# CFD and Virtual Reality in the Built Environment – A Case Study of displacement ventilation.

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**Summary**

Computational Fluid Dynamic (CFD) has rapidly developed as an industrial design and evaluation tool for Building Services Engineering. Providing valuable information via mathematical predictions of fluid flow heat and mass transfer. The aim of the work is to illustrate the integration of CFD data into a truly interactive Virtual Reality (VR) environment to provide engineers with demonstrable design evaluation and visualisation facilities.

To demonstrate the successful integration of CFD and VR an industrial case study of a conference room at Hoare Lea is presented. The case study comprises several CFD models of a displacement ventilation system, in conjunction with static cooling and heating under occupied and unoccupied conditions. The effectiveness of the design configurations in terms of thermal and ventilation effectiveness are evaluated and presented in a Virtual Reality model. The VR model allows the user complete interactive control of the environment and will provide an elegant means of enabling engineering solutions to be appreciated by non-engineers.

## Introduction

As a result of the advances in computer power now available, the amount of computational modelling carried out on most engineering projects has increased in most disciplines. Similarly has the complexity and the number of different models that are generated prior, during and after a buildings construction. Today's modern client wishes to see his building before it is constructed, he likes to ensure that all design options have been evaluated in terms of lighting and building physics and will want to have an understanding of these in layman's terms and would like to "experience" the performance of the design that has evolved.

The objective is for the 'VR Experience' to extend beyond just vision, to encompass:-
The Thermal Properties of the Space; It's enclosing Surfaces, Air and Mean Radiant Temperatures, The Distribution of Air Contaminant and of Age-of-Air together with its Velocity and Direction of Flows. The Visual Properties of Iluminance, Colour Rendition, Contrast Rendering and Acuity. The Acoustical Properties of Sound Level, Absorption and Reverberation Time and the Combination of these Factors in the Comfort Indices of PPD and PMV, all to be displayed and 'Experienced' as desired in any part of the room.

The difficulty in communicating all this information to the client arises from the input required from the numerous types of technical personnel involved (as illustrated below). This brings a need to integrate all the technologies into a common environment that allows the layman to interrogate his building. The ability to communicate vast amounts of technical data in graphical format that can be easily understood by all lends itself to Virtual Reality techniques.

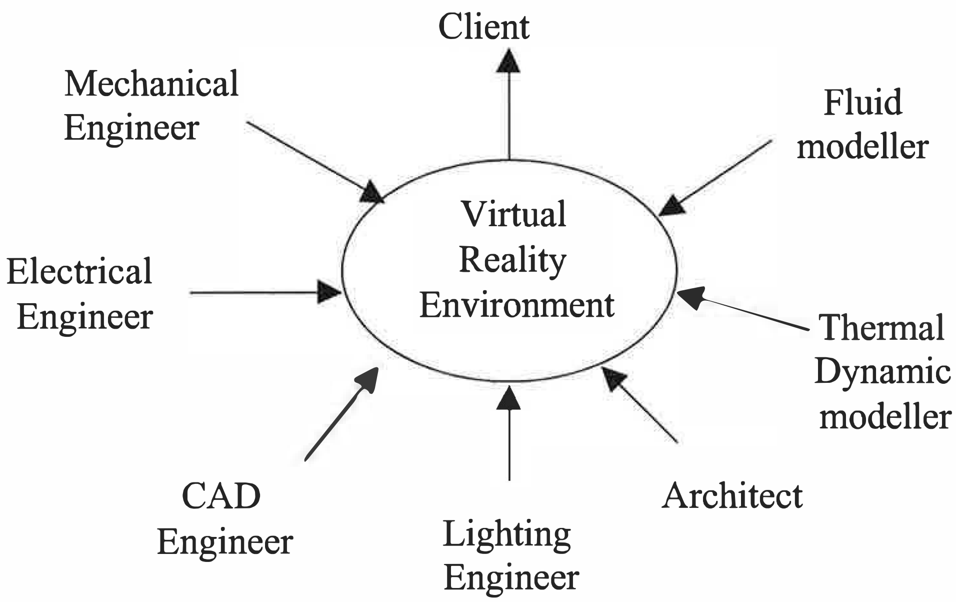


Figure 1.1 - Multiple Discipline Interaction

It is clear that Building Services Engineering requires a method of communicating information between technical and non-technical disciplines that can be easily understood by everybody. They require a methodology of interfacing these multiple disciplines into a single common environment that can be updated or added to easily by each contributor. And finally they want it to be in a format that the layman will understand and can interrogate.

The General Process

All advanced modelling and visualisation methods rely on the creation of CAD drawings, which generally begin life in a 2D format. These drawings are the basis for the 3D model. Once a 3D CAD representation has been constructed the CAD can then used to generate the framework for CFD models, rendered visualisations, and the interactive virtual model.

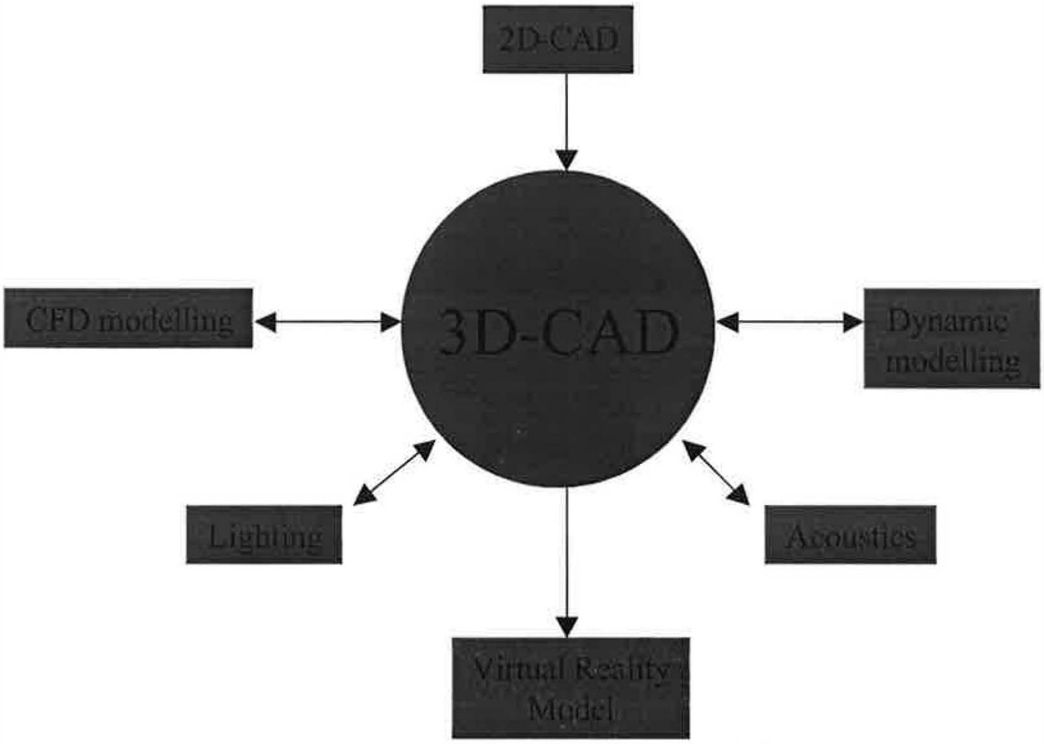

Figure 1.2 - Interaction of Modelling Methods.

Figure 1.2 shows the interaction of most modelling methods. All feed into and from the core 3D CAD. Once all these have been carried out they can all be fed, via the common geometric representation, into the VR environment.

The data sets, in scientific visualisation and CFD, often take the form of 2D and 3D scalar fields. For example, temperature distributions on the wall of a building, or numerical predictions of temperature through a building. These are scalar fields that consist of a real-valued function `f` defined over a 2D or 3D co-ordinate space, which in turn can also be expressed as a function of time adding to the complexity of the data. Due to the size of current day CFD models, often greater than 2 Million cells, and the number of solutions for each model, it is essential that this data is reduced and provided in a graphical form.

## **Experimental Measurements.**

Figure 1.3 Photograph of the conference room.

The conference room used to perform the experiments for the present study is shown in figure 1.3. The conference room used contains two wall diffusers, five floor diffusers, fluorescent lighting, a large window and seating accommodation for 12 people. The conference room is cooled and ventilated using a high efficiency displacement ventilation system.

Two separate sets of experiments were carried out namely a thermographic study of the room and hot wire anemometry measurements. A computer laptop acquired and processed all the experimental data via the PCMA card and the Com ports. An 'Inframerics' infrared camera was used in conjunction with image processing software to acquire the thermal images. A TSI Hot wire anemometer was used to measure local velocities, temperatures and relative humidity's.

Figure 1.4 is a schematic of the thermo graphic measurement and processing methodology. The Conference room was surveyed during normal operating mode using the Infra red camera with typical emissivity values of 0.9. The camera was adjusted to ensure the image scales were within the bounds of the minimum/maximum values of the actual temperatures. A calibration check was made using a thermocouple probe to measure the surface temperatures and was found to be within 0.5 °C. The images were saved in Tag Image File Format and processed using image processing software and the output is shown in figure 2. The results were sampled and stored on a grid corresponding to a $\Delta X$ of 0.001m and $\Delta Y$ of 0.001m respectively. The Kriging method was used to produce the contour plots as this is recommended as the most accurate fill method for a small number of valid data points, ref.(7). Kriging replaces each missing data value with a weighted calculation that minimises the statistical variance of the array. In Kriging, every known data value and every missing data value on the grid has a variance associated with it. The variance is a measure of the uncertainty of a value. This uncertainty is defined as the square of the standard deviation. By using variance, Kriging records the distance between values in terms of statistical distance. The final Kriging step is a weighted fill based on contributions from its neighbours using a bi-cubic spherical interpolation method (1/ variance$^2$); the data is interpolated along the rows and then along the columns in blocks of 100 grid positions.

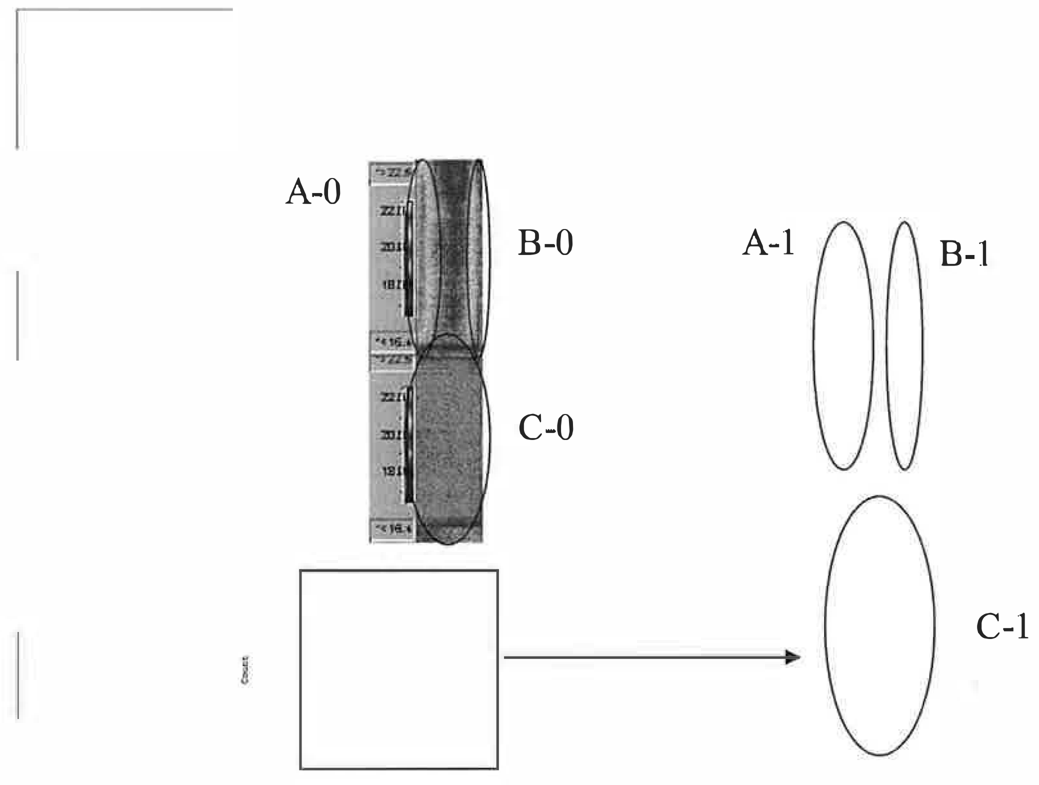


Figure 1.4 Thermographic measurement and processing.

A series of point ensemble measurements were taken in the conference room as shown in figure 1.5. A minimum of 600 data values per point was used to obtain the point average at each measurement point. The data was acquired through the computer COM port and analysed using the authors data manipulation software. The instruments had accuracies: Velocity ±3.0% of reading or ±.015 m/s whichever is greater, Temperature ±0.3°C and Relative humidity ±3% rh.

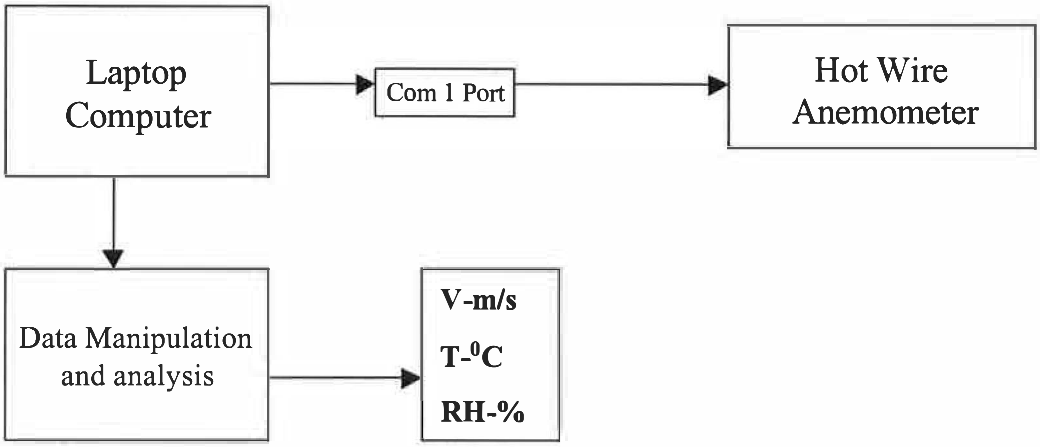


Figure 1.5 a schematic of the experimental process.

## Computational Fluid Dynamic Model.

### Dimensional analysis

For a natural/mixed convection model the physical phenomena can be characterised by studying the basic non-dimensional parameters. These parameters assist in the understanding of the predominant physical features and also allow simplification of the governing equations. In order to non-dimensionalise we require some characteristic data. The wall diffuser height was used as a characteristic length of Lc=0.6 m. The characteristic velocity of 0.3 m/s was used from the previous experiments. From experiment the largest delta T is 8°C. The governing equations can be solved non-dimensionally with the following scaling factors:

$$U^* = \frac{U}{Uc} \quad P^* = \frac{P L_c}{\mu U_c} \quad T^* = \left( \frac{(T - T_{ref})}{\left( \frac{q_c L_c}{k} \right)} \right)$$

$$Gr = \frac{\rho^2 g \beta \Delta T L^3}{\mu^2} = \frac{buoyant \quad forces}{viscous \quad forces}$$

$$Ra = \Pr . Gr = \frac{\rho^2 g \beta C_p \Delta T L^3}{\mu k} = \frac{buoyant \quad forces}{viscous \quad forces}$$

In the case of the steady state model the Ra number is 2x $10^7$ indicating possible transition to turbulence.

## Physical Model.

## Geometry and Boundary conditions.

Two computational models were run the first model was in an unoccupied conference room during a typical cool summer day condition. The geometry used is shown in figure 1.6 with the boundary conditions clearly labelled. Convective heat transfer boundary conditions which account for any heat losses or gains to the room was employed the same conference room with an occupancy of 12 people is shown. The people have been modelled using a distributed heat flux, which relates to a total convective heat emission of 60 W per person, no radiative exchanges are included.

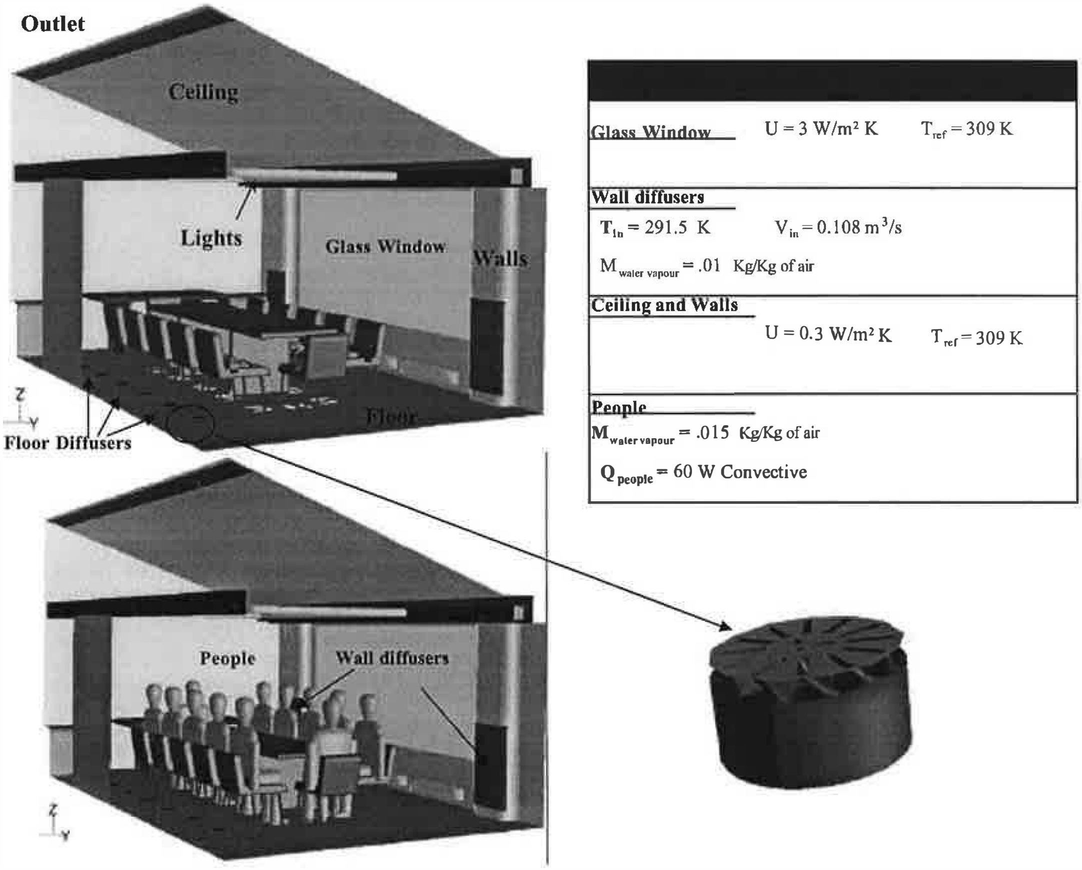


Figure 1.6 Model geometries and boundary conditions.

## Solution Domain.

The solution domain used in both simulations are shown in figure 1.6. A hybrid-meshing scheme was used using boundary layer meshing techniques coupled with unstructured tetrahedral mesh using Gambit (2). The meshes where checked for the usual grid metrics to ensure a good quality solution mesh had been constructed. Particular attention and mesh concentration was given to areas of high thermal and velocity gradients to ensure correct capture of the physical boundary layers primarily the people, windows and diffusers. In order to develop an appropriate mesh capable of capturing the physics an estimate of the velocity and thermal boundary layers was approximated using the work of Gill (1) where the thickness of the layers can be calculated by

$$\delta \approx \frac{L}{Gr^{\frac{1}{4}}}$$

$$\frac{\delta_T}{\delta} \approx \frac{1}{\Pr^{\frac{1}{2}}}$$

Where δ and δT are the velocity and thermal boundary layer thickness respectively. In order to capture the temperature and velocity gradient sufficiently the near wall element must be at least 7 mm away from the wall.

## Numerical Model.

The models were run as turbulent pseudo steady state convection without radiation using the thermo physical properties of air. The governing equations were solved in there non-dimensional form using an incompressible ideal gas law to model the density variations.

Equation 1. 1 - Momentum Equation

$$\sqrt{\frac{Ra}{\Pr}} \cdot u \cdot \nabla u = -\nabla p + \nabla^2 u + \sqrt{\frac{Ra}{\Pr}} .Te$$

Equation 1. 2 - Continuity Equation

$$\nabla u = 0$$

Equation 1. 3 - Energy Equation

$$\sqrt{\frac{Ra}{\Pr}} \cdot u \cdot \nabla T = \nabla^2 T$$

**Turbulence :** In order to model the turbulent effects of the flow field a K-E - RNG model was employed using standard wall functions ref (3) to ensure correct capture of the thermal and velocity boundary layer .

## Data Representation

### Steady state data

Scalar fields say of, temperature, pressure, PPD, age of air, contamination levels, are sampled at discrete points at intervals in space and time. Each one of those sample points are called, pixels in 2D, and voxels in 3D, spatial environments respectively. It is not possible to view 3D scalar fields directly as they consist of masses of numbers in an XYZ spatial grid. We therefore must use an alternative method of visualisation to communicate the data. By taking a 2D slice through the spatial domain and associating a scalar field via a colour distribution scale it is possible to generate a manageable subset of the data for a localised area of the domain, as shown in Figure 1.7 (a).

Isosurfaces are continuous surfaces defined by some scalar quantity, and generally comprise of 3D spatial data (XYZ) as a function of the defining field as shown in the example figures 1.7 (b). Having defined an Isosurface it is also possible to represent other scalars on the surface function using a variable colormap for definitions see Figure 1.7 (c). This provides a 3D spatial representation of a scalar variation on the surface defined by a fixed scalar. Thus displaying 2 scalars in 3D, giving a 5 dimensional data array.

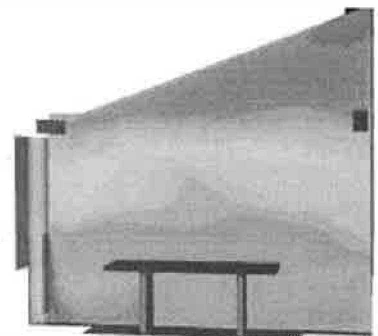

Figure 1.7(a) 2D x-y Contour Plane of Temperature

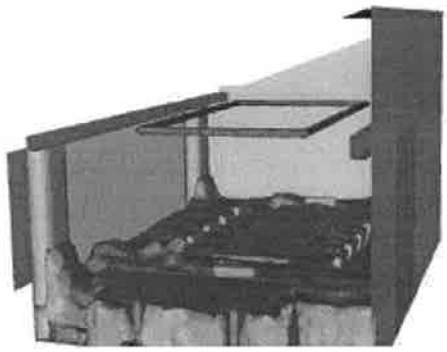

Figure 1.7 (b) - Isosurface of 21°C Temperature

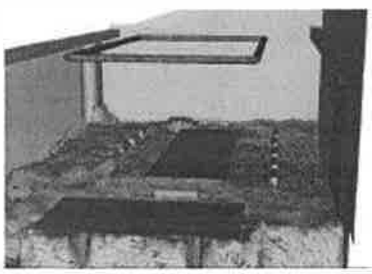

Figure 1.7 (c) - 3D Velocity Vectors Superimposed on a 21°C Iso-surface.

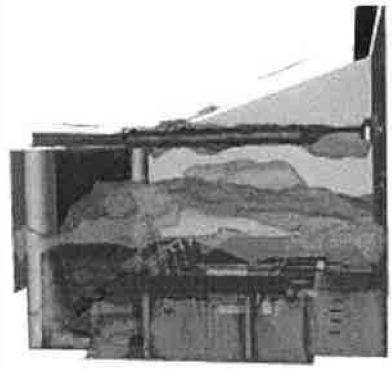

Figure 1.7 (d) - Translucent Isosurface Coloured by Temperature and illumination.

Volumetric rendering provides another method of displaying complex data, using lighting and illumination. A series of Isosurfaces are created as a function of a single scalar value and each is coloured using a colormap scale. However it is not possible to see the Isosurfaces because they overlap. Ray tracing and reflections are employed to make it possible for Isosurfaces to be distinguishable by the accumulation of colour and opacity as a function of the scalar. See figure 1.7(d). Due to the complexity of this visualisation it is generally advisable to take several view point renderings and add translucency to give better visibility of the data.

### Transient Aspects of Data Visualisation

All of the data representations mentioned can be extended to give transient visualisation by inclusion of the additional variable of "Time." The ability to present 'streakline timelines' is very important as they are the only means of correctly and clearly establishing the existence of vortex shedding and breakdown in fluid flows. It is simply not possible to extract this information from instantaneous flow visualisation techniques. Unfortunately that is a common failing of many of today's simple CFD models.

Streaklines reflect the behaviour of the flow by having particles continuously injected into the flow from a fixed location. If the flow field is steady then they are the equivalent of streamlines. Numerical flow data is stored at discrete points in time and space. Taking the velocity field from the numerically simulated flow over Time $t_o$ to $t_n$ at distinct grid points, p (t) is the position of the particle at Time (t) and V (p (t), t) is the velocity of the particle p(t) at time T, incrementing time by a fixed $\Delta$t of position of the particle the equation becomes:

$$p\,(t+\Delta t) = p\,(t) + \int_{+}^{t+\Delta t} v\;\big(p\,(t),\,t\big)\,dt$$

Figure 1.8 (a) Streak line/Timelines

Figure 1.8 (b) Path lines/Streamlines

## CFD and Experimental Results

The unoccupied CFD model agrees, well with both the thermo graphic and the hot wire anemometry measurements. In the interest of brevity the reader is referred to references (4,5,6) for a more detailed description. As an example figure 1.9 is a comparison of the surface temperature measurements taken using Infrared and the same in the CFD model. Good agreement can be seen, with the infrared image also highlighting the sun-patch on the side of the wall, which is not in the CFD model due to boundary condition type that was used which neglected the radiative effects of the heat transfer. The room air temperatures, velocity and relative humidity's agree well with the model predictions and illustrate the benefits of CFD in understanding complex physical flow and heat transfer. Based on the unoccupied case scenario it is reasonable to accept that the occupied scenario will provide equally useful information.

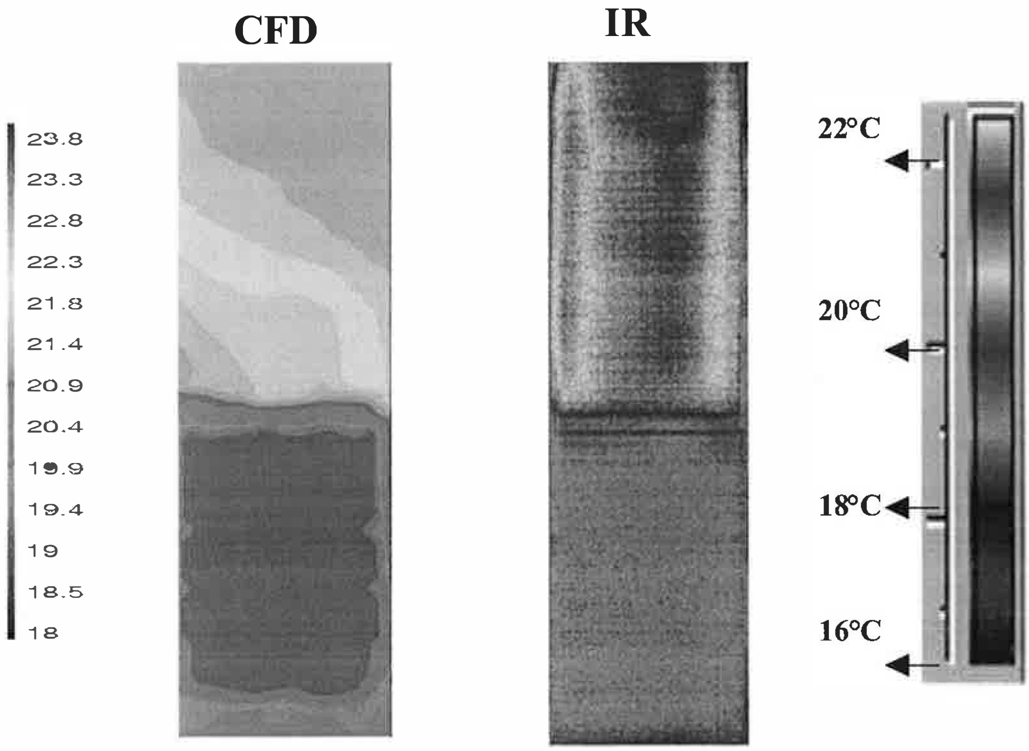


Figure 1.9 Comparison of CFD and Thermography

Figure 1.10 is a transient line plot of the Velocity, Temperature and Relative Humidity at two monitoring positions in front of the wall grille (as shown). The experimental results indicate a pseudo steady state condition with mean velocities of .075 and 0.085 m/s with oscillations about the mean attributed to turbulence and mean flow fluctuations characteristic of a mixed convection airflow. The relative humidity is on average 60% and the temperature of the air in front of the grille is a constant 18.5 °C.

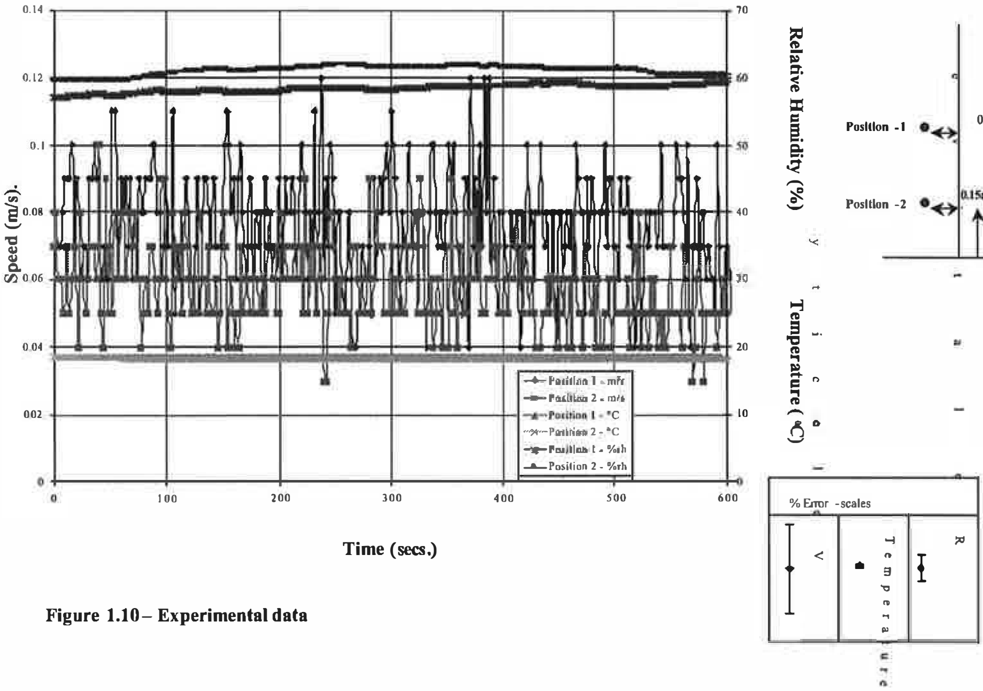


Figure 1.10 – Experimental data

The CFD results corresponding to speed, Temperature and relative humidity are shown in figures 1.11 (a), (b) and (c) respectively. Figure 1.11 (a) clearly shows the introduction of the fresh air via the wall diffuser with peak velocities of 0.25 m/s and the entrainment of air as a result. The temperature contour plot in figure 1.11(b) shows the cool air entering and stratifying as it displaces the warmer air. The relative humidity level at the wall diffuser is approximately 59% rh and is also stratified as shown in figure 1.11 (c).

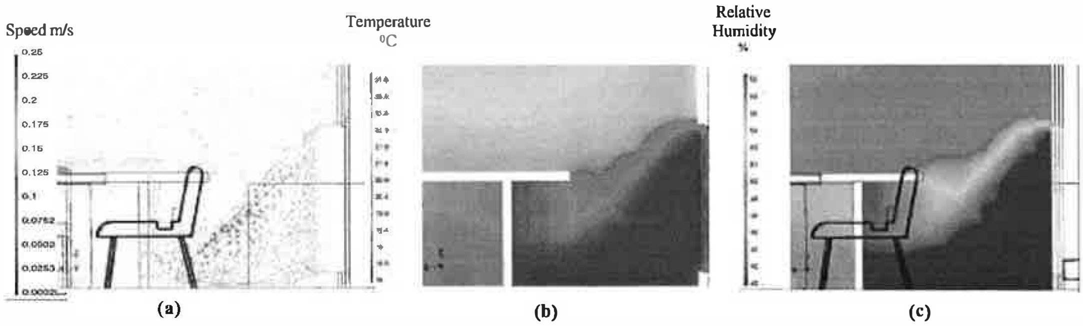


Figure 1.11 Vector plot of Speed and contours of Temperature and Relative Humidity.

| Comparison of CFD and Experimental Results | | | | |
|---|---|---|---|---|
| | Position-1 | | Position –2 | |
| | Experiment | CFD | Experiment | CFD |
| Speed | 0.085 m/s ±.015 m/s | 0.125 m/s | 0.075 m/s ±.015 m/s | .1 m/s |
| Temperature | 18.5°C ± 0.3°C | 18.6 °C | 19.5°C ± 0.3°C | 18.6 °C |
| Relative Humidity | 58 % ± 3% | 59.6 % | 61 % ±3% | 59.6 % |

Table 1

The CFD and experimental results are shown to give good agreement are quantified in table 1.

## Virtual Reality Environment.

### Introduction to Virtual Reality

Virtual reality provides computer generated multi-sensory information that tracks the users perception in real time. This can enhanced with the use of headsets and feedback devices.

### Objectives

The objectives of this visualisation are to:

- Create an environment that the user has control over.
- Provide user driven dynamic responses.
- Give the ability to examine numerous configurations within a single environment.

The purpose to establish the integration of 3D CAD → CFD → VIRTUAL REALITY into one common environment.

The following case study provides an insight into the creation of such an environment, which is one that can be viewed locally or on the World Wide Web.

### Implementation of User Interaction

The main objective requires a computer-generated representation of a 3D space. The environment must then allow object manipulation, navigation and application control. Figure 1.12 shows the layout of our case study. Objects can be manipulated using a joystick, mouse or keyboard.

Navigation through the space is also achieved using joystick, mouse or keyboards and it is also possible to have prescribed walk through which can be 'Event-activated' or 'User-initiated'. The control of the model is simplified using a graphical user interface as shown in Figure 1.13.

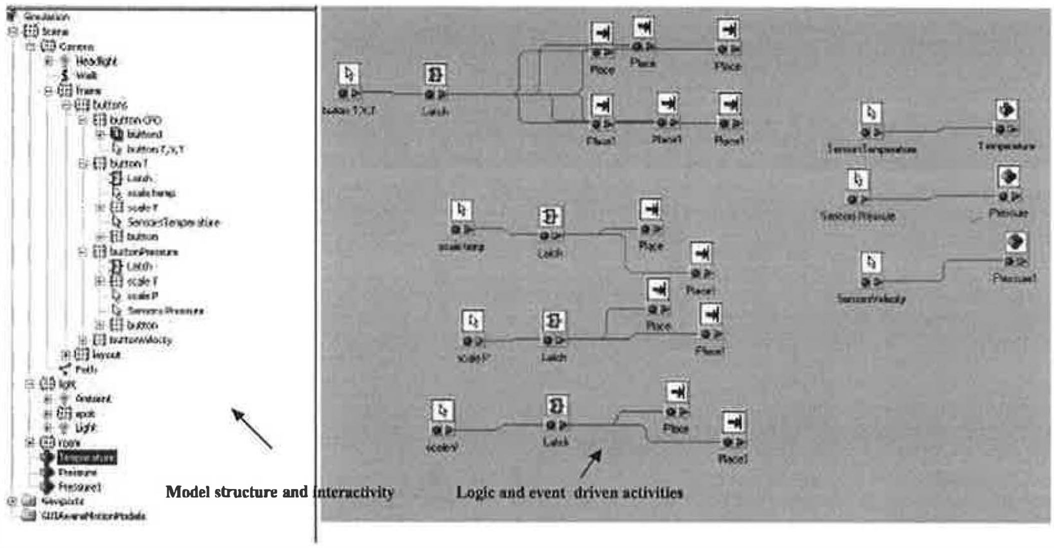


**Figure 1.12 Virtual Reality layout for the case study.**

## Virtual Reality Layout

The initial environment is based on the 3D CAD of the conference room and of all the objects contained within the room. In this case we have a conference room, tables, chairs, lights, floor diffusers, wall diffusers, windows, pictures, projection screens, radiators, chilled ceilings and beams and other objects. Each one of these objects have their characteristic and particular attributes and may or may not also have dynamic responses, all these features have to be defined.

## Integration of the CFD within the VR Environment

The CFD models that have been run are post processed using the data representation methodologies described earlier. Each data representation reflects an object in the VR environment. Having created all the post processing files and reduced the data to manageable fitted equations, image formats and surface data, the information is combined into useable formats.

Interacting with the CFD solution scalars is enabled using an imaginary grid structure within the 3D space. The grid can be switched on or off as required using buttons, which are initiated by the user.

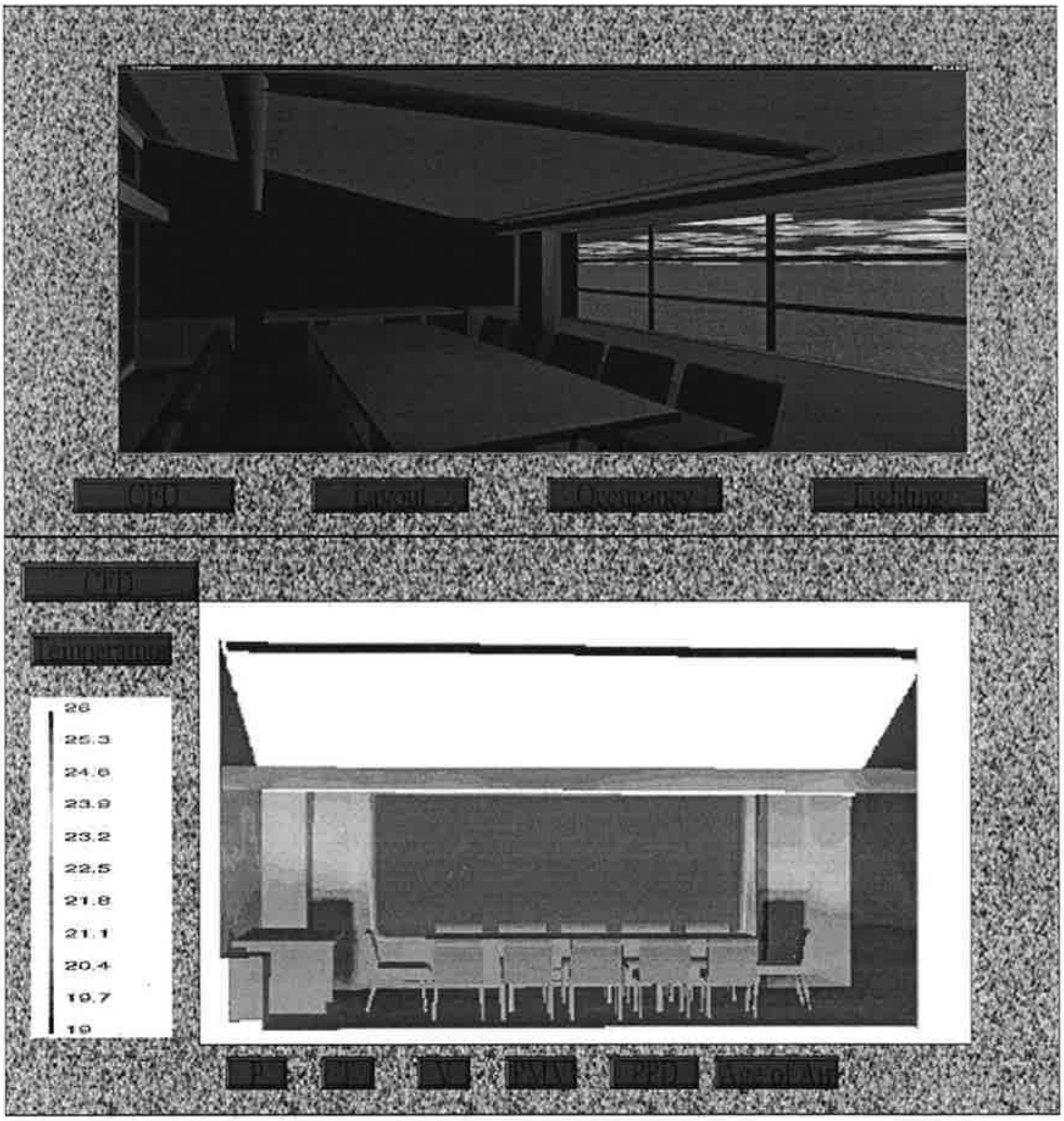


**Figure 1.13 Virtual Reality user interface and integrated CFD**

Individual planes drop down and allow projection of the corresponding variable onto them. The images can be animated and linked to real time using time dependent frame rates. The scalar type can be changed on the projection screen using the interactive menu buttons see Figure 1.13. For example the user can change between Temperature Distributions in the plane to Thermal Comfort Indices etc...

## Methodology

The room was constructed as shown in Figure 1.13. This room was the base for the CFD model. A series of projection planes were created at 0.2m increments along the length and width of the room producing a matrix.

Each of these planes, can be activated using buttons or motion sensors, and we can project 2D plane contour data onto each plane for the corresponding xyz co-ordinates of our CFD models.

## Conclusions

The vast quantity of data generated by the Engineer and its mathematical and engineering complexity is shown via the case study of the displacement ventilation. Whilst most engineers can comprehend all the information and data generated, it is not generally understood or called for by architects, project managers, clients and the general layman. By using virtual reality we have shown the reduction for communication of the engineering concepts and design implications via visual means, with the intention of providing an environment, which the user can interpret more readily.

The techniques described are already possible and will be developed into 'conventional' usage in the near future. This will eventually give Building Service Engineers the visualisation of their designs to match that already enjoyed by Architects.

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