

FORMAL CALIBRATION METHODOLOGY FOR A CFD MODEL OF A NATURALLY VENTILATED ROOM

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ABSTRACT

This paper describes a systematic methodology for the development of calibrated thermodynamic Computational Fluid Dynamics (CFD) models for controlled environments in buildings utilising wireless sensor networks. The calibrated CFD model will be used to optimise the positions of the physical sensors for the management of energy efficient internal environments by building operators. This methodology could result in significant energy and economic savings and lead to more accurately controlled internal environments.

For the simulation of an internal environment, a CFD model of one of the study rooms in the Nursing Library at the National University of Ireland in Galway, Ireland has been developed. Data obtained from an on-site weather station and wireless sensors provided boundary conditions for the CFD model. A well-positioned wireless sensor network collected real-time data at multiple locations within the indoor environment. The data were compared with CFD model results and a calibration procedure was developed. The presented research compares the model outputs and the measured data, and outlines the calibration procedures to date.

INTRODUCTION

NEMBES Project

The work presented concentrates on the management of internal environments from an environmental and energy point of view. As a part of the Irish Higher Education Authority (HEA) Network Embedded Systems (NEMBES) Project (NEMBES 2010), this research investigates the optimal selection and deployment of the wireless sensor networks to best control internal environments in buildings. The multi-disciplinary research programme NEMBES examines the application of network-embedded systems in the design and management of the built environments.

CFD and built environments

The Building Life Cycle identifies three main stages: (i) Design, (ii) Construction and (iii) Operation. There is a little integration in terms of personnel, systems or data between the Design and Operation.

This has resulted in a weak feedback from the Operation to the Design stage.

In the recent years CFD became a very popular tool for predicting the airflow in buildings. An about 70% of the ventilation performance studies published in year 2008 used the CFD in their analysis (Chen 2009).

Chen & Srebric 2002 specified the guidelines for the verification, validation and results reporting of CFD models of indoor environments. However, no systematic methods for calibration of those models were determined.

That shows the need for easily calibrated CFD models which provide good representation of the real environment. Being an effective tool for building design and optimisation, reliable CFD models would lead to cleaner, healthier and better controlled internal environments.

Existing CFD models refer mostly to the Design stage (Allocca et al. 2003); (P.-C. Liu et al. 2009). There are no systematic methods to explicitly link and measure the accuracy of the CFD models created at the Design, during the Operation phase of the Building Life Cycle. Also, there is little use of CFD models at the Operation phase particularly in the case of retrofit, because there is rarely a sufficient amount of instrumentation available to support robust calibration of the initial CFD model.

Research goals

A goal of the research is to develop a systematic methodology for calibration of CFD models relating to internal environments in buildings. The methodology will support the determination of the best position of sensors for controlling those environments. Such a validated virtual model with the set of well located sensors in the real building would be a robust and reliable tool for controlling and optimising internal environments.

Figure 1 describes the calibration methodology in a systematic manner. Firstly, different runs of the initial CFD model are performed; each with a finer mesh and their results are compared to achieve the grid independence. The grid independent solution is the one, in which the results do not change while increasing the number of mesh cells. The criterion of

this work determines the relative difference of the air temperatures up to a maximum 1%.

Next, the validation procedure takes place. This includes the comparison between measured and simulated air temperatures and velocities inside the room. The accuracy criteria for validation depend on the application (Chen & Srebric 2001). This study assumes the criteria for the validation of the relative difference between measured and simulated air temperatures below 2%, and air speeds below 20%.

If the model meets the specified criteria, it may be called a true representation of the real environment.

If the specified criteria are not met, the sensitivity analysis is performed. Sensitivity analysis allows for the determination of the input parameters that influence the model output the most.

The next step is the process of improving the agreement between experimental and simulated data by adjusting the high importance parameters. This step is repeated as long as the CFD model meets the criteria of being a good representation of the real environment.

A well-calibrated model will help to determine the sensors' optimal position in indoor environments.



Figure 1 Calibration methodology

EXPERIMENT

Demonstration building

The demonstrator in this research is the Nursing Library expansion to the James Hardiman Library at the National University of Ireland (NUI) in Galway, Ireland (Figure 2). It is a 3-storey building, with a gross floor area of 800 m² and has been operating since September 2009.



Figure 2 Nursing Library building at the NUI Galway campus

This building accommodates library 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 mostly an open plan area with book stacks or reading spaces. The first floor includes an open study area, closed study rooms and an air-conditioned computer room.

The building operates with the mixed mode ventilation. The Building Management System (BMS) monitors and controls internal temperatures, CO₂ concentrations and energy consumption.

The building provides researchers with good access to monitored data. As the experiments were carried out during the typical operation of the building, the research team met many challenges, including natural ventilation, solar irradiation, human occupants, etc.

Model room

The CFD simulation was performed on the internal environment of one of the study rooms in the Nursing Library building (Figure 3). Office spaces require the calculation of air velocities and temperatures to evaluate the thermal comfort of the occupants. The room chosen for the simulation is a good representation of the internal environment that demands special conditions.

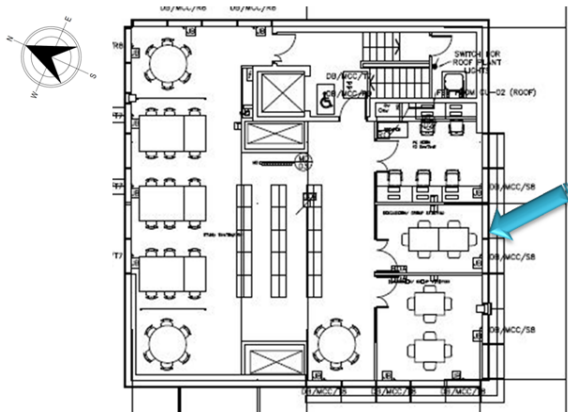


Figure 3 First floor plan of the Nursing Library with a modelled room showed

The internal dimensions of the study room are 2.70 m (D) x 4.46 m (L) x 3.10 m (H).

The naturally ventilated room consists of the following heat sources: lamps, computer, people and radiator. External wall of the room is made of glass thus allowing for solar irradiation. The wall is facing southeast direction with a surface azimuth angle of 66°. On the opposite internal wall, there are a door and a glass surface.

Outdoor measurements

The automatic weather station (Campbell Scientific 2011) enables the measurement of weather conditions at NUI Galway campus. The weather station was installed on the roof of an adjacent university building, approximately 150 m from the demonstration building. It measures air temperature (°C) and relative humidity (%), barometric pressure (mBar), wind speed (m/s) and wind direction (°), total and diffuse solar irradiance (W/m²) and rain fall (mm). The weather station provides specific boundary conditions for the CFD model.

The data logger, with a Compact Flash Memory (CFM) card, records and stores the weather data. The Ethernet module allows for downloading data via an 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 provides essential data for the CFD simulation and calibration at any time of the year.

Indoor measurements

A crucial aspect in the calibration of the CFD models is the data that represent the real environment. Those data may be acquired from the small-scale or the full-scale experiments. The small-scale models are effective and more economical than the full-scale experiments to study ventilation performance in buildings, but challenging in the matter of scaling (Chen 2009). Full-scale experiments consist of laboratory experiments and in-situ measurements. Creating the controlled laboratory environments,

mainly environmental chambers, is expensive and time consuming.

As observed in this work, it is important for the building operators to be able to gather data in the already operating indoor spaces. Those data can be then used to support the calibration of the CFD model.

Experimental data in the study to date were obtained from the Egg-Whisk Wireless Sensor Network (WSN) (NAP 2008) and wireless sensors (Onset Data Loggers 2011).

The Egg-Whisk WSN system is based on the Tyndall modular prototyping mote (B. O'Flynn et al. 2005). The platform performs environmental sensing and is specifically designed to obtain a comprehensive record of the environmental conditions at various spatiotemporal points within an indoor space. The main component of the Tyndall system prototyping mote has been developed to address a wide array of scenarios in the WSN application space (S. J. Bellis et al. 2005). The implementation consists of a variable number of layers that are stacked on top of each other in order to satisfy application requirements.

To provide wireless communications capability between sensor nodes, a transceiver/microcontroller layer is included in the Egg-Whisk mote configuration. This module incorporates a microcontroller and transceiver transmitting in the 2.4GHz ISM band. This layer is coupled with the 25 mm Multisensor Layer that measures ambient lighting levels, temperature, humidity, movement and sound. A custom designed interface board allows the 25 mm Tyndall mote system to gather additional sensory data from CO₂ and air speed sensors. Air flow sensing is accomplished using an integrated hot bulb type air speed sensor (Dantec Dynamics 2011) with the capability to measure indoor convection air speeds between 0.05 – 1 m/s with a sensitivity of 0.01 m/s.

The interface illustrated in Figure 4 is compliant with the 25 mm Tyndall mote system. The wireless and compact nature of the device enables increased mobility and flexibility allowing for ease of use in ambient indoor spaces.

To extend sensing coverage area a number of Egg-Whisk motes are deployed in tandem. In this configuration, up to five Egg-Whisk motes at a sampling frequency of 1 Hz continuously transmit sensory data. The sensor readings are gathered at a central base station connected to a personal computer. A graphical user interface (GUI) displays data in real-time and logs the sensor information to file for further analysis.

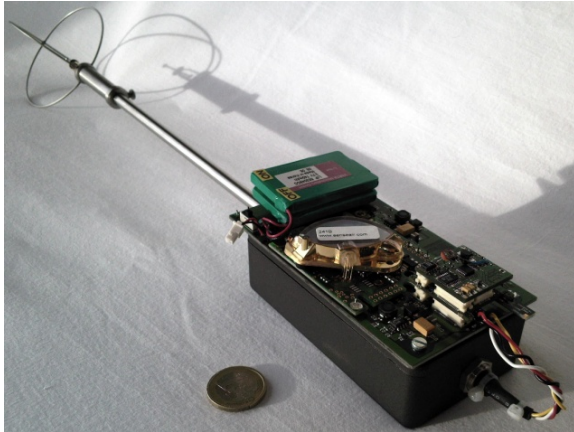


Figure 4 The fully assembled Egg-Whisk mote

For additional measurement of indoor temperatures and air speed, the Hobo U12 data loggers and air velocity sensor were used (Onset Data Loggers 2011). The air velocity sensor has a measurement range between 0.15 and 5 m/s, with the accuracy greater of 10% of reading or ± 0.05 m/s or 1% full-scale. The Hobo U12 data loggers measure temperature between -20°C and 70°C with the accuracy of $\pm 0.35^{\circ}\text{C}$ from 0° to 50°C .

Experimental setup

The experiment took place on the cloudy day of the April 10th, 2011. There were four Egg-Whisk motes, fourteen temperature sensors and one air velocity sensor available. The air entered the room through the open window and exited through the door opening. A person and the computer acted as the heat sources inside the room.

For the measurement setup, four Egg-Whisk motes (EW) measuring the air speed, were placed 0.3 m above the floor with the other temperature sensors (S) above them, as shown in Figure 5.

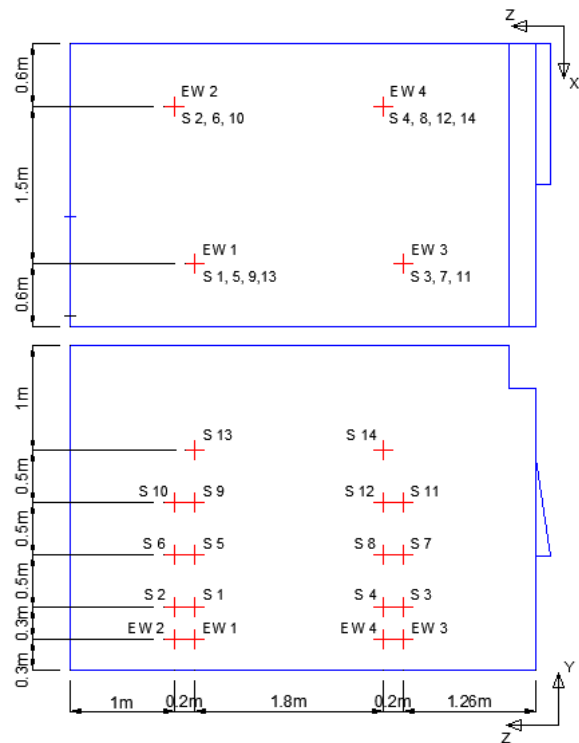


Figure 5 The measurement setup

SIMULATION

CFD model

The CFD analysis was performed using the commercial code Ansys CFX v.12.1 (ANSYS 2011). The CFD simulation predicting air temperatures and air velocities ran for the room containing personal computer and a person as the heat sources (Figure 6). For reasonable convergence of the model the Root Mean Square (RMS) residuals for mass and momentum equations were taken as 0.01%. The conservation target was set to 1% (ANSYS 2011).

The experiments were carried out in a cloudy day. The weather station recorded the average total solar irradiance of 220 W/m^2 for the period monitored. Taking this into account as well as the presence of shading outside the windows it was decided that the portion of solar irradiation getting into the room was not significant in comparison to the convection inside the room. As a result, no radiation model was included in the CFD simulation.

The mesh of the grid independent model contained approximately 600,000 unstructured elements and a steady state simulation was performed.

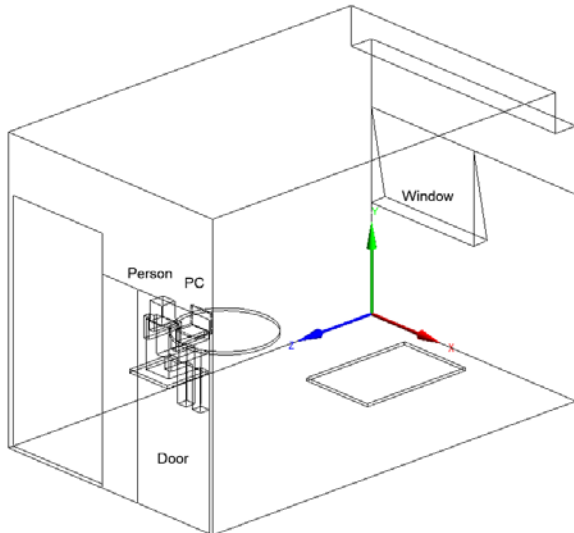


Figure 6 Geometry of the CFD model

Data obtained from the weather station (barometric pressure, outside air temperature) and the air velocity sensor at the window provided boundary conditions for the model. The open window acted as a velocity inlet with an average air speed of 0.47 m/s for the period monitored. The flag placed at the window marked out the approximate direction of the air coming into the room, which was similar to the wind direction measured by the weather station.

Figure 7 shows the comparison of the air speeds measured by the weather station and at the window of the modelled room.

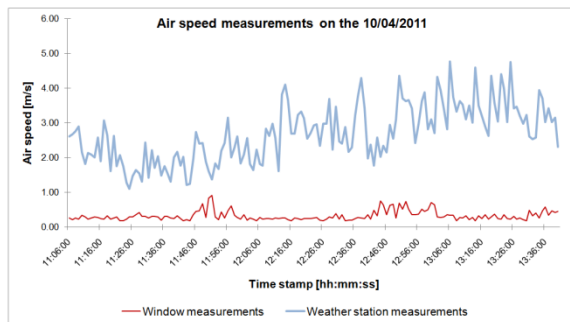


Figure 7 Comparison of the air speeds measured by the weather station and at the window

The scatter plot in the Figure 8 illustrates the correlation between the 'Weather station air speed' and 'Window air speed'. The Pearson's correlation coefficient equals to 0.024, which indicates almost zero correlation between those two sets of data. This may be due to the buildings surrounding the Nursing Library that change the speed of the air entering the room.

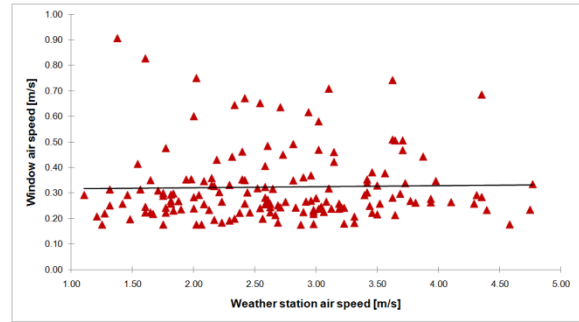


Figure 8 Correlation between the air speeds measured by the weather station and at the window

The outside temperature was 13.38 °C and window surfaces were specified with the heat transfer coefficient of 2.8 W/m²K (double-glazing) (Environment, Heritage and Local Government 2008). The door acted as a pressure opening with the temperature of 23.2 °C measured in the adjacent room. All surfaces, except inlet and openings, had the non-slip boundary conditions specified. The walls and floor of the room were assumed adiabatic. The roof panel temperature was 17.37 °C and its heat transfer coefficient was 0.2 W/m²K (Kingspan Group PLC 2011). The computer generated 30 W and the person sitting 60 W/m² (ASHRAE 2005).

The simulation ran the Standard k-ε turbulence model. This model is the most widely used turbulence model and its performance has been evaluated against many practical flows e.g. environmental flows (Tu et al. 2008).

DISCUSSION AND RESULTS ANALYSIS

The grid independent solution was identified using 18 points inside the room. The locations of the points were the same as the locations of the wireless sensors (S) and Egg-Whisk motes (EW). Air temperatures and speeds of the models with different mesh sizes were compared. The CFD model containing approximately 600,000 elements met the grid independence criterion of maximum 1% relative difference of the air temperatures.

Figure 9 shows the air velocities streamline. The air enters the room through the open window, drops down to the floor and exits through the door opening. The Egg-Whisk motes were placed close to the floor level because the biggest changes of the air velocities had been expected there.

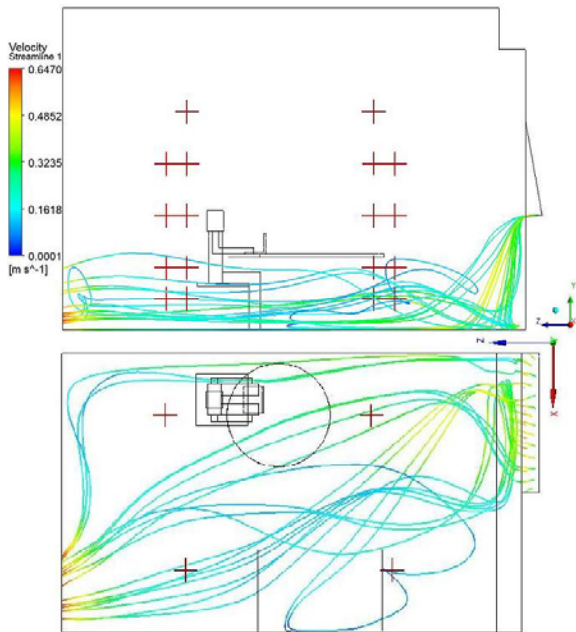


Figure 9 Air velocity streamline from the window inlet to the door opening

The CFD model was validated with the average measured data. The validation criteria allowed for the relative difference between measured and simulated air temperatures below 2%, and air speeds below 20%.

After the experiment was carried out, it was discovered that one of the wireless sensors (S8) stopped working during the measurement. Because of this, the measured and simulated air temperatures at 13 points (S1-S7, S9-S14) and air speeds at 4 points (EW1-EW4) were compared. Table 1 shows the relative difference between the measured and simulated data in specified locations.

Table 1

Comparison of average measured and simulated data

LOCATION	MEASURED	SIMULATED	RELATIVE DIFFERENCE
EW1	0.16 [m/s]	0.16 [m/s]	0.00 [%]
EW2	0.15 [m/s]	0.03 [m/s]	80.00 [%]
EW3	0.17 [m/s]	0.14 [m/s]	17.65 [%]
EW4	0.19 [m/s]	0.14 [m/s]	26.32 [%]
S1	22.21 [°C]	23.05 [°C]	3.78 [%]
S2	22.42 [°C]	22.39 [°C]	0.13 [%]
S3	22.36 [°C]	22.73 [°C]	1.65 [%]
S4	22.19 [°C]	23.16 [°C]	4.37 [%]
S5	22.54 [°C]	23.26 [°C]	3.19 [%]
S6	22.61 [°C]	23.12 [°C]	2.26 [%]
S7	22.78 [°C]	23.25 [°C]	2.06 [%]
S9	22.81 [°C]	23.20 [°C]	1.71 [%]
S10	22.85 [°C]	23.27 [°C]	1.84 [%]
S11	22.87 [°C]	23.58 [°C]	3.10 [%]
S12	22.67 [°C]	23.55 [°C]	3.88 [%]
S13	22.93 [°C]	23.65 [°C]	3.14 [%]
S14	22.80 [°C]	23.53 [°C]	3.20 [%]

The above results show, the air temperatures prediction by the base model is very close to the measurements. However, the model failed to accurately predict the air speeds. The relative difference at the location EW2 reaches 80%. The mote EW2 is placed behind the sitting person who may block the air coming from the window and may cause the discrepancy between the measured and simulated data. Nevertheless, at the other Egg-Whisk locations, the simulated air speeds are fairly close to the measurements.

The validation criteria are not met and thus the sensitivity analysis is carried out. The analysis verified how six input boundary conditions (outside air temperature, roof panel temperature, air velocity X and Z components, person heat flux and computer heat transfer) influence the model output.

The local sensitivity plots showed the impact of the single input to the output parameters (Figures 10 and 11). The value of each input parameter was changed on four occasions (base model \pm measured standard deviation and base model \pm 20%) and in each case all other input parameters, apart from the changed one, were held at their 'base model' values. This resulted in 24 different CFD models, i.e. 24 sets of results (air speeds EW1-4 and air temperatures S1-7, 9-14). The data of every input parameter, together with its results, were normalized and displayed on the graph. The slopes of the plots represented the local sensitivities of the output to the input parameters.

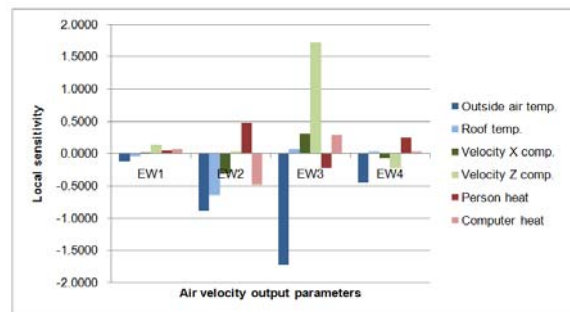


Figure 10 Local sensitivity plot of the output air speeds to six input boundary conditions

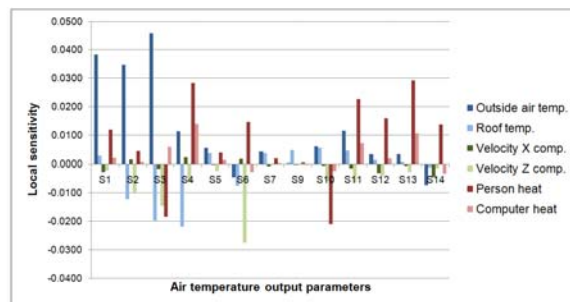


Figure 11 Local sensitivity plot of the output air temperatures to six input boundary conditions

Local sensitivity plots show clearly that the input parameters have much bigger impact on the internal air speeds than on the air temperatures. It is evident that the outside air temperature, air velocity Z component and person heat flux influence the air temperatures and speeds inside the room to the greatest extent.

At the location EW1, simulated air speed is the same as the measured value. This sensor is placed beside the door opening and thus the six boundary conditions used in the sensitivity analysis do not influence the air speed at this point.

At the location EW2, all input parameters, except the air velocity X component, influence the air speed.

The outside air temperature and air velocity Z component have the biggest impact on the air speed at the location EW3. This may be caused by the fact that the outside air entering the room turns left towards the door opening and goes through the EW3 location (Figure 9).

The air speed at the location EW4 is influenced by the outside air temperature, air velocity Z component and person heat flux. However, it is less sensitive to the input parameters than EW2 or EW3.

CONCLUSIONS AND FUTURE WORK

This paper describes the proposed systematic calibration methodology to date.

The sensitivity analysis selected the input boundary conditions that influence the internal air temperatures and air speeds the most. The high importance parameters are the outside air temperature, air velocity Z component and person heat flux.

The future work will focus on improving the agreement between experimental and simulated data by adjusting the high importance parameters. As the person heat flux has a big influence on the output data, it is planned to include the radiation model in the future simulation. This will help to achieve the CFD model that best represents the real environment.

Next, the calibrated CFD model will help in determining the best position of the physical sensors to manage internal environments that demand specific conditions. The methodology will be then tested on a different type of internal environment, i.e. mechanically ventilated space.

A reliable CFD model with the set of well located sensors in the real building would be a valuable tool for controlling and optimising internal environments.

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