The Calibration Process for a CFD Simulated Model of a Naturally Ventilated Auditorium

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Abstract

The majority of information regarding naturally ventilated CFD modelling calibration processes focus on small spaces, with ceiling heights less than 3.5m, and office type occupancy levels.

Dense occupation of a space, with multiple levels of seating in the same volume and a substantial ceiling height, leads to stratification of air temperatures. This stratification can create extreme differences in occupancy comfort within the same space.

Through analysis of the Royal Wanganui Opera House, this paper discusses the process of calibrating CFD models of naturally ventilated auditoria.

By following this calibration process, the results of CFD simulations can be quality assured and therefore enable a degree of trust for the predictions of natural ventilation strategies proposed for large spaces.

Introduction

This paper discusses the application of CFD software to predict occupant comfort in large auditoria. CFD simulates three-dimensional airflow within a space. The modelling process is documented for a case study of the Royal Wanganui Opera House, Whanganui, New Zealand, seen in Figure 1.

The Royal Wanganui Opera House (RWOH) has a history of natural ventilation design, but the many alterations since the building's construction in 1899 have seen this system become obstructed. Having recently completed seismic strengthening work, the Whanganui District Council became interested in making the internal environment more comfortable for the audience during summer performances. CFD modelling to test the likely success of new or restored interventions to the ventilation scheme has been undertaken, but before the new designs could be assessed. However, before the new designs could be evaluated, the CFD model was calibrated against a series of observations of the performance of the existing building.

Designed to ventilate without mechanical assistance, the RWOH in its existent state with an 830 person occupancy today receives numerous complaints regarding the internal air quality during performances in summer months. The building has a large dome above the main seating area with a grille vent into the ceiling space, Figure 2. From the ceiling space, original plans show two penthouse louvres located above the stage space and seating area. The large penthouse louvre over the seating area has been replaced with a curved ridge vent with a smaller aperture. The penthouse louvre over the stage is boarded up.

Figure 1: The Royal Wanganui Opera House (Wanganui Opera Week, 2016).

Within the auditorium, multiple external openings are situated at the perimeter of the high level seating space, Figure 2. These openings appear to be the main exhaust air location for the higher level seating.

Due to light and noise pollution however, these openings are shut tight during performances and, despite comfort complaints, no mechanical system has been added. An upgrade to the non-existent ventilation system in the Opera House is urgently required.

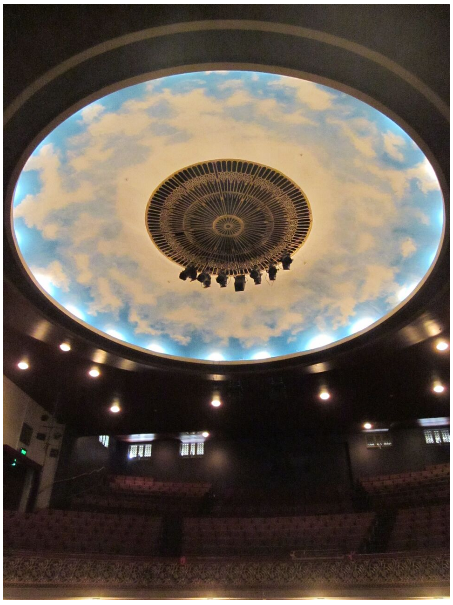

Figure 2: The Dome above the Seating Area, and External Perimeter Openings (Author's Image, 2016).

CFD

Computational Fluid Dynamics (CFD) is a type of computer analysis software that can be used for the prediction of airflow in buildings (Allard, 1998). CFD programs are based on 'Navier-Stokes' equations regarding the conservation of mass, momentum, and energy which are used to describe the motion of fluids. As a design tool, CFD is unique as it can predict the air motion at all points in the flow. CFD modelling can be used to predict temperature and velocity fields inside buildings for steady-state problems (Allard, 1998). Due to the extensive nature of the computations, CFD is normally only used to generate 'snapshots' of how the design would work at a given point in time (CIBSE, 2005). Accordingly, this software can be used to test extreme or representative conditions at a single point in time. This is different from thermal analysis programs which generally calculate an energy balance for each hour of the year. This is a key limitation of CFD, as the modelling does not take into account what is happening in the space before and after the analysis, making the specification of boundary conditions to define the existing space extremely important.

With the addition of thermal equations, CFD can predict the effects of buoyancy and the temperature field, addressing questions of stratification and local air movement (CIBSE, 2007). This is particularly important in auditoria such as RWOH, as inlet and outlet levels as well as the height of an auditorium, affect the stratification levels of air. Warm stale air collects below the ceiling; CFD can be used to test whether this air will remain above the height of the highest head and therefore out of the occupied zone (Short & Cook, 2005). Since indoor conditions of naturally ventilated spaces are difficult to predict using alternative building simulation tools the use of CFD simulation becomes necessary (Hajdukiewicz, Geron & Keane, 2013a).

Measurement Data

To calibrate the CFD simulation of the existing situation thirteen temperature and humidity recording devices were placed throughout the RWOH for a period of two weeks. Thirteen temperature-measuring devices were sufficient to give readings for every occupied space, major air inlet location, and air outlet. The devices were arranged throughout the space, with locations selected due to the expected stratification, and the predicted airflows. The type of devices installed were Testo-175-H2, which have a measurement range of 0-100% relative humidity and -20 to +70^{o}C. The devices were set to record at 5-minute intervals throughout the two-week period. The location of each device can be seen in Figure 3.

During the two-week period that the devices remained in the RWOH, several performances occurred including the local school production. The day performance of the school production was attended in order to make operational alterations to the ventilation of the space during the interval. The smoke exhaust bypass dampers above the main seating area, one of the vents above the high level seating, the roof access door above the main seating area, the sliding shutters in the roof above the stage area, and the roof access door above the stage area were opened for the second half of the performance.

Recordings from these performances, as well as when the building was empty, and real time external data from the Whanganui Weather Station provide the calibration data. Due to the one off nature of the CFD calculation, the calibration exercise was deliberately planned to test the model under as wide a range of operational and occupancy conditions as was feasible in the time available.

The recorded data of the temperature measurements taken during the two performances, in different weather conditions, show stratification in air temperature. This stratification has been recreated in a simulated CFD model of the auditorium.

To determine the accuracy of the results from the Testo devices, a calibration exercise was undertaken. The thirteen Testo devices were placed in both a warm (of approximately 30^{o}C) and cool (of approximately 4^{o}C) temperature controlled environment with the calibrated thermometer of an Assman aspirated hygrometer, which measures temperature to 0.001^{o}C. Readings from each device, as well as the hygrometer, were taken every 5 minutes for a two hour period in each climate. The results were analysed, with a correction factor noted to be applied to readings from specific devices where needed. The correction factor for each device has been taken into consideration in the calibration process of the simulated model for the space.

Simulation

3D Modelling

A combination of original plans, updated drawings from the recent seismic renovations, photographs, and measurements taken on site contributed to the 3D modelling of the RWOH in Autodesk Revit Software.

In order to import a 3D model into Autodesk CFD (the air flow assessment software) the 3D model needs to be as simple as possible. A basic Revit model has been completed of the space, maintaining volume, wall area and the shell geometry. The renovation plans of the building, the original plans, and on site measurements did not align. Without the capacity for point cloud scanning or further and more invasive on site investigation, the modelling relied heavily on the onsite measurements and photographs.

Due to the hierarchy of importance of elements and low complexity level required for a CFD model, ensuring the external shell and volume within the occupied space is as closely aligned with reality as possible is the main priority, and this has been achieved. Elements such as columns within the seating area were not modelled due to the increase in model complexity and likely minimal effect on air flow. Detail including individual seating, and balustrades were not modelled. The operable area of openings has been modelled, and each external window and door has been modelled as a slot even when closed to account for air seepage.

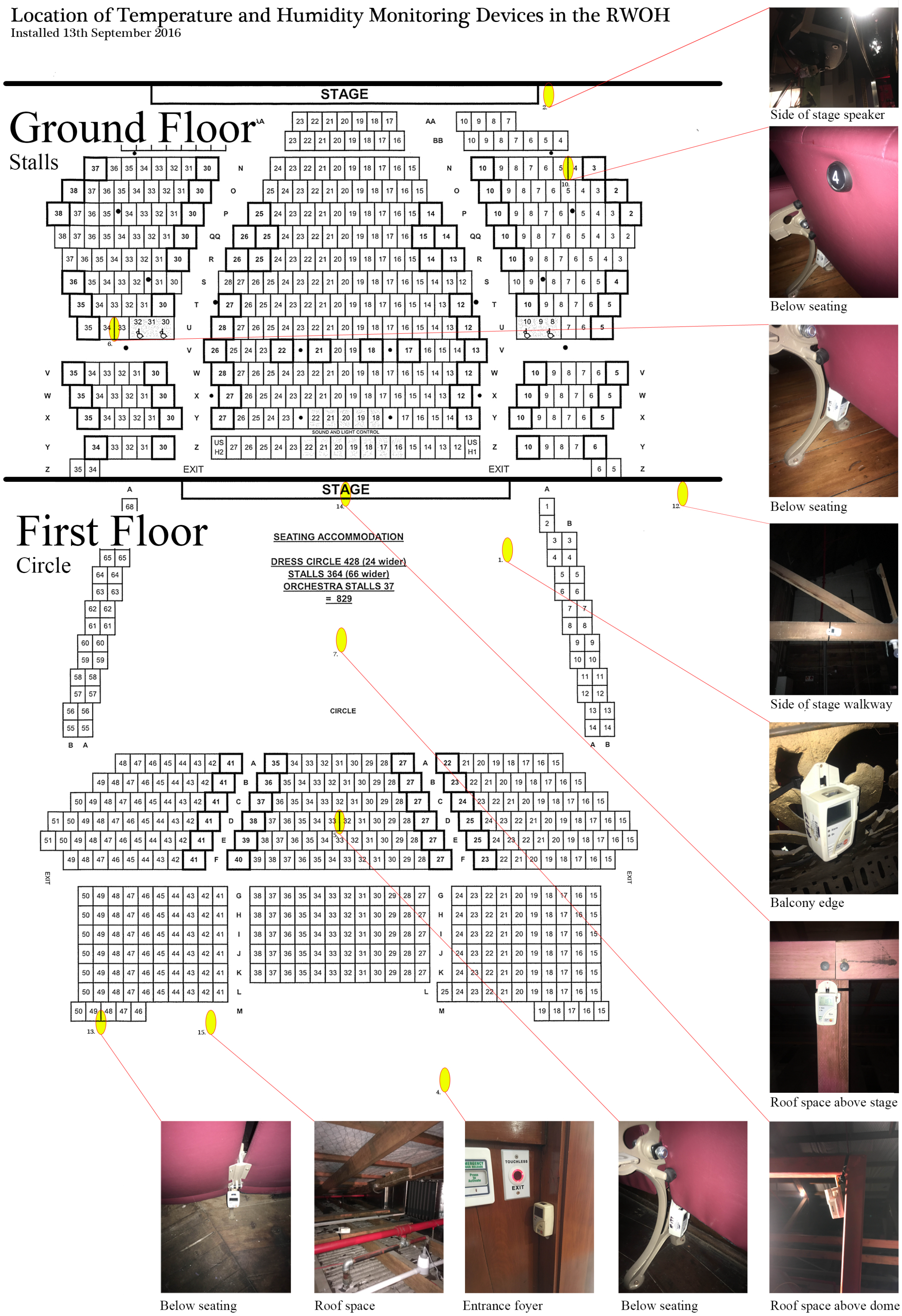

Figure 3: Location Map of the Monitoring Devices at RWOH, Measured Data Later Compared to Same Locations in CFD Simulation

Detail has been incrementally added to the model in order to more closely align the simulated result with the measured data. The dome ceiling shape needed to be made more complex in order to reflect the pattern of air movement within the space, see Figure 4.

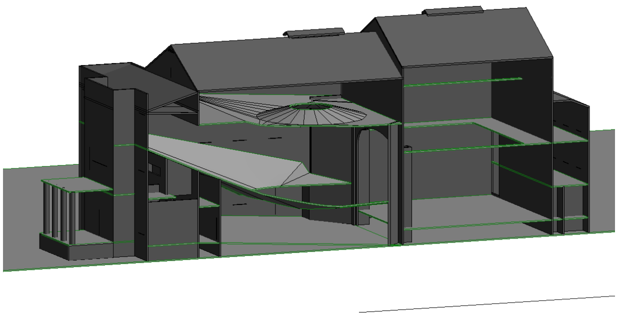

Figure 4: Longitudinal Section through the 3D Model of RWOH, Showing the Detail Required for the Dome Ceiling in order to Calibrate the CFD Analysis.

The CFD Analysis

Calibration of the CFD modelling for the RWOH consisted of two stages. First, the model of the existing building was calibrated for the building's simplest situation: an unoccupied space during temperate weather conditions. Following a series of simulated iterations, incrementally altering the boundary conditions, turbulence equations, solar radiation inputs, wind speed ratios, existing surface temperatures, assumed dimensions, and modelled materiality, the CFD outputs aligned with the measured data and fitted within the specified calibration tolerances and the limitations of the measuring devices.

The second stage of the CFD modelling involved calibrating two models of the RWOH during an occupied time, when the number of occupants and state of the openings were known. One of the models depicted the space in usual operation with the majority of the openings closed, and the second occupied model simulated the space when several high level openings had been opened. These models used the materiality, turbulence equations, solar radiation process, and assumed dimensions, that were confirmed in the stage one calibration. Following a series of simulated iterations, to determine the most effective way of modelling human heat gains within the space to decipher their influence on air temperature, the outputs from both models became aligned with the measured data and fitted within the specified calibration tolerances and the limitations of the measuring devices.

These calibrated models were a Quality Assurance exercise designed to ensure a reliable performance prediction for the following models of design changes to the building.

Calibration Tolerances

In order to compare modelled data with measured data for long term hour-by-hour simulations, statistical comparison techniques are often used to determine whether the modelled outputs are within acceptable calibration tolerances (ASHRAE, 2002).

The Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)) are the two statistical indices used to determine compliance with calibration tolerances. According to ASHRAE Guideline 14 (2002), a model is declared to be calibrated when it will produce:

MBE within ± 10%, and CV(RMSE) within ± 30%, when using hourly data, and

MBE within ± 5%, and CV(RMSE) within ± 15%, when using monthly data.

The MBE measures how closely modelled energy consumption aligns with reality. However, if some hours of modelled data exceed the measured data and other hours are less than the measured data, the errors can become offset. Consequently, the CV(RMSE) is needed to determine the proportion of variation that occurs between the modelled and measured data (ASHRAE, 2002).

The issue for the RWOH analysis is that CFD models represent a dynamic airflow as a single mass balance within a space. Calibration requires some knowledge of the 'boundary conditions'. In this case, knowledge of how much air is coming in from outside, and going out elsewhere through the fabric; how much heat gain there is in the auditorium (if there is an audience and the lighting is on for example); and what the temperatures are of the surfaces in the space. Choosing first, measurements in an empty building from a calm day so the pressures driving the air flow in and out of the building are merely temperature differences, enables a simple model calibration. Choosing then to add complexity of internal heat gains from people and lights is the next stage of calibration.

As the whole process is a series of single case studies, the ASHRAE Guideline 14 does not outline a particularly suitable process as it focuses on simulations where hundreds, if not thousands of hours of data for a year are available. What is proposed, in the absence of other independently verified guidelines, is that initially the calibration goal should be that the average deviation of all temperature sensors together is less than 10%, and that no individual measurement should be more than 30% 'out'.

Selection of the Turbulence Model

Within Autodesk Simulation CFD, the selected software package for the analysis, there are eight different turbulence models. Three of the turbulence models that can be selected to run analyses can be used to assess natural ventilation simulations, which utilise natural convection and buoyancy-driven flows. These three models, of k-epsilon, Low Re k-epsilon, and Mixing Length, were all tested for calibration one and two with the same result. For both studies, the k-epsilon turbulence model produced simulated outputs closest to the measured data in the RWOH. The use of the Mixing Length turbulence model exaggerated the external heating from the building, and the Low RE k-epsilon turbulence model is better suited to a space with less air-flow. The latter model often diverged in the calculation therefore not rendering a result.

Solar Heating Radiation Modelling

In order to run an analysis of the solar heating that occurs in the RWOH using Autodesk Simulation CFD, a separate model for each analysis needed to be conducted. The need for a separate model was due to the size requirements for the types of modelling that had to be undertaken. As per the recommendation of the Autodesk Modelling Strategy, for a combined internal and external flow natural ventilation model the shape of the modelled bounding box around the building needs to be arranged in the direction of the airflow, four times the depth of the building in the airflow orientation, and five times the width of the building in the adjacent direction, as seen in Figure 5. A solar radiation simulation cannot be undertaken in a bounding box of this size when analysing natural convection and buoyancy induced-flow, as the small volume will influence and potentially complicate the analysis.

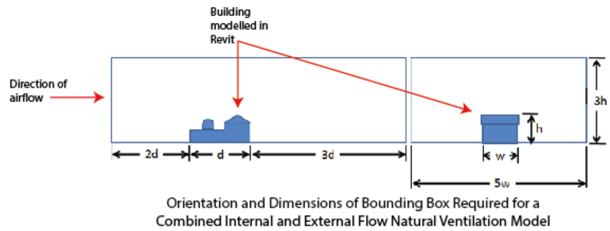

Figure 5: Natural Ventilation Model Bounding Box Requirements (adapted from Autodesk Inc, 2015)

For a solar heating model to be tested in Simulation CFD, the bounding box needs to be approximately 20 times the width and 10 times the height of the building object. The ground volume needs to be approximately 1m thick, rather than the flat plane of a natural ventilation model set up. While a natural convection study could be undertaken with the bounding box of this size, a test run of this modelling process greatly complicated the analysis, resulting in a simulation time of approximately 15 hours before the system crashed. The length of these simulations was not viable in the time frame for the number of models required. Therefore, the solar radiation simulations were undertaken separately, with their results used to inform the natural ventilation simulations.

For the solar radiation simulations, the longitude and latitude of the RWOH, as well as the time of day for each individual simulation was entered into the analysis. The greater site of the RWOH including surrounding buildings, the adjacent hill, and the colour of the exterior surfaces also needed to be modelled due to solar shading and reflectance. The white colour of the building is beneficial in reducing the effect of solar radiation, as white surfaces, and shiny surfaces, reflect a far greater percentage of the sun's energy. The resulting internal temperatures from the solar radiation calculations were applied as boundary conditions to the natural convection simulation. From this analysis, the solar heating radiation had very little effect on the air temperature results of the CFD modelling.

Figure 6. View of the RWOH from the adjacent hill, showing the surrounding solar shading, and white colour of the building (Author's image).

Wind Input

The wind speed curves utilised for the two calibration models were created by using data recorded at the Whanganui Airport weather station (NIWA, 2016). The wind speeds recorded were extrapolated using an atmospheric turbulent boundary layer Power Law to correct the speeds for the more sheltered central city location (Gandemer & Guyot, 1976). In order to input the wind on site into the Simulation CFD model, the extrapolated wind speeds were then formed into a transient piecewise linear curve to account for the different wind speeds at different heights above the ground plane. Guidance from AS/NZS 1170.2:2011 Structural Design actions: Wind Actions, was used to create the piecewise linear curve in order to interpolate wind speed values above and below the 10m height at which the Airport weather station data is collected.

The Category 3 terrain/height multiplier, for terrain with numerous closely spaced obstructions 3m to 5m high, was selected in order to create a linear curve.

The most prominent wind direction in Whanganui throughout the year, and during summer months, is 290 degrees of West-North-West. Thus for greatest benefit of wind driven natural ventilation, the inlets should ideally be on the West-North-West side of the RWOH, when facing the entrance to the building this length is the right hand side stretching from the front entrance to the back of stage.

Boundary Conditions

The bounding box requires the boundary condition of slip/symmetry to be applied to the inner surface of the 'walls', parallel to the wind direction, and 'roof' elements in order not to influence the external air flow. The void surface of the open section of the bounding box in the direction of airflow requires the velocity boundary condition to be applied, as well as the air temperature. The axis is identified to select the direction of the velocity, and its magnitude is imported as a piecewise linear curve in m/s for corresponding heights above the ground plane in the form of a csv file. The wind inputs in this file are extrapolated from airport data, as described above. The final side of the bounding box, adjacent to the direction of velocity, has a pressure of 0 applied to it, to ensure no interference with the wind direction.

The locations where the audience, performers and internal heat gains are located have a boundary condition of total heat generation in watts applied to them. The total heat generation of humans has been calculated from the occupancy numbers in each scenario and the metabolic rate of a human seated quietly, of 100W (ISO, 2005). The internal heat gains from performers were assumed to be 250W per person, the metabolic rate of moderate dancing, and the lighting and heaters (on for calibration two) used in the space were modelled from a combination of recorded unit information and assumptions, then incrementally altered to align the calibration with the measured data outputs. The seating information of 823 total, with 428 in the dress circle, 353 in the stalls, and 37 in the orchestra stalls, as well as the lighting equipment information for the front of house and stage space was taken from information recorded in May 2010.

For calibration one, the measured data showed the internal temperatures at low level to be less than the external measured temperature. Due to the steady state of CFD a boundary condition of temperature needs to be applied to the surface of the low level seating in order to account for the initial temperature of the space being lower than the source air for the simulation. As cold air is denser and therefore heavier, if there is only a low air flow through a space the cold air is able to drop and stagnate at low level. As the space was unoccupied for this calibration, all openings remained closed and there were no internal heat gains for the duration of the day, resulting in the cold air at the average temperature from the past 24 hours, remaining uninfluenced by changing external conditions. This is a useful discovery as a characteristic of the space, and may enable a cooling strategy for summer months.

Modelling Materiality

Due to the number of iterations, and in order to reduce the simulation time, the complexity of the materiality modelling was kept to the minimum level required to calibrate the model. For the solar modelling, external surfaces were modelled as paint white, however for the natural ventilation models timber construction was used throughout the space. Chairs, balustrades, curtains, and other soft elements were not modelled in Revit, and their materiality was not defined in CFD. For the occupied scenarios, the surface planes creating heat generation of internal heat gains including the audience, were given the materiality of humans, a feature within Simulation CFD. The external ground plane was modelled with the materiality of concrete, in order to replicate the roughness of the external environment surface. Air volumes within the space were modelled with fluid air materiality, with a variable environment, allowing the temperature of the air volumes to experience natural convection and stratify according to the surrounding surface temperatures.

Mesh Sizing & Solver Settings

Once the geometry is complete, the boundary conditions applied, and materiality selected, the model can be simulated using the CFD solver. Before the solver can start, a calculation mesh needs to be applied to all surfaces of the model. For this analysis the default automatic mesh sizing was utilised, as complexity of mesh extends the simulation time. A trial of a finer mesh was undertaken on the calibrated unoccupied space model. The simulation had a ten times greater run time and showed little deviation in results from the automated mesh sizing, still remaining within the calibration tolerances. Therefore automated mesh sizing was used for the remainder of the simulations.

Several settings are required for the solver to operate, including the selected turbulence model of k-epsilon. Numerous different settings including flow, heat transfer, radiation, gravity, earth direction, and auto forced convection were all trialled to review their influence on the simulation and select the settings, which were required to closely align the simulation outputs with the measured data. Flow and Heat Transfer were required, Gravity with an Earth Direction of 0, 0,-1 was selected, and Radiation allowed the heat generation boundary conditions to influence the air temperatures.

The Calibration Simulations

The first calibration undertaken was a steady state model from the unoccupied space at 6pm on the 26th of September. The model consisted of the simplest state of the building.

No internal heat gains were assumed at this time, and all operable openings were closed. Openings modelled were the permanent ridge vent above the seating space, and seepage through the doors and windows.

Using the measured data from the devices, which were placed throughout the RWOH, as well as NIWA data for external weather conditions of wind speed and temperature, the modelling process involved a pre calibration approach. Inputting the external temperature and extrapolated wind speed, utilising simple materiality, inputting surface temperatures of the lower levels of the space, and undertaking a solar radiation assessment, allowed the CFD model to align closely with the recorded data. Each simulated point was within 10 percent of the measured data point, and therefore after several iterations of alternating settings the most plausible calibrated model was determined.

The second stage of the calibration process involved two steady state models of the occupied space during a school production day performance at the times of 10.45am and 11.45am, when the number of occupants, 365, state of the openings, and external temperatures and wind speeds were all known.

For this set of measured data, the devices were in the

RWOH for an extended period before and after the school production day performance. The show began at 10am; the state of the openings was recorded at this time and used to inform the modelled state of the building at 10.45am. At 11am, during the performance's interval, several openings in the space were operated. The consequent state of the building at 11.45am during the second half of the performance was modelled including the following additional openings:

- The door at the north east of the roof void above stage, 475mm wide x 690mm high opening area,
- Sliders opened to ridge vent in roof void above stage,
- The door at the north east of the roof void above seating space, 785mm wide x 980mm high opening area,
- Smoke exhaust butterfly dampers in roof void above seating space set to open position on magnets,
- Operable vents in fan ducting at the north east end of roof void above upper dress circle, two openings of 450mm x 450mm.

The addition of the openings to the space, combined with the increased external temperature of 11.45am compared with 10.45am, showed an influence in the stratification of air within the auditorium. The CFD analysis with the openings operated showed a diversion of the levels of stratification of air in the space higher, however the airflow within the space did not greatly increase. This was assumed to be due to the lack of additional inlets at low level.

These models also involved pre-calibration to align the boundary conditions with the measured data set. The heat transfer between the occupied elements and the air was initially unsuccessful, and the type of heat generation as well as the heat transfer settings of the models needed to be altered. With these alterations the models were able to align with the measured data, to within the set calibration tolerances, for all thirteen points at both times assessed. The lessons learnt, regarding the most effective way to model the heat generated from internal heat gains in order to influence the air temperature, have been carried through to the redesign CFD models.

Figure 7 shows the calibrated model of the occupied space at 10.45am, before the openings were operated. The stratification of air seen in the model aligned with measured data points. This modelling also highlighted areas of concern for potential overheating in summer months to come.

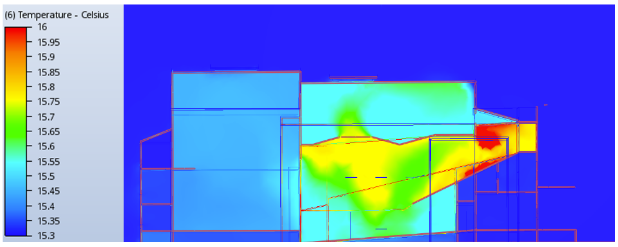

Figure 7. The Calibrated Occupied Space Model at 10.45am on the 20th September 2016.

Discussion and Analysis

Simulation CFD displays results in an image format, rather than a quantitative output. Accordingly, in order to assess the results, a grid of 1m by 1m was applied to a 2D plane in Simulation CFD, and data was extracted in the form of a numerical CSV file. The CSV files were then imported into Microsoft Excel, and formatted to represent the length and width of the plane for which they were calculated. This allowed the architecture of the building's cross and longitudinal sections to be overlaid to each set of data in Excel. The overlaid images allow the locations of the measuring devices to be located to within a 1m^2 grid point between the measured and simulated temperature reading, as shown in Figure 8 for the building in an unoccupied state during temperate external conditions. A 2D plane of data was exported from Simulation CFD to represent each of the thirteen measuring device locations. The technique of formatting the data in Excel was used to locate the measured data points in order to assess calibration against numerical values, rather than assessment undertaken by using the graduated image of the model within Simulation CFD. The selected simulated data point was assessed as to whether it lay within 10% of the measured data point. Incremental changes were made to the models as described above until each data point remained within the calibration tolerances.

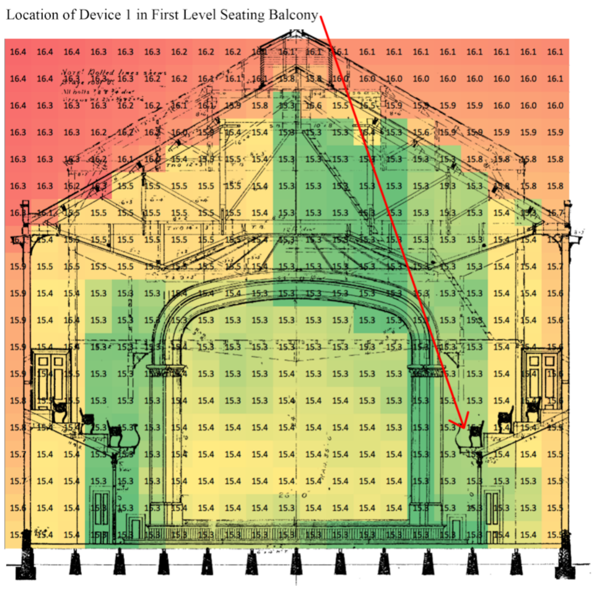

Figure 8. A Cross Section of the Exported Data from Simulation CFD for an unoccupied state, with an Overlay of the Architecture and Device 1 Location.

Conclusion

The ability of a CFD model to reproduce the stratified airflow within the space has been assessed by comparing predicted to measured temperatures. The recorded data of the temperature measurements taken during the two performances, in different weather conditions, show stratification in air temperature. This stratification has been recreated in a simulated CFD model of the RWOH.

While CFD modelling is a tool used to assess airflow within a space, the movement of air and quantity incoming from the external environment also dictate temperature within an unconditioned internal environment. Measuring airflow directly is possible with laser Doppler anemometry, however the cost of and lack of accessibility to this equipment is a major limitation. As an alternative, temperature-measuring devices were available with the ability to record information in different locations throughout the space simultaneously and over a long period, allowing for a more comprehensive and three-dimensional picture of the space to be analysed. Therefore, a method of calibrating utilising temperatures was selected.

While this study is based on CFD analysis, ultimately the measure of success for subsequent design alterations is the comfort of people within the RWOH. Accordingly, calibrating the CFD modelling by using temperature readings from within this space relates directly to the purpose of the CFD modelling process, and allows calibration utilising a measure that is more feasible to assess than air movement.

The value of the calibrated CFD models is their potential for future application, examining the feasibility of reintroducing natural ventilation to modern buildings. By following this calibration process, the results of the CFD simulations can be quality assured and therefore enable a degree of trust for upcoming iterations. These models can also be used to predict occupancy comfort for any proposed reintroduction of a natural ventilation system to the RWOH. CFD has been used to test additional inlets and outlets for the RWOH in a summer scenario, and recommendations from this modelling are under construction. This creates a further degree of excitement for the CFD process, as physical application is underway and the outcome in reality can be assessed against the design change simulations.

Because the temperature recordings and subsequent calibration exercise was undertaken during spring rather than summer, when comfort issues occur, there is a degree of uncertainty as to whether the CFD modelling will accurately reflect the summer scenario. Due to the calibration tolerances allowed for the spring scenario modelling, the margin of error for the summer scenarios has been limited. The temperature recording devices are due to be placed back in the RWOH in early 2017, to verify the summer scenario modelling and implemented design changes. This process will further allow conclusions regarding the extent of data needed to create a reliable simulation. The fewer calibration scenarios needed to ensure a trustworthy model within 10% of reality, increases the feasibility of replicating this CFD process for other buildings.

A further outcome of this process is to enable investigation of whether the RWOH's original natural ventilation system with penthouse louvres might have been successful, and if so there is historical as well as functional value in their reinstatement.

The same process applied to the RWOH can be replicated for many other large-scale buildings. Successful naturally ventilated spaces not only have the ability to provide healthy and comfortable indoor conditions, but also have the potential to reduce energy consumption. The value of the calibration process for large-scale CFD models is its potential for future application, examining the feasibility of reintroducing natural ventilation to modern buildings that house large crowds.

Acknowledgement

Many thanks must be given to the Whanganui District Council for advocating the analysis of the Royal Wanganui Opera House to enable its future as a naturally ventilated building.

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