code can be regarded as an effective tool for accurately predicting airflow and temperature distributions, and for assessing the adverse effect on the air quality in such combination environments.

It is now our intention to investigate techniques that can be used to suppress the downward cold convection currents from a chilled ceiling, thereby helping that the combined arrangement to work together more effectively. The authors are currently researching possible solutions. The study will be based on findings predicted by CFD and validated using laboratory measurements.

## REFERENCES

Alamdari F, Eagles N (1996), Technical Notes 2/96 Displacement Ventilation and Chilled Ceiling. Produced by BSRIA, ISBN 0 860224 333.

Brohus H (1998), Influence of Cooled Ceiling on Indoor Air Quality in a Displacement Ventilation room Examined by means of Computational Fluid Dynamics, *The 6th International Conference on Air Distribution in Rooms, RoomVent'98, pp53-60*, Sweden.

Cook MJ (1998), An Evaluation of Computational Fluid Dynamics for Modelling Buoyancy Driven Displacement Ventilation Ph.D. Thesis De Montfort University England.
Fitzner K (1996), Displacement Ventilation and Cooled Ceiling, Results of Laboratory Tests and Practical Installations. *The 7th International Conference on Indoor Air Quality and Climate Indoor Air'96*, Vol. 1, pp 41-50, Nagoya, Japan.
ISO Standard 7730 (1994) "Moderate Thermal Environments- Determination of the PMV and PPD Indices and Specification of the Condition for Thermal Comfort".
Kruhne Holger (1993), Effects of Cooled Ceilings in Rooms with Displacement Ventilation on the Air Quality. *6th International Conference on Indoor Air Quality and climate Proceedings of Indoor Air 93 Vol 5, pp 395-400.*
Loveday DL, Parsons KC, Taki AH (1998), Designing for Thermal Comfort in Combined Chilled Ceiling/Displacement Ventilation Environments. ASHRAE Transactions: Symposia Vol 104, pp 901-911, ISSN 0001-2505.
Rees SJ, Haves PA (2001), Nodal model for Displacement Ventilation and Chilled Ceiling Systems in Office Spaces. Building and Environment 36, pp 753-762.
Skistad Hakon (1994), Displacement Ventilation, ISBN 086380 1471 Research Studies Press Ltd. Taunton, Somerset, England 1994.
Taki AH, Loveday DL, Parsons KC (1996), The Effect of Ceiling Temperature on Displacement Flow and Thermal Comfort- Experimental and Simulation Studies. *5th International Conference on Air Distribution in Rooms ROOMVENT 96, July 17-19, pp307-314* Japan.
Taki AH, Jalil L and Loveday DL (2002) Use of Computational Fluid Dynamics for Modelling Displacement Ventilation Environments. *To be published in the International Conference on Research Trends in Science and Technology,* Lebanon.
Wittles, GE (1986), Computational of Air Movement and Convective Heat Transfer within Buildings International Journal of Ambient Energy. Vol.7, No.3, pp 151-164.
Wittles, GE and Jones, PJ (1992), Computational Fluid Dynamics (CFD) for Buildings Airflow Predictions-Current status and capabilities. Building and Environment Vol. 27 no 3, pp 321-338.