Efficient dynamic thermal modelling using CFD

Shini Somarathne[a,b,*], Mark Seymour[a], Maria kolokotroni[b]

[a]*Flomerics Limited, Hampton Court, Surrey, KT8 9HH, UK;* [b]*Department of Mechanical Engineering, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK*

ABSTRACT
CFD and DTM both require the specification of similar building constructional details, but provide airflow and heat transfer simulations using very different time constants. In order to overcome their deficiencies as single tools, both codes can use information from each other. Embedding DTM techniques into CFD is a relatively novel approach to the development of a single tool. CFD contains all functions necessary to be able to model heat transfer through building fabric.

Through a series of case studies, functions such as 'freeze fluid flow', 'freeze solids', transient and steady state solutions, available within a CFD code, have been used to dynamically model the effects of external ambient variation on building envelopes. The consequential effect on the airflow and heat transfer inside a basic room has been examined. Results obtained show good potential for the further development of a fully automated single tool.

INTRODUCTION
Computational Fluid Dynamics (CFD) models are extensively used to provide a detailed simulation of the airflow within a building at steady state, although in reality internal and external conditions change. The rate of response of the different elements of a building to these dynamic thermal changes is significantly different; solid parts of the building respond much slower than the air.

The current practice of accounting for the effect of thermal transfer through material is to use two software programs in tandem. The first software tool can perform Dynamic Thermal Modelling (DTM) simulations, and the second software program is a computational fluid dynamics code (CFD). DTM provides a very coarse thermal analysis of the conditions inside an entire building, over a substantial length of time (to account for internal and external thermal variations). DTM is mainly employed to provide bulk time-averaged surface temperatures for walls and other boundaries of a room, which are usually manually transferred into a CFD model.

This current modelling technique, however, could lead to unnecessary duplication of effort as similar building details must be input into both simulations. CFD alone could be used to model the effect of heat transfer through materials and air simultaneously. However, allowing for the CFD simulation of significantly different rates of heat transfer through both mediums generates large quantities of data. This has been a significant limitation in dynamically modelling zones within CFD, to date.

This paper describes tests of a newly developed dynamic thermal modelling procedure used within CFD. The technique proposed is computationally efficient and provides a solution to combining the thermal effects through very different mediums, whilst accounting for external and internal ambient thermal changes over time.

[*] Corresponding author. E-mail: shini.somarathne@flomerics.co.uk

BACKGROUND OF DTM AND CFD AS SEPARATE TOOLS

DTM

DTM splits a building system into a number of interrelated finite regions. These regions represent fabric/constructional materials, air volumes and plant components, which are interconnected by means of time varying thermal/flow resistances, and also internal and external zone surfaces. Conservation equations of mass and energy are written for each finite region to prescribe convective, conductive, radiative, fluid flow and storage processes at region interfaces, while subjecting the system to appropriate climatic conditions. Due to the complexity of modelling an entire building, DTM uses a relatively crude grid to include all regions of a building, which often results in an over-simplification of the analysis.

CFD

Conversely, CFD provides relatively detailed (often as a steady state simulation) analysis of the conditions within a zone of a building. In addition to the equations used in DTM, momentum equations are further included in the set of governing equations and an appropriate turbulence model (in this project the k–ε turbulence model was judged to be the most appropriate) is used in CFD. Again, the equations are based on the principles of conservation of:

- fluid mass (continuity),
- fluid momentum in the Cartesian grid, x, y and z directions—u, v, and w,
- thermal energy—T.

PREVIOUS WORK

It was not until the mid-1990s that hardware was able to cope with a shift in the focus of the research. Rather than developing DTM, CFD was now being developed to incorporate DTM techniques. Tang (1998) used MICROFLO which utilized the 'suite of software modules' concept by grouping them together, the core element of MICROFLO was a CFD simulation engine. Towards the late 1990s, several research groups were experimenting with embedding CFD into DTM. All research had a common style, in that the emphasis was on swapping and exchanging information between the separate codes.

Negrao (1998), however, identified that temperature solutions provided a strong and important link between the two codes, an idea relating to the concept of 'conjugate heat transfer', where a CFD model is extended to include the heat transfer within the building fabric. The 'conjugate heat transfer' model was also experimented with by Moser *et al.* (1995), Kato *et al.* (1995) and Schild (1997).

The procedure described in this paper to dynamically model within CFD extends and develops the concepts of 'conjugate heat transfer' further. The procedure provides the potential for solving the problem of generating large quantities of data, whilst effectively modelling heat transfer through building fabric and internal air simultaneously. The performance of the procedure has been rigorously tested through three phases and assessed through inter-model comparisons of fully transient simulations using the same CFD code.

THE DYNAMIC THERMAL MODELLING PROCEDURE

The dynamic thermal modelling procedure was developed using various functions available within the existing CFD code, hence abandoning the use of a separate DTM code. A combination of transient, steady-state solution procedures, 'Freeze-Flow' and 'Freeze Fabric' functions, has been used in a carefully constructed sequence. The operation of each function has been described below:

Fluid Freeze Flow Function

All equations of fluid flow except the temperature equations can be temporarily paused using this function. This function is used during a transient solution period, where the changes of other parameters, particularly velocities of the air within a zone are considered to be minor, over the designated transient period. Transient solution periods will be used typically over a relatively long period of simulation time, to account for the conduction of the external ambient through the building envelope.

Fabric Freeze Flow Function

The fabric freeze flow function fixes temperatures within solids. This function would typically be used when a steady state solution is solved. By freezing the thermal conditions within the solid boundaries the thermal interaction between the components (both solids and fluid) would prevent the entire enclosure from reaching thermal equilibrium during a steady state update. Instead, the other parameters, which would have been temporarily paused during the transient period, using the 'freeze-flow' function, would be allowed to update to any thermal changes that would have occurred over the boundaries, during the previous transient period.

Summary of the DTM–CFD Procedure (Transient/Frozen-Steady/Unfrozen Solution)

- The methodology of obtaining the fully dynamic thermal solution begins with a transient solution, where the temperature equation is solved for 4 h (14 400 s) with the flow in a frozen state, i.e. the Fluid Freeze Flow Function is switched on. This transient solution period contains 360-s time steps. At the end of 14 400 s of transient solving, the solution is saved.
- This saved solution is then readjusted to being a steady state case, and the Fluid Freeze Flow Function is switched off and the boundary Freeze Function is switched on. By saving and re-saving, the initial conditions of this steady state solution are the final conditions of the previous transient solution. After the steady state solution has converged (and hence updated to changes in boundary conditions), the steady state case is saved.
- This steady state case is readjusted and resaved as a transient solution. The initial conditions of the steady state case were the final conditions of the previous transient case.
- The coupling of transient and steady state is repeated in succession over a total transient solution period of 2 days.

In order to test the performance of the dynamic thermal modelling procedure within CFD, the simulations results of temperature at a location within the air adjacent to the wall will be compared with the temperatures at the same location of a fully transient case. The fully transient case is geometrically identical and is also solved over 2 days, using 360-s time steps. All the equations during the fully transient solution are fully functioning. The model subjected to the DTM–CFD procedure and the fully transient case has both been subjected to three previous days of the external ambient to pre-condition the enclosure.

A generic geometrical model has been constructed that will be consistent throughout all of the tests. The most important component of the CFD model construction, common among all tests, is the geometrical grid. Previous tests were implemented to establish an optimum grid that does not require excessive computational time but also provides acceptable accuracy. The computational demand by the geometrical grid must be limited because the transient grid also requires high computational processing. The establishment of the grid followed two fundamental stages of sensitivity analysis to determine the:

1. optimum geometrical grid to be embedded within the external wall;
2. optimum geometrical grid to be embedded within the airspace of the enclosure.

The results of the sensitivity analysis of the geometrical grid concluded in embedding grid of 0.02 m × 0.02 × 0.02 m cells within the 1 × 3 enclosure. The enclosure is bounded by two walls; one wall acting as an external wall (0.22 m thick, containing 22 grid cells), which is exposed to an external ambient. The external ambient ranges sinusoidally from 12.5 to 27.5°C over a period of 24 h. The external wall is made from brickwork (outer leaf), with the following thermal characteristics:

Thermal conductivity = 0.84 W/(m K)
Density = 1700 kg/m^3
Specific heat capacity = 800 J/(kg K)

The second wall acts as an internal partition that has a fixed temperature of 20°C (the fixed temperature setting overrides the material characteristics of this internal partition). The other bounding surfaces of the cubed enclosure are adiabatic (i.e. no heat transfer across them). The enclosure is sealed, i.e. unventilated is all cases.

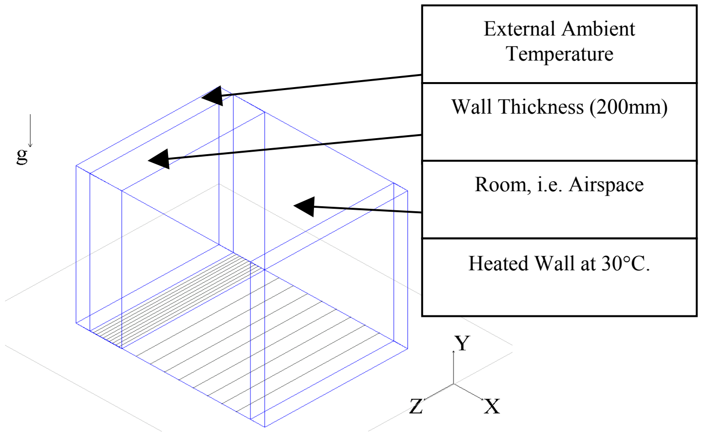

Figure 1 Illustration of the geometry of the enclosure (including grid construction).

This procedure was first tested using the brickwork (outer leaf) material, and the results indicated that the procedure provided acceptable accuracy for predicting temperatures to less than ±0.5°C of the fully transient results. The two main contributions to error were identified as being:

1. transient periods of frozen flow;
2. transient time-step lengths within each transient period.

To further test the DTM–CFD procedure, the above-identified possible sources of error were further investigated. Transient frozen periods ranging from 6 min to 8 h were tested. This range of transient periods was tested on a variety of materials. The objective of the tests was to establish the effect of thermal characteristics on the choice of transient frozen periods and time steps within each transient period.

The original material of the external wall (brickwork, outer leaf) was replaced in turn by a variety of typical building materials ranging from very lightweight and low resistance to extremely heavyweight and high thermal resistance. Nine materials (see Table 1) with a range of thermal conductivities (W/m K) (*C*) and thermal weight (*W*) (J/m^3 K) were tested for a variety of transient frozen flow periods.

Table 1 Material thermal characteristics to be tested using the DTM–CFD procedure

	C1 = 0.03 (W/m K)	C2 = 0.84 (W/m K)	C3 = 1.5 (W/m K)
W1 = 14 000 (J/m^3 K)	W1C1	W1C2	W1C3
W2 = 1 380 000 (J/m^3 K)	W2C1	W2C2 (brickwork)	W2C3
W3 = 2 300 000 (J/m^3 K)	W3C1	W3C2	W3C3

The results indicated that the length of time steps within a transient period of frozen flow did not significantly affect the accuracy of the DTM–CFD procedure. The length of transient frozen flow period did not significantly affect the accuracy of the procedure used on the high thermal resistance materials. Lightweight materials, however, were more sensitive to the procedure and less accurate simulations were obtained for longer lengths of transient frozen flow of more than 30 min.

To investigate the exact effect of the procedure upon the lightest weight materials, Material C3W1 was examined further using a harsher external ambient sinusoidal setting. All specifications of original external ambient sinusoid remained the same, except the period of the sinusoid, which in these further tests was condensed by a factor of 5. Hence, instead of the period being 24 h, the period was reduced to 4.5 h.

The results indicate that the fundamental procedure upon which the procedure is based introduces errors, which becomes more significant with very light thermal weighting materials. A variety of transient frozen flow periods were tested. The results showed that despite the transient period of frozen flow, the errors still follow a defined path, reaching maximum values during high rates of change of the external ambient.

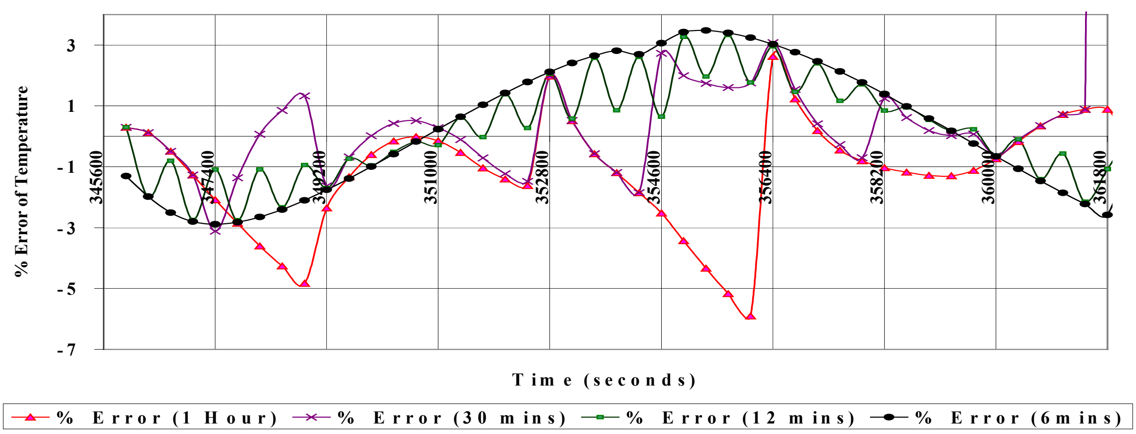

Figure 2 Percentage error of transient 'frozen flow' period for a high frequency sinusoid.

CONCLUSIONS AND FURTHER WORK

- For typical building materials exposed to typical diurnal ranges, the transient-steady DTM–CFD procedure works very well.
- For highly fluctuating external ambient conditions, temperature changes on the internal surfaces of the boundaries must be restricted to less than 0.5°C. A 'trigger' should be developed and placed within the software that detects temperature changes both at the internal surface boundaries of the enclosure, but also around internal sources. This trigger should stimulate a steady-state update.
- Cumulative errors are inevitably present with the procedure, but the errors, even with a highly fluctuating external ambient, are of the order of approximately 0.1°C.
- Much improvement and further understanding of the physics is required of the developed DTM–CFD procedure; however, preliminary results do indicate a good potential of further development of the technique.

REFERENCES

CIBSE Guide (1986). *Volume A: Design Data, Section A5: Thermal Responses of Buildings*. London: CIBSE.

Kato, S., Murakami, S., Shoya, S., Hanyu, F. and Zeng, J. (1995). CFD analysis of flow and temperature fields in atrium with ceiling height of 130 m. *ASHRAE Transactions* **101** (Part 2), 1144–1157.

Moser, A., Schalin, A., Off, F. and Yuan, X. (1995). Numerical modelling of heat transfer by radiation and convection in an atrium with thermal inertia. *ASHRAE Transactions* **101** (Part 2), 1136–1143.

Negrao, C.O.R. (1998). Integration of computational fluid dynamics with building thermal and mass flow simulation. *Energy and Buildings* **27**, 155–165.

Schild, P. (1997). Accurate prediction of indoor climate in glazed enclosures. PhD Thesis, Department of Refrigeration and Air-Conditioning, Norwegian University of Science and Technology (NTNU), Norway.

Tang, D. (1998). Virtual environment for the prediction of air movement in buildings. Integrated Environmental Solutions Limited, Glasgow, UK. (Also *International Conference on Air Distribution in Rooms*, Stockholm.)