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VIRTUAL ENVIRONMENT FOR THE PREDICTION OF AIR MOVEMENT IN BUILDINGS

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ABSTRACT

This paper introduces the infrastructure of Microflo CFD modelling system in conjunction with the virtual simulation environment. The theoretical basis is described and particularly the graphical user interfaces for pre and post processing are described in detail. Features of the Microflo system are further demonstrated through its application in the design projects.

KEY WORDS

CFD, Air flow pattern,

INTRODUCTION

Airflow within building may be characterised by the nature of re-circulation, turbulence, in association with mechanical and buoyancy forces in three-dimensional spaces. While simplified methods provided by the Guides might find its roles in traditional design practice but powerless to provide answers to increasing demand emerging from innovative design concept. Solution to the aerodynamic problem requires rigorous mathematical and numerical techniques as well as extensive computing power known to be the computational fluid dynamics (CFD).

Over the past decades considerable progress has been achieved in the field of CFD, when most of the basic methodology is, and will remain, well established. A number of three-dimensional CFD systems are available in commercial and public sectors. [Gunton, et al 1983] [Kumar et al 1995] Despite the success in their applications, there still are issues that restrict the use of CFD as a design tool in practice, namely:

- interaction of the CFD simulation with the responses of the entire building;
- facilities for creating 3-D geometry and computational grids;
- visualisation and presentation of CFD simulation results.

THE MICROFLO CFD MODELLING SYSTEM

Microflo is a suite of software modules comprising IES<Virtual Environment>. [IES, 1997] The core element of Microflo is a general purpose CFD simulation engine capable of modelling problems associated with transient three-dimensional, turbulent air flow with thermal buoyancy and concentration diffusion for either inside and external of buildings. Microflo provides extensive graphical user front-ends and pre/ post-processing tools for creating 3-D geometry, automatic grid generation, boundary condition specification, and visualisation of simulation results. As an integral part of the IES<Virtual Environment>, all the Microflo modules have direct access to the integrated data model, the IES-IDM. This enables the Microflo modules to acquire dynamically boundary conditions from the other modelling system, e.g. ESP for comprehensive thermal analysis; Macroflo for network based fluid flow analysis, as well as providing the latest information to other modelling system, e.g. Simulex to direct evacuation of occupants in case of building in fire.

THE MATHEMATICAL MODEL

Airflow is a natural phenomenon that is associated with three dimensional spaces, time dependency, turbulence, buoyancy, etc. In Microflo, the general air flow is characterised by a set of conservation partial differential equations of mass, momentum, energy and concentration, known as the Navier-Stokes equation. The turbulence fluctuation and time averaging technique based two equation k-ε turbulence model is introduced initially as the mathematical model to the Reynolds stress for turbulence enclosure. The k-ε turbulence model was developed based upon the assumption that the Reynolds stress, a random process, may be modelled in a way analogue to molecular diffusion.

Details of the theory and numerical techniques may be found elsewhere. [Launder et al, 1974]

THE NUMERICAL AND SOFTWARE IMPLEMENTATIONS

In Microflo the solution of system equation in Cartesian co-ordinate is achieved by an improved MacCormack's scheme, an explicit time marching finite difference method with second-order temporal and spatial accuracy for transient solution. Improvement has been made by introducing a second order spatial accuracy up-wind scheme that operates in parallel to the central differencing scheme by a dynamic switching algorithm to improve numerical stability. Variable time stepping is also provided for fast steady-state solution.

Microflo system is a new generation of computer software that has been developed upon the concept of modularity, expandability and reusability. Microflo is written in 'C' and uses dynamic memory allocation for all vectors. All multi-dimensional variables are stored in one-dimensional arrays that are created at run-time. Powerful addressing algorithms were developed for the mapping between the one-dimensional array and the three-dimensional variables using the sparse matrix technology. Therefore there is no limitation in cell numbers for any physical system to be modelled. The only limitation is the size of the virtual memory or swap spaces of the particular hardware that is running Microflo. Also, there is no machine memory wasted since the size of memory allocated for Microflo at run-time is exactly the size of the physical model.

The modularity of the software code enables the users to customise the system to their own needs by 'plug-in or unplug' some of the software modules that are to be built into the software configuration, e.g.

- adding or removing transient modelling facilities;
- choice of different turbulence models preferred by the user;
- adding conjugate conductive, solid and gas radiative heat transfer facilities;
- removing the turbulence model for the modelling of super-sonic flow based on Euler equation; etc.

Microflo provides the use of time-dependent boundary conditions. These may be defined either as continuous time functions or time discrete events. By doing so, Microflo is able to model the real time, instantaneous response of a building, such as the disturbances of air flow caused by the activation of a ventilation fan, pressure on windows of a high-rise building due to changes of wind directions, and instantaneous release of contaminants, etc.

In general Microflo is capable of modelling the following building related thermal-air flow phenomenon:

- Industrial ventilation with heat and contaminant generation sources;
- Air movement in enclose space or open space like atrium in office and public buildings;
- Domestic housing where no forced ventilation is used;
- External air flow pattern around cluster of buildings and distribution of pollution;
- Transient movement of smoke and contaminant within buildings;

Other applications of the Microflo may also be found in mechanical system designs, wind pressure on high-rise buildings and bridges, hospital hygiene, automobile aerodynamics, etc.

ELEMENTS OF MICROFLO

Recent developments at IES have focused on the provision of an Integrated Building Design System capable of integrating the building design processes. The outcome of this is the IES<Virtual Environment>.

THE IES<VIRTUAL ENVIRONMENT>

The IES<Virtual Environment> is built upon the integration of a wide range of modelling software tools based on first principle theories of lighting, energy and aerodynamics incorporating the techniques of virtual reality. Central to the IES<Virtual Environment> lies the Integrated Data Model, the IES-IDM that acts as the internal standard for data exchanges among various software modules. Within the IES<Virtual Environment> all software tools operate based upon this single data model and thereby facilitating transfer of data, saving time and minimising error. Once data and other information have been entered and held in the IES-IDM, it is available to all processes during the lift-time of the design project. The IES-IDM is a multi-layered, multi-threaded open database structure that contains standardised primitive building descriptive data and data derived from the primitives.

The IES<Virtual Environment> can be characterised by the following elements:

- All software tools are equipped with X/Motif or MS/Windows look graphic front-end.
- An IES internal standard open structure Integrated Data Model, the IES-IDM that contains all information pertaining to the design and supports CAD's DXF and ISO STEP data exchanges.
- All simulation and calculation tools access a single standard computer based model, the IES-IDM, and thereby, dispense with the need of multiple data input.
- Comprehensive graphical facilities for displaying simulation results, including conventional 2D figures, 3D surfaces, 3D solid display with hidden line remove and 3D real time animation with digital illumination.

Figure 1 shows the conceptual diagram of the IES<Virtual Environment>.

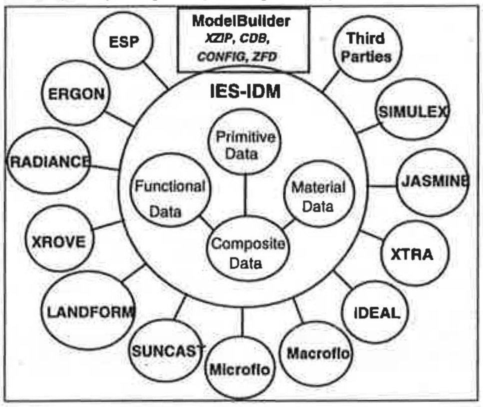

Figure 1. The IES<Virtual Environment>

A brief description of part of the modules in Figure 1 are given as follows:

ERGON - fuel and utilities management system for Combined Heat and Power (CHP), tariff analysis, cost and pay-back estimations, etc.

ESP - comprehensive building energy simulation system based on first principle theories of many branches of physical science.

IDEAL - feasibility analysis tool for sketch design and capital cost evaluation of the project.

JASMINE - general purpose fire and smoke modelling system developed by the Fire Research Station of BRE.

Macroflo - network air flow simulation system for air movement and infiltration of buildings.

RADIANCE - lighting simulation system based on first principle optics theory.

SIMULEX - fire and safety modelling system for occupant movement and evacuation from building.

SUNCAST - solar shading, isolation and shadow modelling for a building using sun tracking and a hidden surface removal algorithms.

XTRA - time-series analysis tool that is able to display time dependent simulation results.

Detailed description of the IES<Virtual Environment> can be found elsewhere. [Tang, 1996]

THE MICROFLO SUITE

Microflo provides an innovative set of fully interactive graphical user interface for pre/ post processing and enables the users to view the simulation through a true CAD environment in which the complexity of the CFD is largely hidden. Figure 2 shows the organisation of the Microflo and the information flow among all the participating modules.

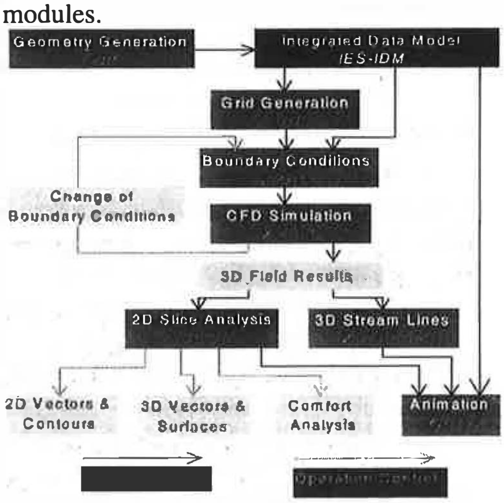

Figure 2. The Microflo modules.

A brief summary of each module is given as follows:

XZIP

Xzip is a 3D geometry modelling system capable of creating geometrical models of building with an unlimited degree of complexity. Xzip provides a set of 3D primitive objects from which any physical object may be created. Different layers can be defined for different objects e.g. furniture, terrain, trees and other site obstructions. Xzip supports DXF CAD format data exchange and thereby models created with commercial CAD packages, e.g. AutoCAD can be imported. 3D geometry models created by Xzip can also be exported in DXF format by taking orthogonal cutting planes from the 3D geometry.

XROVE

Xrove provides animation of a 3D model in perspective view displayed in full colour with textures and realistic lighting effects. In Microflo, Xrove is used for displaying 2D cut-planes, 3D velocity vectors and iso-surfaces for the selected parameters in 3D air flow fields onto the physical geometry of the building; animating the movement of air flow stream lines within the 3D geometry.

XGRID

Xgrid generates automatically the computational non-uniform, structured grids required for CFD simulation from a 3D geometric model. In doing so, any object with non-orthogonal shape is automatically discretised into a collective series of rectangular prisms which conforms to the outline of the original non-orthogonal object.

XPRO

Xpro is an interactive graphic user interface for defining and editing initial and boundary conditions, setting simulation conditions and adjusting simulation parameters. Xpro provides a clearly defined hierarchically layered menu system to guide the users through the complex process. Facility for defining three different types of thermal boundary conditions is provided. Such facility is equally applicable to boundary of concentration.

XMFLO

Xmflo is a graphical user interface for monitoring the CFD simulation, tuning simulation parameters and setting time step for transient simulation. As a CFD simulation is usually extremely time consuming, Xmflo also supports simulation in batch mode for large projects whereby the parameters for convergence control will be tuned automatically to the optimum during a period of simulation and results saved at given intervals.

SLICE

A post-processing tool for CFD result analysis. Part of the processing capabilities include:

- display of results of any variable as 2D vector and contour or 3D vector and iso-surface;
- interactive selection of arbitrary cut planes through the model geometry;
- comfort contours based on the PMV and PPD algorithms;
- exporting of 2D colour slices that conforms to the IES-IDM format for 3D visualisation.

XSTREAM

Xstream is an interface for the generation of air flow streamlines within the 3D air flow field. The streamlines are coloured according to the magnitude of a selected variable. The movement of the streamlines shows the actual air flow velocity and direction. The streamlines are predicted based upon the movement of particles in the air stream underlying the theory of particle mechanics. The real-time animation of the flowing streamlines is an numerical analogue to the physical flow visualisation techniques that are commonly used in wind tunnel experiments using smoke and particles.

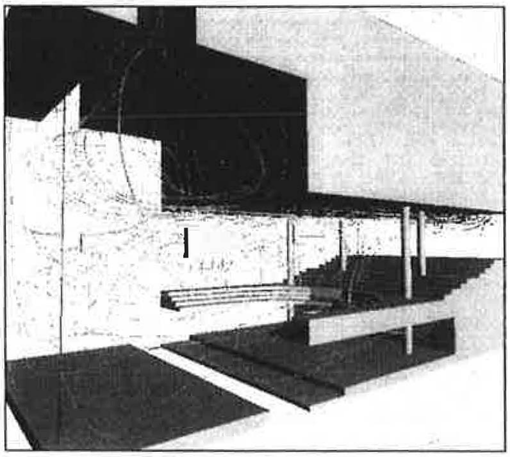

Figure 3. Animation of streamlines.

Figure 3 shows the impression of the air movement by stream lines within a theatre. The colour on a streamline indicates the variation of temperatures of the air as it is travelling.

Figure 4 shows one of the animation sequences from a transient CFD simulation for environmental pollution studies, in which the CFD simulation results were firstly saved for pre-specified time steps and then the iso-surfaces for a constant level of concentration of contaminant were obtained by using Xpost.

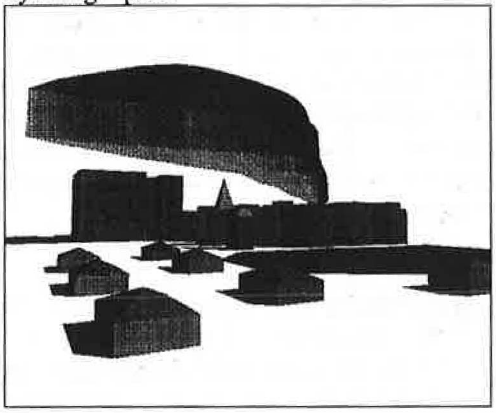

Figure 4. Animation of isosurface.

HANDLING OF BOUNDARY CONDITIONS

Typically a CFD simulation would require the following information as its time-dependent initial and boundary conditions:

- temperatures of solid surfaces that are enclosing the air space, e.g. walls, furniture, human body, etc.
- pressure on the enclosure of the space, e.g. an opened window, ventilator grilles, gaps around windows and doors;
- air infiltration rate and air flow from adjacent spaces;
- heat emissions from internal sources;
- moisture generation from human perspiration, etc.

Whilst Microflo has provided adequate facilitates for the users to defined various boundary conditions, the use of accurate boundary condition is always an important aspect in CFD modelling. Ideally, a CFD modelling system could incorporate into it all the required algorithms as additional differential equations, e.g. to include the 3D solid conduction, solar radiation, grey gas radiation, combustion and chemical reaction, thermal and structural strcsscs, etc. These, when combined come into the CFD system, would easily go beyond the computing power that our current machine environment could deliver.

Alternative techniques emerged from the development in combined CFD and thermal modelling of buildings. The commonality of such techniques lie in the ability of handling the mathematics of the complete physical system of the building in a simultaneous manner while maintain the computational cost at minimum level.

For the modelling of combined CFD and building thermal structures the following methodologies are envisaged: [Zhang, 1990]

- The *Sequential substitution method*, by which the transformations are established between the two systems. The thermal and CFD simulations are carried out in a prescribed sequence. The results from one simulation are then transformed to the other as correctors to the participating variables;
- The *Modified air temperature gradient method*, which similar to the above but provide higher resolution to air temperature to the thermal simulation using the temperature gradient obtained from CFD simulation;
- The *Construction multi-division method*, which is similar to the above but with finer divisions in thermal simulation to further account for the resolution of the CFD simulation;
- The *Simultaneous decoupling method*, an innovative method based on the theory of graph and low-rank perturbation technique to allow an equivalent of the simultaneous solution of the combined systems.

In Microflo the methodology of Sequential-substitution is employed by which the simulation modules of ESP and Macroflo are used prior to Microfo and the results are then entered into to the IES-IDM to be subsequently retrieved by Microflo.

ESP is a comprehensive system for building thermal simulation that employs the finite volume heat balance numerical methods for the modelling of the transience of building with interactions of structure, occupancy, operations of HVAC system and control against realistic climatic conditions for the entire building. In ESP the surface temperatures and volumetric averaging air temperatures for all the rooms are calculated by using first principle theories of radiation, convection, conduction, inter-zone air movement, solar radiation and insolation, etc.

Macroflo is a network based macroscopic air flow simulation system that models the combined effect of air flow within the entire building by taking into account of the effects of internal ventilation, wind pressure outside the building, buoyancy and stack effect, infiltration from openings of windows and doors and from any cracks and gaps of the building and operations of the control system of the entire building. Macroflo runs simultaneously with ESP and thereby generates sufficiently detailed and accurate information required by a CFD simulation.

Because of the limitation in computing power, a CFD simulation is usually associated with a confined space of the building, e.g. an open planned office, atrium, etc. for detailed studies but not so often for the entire building. Once the information is available, Microflo retrieves required information from the IES-IDM to build up its boundary conditions. This can be done either manually by selecting data items from the outputs of the preceding simulations or automatically through the tools provided by the IDM. In the CFD simulation, Microflo calculates the volumetric averaging air temperature of the space (or each individual space) at each time step and compared meticulously with the same air temperature calculated from the preceding simulation. As the two systems, i.e. ESP and Microflo, use the same principle or equation of energy conservation, the conservation of energy is usually closely followed. On the other hand, the 3D temperature field calculated from the CFD simulation may also be transformed back into the thermal simulation of ESP and Macroflo for higher degree of accuracy underlying the principle of the Modified air temperature gradient method.

Ultimately the true simultaneous CFD and thermal simulation of buildings would require the implementation of the Simultaneous-decoupling method. This has been targeted as one of the principle tasks of strategic development for the next generation of the Microflo system.

VALIDATIONS

Validation exercises for Microflo have been carried out extensively and continuously throughout its development via various sources. These include:

Analytic analysis:

By analytic analysis the thermal, concentration coupled air flow within the enclosed spaces were solved analytically for simplified and idealised conditions. The solutions are then used as references to compare with the results obtained using CFD simulation of Microflo under the identical conditions.

Dedicated experimental analysis:

The results of Microflo simulations are compared with data that were meticulously monitored from experiments. Several data sets are available. One of the dedicated example shows here by which extensive measured data were obtained from purposely built experimental facility that was equipped with automatically controlled climatic chamber with double buffer space, employing high precision instruments and censors, robotic control and the extensive use of data logging and processing. Measured parameters included 3D information of air velocities, air temperature, turbulence energy, distribution of surface temperatures of the climatic chamber and the rate of heat generation. [Tang et al, 1989]

General comparison exercises:

This forms one of the regular routine validation exercises of the Microflo at IES whereby results of the Microflo simulations were compared with other CFD simulations running under the identical conditions. At IES, a library of test data sets obtained from references found in the public and private sectors are established to which extensive validations were carried out. Currently collaboration for the validation exercise is under way with the Energy System and Research Unit of the University of Strathclyde.

ENGINEERING APPLICATIONS

In its use, Microflo, in conjunction with other simulation modules of the IES<Virtual Environment>, provides integrated information on the performance of the design to enable the design team to actually 'see' and 'feel' the building before it is being built. IES Limited have used Microflo on a large number of commercial projects in conjunction with architects and utility engineering organisations and provided considerable improvement to the original designs. Some of the projects which Microflo has been applied to on a design support consultancy basis are described in the following examples.

Environmental Control:

In a project in conjunction with a pharmaceutical company, aerodynamic simulations were conducted to investigate the possible pollution caused by emission from a chimney and such that to ensure it did not cause impact to surrounding areas. On the basis of an external air flow simulation the aerodynamics characteristic of the chimney was established and options for the improvement of environmental impact were provided to minimise the risk to the residents in the surrounding buildings from the emitted substances. The atmospheric dispersions of pollutant were shown visually in real-time animation for a variety of design options and wind conditions.

Running Cost Savings:

In an engineering laboratory refurbishment project, the Microflo was used to ensure that the design criteria could be met. A combined thermal and CFD simulations were conducted. Based upon the simulations the design air flow supply was found to be too high and through simulation the appropriate air supply rate established. The capital cost savings achieved by replacing the original system with a smaller ones while still able to maintain the design conditions was in the order of £250,000 and the running costs savings are predicted to be in excess of £5,000,000 over the next twenty years. In addition, it was found that the design criteria was not met at the some part of the laboratories and that the suggestion for the modification of the original design were provided. If this had not been found it would have resulted in retrofit costs.

Legal dispute:

In an industrial dispute where a public building was under criticism by the property owner and occupants over its comfort conditions. It was suspected that the warm air ventilation system installed did not seem to satisfied with the design standard and the designer argued that the system was altered by the contractor. Microflo was applied to verify the situation. An intensive study by an iterative thermal and CFD simulation was carefully conducted. The simulation results had revealed a number of design deficiency as well as failures caused by alternations made to the original design. After an institution of third party experts was invited to examine the results from CFD simulation, Microflo was invited to the city's Sheriff court to stand as citation of expert witness to the legal case.

CONCLUSION

Development in CFD has given rise to the prospect of sophistication in both theory and numerical techniques to allow the technology to be used at design stage. As an integral part of the IES Virtual Environment, the Microflo CFD simulation environment has been developed to enable the designers to assess the performance of a proposed new or refurbished building with the aid of virtual-reality technology.

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