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# REDUCED ORDER MODELLING OF THE THERMAL BEHAVIOUR OF AN OFFICE SPACE

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## ABSTRACT

Reduced Order Models (ROMs) have proven to be a valid and efficient approach to model the thermal behaviour of building zones. The main issues associated with the use of zonal/lumped models are how to (1) divide the domain (lumps) and (2) evaluate the parameters which characterise the lump-to-lump exchange of energy and momentum. The object of this research is to develop a methodology for the generation of ROMs from CFD models. The lumps of the ROM and their average property values are automatically extracted from the CFD models through user defined constraints. This methodology has been applied to validated CFD models of a zone of the Environmental Research Institute (ERI) Building in University College Cork (UCC). The ROM predicts temperature distribution in the domain with an average error lower than 2%. It is computationally efficient with an execution time of 3.45 seconds. Future steps in this research will be the development of the procedure to automatically extract the parameters which define lump-to-lump energy and momentum exchange. At the moment these parameters are evaluated through the minimisation of a cost function. The ROMs will also be utilised to predict the transient thermal behaviour of the building zone.

*Keywords: CFD, Reduced order models*

## INTRODUCTION

The availability of low cost wireless sensors to measure temperature, velocity and humidity in building zones is changing the way in which thermal comfort in office spaces can be addressed. The possibility to have several sensors in a room and the ease of their deployment can assist in achieving a deeper understanding of room temperature profiles and in developing and validating thermal models for energy saving strategies or user comfort policies. Computational Fluid Dynamic (CFD) simulations have been successfully utilised to analyse thermal behaviour and user comfort of office space [1, 2, 3] in combination with wireless sensor networks [4]. Nevertheless CFD simulations are computationally expensive, especially if unsteady simulations are required or if they are to be used in conjunction with Building Management Systems (BMS) for operational strategies. For these scenarios the development of reduced order models (ROMs) can be a valid alternative.

ROMs can be distinguished into two categories[5]: (1) state space models in which the problem is divided into input and output, and (2) distributed parameter models [6, 7]. In the category of state space models it is possible to allocate the Compact Thermal Models (CTMs) successfully utilised in the field of electronic components [8, 9, 10], Flow Network Models (FNMs) [11] and lumped and zonal models in building sector [12, 13, 14]. The main issue which arises from the development of zonal/lumped models is that the decision on how to divide the domain (lumps) is left to the experience of the researcher. The researcher will also utilise empirical data or correlations to evaluate the parameters which characterise lump-to-lump energy or fluid exchange.

The object of this research is to develop a holistic methodology for the generation of ROMs from CFD. The lumps will be automatically extracted from the CFD models through user defined constraints. Lump-to-lump interactions (e.g. mass flow rate, convection coefficients) will also be extracted from the simulation.

The development of this methodology consisted of three stages. Stage 1: collection of experimental data are. Wireless sensors, deployed in a zone of the Environmental Research Institute (ERI) Building in University College Cork (UCC), record temperature, velocity and humidity values of the room. Stage 2: the data are utilised to generate and validate steady state CFD simulations. Stage 3: a lumped model (CTM) of the room, is developed from the CFD simulations. The automatic extraction technique is not fully developed yet thus parameters which characterise the energy exchange between zones are evaluated from the CFD or in the ROMs through the minimisation of a cost function minimisation. The commercial package SINDA/FLUINT [15, 16] is utilised to solve the ROMs. Their accuracy of the ROM will be assessed by comparison with CFD simulations and experimental data.

## METHOD

The research activity framework comprises three main phases. In the first phase an iterative process is used for the design and deployment of wireless sensor network (WSN) in a building zone. Preliminary CFD simulations are generated to individuate optimal wireless sensor deployment. CFD simulations are then validated against the WSN data. In the second phase the validated steady state CFD simulations are post processed to generate the ROMs. Lumped parameters are automatically extracted according to user defined constrains on temperature, velocities and/or relative humidity. Lump to lump connector characteristics will also be automatically extracted. Average values for temperature, velocities and humidity for each lump and characteristic connectors will then been prepared for the ROMs solver (SINDA/FLUINT). In the third phase steady state results from the ROM will be compared with the CFD values to assess the accuracy of the ROMs. Consequently unsteady ROMs model will be run and possibly integrated with BMS for building operational strategies.

## MODELS

### Experimental set up

The location for the study is a north facing room in the ERI Building, shown in figure 1 which has dimensions 5.2x5.6x2.9m. The room is heated by two "Dimplex SmartRad" fan convectors. Two windows, electronically controlled, are also present with maximum aperture of 20°. Furniture comprises of five desks and chairs, and shelf units. No additional heating/momentum sources are present (i.e. computers and people). A set of 38 temperature (TelosB) and 4 anemometers (4 hobo) are used for experimental measurements. The anemometers were positioned in front of the opened windows to evaluate the normal component to the opening and on top of the fan assisted convectors. The temperature sensors were deployed at three different levels: Ceiling ( 2.65m above floor), User (1m above floor) and Floor (0.2m above floor) as shown in Figure 1. Ten sensors were dispersed at floor level, 20 sensors at user level and 5 at ceiling level. Three different boundary conditions were analysed and deemed as the most influential: the convectors, the windows and the door. The convectors have been studied only at full regime. The windows have been considered open at an angle of 20°. The door has been considered closed or fully opened at 90°.

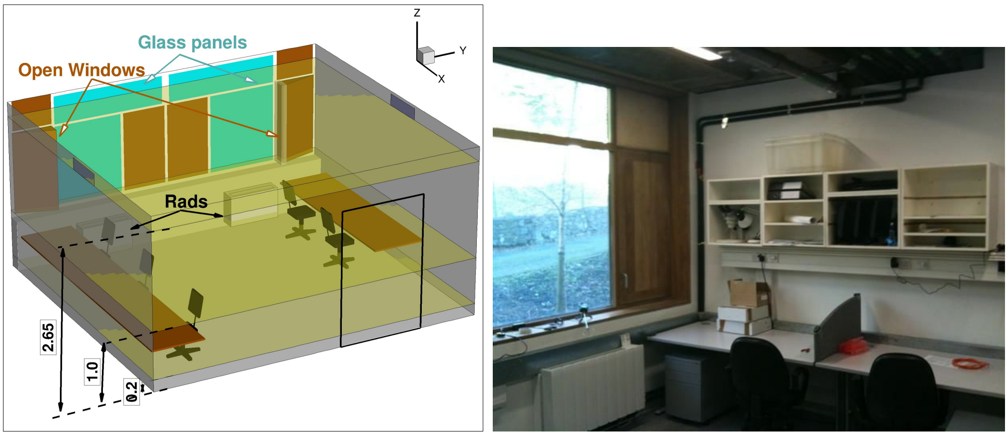



*Figure 1: Numerical and physical domain*

## CFD model

CFD models have been developed to generate a database of test cases. For all simulations, steady state Reynolds Average Navier-Stokes (RANS) equations have been solved coupled with the RNG k-$\epsilon$ turbulence model and with air modelled as an incompressible ideal gas. The domain has been discretized using a structured grid to give 1,572,165 cells (115x147x93). Constant temperature boundary conditions have been utilised for the ceiling and the floor, with all other objects considered adiabatic. The glass panels have an overall heat transfer coefficient of $U = 1W/m^2K$. The door, when opened, has been modelled as a zone of constant pressure. The two convectors have been modelled considering two surfaces: an inlet surface, where velocity and temperature were imposed and an outlet surface where an extraction mass flow rate was imposed. Opened windows were also modelled as inlet surfaces.

## Reduced Order Model

The number and type of lumps for the ROM are evaluated by post processing the CFD simulations through user defined constraints for temperature. At present, lumps have been defined on the three previously defined levels: Floor, User and Ceiling. The output of the post processing procedure and the lump model generated in SINDA/FLUINT are shown in figure 2. The parameters which characterise the lump-to-lump connectors were obtained in post-processing through the minimisation of a cost function $C = \sqrt{\sum_{i=1}^{Ntot}\left(T_{i_{Lump}} - T_{i_{CFD}}\right)^2}$

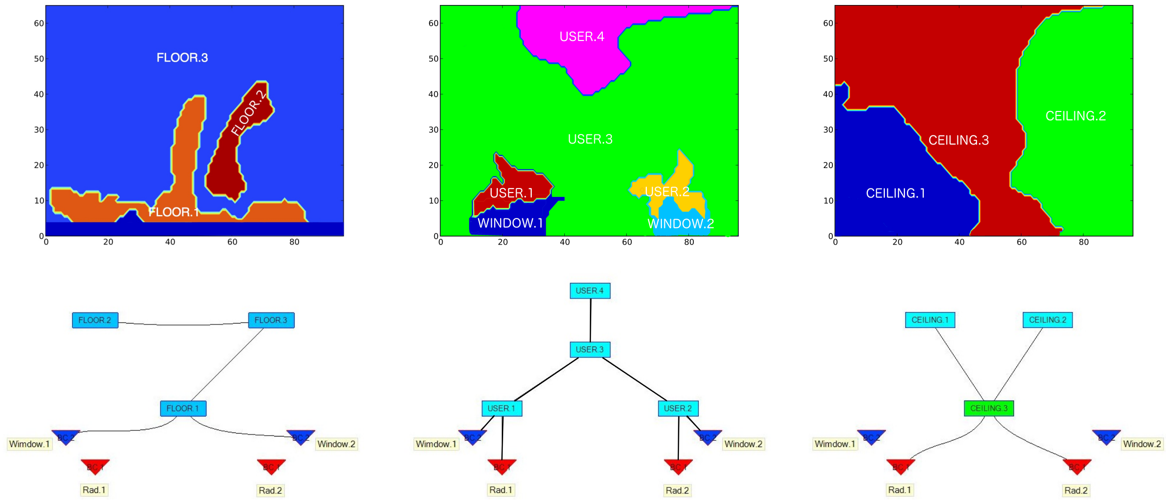
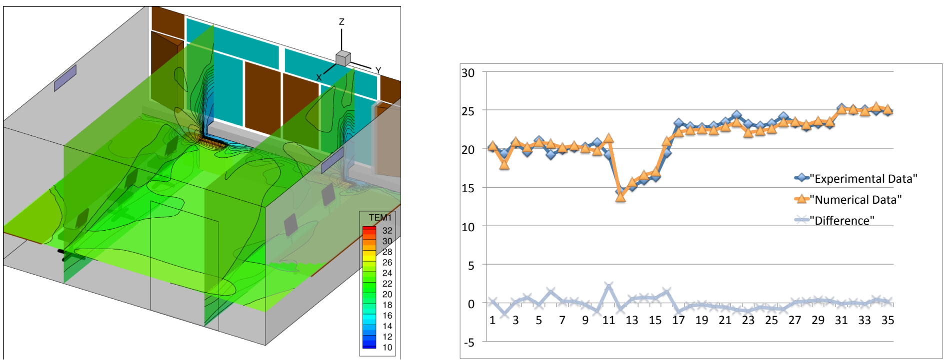



*Figure 2: Example of result for for post processing procedure of CFD simulations*

## RESULTS

### Validated CFD simulations and ROMs

CFD results have been qualitatively analysed and compared with experimental data as shown in figure 3. Experiments were run for 6 hours and were deemed at steady state when 10-minute temperature variation was ¡1%. At steady state average values were found for the 35 sensors. In figure 3 b) the comparison between temperature predicted and average temperature recorded has been reported for the test case simulating windows opened and convectors at full power. The good agreement shown between experimental and numerical data shows that the CFD simulations can be confidently used to generate and optimise ROMs.




a) Temp contours b) Temp comparison

*Figure 3: Temperature contours on three different planes and comparison with experimental data*

The ROM was solved utilising SINDA/FLUINT, an equation solver for CTFM with capability to solve optimisation processes. This capability was utilised to evaluate thermal parameters which were not extracted from the CFD simulations. The results obtained from the ROM are compared versus the average values evaluated for each lump from the CFD simulation and are reported in table 1. In the table the percentage error has been defined as $\%err = \frac{(T_{ROM}-T_{CFD}}{T_{CFD}-T_{rads}}$ where $T_{rads}$ is the air temperate from the fan assisted radiators. The table shows the temperature predictions of the ROM are close to the values extrapolated from the CFD simulation with a maximum error of $-4.93\%$ for USER.4 lump, and average error of 1.95%. The computational efficiency of the ROM is highlighted by the running time of the ROM (3.42sec) versus that of the CFD model (5hours).

| Plane | Lump | $T_{ROM}$ | $T_{CFD}$ | % Error |
|---|---|---|---|---|
| FLOOR | 1 | 20.15 | 20.65 | 2.05 |
| | 2 | 21.99 | 21.48 | -2.17 |
| | 3 | 22.65 | 22.1 | -2.40 |
| USER | 1 | 24.95 | 24.82 | -0.64 |
| | 2 | 24.01 | 23.83 | -0.85 |
| | 3 | 23.46 | 23 | -2.09 |
| | 4 | 22.65 | 23.7 | -4.93 |
| CEILING | 1 | 26.08 | 25.8 | -1.46 |
| | 2 | 25.01 | 25.3 | -1.47 |
| | 3 | 24.62 | 24.9 | 1.39 |

*Table 1: Comparison temperature prediction ROM and CFD*

## DISCUSSION

ROMs have proven to be a valid and efficient numerical approach to model the thermal behaviour of building zones. The main issues associated with the use of zonal/lumped models are how to (1) divide the domain (lumps) and (2) evaluate the parameters which characterise the lump-to-lump exchange of energy and momentum. This decision is usually left to the researcher who will utilise his/her experience to divide the domain and empirical data or correlations to evaluate lump-to-lump exchanges. The object of this research is to develop a methodology for the generation of ROMs from CFD models. The lumps of the ROM and their average property values are automatically extracted from the CFD models through user defined constraints. At this stage the parameters which characterise energy and momentum exchange are evaluated through an optimisation procedure. It is foreseen that more parameters (e.g. mass flow rate, heat transfer coefficients) will also be extracted from CFD models. The ROM extracted with this procedure accurately predicts the temperature distribution in the zone with an average difference with the CFD model lower than $0.4^oC$. The ROM is also computationally efficient (3.4 sec) allowing its possible integration with BMS. Future development of this procedure will allow the extraction from the CFD model of the lump to lump energy and momentum exchange parameters. The overall aim will be to develop a ROM of the room which is able to accurately predict the transient thermal behaviour of the office space under different set of boundary conditions.

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## REFERENCES

1. Chiang, W., Wang, C., and Huang, J.: Evaluation of cooling ceiling and mechanical ventilation systems on thermal comfort using CFD study in an office for subtropical

region. *Building and enviroment*, 48:113–127, 2011.

2. Catalina, T., Virgone, J., and Kuznik, F.: Evaluation of thermal comfort using combined CFD and experimentation study in a test room equipped with a cooling ceiling. *Building and environment*, 44(8):1740–1750, 2009.
3. Hajdukiewicz, M., Geron, M., and Keane, M. M. M.: Formal calibration methodology for CFD models of naturally ventilated indoor environments. *Building and Environment*, 59:290–302, Aug. 2012.
4. Wang, X., Wang, X., Xing, G., Chen, J., Lin, C.-X., and Chen, Y.: Towards optimal sensor placement for hot server detection in data centers. *2011 31st International Conference on Distributed Computing Systems*, pages 899–908, 2011.
5. Shapiro, B.: Creating compact models of complex electronic systems: an overview and suggested use of existing model reduction and experimental system identification tools. *IEEE Transactions on Components and Packaging Technologies*, 26:165–172, Mar. 2003.
6. Rambo, J. and Joshi, Y.: Reduced-order modeling of turbulent forced convection with parametric conditions. *International journal of heat and mass transfer*, 50:539–551, 2007.
7. Cardoso, M. and Durlofsky, L.: Linearized reduced-order models for subsurface flow simulation. *Journal of Computational Physics*, 229(3):681—-700, 2010.
8. Lasance, C., Vinke, H., Rosten, H., and Weiner, K. L.: A novel approach for the thermal characterization of electronic parts. pages 1–9, 1995.
9. Bosch, E. G. T. and Sabry, M. N.: Thermal compact models for electronic systems. pages 21–29, 2002.
10. Sabry, M.-N.: High-precision compact-thermal models. *IEEE Transactions on Components and Packaging Technologies*, 28(4):623–629, Dec. 2005.
11. Miana, M., Cortes, C., Pelegay, J. L., Valdes, J. R., Putz, T., Moczala, M., and Cortés, C.: Transient Thermal Network Modeling Applied to Multiscale Systems. Part I: Definition and Validation. *IEEE Transactions on Advanced Packaging*, 33(4):924–937, Nov. 2010.
12. Musy, M., Wurtz, E., and Sergent, A.: Buildings air-flow simulations: automatically-generated zonal models. *Proceedings of Building Simulation*, pages 593–600, 2001.
13. Griffith, B. and Chen, Q. Y.: A Momentum-Zonal Model for Predicting Zone Airflow and Temperature Distributions to Enhance Building Load and Energy Simulations. *HVAC&R Research*, 9(3):309–325, July 2003.
14. Beausoleil-Morrison, I. *The adaptive coupling of heat and air flow modelling within dynamic whole-building simulation*. PhD thesis, 2000.
15. Cullimore, B., Ring, S., and Johnson, D. General Purpose Thermal/Fluid Network Analyzer V5.5, Oct. 2011.
16. Cullimore, B., Beer, C., and Johnson, D.: Propulsion applications of the NASA standard general purpose thermohydraulic analyzer. *AIAA*, (3723), 2000.