FORMAL CALIBRATION METHODOLOGY FOR CFD MODEL DEVELOPMENT TO SUPPORT THE OPERATION OF ENERGY EFFICIENT BUILDINGS.

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ABSTRACT

Computational Fluid Dynamics (CFD) is a robust tool for modelling interactions within and between fluids and solids. CFD can help understand and predict phenomena that are difficult to test experimentally leading to cleaner, healthier, and better controlled internal environments.

In this research a CFD model of the internal environment of an office space will be developed. The CFD model will then be calibrated using real data taken from a well-positioned wireless sensor network and weather station.

The work focuses on developing systematically calibrated CFD models for controlled environments that include clean rooms, health environments, pharmaceutical storage rooms and information and communication technology locations, utilising wireless sensor networks.

The calibrated CFD model will be used to optimise the positions of the physical sensors for the control of energy efficient internal environments by building operators. This could result in significant energy and economic savings and lead to more accurately controlled internal environments.

Keywords:
Computational Fluid Dynamics, Indoor environment, Calibration, Wireless Sensor Network

1. INTRODUCTION

1.1. The NEMBES Project

The Network Embedded Systems (NEMBES) Project examines the application of network embedded systems in the design and management of the built environments (NEMBES Website 2010). NEMBES consists of three main research groups: (i) Health, (ii) Transportation and (iii) Facilities Management (FM).

This work is a part of the FM cluster and concentrates on the management of internal environments from an environmental and energy perspective. The optimal application of the wireless sensor networks is being investigated in this research.

1.2. CFD and the built environment

CFD is a robust tool for modelling interactions within and between fluids and solids. CFD describes various phenomena underpinned by systems of differential equations and uses discretization methods to solve these equations under diverse conditions. CFD can help understand and predict phenomena that are difficult to test experimentally leading to cleaner, healthier, better controlled internal environments (Zhai 2006).

Developing CFD models requires a high level of expertise that in many cases may not be available (O'Grady & Keane 2006). Previous research has focused on developing and validating CFD models for different internal and external environments (Demokritou et al. 2002); (Horan & Finn 2008); (Li et al. 2009); (Nahor et al. 2005); (Srebric et al. 2008). Previous models have been applied to controlled laboratory environments (Xu et al. 2009) or small scale representations to develop calibration procedures (Lee & Awbi 2004). However, limited work has been done in developing formal procedures for calibrating CFD models and in using these calibrated CFD models to determine the optimal physical sensor positions so that both the environmental and energy efficiency constraints are achieved. Also, a formal calibration procedure demands access to real data that, in many cases, are difficult to obtain or do not exist.

The Building Life Cycle may be divided into three stages: (i) Design, (ii) Construction and (iii) Operation. There is a good cooperation between the Design and Construction stages, as well as Construction and Operation stages. Unfortunately there is a limited feedback from the Operation stage to compare if it is as predicted in the Design.

The goals of this research are (i) to develop a formal calibration methodology for indoor environments that require specific conditions (e.g. office spaces) and (ii) to determine the best position of sensors to achieve optimal environmental control and energy efficiency.

A real, uncontrolled library environment will be modelled in its typical operation and the relationship between the Design and Operation stages of Building Life Cycle will be investigated.

2. METHODOLOGY

2.1. Real data

Using existing geometrical documentation and real data gained from the on-site measurements, a reliable 3D virtual model of indoor environment is being developed. Such a model can be used by building operators at every stage of the Building Life Cycle.

The CFD model will be then calibrated with real data gained from a well-positioned wireless sensor network and weather station (Figure 2.1).

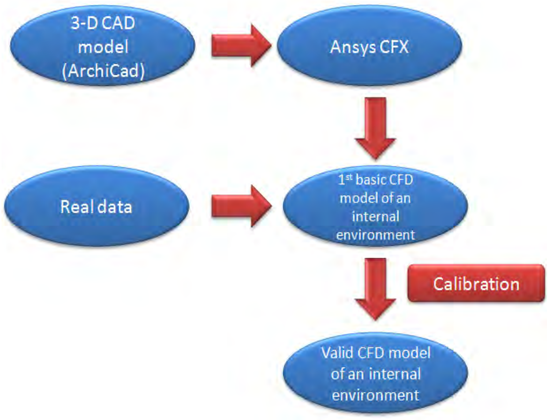

Figure 2.1. Process of achieving a valid CFD model of internal environment

2.2. Modelled environments

This area of research embraces the internal environments that demand controlled conditions. These include offices that require thermal comfort standards (ANSI/ASHRAE Standard 55-2004 2004), health environments with specified air quality (ANSI/ASHRAE Standard 62.1-2004 2004), information and communication technologies environments, highly controlled clean room environments (ISO 14644-2 2000) and pharmaceutical storages or biomedical environments.

Special conditions, including temperature, humidity or contaminant concentration, may be specified in legislation or required for production, or storage reasons. The requirements for many internal environments can be found in Building Regulations, EU Directives and International Standards (International Organization for Standarization Website 2010)

2.3. Model development

A very important aspect when creating a CFD model is the specification of the boundary conditions. Models consist of many simplifications that may lead to errors and inaccuracies. Of crucial importance are the settings of various boundary conditions, such as contaminant source area, convective/radiative fluxes and shape/size of human simulators, and their impact on the simulation accuracy (Srebric et al. 2008). It is not necessary to model the human occupants in detail as there is no significant difference, in the simulation results, between a simple rectangular and more complex, humanlike geometry (Topp et al. 2003).

Calculation of convective/radiative ratio for the heat sources is an important aspect of defining the boundary conditions. The heat from the source should be divided into convective and radiative parts. The convective part is specified as the boundary condition and the radiative part is added to the surface temperature (Chen & Zhai 2003). The convective/radiative ratio for the heat flux from the human simulators has been previously detailed and can be applied to this study (Srebric et al. 2008).

When designing a naturally ventilated environment the external mean wind speed and wind direction should be considered. Horan & Finn (2008) explored the dependence of the air change rate for varying external different wind speeds and directions. Natural ventilation, except for steady state simulations, demands a transient state simulation with initial conditions specified.

The grid resolution must be carefully chosen when creating a CFD model. The grid resolution must be fine enough to provide satisfactory results, so that a grid independent solution is achieved. A grid independent solution is a solution that does not differ significantly when the number of mesh elements is increased. Chen & Zhai (2003) showed that a locally refined coarse grid, which does not demand as much computational resources as a fine grid, may also provide acceptable results. It is important to provide a good grid resolution in the regions near walls because significant differential velocities exist at these boundaries (Pope 2000).

Another challenge that is examined in this work is the choice of a suitable turbulence model. Previous studies investigated different turbulence models for internal environments and compared them with experiments (Srebric et al. 2008); (Stamou & Katsiris 2006). It is crucial to decide which model shows good correlation with the measurements, while being efficient in terms of computational time and requirements. It is advised to start the simulation with a basic turbulence model and if the results are not satisfying, more complex models can be tested (Qingyan Yan Chen & Srebric 2002).

2.4. Model calibration

Calibration involves 'the process of adjusting numerical or physical modelling parameters in the computational model for the purpose of improving agreement with experimental data' (AIAA G-077 1998).

The first step of the calibration is the qualitative comparison. The general airflow pattern between the real and simulated model, as well as air velocity, temperature, contaminant concentration, etc. should be compared. A quantitative comparison in multi locations that evaluates all the uncertainties and errors that arose can then be carried out. The final step of the calibration is the process of improving the agreement between experimental and simulated data (Qingyan Yan Chen & Srebric 2002).

3. DEMONSTRATION BUILDING

3.1. Overview of the building

The demonstration building that will be used in this study is a 3 storey 'Nursing Library' expansion to the James Hardiman Library at the National University of Ireland (NUI), Galway (Figure 3.1). The building has a gross floor area of 800 m^2 (8611 ft^2) and was opened in September 2009 (Figure 3.1).

Figure 3.1. Nursing Library building at NUI Galway campus

The demonstration building accommodates reading spaces, group study rooms, computer study spaces and book stacks. The basement consists of an open plan reading space and a large, air conditioned computer room. The ground floor is generally an open plan room with book stacks or reading spaces. The first floor has an open study area and comprises closed study rooms and an air conditioned computer room.

The building is naturally ventilated with the support of mechanical ventilation and is monitored by a Building Management System (BMS). The BMS provides a record of the internal and external temperatures, CO_2 concentrations and the energy consumption. The BMS controls dampers and windows depending on the internal temperatures and CO_2 concentrations.

The building uses a passive cooling technique (Buildings Office, NUI Galway Website 2010). The Nursing Library has an earth tube installed underground (Figure 3.2). The earth tube changes the temperature of air entering the building, so the difference between the internal air and the air that enters the building is minimised.

Figure 3.2. Earth tube installed in Nursing Library building

The building provides the researchers with good access to monitoring data. It is equipped with new technologies for controlling and maintaining internal environments. This building poses many challenges for the research team including: natural ventilation, solar radiation, human occupants, etc. Gaining familiarity with those problems will help to develop a high level of expertise and confidence which are very important in creating reliable CFD models of internal environments.

3.2. Data acquisition – The 'Egg-Whisk' Wireless Sensor Network

Calibration data in this study will be obtained with data from the 'Egg-Whisk' Wireless Sensor Network (WSN) (NAP Website 2010) and a weather station (Campbell Scientific Website 2010).

The Egg-Whisk network is comprised of a number of wireless Egg-Whisk motes connected via a dedicated 'Star Network' to a base control and storage computer. The Egg-Whisk mote (Figure 3.3) is an environmental sensing microsystem specifically designed to obtain a comprehensive record of the environmental conditions at a particular point within an indoor space via a number of on-board sensors. The mote measures air speed (as low as 0.05 m/s (0.16 f/s)), CO_2 concentration (ppm), temperature (^oC), humidity (%), light (lx) and noise (dB).

The Egg-Whisk network can therefore collect detailed data from multiple locations within an indoor environment. Also the wireless and compact nature of the network gives great portability and flexibility allowing for ease of use in operational indoor spaces.

The Egg-Whisk technology is based around the Tyndall modular WSN prototyping system (Barton et al. 2006); (O'Flynn et al. 2005), with application specific sensor layers developed for the indoor environment scenarios under investigation in the study. As the system is battery operated, low power consumption sensors and implementation have been utilised where possible.

The transceiver/microcontroller layer (O'Flynn et al. 2005) was developed to provide radio frequency (RF) communications capability between sensor nodes. The layer incorporates a microcontroller driving a transceiver operating in the 2.4GHz ISM band. The embedded microcontroller is the Atmel AVR ATMega128L (Atmel Corporation Website 2010), an 8-bit microcontroller with 128 Kbytes in-system programmable flash, allowing the user to develop custom communication protocols and sensor interface solutions. The transceiver used is a 2.4GHz ISM band transceiver from Nordic VLSI (Nordic Semiconductor Website 2010), the nRF2401, capable of transmitting and receiving data in high data rate bursts to implement reduced power consumption functionality.

The mote was developed by the Tyndall National Institute, Ireland (Tyndall Website 2010) and the IRUSE Group in the National University of Ireland, Cork (IRUSE Website 2010) as part of the SFI funded National Access Program project (NAP website 2010). The NAP project is the predecessor of the NEMBES project which is currently funding this work.

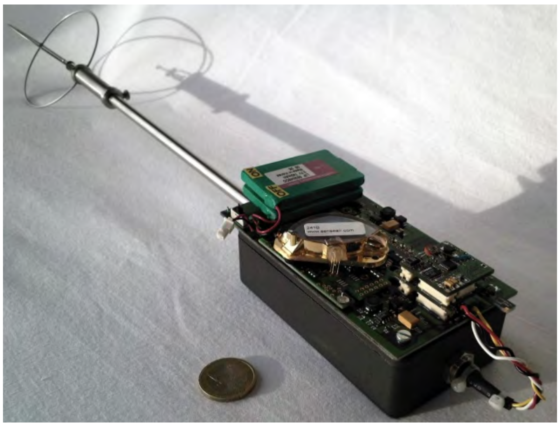

Figure 3.3. The Egg-Whisk mote

The automatic weather station (Figure 3.4) is installed on the roof of another building at NUI Galway campus, and is approx. 150 m (492 ft) distance from the demonstration building. It measures air temperature (^oC) and relative humidity (%), barometric pressure (mBar), wind speed (m/s) and wind direction (^{o}), total solar radiation (kW/m^2) and rain fall (mm). Data are stored on the Compact Flash Memory (CFM) card using a data logger and can be downloaded from the card or by the internet connection. The data collection time step is 1 minute for all sensors except rainfall, for which it is 1 hour. The weather station gives a reliable overview of the weather conditions and will provide essential data for the CFD simulation and calibration at any time of the year.

It is planned, in the near future, to obtain an additional anemometer and wind vane for defining wind pressure coefficients directly from the demonstration building.

Figure 3.4. The weather station installed at the NUI Galway campus

3.3. Proposed Model

One of the study rooms in the Nursing Library building has been chosen for the first CFD simulation of an internal environment (Figure 3.5). Its internal dimensions are 2.7 m (D) x 4.4 m (L) x 3.1 m (H) (8.9 ft x 14.4 ft x 10.2 ft).

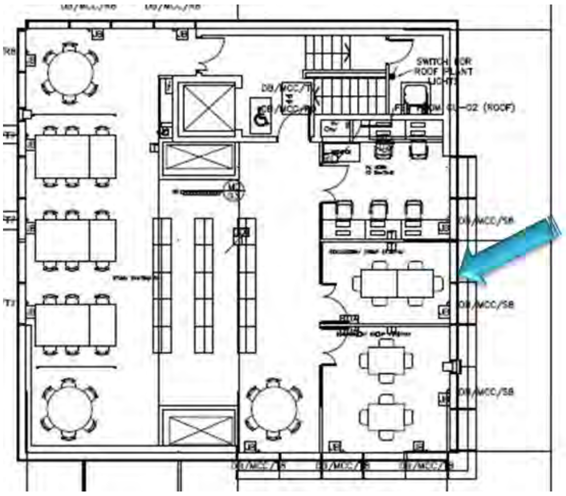

Figure 3.5. First floor plan of the demonstration building with a modelled room showed

The room is naturally ventilated and uses a radiator as a heat source. Other heat sources are computers, a television, lamps and people. One wall of the room is made of glass thus allowing for solar radiation. The wall is facing south – east direction with a surface azimuth angle of 66°. There are two windows that can be opened on this wall. On the opposite wall there is an internal door and a glass surface.

The CFD analysis is performed using Ansys CFX code (ANSYS Website 2010). The first CFD simulation predicting air temperatures and air velocities is run for the room without any obstacles and human simulators inside (Figure 3.6). An initial basic model was implemented which can be added to in a step by step manner. The mesh of the model contained 23,787 nodes and a steady state simulation was carried out.

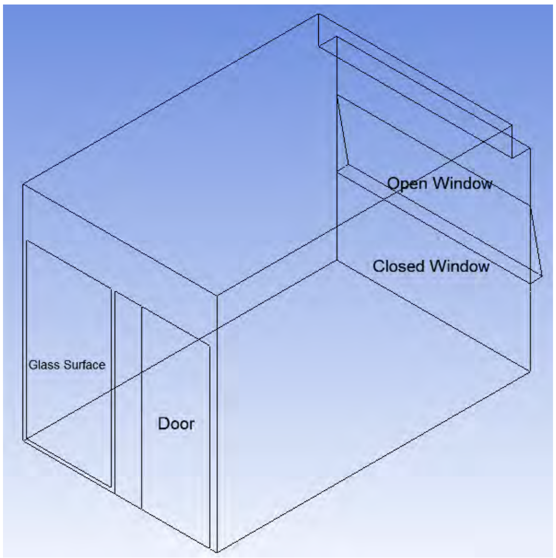

Figure 3.6. Geometry of the room for the first CFD simulation created in Ansys CFX

Data obtained from: (i) the weather station (barometric pressure, outside temperature) and (ii) the Egg-Whisk mote (air speed at the window) provided boundary conditions for the model. The open window acted as a velocity inlet with an average air speed of 0.3 m/s (0.98 f/s) for the period monitored. As external wind readings changed significantly during the experiment it was decided to use the average air speed readings taken by the mote at the window. The outside temperature was 15.2 °C (59.4 °F) and window surfaces were specified with the heat transfer coefficient of 2.7 W/m^2K (0.475 Btu/ft^2h^oF). The door was modelled as a pressure opening.

The experiment was carried out on a cloudy day, so the first simulation did not include radiation heat exchange. However, the readings from the weather station show the presence of solar radiation, so next simulation will take account of radiation model. For all surfaces, except inlet and openings, the non – slip boundary conditions were specified.

For the simulation, the *k-ω* based Shear Stress Transport (SST) turbulence model was chosen. The SST model is a good choice for a general turbulence model (ANSYS Website 2010).

3.4. Initial results

The initial measurements of air temperature and air velocities for the room in Nursing Library building were taken on the 21st July 2010.

The Egg-Whisk mote was placed at various locations inside the room (Figure 3.7). As only a single mote was available, air velocities readings from each location were not taken simultaneously but were taken with 15 minutes of each other. In future experiments readings will be taken simultaneously from each grid point. That will allow for a comparison of measured and simulated data. Air temperature data were taken throughout experiment at one location in the middle of the room at height of 1.2 m (3.9 ft).

Sample air speed data obtained from the weather station and Egg-Whisk mote at different locations inside the room are shown in Figure 3.8.

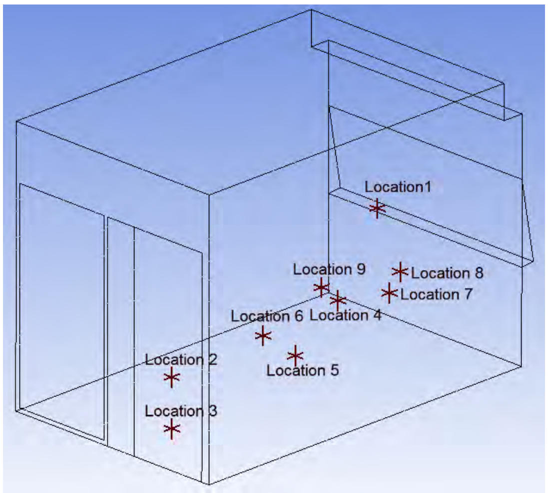

Figure 3.7. Egg-Whisk mote locations inside the room.

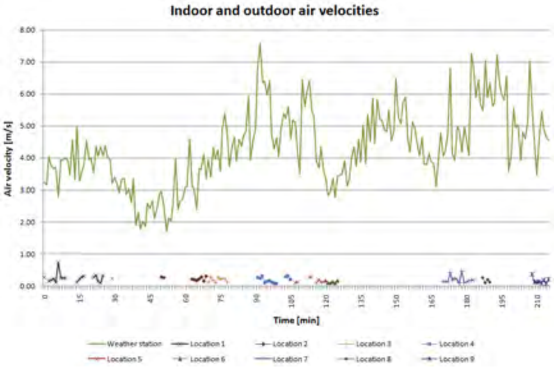

Figure 3.8. Indoor and outdoor air speeds measured on the 21st July 2010

To calculate the solution, the simulation was set to maximum 2000 iterations with 1 s time step. For reasonable convergence of the model the Root Mean Square (RMS) residual for mass and momentum equations was taken as 0.01%. The conservation target was set to 1% (ANSYS Website 2010).

In Figures 3.9 and 3.10 an airflow pattern and a temperature distribution in the room are shown.

At the measurement location average measured and simulated temperatures were 22.9 ^{o}C (73.2 ^{o}F) and 22.4 ^{o}C (72.3 ^{o}F) respectively. The difference may be caused by the lack of solar radiation specified in the model, the heat gains from a person taking measurements and the lamps that were not included in the model.

A comparison of air velocities inside the room is not possible because measurements were not taken simultaneously. Wind speed measured by the weather station increased during the day when the experiment was carried out, which affected the air at the window. Another consideration is the measurement of wind direction entering the room. Those aspects must be regarded in the future work.

Figure 3.9. Air temperature distribution inside the room (plane through the middle of the door)

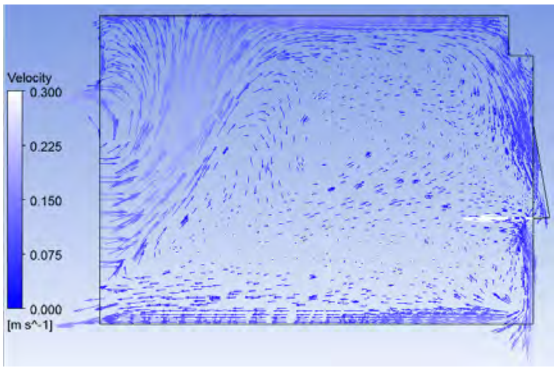

Figure 3.10. Air velocities distribution inside the room (plane through the middle of the door)

3.5. Model calibration

Air temperature and air speed from the initial model will be compared to the equivalent data from the Egg-Whisk network. A grid approximately 1 m x 1 m x 1 m (3.3 ft x 3.3 ft x 3.3 ft) of wireless sensors will be installed to obtain data for the calibration process. Then assumptions, such as geometry simplification, grid resolution and turbulence model will be checked.

A sensitivity analysis to determine the importance of input parameters will be carried out. The aim of which is to check how the boundary conditions influence the model output. These may include turbulence intensity, wall roughness, radiation parameters (emissivity, diffuse fraction), etc. Calibration of these boundary conditions to improve model accuracy will then take place.

It is believed that once a correlation between input and output parameters is found, the calibration process may be completed. Having well calibrated models will help to determine the optimal sensors' position in indoor environments.

4. CONCLUSIONS AND FUTURE WORK

CFD is a very useful tool for designing internal environments. However, a high level of expertise in CFD modelling is needed, to gain the confidence that the CFD model is a true representation of the real environment.

Currently, there are no fixed procedures for calibration of internal environments modelled using CFD. Guidelines for the verification, validation and reporting of CFD results have been defined (Qingyan Yan Chen & Srebric 2002) but no standards for the calibration process have been determined. A developed formal methodology for calibration of internal environments could be a vital tool in allowing designers to become familiar with CFD and enable more efficient modelling of internal environments.

The calibrated CFD models of internal environments would be used to optimise the best positions of the physical sensors controlling these environments. This could result in significant energy and economic savings and lead to more accurately controlled internal environments.

Future work will include the thermal radiation model implementation to simulate the radiation effects through the windows and from the radiator. It is shown in the literature (Gendelis & Jakovičs 2007) that thermal radiation has a big influence on the room temperature and airflow distribution. The additional wind vane will be obtained for defining the exact direction of the wind entering the room.

Full-day observations of the room environment will be carried out. A 1 m x 1 m x 1 m (3.3 ft x 3.3 ft x 3.3 ft) network of Egg-Whisks will measure the air temperatures and air velocities. Those measurements and data obtained from the weather station will provide the boundary conditions and comparison points for the calibration process. New models will be developed containing additional heat sources such as lamps, computers, and human manikins. It is planned to run a transient simulation as well.

Furthermore, work will focus on developing systematically calibrated CFD models for controlled environments that could include clean rooms, health environments, pharmaceutical storage rooms, information and communication technology environments, utilising wireless sensor networks.

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