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Massimo Fiorentini

University of Wollongong, massimo@uow.edu.au

Georgios Kokogiannakis

University of Wollongong, gkg@uow.edu.au

Warwick Jackson

Arens, warwick@arens.com.au

Zhenjun Ma

University of Wollongong, zhenjun@uow.edu.au

Paul Cooper

University of Wollongong, pcooper@uow.edu.au

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Keywords

evaluation, implementation, methodology, control, ventilation, strategies, natural

Disciplines

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Evaluation Methodology and Implementation for Natural Ventilation Control Strategies

Massimo Fiorentini^{1#}, Georgios Kokogiannakis², Warwick Jackson^{3*}, Zhenjun Ma⁴, Paul Cooper⁵

[#]*Sustainable Buildings Research Centre (SBRC), Faculty of Engineering and Information Sciences, University of Wollongong, New South Wales, 2522, Australia*

¹massimo@uow.edu.au

²gkg@uow.edu.au

⁴zhenjun@uow.edu.au

⁵pcooper@uow.edu.au

^{*}*ARENS International, 10 Kylie Place, Cheltenham, Victoria, 3192, Australia*

³warwick@arens.com.au

Abstract

This paper describes a methodology for evaluating the effectiveness of various control strategies for the operation of window actuators to control the indoor climate, and their implementation in a full scale case study building. In this study, the effectiveness of a control strategy is considered in terms of the capability of the controller for maintaining the indoor thermal comfort in a prescribed variable range, and its effect on the minimisation of the operational energy consumption of the building, due to a lower thermal energy demand to be met by the heating and cooling system. A model of the case study building, the award winning Team UOW Solar Decathlon house, was developed and calibrated with measured data. A control strategy was simulated using the ESP-r tool as a building simulator and the Building Control Virtual Test Bed (BCVTB) as a flexible control strategy development platform. The measured states and disturbances of the system from ESP-r are sent to BCVTB at each simulation time step, to determine the windows opening percentage at the next time step. The controller and the house response were simulated in summer conditions in Sydney, and the results from the house with only mechanical cooling, when using natural ventilation only at daytime and when using natural ventilation also at night time have been compared. The base thermal demand of the building, with only mechanical cooling, was reduced by 28.9% using natural ventilation at daytime, and by 54.9% using natural ventilation also at night time.

Keywords - Natural Ventilation, Control Systems, Thermal Comfort, Building Management Systems, Building Simulation

1. Introduction

A large proportion of the energy consumption in buildings is associated with the use of heating and cooling for maintaining the indoor air conditions

within the thermal comfort range [1,2]. To reduce the buildings' energy consumption various conventional and innovative energy efficient technologies have been studied, for example improvement of building fabric, introduction of smart shading devices, incorporation of efficient HVAC equipment, intelligent energy management systems for a more efficient delivery of the required thermal energy, etc [3].

Depending on the location, the ambient conditions could be favouring significantly the reduction of the energy consumption of the building, by simply allowing air exchange between the indoor and outdoor via operable windows or other types of operable openings. Benefits are not only limited to a reduction of the energy consumption, but also include an improvement of the indoor air quality if the building is located in a non-polluted area and a reduced risk of overheating in summer.

While Australian climates are suitable for utilising natural ventilation in buildings for most periods of the year, there are not many buildings that fully exploit the benefits from an optimised natural ventilation strategy. This is because for the cases without an automated control system for the openings the occupants do not have the time, knowledge and ability to open/close the openings in a suitable way. When an opening control system is in place the reasons are difficulty in integration and coordination of operable windows with a conventional HVAC system, and limitations of the control logic implemented to operate the mode selection and window opening, which results in poor perceived thermal comfort in the building[4]. To overcome some of the above barriers for adopting natural ventilation with controllable openings in buildings, the authors have developed a methodology to evaluate the effects of a natural ventilation control strategy on a specific building, by simulating the response of the building to a real-time controller that varies the percentage opening of the windows in specified increments.

Current building simulation software lacks flexibility in terms of implementation of advanced control strategies, and generally proposing limited options of rule-based logic or PID controllers that can be utilised for real time control of operable windows. In this paper, we introduce a virtual environment for the performance evaluation of natural ventilation control strategies and investigate their impact on fully naturally ventilated or mixed mode buildings, by using the ESP-r building simulation program [5] and the BCVTB platform [6].

The simulation approach allows the users to trial different controllers, which could then be deployed to a real building. In this paper, an example of this process is presented utilising the 'Illawarra Flame' house, a net-zero energy retrofit home that won 2013 Solar Decathlon China Competition. Section 2 describes the development of the flexible simulation testing platform for natural ventilation control strategies, while an introduction to the building used for testing the simulation development and the model calibration process is given in Section 3. Finally, Section 4 provides an

example of integration of a natural ventilation controller with the case study building, and the outcome in terms of performance of its utilisation at daytime and night time compared to a baseline of the building only mechanically conditioned.

2. Natural Ventilation Strategy Simulation Environment

ESP-r is a finite volume dynamic building simulation program that uses numerical discretisation to represent all relevant building and plant components, and simultaneous solution techniques to solve the set of equations derived for the control volumes [7]. It was selected for its flexible and complete building modelling capabilities, which include important features for this study, such as natural ventilation modelling (pressure, buoyancy driven), multi-zone airflow (via pressure network model), hybrid natural and mechanical ventilation, controlling of window openings based on zone or external conditions, displacement ventilation, mix of flow networks and CFD domains [8]. The internal coupling between the thermal, air flow and CFD domains in ESP-r has been thoroughly described in the literature [9–11] Its open source nature was also necessary to increase its control logic testing capability, by extending its integration with an external controller design software, for instance, the Building Control Virtual Test Bed (BCVTB) in this case.

The connection between ESP-r and BCVTB was previously developed and presented by Hoes *et al.* [12], where the HVAC heating and cooling delivery was managed by a Matlab MPC controller via BCVTB. A version of ESP-r with BCVTB functionality is available for download from one of the ESP-r developers' branches called '*ESP-r_BCVTB*'.

The authors have utilised these communication functions (Figure 1), and integrated them in the ESP-r code where exchange of data is needed. In this study it was necessary to extend the capabilities of the operable window controllers by modifying the source code of the ESP-r controllers that manage the airflows.

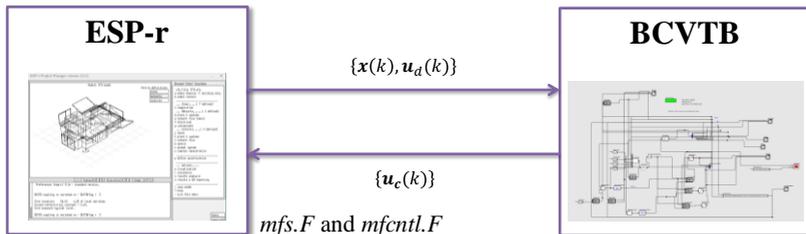


Figure 1: Natural Ventilation Strategy Simulation Environment, based on ESP-r and BCVTB. At each time step ESP-r sends states and disturbances (e.g. weather and indoor conditions) to BCVTB, which computes the window opening and sends a control action to the ESP-r model.

At each time step, the BCVTB controller is provided with an array of information from the ESP-r model, which includes the measured states $\mathbf{x}(k)$ of the system (sensed indoor temperature of the zones T_1, \dots, T_n), and the measured disturbances $\mathbf{u}_d(k)$, such as the outdoor temperature T_{out} , wind velocity V_w , the wind direction W_d , the outdoor humidity ratio HR and the time stamp. The arrays of measured states and disturbances are set up to replicate the information and measurements that a commercial natural ventilation controller would have by utilising available local sensors which can be utilised by a logic that could vary from simple to highly complex. The BCVTB controller, which can virtually implement any control logic, then responds to the ESP-r model with an array of opening percentages $\mathbf{u}_c(k)$ to be applied to each window group.

The mechanical heating and cooling delivery to each zone in this study is managed independently by the ESP-r model, and combined with the BCVTB natural ventilation controller it becomes possible to test mixed mode buildings and their performance. The scope of this platform is to highlight the integrated performance of a building in terms of thermal comfort indices and HVAC energy consumption, highlighting advantages and issues of different ventilation control logics.

3. Case study description and model calibration

This paper presents the modelling, simulation and testing of a natural ventilation control strategy on a case study building, the Team UOW “Illawarra Flame” Solar Decathlon house. The house is located at Innovation Campus, University of Wollongong, Australia. A plan view with the operable windows and their locations (positions A to E for the low level windows and H for the high level windows) and the location of the temperature sensors is presented in Figure 2.

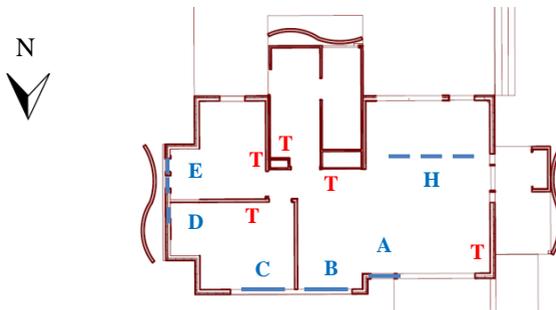


Figure 2: Illawarra Flame house – Locations of temperature sensors are shown in red. Operable windows are shown in blue.

The house has been modelled according to its design specifications in ESP-r, with a detailed flow network to simulate the air movement into the

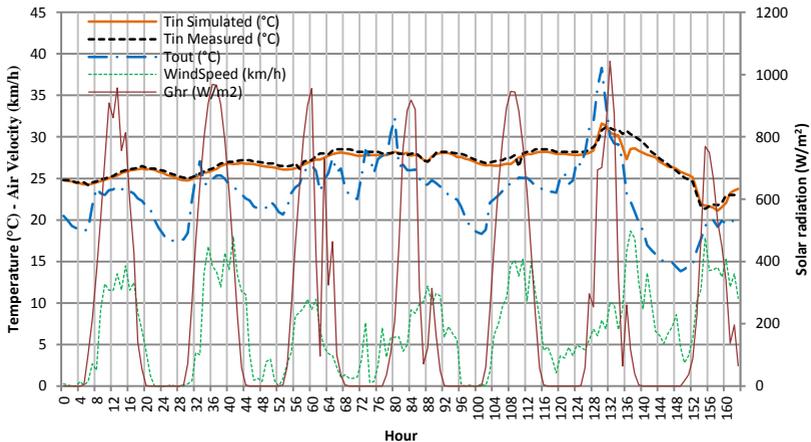
house with and without the windows open. The house and the ESP-r model are presented in Figure 3.



Figure 3: Illawarra Flame house and ESP-r model.

The model has been calibrated utilising climate data acquired via a Davis Vantage Pro II weather station installed on the Illawarra Flame house roof and the operational house data from the Clipsal Building Management and Control System (BMCS). The weather data collected from the house was used to create a weather file for the ESP-r model, which was then utilised to calculate the indoor temperature profiles of the house for the given profile of opening percentage.

The test was conducted between the 9th and 15th of January 2016, where the windows were intermittently opened (opening profile presented in Figure 4 b).



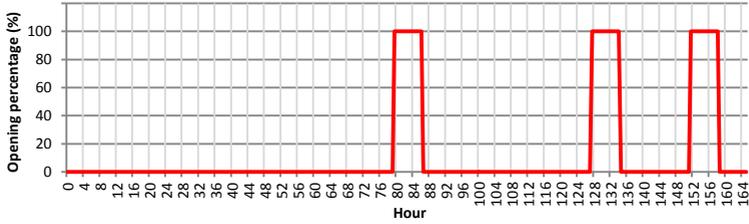


Figure 4: Illawarra Flame house calibration test: a) simulated and experimental temperature profiles and b) window opening percentage.

The windows were fully opened on three days, between 9am and 3.30pm. The comparison of the average simulated indoor temperature profile and experimental one is also presented in Figure 4, showing an adequate agreement between the two sets of data.

4. Controller Simulation and Analysis

A controller was designed to utilise the natural ventilation considering all the available information to make the decision on the window opening. Considering the current thermal comfort models [13,14], the setting on the higher and lower limits of the comfort band should consider more than a standard temperature constant and should be dynamically corrected. Some of the variables that affect the perceived comfort are available to the controller, such as the humidity ratio HR and the indoor air velocity, which in the case of natural ventilation is a function of the wind velocity and the window opening in a defined setup of the windows in a room. The higher $\overline{T_b}(k)$ and lower $\underline{T_b}(k)$ temperature boundaries, which vary at each time step k , can be therefore written as generic functions:

$$\begin{cases} \overline{T_b}(k) = f(V_w(k), W_d(k), HR(k)) \\ \underline{T_b}(k) = f(V_w(k), W_d(k), HR(k)) \end{cases} \quad (1)$$

A similar correction function to the one applied to the temperature boundaries can be applied to the temperature set-point T_{set} the controller tries to converge to:

$$T_{set}(k) = f(T_{set}^*, V_w(k), W_d(k), HR(k)) \quad (2)$$

Where T_{set}^* is a constant uncorrected set-point.

The conditions for which the natural ventilation can be operating must include the following:

$$\begin{cases} \underline{T_b}(k) \leq T_{in}(k) \leq \overline{T_b}(k) \\ \Delta T_{i-s}(k) \cdot \Delta T_{i-o}(k) \geq 0 \end{cases} \quad (3)$$

Where T_{in} is the average indoor temperature, ΔT_{i-s} is the difference between the indoor and the set-point and ΔT_{i-o} is the difference between the indoor and the outdoor temperature. The first condition of (3) defines the operative range of the natural ventilation mode, outside which mechanical heating or cooling is required. The second condition of (3) ensures that the natural ventilation is working towards cooling the building when cooling is required or heating when heating is required, not allowing the indoor temperature to diverge away from the set-point.

If the natural ventilation mode is active at the time step k , the opening percentage P of the window could be calculated as a function of any of the variables aforementioned:

$$P(k) = f(\Delta T_{i-s}(k), \Delta T_{i-o}, V_w(k), W_d(k)) \quad (4)$$

An example of the controller in operation is given in Figure 5, where the ESP-r model of the Illawarra Flame house has been simulated for 7 summer days, using the Sydney IWEC weather data between the 22nd and the 28th of February. During this simulation, the ESP-r model was given the possibility to utilise mechanical cooling with a fixed set-point at 25.5°C, and the BCVTB natural ventilation controller was set to only be active between 9am and 6pm.

It is noticeable that the boundaries of the natural ventilation band are variable with time, since they are dependent on the wind and humidity conditions. The natural ventilation set-point follows these variations accordingly. In summer conditions, observing Figure 5, it can be noticed that some days are suitable for natural ventilation and the temperature can be kept in the comfort band without the need of mechanical cooling (e.g. the first two days, from hour 0 to 48, and during the fourth and fifth day, from hour 80 to 120). In other cases, natural ventilation can help at the beginning of the day, when the outdoor temperature is below the indoor temperature, but air conditioning is required to maintain acceptable thermal comfort conditions (e.g. the third day, hours 60 to 76 and sixth day, between hours 131 and 144). In more extreme conditions, such as the last day, natural ventilation cannot be utilised and the house can only rely on air conditioning.

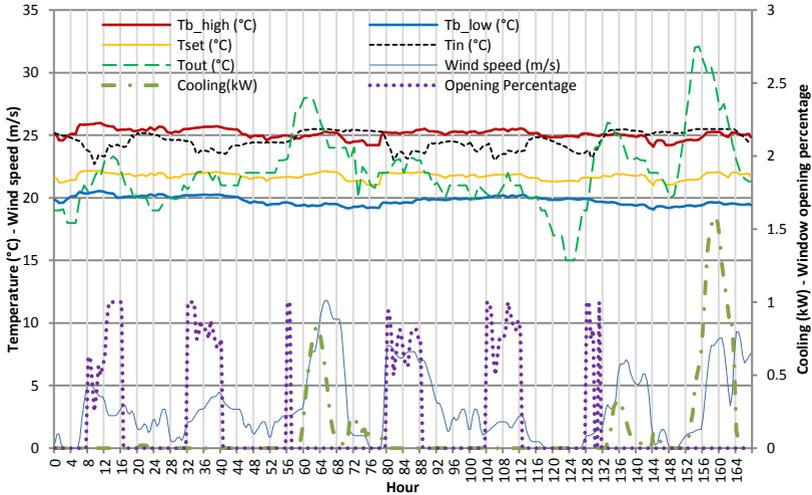


Figure 5: Natural Ventilation controller on the Illawarra Flame house ESP-r model, Sydney IWECC weather data, February

From Figure 5 it can also be noticed that the controller responds to the variation of the wind conditions and indoor, outdoor and set-point temperature, resulting in a smooth management of the internal temperature. During the test week, the controller utilised natural ventilation for 5.36 hours/day on average, out of the possible 9 hours that was set to be active. The total calculated cooling demand (thermal) for the week was 17.76kWh, or an average of 2.54kWh/day.

The same simulation was performed considering that natural ventilation is not available, and allowing the house to utilise only air conditioning to maintain indoor thermal comfort. The total calculated cooling demand for the week was equal to 25kWh, or an average of 3.57kWh/day.

A third simulation was performed on the same dataset, considering this time the possibility to open the windows also at night. In this case the total calculated cooling demand for the week was equal to 11.27kWh, or an average of 1.61kWh/day. This is an expected result, since in this dataset the house only requires cooling and the natural ventilation controller can pre-cool the thermal mass of the building when the ambient temperature is low at night time.

In summary, using a daytime natural ventilation control strategy reduced the cooling demand of the building by 28.9%, and allowing the natural ventilation to be active also at night time helped reducing the cooling demand by 54.9% compared to the case with only mechanical cooling. While these tests are referring to a specific climate and control algorithm, the

simulation platform demonstrated the possibility to benchmark virtually any control strategy on various buildings and climate conditions.

5. Conclusions

This paper presented an effective platform for testing natural ventilation control strategies, which allows a control engineer to have complete flexibility on the algorithm to be tested before deployment on a full scale building. The simulation environment is based on the building simulation software ESP-r and the control platform BCVTB, and their integration has been successfully extended to the control of window openings. The resulted development from this paper allows for any complex multi-zone and multi-sensor window control strategy to be simulated in an integrated manner with any potential building design.

The authors have calibrated an ESP-r model of a net-zero energy case study building, the Team UOW Solar Decathlon “Illawarra Flame” house, by using an experimental dataset, prior to trialling a natural ventilation control strategy combined with mechanical air conditioning. A controller for the opening percentage of windows with variable weather-dependent comfort bands and an adaptive set-point was developed and its performance evaluated. The controller has shown the capability to dynamically control the window openings across the whole building and account for the house states and weather conditions, successfully integrating its operation with the controller of the mechanical air conditioning. To quantify the effectiveness of an optimised natural ventilation control strategy, the building was simulated for a summer week in Sydney, using an IWEC weather dataset, and it was found that the energy demand for cooling could be reduced by 28.9% when using natural ventilation at daytime, and by 54.9% when setting up the natural ventilation controller to operate also at night time. The development of the control testing platform that was presented in this paper enables us to run simulations in the future for other climates within Australia and worldwide, and quantify the potential benefits from a wide range of natural ventilation control strategies.

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