Theoretical Modeling and Estimation of CO$_2$ Concentration at CIRS Auditorium

by

Vivek Vasudevan Shankar

&

Sheikh Mohammad Samiur Rahman

under the supervision of

Prof. Karen Bartlett

and sponsored by

James Montgomery and Stefan Storey

A REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR SUSTAINABLE BUILDING SCIENCE PROGRAM -PROJECT COURSE (CIVIL 592A)

THE UNIVERSITY OF BRITISH COLUMBIA (Vancouver)

April 2013
# Table of Contents

Table of Contents ................................................. ii

Acknowledgements ................................................. iii

1 Introduction .................................................. 1
   1.1 The CIRS auditorium ........................................ 3
   1.2 Background ................................................ 4

2 Methodology .................................................. 5
   2.1 Theoretical model ........................................... 5
   2.2 Calibration of the airflow rate sensors ....................... 8
   2.3 Infiltration rate ............................................ 10
   2.4 CFD Model Setup ........................................... 12

3 Results and discussion ....................................... 15

4 Conclusion .................................................. 20
   4.1 Limitations of the current model ............................ 20

Bibliography .................................................. 21

Appendices

A Air-flow measurement ........................................ 22

B Zonal division ............................................... 23

C Zonal boundary parameters ................................. 25
Acknowledgements

We would like to thank our project coordinator, Prof. Bartlett for supporting us throughout the project and providing us with the measuring equipment. We would also like to extend our special thanks to James and Stefan for extending generous help and valuable advice through the course of the project.
Chapter 1

Introduction

During the twenty first century, HVAC systems have earned their place among one of the crucial components, amongst the construction of habitable architectural structures, which have to be integrated within each structure. With the growing awareness of the need to maintain healthy air quality within the habitable zone of the structures, several control strategies for HVAC systems and a wide range of IAQ (Indoor Air Quality) standards have been devised by different regional governing bodies such as ASHRAE. Maintaining these standards while operating the ventilation system means the introduction of adequate fresh/outside air into the occupied zone through the supply air vents.

The introduction of fresh air could be controlled efficiently through dampers, although the energy required to condition the outside air could prove to be highly energy intensive. Moreover, with the increasing cost of electricity and the threat of global warming due to CO\textsubscript{2} emissions resulting from burning of fossil fuels, there are increasing demands of energy conservation in both the residential and commercial buildings. It is estimated that approximately 45-50\% of a building’s energy is consumed by the HVAC system. Therefore upon realizing these facts, governments are implementing standards and incentives to encourage energy efficient HVAC systems in buildings.

Ventilation systems in North America are usually designed to comply with the requirements set by ASHRAE Standard 62.1 2004-2010 [2], which intends to dilute the contaminants generated by occupants and building related sources. However, in order to meet those standards typical ventilation systems are designed to operate based on 100\% occupancy level of the space at all times. This strategy does successfully provide adequate fresh air supply but leads to excessive energy consumption due to the fact that, such spaces are usually not occupied to maximum capacity thus leading to over ventilating the space. However, to prevent such inefficient systems, innovative ventilation strategies have been developed, such as the CO\textsubscript{2}-based DCV (Demand Control Ventilations) system which operates by monitoring the CO\textsubscript{2} con-
Chapter 1. Introduction

Figure 1.1: Figure showing the variation in outside intake air percentage based on occupancy level [1].

centration level within the space and thus setting the outside air damper positions to an optimum level. A typical example of DCV strategy being implemented on a multi-storey building is displayed on Figure 1.1.

The DCV strategy has the potential to lower the energy use by preventing over ventilation of the space and is mostly suitable for spaces with highly variable occupancy. But when the DCV strategy is applied through the feedback of CO$_2$ concentration at fixed positions within the space, it usually leads to poor quality of air inside certain zones of relatively larger spaces. Implementing an effective DCV system is not simple, as it is required to identify the concentration of CO$_2$ within each zone with certain accuracy. Thus, the main aim of this paper is to propose a methodology to successfully model the CO$_2$ concentration within a large space with highly variable occupancy. The Auditorium at the Centre for Interactive Research on Sustainability (CIRS) building of the University of British Columbia (UBC) seemed to be the ideal space for carrying out further analysis. Detailed specifications for the auditorium are illustrated in the following sections.
1.1 The CIRS auditorium

The CIRS Auditorium is integrated within the CIRS (Centre for Interactive Research on Sustainability) building at UBC (Figure 1.2). Besides its complex architectural design, the space is equipped with state-of-the-art technology to maximize the comfort of its occupants and has a sitting capacity for approximately two hundred occupants. The supply air from the AHU (Air handling unit) is introduced into the space through more than 200 vents spread all over the floor area of the auditorium. There are six return vents located at the front and the back of the auditorium (See appendix A). The total volume of the space is estimated up to 2800m$^3$ and the access to the space is provided through two double door entrances.

![Figure 1.2: Panorama view of the CIRS Auditorium.](image)

The air quality of the space is constantly tracked through four different CO$_2$ sensors located at each corner of the auditorium and airflow rate sensors located within the ducts to monitor the supply and exhaust air-flow rates. However, the majority of the airflow rate sensors are uncalibrated. Currently the auditorium is utilized to hold regular lectures for different courses in addition to seminars and events. Although, the auditorium is operated from 8am till 5pm regularly during the weekdays, the occupancy level varies considerably during its operational hours. Besides mechanical ventilation, the auditorium is also ventilated through natural ventilation, which however remains non-operational most of the time. The mechanical ventilation system within the space is operated at a 50% fan power rating for the supply air despite of the varying occupancy. This indicates the potential for energy saving opportunities if the introduction of fresh air could efficiently be controlled to maintain the desired balance between energy efficiency and CO$_2$ concentration level.
1.2 Background

When properly applied in spaces where occupancies vary below design occupancy, CO₂ based DCV can reduce unnecessary over ventilation while implementing target per person ventilation rates. Ventilation systems can use occupancy as an indicator of CO₂ concentration to modulate ventilation below the maximum total outdoor air intake rate while still maintaining the required ventilation rate per person [2]. Shendell [3] acknowledged the energy saving possibilities by implementing CO₂ based demand control ventilation when properly applied to a space. Their work has affirmed that CO₂-based demand control ventilations system comply with standards set by ASHRAE Standard 62. Moreover, the CO₂-based DCV strategy was considered to be improving the comfort level for the occupants in terms of humidity, unknown leakages and indoor air quality level within the space by allowing greater control over outdoor air intake. They also demonstrated that the CO₂ logged data over time can be used to estimate ventilation/infiltration rate, which is one of the crucial part of the current analysis.

Lawrence and Braun [4, 5] present a method that allows a reasonable estimate of the actual ventilation rate required per person being delivered to the space based on the predicted CO₂ concentration level. Their analysis was conducted on three different spaces with highly variant occupancy levels. The internal volumes of the spaces were within the range of 200m³ to 3500m³, each with variation of occupants at different time of the day and with distinct building types. The approach undertaken in buildings [4] involved modelling CO₂ concentration by considering the entire space as a single zone during quasi static modelling and multi-zone during transient modelling. In the absence of physically measured data required for multi-zone CO₂ concentration modelling, the paper presents a guideline to setup the computational fluid dynamics models required to evaluate the base line data. However, Lawrence and Braun [4] have concluded through their analysis that the simulated CO₂ concentration results were obtained through transient and quasi-static modelling which were quite similer to each other and therefore the need of undertaking complex transient models for evaluating CO₂ concentration was not necessary.
Chapter 2

Methodology

The work in this chapter covers the development of the theoretical model, calibration of flow sensors and study of flow through CFD.

2.1 Theoretical model

A multi-zone transient model with inter-zonal airflow was developed for modem
2.1. Theoretical model

elling the concentration of CO$_2$ at CIRS in the lines the work by Lawrence and Braun [4]. This model evaluates the variation of CO$_2$ across time in all the different zones. However, spatially, the concentration of CO$_2$ is assumed to be a constant in each zone. The auditorium was divided into seven zones based on the concentration of CO$_2$ that is expected from the auditorium as shown in figure 2.1. In the figure 2.1 the height of the auditorium is divided into two regions (a) and (b). The darker colour shades represent a higher concentration of CO$_2$ in the zones. Zones 4 and 6 would have the highest levels of CO$_2$ concentration since it is the region of CO$_2$ generation by the occupants. Regions 5 and 7 would have lesser concentration than 4 and 6 due to proper mixing of air. Regions 2 and 3 would have low concentration levels due to infiltration of fresh air from the doors.

Once the auditorium was divided onto zones, mass balance equation was written for each zone. A flow structure is assumed as shown in figure 2.2. In the figure shown, there is infiltration through the doors into zones 4 and 6. The supply air inlets are at zones 4 and 6. Regions 5 and 7 are zones where the return vents are located.

The mass balance equations for zones 1-7 are described in equations 2.1 to 2.7

\[
V_1 \frac{\partial C_1}{\partial t} = \dot{V}_{14} (C_4 - C_1) + \dot{V}_{15} (C_5 - C_1) + \dot{V}_{16} (C_6 - C_1) + \dot{V}_{17} (C_7 - C_1)
\]  
\hspace{2cm} (2.1)

\[
V_2 \frac{\partial C_2}{\partial t} = \dot{V}_{\text{inf}1} (C_{\text{inf}} - C_2) + \dot{V}_{24} (C_4 - C_2) + \dot{V}_{25} (C_5 - C_2)
\]  
\hspace{2cm} (2.2)

\[
V_3 \frac{\partial C_3}{\partial t} = \dot{V}_{\text{inf}2} (C_{\text{inf}} - C_3) + \dot{V}_{36} (C_6 - C_3) + \dot{V}_{37} (C_7 - C_3)
\]  
\hspace{2cm} (2.3)

\[
V_4 \frac{\partial C_4}{\partial t} = \dot{V}_{24} (C_2 - C_4) + \dot{V}_{45} (C_5 - C_4) + \dot{V}_{46} (C_6 - C_4) + \dot{V}_{14} (C_1 - C_4)
\]
\[+ \dot{V}_{s1} \left( R_{OA} C_{OA} + (1 - R_{OA}) \left( \frac{C_5 + C_7}{2} \right) - C_4 \right) + N_{p1} G
\]  
\hspace{2cm} (2.4)
Figure 2.2: Zoning of the CIRS Auditorium based on concentration.

\[ V_5 \frac{\partial C_5}{\partial t} = \dot{V}_{25} (C_2 - C_5) + \dot{V}_{45} (C_4 - C_5) + \dot{V}_{57} (C_7 - C_5) + \dot{V}_{15} (C_1 - C_5) \]  \hspace{1cm} (2.5)

\[ V_6 \frac{\partial C_6}{\partial t} = \dot{V}_{36} (C_3 - C_6) + \dot{V}_{67} (C_7 - C_6) + \dot{V}_{46} (C_4 - C_6) + \dot{V}_{16} (C_1 - C_6) + \dot{V}_{s2} \left( R_{OA} C_{OA} + (1 - R_{OA}) \left( \frac{C_5 + C_7}{2} \right) - C_6 \right) + N_{p2}G \]  \hspace{1cm} (2.6)

\[ V_7 \frac{\partial C_7}{\partial t} = \dot{V}_{37} (C_3 - C_7) + \dot{V}_{67} (C_6 - C_7) + \dot{V}_{57} (C_5 - C_7) + \dot{V}_{17} (C_1 - C_7) \]  \hspace{1cm} (2.7)
2.2 Calibration of the airflow rate sensors

In the equations shown, \( C \) represents the concentration of \( \text{CO}_2 \), \( V \) the total volume of the zone, \( \dot{V} \) the internal flow rate, \( R \) the damper ratio, \( OA \) meaning outside air, \( N \) the number of occupants and \( G \) the rate of generation of \( \text{CO}_2 \).

The auditorium usually operates at 50% damper configuration—this means the supply air is a mixture of 50% fresh air and 50% recirculated air. In order to study the effect of the damper configuration, variable \( R_{OA} \) is introduced. For recirculated air, the average of concentration of \( \text{CO}_2 \) in the zones having the return vents (zones 5 and 7) are taken into consideration as shown in equations 2.4 and 2.6. In order to study the effect of population distribution on the left and right side of the auditorium, variables \( N_{p1} \) and \( N_{p2} \) are introduced.

2.2 Calibration of the airflow rate sensors

The CIRS auditorium has a central monitoring system that records feedback from various sensors. However, the sensors that measure the supply airflow rate were found to be uncalibrated. It was determined that it was necessary to calibrate the airflow sensors in order to accurately model the \( \text{CO}_2 \) concentration at CIRS. In order to calibrate the sensor, the total volume flow rates physically measured from all the supply vents would have to be interpolated to the volume flow rate data recorded by the sensors. This however proved to be an issue since the numbers of supply vents were found to be over 200 in number. The auditorium was equipped with six return vents, two return vents placed at the front of the auditorium, which were approximately 4m high from the ground level and had an opening of approximately 1.22m by 0.91m. The remaining four return vents were placed at the back of the auditorium at a height of 2.5m and each had an opening dimension of approximately 0.61m by 0.61m. The volume flow rate entering the auditorium equals the volume flow rate leaving it. The number of return vents being just four, it was decided that the volume flow rate would be measured from them.

The measurement the airflow rates through each of the return vents required specialized instruments capable of capturing the entire airflow rate through each vent opening with minimal leakage and minimal resistance to airflow through the return vents. Therefore, the instrument called Accubalance [6] was used to take the measurements. The Accubalance was fitted with a hood of opening 2”X2” and the handle of the instrument was attached with two extendable rods in order to lift the entire assembly of the instrument up to the required height. While taking
2.2. Calibration of the airflow rate sensors

Table 2.1: Table showing the measured and recorded air flow rates.

<table>
<thead>
<tr>
<th>Vent no. (Left-Right)</th>
<th>Flow-rate (CFM) measured</th>
<th>Total (CFM)</th>
<th>Flow-rate (CFM) sensor</th>
<th>Fan speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>426</td>
<td></td>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>2</td>
<td>370</td>
<td></td>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>3</td>
<td>304</td>
<td></td>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>4</td>
<td>655</td>
<td>1755</td>
<td>2154</td>
<td>30%</td>
</tr>
<tr>
<td>1</td>
<td>715</td>
<td></td>
<td></td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>565</td>
<td></td>
<td></td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>545</td>
<td></td>
<td></td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>1040</td>
<td>2865</td>
<td>3197</td>
<td>50%</td>
</tr>
<tr>
<td>1</td>
<td>770</td>
<td></td>
<td></td>
<td>60%</td>
</tr>
<tr>
<td>2</td>
<td>675</td>
<td></td>
<td></td>
<td>60%</td>
</tr>
<tr>
<td>3</td>
<td>615</td>
<td></td>
<td></td>
<td>60%</td>
</tr>
<tr>
<td>4</td>
<td>1240</td>
<td>3300</td>
<td>3637</td>
<td>60%</td>
</tr>
<tr>
<td>1</td>
<td>930</td>
<td></td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>2</td>
<td>775</td>
<td></td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>3</td>
<td>700</td>
<td></td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>4</td>
<td>1370</td>
<td>3775</td>
<td>4110</td>
<td>70%</td>
</tr>
</tbody>
</table>

the measurements the entire assembly of the instrument was hoisted using three extendable rods to maintain the instrument vertically aligned as shown in figure A.2 under appendix A, illustrating the entire assembly of the equipment and the hoisting procedure. The return vents located at the front were identified as non-operational (figure A.1), and the airflow rates through them were experimentally verified to be zero CFM. The airflow rates from the remaining four vents at the back (figure ??) were measured at multiple supply fan power ratings. Out of these measurements, two of them were chosen beyond the operating range in order to accurately extrapolate the graph for proper calibration. The measurements were taken five minutes after the fanpower percentage was changed to ensure the flow had stabilized. The measurements were taken in coordination with the operator who was monitoring the airflow rate obtained from the sensors at the exact point of time when the measurements were being taken. The physically measured data and the observed data are tabulated in table 2.1.

The measured data showed a linear relationship with the sensor data. The measured data was curve fitted with a linear line as shown in figure 2.3. The measured and the sensed data were found to be related as,
2.3 Infiltration rate

In order to incorporate the infiltration of air from the openings into the auditorium into the theoretical model, it was necessary to measure it. Since the sources of infiltrations were unknown, the method described by Martinez et al.\cite{7} seemed to be ideal for applying in the current scenario. In the previous work, the method was applied for identifying the infiltration rate for classrooms by observing the decay of a tracer gas known as Sulphur hexafluoride (SF$_6$). The decay of the tracer gas was modelled through the decay in concentration of SF6 under the assumption that the

\[ y = 1.0338x - 0.2179 \quad (2.8) \]

where $y$ and $x$ are the measured data and sensed data respectively.

Figure 2.3: Curve fitting between measured and sensed airflow rates.

\[ y = 1.0338x - 0.2179 \]

where $y$ and $x$ are the measured data and sensed data respectively.
2.3. Infiltration rate

tracer gas was well mixed within the room air is described in equation 2.9

\[ C_s(t) = C_s(0)e^{-at} \]  

In equation 2.9 the term, \( a \), represents the ratio of infiltration rate in \( m^3/s \) into the volume of the space; alternatively this term is known as air exchange rate. \( C_s(t) \), represents the concentration the tracer gas at time \( t \) and \( C_s(0) \) is the initial concentration of the tracer gas.

Figure 2.4: CO\(_2\) concentration data recorded by sensors present in the auditorium.

However for the current case, the decay of CO\(_2\) concentration studies were performed when the auditorium was unoccupied under similar assumption that the CO\(_2\) in the space was well mixed with air. The local CO\(_2\) concentration data was available for an entire week, which was measured by the CO\(_2\) sensors present at the four corners of the auditorium. The time stamp was recorded every minute continuous across the week. The concentration of CO\(_2\) at the point when all the people
had just left the room to the time when the concentration reached a steady state was recorded for all the days. During those times, the main entrance doors of the auditorium remain closed and supply air was switched off. Two samples of the CO$_2$ sensor data, which were recorded, are plotted in figure 2.4. The plot clearly demonstrates the exponential characteristics of the decay of CO$_2$ concentration within the space. Similarly thirteen plots were obtained from the four sensors observed for the entire week. The air exchange rate ($a$) was calculated from each of the plots and then averaged. The average infiltration mass flow rate of the air was calculated to be 0.1779 kg/s. The calculated infiltration flow rate value was utilized for the rest of the modelling and the main entrance doors were considered to be the major sources of infiltration.

2.4 CFD Model Setup

As seen in the theoretical model, the auditorium was required to be divided into different zones based on concentration. The fluid flow in the auditorium was required to be studied in order to evaluate the inter-zonal volume flow rates of air across the boundaries dividing the zones. In addition to this it can be argued that the airflow would affect the concentration in the different zones. So in addition to the concentration, even the airflow was to be considered when dividing the auditorium. CFD was used to analyze the fluid flow in the auditorium. For example, in figure 2.5 the fluid flow due to infiltration of air (blue streamlines), moves along zones 4 and 5 before exiting out of the return vents. It can be seen that there is no direct flow of air from zone 2 into zone 1. The concentration in zone 1 would be affected by infiltration from zone 2 only through zones 4 and 5. This was used as a guideline to split zones 1 and 2, which were designed not to interact with each other. A similar idea was used to effectively divide other boundaries too.

In order to model the fluid flow as closely as possible, the architectural drawings of the auditorium were carefully analyzed and the CAD model of the fluid domain was created on Solidworks [8]. The fluid domain was modelled in such a way as to balance out between accuracy and mesh complexity. The detailed CAD drawings are presented in figure B.1 under appendix B, where five different views of the auditorium are provided along with the supply inlet, return outlet and the sources of infiltration airflow being identified.

The simulation was first run with a medium density meshing and with known
2.4. CFD Model Setup

Figure 2.5: Figure showing streamlines of flow velocity along with zone divisions.

inlet, outlet and infiltration boundary conditions. The results illustrating the flow pattern using streamlines are displayed on figure 2.5, where the blue coloured streamlines indicates the infiltration airflow pattern and the red coloured streamlines indicates airflow pattern from the supply vents.

Based on the visual streamline data, the entire fluid domain was divided in to seven different zones as identified in figure 2.5. Later with the zone boundaries identified, the CAD model was broken down into seven different sections and assembled together as displayed in the image shown in figure B.2 of appendix B. This step was necessary to enable extracting the inter-zonal variable from the boundaries once the final simulation was completed. Once the CAD model was set up, it was then imported to Ansys Mesh [9] to generate a detailed meshing with higher mesh densities at the inlet, outlet and the infiltrations regions. Later the mesh was exported to Ansys CFX-Pre in order to set up preconditions for flow analysis.

Two different simulation cases were run, one with infiltration airflow rate defined as the sole inlet source of air and other with both the supply and infiltration defined as the inlet sources of air. Details on the nature of the simulations, boundary conditions and simulation data are summarized in Table 2.2. The simulation was set up to obtain a flow configuration similar to what was observed during the physical measurements while the supply fan power was set to 50%. This configuration was chosen for the simulation since it was the optimum operating condition at CIRS. On the other hand, the effect of discharge coefficient was neglected at the return vents since the pressure inside the auditorium was considered to remain uniform. Due to lack of hard data regarding the angle of flow from the supply vents and the
2.4. CFD Model Setup

Table 2.2: Table showing CFD simulation details.

<table>
<thead>
<tr>
<th>Category</th>
<th>With Infiltration &amp; Supply airflow</th>
<th>Only infiltration &amp; no supply air flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation type</td>
<td>Turbulence k-epsilon</td>
<td>Turbulence k-epsilon</td>
</tr>
<tr>
<td>Analysis type</td>
<td>Steady state</td>
<td>Steady state</td>
</tr>
<tr>
<td>Material</td>
<td>Air at 25°C</td>
<td>Air at 25°C</td>
</tr>
<tr>
<td>Boundary</td>
<td>50% fan power rating</td>
<td>Infiltration: 0.1779kg/s</td>
</tr>
<tr>
<td></td>
<td>Inlet: 1.786kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infiltration: 0.1779kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outlet total: 1.786kg/s</td>
<td></td>
</tr>
<tr>
<td>No. of mesh elements</td>
<td>516197</td>
<td>516197</td>
</tr>
<tr>
<td>No. of iterations</td>
<td>250</td>
<td>6200</td>
</tr>
<tr>
<td>Time to converge</td>
<td>55 min</td>
<td>1200 min</td>
</tr>
</tbody>
</table>

infiltration sources, the air was assumed to be leaving normal to their sources during simulation runs.

Despite the fact that both the simulation cases had a similar initial setup, the simulation with only infiltration as the source of inlet took considerable amount of time and iterations to converge (Table 2.2) due to very minor inlet airflow rate for a large volume of space.
Chapter 3

Results and discussion

The mass balance equations are simultaneous Ordinary Differential Equations (ODE). These equations were solved using Runge-Kutta convergence method in Matlab [10]. ode45 function was used in Matlab which represents 4th and 5th order Runge Kutta method which offers a more accurate solution than ode23. The following values for the parameters were assumed for the Matlab code:

\[ Q_{i1} = Q_{i2} = 0.075 \]
\[ R_{OA} = 0.95 \]
\[ C_{OA} = 450 \]
\[ C_{inf} = 550 \]
\[ G_1 = 404 \]
\[ P_d = 0.5 \]
\[ Np1 = P_d \]
\[ Np2 = 1 - P_d \]

Since the infiltration was determined through CO\textsubscript{2} decay rate, there is no possible way to determine the individual contribution of each door opening. So the infiltrate volume flow rate \( Q_i \) was divided equally among the two doors. The damper configuration, \( R_{OA} \) was taken to be 0.95. Though \( R_{OA} \) was supposed to be 0.5, meaning 50% outside air and 50% recirculated air through the supply vents according to the status at the control room, upon measurement of the actual airflow rates, \( R_{OA} \) was found to be 0.95. Although the outside air concentration of CO\textsubscript{2} is around 350 ppm, it as found that using 450 ppm gave excellent match between the measured and the calculated rate of change of CO\textsubscript{2} concentration. This is due to the fact that CO\textsubscript{2} sensors were not calibrated. In this project work, no attempt was made to calibrate the sensors. The infiltration of air is from the neighbouring atrium. The concentration of CO\textsubscript{2} from the atrium, \( C_{inf} \) would definitely be above the concentration of outside air, \( C_{OA} \). This value was taken to be 550 ppm to get an exact match of
Chapter 3. Results and discussion

slope where there is only infiltration (no supply air) in the auditorium. It should be kept in mind that unless the CO$_2$ sensors are calibrated, the calculated CO$_2$ could be inaccurate. The rate of generation was taken to be 404 mg/min for every person based on the estimation by Martinez [7]. The population distribution $P_d$ determines the distribution of population in the left and right side of the auditorium. For comparing the measured and calculated CO$_2$ data, equal distribution ($P_d = 0.5$) was used. In all the seven zones, the initial value of concentration of CO$_2$ was taken to be 700 ppm, taken from the data recorded by sensors.

The auditorium has a schedule for supply air which is from 8 a.m. to 5 p.m. During the rest of the time the supply is switched off and there is only infiltration. When the supply flow rates vary, the inter-zonal flow rates would be affected. However, since only a steady state model was used, this could not be implemented in the CFD simulation. However, two cases were simulated - one with only infiltration and another with infiltration and supply as discussed in the previous section. This was implemented into the Matlab code as two cases.

The calculated concentration of CO$_2$ in all the seven zones are compared to the measured value by the CO$_2$ sensors in figure 3.1. The linear slope in the graph till $3 \times 10^4$ seconds is until 8 a.m. where there is only infiltration air-flow and no supply. It can be seen that infiltration concentration of 550 ppm gives an exact match to the decay slope. The concentration levels of CO$_2$ were found to be quite similar in all the zones when $P_d$ is 0.5. There is a delay in the increase in CO$_2$ levels in the theoretical model in contrast to the measured data after the occupancy levels increase. However, it was found that the CO$_2$ levels from measured data spiked even before the occupancy increased. This could be due to a delay in the time-stamp recorded by the wi-fi sensors that record occupancy levels. When the population distribution was varied as shown in figure 3.2, there is considerable variation in the levels of CO$_2$ in the seven zones. This is the situation where the results from the theoretical model are possibly more accurate and help model a better DCV system. The levels of CO$_2$ are underestimated by the sensors. By increasing the air flow only from the particular set of supply vents that are exposed to the bigger population, the DCV can be made more effective. The effect of recirculation on the concentration of CO$_2$ is shown in figure 3.3 by changing $R_{OA}$. This shows the role played by the supply air in reducing the CO$_2$ levels. $R_{OA} = 0$ meaning 100% recirculated air would result in CO$_2$ levels of around 1900 ppm.
Figure 3.1: (a) Comparison of the measured and calculated concentration of CO$_2$ in all the zones (top) (b) The occupancy data (middle) and (c) Comparison of the measured and the calculated average CO$_2$ concentration in the auditorium (bottom).
$P_d = 0.5$

![Graph 1](copy.png)

$P_d = 1$

![Graph 2](copy.png)

Figure 3.2: Effect of the distribution of population on the concentration of CO$_2$
Figure 3.3: Effect of recirculation on the concentration of CO$_2$
Chapter 4

Conclusion

4.1 Limitations of the current model

The model used in this work is an approximate model. There are errors related to a few assumptions and issue that are discussed below.

The model assumes a constant inter-zonal flow rate even though the supply air flow is varying. Though this does not change the results very much, it is a source of error that needs to be considered. The model assumes an average CO\textsubscript{2} concentration throughout each zone. This model discretizes the concentration of CO\textsubscript{2} into different zones. The accuracy of the model would improve if the room is divided into more zones. The transport of CO\textsubscript{2} is assumed only due to convection in the theoretical model. This means that the CO\textsubscript{2} is transported only through the flow if air and not by diffusion. The CO\textsubscript{2} sensors in the auditorium were not calibrated due to lack of time. This needs to be addressed to arrive at an accurate model. The pressure inside the auditorium is assumed to be uniform. There were errors related to the measurement of airflow through the return vents for calibration. There was a small leakage close to the Air Handling Unit (AHU) which could not be resolved in the available time. As to whether this small leakage would affect measurement readings is not known. Moreover, it could not be determined if the leakage was present when the data provided by the sponsors was measured. While measuring the airflow using the Accubalance, there was a small gap between the hood and the opening which could not be sealed properly.
Bibliography


Appendix A

Air-flow measurement

Figure A.1: CIRS auditorium showing return vents at the back (left) & front (right)

Figure A.2: Accubalance shown being operated to measure return air-flow.
Appendix B

Zonal division

Figure B.1: Sectional views of CIRS auditorium.
Appendix B. Zonal division

Figure B.2: Zonal division of CIRS auditorium.

Table B.1: Table showing the volume of each zone.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>239.94</td>
</tr>
<tr>
<td>Zone 2</td>
<td>368.79</td>
</tr>
<tr>
<td>Zone 3</td>
<td>362.96</td>
</tr>
<tr>
<td>Zone 4</td>
<td>504.22</td>
</tr>
<tr>
<td>Zone 5</td>
<td>696.7</td>
</tr>
<tr>
<td>Zone 6</td>
<td>506.62</td>
</tr>
<tr>
<td>Zone 7</td>
<td>699.97</td>
</tr>
</tbody>
</table>
### Appendix C

**Zonal boundary parameters**

Table C.1: Velocities at the boundaries with infiltration and supply airflow.

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Area (m²)</th>
<th>Vel. X-plane (m/s)</th>
<th>Vel. Y-plane (m/s)</th>
<th>Vel. Z-plane (m/s)</th>
<th>Ave. Vel. (m/s)</th>
<th>Ave. Volume Vel. (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,6</td>
<td>48.1961</td>
<td>-0.0022</td>
<td>-0.0034</td>
<td>-0.0087</td>
<td>0.019</td>
<td>0.9166</td>
</tr>
<tr>
<td>3,7</td>
<td>66.8125</td>
<td>0.0024</td>
<td>-0.0008</td>
<td>0.0037</td>
<td>0.0153</td>
<td>1.0224</td>
</tr>
<tr>
<td>5,7</td>
<td>107.878</td>
<td>-0.0006</td>
<td>0.0052</td>
<td>0.0004</td>
<td>0.0118</td>
<td>1.2761</td>
</tr>
<tr>
<td>4,6</td>
<td>77.2412</td>
<td>0.0006</td>
<td>0.0037</td>
<td>0.0015</td>
<td>0.0063</td>
<td>0.4863</td>
</tr>
<tr>
<td>5,2</td>
<td>67.6863</td>
<td>0.0044</td>
<td>-0.0015</td>
<td>-0.0046</td>
<td>0.0137</td>
<td>0.9263</td>
</tr>
<tr>
<td>4,2</td>
<td>48.2324</td>
<td>-0.0119</td>
<td>-0.0021</td>
<td>0.004</td>
<td>0.0186</td>
<td>0.899</td>
</tr>
<tr>
<td>1,5</td>
<td>38.146</td>
<td>0.0002</td>
<td>-0.0001</td>
<td>-0.0007</td>
<td>0.0015</td>
<td>0.059</td>
</tr>
<tr>
<td>1,7</td>
<td>38.146</td>
<td>0.0004</td>
<td>0.0002</td>
<td>0.0006</td>
<td>0.0017</td>
<td>0.0642</td>
</tr>
<tr>
<td>1,6</td>
<td>22.711</td>
<td>0.0005</td>
<td>-0.0004</td>
<td>0.0003</td>
<td>0.0009</td>
<td>0.0215</td>
</tr>
<tr>
<td>1,4</td>
<td>22.711</td>
<td>0.0006</td>
<td>-0.0004</td>
<td>-0.0006</td>
<td>0.001</td>
<td>0.023</td>
</tr>
<tr>
<td>6,7</td>
<td>137.021</td>
<td>0.0021</td>
<td>0.008</td>
<td>-0.0029</td>
<td>0.0164</td>
<td>2.2536</td>
</tr>
<tr>
<td>4,5</td>
<td>136.301</td>
<td>0.0053</td>
<td>0.0051</td>
<td>0.0029</td>
<td>0.0118</td>
<td>1.6137</td>
</tr>
</tbody>
</table>
### Appendix C. Zonal boundary parameters

#### Table C.2: Velocities at the boundaries with only infiltration and no supply airflow.

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Area (m²)</th>
<th>Vel. X-plane (m/s)</th>
<th>Vel. Y-plane (m/s)</th>
<th>Vel. Z-plane (m/s)</th>
<th>Ave. Vel. (m/s)</th>
<th>Ave. Volume Vel. (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,6</td>
<td>48.1961</td>
<td>0.00178</td>
<td>0.0024</td>
<td>-0.0027</td>
<td>0.00532</td>
<td>0.2564</td>
</tr>
<tr>
<td>3,7</td>
<td>66.8125</td>
<td>-0.00218</td>
<td>0.00037</td>
<td>-0.00212</td>
<td>0.00432</td>
<td>0.28843</td>
</tr>
<tr>
<td>5,7</td>
<td>107.878</td>
<td>-0.0002</td>
<td>-0.00012</td>
<td>-0.00018</td>
<td>0.0013</td>
<td>0.13992</td>
</tr>
<tr>
<td>4,6</td>
<td>77.2412</td>
<td>-0.00022</td>
<td>-0.00038</td>
<td>0.00055</td>
<td>0.0025</td>
<td>0.1931</td>
</tr>
<tr>
<td>5,2</td>
<td>67.6863</td>
<td>-0.00183</td>
<td>0.00012</td>
<td>0.0013</td>
<td>0.0034</td>
<td>0.23013</td>
</tr>
<tr>
<td>4,2</td>
<td>48.2324</td>
<td>0.00457</td>
<td>0.00127</td>
<td>0.0016</td>
<td>0.0054</td>
<td>0.26045</td>
</tr>
<tr>
<td>1,5</td>
<td>38.146</td>
<td>0.00033</td>
<td>0.00007</td>
<td>-0.00022</td>
<td>0.00045</td>
<td>0.01717</td>
</tr>
<tr>
<td>1,7</td>
<td>38.146</td>
<td>0.00002</td>
<td>0.00038</td>
<td>-0.00017</td>
<td>0.00059</td>
<td>0.02251</td>
</tr>
<tr>
<td>1,6</td>
<td>22.711</td>
<td>-0.00055</td>
<td>0.00026</td>
<td>0.00001</td>
<td>0.00069</td>
<td>0.01567</td>
</tr>
<tr>
<td>1,4</td>
<td>22.711</td>
<td>-0.0002</td>
<td>0.00014</td>
<td>-0.00017</td>
<td>0.00046</td>
<td>0.01045</td>
</tr>
<tr>
<td>6,7</td>
<td>137.021</td>
<td>-0.00074</td>
<td>0.002</td>
<td>-0.0008</td>
<td>0.0033</td>
<td>0.45217</td>
</tr>
<tr>
<td>4,5</td>
<td>136.301</td>
<td>-0.00006</td>
<td>0.00039</td>
<td>0.00006</td>
<td>0.00174</td>
<td>0.23716</td>
</tr>
</tbody>
</table>