

**ASSESSMENT OF AIR CONTAMINANT BEHAVIOR IN
VAV -HVAC AIR -CONDITIONED SPACE UNDER
VARYING THERMAL LOADS**

BY

AFOLABI OLADAYO POPOOLA

A Thesis Presented to the
**COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS**

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ARCHITECTURAL ENGINEERING

MAY, 2024

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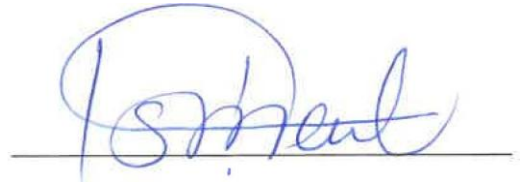
MAY, 2024

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This thesis, written by **AFOLABI OLADAYO POPOOLA** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ARCHITECTURAL ENGINEERING.**



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This thesis is dedicated to:

My **late** elder brother.

Saheed Gbolahan AFOLABI

HND, BTECH, MTECH, PHD (In view)

My Parents,

Alhaji J. O. AFOLABI & Mrs S. T AFOLABI

&

To those who never quit, when life seems hard on them

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

All praises and adorations belong to ALLAH, the Lord of the worlds, HE who provides when no one else can. May His countless peace and blessings be showered upon the noblest of His creatures, Prophet Muhammad (ﷺ), his brethren of prophets and messengers, his family, and his companions.

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ABSTRACT

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Thesis Title : Assessment of Air Contaminant Behavior in VAV-HVAC Air-Conditioned Space Under Varying Thermal Loads

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Ventilation plays a critical role in maintaining indoor air quality and regulating the energy demands of buildings. Adequate ventilation is essential for creating healthy and comfortable living and working environments. Poor ventilation can lead to excessive carbon dioxide (CO₂) accumulation indoors, which has been shown to impair occupants' decision-making abilities and overall work performance. This study evaluates the behavior of CO₂ as an air contaminant under varying thermal loads in a space conditioned by a Variable Air Volume (VAV) HVAC system. To achieve this, a tracer gas experiment using CO₂ as a surrogate was conducted to validate two computational models of (CONTAM-W and ANSYS). The building model was digitally developed using Design Builder (an EnergyPlus-based software) and simulated on a VAV-HVAC system. Key design outputs, such as variable supply air velocities and temperatures, were obtained and incorporated into the validated computational models. Has design builder software produces the volumetric air flow from the HVAC system, CONTAM-W software was effectively used to generate and monitor the contaminant behavior, while ANSYS Fluent (a CFD software), produces the turbulence dispersion and interaction between the contaminant and the airflow within the enclosure. Results from the tracer gas experiment demonstrated that sensor placement within the experimental zone significantly influences the observed contaminant decay rate, which indicates how effectively air contaminants are removed from the space. Furthermore, the study established a linear relationship between weather conditions, thermal loads, human CO₂ exhalation rates, and the VAV-HVAC system's air supply rate on pollutant dilution and removal. For a hot climate like Dhahran, it is safe to say that contaminant displacement and removal are effective during the summer months, and a dedicated outdoor air system (DOAS), should be adopted at the winter months. The findings also revealed that even the minimum airflow velocity of 3.085 m/s effectively diluted CO₂ concentrations within the limits recommended by ASHRAE Standard 62.1 for acceptable indoor air quality. This study underscores the importance of ventilation system design, airflow dynamics, and sensor placement in achieving optimal indoor air quality and highlights the role of advanced simulation tools in informing energy-efficient HVAC strategies.

خلاصة

الاسم الكامل: أفولابي، أولادايو بوبولا

تحت الأحمال الحرارية المتغيرة VAV-HVAC عنوان الأطروحة: تقييم سلوك ملوثات الهواء في الفضاء المكيف

المجال الرئيسي: الهندسة المعمارية

تاريخ الدرجة العلمية: مايو 2024

تلعب التهوية دورًا حاسمًا في الحفاظ على جودة الهواء الداخلي وتنظيم متطلبات الطاقة للمباني. التهوية الكافية ضرورية (CO_2) لخلق بيئات معيشية وعمل صحية ومريحة. يمكن أن تؤدي التهوية السيئة إلى تراكم مفرط لثاني أكسيد الكربون في الداخل، مما ثبت أنه يضعف قدرات اتخاذ القرار لدى شاغلي المبنى وأدائهم العام في العمل. تقيم هذه الدراسة سلوك بحجم هواء متغير HVAC ثاني أكسيد الكربون كملوث للهواء تحت أحمال حرارية متفاوتة في مساحة مكيفة بنظام لتحقيق هذه الغاية، أجريت تجربة غاز تتبّع باستخدام ثاني أكسيد الكربون كبديل للتحقق من صحة نموذجين (VAV) (برنامج قائم) Design Builder تم تطوير نموذج المبنى رقميًا باستخدام (ANSYS و CONTAM-W) حسابيين تم الحصول على مخرجات التصميم الرئيسية، مثل VAV-HVAC وتم محاكاته على نظام EnergyPlus على سرعات الهواء المتغيرة ودرجات الحرارة، وتم دمجها في النماذج الحسابية المعتمدة. وقد أنتجت برامج تصميم البناء بشكل فعال لتوليد CONTAM-W تدفق الهواء الحجمي من نظام التدفئة والتهوية وتكييف الهواء، واستخدم برنامج (برنامج ديناميكا الموائع الحسابية) تشتت ANSYS Fluent سلوك الملوثات ومراقبته، بينما أنتج برنامج الاضطرابات والتفاعل بين الملوثات وتدفق الهواء داخل العلب. وقد أظهرت نتائج تجربة الغاز المنتبّع أن وضع المستشعر داخل المنطقة التجريبية يؤثر بشكل كبير على معدل اضمحلال الملوثات الملحوظ، مما يشير إلى مدى فعالية إزالة الملوثات الجوية من المساحة. وعلاوة على ذلك، أثبتت الدراسة وجود علاقة خطية بين الظروف الجوية والأحمال الحرارية ومعدلات زفير ثاني أكسيد الكربون البشري ومعدل إمداد الهواء لنظام التدفئة والتهوية وتكييف الهواء في تخفيف الملوثات وإزالتها. وبالنسبة لمناخ حار مثل الظهران، فمن الآمن أن نقول إن إزاحة الملوثات HVAC في أشهر الشتاء. وكشفت (DOAS) وإزالتها فعالة خلال أشهر الصيف، ويجب اعتماد نظام هواء خارجي مخصص النتائج أيضًا أن حتى الحد الأدنى لسرعة تدفق الهواء البالغة 3.085 متر/ثانية خفف بشكل فعال تراكيز ثاني أكسيد لجودة الهواء الداخلي المقبولة. وتؤكد هذه الدراسة ASHRAE 62.1 الكربون ضمن الحدود الموصى بها في معيار على أهمية تصميم نظام التهوية وديناميكيات تدفق الهواء ووضع المستشعر في تحقيق جودة الهواء الداخلي المثلى. وتسلط الضوء على دور أدوات المحاكاة المتقدمة في إعلام استراتيجيات التدفئة والتهوية وتكييف الهواء الموفرة للطاقة.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The desert climate is characterized by the most extreme climatic conditions sometimes including high air temperature, high solar radiation, low rainfall, low humidity, and sandstorms; despite all of these, the environment has also been plagued with a series of airborne diseases ranging from SARS-CoV-2 (Covid-19), pertussis (whooping cough), hay fever, influenza, mumps, tuberculosis, to mention a few. Not only do these harsh climatic conditions cause serious concerns for buildings and their users, but it is also necessary to get rid of indoor air pollutants so that humans would not only be productive within the buildings but will also ensure that their general well-being is secured. To address some of these problems in buildings, a system of heating, ventilating, and air conditioning (HVAC) has been created, and its main objective is to satisfy users when it comes to their health concerns - indoor air quality (IAQ), and thermal comfort (Solano et al., 2021). However, research has also shown over time, that these systems employed to provide thermal comfort and acceptable indoor air quality consume a significant part of building energy (Chua et al., 2013). In Saudi Arabia, for instance, residential buildings consume 80% of the energy generated due to HVAC systems trying to cool the indoor space (Felimban et al., 2019). To reduce this quantum of energy consumed by the cooling system, HVAC system professionals devised a Variable Air Volume (VAV) type of HVAC system. In this system, the thermostat sends signals to the Air Handling Unit (AHU) through the variable box, then

the working rate of the HVAC fan is adjusted so that the amount of cooled air (Q) sent to the space is just enough to combat the load, which then in most cases has a corresponding reduction in the amount of energy consumed by the HVAC system, unlike the previous system (constant air volume HVAC system - CAV, which does not have a variable box to adjust itself to the load variations in the room/zone). Research on this VAV-HVAC system operational strategy has also shown, that the system has an energy reduction of 17% - 38% (Yao et al., 2007), however, despite this great improvement in energy reduction, VAV-HVAC system has posed a great threat to maintaining acceptable indoor air quality, due to reduced ventilation effectiveness resulting from reduced capacity and indoor contaminants which are generated within the indoor spaces. Furthermore, the HVAC systems are usually exposed to several air pollutants, especially from filters, cooling coils, and dust accumulated within duct surfaces as a result of poor installation and maintenance (Pinto et al., 2007); more so, these operational strategies of VAV-HVAC systems according to Anand et al., (2019) are characterized with poor ventilation and humidity control under low load conditions and widely varying latent loads, hence calls for the need to optimize this system in a bid to provide adequate ventilation while still having a reduced energy consumption, and to be able to achieve this efficiently, it is necessary to study the movement/dispersion of the contaminant within the space.

1.2 Problem Statement

Indoor air is usually conditioned to attain thermal comfort and acceptable indoor air devoid of contaminants (Kalaiselvam et al., 2006). On December 15, 2023, the World Health Organization, WHO reported on its website, that contamination of air in households was

responsible for an estimated 3.2 million deaths per year in 2020, including over 237,000 deaths of children under the age of 5. The combined ambient and household air pollution effects are associated with 6.7 million premature deaths annually. In the process of having cleaned indoor air (mechanically), and also reducing the amount of energy consumed in this process, a Variable Air Volume (VAV) type of HVAC is usually used in many types of buildings. While this system successfully reduced the amount of energy its building consumed, it has a shortfall in providing adequate ventilation, which still poses a threat to human lives. Hence, to ease this trade-off, this research has tried to examine how air contaminants behave in an indoor space in which air is conditioned using a VAV-HVAC system to optimize the system's operational strategies to achieve acceptable indoor air quality.

1.3 Aim & Objectives

This thesis aims to assess the behavior of air contaminants in an air-conditioned space that is being operated on a VAV-HVAC system under varying thermal loads. The following are the objectives of this research.

- i. To assess the contaminant behavior in a VAV-HVAC air-conditioned space under varying thermal loads.
- ii. To evaluate different VAV system strategies for improving indoor air quality and ventilation effectiveness.
- iii. To develop a guideline for the operation and control of VAV-HVAC systems to achieve indoor air quality.

1.4 Significance of Study

Since the VAV-HVAC system has become the widely used system in different building types, improving the performance of this system in terms of Indoor Air Quality (IAQ) under varying thermal loads becomes pertinent so that humans would not continue to sacrifice attaining thermal comfort and energy reduction at the expense of their health.

1.5 Limitations of the Study

Every research endeavor is subject to certain constraints, and this study is no exception. While the assessment of air contaminant behavior in VAV-HVAC air-conditioned spaces under varying thermal loads has yielded valuable insights, there are inherent limitations that must be acknowledged. These limitations stem from experimental conditions, modeling assumptions, and resource constraints. These constraints provide opportunities for further refinement and exploration. Below are the key limitations characterized by this study:

- **Controlled Experimental Environment**

The tracer gas experiment was conducted in a controlled office environment with limited external variables, which may not accurately represent more dynamic real-world scenarios, such as outdoor temperature, varying outdoor airflow (Infiltration and exfiltration), occupant behavior, and fluctuating HVAC performance.

- **Focus on a Single Zone**

The research focused on analyzing CO₂ concentration and air change rate within a single zone. This limitation restricts the generalizability of the results to multi-zone buildings or spaces with more complex layouts.

- Dependency on Software Accuracy

The study's findings heavily depended on the accuracy of the software tools used (Design Builder, ANSYS, and CONTAM-W). Despite meticulous validation processes, any limitations or inherent errors in these software tools may have affected the final results. More so, external validation from field studies or real-world building performance data was not conducted, limiting the study's practical applicability.

- Restricted Time Frame for Analysis

The analysis primarily focused on short-term CO₂ contamination behavior, leaving long-term trends or seasonal variations unexplored.

- Simplified CO₂ Emission Model

The study assumed a constant CO₂ emission rate from a single source (representing human exhalation), which may not fully represent the variability of human activity or additional sources of CO₂ in real-world conditions.

- Resource Constraints

The scope of the research was limited by the availability of resources, including experimental equipment, time, and computational power for more complex simulations.

CHAPTER 2

LITERATURE REVIEW

2.1 Constituents of Air

It has become common knowledge that the air we breathe is a mixture of different gases like nitrogen, oxygen, argon, neon, carbon dioxide, water vapor, etc. which are essential for animals' and humans' survival. While some of these existed in large quantities, some existed as trace elements. Nitrogen makes up 78 % of this gas, which is mixed with oxygen (21%), water vapor (variable), argon (0.9 %), carbon dioxide (0.04%), and trace gases.(BYJU'S Learning, 2023). There is no apparent scent or color in pure air. Figure 1 below, shows the composition of air, however, this composition of air is not constant and changes from place to place. For example: in polluted areas, because of excessive carbon emissions, that area might have a higher percentage of carbon dioxide, which is detrimental to healthy living conditions.

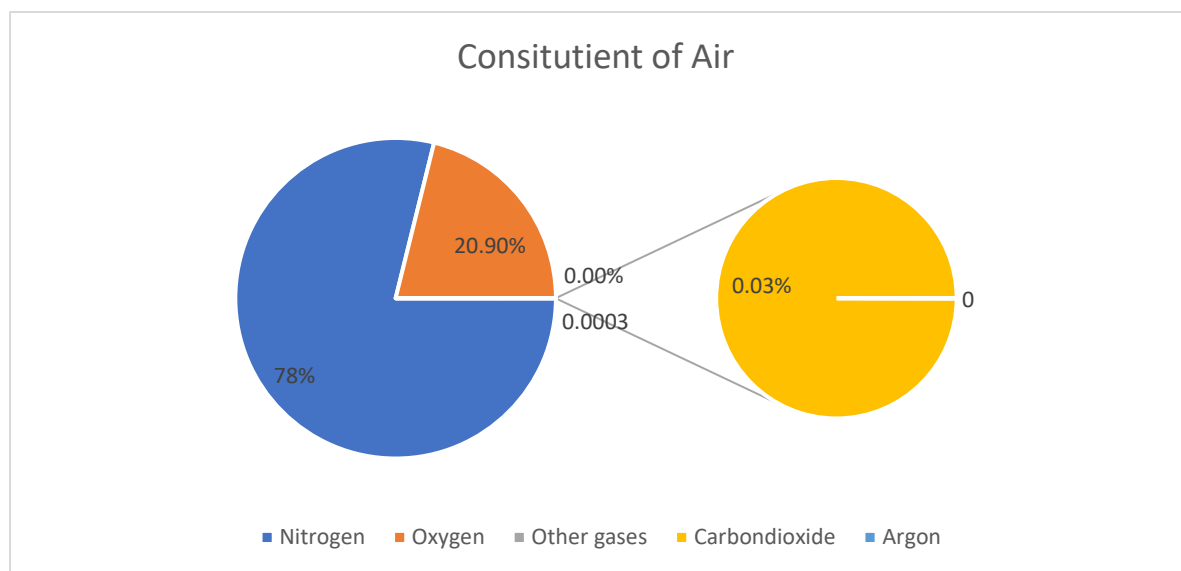


Figure 1: Percentage composition of Air constituents

2.2 The Contamination of Air

2.2.1 Outdoor Air Contamination

The air that we take in to sustain our health is usually polluted with several things caused by solid particles, liquid particles, and certain gases that are suspended in the air. Burning fossil fuels, such as coal and petroleum, and wood, car exhaust, factories, and even wildfires, are among some of the sources of this air pollution, other sources are factories, dust, pollen, mold spores, volcanoes, and wildfires. These solid and liquid particles suspended in our air are called aerosols (USEPA, 2023). With every breath we take, we suck in tiny particles that can damage our lungs, hearts, and brains and cause a host of other health problems. The most dangerous of these particles, which can include anything from soot, and soil dust, to sulfates, are fine particles 2.5 microns or less in diameter, shortened as PM_{2.5}. Even though air pollution is a global problem, it disproportionately affects those living in developing nations and particularly the most vulnerable, such as women, children, and the elderly (UNEP, 2022).

2.2.2 Indoor Air Contamination

This problem of air contamination is not only limited to outdoor air. The Environmental Protection Agency (EPA) says that the air in homes and other buildings can be more seriously polluted than the outdoor air. This is so, because inadequate ventilation, inadequate functioning of the air conditioning systems, human activities, and numerous materials, chemicals, and gases mainly influence indoor pollution. Different organizations, such as the United States Environmental Protection Agency (USEPA) and World Health Organization (WHO) have recognized IAQ as a multi-disciplinary phenomenon and

classified pollutants into several categories (Mannan & al-Ghamdi, 2021). Outdoor air contaminants come into the building through infiltration, natural ventilation, and mechanical ventilation, there are also indoor sources of air contaminant within the building, among which include: Fuel-burning combustion appliances, Tobacco products, Building materials and furnishings (as diverse as Deteriorated asbestos-containing insulation, Newly installed flooring, upholstery or carpet, Cabinetry or furniture made of certain pressed wood products), Products for household cleaning and maintenance, personal care, or hobbies, Central heating and cooling systems and humidification devices and excess moisture. Residential pollution, mostly from cooking and heating using biomass, and generating electricity from fossil fuels for our homes, and transport, are the main human-made sources of fine particles globally.

2.3 Indoor Air Quality in Buildings

The air, water, and food that we take in, are necessary bodily intakes for the sustenance of human life. The average intake (mass) for an adult per day for air, water, and food is about 15 kg (ca. 13 kg inhaled indoors), 2 kg, and 2.3 kg for an 80kg person, respectively (USEPA 2011). According to time-activity pattern investigations in 12 European countries, the USA, and China, people spend about 90% of their time indoors, including the enclosed environment of transportation, during their whole lives (al horr et al., (2016) 'Yinping, (2022)). Specific research in North America has shown that adults tend to spend 87% of their time in buildings, and the remainder of their time is spent in vehicles (6%) and outdoors (7%) (Mannan & al-Ghamdi, 2021). Therefore, indoor air quality (IAQ) can greatly influence human comfort, health, productivity, creativity, and well-being, but not

until the last decade, research on air quality has mostly focused on the outdoors, whereas indoor air quality (IAQ) and its impacts have received considerably less attention (Yinping, 2022). Recently, scientists and the public have focused on risks associated with IAQ because research has established that indoor air is more contaminated than outdoor air since it often combines outdoor air and indoor sources as stated above. In defining what IAQ is, the United States Environmental Protection Agency says Indoor Air Quality (IAQ) is the air quality within and around buildings and structures, especially concerning the health and comfort of building occupants. No doubt understanding and controlling common pollutants indoors can help reduce the risk of indoor health concerns. Research has shown that health effects from indoor air pollutants may be experienced soon after exposure or, possibly, years later. The effect of poor indoor air quality is a function of the time an individual spends in such an indoor space where the indoor air is polluted, while some effects are immediate, some are long-term effects. The immediate effect of poor indoor air quality usually results in irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. (JaCeK NaMIeNIK et al., 1992) (USEPA, 2023). Sometimes the treatment is simply eliminating the person's exposure to the source of the pollution if it can be identified. Soon after exposure to some indoor air pollutants, symptoms of some diseases such as asthma may show up, be aggravated, or worsen. Long-term exposure effect often leads to some respiratory diseases, heart disease, and cancer, and can be severely debilitating or fatal. To reduce some of these problems and bring thermal comfort to humans, the heating ventilation & air conditioning system was introduced in buildings.

To further avert some of these health-related issues, it is of high importance to deepen research on indoor air quality. The World Health Organization (WHO) on her part, has

worked to ensure that health-relevant indicators of household and ambient pollution exposure and disease burden are included in the formal system of Sustainable Development Goals (SDGs) indicators. Leveraging her technical expertise, (WHO, 2023) monitors and tracks progress on health indicators to measure progress toward achieving the SDGs 3, 7, and 11.

Targets of particular relevance to ambient and household air pollution include:

- i. SDG target 3.9.1, which calls for a substantial reduction in deaths and illnesses from air pollution.
- ii. SDG target 7.1.2, which aims to ensure access to clean energy in homes
- iii. SDG target 11.6.2, which aims to reduce the environmental impact of cities by improving air quality.

2.3.1 Building Types & Associated Air Contaminants

Aside from the contaminated outdoor air entering the building, the building types and the associated activities within the indoor space also contribute to the types and rate of air contamination within the space, and these influence how indoor air pollutants impact occupants. Some pollutants, like radon, are of concern because exposure to high levels of the pollutant over long periods increases the risk of serious, life-threatening illnesses, such as lung cancer. Other contaminants, such as carbon monoxide at very high levels, can cause death within minutes. Some pollutants can cause both short- and long-term health problems. Prolonged exposure to environmental tobacco smoke can cause lung cancer, and short-term exposures can result in irritation and significant respiratory problems for some people, particularly young children. Residential buildings tend to have the highest rate of

exposure to some of these air contaminants. The University of California, Riverside classified this air pollutant into primary and secondary pollutants. ***Primary air pollutants:*** Pollutants that are formed and emitted directly from particular sources. examples are particulates, carbon monoxide, nitrogen oxide, and sulfur oxide. While ***Secondary air pollutants:*** Pollutants that are formed in the lower atmosphere by chemical reactions. The two examples are ozone and secondary organic aerosol (haze). Secondary pollutants are harder to control because they have different ways of synthesizing, and the formation is not well understood. They form naturally in the environment and cause problems like photochemical smog. Table 1 below shows the summary of building types, associated air contaminants, sources and associated effects.

2.3.2 Effect of Poor Indoor Air Quality

Table 1 below shows an insight into the possible effect of Indoor Air Quality from different building types, one could say, that when a building is affected or infected, then the building is one way weakened, hence we can say that because of this infection, the building is sick. The term "sick building syndrome" is often associated with inadequate indoor air quality, and indeed, the term has been synonymous with this era of energy-saving. Professionals from various fields such as medicine, psychology, building design, and other engineering have been working to determine the causes behind this newly emerged phenomenon in the building industry (Awbi, 2004). Buildings that have a direct influence on people's health and well-being are known as 'sick buildings'. Major factors associated with these buildings are the lack of fresh air and poor ventilation systems.

(Awbi, 2004) argues further, that in the last two decades, there has been an increase in problems related to indoor air quality, and that this can be attributed to several reasons, including the increase in building air tightness, the reduction in ventilation rates to save energy, the rising use of computers, printers, photocopiers, and other equipment in offices, the increasing use of textile floor covering and furnishings that emit high levels of pollutants, the growing use of air-conditioning, and the lack of maintenance. In addition, recent studies have shown that there is a direct link between the quality of room air and productivity (Povl Ole Fanger, 2000).

In often times, poor indoor air quality can be said to affects people in three main areas: Comfort: e.g. stuffy, odorous environment; Acute health effects: e.g. burning eyes, chest symptoms, transmission of airborne disease; and Chronic (delayed) health effects: may take decades to appear.

2.3.3 Indoor Air Quality & Climate Change

The United Nations has defined Climate change as the long-term shifts in temperatures and weather patterns and has attributed the primary cause of these to the human activity of burning fossil fuels like coal, oil, and gas, which produces greenhouse gases that are causing climate change including carbon dioxide and methane. As we have established above, the air we take in, and ultimately our health, can be impacted by many factors, including the quality of outdoor air, people's activities within the indoor spaces, the design, construction, operation, and maintenance of a building, hence changes in the climate can affect the air we breathe in.

Table 1: Building Types, associated air Contaminants, Sources and associated effects

Building Type	Area	Contaminants	Sources	Possible consequence
Biological Contaminants				
Residential Buildings	Carpets, ,	Allergens	Furry pets, dust mites Presence of cats and dogs, contaminated humidifiers, storage of food waste, lower ventilation rate, increased amount of settled dust	Asthma
	Kitchen waste	Endotoxins	Unattended plumbing leaks, leaks in building fabric, hidden food spills, standing water	asthma, reduced lung function
	Sanitary, etc	Dampness and mold		Upper respiratory symptoms, cough, wheeze, and asthma
Chemical Contaminants				
Residential Buildings	Cigarette	Smoke	Tobacco smoke, firewood smoke, combustion smoke	Premature mortality, lung cancer, coronary artery disease, childhood cough and wheeze, respiratory illness, infant death syndrome
				Combustion of solid fuels releases CO, N ₂ O, particulates, polycyclic hydrocarbons, which increases the risk of lung cancer, childhood asthma
		Coal & biomass fuel combustion product	Cooking and heating	
Industrial Buildings	Local cooking	Carbon Monoxide (CO)	Vehicle exhaust from attached garages, gas stoves, furnaces, wood stoves, fireplaces & cigarettes	Headache, nausea, fatigue
	Fire	Nitrogen dioxide (N ₂ O)	Combustion of fossil fuels e.g., gas or oil furnaces and stoves	Increased risk of respiratory symptoms
	Fumigation process	Pesticides, air fresheners	Contaminated soil, stored pesticide containers	Irritation to the eye, nose, and throat, damage to the central nervous system

Off Gassing emissions (Gases released from indoor materials)				
Residential Buildings,	Furniture	Formaldehyde (HCHO)	Wood-based products assembled using urea-formaldehyde resins, cigarette smoke, paints, varnishes, floor finishes	eye, nose, throat irritation, asthma, bronchitis, and possible carcinogen
Commercial Buildings,	Wall finishes	Volatile Organic Compounds (VOC)	Cigarette smoke, recently dry-cleaned clothes, room deodorizers, paints, carpets	asthma, bronchial hyper-reactivity
educational Buildings, etc		Plastic Compounds	Polyvinyl chloride for flooring, plastic wall material	Bronchial obstruction, asthma, wheezing, cough, and phlegm
Carcinogens				
Residential Buildings	Radon		Natural decay of uranium	Lung cancer, leukemia
Particulate Matter				
Residential Buildings	Ultra-fine particles		Cooking, combustion activities	Serious impact on heart and lungs

For example, changes in the climate can worsen the quality of the outdoor air that comes into the building (infiltration). Rising carbon dioxide (CO₂) levels and warmer temperatures can increase outdoor airborne allergens which also infiltrate indoor spaces. Warmer temperatures and shifting weather patterns can lead to more frequent and severe wildfires. Smoke and other particle pollution generated outdoors, including from wildfire events and dust storms, can infiltrate into indoor environments and contribute to levels of indoor particulate matter. It is worthy of note that the effect of climate change also affect the energy consumption pattern of the building, and in a bid to keep the indoor environment of the building balanced, the HVAC system consumes a lot of energy; further effort to bring down this amount of energy by the VAV-HVAC system type, the system becomes deficient

as it reduces the amount of fresh / recirculated air into the building, thereby impacting the quality of indoor air, since the amount of fresh air supplied into the building is reduced.

2.3.4 Controlling Indoor Air Problems in Buildings

Having understood the challenges that indoor air pollutants/contaminants pose to human health, it becomes necessary to bring these contaminants to the book. Many works of literature have intervened to prevent or control indoor air contaminant problems. Control strategies can be categorized as

- Source control
- HVAC control (a. Ventilation b. Air cleaning)
- Exposure control Successful mitigation often involves a combination of these strategies.

2.3.4.1 Source Control

Christine, (2004) of the Marine Indoor Air Quality Council has defined ***Source Control*** as attempting to *eliminate*, reduce, or *manage* the individual sources of pollution and their emissions. He explained further that eliminating the contaminant from the indoor environment is the primary means to prevent the risk of adverse health effects from exposure to the contaminant, and reducing the pollutant source when it seems that elimination of the pollutant is not possible; while managing the source as a form of control will involve the following task:

- Determine first if other, safer products, appliances or systems are available

- Carefully consider the value of the product, appliance or system with the risk of its use
- Periodically review HVAC and plumbing systems for appropriate application
- Conduct periodic Operations and Maintenance of HVAC and plumbing systems in accordance with design intent.
- Strictly adhere to all manufacturer's specifications for use, installation and maintenance of a product or appliance.
- Strictly adhere to the label instructions for application of chemical products used indoors (Read the material safety data sheet (MSDS) sheets for any chemical product used or stored indoors.)
- Properly store and ventilate, or dispose of material to limit exposures
- Schedule use of contaminants to limit exposure to building occupants

All efforts to prevent or correct IAQ problems should include an effort to identify and control pollutant sources. Source control is generally the most cost-effective approach to mitigating IAQ problems in which point sources of contaminants can be identified. In the case of a strong source, source control may be the only solution that will work.

2.3.4.2 HVAC CONTROL

The use of Heating Ventilation and Air Conditioning (HVAC) system in the control of indoor air contaminants can form in two ways, either through providing ventilation or using the system to clean the air.

a. Ventilation in Building

Several authors have tried to define what ventilation in buildings is all about, and all these definitions drive the fact that Ventilation is a process of changing or replacing air in any indoor space to provide high indoor air quality. Hence suffice to say that the purpose of a ventilation system is to provide an acceptable mini-environment in the space being ventilated (Awbi, 2004), and the main concern of this min-environment is thermal comfort and indoor air quality. These two factors must be considered in the design of a ventilation system for a room or a building, as they are fundamental to the comfort and well-being of the human occupants or the performance of industrial processes within these spaces. Limiting excess ventilation improves the thermal efficiency of buildings; ventilation can account for 50% of the primary energy used in a UK dwelling (CIBSE, 2015). However, sufficient ventilation is required to maintain adequate indoor air quality (IAQ) in occupied buildings (A. K. Persily, 2016). Ventilation results from indoor-outdoor pressure differences, driven by wind, temperature differences, and fans (Few & Elwell, 2023). All designers and operators of ventilation systems must have a good understanding of human comfort needs and the air quality required to maintain a comfortable indoor environment. This will require knowledge of the heat balance between the human body and the internal environment, factors that affect thermal comfort, factors that cause discomfort, and the concentration of indoor pollutants that occupants can tolerate. This process of bringing in outdoor fresh air to the indoor space to remove, displace, or weaken indoor air contaminants could be achieved by various means depending on the building type, building design, or by the local laws or regulations within which the building is to be constructed. As earlier mentioned, the outdoor air has around 21% oxygen and 0.03% carbon dioxide on a volume basis, with the rest being nitrogen. However, significant variations in these

proportions can make it unsuitable for human use. For prolonged exposure, a minimum of 16% oxygen and a maximum of 0.5% carbon dioxide (which may extend to 1.5%) are commonly accepted standards. When seated, a person typically inhales around 18 cubic feet of air per hour (Wilson, 2023). The exhaled air has about 16% oxygen and 4% carbon dioxide. If only 18 cubic feet per hour ($1.4 \times 10^{-4} \text{ m}^3/\text{s}$) of fresh air were provided for each person in a continuously occupied space, the concentrations of carbon dioxide would exceed the permissible levels (ASHRAE recommends that carbon dioxide levels should not exceed 1000 ppm). As activity increases, the consumption of oxygen and production of carbon dioxide increase, and ventilation requirements correspondingly increase. For people standing, the values are about 50% higher than for those seated. Therefore, supplies of outside air in excess of that required to control the effect of respiration on oxygen and carbon dioxide levels, as well as for pressurization of the building, are necessary. The building must be positively pressurized to prevent uncontrolled infiltration. Ventilation in buildings comes in form of various types, and are generally categorized as :

- Natural ventilation
- Mechanical ventilation, and
- Hybrid ventilation.

Natural Ventilation: Natural ventilation utilizes wind and buoyancy to distribute fresh air in buildings for occupants. Natural ventilation can ensure adequate indoor air quality, thermal conditioning, moisture dissipation, and well-being by connecting to nature (Yang & Clements-Croome, 2012). Obtaining a continuous flow of fresh air from natural sources is the best method of ventilation. However, with the increasing need for energy efficiency, modern homes are built to be airtight. This is why it is essential to integrate a natural

ventilation system that can extract a constant supply of oxygen, and this can be achieved via window controls, designed to utilize outdoor air pressure generated by the building and its surroundings; an example is shown in Figures 2 and 3 below.



Figure 2: Minka House in Japan

Electric controls are especially useful in public buildings as they can feature smart technology able to recognize weather patterns and fire alarms, opening or closing as necessary. (LJ Pratley & Partners Ltd, 2018). Before now, this type of ventilation strategy (i.e., Natural ventilation) was usually incorporated into the building through vernacular Architecture, wind towers, and the incorporation of courtyard design (T. Yang & Clements-Croome, 2012). This natural ventilation of buildings depends on the climate, building design, and human behavior. (World Health Organization, 2009).



Figure 3: Domestic Windcatcher (Bagdir Yazd), Iran

Mechanical ventilation also helps to provide fresh air, remove moisture, odors, and other pollutants that can build up inside a home. In this ventilation strategy, the systems circulate fresh air using ducts and fans, rather than relying on airflow through small holes or cracks in a home's walls, roof, or windows. There are various ways by which Mechanical ventilation strategy can be achieved in buildings, and it is usually based on the type of fan installed and the way air is taking out or supplied into the space/building. First of all is the ***Mechanized fans***, which can be directly fixed in windows or walls, or in air ducts to supply or exhaust air from a room. There is a general belief that the Mechanized fan Ventilation system is better when compared to Natural ventilation because of its controllable features in the inflow and exhaust of the outdoor fresh air into and outside the indoor space, and in some cases, a natural ventilation solution isn't possible for some buildings due to the design and location of the building. Because of this feature of being able to be controlled, it is believed that Mechanical ventilation is able to also guarantee better Indoor Air Quality and provides improved comfort within the indoor environment. Another form of ventilation is the **Exhaust Ventilation** Strategy, this ventilation system operates by depressurizing the building and reducing the inside air pressure so it's below outdoor air pressure.

The stale air is sucked out via the exhaust mechanism and through a ducting system outside. It's then replaced by fresh air from a different source, usually another air vent. In residential buildings, exhaust ventilation/fans are generally found within the bathroom, kitchen, or

utility room as shown in Figure 4 below to ensure a build-up of steam and humidity doesn't become too prevalent.



Figure 4: Extractor fan hung on a tiled wall Source: [Forbes.com](https://www.forbes.com)

The opposite of exhaust ventilation is **supply ventilation (Figure 5)**; conversely, supply ventilation works by pressurizing the building and forcing external oxygen particles inside via a fan.

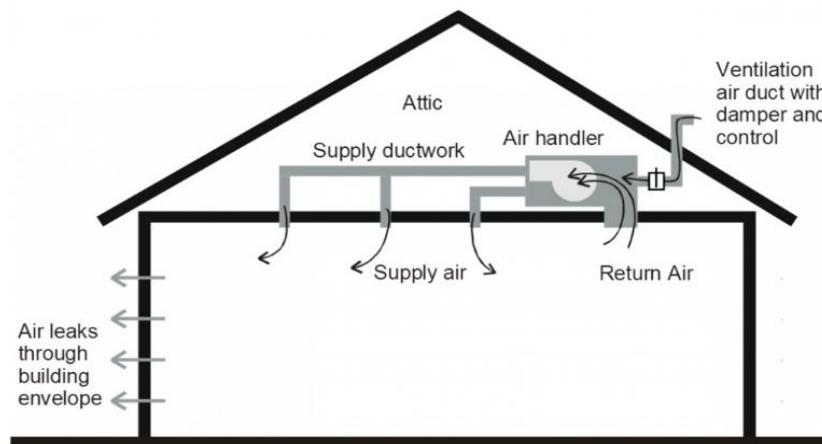


Figure 5: Diagram showing supply ventilation system Source: [Hafeez Smart Solution System](https://www.hafeez-smart-solution-system.com)

Indoor air will then escape via cracks in the building, doors, and windows, or purpose-built ducts and vents. This ventilation strategy is usually used within living rooms and bedrooms, their design allows a better quality of air into the house, filtering out dust and other pollutants. More balanced designs can be implemented to counter the potential

disadvantages of exhaust and supply ventilation that neither pressurizes nor depressurizes the building. Instead, they seek to inject and exhume the same level of air by positioning at least two fans and two duct systems in the most effective positions around the room as shown in Figure 6; this is often referred to as **Balanced Ventilation**.



Figure 6: Multi-port Supply ventilation system

Source : [Hafez smart solution system](#)

When ventilation is neither Natural nor entirely Mechanical or a combination of both, then it is referred to as a Hybrid Ventilation strategy. Hybrid Ventilation is usually a two-mode system (mechanical-natural), which is controlled to minimize energy consumption while maintaining acceptable indoor air quality and thermal comfort. The designer of a hybrid ventilation system has to take a pragmatic approach, not just for the purest or simplest strategy, but for the best solution to meet the ventilation needs of the space, whilst minimizing the cost, maintenance, and energy consumption implications. Like the mechanical system, the hybrid ventilation strategy also has some variances like ***Contingency designs*** which are usually naturally ventilated buildings that have been planned to permit the selective addition of mechanical ventilation and cooling systems where this is needed at a subsequent date; and the opposite can also be applied. ***Complementary systems*** natural and mechanical systems are designed for integrated operation This is the most common variety of hybrid mode systems, and it can operate in

a concurrent manner (or in a changeover manner (on a relatively frequent basis, or alternately on a less frequent basis). In **Zoned systems**, these allow for differing servicing buildings. The zoned approach works best where the areas are functionally different, Figure 7 below shows a description of a hybrid ventilation system.

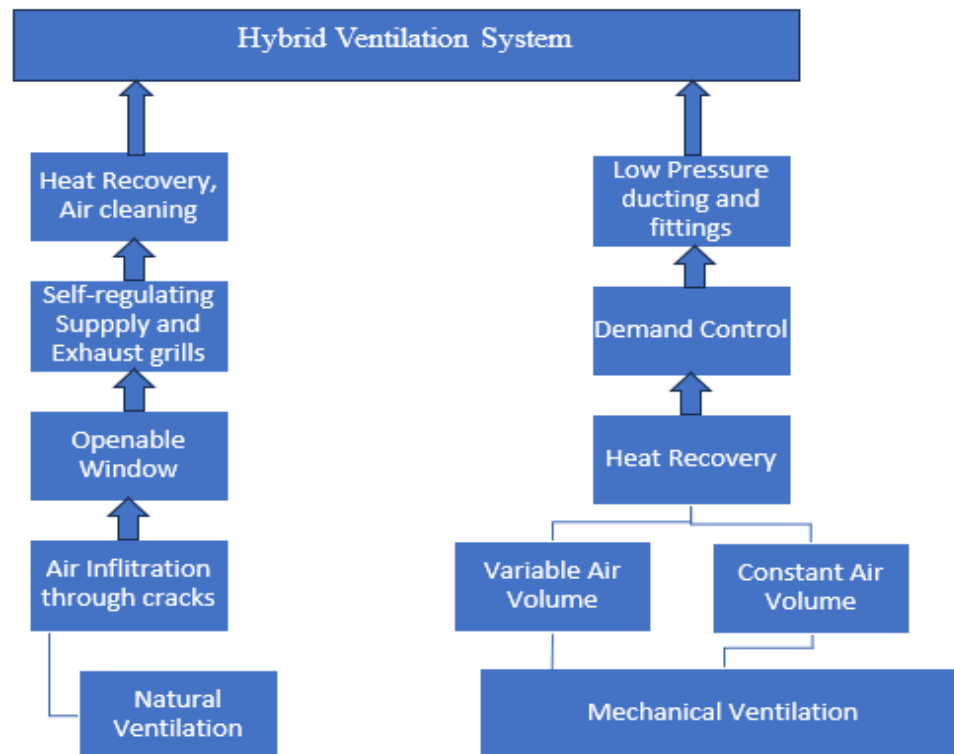


Figure 7: Hybrid Ventilation System

Ventilation can be used to control indoor air contaminants by:

- 1) Diluting contaminants with outdoor air
 - a. Increase the total quantity of supply air (including outdoor air)
 - b. Increase the proportion of outdoor air to total air
 - c. Improve air distribution
- 2) Isolating or removing contaminants by controlling air pressure relationships

- a. Install effective local exhaust at the location of the source
- b. Avoid recirculation of air that contains contaminants
- c. Locate occupants near supply diffusers and sources near exhaust registers
- d. Use air-tightening techniques to maintain pressure differentials and eliminate pollutant pathways
- e. Making sure that doors are closed where necessary to separate zones

2.4 Air Conditioning in Building

Air-conditioning systems are usually classified based on the method of heating and cooling energy transfer between central plants and conditioned building spaces. Generally, air conditioning systems are built either as a central system or a decentralized system. Figure 8 below shows a line diagram of a typical HVAC system.

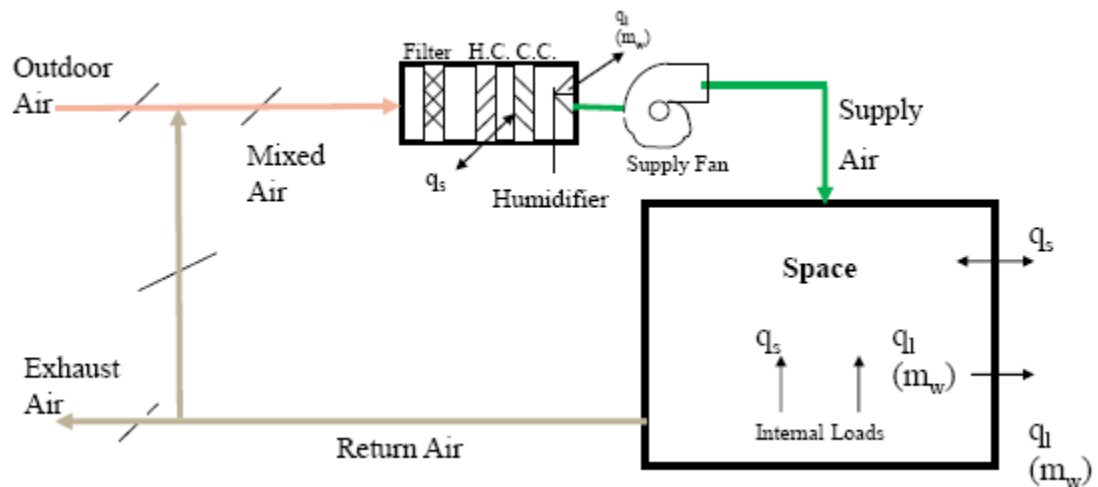


Figure 8: A line diagram of an HVAC system

A central HVAC system can serve one or multiple thermal zones. Its major equipment is located outside the served zone(s) in a suitable central location, whether inside, on top, or

adjacent to the building. The central system must condition zones according to their equivalent thermal load. To achieve this, central HVAC systems have several control points, such as thermostats for each zone. The medium used in the control system to provide the thermal energy sub-classifies the central HVAC system, as shown in Figure 9 below:

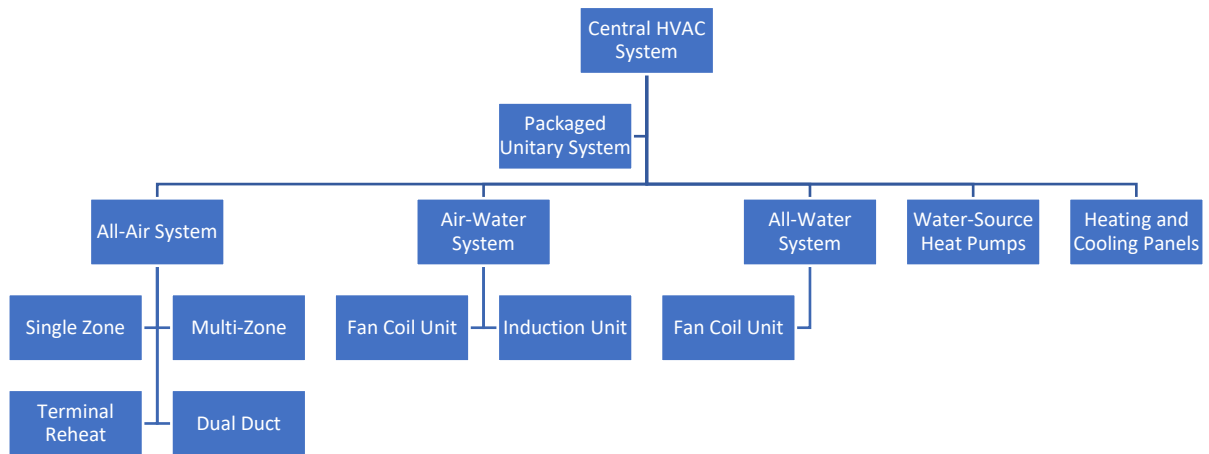


Figure 9: Types of Central HVAC System

Among the types of central HVAC systems, the most commonly used four are the all-air systems, air-and-water systems, all-water systems, and packaged unitary equipment systems; among these four, the All-air systems are mostly used in air conditioning. Two main air-distribution systems associated with all-air air-conditioning systems are constant-air-volume (CAV) and variable-air-volume systems (VAV). Different types of these two approaches are available, such as single-duct, dual-duct, reheat, and multi-zone systems. CAV systems have been used since the introduction of air-conditioning, while VAV systems have been utilized since the 1960s. Energy saving is one of the primary reasons that VAV

systems are very popular design choices today for some commercial buildings and many industrial applications, one major problem with this system is that the volume of the air delivered to the zone being conditioned is usually reduced whenever operating loads are less than design loads, Figure 10 below shows a line diagram of all-air HVAC system for a single zone.

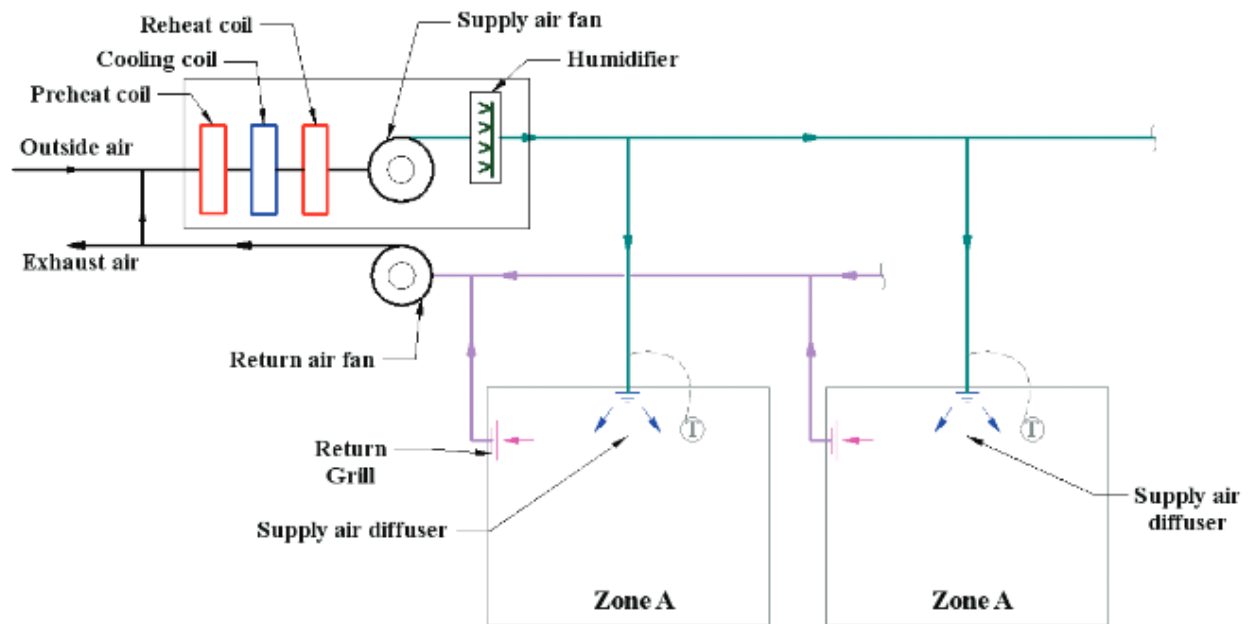


Figure 10: All-air HVAC system for a single zone. Source : <https://www.ncbi.nlm.nih.gov/books/NBK143277/>

2.4.1 Constant Air Volume (CAV)

CAV is a means of delivering conditioned air in a building. As said earlier, this system is becoming less common in new buildings simply because its counterpart, the VAV system, is replacing them due to their superior zone control and much-reduced energy consumption. Constant air volume systems accomplish cooling and heating by varying the supply air temperature and keeping the air volume constant. Despite this demerit of this system, it is fairly cheap to install and they're much simpler to operate. Additionally, hospitals will often still use these systems for their theatres. The operation of the CAV-HVAC system is simple,

the system has an Air Handling Unit (AHU), where the air is collected and mixed, it is usually located in the mechanical room; after the air is processed, the treated supply air exits the duct into the rooms via the diffusers. It circulates around the room and the used stale or dirty air is then sucked into the returned duct via a grille somewhere else in the room. This air will be returned back to the AHU where it can either be dispersed straight out to the atmosphere or some of it can be recycled and reused. Figure 11 below shows a plan view of an installed CAV-HVAC system.

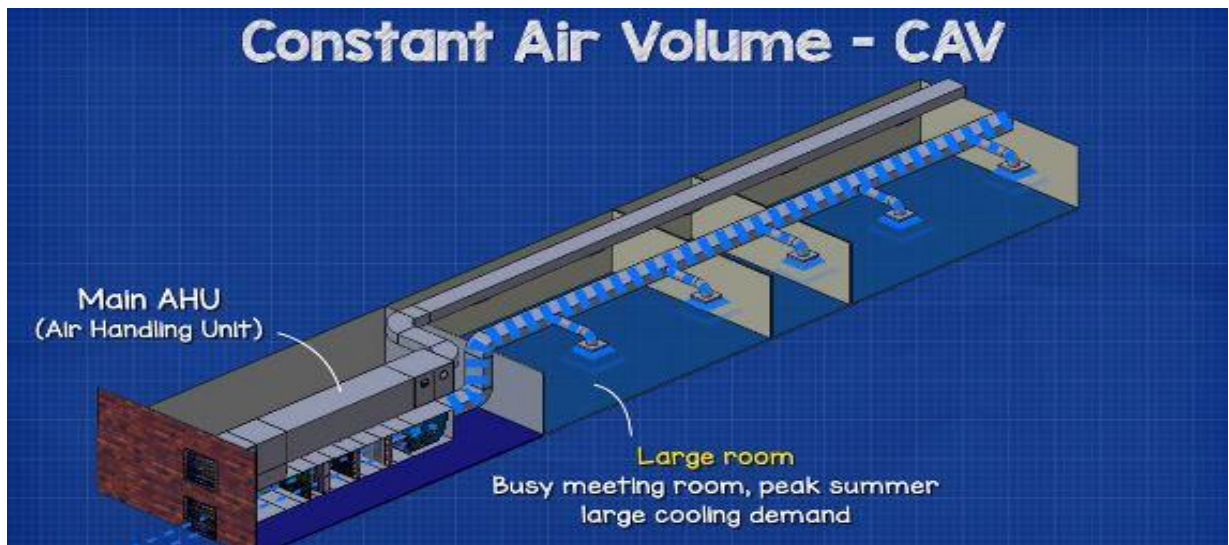


Figure 11: The arrangement of a CAV-HVAC System

Source: Engineeringmindset.com

2.4.2 Variable Air Volume ((VAV)

VAV is known as Variable Air Volume, it is a type of ventilation system commonly used in office buildings. In this type of air conditioning system, the volume of the flow rate of air supplied varies according to the sensible heat load. In other words, thermal comfort in the conditioned space is maintained by having a constant temperature and varying the quantities of supply air (Kalaiselvam et al., 2006) . This system also allows different zones in the same building to operate at different temperatures from the same Ventilation systems

(ductwork / AHU). Supplied air from the AHU is usually at 13°C, the VAV terminal is placed before the zone, and receives signals from the thermostat. Energy is consumed in the AHU of a HVAC system to condition a mixture of return air and outdoor air (OA). The outdoor air is needed to meet ventilation (air quality) requirements. When this ventilation air is supplied at a constant rate, it usually lead to over-ventilation of spaces at part loads and results in higher energy consumption. However, (Kalaiselvam et al., 2006) cited Reddy *et al* (1998) in arguing that if it is supplied as a percentage of total air, it may not meet ventilation requirements, since at part load conditions a decrease in supply air quantity decreases the fraction of outdoor air. Hence there is a need for proper strategy to help eliminate the problems of under ventilation and over ventilation and the associated energy penalty; however, several works have been done to optimize the system, especially in the reduction of energy consumption, while little effort has been exerted on the system to help enhance it for ventilation effectiveness. Wang & Xu, (2004) studied the impact of seasonal variations on indoor air quality and energy consumption of VAV systems, and they outlined a control policy of combining demand-controlled ventilation and economizer control to help achieve adequate indoor air quality with minimum energy consumption in buildings. Savings of cooling coil energy consumption from 88.47% to 41.7% were observed. Pan et al., (2003) also conducted a computer simulation of different control strategies of outdoor air flow rates for VAV systems for four known seasons, Through the analysis and subsequent comparison of results with experimentation, they found that an outdoor air control strategy has a significant impact on the energy savings potential and indoor air quality requirements of VAV systems. Figure 12 below shows a line diagram of a VAV-HVAC system.

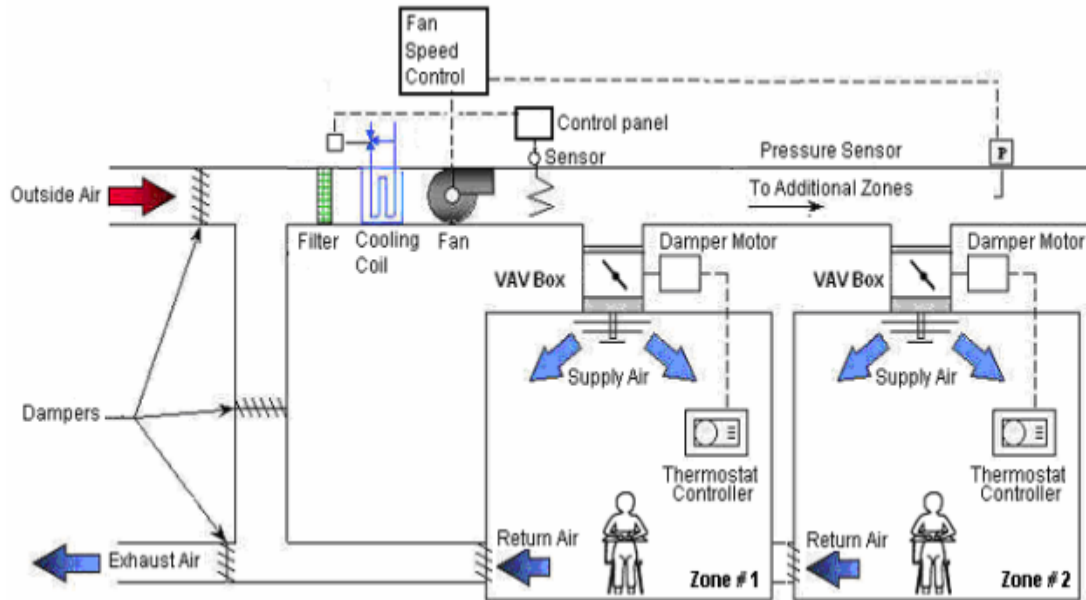


Figure 12: A line diagram of a VAV-HVAC System.
Source: (A. Bhatia, 2020)

To provide the necessary ventilation with VAV systems, a variety of system design and control techniques have been suggested overtime. And some of the strategies include:

- i. Adjusting the outdoor air damper according to the outside airflow data. For example, a minimum position signal equal to 20 percent of the actuator span is set for outdoor air dampers if the system is designed for a minimum of 20 percent outdoor air. Typically, the damper is interlocked to open when the unit is in operation and in an occupied cycle and closed when the unit is shut down. This modulating damper method can also allow CO₂ based demand ventilation control to reduce airflow when spaces have low occupancy. When the unit is turned on and in an occupied cycle, the damper is normally interlocked to open, and when it is turned off, it is closed. When a space is not in use, this modulating damper approach can also enable CO₂ based demand ventilation control to decrease airflow. The minimum outdoor air set point can be a fixed value set for the design minimum

flow rate or can be a variable based on occupancy, CO₂ level or some other parameter.

- ii. To keep the supply and return air fans operating at different volumes of supply air, adjust the speed of the return air fan.
- iii. Provide a ventilating stream fan of fixed air flow quantity and a companion relief fan with control logic to continually rebalance the building ventilation systems.
- iv. Provide an Independent Make Up Air Handling System, which is sometimes called A dedicated outdoor air system (DOAS).

A. Bhatia, (2020) stated that the last option provides the simplest and least costly of the five and when properly applied, provides the best performance. Here a dedicated 100% makeup air handling unit (MAH) treats all of the make-up air and supplies it to recirculating air handling (RAH) systems.

2.5 Airflow in Building

The way air flows through a structure or individual rooms can significantly affect how energy-efficient a ventilation system is. Furthermore, airflow behavior affects general circumstances, the thermal environment, and the spread of airborne pollutants. Building airflow behavior and mixing features are receiving more attention in an effort to optimize design and guarantee a healthy interior. It is frequently challenging to give careful thought to the pattern or impact of air movement on thermal and pollution transfer. The arrangement of the room, the position and strength of the heat source, the interaction of leakage holes, the location of supply and extract terminals, occupant patterns, and room layout all

combine to affect the flow pattern. Figure 13 below shows the pictorial representation of factors influencing air movement in a typical room.

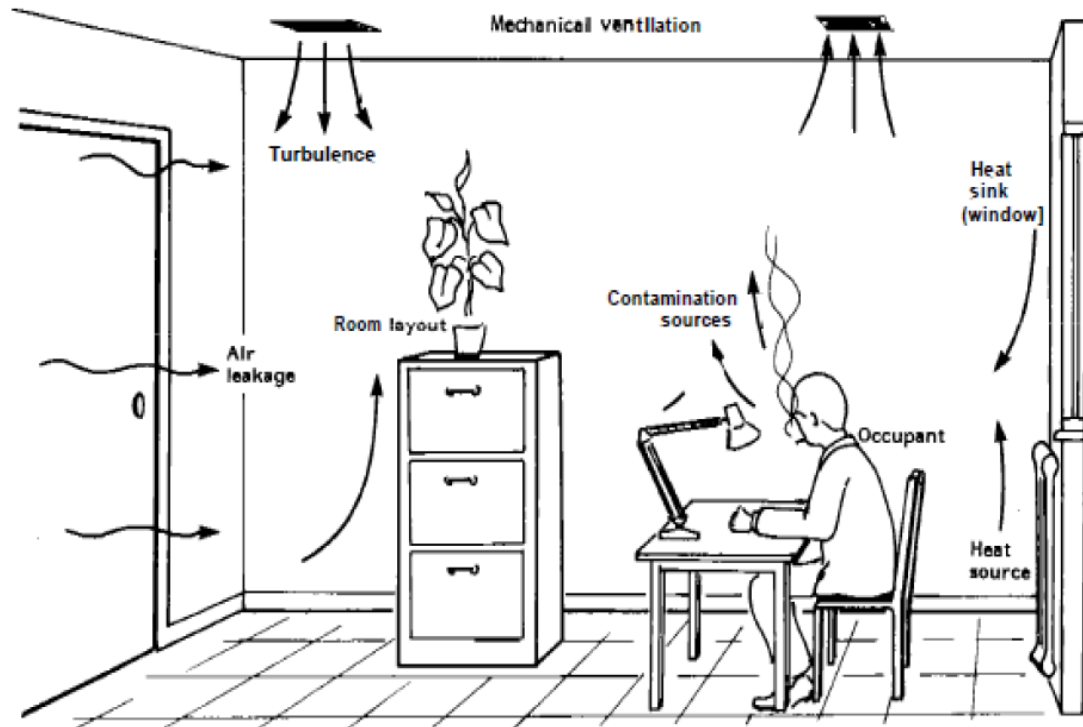


Figure 13: Factors Influencing Air Movement

Historically, mass flow rates through specified apertures and the direction of flow into and out of zones have been the main focus of numerical methods for building air flow analysis. (Martin, 1991). In addition to providing data on interzonal airflow patterns, these techniques can be used to forecast air change rates. Nevertheless, because it is believed that air flow inside particular zones is instantaneously and fully mixed, these approaches overlook this phenomenon. The application of computational fluid dynamics to forecast the pattern of air flow in buildings has drawn more attention recently. More details about computational fluid dynamics is discussed in subsequent section of this study.

2.5.1 Airflow Representation in Building

The air movement in buildings is caused by pressure differences between adjoining air masses, which are maintained by forces that originate from nature or machinery. These forces could be time-dependent, meaning that the pressure distribution changes over time, or they could be constant, meaning that there is a steady state. Figure 17 (a-b) shows the interzonal airflow (flow within each zone is undefined) Conventional multi-zone model, and a typical room airflow (C F D modeling required) Flow within the Zone is defined. To forecast the airflow pattern, temperature field, and ensuing pollutant distribution inside a container, it is essential to depict the force equilibrium at each location in the field that controls flow transport behavior. These expressions must consider momentum, the convective and diffusive properties of air, friction and buoyance forces, turbulence, the temperature field, and the emission and distribution characteristics of pollutant sources. The basic concepts of flow analysis are laminar, Buoyancy, and pollutant transport.

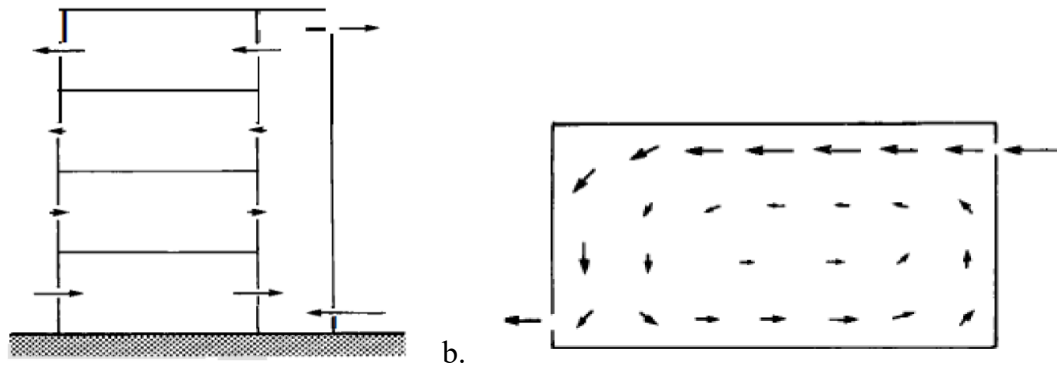


Figure 14: a. Interzonal airflow (Flow within each zone is undefined) Conventional multi-zone model
a. Room airflow (C F D modeling required) Flow within Zone defined.

2.5.1.1 Laminar Flow

Laminar flow of air in buildings could be either forced convection or through buoyancy (i.e. mixed and free convection)

- **Forced Convection**

Under isothermal (uniform temperature) conditions, laminar forced convection can be defined as an undistributed or smooth flow that is governed by mechanical forces. The Navier-Stokes Equation is typically used to describe such flows. These translate the laws of momentum conservation and continuity for an incompressible fluid into mathematical expressions. Essentially, continuity is the exact opposite of mass conservation, where air entering a space and air exiting it are of the same mass. Newton's second law of motion is expressed in terms of the law of conservation of momentum, which considers the stresses involved in the motion of an incompressible, isotropic, viscous fluid element.

- **Buoyancy** (i.e. mixed and free convection)

When thermal gradients exist inside an enclosure, the environment can no longer be considered isothermal; the temperature and air density will fluctuate throughout the enclosed space. The ratio of the temperature differential to the distance between two points or, to put it another way, the change in temperature over a specific length, defines this thermal gradient. A temperature gradient is a measurement that indicates the direction and rate at which the temperature varies fastest in the vicinity of a specific point. The temperature spatial gradient is a vector quantity with the dimension of temperature difference per unit length. Two types of buoyancy-induced convection can be taken into consideration: free convection, where airflow is solely induced by temperature effects, and mixed convection, where buoyant forces alter the pattern of force airflow. A total of six unknowns or dependent variables are usually present in the flow field description, these equations are Continuity- Momentum (U component), Momentum (V component), Momentum (w component), Thermal Transport Equation of the State of an ideal Gas

2.5.1.2 Turbulent Flow

Although laminar flow formulation offers a somewhat simple introduction to the fundamentals of transport flow, it is only useful in situations where air velocity is low. Some cleanroom ventilation systems and displacement ventilation systems could serve as examples. In general, turbulence, which is produced by relatively high supply air velocities and significant temperature differences, dominates the behavior of room ventilation. In these circumstances, random fluctuations in flow patterns appear on top of a mean velocity distribution, replacing the smooth characteristics of laminar flow. As with laminar flow, the concepts of forced, mixed, and free convection are maintained. Also, the Navier stroke Equation remains the same but the velocity variable is replaced by time average and fluctuating components which yield additional stress terms (Reynolds Stresses). More so, additional turbulence and pressure terms are introduced in the temperature and pressure equations.

2.5.1.3 Contaminant Transport

Incorporating the dispersion and spread of pollutants from designated sources is an additional prerequisite for conducting an air quality analysis. To tackle this, the pollutant flow is expressed as an extra transport equation that is similar to the preceding equations. For the purpose of describing the pollutant field within the flow regime, at least one additional equation is required.

2.5.2 Computational Fluid Dynamics (CFD)

In many disciplines, including engineering, molecular dynamics, and astronomy, modeling, and simulation now emerge as the order of the day after theories and experimentation. One way to use prediction science and discover new information is through modeling and simulation. It helps to resolve practical issues that theoretical reasoning cannot address, and that experimental analysis could be costly. Computational fluid dynamics is an

excellent modeling and simulation technique (CFD). Figure 15 below shows how engineering solutions have evolved overtime.

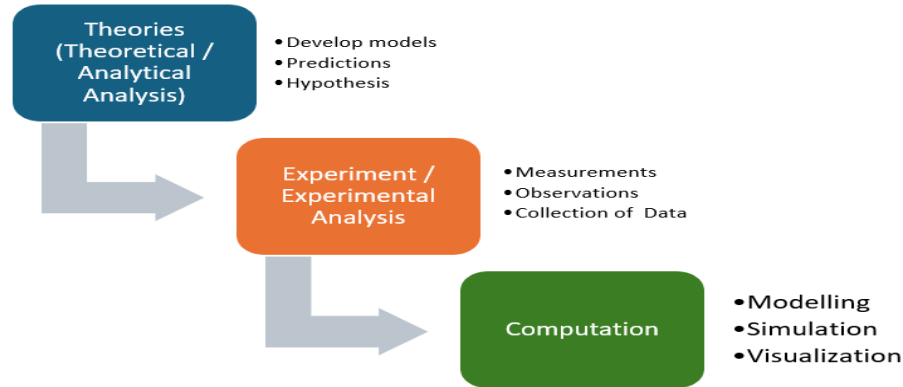


Figure 15: Evolution of Engineering Science

Computational fluid dynamics (CFD) has been defined in many ways by mathematicians and various experts in the field of fluid dynamics, moreover, an agreed definition of CFD has been presented by Sharad, (2023) as a technique of flow predictions by numerically solving governing equations of fluid flows, and the governing equations are conservation of mass, momentum, heat, and mass transfer. Numerical methods are used to convert partial differential equations into algebraic sets of equations. After solving iteratively using computer programs, engineers visualize predicted velocity, pressure, and temperature. The CFD method numerically solves a set of partial differential equations to evaluate velocity, pressure, temperature and the species concentration in fluid flow problems. Both experimental measurements and numerical simulations have been used to design air distributions. Experimental measurements are time consuming and expensive, but numerical simulations, especially computational fluid dynamics (CFD), are very popular with building designers because they can provide detailed information with reasonably high accuracy and acceptable cost (Liu et al. 2012a). Ali, (2014) cited a review by Chen (2009), that CFD is becoming the primary method for designing indoor air distributions.

As would be seen subsequently, solving problems using the CFD involves three (3) steps, vis-à-vis: Pre-processing: Creation of geometry and meshing; Simulation: Solving governing equations over a meshed model; and Post-processing and results analysis: Predicted physical quantities need to be analyzed qualitatively and quantitatively. A package for computational fluid dynamics called FLUENT is used to simulate flow problems. It is built to solve fluid governing equations using the Finite Volume Method (FVM). Due to its two key features, the FVM is highly beneficial in a wide range of computational dynamics applications. In the first, the computational domain is split up into control volumes, and the divergence theorem is used to transform volume integrals into surface integrals in equations including divergence terms. These terms are then estimated as fluxes across the volume surfaces of each finite volume; these methods are dubbed conservative since the flux entering a given volume is equal to the flux exiting the adjacent volume. The finite volume method's ability to work with unstructured meshes is its second benefit (FI, 2003; Ismail-Zadeh and Tackley, 2010). Different physical models, such as incompressible or compressible, inviscid or viscous, laminar or turbulent, etc., are available in FLUENT for different applications of fluid flow. To balance the sum of mass fluxes into or out of a cell from all its neighbors to zero, CFD models typically divide the interior space into a number of cells, in which the conservation of mass is satisfied for each cell. Similarly, pressure, gravity, viscous shear, and energy transfer by turbulent eddies must all be balanced in both directions when determining the momentum exchange from the flow into or out of a cell (Srebric, 2011). The major challenge for transitional and fully turbulent flows that usually exist in room flows is to appropriately describe the transport of energy and momentum. Turbulent flows are three-dimensional and random with many turbulent

eddies (vortices) that improve mixing in the flow field. Additionally, mixing usually leads to a reduction in velocity gradients and dissipation of the kinetic energy of the fluid stream. Therefore, to examine the effect of turbulent mixing on thermal comfort and indoor air quality it is essential to solve the partial differential equation governing turbulent flows. Kato, (2018) cited Srebric, (2011), and Nielsen et al. (2007), to state the governing equations of the instantaneous flow which are:

- **Continuity Equation (Mass Conservation)**

For an incompressible fluid:

$$\nabla \cdot \mathbf{u} = 0 \quad \text{-----} \quad (1)$$

where:

$\mathbf{u} = (u,v,w)$: velocity vector of the fluid in Cartesian coordinates.

For a compressible fluid:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad \text{-----} \quad (2)$$

where:

ρ : fluid density

- **Momentum Equation**

In vector form:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{f} \quad \text{-----} \quad (3)$$

Breaking it down in Cartesian coordinates (x,y,z) :

$$\left. \begin{aligned} \rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) &= -\frac{\partial p}{\partial x} + \mu \nabla^2 u + f_x \\ \rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) &= -\frac{\partial p}{\partial y} + \mu \nabla^2 v + f_y \\ \rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) &= -\frac{\partial p}{\partial z} + \mu \nabla^2 w + f_z \end{aligned} \right\} \text{----- (4)}$$

where:

ρ : density of the fluid,

u : velocity vector (u, v, w),

p : pressure,

μ : dynamic viscosity,

f : (f_x, f_y, f_z): external forces per unit volume (e.g., gravity).

- **Energy Conservation Equation**

$$\frac{\partial}{\partial t} (\rho e) + \nabla \cdot (\rho e \mathbf{u}) = -\nabla \cdot \mathbf{q} + \Phi \text{----- (5)}$$

where:

e : specific internal energy, q : heat flux, Φ : viscous dissipation term.

There are numerous computer software's that have been manufactured to help solve computational fluid dynamics problems, part of which are: OpenFOAM, COMSOL Multiphysics, CFD simulation, STAR-CCM+, Sim-center FLOEFD software, Power FLOW imports, CAD-driven CFD software, FLOW-3D, Ansys Icepak, Design Builder, ANSYS – Fluent, Autodesk CFD, SimScale, CFD Module, Flowsquare, ParaView, Altair, Solidworks. In all of these ANSYS- Fluent has been the most widely used, and the reason for this is not farfetched, as Zou et al., (2018) cited Li (2015) in his comparison of these software, and concluded that ANSYS Fluent was suitable for simulating a complex indoor

environment because the program can obtain the precise point value of any variable at any location when compared to others.

According to Ramponi et al., (2015) CFD simulation has an edge over other ventilation performance evaluation methods in the following ways;

- i. CFD provides whole flow field data on relevant parameters at all points of the computational domain.
- ii. Due to its ability to perform full-scale simulation, CFD avoids incompatible similarity requirements that usually happen in reduced-scale testing.
- iii. CFD permits full control over the boundary conditions and allows parametric studies to be performed easily and efficiently.
- iv. CFD models are presently the most popular and specifically appropriate for studying indoor air quality and natural ventilation.

2.6 Ventilation Effectiveness, Ventilation Rate & Indoor Air Quality

As earlier explained, providing an adequate quantity of fresh air to an occupied space is necessary for the dilution of indoor pollutant concentrations (Daisey et al., 2003), however (Rim & Novoselac, 2010) argued that the increase in the fresh air supply rate, as a single measure that reduces pollutant concentration, does not seem to be an adequate exposure prevention strategy. They both continued that additional strategies for reducing occupant exposure to indoor air contaminants include air cleansing, source emission management, and/or increased ventilation efficiency. Reduction of source emissions and cleaning the air are very effective ways to reduce exposure, but they necessitate the identification of each emitter or the control technology required for each type of source. All of these describe

noting but a good ventilation effectiveness within the indoor space. Ventilation effectiveness is an indicator of the quality of supply air distribution in ventilated rooms, that can be used in both the building design phase and for on-site application. It illustrates how well an area is ventilated in comparison to ideal air mixing conditions. Indicators of human exposure and air quality can be roughly determined by using ventilation effectiveness, which depends on the characteristics of the pollutants and their position in relation to the airflow. The supply flow rate of fresh air per unit space volume, is defined as air changes per hour (ACH), represents a quantitative measure of ventilation, ventilation effectiveness is the qualitative counterpart of ventilation system performance. Because it controls how well supplied fresh air is distributed in the inhabited space, ventilation effectiveness is related to both the dilution and removal of indoor airborne contaminants.(Rim & Novoselac, 2010). Researchers have used several indoor air quality indicators to evaluate the effectiveness of ventilation in relation to pollution control in an occupied space (Chung & Hsu, 2001) (Fisk et al., 1997) (Kato & Yang, 2008). One of the most commonly used indicators in the field is the air-change effectiveness (A. K. Persily et al., 1994). Ventilation rates in occupied buildings can change over short time scales due to changes in weather or window and door positions. This parameter describes the quality of supply air distribution in the space, based on the spatial distribution of age-of-air. Age-of-air is defined as the time elapsed from the moment that air enters into an indoor space and reaches the considered location(Rim & Novoselac, 2010). The local value of age-of-air in a specific location describes the freshness of air, and is directly correlated with the airflow path. Air-change effectiveness is defined as the ratio of the age-of-air for perfect mixing to the average age-of-air in a considered zone (ASHRAE standard 129). There are

various standards that specifies minimum requirement for ventilation rates, part of which are the ASHRAE, CIBSE, ISHRAE, Korean Regulation etc. Some of the specifications by these standards are highlighted below:

- **By Korean Regulations**

According to Standards for Facilities of Buildings, a new office building with a total floor area of over 3000 m² must be equipped with mechanical ventilation systems to ensure a ventilation rate of 29 m³/person/h. In this case, a natural ventilation system (i.e., openable windows) cannot be substituted for a mechanical ventilation system. The standards also mandate specified ventilation rates for other buildings with more than defined floor areas besides office buildings.

According to ASHRAE Standard 62 ventilation-rate procedure, the office rooms and the classrooms should be supplied with fresh air at a flow rate of 28 m³/h per person. Fresh-air requirements for laboratories and corridors are 36 m³/h per person and 1.8 m³/h per square metre, respectively. These resulted in minimum total ventilation rates of 7001 m³/h for the school building and 3359 m³/h for the office center. Table 2 below shows other minimum ventilation rates in various office spaces.

Table 2: Ventilation Rates specification from ASHRAE

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TABLE 6.2.2.1 Minimum Ventilation Rates in Breathing Zone (Continued)
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate <i>R_p</i>		Area Outdoor Air Rate <i>R_a</i>		Notes	Default Values			Air Class
	cfm/ person	L/s- person	cfm/ft ²	L/s·m ²		Occupant Density (see Note 4)	Combined Outdoor Air Rate (see Note 5)		
						#/1000 ft ² or #/100 m ²	cfm/ person	L/s·person	
Office Buildings									
Breakrooms	5	2.5	0.12	0.6		50	7	3.5	1
Main entry lobbies	5	2.5	0.06	0.3	<u>H</u>	10	11	5.5	1
Occupiable storage rooms for dry materials	5	2.5	0.06	0.3		2	35	17.5	1
Office space	5	2.5	0.06	0.3	<u>H</u>	5	17	8.5	1
Reception areas	5	2.5	0.06	0.3	<u>H</u>	30	7	3.5	1
Telephone/data entry	5	2.5	0.06	0.3	<u>H</u>	60	6	3.0	1

2.7 Tracer Gas Experiment (TGE)

Tracer gases are gases we use in buildings to diagnose/investigate gaseous fluids when carrying out building performance assessments. Clifford, (2017) defines a tracer gas as any gas that is injected into the main body of air in small amounts to measure the air current or leakage channels in a ventilation system is called an air tracer. This assessment can come in a wide range of diagnostic techniques including leak detection, atmospheric tracing, and ventilation (i.e. air flow) in buildings (Cui et al., 2015). A substance known as an air tracer allows one to track the movement of air over space and time once it is released into the atmosphere. Ventilation is an important process in buildings because of its impact on both energy requirements and indoor air quality--both of which are topics of concern in our modern world. Simply put, a tracer gas can be defined as an idealized substance used to tag volumes of air to be able to infer their bulk movement (Laussmann & Helm, 2011). The measurement of the tracer gas combined with conservation laws allows a quantitative determination of the tracer transport mechanism (i.e. a measurement of the air flow). Several authors have argued that the use of trace gas has not been limited to buildings alone, for instance, the leak testing that tracer gas offers has been used in the petrochemical industry, the automotive industry, and in the manufacture of semiconductors, among other uses.

2.7.1 Fundamentals of Tracer Gas Measurements

As mentioned earlier, outdoor air comes into the building, and the indoor air also goes out; because it is almost impossible to make the buildings airtight, as presented schematically in Figure 13 below. It is important to also know the air flow rate through the envelope of the space due to energy issues and indoor air quality. However, when it is necessary to

compare different spaces regarding global air leakage (or air tightness), it is more important to know how many times per hour the inside air is replaced (changed) by new one coming from outside—air exchange rate, I (air changes per hour).

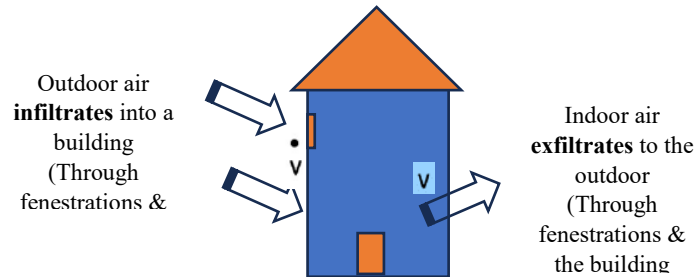


Figure 16: A schematic illustrating of the air exchange in a closed space

By defining, mathematically I we can say:

$$I = \dot{v} / V \dots\dots\dots (6)$$

where I is the Air Change/hour

For example, if $I = 1$ ach, this means that all the inside air of the space is replaced by outside one in one hour.

Since the space under study is a single zone, i.e. with a uniform inside tracer gas concentration. The tracer gas balance of the space results in the following mathematical equation:

$$q \cdot dt - (c - c_{atm}) \cdot I \cdot V \cdot dt = \left(\frac{dc}{dt} \right) \cdot dt \cdot V \dots\dots\dots (7)$$

Where:

q = mass flow rate of tracer gas released

C_{atm} = environment tracer gas concentration

V = volume of the space

c = concentration inside the space

I = air exchange rate through the envelope of the space t = time

Reorganizing the terms, it is possible to get the non-homogeneous first-order nonlinear equation:

$$\frac{dc}{dt} + I \cdot c = I \cdot c_{\text{atm}} + \frac{q}{V} \dots \dots \dots (8)$$

And the solution for this could be

$$c = K \cdot e^{-I \cdot t} + c_{\text{atm}} + \frac{q}{I \cdot V} \dots \dots \dots (9)$$

As at the beginning of the tests, the initial tracer concentration can be written as $c = C_{\text{atm}} + C_0$ (C_0 is the initial concentration in the space), and the last equation becomes:

$$c = c_{\text{atm}} + \frac{q}{I \cdot V} \cdot (1 - e^{-I \cdot t}) + c_0 \cdot e^{-I \cdot t} \dots \dots \dots (10)$$

As the mass flow rate q tends to zero (0) because of the decay, the equation (10) then becomes:

$$I = \frac{1}{t} \cdot \ln\left(\frac{c_0}{c}\right) \dots \dots \dots (11)$$

where $c = c - C_{\text{atm}}$

It is evident from the equation presented above that measuring the tracer concentration only twice (C_0 and C for a specific time interval) would be sufficient to calculate I for the given space; and that is why the formula is sometimes referred to as a ***two-point decay formula***. However, it is crucial to note that in this scenario, the error in evaluating I can be significant as the measured value of c at one time (t) may vary from its value at another time instant.

To calculate the air exchange rate of a space, it is common practice to take multiple measurements of the tracer concentration at set time intervals. These values can then be plotted on a graph, with $\ln(c)$ on the y-axis and time on the x-axis. The resulting line should be nearly straight, and the absolute value of its slope equals the air exchange rate of the space. It is worthy of note, that equation (5) above will produce a straight-line graph, which its gradient represents the value of I , the air change rate.

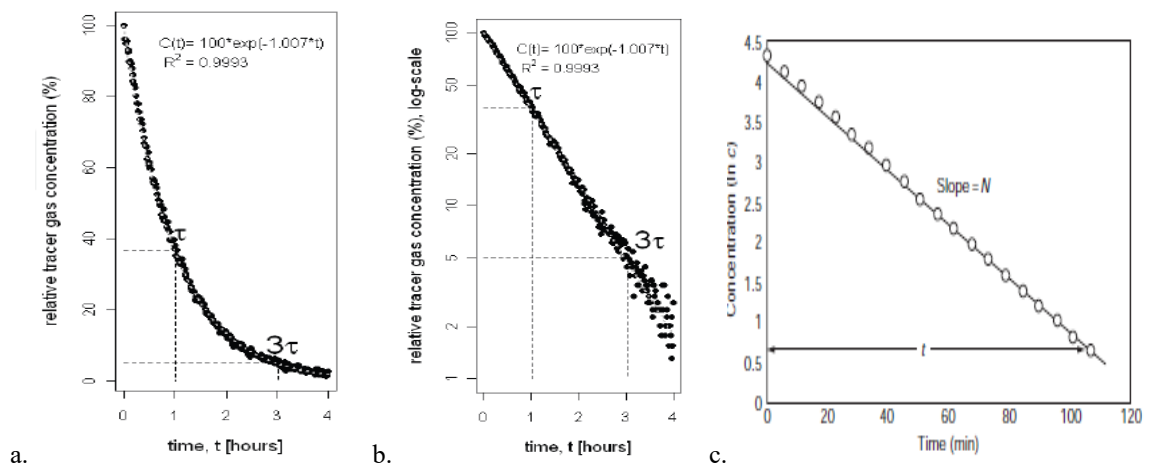


Figure 17: Typical tracer gas decay rate measurement in a ventilated room, showing line graph of Natural Log of Concentration Vs Time
a. untransformed ordinate; b & c after logarithmic transformation

2.7.2 Techniques of the Use of Tracer Gas

Mostly for ventilation studies i.e., to measure the air change performance of a ventilation system in buildings, the tracer gas technique is the most common way. It has been practiced for a long time. It has been preferred to other air change performance measurement methods since they are more convenient and accurate (Chao et al., 2004), in fact, Hitchin & Wilson, (1967) argued that to see an alternative method to replace it might be very difficult. Awbi, (2004) when describing the methods of measuring Tracer gases, explained,

that there are two techniques in use for measuring tracer gas concentrations: the direct and indirect method. Figure 18 shows a typical flowchart process for a tracer gas experiment.

The indirect method in which case an air sample is collected from the measuring site for analysis in a laboratory; the sample can be collected using plastic bags or bottles, or the gas adsorbed using charcoal, silica gel or porous polymers. The gas sample collected using a bag or bottle can be directly analysed whereas the adsorbed gas in a sample will require flushing out by heating the sample or using a suitable solvent. There are two main categories of gas analysis equipment: infrared absorption spectroscopy (IRAS) and gas chromatography (GC).

The direct method in which case the tracer concentration is measured on site. This tracer gas dilution method is based on a mass balance of the tracer gas in the indoor air (Almeida et al., 2020b). The most common technique to measure ventilation rates is using a tracer gas dilution method (Concentration decay method, constant injection method, and constant concentration method). However, in very specific conditions as in very airtight buildings where airflows occur in ductwork, *velocity transverse methods* can be used to estimate airflow rates. Infiltration rates in buildings are frequently assessed by *pressurization techniques*, commonly known as the *Blower Door Test*, sometimes in association with infrared thermography to obtain information about the air leakage pathways. The three

most used techniques are discussed below:

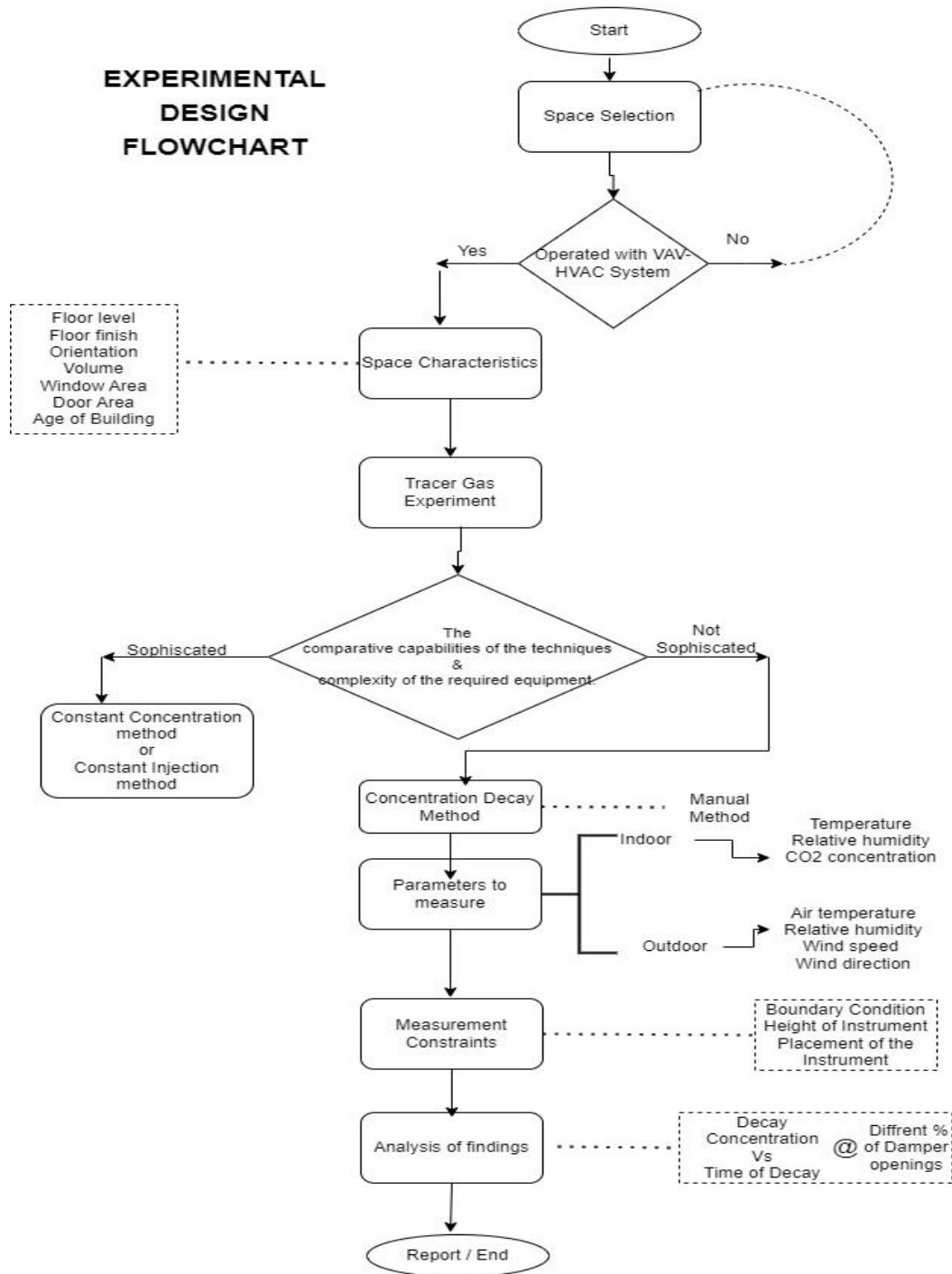


Figure 18: : Tracer gas experimental flowchart

2.6.5.1 Concentration decay method

In this method, the tracer gas is injected into the room for a short period of time, either from a gas bottle with a pressure reducer or manually from filled gas tanks. After mixing with the room air the tracer gas concentration is measured at regular time intervals. The decay curve of the tracer gas concentration usually follows an exponential course when completely mixed with the room air. With time, the tracer gas begins to decay, as the decay occurs, each sampling will not only remove old air but also a certain amount of fresh air supply as well. The concentration is monitored during the period of zero injection and then used to infer the ventilation rate, λ . Almeida et al., (2020b) stated that this method which uses linear regression method in its analysis is well established in the literature and the procedure has been fully described in the standards ISO 12,569 and ASTM E 741. However, as opposed to Almeida et al., (2020), Laussmann & Helm, (2011) cited Sherman, (1990) that this method could also use non-linear regression analysis, in which case the air-change-per hour can be determined when tracer gas-concentration at time $t=0$. However, Sherman, (1990) stated that there are three different approaches to analyzing a tracer decay, all of which are transient approaches, and they include the decay regression analysis, integral decay analysis, and two-point (average) decay analysis.

Advantages

- i. it is the simplest approach is using the decay technique.
- ii. it is cheaper and the system is far less complex.
- iii. The period over which measurements have to be taken is not unduly long

Disadvantages

- i. Doubt about the accuracy of the measured rate or average rate (i.e. systematic error) during ventilation studies
- ii. Sometimes (for example, when there is a relatively large flow into enclosed spaces such as furniture) the decay of tracer is usually non-exponential. In this case, the fitting for an exponential decay curve to the data is difficult.
- iii. To obtain uniform concentration at the test requires either complicated pipe work and may release points, or artificially stirring the air, which may alter the prevailing conditions.

2.6.5.2 Constant injection method

In this method, a defined amount of tracer gas is constantly emitted over a certain period of time (ie the flow release rate must be known). Thus, the tracer gas concentration increases with time and reaches a stable value (equilibrium concentration) which depends on the room volume V_R , the air change rate λ , and the emission rate E . At that time point, one or more air samples are taken, and the tracer gas concentration is determined for each sample. According to ASTM E 741 – 00, the tracer gas concentration should have reached at least 95% of the equilibrium concentration before measurements can be started.

Advantages

- i. It can be used for indoor hygiene studies addressing the relationship between pollution and air change in daily used rooms.
- ii. The derived quantity is meaningful without the need to make hypothesis about mixing

Disadvantages

- i. Many measurement positions are needed to determine the ventilation in one room
- ii. In rooms with very low air changes, it will be difficult to correctly measure ACRs with this method, because the build-up time to reach nearly equilibrium concentrations is too long.
- iii. The constant injection method is suitable only for short-term measurements of ACR above 0.3 h^{-1} when diffusion tubes are used as tracer gas source.
- iv. Either a long-time interval or frequent (or continuous) determination of concentrations are required

2.6.5.3 Constant concentration method

During constant and thorough mixing with the indoor air, tracer gas is released in the room until a predefined concentration is reached, the gas concentration is kept constant and the flow release rate must be known. During the entire measurement, the tracer gas concentration is kept constant with an automated dosing and control system. Under the condition of constant tracer gas concentration, the air supply is proportional to the tracer gas supply rate. The air supply rate can then be calculated from the ratio of the tracer gas supply to the tracer gas concentration. If the room volume is known, the ACR can be calculated from this ratio (Chao et al., 2004)

Advantages

- i. Short-term changes of air supply can be easily detected in the process.
- ii. A straightforward single measurement is sufficient if perfect mixing occurs.

- iii. The transfer index from the from the tracer release point to any point in the room can be measured, and only one detector is needed

Disadvantages

- i. The technical equipment required for this method is, however, rather expensive, when compared to other methods and thus this method is comparatively rarely used for indoor air quality evaluation
- ii. A long time is usually needed before equilibrium is reached, as a result of this, more tracer is usually needed per test than other methods
- iii. Errors due to non-static conditions of weather and room usage are more likely to occur and difficulties may arise in ensuring a constant rate of gas

2.7.3 Tracer gas Experiment as a determinant of Ventilation Rate

The tracer gas experiment is used to examine three basic aspects of building air exchange including air exchange rates, interior air movement, and building envelope airtightness (Andrew K. Persily, (1988); Men et al., (2020)). As explained earlier, the measurement of building air exchange rates is important as these rates relate to energy consumption and indoor air quality. Their measurement is useful for determining whether the outdoor air intake rate is compatible with design specifications, and whether relevant ventilation standards are being met. Tracer gases can also be used to examine interior air movement patterns, which are important as they relate to thermal comfort within the occupied space. These interior air movement measurement procedures can also be used to evaluate the performance of a building's air distribution system in providing ventilation air to the

occupants and removing internally generated contaminants. Finally, these tracer gas procedures can be used to verify the isolation of special-use spaces, where hazardous substances are in use, from the rest of a building's interior (Daghigh et al., 2009; Jiangyue et al., 2013). Zhuang et al., (2023), investigated the air change rate in a single room using multiple carbon dioxide breathing models in China; a tracer gas experiment was used; in that study three models (the ASHRAE model, the ASHRAE China-specific modified model, and the BMR model), were proposed to estimate the AER based on exhaled CO₂. Their results indicate that the ASHRAE China-specific modified model has the best performance with an average deviation of -6.67% and a maximum deviation of -14.6% with multiple measurement points. In 2020, Men et al., carried out an experimental study on tracer gas method for building infiltration rate measurement using occupant-exhaled CO₂ as surrogate, they found that an extended monitoring period can reduce the impact of indoor air distribution; they recommended that in actual measurements in residential building, to select the data after occupants have been in the room for half an hour and to take measurements over 1 h is better. To measure air infiltration and natural ventilation using tracer gas technique, Afonso, (2015) carried out a case studies for measurement of mechanical air ventilation in ducts, they concluded that with accurate measurements of air flow rates, it is possible to reduce CO₂ emissions due to air heating or cooling in buildings.

2.7.4 Requirements for ideal and commonly used tracer gases

In the previous section, the name of carbon dioxide is often mentioned for tracer gas experimentation, however, this is not the only gas used in tracer gas experimentation. (Laussmann & Helm, 2011) stated that, historically, a variety of gaseous materials have

been investigated and tested for the purpose of determining the air change rate, primarily in relation to other tracer gases. These materials include helium, hydrogen, oxygen, carbon monoxide, methane, acetone, and the radioactive noble gases argon-41 and krypton-85. He went further to cite reviews done by Grimsrud et al. (1980), Shaw (1984), Sherman (1990), Schulze & Schuschke, (1990) that until the early 1990s, krypton-85 was still used for air change measurement, but later skipped for safety reasons (radiation protection). In the late 90s, the following tracer gases are mainly used in practice (Raatschen, 1995): Nitrous oxide (N_2O), Sulphur hexafluoride (SF_6), Halogenated hydrocarbons, such as hexafluoro benzene (C_6F_6) and perfluorocarbons (PFC). Since the type of gas to be used as tracer for ventilation studies is important as it can affect the accuracy of tracer-gas measurements. (K.W. Cheong & S.B. Riffat, n.d.), the following have been suggested as watchword in any gas to be used as a tracer gas in modern tracer gas experimentation:

- Safety: Nothing in and around the test area should be at risk from the presence of tracer, including persons, objects, or activities. Therefore, the tracer needs to be non-explosive, non-flammable, non-toxic, odorless, and non-irritating.
- Non-reactivity: The tracer gas cannot physically (e.g., be absorbed by the air filters in the ducts) or chemically (e.g., react with duct surfaces, room air, or decompose (affecting measurements) with any component of the system being studied.
- Sensitivity: the processes under study should not be impacted by the tracer's presence. Therefore, the air flow and air density in the system should not be impacted by the ideal tracer gas.
- Distinctive: a perfect tracer shouldn't typically be found in a building or be a part of the air. However, if the backdrop is stable and the extra tracer concentration is

noticeably more than the steady background, a tracer with a non-zero background may be employed.

- Measurability of the concentration aloft in the infrared spectrum needs to be quantifiable using a recognized experimental method that eliminates air interference. It needs to be quantifiable with ease, affordability, and great dependability using some kind of instrumentation.
- Availability: The tracer needs to be able to be purchased commercially.
- Others include the tracer-gas concentration having to be measured to a good degree of accuracy even when considerably diluted, and being easily carried, stored, and disseminated as an atmospheric gas. It should be comparable to air in terms of density, specific heat, and diffusion characteristics. In addition to these requirements, Laussmann & Helm,(2011) cited Raatschen, (1995), when the latter stated that the following should also be considered in the selection of any gas for tracing technique purposed health safety aspects, low environmental burden, high availability, and good handling in practical use at the lowest costs possible and, not least, tracer gases should be well recordable with established measurement techniques over a wide concentration range and with high selectivity. Cui et al., (2015) summed up the requirements in consonant with the above by saying that the tracer gas should be safe (non-toxic, non-allergenic, nonflammable), non-reactive (it should not react chemically or physically with the environment) and easily measurable (preferably it can be measured with low-cost instrumentation which should be able to measure low concentrations), and that the tracer gas should

perfectly mix with air (similar density) and should be distinguished from the constituents of air.

2.7.5 CO₂ and its Preference for the Built Environment in Tracer Gas Experimentation

The use of CO₂ as a tracer gas has been the vogue for centuries, Few & Elwell, (2023) cited Penman, (1980) who developed the use of metabolic CO₂ as a tracer gas for ventilation measurement because this may be more acceptable to occupants than injecting other tracer gases, and because metabolic CO₂ negates the global warming concern that has been witnessed in the use of SF₆ and perfluorocarbons (BSI, 2017), (Almeida et al., 2020). More so, the use of CO₂ comes with ease since it is measurable using relatively inexpensive non-dispersive infrared (NDIR) sensors. Few & Elwell, (2023) continued by saying numerous authors have applied this technique since Penman, particularly in schools and offices (Batterman, 2017), and the use of CO₂ as a tracer gas has also been described in several standards (e.g. BSI, 2017; ASTM, 2018). Cui et al., (2015b) added that apart from its merit when it comes to the greenhouse effect, the use of CO₂ as tracer gas has a cost-effective approach because its density is quite near to that of air, and its use is non-explosive and non-toxic at low doses. Laussmann & Helm, (2011) and Few & Elwell, (2023) also stated that the quantifiable feature of CO₂ with low-cost sensors facilitating multi-point measurements has given it more prominence among other tracer gas, and because of the above, one could arguably say that CO₂ fulfills a number of the above-mentioned specifications of a good tracer gas.

2.8 Building Energy Simulation

In the quest for sustainable and energy-efficient buildings, accurate prediction and analysis of energy consumption have become paramount. Building Energy Simulation (BES) tools

play a crucial role in this process, enabling designers, engineers, and researchers to evaluate the energy performance of buildings under various conditions.

About one-third of the energy consumption in buildings is used to increase the thermal conditions of the dwellings and for lighting. Thermal simulation software tools for buildings allow to:

- Determine the appropriate size of HVAC systems
- Analyze the energy consumption
- Calculate the cost of the energy used.

Using energy simulation software, building designers can consider specific choices, (e.g., heating and cooling), the thermal behavior of buildings prior to their construction can also be predicted, the simulation of the costs of energy in existent buildings in their current conditions, establishing the best thermal retrofitting measures to adopt in the buildings under analysis are also done with the aid of good building energy software. Besides energy consumption, simulation software tools can also be used to calculate the following variables: Indoor temperatures; Needs for heating and cooling; Consumption needs of HVAC systems; Natural lighting needs of the occupants; • Interior comfort of the inhabitants; Levels of ventilation. The calculation of energy consumption spent in dwellings still to build or to retrofit allows a more accurate determination of design charges and helps to decide with the highest accuracy the possible devices to be used in a room (limited zone) or dwelling. Energy simulation software tools can also allow considering all the regulations in force and simultaneously provide a sense of comfort to its inhabitants through a correct design of heating and cooling systems. Such software have also available tools to improve constructive solutions through simulating the incorporation of passive

solar systems in buildings, such as horizontally and vertically shading systems, and a more accurate study of the HVAC system loads to use.

2.8.1 Software for Building Energy Simulation

Joana Sousa, (2012) in his review of software used for Building energy simulations, he categorizes these software into the following:

- Energy Plus
- ESP-r (Energy Simulation Software tool)
- TRNSYS
- IDA ICE
- IES VE (Integrated Environmental Solutions - Virtual Environment)

Energy Plus

Energy Plus is one of the best-known energy simulation software tools. Its development began in 1996, and it was sponsored by the Department of Energy (DOE) from the United States of America (USA). Energy Plus aims to develop and organize software tools in modules that can easily work together or separately. It is important to outline that Energy Plus does not have a visual interface that allow users to see and concept the building. In this case, third-party software tools like Design Builder need to be used. Energy Plus is a thermal simulation software tool that allows the analysis of energy throughout the building and the thermal load and it is used by engineers, architects and researchers to model the energy use and water use in buildings. The software tool simulates models for heating, cooling, lighting, ventilation, other flows of energy, and water use.

ESP-r (Energy Simulation Software tool)

The software tool ESP-r (Energy Simulation Software tool) is intended to support the construction project concerning energy and environmental performance, realistically and

accurately. The software tool is mathematical software for a project manager that coordinates the data, simulation, CAD applications, different tools for evaluating performance, display and report generators, etc.. The ESP-r uses several complex equations to deal with all aspects at the same time (geometry, construction, operation, distribution, heat dissipation, etc.). These equations are integrated in successive time steps in response to the influences of the occupants, and climate control systems. The operating conditions are determined through database support. Shading, insulation, HVAC systems, areas of computational fluid dynamics (CFD), electricity, renewable energy embedded systems, lighting, natural ventilation, combined heat and power generation, facades photovoltaic systems for control of indoor air quality can also be included in the models pre-determined. The ESP-r is extremely useful and is a powerful tool to simulate many innovative technologies. However, the program requires a great knowledge and expertise from its users, and requires a long learning process.(Joana Sousa, 2012)

IDA ICE

The thermal simulation software tool IDA Indoor Climate Energy is based on a general system simulation platform with a modular system. The multi-domain physical systems are described in the IDA using symbolic equations starting with a simulation language Neutral Model Format (NMF - Neutral Model Format). The user defines the tolerances which control the accuracy of the solution, thus allowing the isolation of numerical modeling approaches

IES VE (Integrated Environmental Solutions - Virtual Environment)

The simulation software tool IES provides the design professionals with a variety of variables in simulation analysis of buildings. The model works on the geometric representation that represents the building. The software tool allows interaction with other energy simulation software tools. The simulation software tool incorporates a tool for dynamic thermal simulation of heat transfer processes of buildings, which is the ApacheSim. The simulation software tool was tested using the IES ASHRAE 140 and is qualified as a dynamic model in CIBSE system of classification. The software tool provides an environment for the detailing of the building systems, allowing their optimization taking into account criteria such as comfort and energy.

TRNSYS

TRNSYS is a transient system simulation software tool with a modular structure that has been specially designed to develop complex systems related to energy, outlining the problem in a number of smaller components. The components ("Types") may range from a simple heat pump to a multi-zone of a building complex. The components are configured through the graphical user interface known as TRNSYS Simulation Studio. In the simulation software tool energy, TRNSYS the construction of the building can be achieved by the introduction of data on a dedicated visual interface, known as TRNBuild.

2.8.2 Design Builder Software

Design Builder is a comprehensive modeling tool that integrates building performance simulation with a highly visual and intuitive user interface. It is built on the EnergyPlus simulation engine, which is recognized for its robust and detailed modeling capabilities.

Design Builder facilitates the creation of 3D models of buildings, which can then be used to simulate and analyze various aspects of energy performance, including heating and cooling loads, lighting, ventilation, and overall energy consumption. Figure 19 below shows the interface of a Design-Builder software.

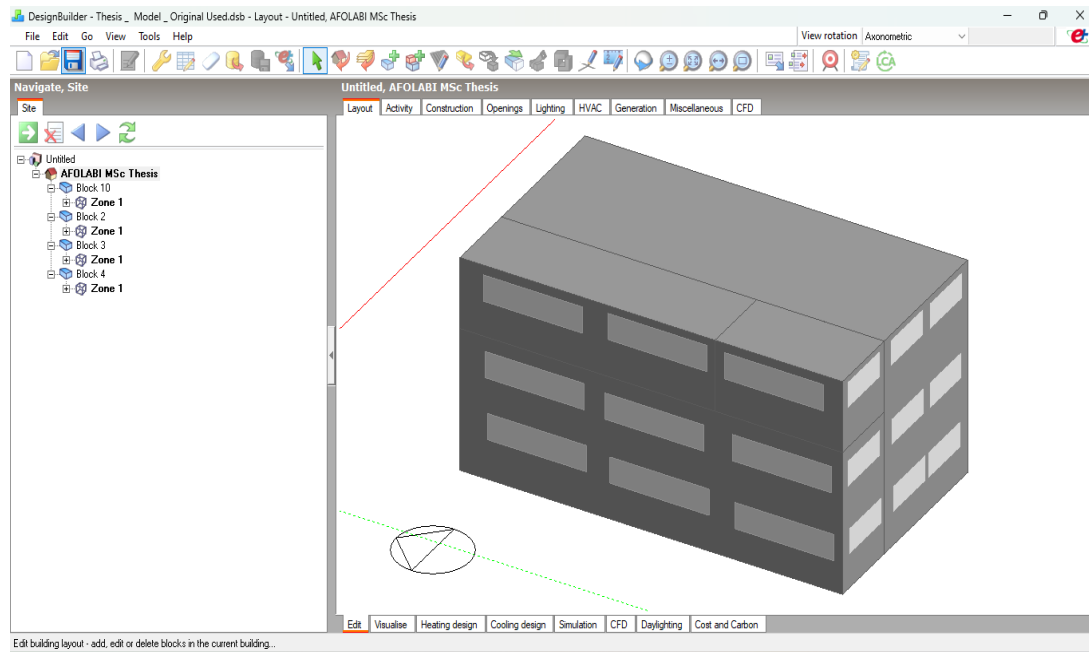


Figure 19: Office building geometry, generated with Design Builder

2.8.2.1 Objectives of Using Design Builder in This Study

The primary objective of using Design Builder in this thesis is to simulate the energy performance of the proposed building model, thereby generating various airflow supplied by the VAV-HVAC system into the zone, which was designed with almost the same feature as the experimental office. The process involved in the use of design builder includes:

- Geometry / Model Creation: Developing a detailed 3D model of the building, including architectural features, materials, and internal spaces.
- Activity Build-up / Input Data Specification: Defining key parameters such as weather data, occupancy schedules, internal gains, and HVAC systems.

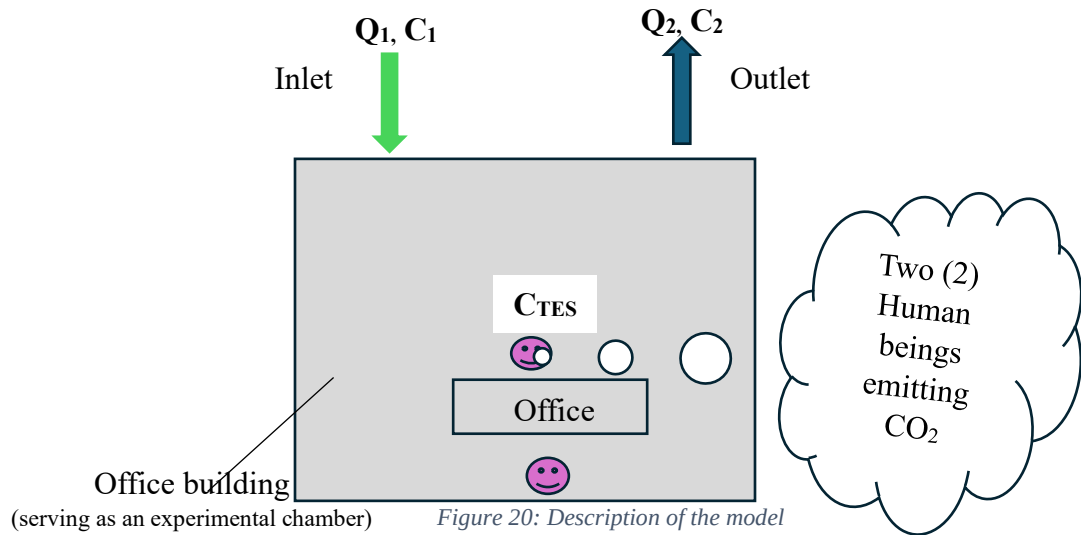
- Main Envelope Construction: Wall, floor, Roof definitions; Air tightness, ...
- Simulation Execution: Running simulations to predict the energy consumption and performance of the building under various scenarios.
- Results Analysis: Interpreting the simulation results to identify potential energy-saving measures and to validate the design against energy efficiency standards.

2.9 Physical Characteristics of the Model

The physics of this study is based on the principle of mass balance equation to estimate CO₂ (carbon dioxide) concentration levels of indoor air by indoor environment configuration (an office with a single inlet and a single outlet as previously described) and using the number of people. IAQ models of this nature are used to analyze the effects of sources and sinks indoors, calculate indoor pollutant concentrations, understand interactions of ventilation and indoor environment characteristics, and control whether indoor air is good. Figure 20 shows the description of the study.

2.9.1 Mass Balance Equation / Model

The mass balance model is a fundamental approach to evaluating indoor air quality (IAQ) by predicting pollutant concentration levels, including carbon dioxide (CO₂), over time. This approach relies on the conservation of mass, whereby the change in pollutant mass within a space is equal to the difference between the rate of pollutant inflow, generation, outflow, and removal.



For CO₂ concentration modeling, the mass balance equation can be expressed as follows:

$$\frac{dC}{dt} = \frac{G}{V} + \frac{Q_{in} \cdot C_{in} - Q_{out} \cdot C}{V} - \frac{\lambda C}{V} \quad \dots\dots\dots 12$$

Where: C is the CO₂ concentration in the room; G is the CO₂ generation rate (e.g., from human respiration); V is the room volume; Q_{in} and Q_{out} are the ventilation inflow and outflow rates, and C_{in} is the CO₂ concentration in the inflow air. The last term λ , represents the removal or deposition rate of CO₂ on surfaces or through other processes (Chen & Hildemann, 2009).

This formula was also written by Nesibe et al., (2015) as:

$$\frac{\text{mass at time } (t + \Delta t)}{\text{at time } t} = \frac{\text{entered mass}}{\text{from } t \text{ to } \Delta t} + \frac{\text{generated mass from the sources}}{\text{between } t \text{ and } \Delta t} - \frac{\text{exited mass}}{\text{from } t \text{ to } \Delta t} \quad \dots (13)$$

And for a single compartment i in multi compartment IAQ model, pollutant mass equation is written as follows:

$$V_i \frac{dC_i}{dt} = S_i - L_i \quad \dots\dots\dots (14)$$

where: C_i is indoor pollutant concentration in compartment i (mg/m³), t is time (s), V_i is the volume of compartment i (m³), S_i describes the sum of generation rates of all sources (mg s⁻¹/m³) and L_i is sum of loss rates due to all sinks (s⁻¹) within compartment i

This model assumes a well-mixed indoor environment, where CO₂ generated by occupants disperses evenly within the space, simplifying calculations and allowing for accurate predictions under controlled conditions (William W Nazaroff, 2004). Variations in indoor CO₂ levels arise based on occupancy, ventilation effectiveness, and external air quality, making the mass balance model particularly useful for assessing ventilation adequacy and potential exposure levels to CO₂ and other airborne contaminants in indoor settings (Noh, 2011).

For IAQ assessments, this model has been widely applied to quantify ventilation requirements, assess exposure levels, and optimize HVAC system performance. Through the mass balance approach, researchers can link CO₂ concentration with ventilation rate and pollutant source strength, helping ensure that IAQ meets health and comfort standards (ASHRAE Standard 62, 2019)

2.9.2 Defining the Model Source Term

In computational fluid dynamics (CFD) simulations using ANSYS Fluent, a source term is a critical component of the governing equations that represents the addition or removal of

mass, momentum, energy, or species within a defined control volume. For this study, the source term is configured to emit carbon dioxide (CO₂) into the computational domain, representing a human occupant's metabolic activity or a mechanical emission source.

The CO₂ source term is modeled as a volumetric entity or surface boundary within the domain, ensuring an accurate representation of emission rates in line with the scenario being studied. CO₂ is treated as a scalar transported species, governed by the convection-diffusion equation and influenced by turbulent mixing within the flow field. This setup allows for detailed analysis of CO₂ distribution, including accumulation zones, dispersion patterns, and interaction with ventilation strategies. Defining a source term makes it possible to simulate realistic conditions where CO₂ concentrations vary due to internal sources rather than solely from boundary conditions (Versteeg, 2007).

For this study, the source term is applied within a designated box, modeled as a simplified CO₂ emitter, where the emission rate represents typical human exhalation. This approach allows for an accurate representation of indoor CO₂ levels, capturing dynamic changes based on occupancy and enabling an assessment of ventilation effectiveness (ANSYS Inc, 2023). The parameters that are required in the definition of the source term are, the mass source, momentum source, turbulence kinetic energy, turbulence dissipation rate source, and its energy source. These parameters are defined thus:

- **Mass Source** (kg/(m³.s))

In computational fluid dynamics (CFD), source terms are utilized to represent additional influences or contributions to governing equations, such as mass, momentum, or energy, from sources within the computational domain. In ANSYS Fluent, source terms allow the

simulation of phenomena like mass addition, heat generation, or chemical reactions by explicitly specifying their rates per unit volume. For instance, a mass source term (S_m) directly contributes to the continuity equation and is defined with units of $\text{kg}/(\text{m}^3.\text{s})$, representing the mass added or removed from the system per unit volume and time.

The governing equations, including the continuity equation, are augmented with user-defined source terms to model specific physical processes (ANSYS, 2023). For problems involving a single species, a mass source can be defined solely for that species, ensuring compatibility with the conservation equations. This flexibility facilitates the accurate representation of localized phenomena, such as emissions from objects, heat dissipation, or chemical species evolution. The expression for mass source is given in expression in equation 15 below:

$$\text{Mass source} = \frac{\text{Mass flow rate}}{\text{Volume of Source term (box)}} \quad \text{-----} \quad (15)$$

Where:

$$\text{Mass flow rate (kg/s)} = \text{CO}_2 \text{ emission rate (m}^3/\text{s)} \times \text{Density CO}_2$$

- **Momentum Source** (N/m^3) for X, Y, Z (Depending on the direction of emission)

The momentum source term in ANSYS Fluent is used to account for additional forces exerted on the fluid, such as those arising from external influences or flow interactions. Expressed in units of N/m^3 , the momentum source represents the force per unit volume applied within the computational domain. In this study, the momentum source term is defined to simulate the effect of a localized force caused by human exhalation. The momentum source term, S_{momentum} , is calculated using the relationship:

$$\text{Momentum source (N/m}^3\text{)} = \frac{\text{Mass flow rate} \times \text{Exhale Velocity}}{\text{Volume of Source term (box)}} \text{----- (16)}$$

This approach integrates the localized momentum contribution into the Navier-Stokes equations, ensuring the accurate simulation of flow dynamics resulting from human exhalation. By applying the momentum source term, the flow field is effectively influenced by the force generated by exhalation, leading to a realistic representation of airflow behavior within the computational domain.

- **Turbulence Kinetic Energy (kg/(m.s³))**

The turbulence kinetic energy (k) source term in ANSYS Fluent represents the rate of energy per unit mass associated with the fluctuating velocity components in a turbulent flow. This source term is critical in capturing turbulence effects resulting from localized flow phenomena, such as exhalation or jet flows. For this study, the turbulence kinetic energy at the source is calculated using the relationship:

$$k = \frac{3}{2} \cdot (\text{Turbulence Intensity} \cdot v_{\text{exhale}})^2 \text{----- (17)}$$

where:

Turbulence Intensity (I) is the ratio of velocity fluctuations to the mean flow velocity, typically expressed as a percentage,

v_{exhale} is the exhale velocity (m/s)

- **Turbulence Dissipation Rate Source** (kg/(m.s⁴))

The turbulence dissipation rate (ε) represents the rate at which turbulence kinetic energy (k) is converted into thermal energy due to viscous forces in the fluid. It plays a crucial role in determining the small-scale turbulence behavior in computational fluid dynamics (CFD). The source term for ε is expressed in units of m²/s³ and is incorporated into the turbulence transport equations to model the decay of turbulence over time and space. In this study, the turbulence dissipation rate source term is calculated using the relationship:

$$\varepsilon = C_{\mu}^{3/4} \cdot \frac{k^{3/2}}{l} \quad \text{----- (18)}$$

where:

C_{μ} : a turbulence model constant (typically (0.09),

k : turbulence kinetic energy,

l : turbulence length scale (m), which represents the characteristic size of the largest eddies in the flow.

For flows involving human exhalation like this study, the turbulence length scale can be approximated as: $l = 0.07 D$

where

(D) is the characteristic dimension of the exhalation source (e.g., the diameter of the mouth or the source box).

By defining the turbulence dissipation rate source term, the model accounts for the energy transfer from larger turbulent eddies to smaller scales, leading to an accurate representation of turbulence decay. This is particularly important in applications where localized turbulence, such as that caused by exhalation, significantly impacts the flow dynamics.

- **Energy Source (W/m³)**

The energy source term (S_E) in ANSYS Fluent represents localized heat addition or removal within a specific volume. This term is crucial for accurately modeling the thermal effects of processes like human exhalation, electronic heat generation, or chemical reactions. In this study, the energy source term is defined in units of W/m³ and calculated as:

$$S_E = \frac{\dot{m} \cdot c_p \cdot T_{\text{indoor}}}{V_{\text{source}}} \quad \text{-----} \quad (19)$$

where:

$\dot{m}$: mass flow rate of exhaled air (kg/s),

c_p : specific heat capacity of the exhaled air (or CO₂, depending on the dominant gas in the model) (J/kg.K),

T_{indoor} : ambient indoor temperature (K), V_{source} : volume of the source term (m³).

This formulation assumes the exhaled air is at the same temperature as the indoor environment. It simplifies the energy source term by focusing on the contribution of the specific heat capacity and mass flow rate within the source volume. By incorporating this term, the simulation accurately captures the localized heat generation or dissipation effects from human exhalation. This is essential for assessing thermal comfort, indoor air quality, and energy efficiency in confined spaces.

2.10 Indoor Air Quality Modelling using CONTAM (W)

CONTAM (W) is a multi-zone airflow and indoor air quality (IAQ) simulation software developed by the National Institute of Standards and Technology (NIST). It is widely used to predict airflows, contaminant transport, and ventilation performance in buildings, aiding researchers and professionals in evaluating the impact of various factors on indoor environmental quality (Walton & Dols, 2013). The software supports the simulation of both infiltration and ventilation airflows, which are critical for assessing energy performance and occupant comfort in built environments. CONTAM allows users to define building layouts, including zones, airflow paths, and contaminant sources, making it an essential tool for examining pollutant dispersion and validating ventilation strategies (Andrew K. Persily & Elizabeth M. Ivy, 2001). A significant advantage of CONTAM lies in its ability to model complex interactions between airflows and contaminants across multiple zones. Its applications extend to diverse areas, including evaluating natural and mechanical ventilation systems, assessing exposure risks to airborne contaminants, and optimizing building designs for energy efficiency and IAQ compliance (Dols & Emmerich, 2001).

CONTAM is reliable and scientifically validated software. Numerous studies have cited its use for simulating airflow patterns and contaminant dispersion. Its robustness in handling detailed inputs and providing customizable outputs ensures that it remains a preferred tool in building science and environmental engineering. For instance, Verijkazemi et al., (2018), worked on the evaluation of Indoor PM Distribution by CONTAM Airflow Model and Real-Time Measuring: Model Description and Validation. In 2015, Temenos & Nikolopoulos, worked on the modelling of the Indoor Air Quality of Greek Apartments also using CONTAM(W) Software. Alonso et al., (2019) did a co-simulation between

Energy Plus and CONTAM to develop IAQ and energy-centric demand-controlled ventilation systems. Budaiwi & Mohammed, 2023) worked on acceptable indoor air quality at reduced energy consumption for high-occupancy buildings with intermittent operation, also modeling with CONTAM W.

2.10.1 CONTAM (W) and the Principle of Mass Balance Equation

The software's operation is fundamentally rooted in the principle of the mass balance equation, which is essential for accurately predicting the transport and accumulation of contaminants within a control volume. The mass balance equation ensures that the sum of all inflows, outflows, sources, and sinks of a substance within a defined space equals the rate of change of that substance's mass within the volume over time. This principle is mathematically represented as:

$$\frac{dC}{dt} = \frac{\dot{m}_{in} - \dot{m}_{out} + S}{V} \text{-----(20)}$$

where :

- C is the contaminant concentration (kg/m³)
- $\dot{m}_{in}$ and $\dot{m}_{out}$ are the mass flow rates of the contaminant entering and exiting the zone (kg/s)
- S represents the source or sink term (kg/s),
- V is the zone volume (m³).

This equation forms the backbone of CONTAM's computational approach, enabling it to model contaminant dynamics precisely. The mass balance equation is applied

iteratively to each zone within a multizone building model, accounting for airflow paths, pollutant sources, and boundary conditions. This approach ensures that even transient states, where ventilation patterns or source strengths vary over time, are accurately simulated.

By adhering to the mass balance principle, CONTAM provides robust simulations of pollutant dispersion under a wide range of conditions. For example, it can model the effects of varying ventilation rates, external weather influences, and pollutant generation rates, allowing for the evaluation of both steady-state and dynamic scenarios. Additionally, it incorporates advanced algorithms to handle non-uniform distributions of airflow and contaminants, making it suitable for complex building designs and ventilation strategies (Dols & Polidoro, 2015).

This robust application of the mass balance principle, combined with CONTAM's multizone modeling capabilities, ensures reliable and scientifically sound predictions, making it an indispensable tool for evaluating indoor air quality (IAQ) in complex buildings. By enabling evidence-based decisions, CONTAM supports researchers and engineers in developing energy-efficient, healthy, and sustainable indoor environments.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Research Approach

To achieve the objectives of this study, a research approach involving several steps in five phases has been designed as shown in Figure 21 below. Each of these steps is also explained thus:

Phase 1. Gap Identification & Problem Identification (Literature Review):

- i. An extensive Literature review was carried out to understand the issues related to indoor air quality and the effects of indoor pollutants on humans, ventilation types, and how mechanical systems have been used over time to displace indoor pollutants.
- ii. The need, process, and procedures necessary in carrying out a tracer gas experiment
- iii. To know what thermal loads are in the design of HVAC systems and the types of thermal loads used in such design.
- iv. Understand airflow models and design simulations.
- v. Identify State-of-the-art integrated CFD, and Energy Simulation tools; and their modulus operandi.
- vi. All of these have assisted in the identification of the research gap and formulation of the problem at hand

Phase 2. Tracer Gas Experimentation:

- i Conduct a reconnaissance on the proposed building/room to be used for the experiment/test chamber
- ii Select the best gas to be used as a surrogate for the experiment
- iii Select indoor environmental measuring tools and sensors/loggers best suited for the experiment
- iv Inject the gas into the room as best suited using either of the three methods of conducting a tracer gas experiment
- v The air change rate was calculated from the experiment

Phase 3. Energy Simulation:

- i. A state-of-the-art energy-simulated software was selected for the simulation
- ii. An arbitrary geometry was designed with a VAV-HVAC system to supply airflow into the building, this arbitrary building must have a zone similar to the room for the experiment
- iii. The airflow was extracted with other parameters for onward use for CFD simulations
- iv. A CFD simulation was done with inputs from the energy simulations
- v. Various graphs and curves were derived with different calculated air change rates
- vi. Results from (v) above were compared with relevant standards like ASHRAE

Phase 4. ANSYS - CF D Model (Generation & Validation) :

This phase uses tracer gas experimentation to validate a computational fluid dynamics model, and the validated model will be used for the main study. The following are some of the highlighted steps:

- i. Selecting a software tool from a group of available CFD programs for modeling and simulation of the office building.
- ii. The office building's base case model was modeled by inputting the building characteristics obtained from physical inspection and the literature.
- iii. Simulate the base case model, and study the rate of contaminant (CO₂) decay along with the air change rate from the HVAC system; for every experimental scenario/cases
- iv. The air change rate from the experiment was compared with the air change rate from the CFD simulation.
- v. To access the contaminant behavior, a source term is put inside the validated computational domain and allowed to emit CO₂ under varying thermal loads.
- vi. The software produces the turbulence dispersion of the contaminant and the air distribution.

Phase 5. CONTAM Indoor Air Quality Modelling:

- i. Every step of model validation, source term inclusion, and every step in Phase 4 above was repeated with CONTAM Indoor air quality state-of-the-art software.
- ii. The software produces the behavior of the contaminant within the computational domain.

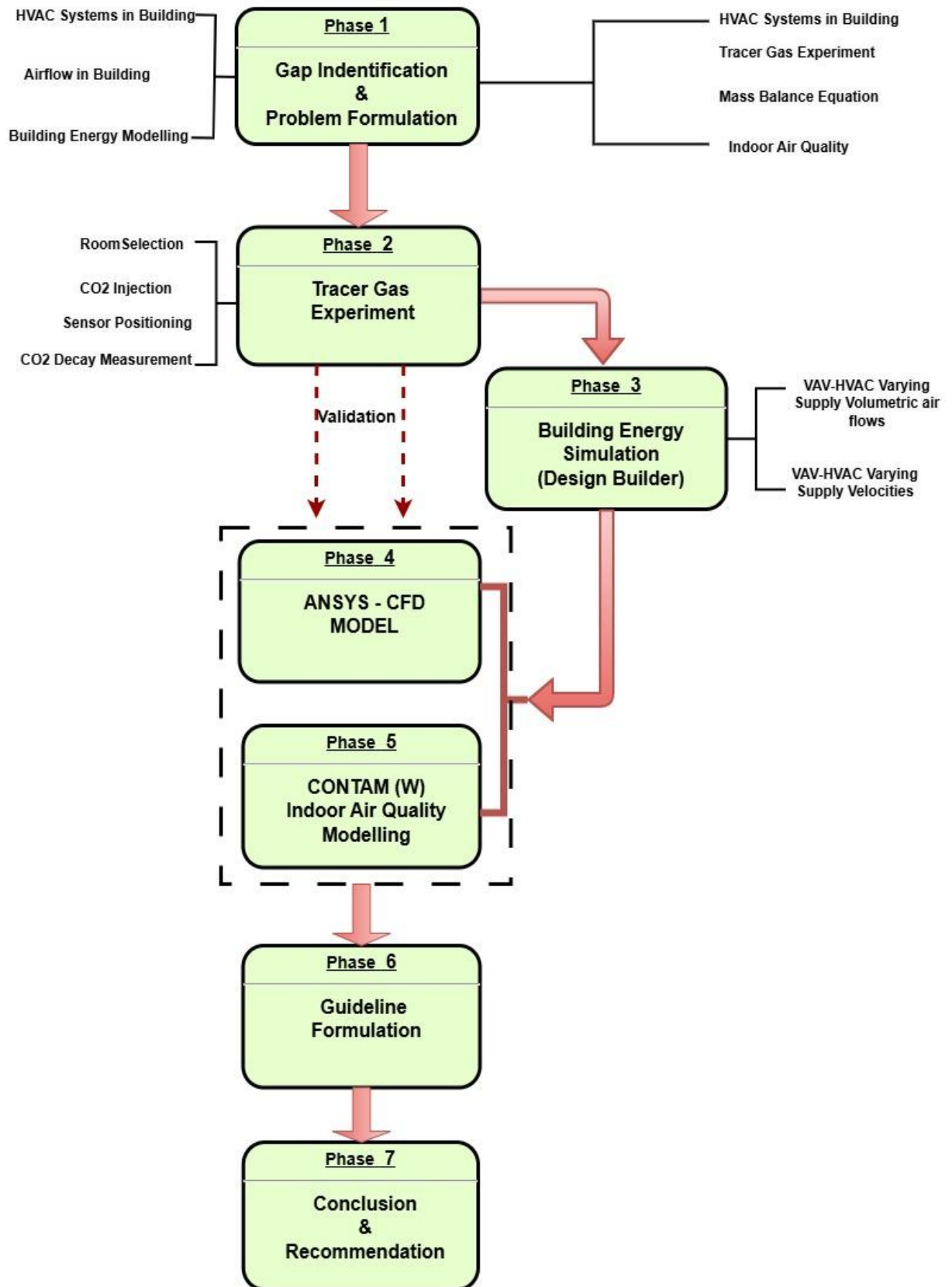


Figure 21: Research Approach

Phase 6. Guideline Formulation:

All the output from the above is used to formulate a guideline that affects Building Energy and Indoor Air Quality highlighting the following:

- i. Stage 1 – System Selection
 - a. Region / Location
 - b. Room / Experimental Zone definition
 - c. Ventilation System definition
- ii. Stage 2 – Energy Simulation
 - a. Simulation software selection
 - b. Defining the building envelope system
 - c. Room/Zone activities & Number of Occupants definition
- iii. Stage 3 – Indoor Air Quality Simulation
 - a. Software selection & Validation
 - b. Defining other parameters as requested by the software putting on mind output from Stages 1 and 2
- iv. Regulatory and Industry Standards

Phase 7. Result Analysis & Recommendations:

- i. All the results of experimentation, and simulations were presented in the form of graphs, tables, and charts
- ii. Conclusion were drawn from (i) above.
- iii. Recommendations were suggested based on the outcome of (i) above.

Figure 22 below shows a general data collection and data processing procedure that was adopted for this study.

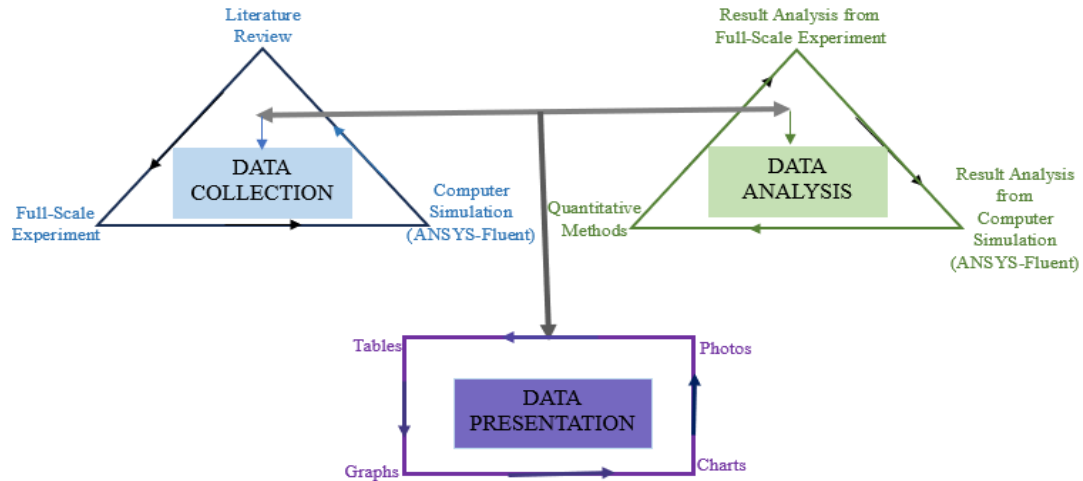


Figure 22: General Data collection & Processing procedure

3.2 Research design

This thesis is quantitative research that uses a combination of computer simulation with full-scale experimentation to respond to the question that emanates from the objectives of this research. This method has not only been used over time for research like this, but they are also carefully selected by considering the nature of the study, reliability, accuracy, practicality, easiness, time, and cost-effectiveness. As this study tends to assess the behavior of air contaminants in VAV-HVAC air-conditioned space under varying thermal loads, an office room as described above has been selected for this research as a case study to ascertain its indoor air quality and ventilation levels. The data obtained from the experiment was used as input to a state-of-the-art Computational Fluid Dynamic (CFD) software (ANSYS academic version).

The result of the ANSYS CFD simulation was then compared with that of the experiment (which shows validation). Another state-of-the-art energy simulation software was used to design the office building, and the amount of air supplied to the office by the selected VAV-HVAC system in the software was then supplied to the CFD software to generate/calculate the air change per hour of the office. Figure 21 below shows the pictorial overall description of the research approach of this study. The research methodology comprises data collection and analysis methods on the design strategies, while a few secondary data were collected through a literature review (as a form of guide during the process of the study). The results were presented in the form of charts, tables, photos, and graphs. The data collection methods include the use of secondary and primary data. The primary data was collected in office space with full-scale experimentation and CFD simulation. A detailed discussion of the data collection and analysis methods is presented in the subsequent sections.

3.3 Study Area

The area for the study (for the experiment) is located on decimal degrees 26.30583211 50.139666108, (i.e.. 26°18'21.00" N and 50°08'22.80" E) with a Universal Transverse Mercator coordinate system of 39R 414121.98095897 2909839.2759686. This coordinate is at the heart of Dhahran, Saudi Arabia, which houses King Fahd University of Petroleum and Minerals, in the country's Eastern Province. It was officially established by Royal Decree on 23 September 1963. The University has eight (8) colleges/faculties with twenty (29) academic departments. As with most standard universities, this university has many academic buildings one of which this research is based), sports buildings, restaurants, malls, staff and student housing etc.

3.4 Case Study Building Description

The thrust of the university is to be a preeminent institution known for its globally competitive graduates, cutting-edge research, and leadership in energy fields, hence it established several faculties, part of which is the College of Design and Built Environment, popularly known as Building 19. This building was originally built as an open-plan office and is gradually partitioned to accommodate several indoor activities based on needs, as the faculty grows. At present, this academic building comprises classrooms, offices, convenience rooms, conference rooms, laboratories, drawing studios, open circulation areas, and student presentation area, with workstations strategically positioned. The building also consists of lifts, and staircases as the building has four (4) different floors. A pictorial view of Building 19 is shown in Figure 23 below.



Figure 23: College of Design & Built Environment (Building 19) KFUPM

An office room within the college was selected for the experimentation part of this research since most of the offices in the college are meant for the lecturers/teachers who are line functions in the university system. This office is on the third floor, with no environmental factors or parameters acting on it. The office space has a dimension of 2.78m (width), 4.91m (length), and 2.43m (height); making a floor and ceiling area of 13.64m² and a

volume of 33.17m^3 , and this dimension is typical office space for most offices within the college. The architectural plan and internal perspective of the room are shown in Figures 25 and 26 below respectively. For this study, a dedicated HVAC duct carries fresh air from the Air Handling Unit (AHU) to the zone (as shown in Fig 24 below), and for proper analysis, the duct is allowed to supply the same air characteristics to the open circulation area before the office, so that:

- 1) parameters of the supplied air can be recorded from the outside of the zone (office space)
- 2) to be able to determine if the CO_2 injected into the office space is recirculated back into the zone.

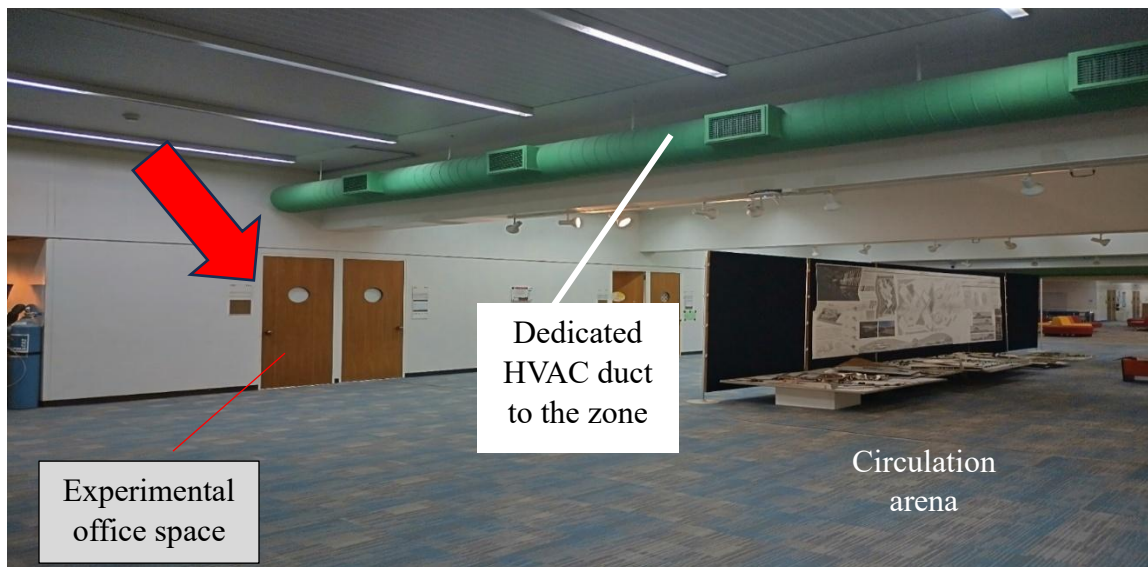


Figure 24: Experimental Office Room

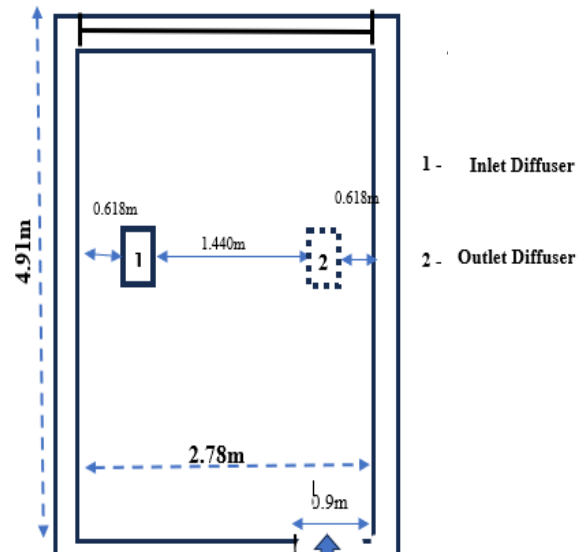


Figure 25: Architectural layout of the room



Figure 26: Internal Perspective of the office space

3.5 Data Collection and Analysis

3.5.1 Methods of Data Collection

Measurement of ventilation performance in office space varies depending on several factors and is done in various ways. The data collection methods discussed earlier were

primarily from the tracer gas experimentation, the CFD - ANSYS Fluent simulation, the Design-Builder Energy Simulation, and the CONTAM W indoor air quality simulation software. The CFD simulation was initially used to validate the full-scale measurements and later to evaluate and optimize the performance of different ventilation strategies for a VAV-HVAC system. The parameters and instruments used in ascertaining the level of IAQ and ventilation performance in the tracer gas experiment are illustrated in Figure 27 below; while CO₂ was used as the main surrogate, parameters like other indoor parameters such as temperature and humidity were also measured alongside the CO₂. Environmental factors like wind speed, the effect of sun radiation, etc. were of no effect, as they have no impact on the office space since no part of the office space is exposed to the environment.

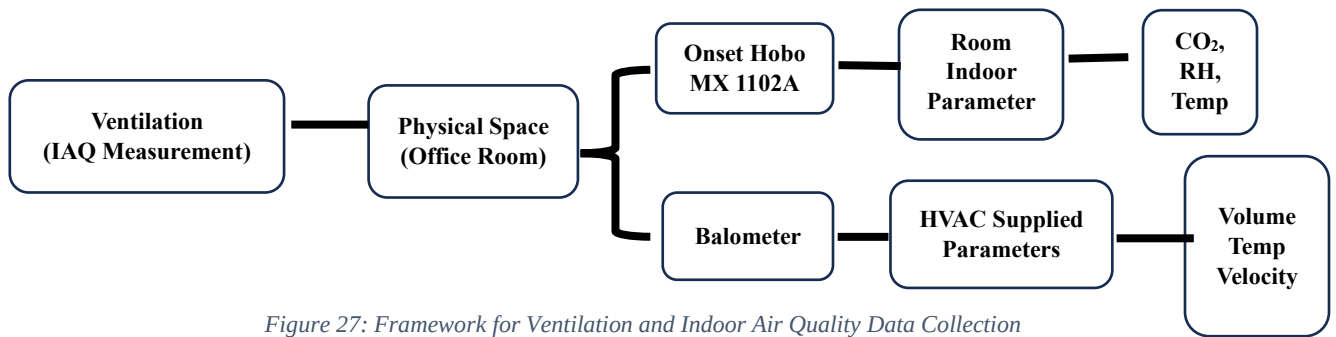


Figure 27: Framework for Ventilation and Indoor Air Quality Data Collection

3.5.2 Method of Data Analysis

The source of data for this study as stated earlier is mainly a quantitative output from experimentation and simulation. State-of-the-art Computational Fluid Dynamic (CFD) software ANSYS academic version (2023 R1) was used to simulate the airflow characteristics in office space, showing the turbulence distribution between the airflow supplied and the CO₂ contaminant, Design-Builder (v7.3.0.027 – Licensed) was used to generate VAV-HVAC volumetric airflow, which was later used by the CFD software and the CONTAM (W) software, and CONTAM (W) software was used to determine the

behavior of the CO₂ contaminants in the zone. Most outputs are in the form of charts and numbers showing airflow patterns, airspeed and direction, and air temperature of the interior space. The Fluent solver is coupled with a design modeler (the geometry creation section of the software) and ANSYS meshing (meshing program) the integration of these two subprograms is what is known as the ANSYS Workbench. In this study, the geometric models were created using a design modeler, The meshed geometries were simulated using a FLUENT solver. The simulation and its data analysis process is illustrated in Figure 28 below

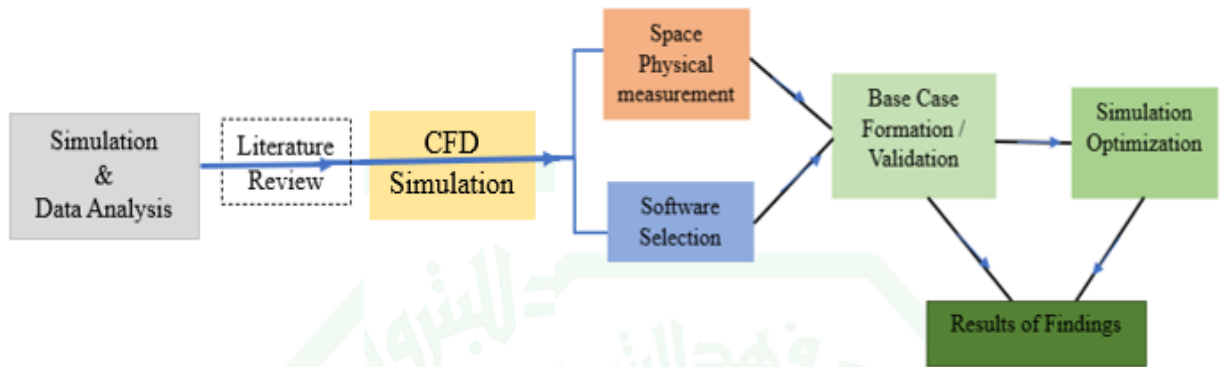


Figure 28: Data Analysis flow path for the simulation

The analysis of tracer gas concentration is usually done on-site simultaneously with the sampling process or off-site when the gas samples are collected in sealed containers (ASTM Standard, 2011) depending on the choice adopted by the research. However, for this study, the tracer gas concentration analysis was conducted on site. The measurement was carried out using tracer decay techniques with CO₂ as the tracer gas. The tracer gas concentration was recorded with the aid of CO₂ data sensors (these sensors are explained below). The results obtained from these measurements were used to estimate the air change

rates of the space using the mathematical expression in equation 7, which is the same as equation 21 below.

$$N = \frac{\ln C(0) - \ln C(\tau_1)}{\tau_1} \text{-----}(21)$$

Where:

N = Air Change Rate C = Tracer Gas Concentration in Rooms

τ = Time (hr : min) $\ln C(0)$ = Logarithm concentration of the Tracer Gas

3.6 Experimentation Instruments

The instruments used for the study are basically the ones used for tracer gas experimentation. Some of these instruments need on-site calibration before they are used while the factory already standardizes some. Each of these instruments and their process of calibration are discussed below.

3.6.1 Measuring Tools & Equipment

Several measuring tools and equipment have been used in this study to measure important physical parameters, some of which include: temperature, humidity, CO₂, HVAC volumetric flow rate, etc. These instruments are presented in table 3 below:

Table 3: Major measuring tool for the study

S/N	Instrument Name	Properties
1	Onset Hobo	CO2 sensors
2	Alnor Barometer	HVAC Supply Air measurement
3	Infra-red Thermometer	Surface Air Temp. measurement
4	AdvancedSense Pro-Environmental Test meter with Airspeed probe	Indoor parameters measurement

3.6.1.1 Onset Hobo

The measuring equipment used for the building's indoor environmental parameters is manufactured by Onset Hobo company. This equipment can detect and measure CO₂, temperature, Dew point temperature, and relative humidity simultaneously. The Onset Hobo part number was specifically adopted was Onset Hobo MX1102A. A typical diagram illustrating the telemetry of the data logger and the transmitters is shown in Figure 29 below. The Onset Hobo data logger was used to receive CO₂, temperature, and relative humidity from three (3) transmitter channels.

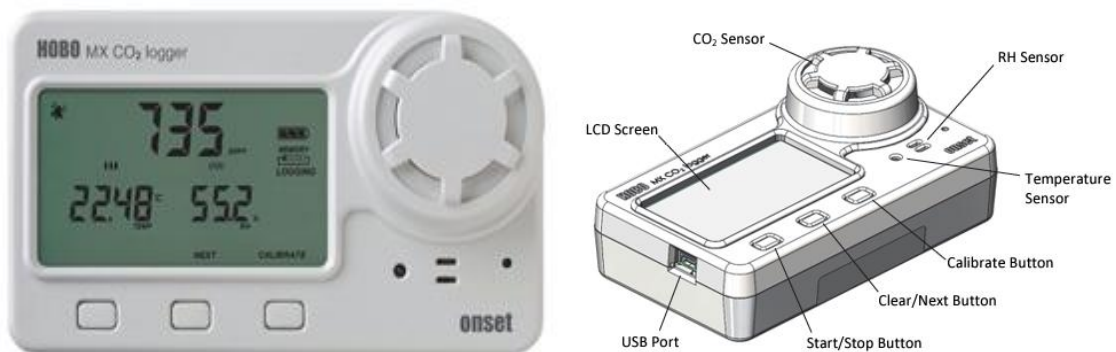


Figure 29: Onset Hobo MX1102A

For the CO₂ channel, this device has a range from 0 to 5,000 ppm, with an accuracy of ± 50 ppm $\pm 5\%$ of reading at 25°C (77°F), less than 90% RH (non-condensing) and 1,013 mbar, it has a Warm-up Time of 15 seconds. The calibration process can either be Automatic or manual to 400 ppm. It has a Non-linearity of $<1\%$ of FS, with a pressure Dependence of 0.13% of reading per mm Hg (corrected via user input for elevation/altitude). The Operating Pressure Range is from 950 to 1,050 mbar (use Altitude Compensation for outside of this range). Its Compensated Pressure Ranges from -305 to 5,486 m (-1,000 to 18,000 ft). Its sensing method is Non-dispersive infrared (NDIR) absorption. The temperature Sensor, ranges from 0° to 50°C (32° to 122°F), with an accuracy from $\pm 0.21^\circ\text{C}$ from 0° to 50°C, it has a resolution of 0.024°C at 25°C, with a drift of $< 0.1^\circ\text{C}$ per year. While Relative Humidity Sensor ranges from 1% to 90% RH (non-condensing), its accuracy range is $\pm 2\%$ from 20% to 80% typical to a maximum of $\pm 4.5\%$ including hysteresis at 25°C (77°F); below 20% and above 80% $\pm 6\%$ typical, and its resolution is 0.01%, with a drift of $<1\%$ per year typical.

Other measuring tools used for this experiment are:

- Alnor Barometer
- Infra-red Thermometer
- AdvancedSense Pro-Environmental Test Meter with Airspeed probe

3.6.1.2 Alnor Barometer

The Alnor Electronic Balometer system with the APM 150 meter (Figure 30), is designed to measure supply or exhaust airflow from diffusers or grills in HVAC systems. The assembly consists of a meter, nylon hood, handles, and a base. The meter has a digital

readout of volume flow and temperature when used with a Balometer base. The range of measurement spans from 50 to 2000 CFM (85 to 3400 m³/h or 24 to 945 l/s) and 32°F to 122°F (0°C to 50°C). The meter sums and averages airflow up to 100 points. This TSI barometer uses laminar flow elements as the standard to calibrate Barometers. These are devices that are made up of an excellent honeycomb mesh. The pressure drop across a laminar flow element is approximately linear with the flow going through the element. Alnor Balometers are calibrated using a standard two by two foot square diffuser.

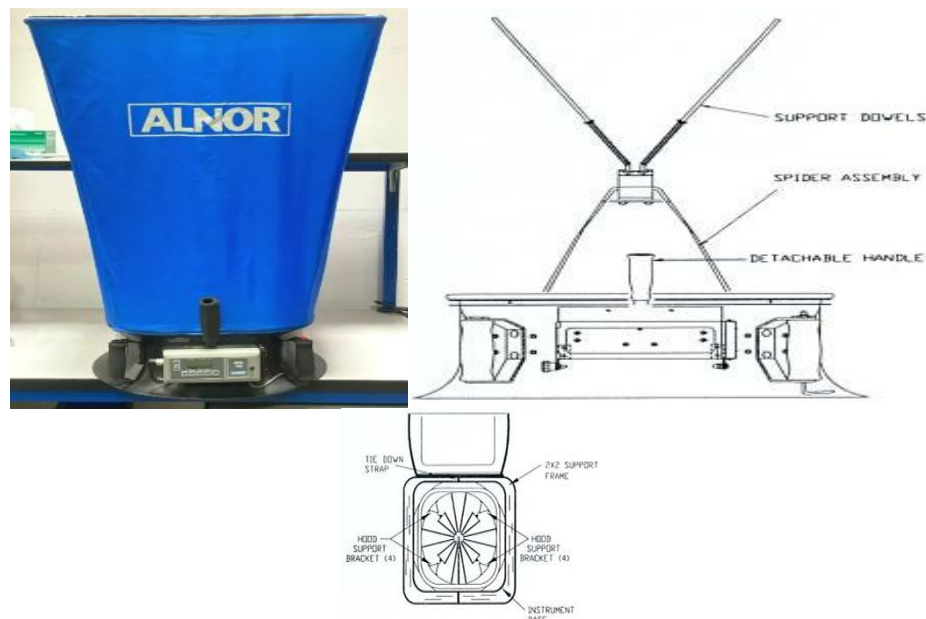


Figure 30: Alnor Balometer 150 and its parts

3.6.1.3 Infrared Thermometer

This is the Edinson Infrared Thermometer of Model IRT 537 (figure 31), the thermometer detects infrared energy, which is emitted by all objects. It is manufactured to comply with EN61326:1997 / +A1:1998/+A2:2001/+A3:2003, this instrument has an accuracy of -20°C to 50°C $\pm$ 2.5°C. This infrared energy is captured by the thermometer and processed

through a sensor. The sensor generates a measurable voltage output which is in proportion to the target temperature. The output is processed and displayed on the LCD.



Figure 31: Infrared Thermometer (Laser)

Depending on the nature of the material that is to be scanned, different levels of energy will be encountered (emissivity). However, most organic and painted or oxidised surfaces have an emissivity of 0.95. To overcome any problems with polished or mirrored surfaces, it has been suggested that the surface should be covered in masking tape or matt black paint before scanning, and sufficient time be allowed for the tape or paint to attain the same temperature as the target object before scanning. The D:S Ratio (Distance to Spot size) or Field Of View is 12:1 (figure 32). The ratio indicates that when the target object is 300mm (12") away from the thermometer, then the target object should be at least 25mm (1"). In general, it is good practice to ensure that the target is larger than the spot size. The smaller the spot size, the closer the thermometer should be to the target object. For increased accuracy, the target should be twice the size of the spot size.

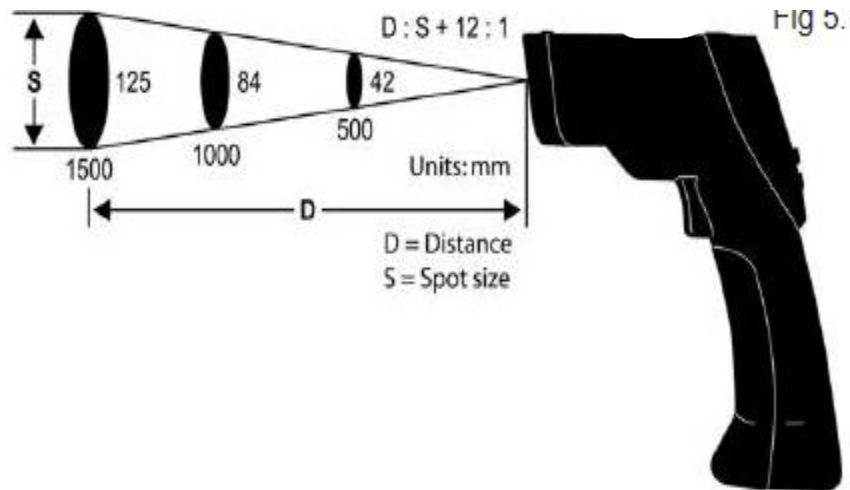


Figure 32: The infrared showing Distance to Spot ratio

3.6.1.4 AdvancedSense Pro-Environmental Test meter with Airspeed probe

The AdvancedSense XM continuously monitors air quality parameters and displays real-time readings on its intuitive LCD screen. It also features comprehensive data logging capabilities, allowing users to analyze historical trends, identify potential issues, and make data-driven decisions. The built-in Barometric Pressure sensor will compensate mass concentration readings for pressure changes when enabled. Include differential pressure, airspeed, and other parameters, for a comprehensive range of measurements. These readings include various air quality parameters such as temperature, relative humidity, carbon dioxide, carbon monoxide, etc. The readings are updated continuously and can be viewed at a glance. The Airspeed probe as shown in Figure 34, was inserted into the 2 x Rugged push-pull sockets for GrayWolf DirectSense II probes. It is used to capture the speed of the air from the HVAC system as it enters the space.



Figure 33: AdvancedSense Pro-Environmental Test meter with Airspeed probe

3.6.1.5 Standing Fan

This is called the Slim Cooling Tower Fan; it offers a 60 ° oscillation and space-saving design that fits seamlessly into any indoor space. This fan is used to distribute CO₂ evenly in the office, to maintain equilibrium. The airflow of this high-tower fan is 9 m³/hour and it is fitted with a 3-speed mode (fast, medium, and low) and blade-free design to deliver maximum air delivery and good area coverage. It delivers a high volume of air circulation while maintaining minimal noise output. It comes with a detachable base and is simple to assemble, the fan is shown in Figure 34 below.



Figure 34: Cooling Tower Fan

3.6.2 Calibrating the Measurement Equipment

3.6.2.1 The Onset Hobo MX1102A

The manual calibration of the equipment was adopted for this research, for it is believed to be more reliable. The process for the calibration goes thus:

1. The logger is taken outside in the fresh air on a dry day where the carbon dioxide level is 400 ppm.
2. Press the Calibrate button on the logger for 5 seconds until it beeps. The logger calibrates for 5 minutes, while the device is swung as shown in Figure 35 below; The CO₂ and Calibrate symbols on the LCD flash while calibration is underway. A time- and date-stamped manual calibration event is logged in the data at the end of the 5-minute calibration sequence (Figure 36).
3. Once the Calibration process is complete, the logger is returned to its office of use.
4. The logger is allowed to function for a while before the injection of the CO₂ into the room

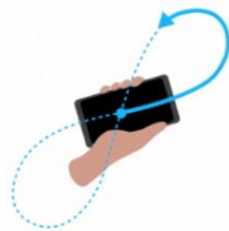


Figure 35: The swinging path of the tool



Figure 36: Hobo MX CO₂ Logger, during calibration

3.6.2.2. Alnor Balometer

Like all other tools used for this study, the Balometer or hood is calibrated to some standard. Alnor (the manufacturer of this Balometer) uses laminar flow elements as the standard to calibrate theirs. As reported on its use manual, these are devices that are made up of a very fine honeycomb mesh, the pressure drop across a laminar flow element is approximately linear with the flow going through the element. Alnor Balometers are calibrated using a standard two by two foot square diffuser (although other manufacturers may use orifice plates or nozzles and may not use a diffuser. Some balometers use proportional balancing techniques but these differences will not be important as highlighted by Alnor manufacturer.

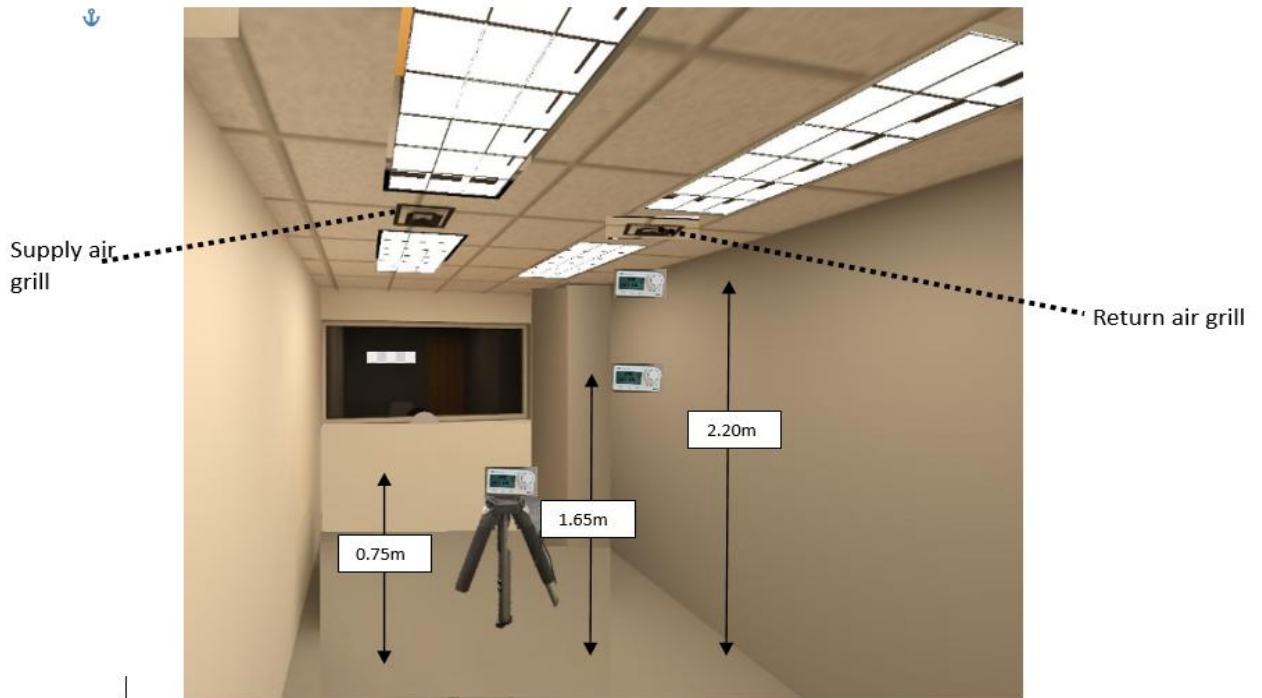


Figure 37: Experimental room. showing different logger position

However, when comparing Balometers against other hoods, or when comparing Balometers calibrated at Alnor with other calibration facilities, these differences may be important. It is not unusual to see air flow calibration differences on the order of 5% because of different standards.

3.7 Other Tools & Equipment

Other tools for this study are the computer software vis-à-vis :

- ANSYS Fluent for CFD Simulations (as described above).
- Design Builder Software for Building Energy Simulation (as described above).
- Microsoft Excel for Data Analysis and Presentation

CHAPTER 4

EXPERIMENT AND SIMULATION SETUP

Having understood the importance of modelling indoor air quality and computational fluid dynamics in airflow simulation in buildings as explained in previous chapters of this study, the accurate prediction of ventilation systems that send in fresh air into the building requires a state-of-the-art tool that is reliable, cost-effective, easy to use, and readily available. In this study, the indoor air quality modelling of our contaminants is generated, and the accuracy of the CFD-simulated office was validated against the full-scale measurement results of ventilation rates using tracer gas techniques (procedures explained in subsequent sections); the processes and guidelines followed in conducting the CFD simulation and the CO₂ generation processes together with the boundary conditions employed, which consist of the processes right from model construction, computational mesh, turbulence model and convergence criteria were all described below.

Aside from the CFD Model (by ANSYS) and the air quality model (by CONTAM -W), the Building Energy model was also created using Design Builder Software, in this energy model software, the same office building used for the experiment and modeled for ANSYS simulation was created (virtually) in the dry humid climate of Dhahran in Saudi Arabia, the climatic influence was set to act over the building model, and a corresponding air supplied to the zone under consideration in the model, was recorded and subsequently used in the CFD-validated-model.

4.1 Tracer Gas Experimentation

Figure 38 below shows the flowchart representation of the tracer gas experimentation adopted in this study.

➤ The Preliminary Procedure

- i Getting the Gas: The gas for this study was carbon dioxide (CO_2), which was supplied by Air Products and Chemicals, the gas is of Grade 5 (99.999) specification, with less than 10 PPM of impurities.
- ii The office Space: The office space was prepared, by removing all furniture, books, and other all materials that could emit / off gas formaldehyde or any other gas. The monitors are put in place as described above.
- iii The Apparatus: Gas cylinder, Gas regulator, Hose pipes, Clamp, strings, notes, pen and other mentioned tools and equipment mentioned in subsequent section above.
- iv Calibration of Apparatus: apparatus was calibrated as described above

➤ 4.1.2 Safety Precautions

- i. Built environment compatible gas CO_2 is used for the experiment
- ii. Necessary PPEs were worn

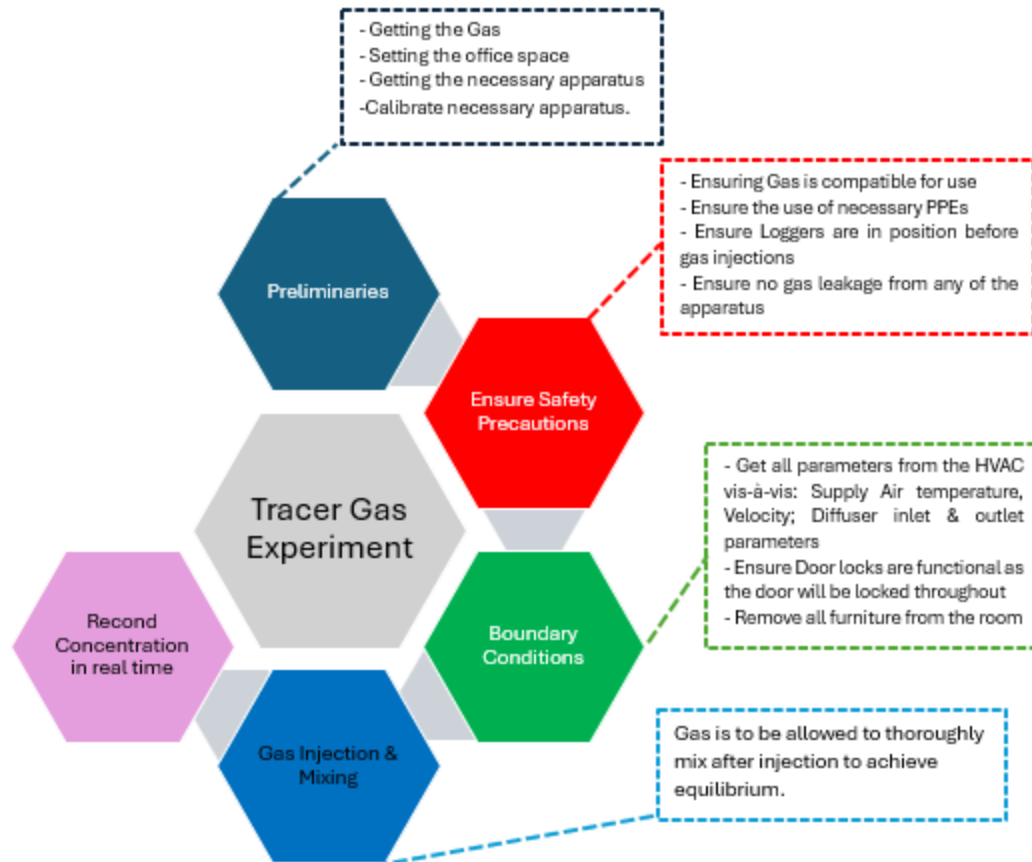


Figure 38: Tracer Gas Experiment flow process

4.2 Building Energy Simulations – Design Builder Software

In section 2.8.2.1, Design Builder Software was introduced as having five (5) distinct setups before the energy simulation can be done, these setups range from activity, construction, HVAC, openings, and lighting. The settings from these setups used shall be x-ray below:

➤ Model Description (Layout Tab):

The building under consideration is an office complex in the eastern province of Dhahran, in Saudi Arabia. It is a three (3) story building, which is divided into four (4) parts A, B, C,

D. Part B is a multiple of part A in volume, part C is also a multiple of part B, and part D is a multiple of part C; i.e. part A is the smallest unit in the whole structure, and it was centered for you for the research. The details of part A which this study centered on include:

- Floor = 13.652m^2
- Flat Roof element = 13.652m^2
- Internal Partition 1 = 11.931m^2
- Internal Partition 2 = 6.756m^2
- Wall 1 – 11.931m^2 ; 270°C [External wall = 8.495m^2 , Window (External) = 3.436m^2]
- Wall 2 – 6.756m^2 ; 180°C [External Wall = 4.796m^2 , Window (External) = 1.960m^2]

Figure 39a below shows the rendered 3D model of the whole building (parts A – D), while the call-out as shown in Figure 39b is the part D as described.

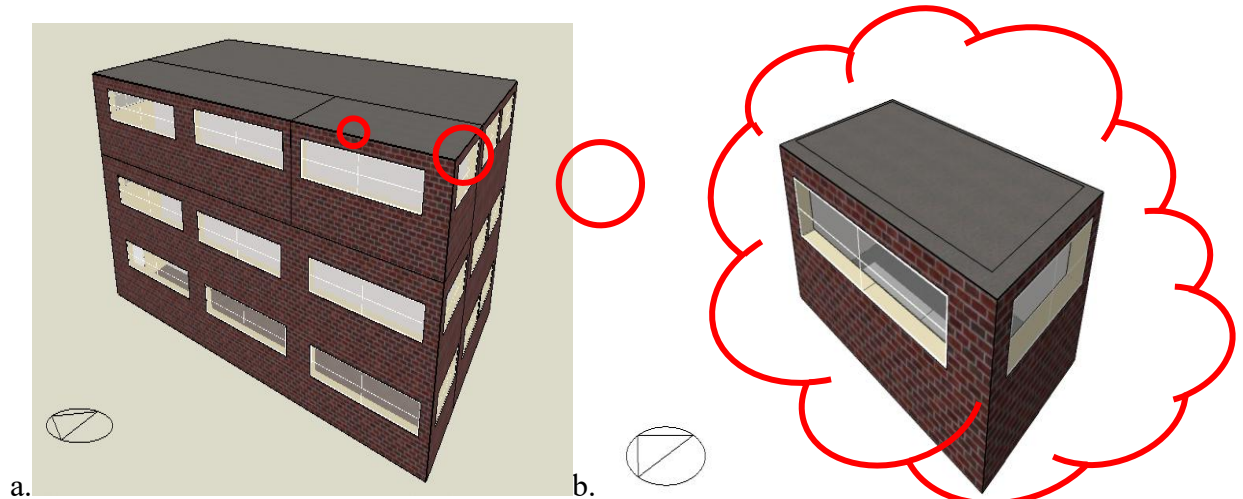


Figure 39 (a-b): Thesis model in the design-builder interface (rendered view; & the block under consideration)

Design Builder software shows an overlaid with a solar path diagram in Figure 40 below. The solar path indicates the sun's position in the sky at various times and throughout the year, as represented by concentric green circles (altitude) and angular markings (azimuth). The building's orientation is depicted in relation to the solar trajectory, which allows an

assessment of solar exposure on different facades. This analysis is crucial for optimizing daylighting, shading devices, and energy performance in building design, particularly in addressing heat gains and visual comfort.

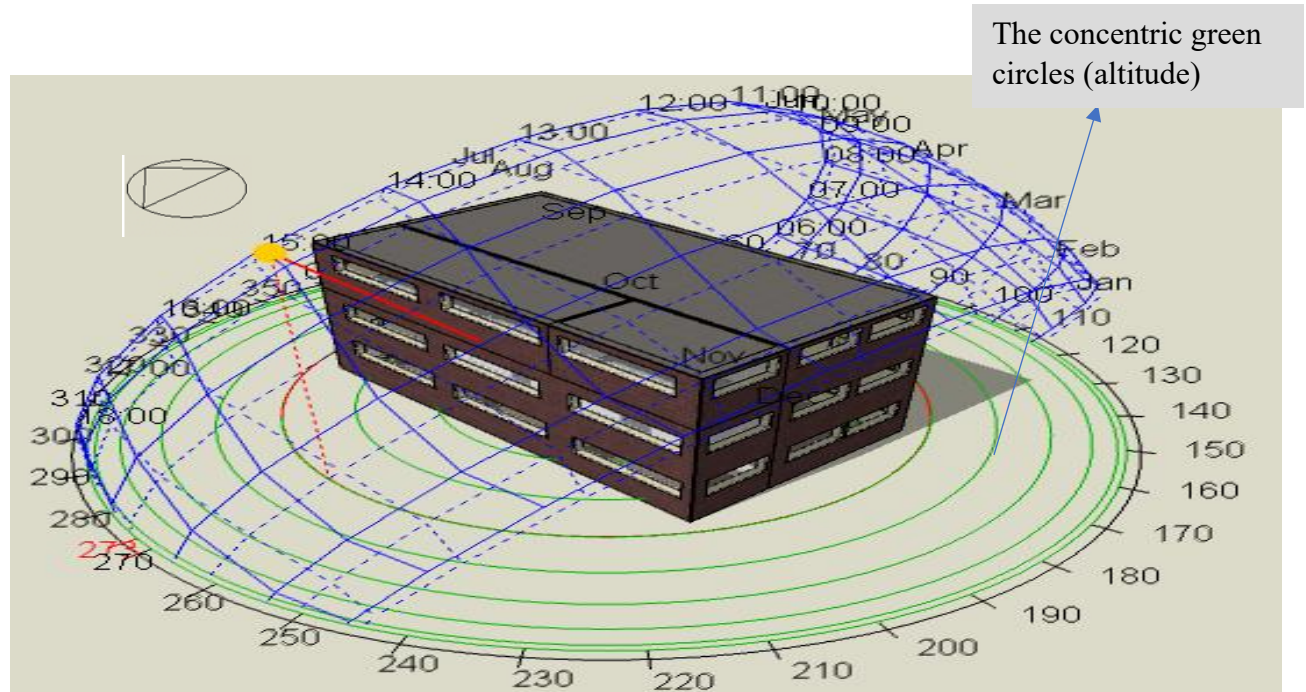


Figure 40: The building model showing the solar path

➤ 4.2.2 Settings (Activity Tab):

A copy of a typical office setting from the software template was adopted for this research, its basic settings are shown in figure 41 below. Another setting adjusted on the activity tab was that it was assumed, that two (2) human beings would be in the room in the occupancy section, the heating setpoint temperature was set at 18°C; computers and office equipment were checked, so that the model could generate enough internal heat gain. As for the schedule, the model is set to operate continuously around the clock.

MY__Copy of Generic Office Area	
Areas to perform office work including offices and meeting rooms. It can include internal corridors providing access to other areas.	
Source	UK NCT
Category	Offices / Workshop businesses
Region	General
Sector	B1 Offices and Workshop business
Holidays	
Holidays	No
Colour Shading in Model	
Floor shade colour	
All Gains	
Power density (W/m2)	11.77
Occupancy details	
Occupancy density (people/m2)	0.1110
Number of people	0.00
Metabolic Heat	
Metabolic rate	Light office work/Standing/Walking
Metabolic factor (0.85 for women, 0.75 children)	0.90
CO2 generation rate (m3/s-W)	0.0000000382
Latent fraction	0.5000
Clothing	
Clothing schedule definition	1-Generic summer and winter clothing
Winter clothing (clo)	1.00
Summer clothing (clo)	0.50
Clothing schedule	Default clothing schedule (Northern)
Workday profile	
Occupancy	From 7 to 19
Days / week	5
Heating	
Set point temperature (°C)	22.000
Set back temperature (°C)	12.000
Workday profile	
Operation	From 5 to 19
Schedules	
Schedule	Office_OpenOff_Heat
Cooling	
Set point temperature (°C)	24.000
Cooling set back (°C)	28.000
Workday profile	
Operation	From 5 to 19
Schedules	
Operation	Office_OpenOff_Cool
Ventilation Set Point Temperatures	
Natural Ventilation	
Nat. vent. set point (°C)	24.000
Schedule	Office_OpenOff_Occ
Mechanical Ventilation	
Mech. vent. set point (°C)	10.000
Schedule	Office_OpenOff_Occ
Lighting	
Target illuminance (lux)	400
Default display lighting density (W/m2)	0.000
Ventilation Fresh Air	
Min fresh air (l/s-person)	10.000
Mech vent per area (l/s-m2)	0.000

Figure 41 : Model Activity Tab Buildup

➤ 4.2.3 Model Envelope Description (Construction Tab)

Figure 42 below shows the envelope assembly of the building, the block wall has a U-value of 0.403 W/m²-K. This wall consists of 100mm outer brickwork, 66.80mm XPS extruded polystyrene, 100mm concrete Block (medium), and 13mm gypsum plaster at the inner surface. As for the roofing component, a 10 mm asphalt layer is exposed to the atmosphere,

131.60 mm of MW Glass wool follows, and a 200mm air gap is between the glass wool and a 13mm plasterboard, all making a U-value of 0.272 W/m²-K.

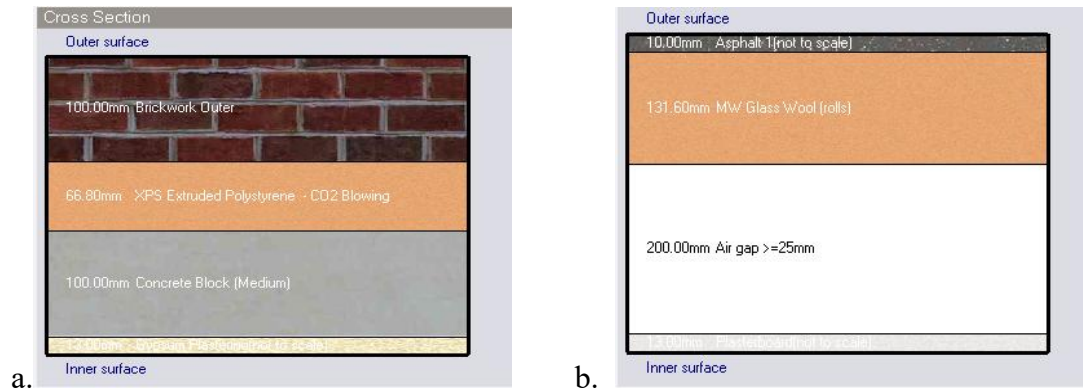


Figure 42: The cross-section of the building envelope build-up [(a) Wall (b) Roof]

➤ 4.2.4 Gazing Properties (Opening Tab)

A Project glazing template in the software was also adopted, the opening layout has two (2) layers, a generic PYR B Clear 3mm at its outermost layer, a 13mm air gap, and a generic 3mm clear glass at the innermost layer with a wall façade having 40% vertical glazing, ASHRAE 90.1 Appx G

➤ 4.2.5 HVAC Properties (HVAC Tab)

One of the simplest HVAC templates was selected for this thesis, this template is named VAV, Air-cooled Chiller, Outdoor air reset. This template has some features including the Auxiliary Energy of 35 KWh/m², other features are:

- Mechanical Ventilation: is on; Rate (ac/h) of 3.0; Design flow rate 0.10000; the outside air definition method is defined as 4mins fresh air (sum per person + per area)

- Fans: Fan type 1-Supply, Pressure rise (Pa) 700.0; Total efficiency (%) 7.0
- Cooling: on; Cooling system seasonal CoP 1.80; Minimum Supply air temperature 12C, minimum supply air humidity ratio (g/g) 0.0008
Air Temperature Distribution: Distribution mode = 1-mixed; interpolation mode: 3-Inside-outside Delta

Other settings in the model options are:

- Construction & Glazing Data: General; Multi-State electrochromic control method: Sensor Groups
- Gains Data: Early
 - Gain Definition Level – Globally in model options
 - Occupancy method – Number of people
 - Occupancy latent gains – Dynamic calculations
 - Equipment gain Units – Power density
 - Lighting gain units – Normalized Power Density
- HVAC mode: Simple
 - HVAC Sizing: Autosize; Simple HVAC Autosize method: Energy Plus
 - Specify Simple / Design HVAC details: **Checked**
 - Auxiliary Energy Calculations: Separate Fans & Pumps
 - Mechanical Ventilations Method: Room Ventilation
- Natural Ventilation & Infiltration: Schedule
 - Infiltration Units: 1-ac/h

4.3 ANSYS CFD Model

The process of solving CFD problems as identified above is usually grouped into three phases, vis-a-vis, pre-processing, processing, and post-processing. Figure 43 below shows the system process for the simulation as designed by ANSYS. A simplified approach to these processes is presented in a flowchart in Figure 45 below. The CFD simulations were performed in some workstations: Dell version 10.0.19044 Build 19044, with the following processor detail: Intel ® Xeon® W-2255 CPU 3.70GHz, 3696 MHz, 10 cores(s), 20 logical Processing, installed Physical RAM of 32Gb. The software used was academically licensed Ansys Fluent® 2023R1 provided by the ICT department of the University to the Department of Architectural Engineering and Construction Management, where this study was carried out.

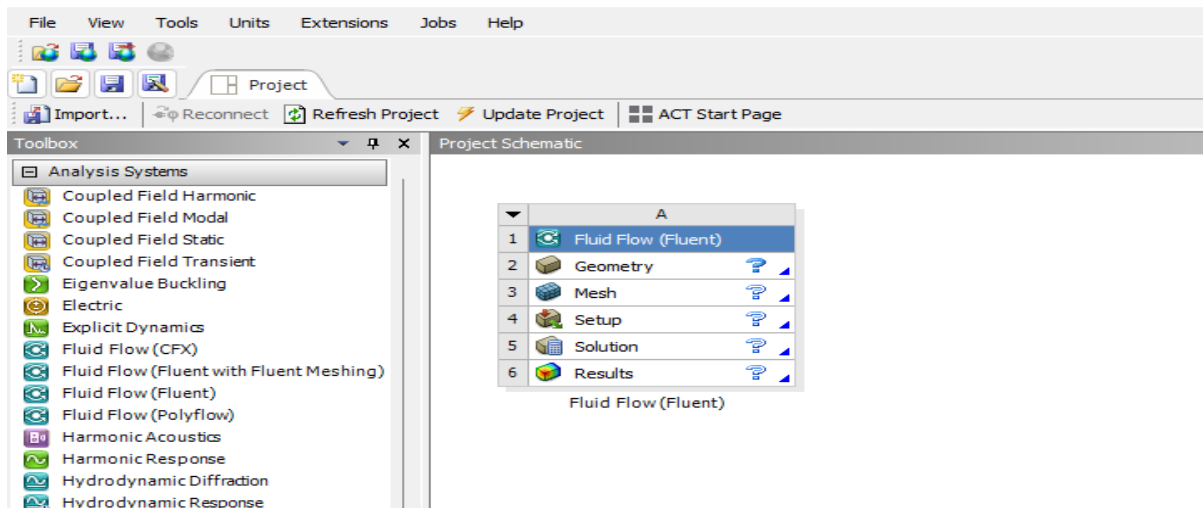


Figure 43: A project schematic view of ANSYS Workbench Interface

The three (3) main processes (pre-processing, processing, and post-processing) as used for this study are hereby discussed below:

4.3.1. Pre-processing:

This is the first stage in any ANSYS CFD simulation, it comprises of different sub-stages which are described below:

4.3.1.1 Geometry Preparation

Geometry preparation plays a crucial role in the simulation process, serving as the basis upon which accurate analyses are built. Be it a complex mechanical component, optimizing fluid flow patterns, or simulating electromagnetic phenomena, mastering geometry preparation is essential for achieving reliable results. In this study, the geometry shown in Figure 44 was drawn as a fluid volume with a design modeler; one of the drawing tools which is embedded in ANSYS software. A rectangular shape was taken from one of the basic/primitive shapes, and the x,y,z data (2.75m, 4.91m, 2.24m) coordinates were chosen as represented in Figure 46. “Plane”, and ‘Face Slice” tools were mostly used in the preparation of the geometry.

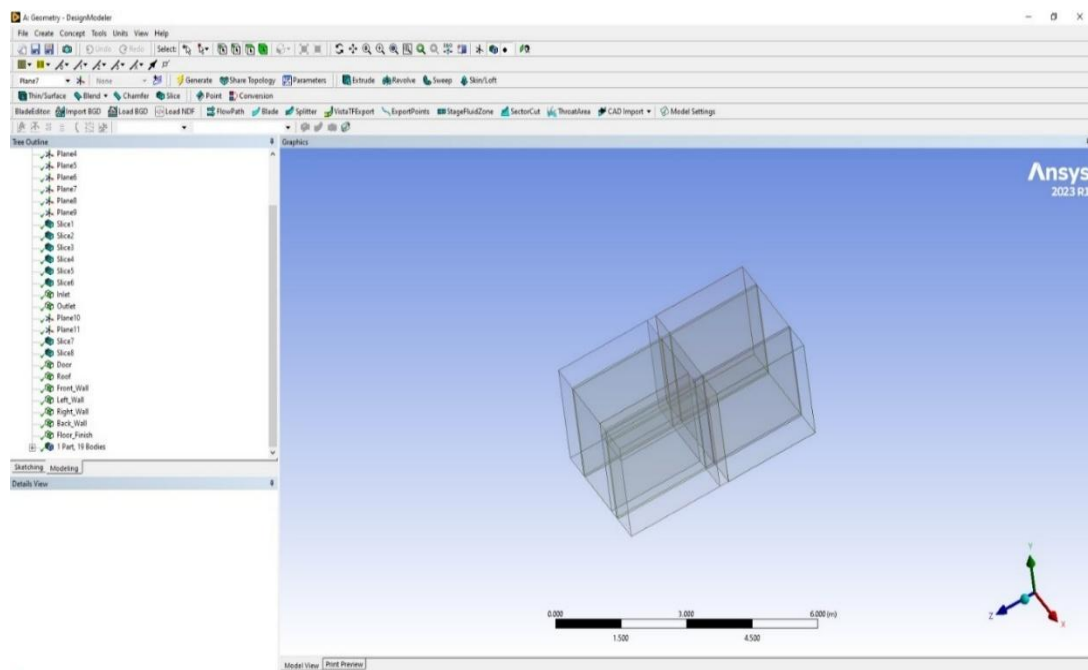


Figure 44: Design Modeler Geometry

The width of the room is as the X-axis, while the length of the room is the Y-axis and the headroom of the room is taken as the Z-axis of the room; Figure 46 is the pictorial representation of this description.

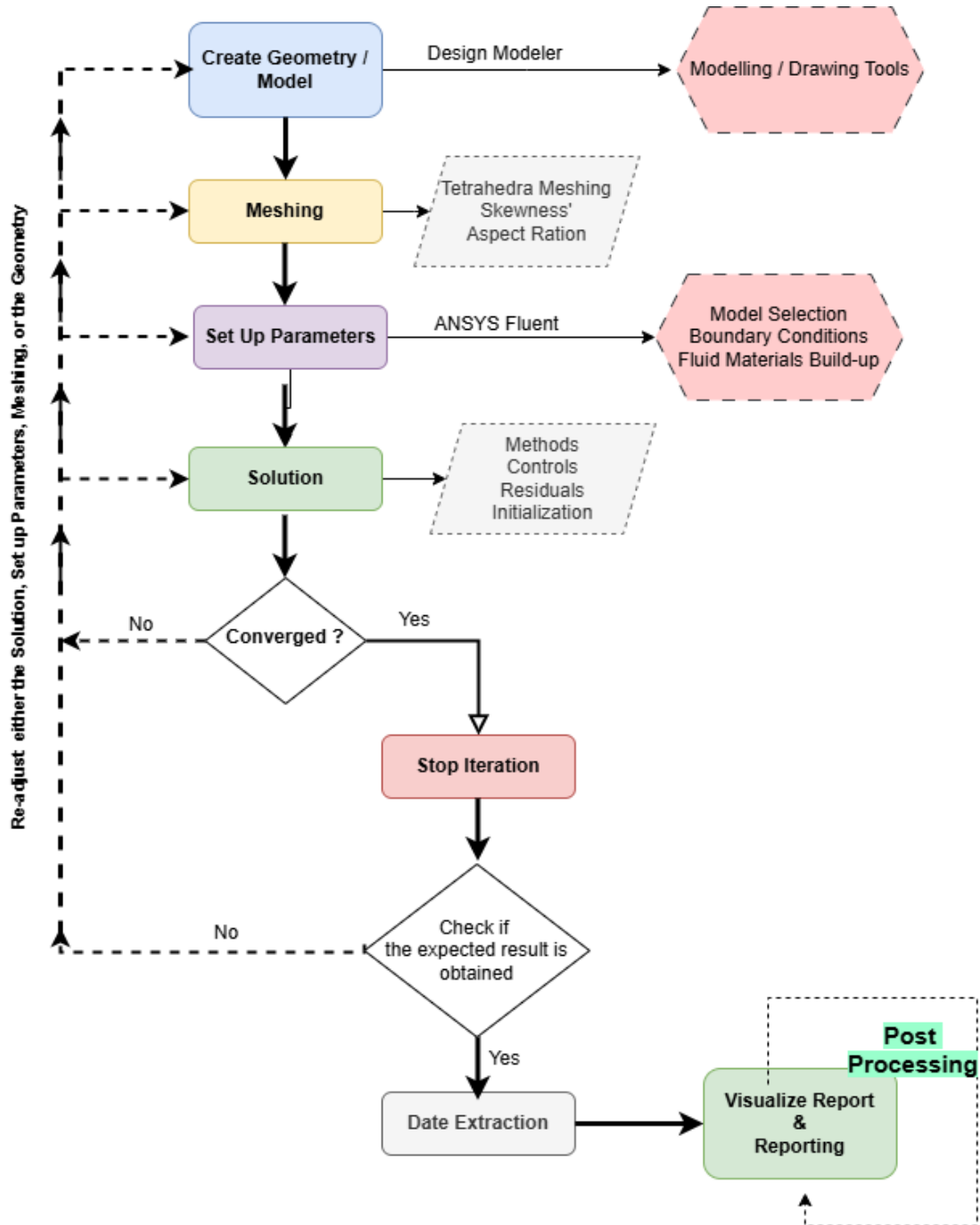


Figure 45: ANSYS CFD Flow process



Figure 46: Geometry cartesian configuration

4.3.1.2 Mesh Generation

The office space above was discretized using a uniform tetrahedral mesh, the main advantage reported by Martin, (1991), that part of the advantage of a uniform mesh is that it is the most straightforward method of discretization and that it is relatively easy with the flow equation. He continued that a uniform discretization technique does not provide the opportunity to concentrate cells at locations where detail is required; to avert this, he suggested that a large number of cells be made through the entire space. Tu et al., (2018) and Mehmert, (2023) said a tetrahedral mesh has the advantage of being able to well approximate the surface contour. To achieve good results, higher-order elements like quadratic interpolating 10-node tetrahedral elements should be used rather than 4-node ones, which can only interpolate linearly. Although this increases the computational costs, the improved result quality makes it worthwhile.

The target skewness of the meshes is 0.9 (default), with a high smoothing and a bouncing box diagonal of 6.1434m. The minimum edge length is 5.2×10^2 m, with a surface area of 1.705 m^2 . The differences between the meshes used for this study are resented in the table below:

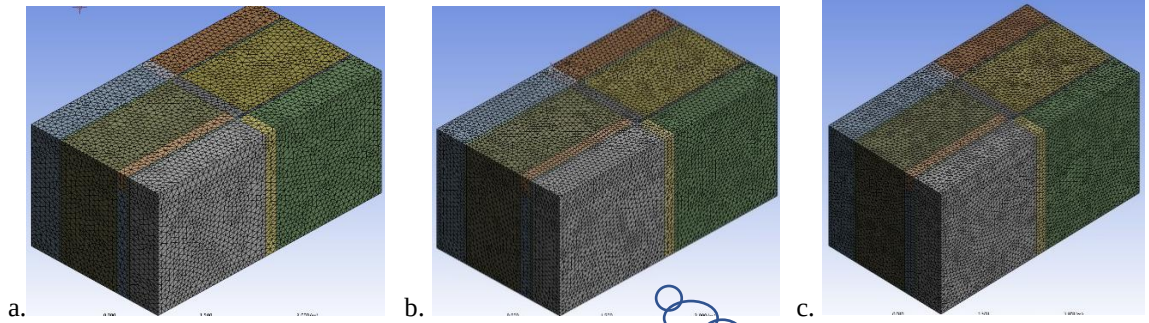


Figure 47: The three types of tetrahedral mesh used for this study

Sizes:
 Mesh A: 210,183
 Mesh B: 308,141
 Mesh C: 406,500

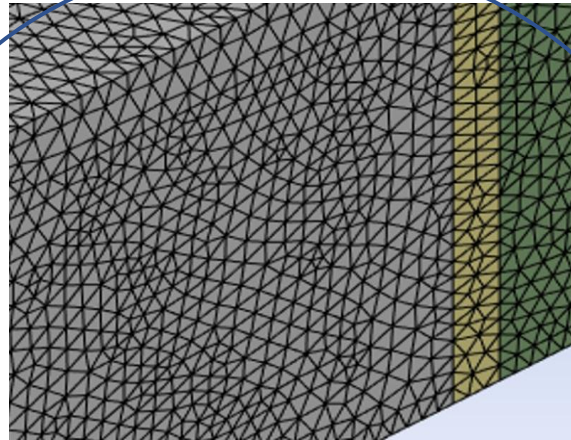


Table 4: Details of Mesh used for the study

S/N	Mesh	Nodes	Number of Element	Element Size
1	A	39,353	210,183	7.8×10^{-2} m
2	B	57,305	308,141	6.6×10^{-2} m
3	C	75,136	406,500	5.95×10^{-2} m

4.3.1.3 Grid Independence Test

A grid-independent analysis was needed to be carried out by constructing a set of grids with different grid numbers to ensure the accuracy of the computational results, the grid

number is usually increased until the numerical results will not be affected by the grid size (Zhou et al., 2022). In this study, a mesh independence test was carried out by running the simulation at various element sizes of the created mesh and comparing the obtained findings appropriately. Determining the ideal element size for the simulation is the primary goal of the independence test. Increasing the number of elements in the designed model is equivalent to minimizing the size of the element. Nevertheless, a larger computational cost would be necessary due to the enormous number of elements. A smaller size of the element would result in a high-accuracy solution. However, the time taken to finish the solution would be prolonged. Three element size simulations were compared in this study and the profile was selected as a parameter to observe which element size is likely to be the optimum element size for this simulation. Table 4 above demonstrates the data for the mesh independence test. While most research uses some parameters like temperature for most mesh dependency tests, one of the experimental scenarios was used as a comparison criterion. The data obtained were measured from the inlet vent and directed upward to the ceiling of the room. Based on the data obtained, each element size shows the same trend of decay.

4.3.1.4 . Boundary Conditions

In ANSYS, boundary conditions play a crucial role in defining the behavior of a physical system under simulation. They represent the constraints or influences exerted on the system at its boundaries, affecting how the system interacts with its surroundings or responds to external stimuli. ANSYS offers a variety of boundary condition types to accurately model real-world scenarios across different engineering disciplines. Here are some common

ANSYS boundary conditions: fixed Support, displacement, pressure, temperature etc.

Table 5 below shows the boundary conditions for this study.

Table 5: Boundary Conditions

Boundary	Type	Details
Inlet	Velocity inlet	Momentum Specification: Magnitude & Direction Ref Frame: Absolute Velocity Magnitude: Depending on Experimental measurement & Data from the Energy Plus Software Turbulence: Default Thermal Depending on Experimental measurement
Outlet	Pressure Outlet	Default
Internal	Interior-full body-building	
Ceiling	Momentum	Wall Motion: Stationary
Wall (Front, Back, Right & Left)	Thermal	Adiabatic Condition with no Heat Flux
Floor		
Door		

4.3.1.5 . Material Properties

In ANSYS, material properties define the mechanical, thermal, electrical, magnetic, and other material behaviors necessary for accurately simulating physical systems in engineering analyses. These properties play a crucial role in determining how materials respond to applied loads, temperature changes, electromagnetic fields, and other environmental conditions. ANSYS provides comprehensive tools for specifying and

managing material properties across various simulation disciplines. In this study, A mixture template of gas was created, where carbon-dioxide was made to mix with other constituents of air thoroughly, and these gasses are made to fill the room adequately.

4.3.2 Processing (Solving):

4.3.2.1 Numerical Solution

The Energy equation was activated; under the viscous model, the study used the k-epsilon and activated the realizable, which is the best method for studying separated flow with simple second-flow features. Under the near-wall treatment, the standard wall functions were activated to study the flow behavior near the wall. The species transport model was activated and used the diffusion energy source. To create the mixture of air and CO₂ we used incompressible ideal gas density. This set up was adopted from Al-Rawi et al., (2022), although theirs was a mixture of air and water. The governing equation of viscous flow, the Navier-Stokes equation for conservation of mass, momentum and energy related to the turbulent reacting flow, was solved using a pressure-based solver with the simple algorithm. The general form of the differential equations involved have been presented in sec 2.7.2 above. The default setting was adopted, which contains The Least Squares Cell Based approach was used for gradients of solution variables. Having a second-order upwind for pressure, momentum, and energy in the spatial discretization. And first order was selected for turbulent kinetic energy, turbulent dissipation rate and the boundary condition implemented in this simulation is shown in Table 4. It is worthy of note, that this set up adopted was also adopted by Nur'Amirah Busu et al., (2022) except that they adopted a first-order upwind for energy in the spatial discretization.

The k-epsilon realizable model considers the flow in motion as a free-shear layer and enhances the evaluation of pressure gradients and boundary layers. This turbulence approach allows the simulation of strong streamlines with curvatures, vortices, and rotation. the k-epsilon realizable model also has a better performance for several separated flows and/or flows with complex secondary flow features (The OpenFoam Foundation, 2017; ANSYS, 2016; Shih et al., 1995). The detail of this model is shown in table 6 below.

Table 6: k-epsilon realizable model parameters used for the CFD

S/N	Parameter	Model Constants	User Define
		Value	Functions
1	C2	1.9	
2	TKE Prandtl Number	1	None
3	TDR Prandtl Number	1.2	None
4	Energy Prandtl Number	0.85	None
5	Wall Prandtl Number	0.85	None
6	Turbulence Schmidt Number	0.7	None

In the k-epsilon realizable model the term “realizable” means that this alternative model satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows.

4.3.2.2 Time Stepping:

Simulations were performed for more than 40000 seconds clock time, with a time step of 0.01 seconds based on the Courant Number (Co) criterion (Guevara Luna et al., 2019)The

Courant Number was calculated using the mass velocity in the flow domain (v), the time step (δt), and the mesh minimum element size (δx , Table 7 below).

$$Co = \frac{v\Delta t}{\Delta x} \text{-----} (22)$$

For the whole experimental scenario, the highest Courant Number with a value of 4.2 is lower than 25, the recommended maximum value for the flow simulation to converge according to Guevara Luna et al., (2019) who also cited Riaño et al., (2018); Guevara Luna, (2003); Versteeg and Malalasekera, (1995).

Table 7: Courant Number of meshes based on experimental scenarios

Scenario		Velocity in the flow domain (v) (m/s)	Time Step	Mesh Label	Element Size (m)	Courant Number criterion (Co)
Strategy 1	No ventilation – HVAC System off	-	0.01	-	-	-
Strategy 2	The HVAC System damper opened at 40%	1.00	0.01	A	0.0078	1.282
				B	0.0066	1.515
				C	0.00595	1.681
Strategy 3	The HVAC System damper opened at 60%	2.2	0.01	A	0.0078	2.821
				B	0.0066	3.333
				C	0.00595	
						3.697
Strategy 4	The HVAC System fully opened at full capacity	2.5	0.01	A	0.0078	3.205
				B	0.0066	3.788
				C	0.00595	4.202

4.3.2.3 Convergence:

Some criteria need to be met to achieve converged numerical solutions. Two criteria are used to check the solution convergence. The first criteria is residuals of each conservation equation, which is a specified tolerance defined by Fluent. The residual sets for each equation are given in Table 8 below.

Table 8: Convergence Criteria		
S/N	Equations	Absolute Criteria
1	Continuity & Epsilon	10^{-4}
2	K	10^{-5}
3	X, Y, Z, Energy	10^{-6}

Sometimes the residual may reach the convergence criterion, but the solution still changes with more iterations. Therefore, a second criterion is used, which monitors variables of the solution until it no longer changes with more iterations. In this study, both forms of convergence are adopted. While some equations converged, the iterations were set to continue until there was no possibility of decay from the curve.

4.3.3 Sensitivity Analysis

Sensitivity analysis, also known as parametric analysis or design optimization, is a process used to assess how changes in input parameters or design variables affect the output responses or performance metrics of a simulation model. Sensitivity analysis plays a crucial role in engineering design optimization, allowing engineers to understand the impact of design variations on product performance, identify critical parameters, and optimize designs to meet specified objectives. This concept was applied in the selection of

turbulence model for this study. Many researchers among which includes; (Nur'Amirah Busu et al., 2022), Al-Rawi et al., (2022), even Fan et al., (2022) cited Wang, X.X (2012) to assert that any of the K – epsilon (Standard k- ϵ model, Realizable k- ϵ model, and RNG k- ϵ model) are usually adopted for airflow simulation of this nature. To determine the most optimal model, a tetrahedra mesh using the three K- ϵ models was simulated, alongside a cube-mesh Realizable k- ϵ model was also simulated together, since most literature supported the Realizable k- ϵ model. The outcome of this analysis is presented in sec 5.2.2.2 below.

4.3.4 Post-processing:

This section of CFD is about visualization and analysis, it involves Data Extraction, Contour Plots, Path lines and Particle Tracking, Reports and Animations. More of this are presented in the next chapter.

4.3.5 Validation & Calibration Studies

Verifying the effectiveness of a proposed computational method also requires an exercise in experimental validation. In contrast to calibration, which is an iterative process of comparing the model with the real system, modifying the model as needed, and comparing again until a model is acceptable, validation is the process of comparing the model and its behavior to the real system and its behavior (validated). In this study, the experimental data from the case scenario were inputted into the ANSYS-CFD software and the output were compared with the real experimental result. Subsequent sections show the result of the validation/calibration exercise.

4.3.6 Source Term Calculations in ANSYS – CFD – Model

Parameters

- CO₂ Emission rate (L/s) = 36 L/s (for 2 people)
- CO₂ density = 1.842kg/m³
- Source term (Box) volume = (0.14 x 0.14 x 0.2) = 0.00392 m³
- Exhale velocity of CO₂ = 0.2m/s (From Literature)
- Turbulence intensity = 0.15¹ (Average turbulence intensity 15% or 0.15)
- Characteristic Length Scale = (0.07² x box height) = 0.07 x 0.2 = 0.014
- Specific Heat of CO₂³ = 844J/(kg.K)
- Indoor temp = 23°C (298K)
- C_u = 0.09 (Empirical constant for turbulence K – ε dissipation rate calculation)

Calculations for the source term boundary conditions

1. Mass Source (kg/(m³.s))

$$\begin{aligned}\text{Mass flow rate (kg/s)} &= \text{CO}_2 \text{ emission rate (m}^3/\text{s)} \times \text{Density CO}_2 \\ &= 0.036 \text{ m}^3/\text{s} \times 1.842\text{kg/m}^3 \\ &= 0.066312 \text{ kg/s}\end{aligned}$$

$$\begin{aligned}\text{Mass source} &= \frac{\text{Mass flow rate}}{\text{Volume of Source term (box)}} \\ &= \frac{0.066312 \text{ kg/s}}{0.00392 \text{ m}^3} = \mathbf{16.92 \text{ kg/m}^3.\text{s}}\end{aligned}$$

¹ Typical indoor settings use a turbulence intensity of around 10–20%.

² This value of 0.07 is based on empirical studies that provide reasonable approximations for internal flows under turbulent conditions

³ The specific heat capacity of CO₂ at constant pressure, *C_p*, is often taken to be around 844 J/(kg·K) for certain temperature ranges. This value is an average approximation based on the specific heat behavior of CO₂ around room temperature (approximately 300 K).

The specific heat of CO₂ varies with temperature, but for many engineering applications, an approximate value like 844 J/(kg·K) is used for simplicity when the temperature range does not vary drastically. This value is consistent with data found in thermodynamic tables and sources such as the Engineering Toolbox and NIST Chemistry WebBook, which provide temperature-dependent values of specific heat for various gases

2. Momentum Source (N/m³) for X, Y, Z (Depending on the direction of emission)

$$\begin{aligned}\text{Momentum source (N/m}^3\text{)} &= \frac{\text{Mass flow rate} \times \text{Exhale Velocity}}{\text{Volume of Source term (box)}} \\ &= \frac{0.066312 \frac{\text{kg}}{\text{s}} \times 0.2 \text{m/s}}{0.00392 \text{ m}^3} = \frac{0.0132624}{0.00392} \\ &= \mathbf{3.38 \text{ N/m}^3}\end{aligned}$$

3. Turbulence Kinetic Energy (kg/(m.s³))

$$\begin{aligned}\text{Turbulence kinetic energy} &= 1.5 \times (\text{Turbulence Intensity} \times \text{Exhale Velocity})^2 \\ &= 1.5 \times (0.15 \times 0.2)^2 \\ &= \mathbf{0.00135 \text{ kg/m.s}^3}\end{aligned}$$

4. Turbulence Dissipation Rate Source (kg/(m.s⁴))

$$\begin{aligned}\text{Turbulence dissipation rate } (\epsilon) &= C_u^{3/4} \times \frac{K^{3/2}}{\text{Characteristics Length Scale}} \\ &= (0.09)^{3/4} \times \frac{(0.00135)^{3/2}}{0.07 \times 0.2 = 0.014} \\ &= 0.164 \times \frac{0.00004960}{0.014} \\ &= \mathbf{0.0005810 \text{ kg/m.s}^4}\end{aligned}$$

5. Energy Source (W/m³)

$$\begin{aligned}\text{Energy source} &= \frac{\text{Mass flow rate} \times \text{Specific Heat of CO}_2 \times \text{Indoor Temp}}{\text{Volume of Source term (box)}} \\ &= \frac{0.066312 \times 844 \times 298}{0.00392} = \mathbf{4254659.12 \text{ W/m}^3}\end{aligned}$$

4.5 CONTAM - W

With the importance of using CONTAM-W for accurate indoor air quality modeling, this thesis modeled the same experimental room described in the previous section. The software's interface is shown in Figure 48 below. The modeling setup begins with accurate

weather settings, ambient, and other data necessary (air handling system, air supply setting, etc.) for the simulation after defining the sketchpad / working window.

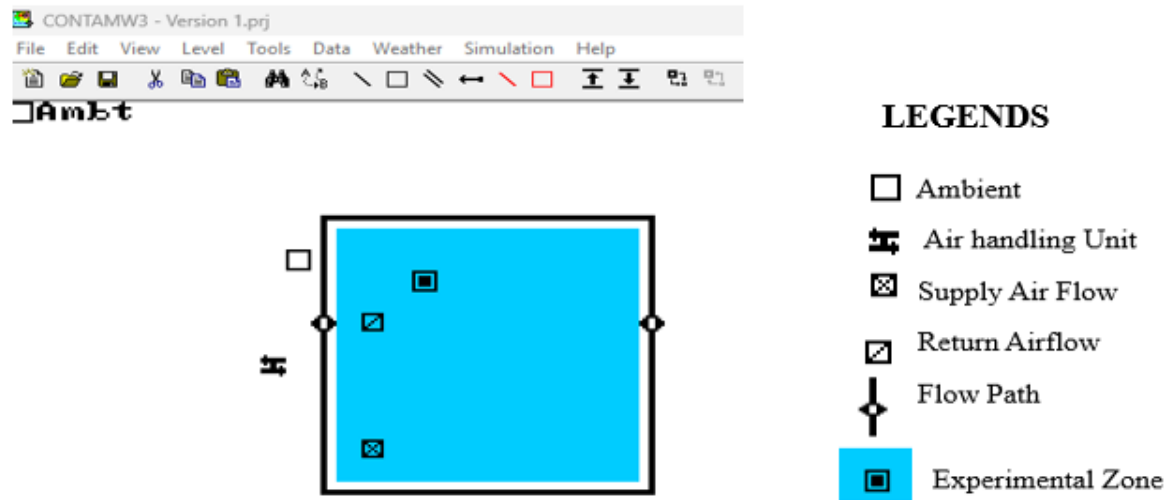


Figure 48: Work interface of CONTAM (W) Software

Similar to the process carried out for ANSYS, a systematic approach is applied when using the CONTAM software. The procedure begins with experimental validation, ensuring that the software's simulation aligns with real-world data. Following validation, the main task involves incorporating a source term within the model, allowing it to effectively simulate the generation and dispersion of contaminants. Additionally, data obtained from the experimental setup and Design Builder simulations are integrated into the CONTAM model. This integration ensures consistency across the different tools, enabling accurate representation of contaminant behavior and improving the reliability of the results.

Table 9 below shows some boundary conditions used in the setup for the CONTAM -W software.

Table 9 Some: Boundary Condition Settings for CONTAM Software

S/N	CRITERIA		PARAMETERS	MEASUREMENTS
A.	Environmental Conditions	i	Interior Temperature	23°C
		ii	Outdoor Temperature	46.5°C – Experiment Validation
		iii	Atmospheric Pressure	Varied based on the time of the year adopted 101325 pa
B.	Contaminants	i	Ambient CO ₂	480 ppm
		ii	CO ₂ Level for Experiment Validation	5000 ppm
		iii	CO ₂ generation (Main)	18 L/hr.
C	Air Condition	i	Air Supply & Air Return	Experimental Data Supply Airflow from Design Builder Software
D	Air Leakage Data (Opening Exterior walls)	i	Two-way Model (Single Openings)	Model Parameters - Height (0.1m), Width (0.1m), Discharge Coefficient (0.5)

CHAPTER 5

RESULT ANALYSIS AND DISCUSSION

This research follows a structured sequence of analyses aimed at achieving model validation, integration, and alternative simulation. First, the results of a full-scale tracer gas experiment conducted in a physical setting was presented. Following this, a CFD simulation of the tracer gas experiment, conducted using ANSYS software and contaminant transport simulation, CONTAM-W software, will be reported to establish a basis for validation. The primary objective is to ensure that the CFD model accurately replicates the physical experiment's results, thereby confirming its validity. Once validated, the thesis presented the energy model results, which subsequently served as inputs for further simulations using the validated CFD model, forming the basis for the final research outcomes.

5.1 Experimentation Results

Having seen the importance of ventilation rates to achieve an acceptable indoor quality in Chapter Two. It is on that basis that this study carried out a full-scale ventilation measurement using tracer gas techniques using CO₂ as a surrogate. The section presents the results of the tracer gas techniques showing the air change rates using an office (as described above). This experiment was intended to validate the model created with the CFD simulation as a response to objectives number 1 and 2, which is “To assess the contaminant behavior distribution in a VAV-HVAC system served air-conditioned space under varying thermal loads to improve ventilation effectiveness and to evaluate different

VAV system strategies for achieving improved indoor air quality while maintaining energy efficiency” respectively.

The graph of the natural log of the CO₂ concentration against time produces a linear graph with the slope of the graph being the air change rate (**I**) as earlier explained with equation 6 and equation 20 above. Table 10 below shows the summary of the tracer gas experiment with details. Several series of experiments were carried out with different strategies by varying several percentages of damper openings, and labeling each series of experiments as “strategy”. As the percentages of the damper openings are being altered to achieve a varying amount of ventilation during the experiment, a corresponding air change rate is being derived. This is to mimic the operation of a typical VAV-HVAC system. For each of the experiments, downward (negative) exponential decay curves were derived as was in Figure 14a, these curves are transformed into a straight line by finding the natural logarithm of each point on the curve (fig 14 b-c). The slope was derived after using a trendline, an Excel function that tries to draw a best-fit line across various points on the graph, and the trendline corresponding R² value was appropriately displayed. The R² is known as the coefficient of determination, and it is most described as a statistical measure in a regression model that determines the rate at which a best-fit line cuts across various points in a graph. Strategy 1 – 4 shows different experimental days, where the damper openings of the HVAC systems were varied to produce different scenarios; at the end of every case, a table is presented to give a summary of what happened. It is worthy of note, that throughout the experiment, there is no significant relationship between the injected CO₂ in the room and the indoor parameters like room temperature, relative humidity, and the dewpoint

temperature. More so, the average ambient ppm of CO₂ in overtime has been 490 ppm, and it is at the point that the readings from the sensors are terminated.

5.1.1 HVAC Parameters and Air Change Rate

Table 10 below shows the measured parameters from the HVAC systems, these parameters are also imputed to the CFD Simulation software. The tools and equipment and their calibration procedures have been described in previous chapters of this thesis. In strategy 1, the system is off, hence, there was no record from the HVAC system, the only airflow could be due to infiltration from the adjacent space.

Table 10: Different Experimental Scenarios

Scenario	Supply Air Temp (°C)	Supply Air Speed	Supply Air Volume
		(m/s)	(m ³ /hr)
Strategy 1	-	-	-
Strategy 2	21.30	2.69	106.56
Strategy 3	25.40	2.20	91.80
Strategy 4	22.00	2.50	97.20

Strategy 1 – When the HVAC system was fully closed

In this scenario, the HVAC system is fully closed, thereby no ventilation at all into the room. It took a very long time of four hours and twenty-four minutes (15840 sec) before the injected air contaminant of 5000 ppm could return to the ambient concentration of 490 ppm. The decay was only possible due to exfiltration from the office space to the surrounding space from escape due to tiny spaces from the base of door, possible voids in

the wall and ceiling materials, etc; this also shows that there is a great linear effect on the supply of air (ventilation) into the room and the rate at which the contaminant evacuates the zone. The air change rate for this case is 0.36 ACH, with an R^2 of 0.96. Figure 48 below shows the graph in this scenario.

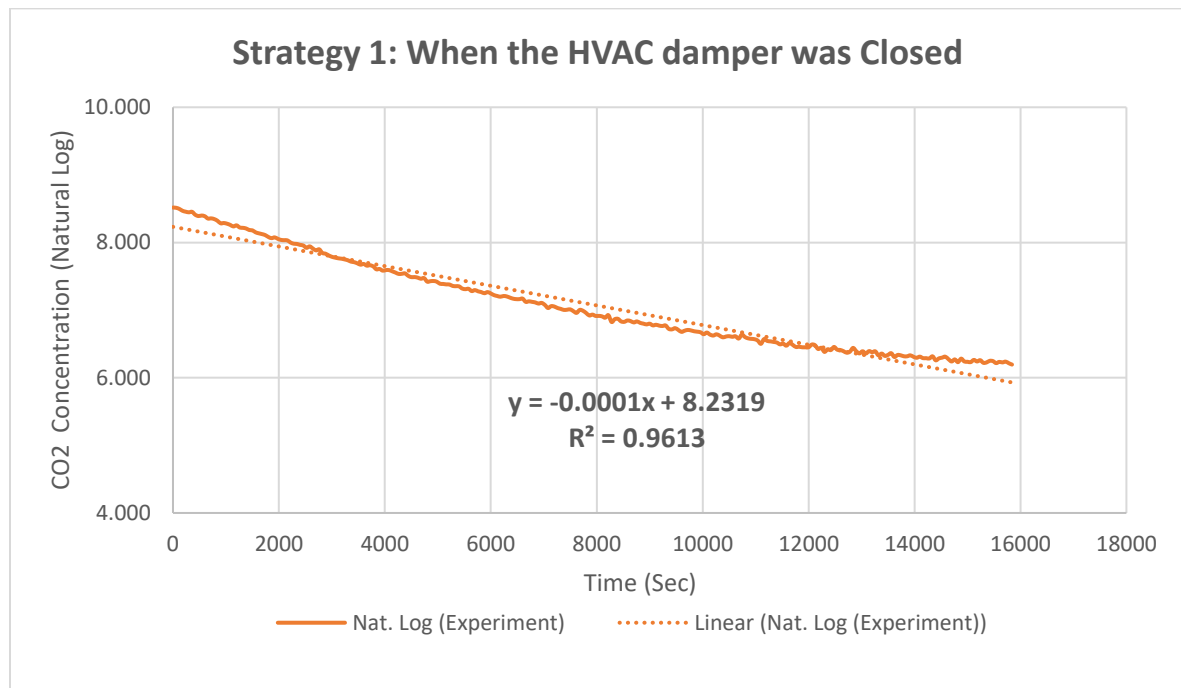


Figure 49: Strategy 1, when the damper was fully closed

Strategy 2 – When the HVAC was slightly opened (40%)

In this case, the HVAC damper is slightly opened at 40%, it only took about one (1) hour fifty -four (54) minutes (6840.00 sec) of the injected CO₂ of 5000ppm to return to its ambient, with a supply air volume of 29.6L. Despite this increase in decay time, the air change rate was 1.08 ACH. Figure 49 below also shows the graph of this Strategy. Compared to strategy 1, this strategy is capable of removing contaminants from the space due to the supply of air at 40% damper opening.

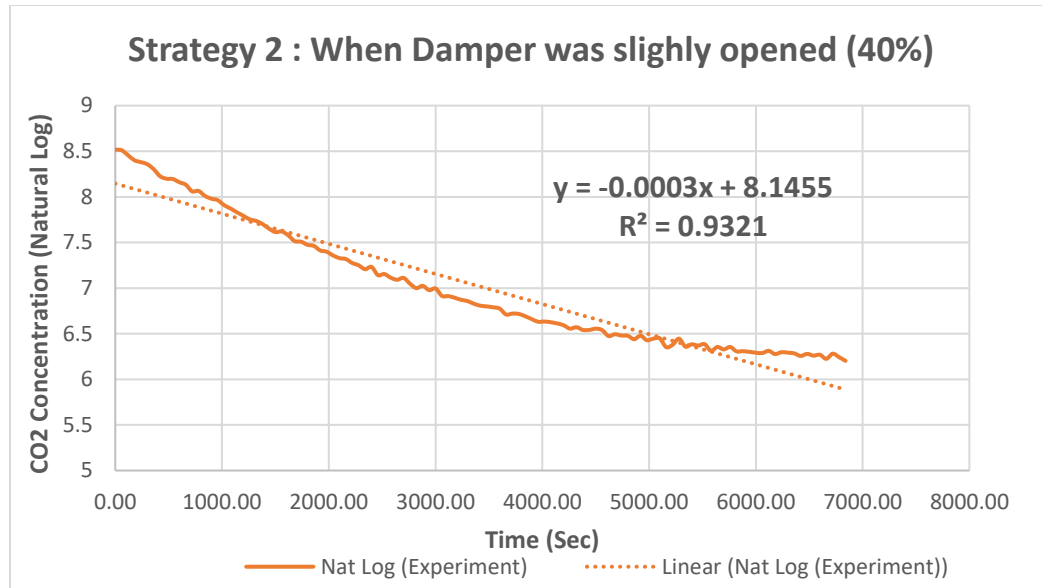


Figure 50: Strategy 2, when the HAVC damper was slightly opened

Strategy 3 - When the HVAC was slightly opened (60%)

Gradually, the injected air contaminant decayed faster in this scenario. It took the injected gas an average time of one (1) hour, thirty-four (34) i.e. 5640 sec for the decay to return to the ambient, making it 20 minutes faster than the last case. It has an R^2 value of 0.96 which produces an air change rate of 1.44 ACH. Thus, the CO₂ decay is directly proportional to damper openings.

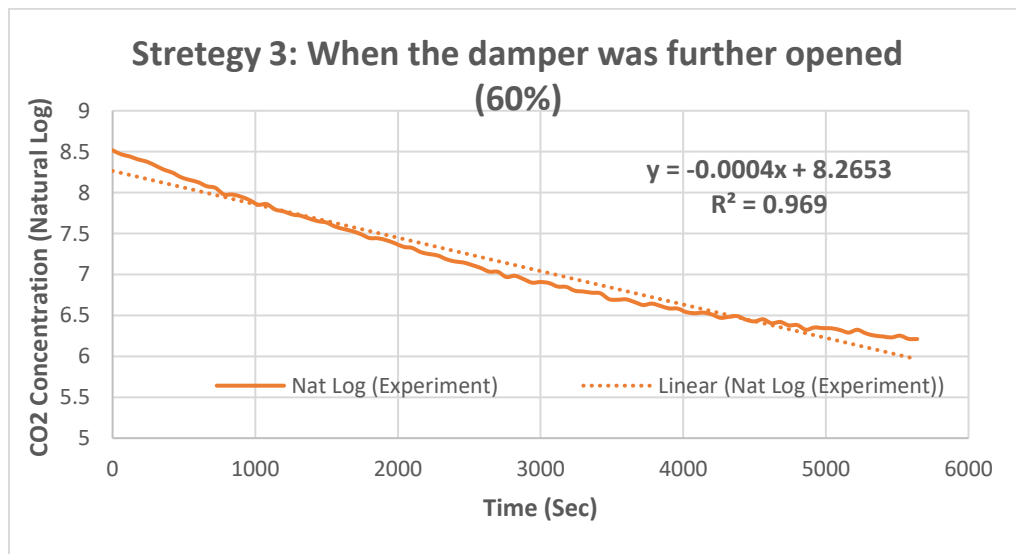


Figure 51: Strategy 3, when the HAVC damper was opened further

Strategy 4 – When the Damper was fully opened

As more openings are made to the damper, the airspeed and the volume of air from the system increase, and the decay rate also increases. In this case, the damper is fully opened, and it took about one (1) hour, thirty-one (31) minutes i.e. 5460 sec to get the same quantity of air contaminant of 5000 ppm of CO₂ to evacuate the experimental room and return to an ambient of 490 ppm before injecting. However, the air changes per hour for this case are same as that of the previous one.

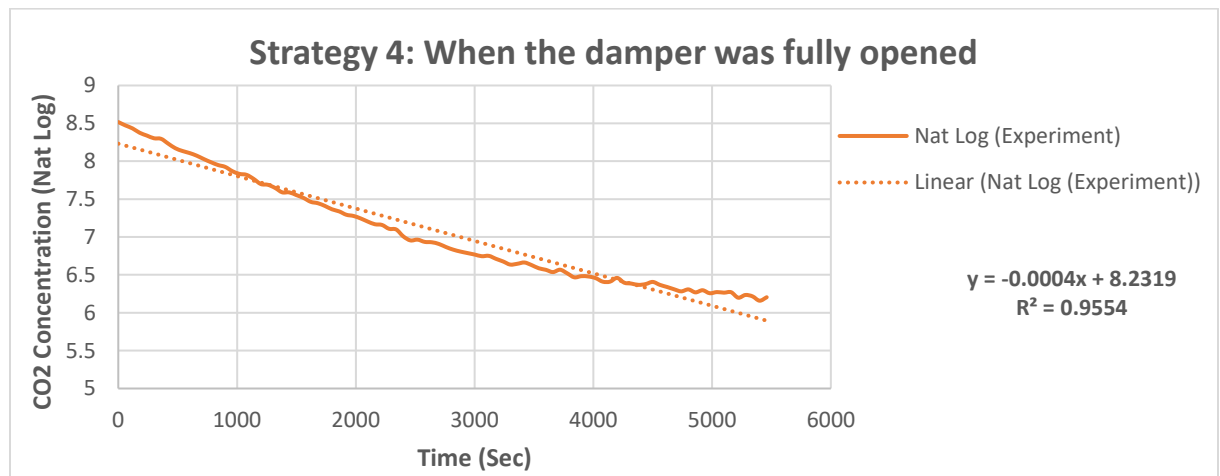


Figure 52: Strategy 4, when the HAVC damper was fully opened

Table 10 below shows that summary of the results of the experiment, which implies that there is a linear relationship between the amount of airflow and the rate of decay and air change rate of contaminants within the room of the experiment.

Table 11: Showing Experimental Decay Time & the Air Change Rate

Scenario	Decay Time (sec)	R ²	ACH ⁻¹
Strategy 1	15840	0.9613	0.36
Strategy 2	6840	0.9321	1.08
Strategy 3	5640	0.969	1.44
Strategy 4	5460	0.955	1.44

5.1.2 Alternative sensor positioning and their effect on Air Change Rate

To determine the impact of sensor placement on air change rates within the room, this study incorporated two additional sensors positioned at different heights, as illustrated in Figure 37 above. These sensors were installed simultaneously with the main logger, which was placed at the return diffuser of the room. Data extracted from the sensors and logger were utilized to analyze the rate of decay, allowing for a comparative assessment of how sensor positioning influences the measurement of air change rates. The initial sensor/logger reported was the one placed at the height of 2.2m from the floor (i.e. close to the outlet of the room). These alternatives explore the data from the data placed at the height of 0.75m and 1.65m from the floor. Table 11 below shows the decay time, R^2 value, and the air change rate from the sensors/loggers at the new heights of 1.65m and 0.75m.

Table 12: Results of Experiments with additional logger positions a. At 1.65m b. At 0.75m

A. Experimental results when the Logger is at 1.65m				B. Experimental results when the Logger is at 0.75m			
Scenario	Decay Time (sec)	R^2	Air Change Rate	Scenario	Decay Time (sec)	R^2	Air Change Rate
Strategy 1	15600	0.958	0.36	Strategy 1	16380	0.9567	0.36
Strategy 2	7860	0.897	1.08	Strategy 2	6840	0.9321	1.08
Strategy 3	4860	0.988	1.80	Strategy 3	6120	0.9585	1.44
Strategy 4	4860	0.973	1.80	Strategy 4	5820	0.9497	1.44

Figure 52 - 55 below shows the relationship between the Natural log of the concentration (in ppm) and the decay time (in sec) for each of the alternative sensor/logger placements.

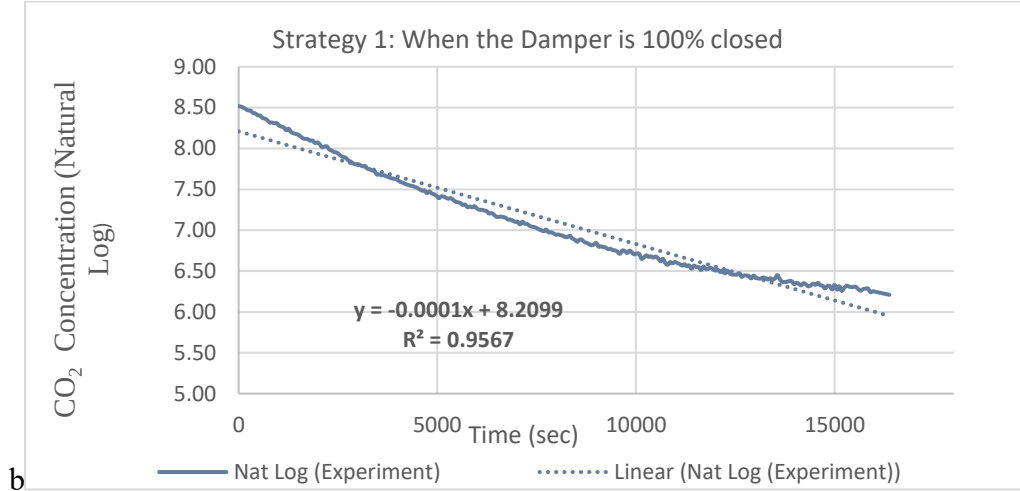
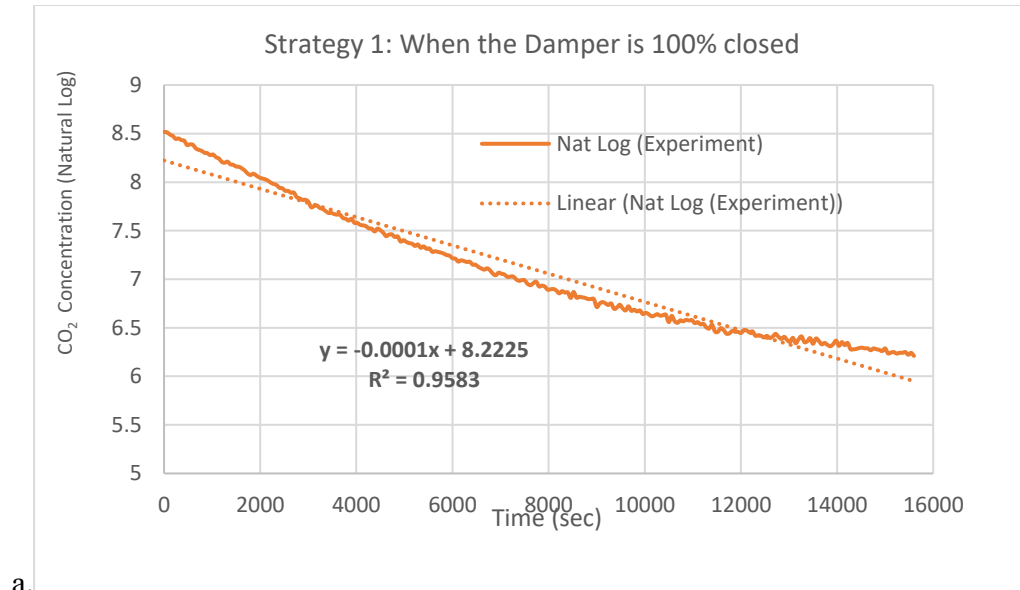
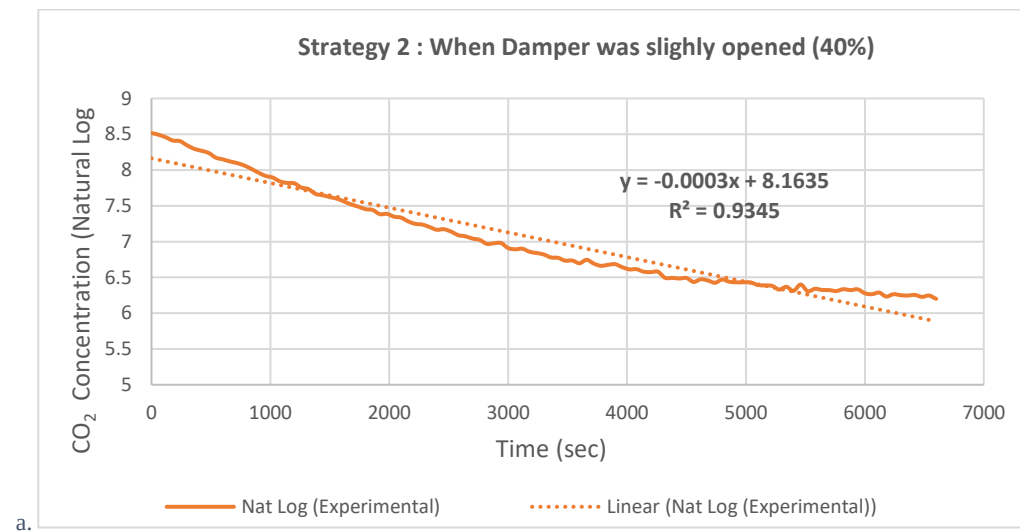
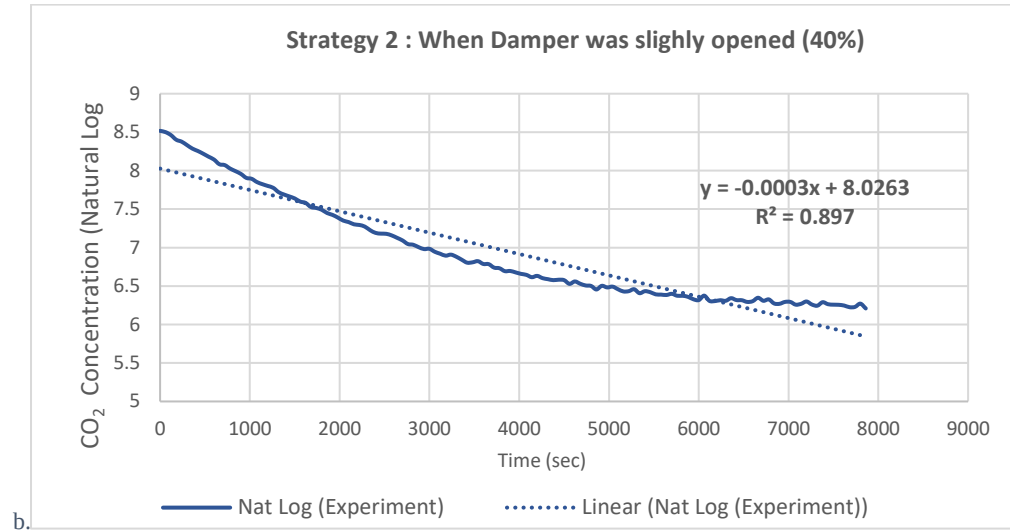


Figure 53: a, Logger @ 1.65m;

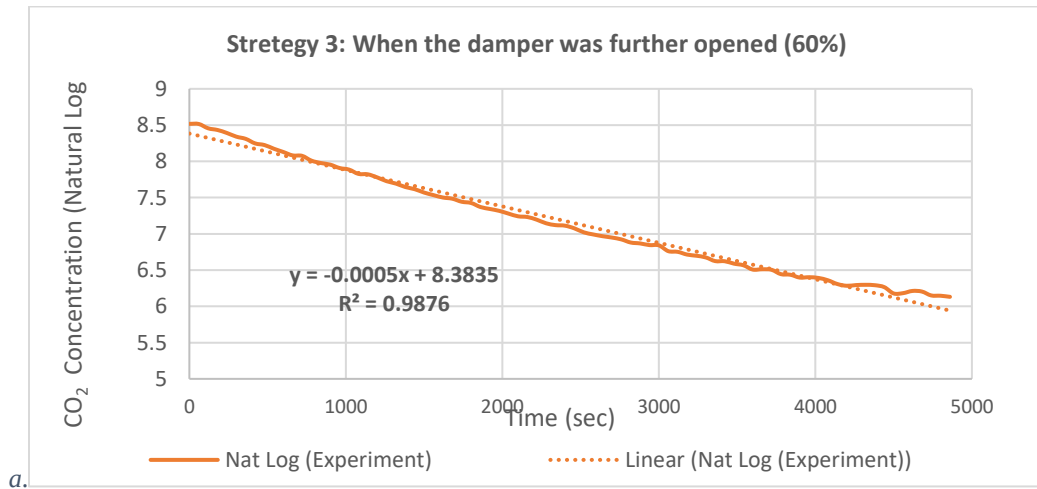
b, Logger @ 0.75m (table height)



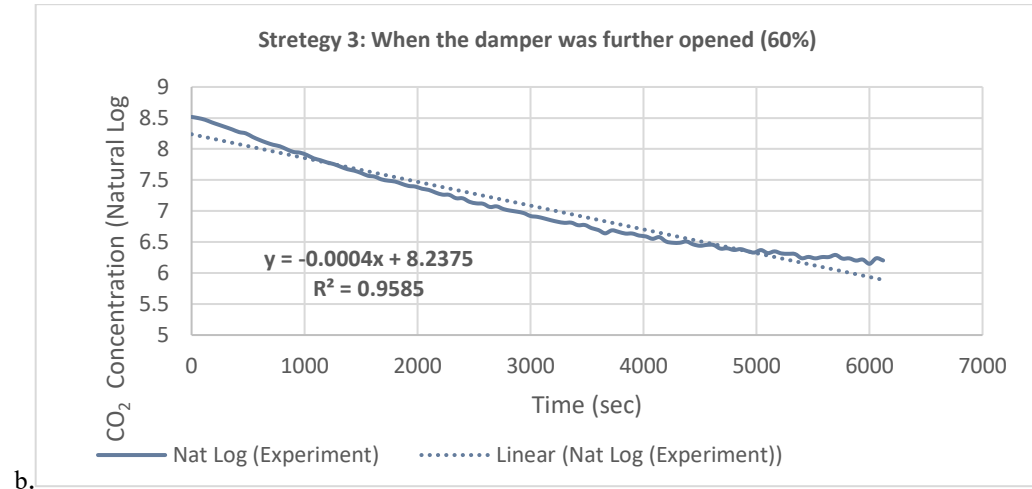


b. Figure 54: a, Logger @ 1.65m;

b, Logger @ 0.75m (table height)



a.



b.

Figure 55: a, Logger @ 1.65m;

b, Logger @ 0.75m (table height)

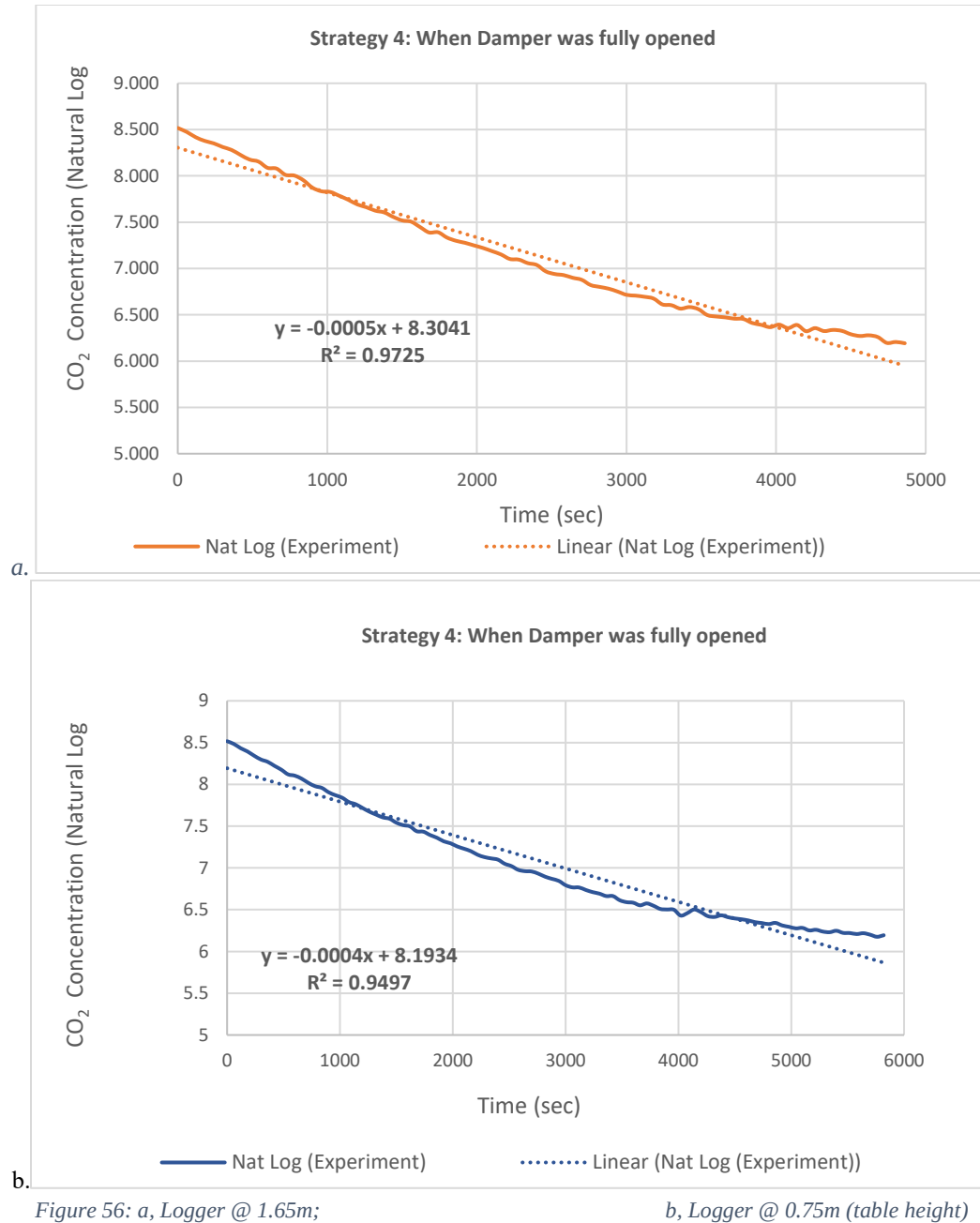


Figure 56: a, Logger @ 1.65m;

b, Logger @ 0.75m (table height)

The results of the tracer gas experiment were analyzed by comparing data from three different sensors/loggers positioned at varying heights (2.2m, 1.65 m, and 0.75 m). The parameters observed include decay time (in seconds) and air change rate (ACH^{-1}), as summarized in Table 12 below and illustrated in the bar chart in Figure 56 below.

Table 13: Experimental results comparing three different logger positions

Scenario	Height					
	2.2m		1.65		0.75	
	Decay Time	ACH ⁻¹	Decay Time	ACH ⁻¹	Decay Time	ACH ⁻¹
Strategy 1	15840	0.36	15600.00	0.36	16380.00	0.36
Strategy 2	6840	1.08	7860.00	1.08	6840.00	1.08
Strategy 3	5640	1.44	4860.00	1.8	6120.00	1.44
Strategy 4	5460	1.44	4860.00	1.8	5820.00	1.44

Discussions

Strategy 1:

- Across all sensor heights, the decay time was approximately 15,840 seconds at 2.2 m, 15,600 seconds at 1.65 m, and 16,380 seconds at 0.75 m.
- The corresponding air change rate (ACH) was uniform across all heights, measuring 0.36 ACH⁻¹.
- This indicates the minimal influence of sensor height on air change rates in low ventilation scenarios.

Strategy 2:

- The decay times for this case were 6,840 seconds at 2.2 m and 0.75 m, with a slightly higher 7,860 seconds at 1.65 m.
- The air change rate recorded was consistent at 1.08 ACH⁻¹ across all heights.
- This uniformity suggests that under moderate ventilation conditions, the effect of sensor height remains negligible.

Strategy 3:

- The decay times varied noticeably: 5,640 seconds at 2.2 m, 4,860 seconds at 1.65 m, and 6,120 seconds at 0.75 m.
- The corresponding ACH values were 1.44 ACH⁻¹ at 2.2 m and 0.75 m, while a slightly higher rate of 1.8 ACH⁻¹ was recorded at 1.65 m.
- This suggests that at higher ventilation rates, the sensor positioned at mid-height (1.65 m) may better capture the dynamics of air exchange.

Strategy 4:

- Similar to Strategy / Case 3, the decay times varied, with 5,460 seconds at 2.2 m, 4,860 seconds at 1.65 m, and 5,820 seconds at 0.75 m.
- Air change rates mirrored those in Strategy / Case 3, with 1.44 ACH⁻¹ at 2.2 m and 0.75 m, and a peak of 1.8 ACH⁻¹ at 1.65 m.
- These results further reinforce the finding that the mid-height sensor provides a more accurate representation of air change rates in scenarios with high ventilation.

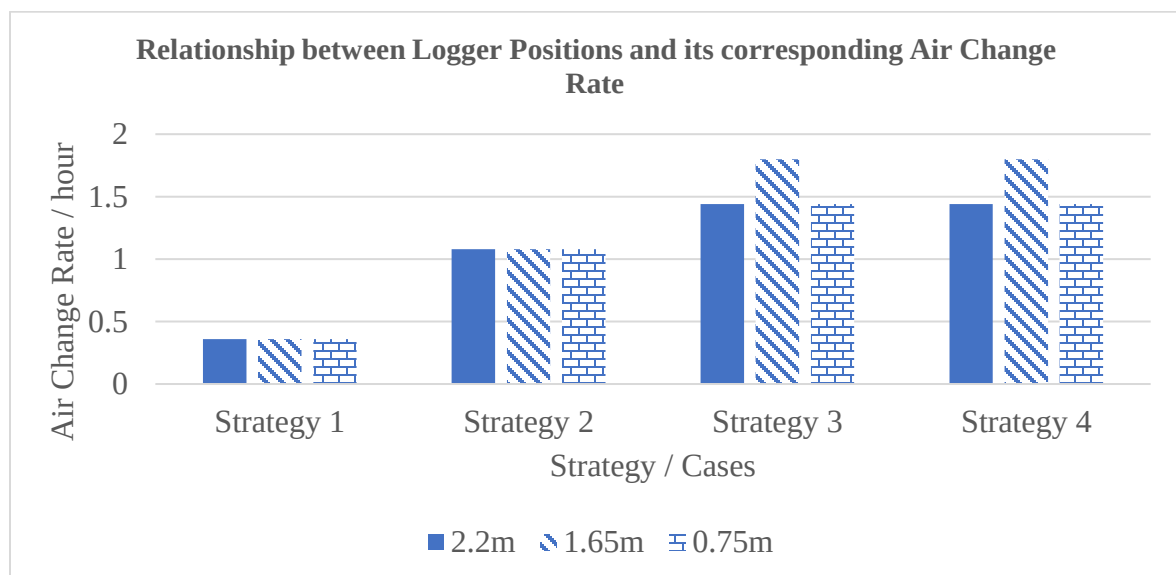


Figure 57: Experimental results comparing three different logger positions

Important Observations:

Impact of Sensor Height:

- In low ventilation scenarios (e.g., Strategy / Case 1), sensor height had negligible influence on air change rates.
- However, at higher ventilation levels (Strategy / Cases 3 and 4), the mid-height sensor (1.65 m) consistently recorded the highest air change rates, indicating better sensitivity to air exchange dynamics.

Uniformity Across Strategies:

- ✚ For Strategy / Cases 2, 3, and 4, the ACH values at 2.2 m and 0.75 m were often similar, while the 1.65 m sensor showed slight deviations, likely due to its proximity to the central airflow zone.

Decay Time Variation:

- ❖ Decay times were shorter at higher air change rates, as expected, due to faster removal of the tracer gas. This correlation is evident across all sensor positions.

Conclusively, the study highlights the influence of sensor placement on measuring air change rates, particularly under higher ventilation conditions. While some studies encouraged putting the sensors near the outlet, in this study, all sensors provided consistent readings in low ventilation scenarios, and the mid-height position (1.65 m) appeared more responsive to variations in air exchange, offering valuable insights for optimizing sensor placement in similar experiments.

5.2 Building Energy Simulation – Design Builder

The building energy simulation produces data that is further used as inputs in the ANSYS-CFD simulation and the CONTAM-W indoor air quality simulation. Figures 58 – 62 below show the supply air flows, velocity, and other profiles for the year.

Figure 58 below shows the simulation results from the Design-Builder for the outdoor air dry-bulb temperature in Dhahran, Saudi Arabia, which demonstrates a typical annual temperature profile for this hot desert climate. As depicted, the temperature peaks during the summer months, reaching a maximum of approximately 48°C in July. This period represents the highest thermal stress when the demand for cooling and thermal comfort is highest. The data highlights the environmental conditions that buildings in this region must endure, underscoring the importance of high-performance design solutions.

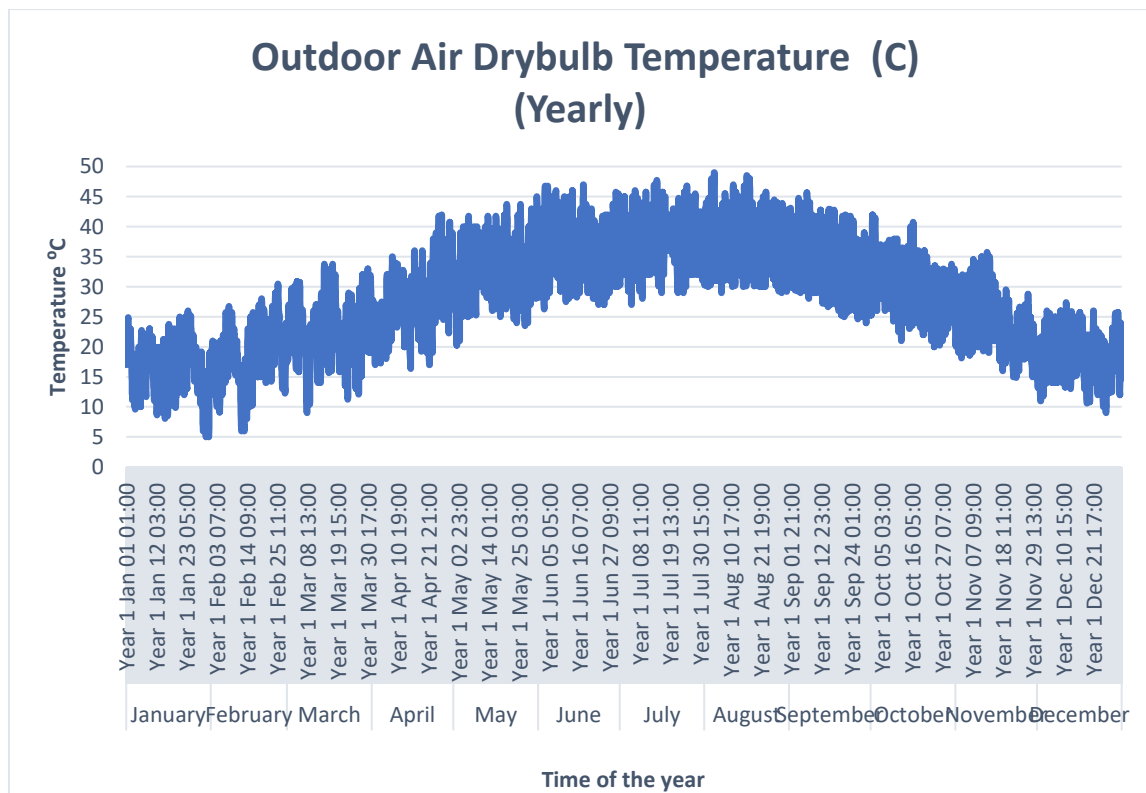


Figure 58: Outdoor Air Dry bulb Temperature (C)

Figure 59 below illustrates the volumetric air flow rate of the Variable Air Volume (VAV) HVAC system supplied to the zone over a typical year. The airflow rate closely follows the seasonal pattern of the outdoor air dry-bulb temperature, peaking during the summer months when solar radiation and outdoor temperatures are highest. This indicates a responsive HVAC operation, with increased airflow during warmer periods to maintain indoor comfort levels. The reduced air flow in cooler months highlights the system's adaptability in adjusting to lower cooling demands, thereby enhancing energy efficiency and supporting the building's thermal comfort needs year-round.

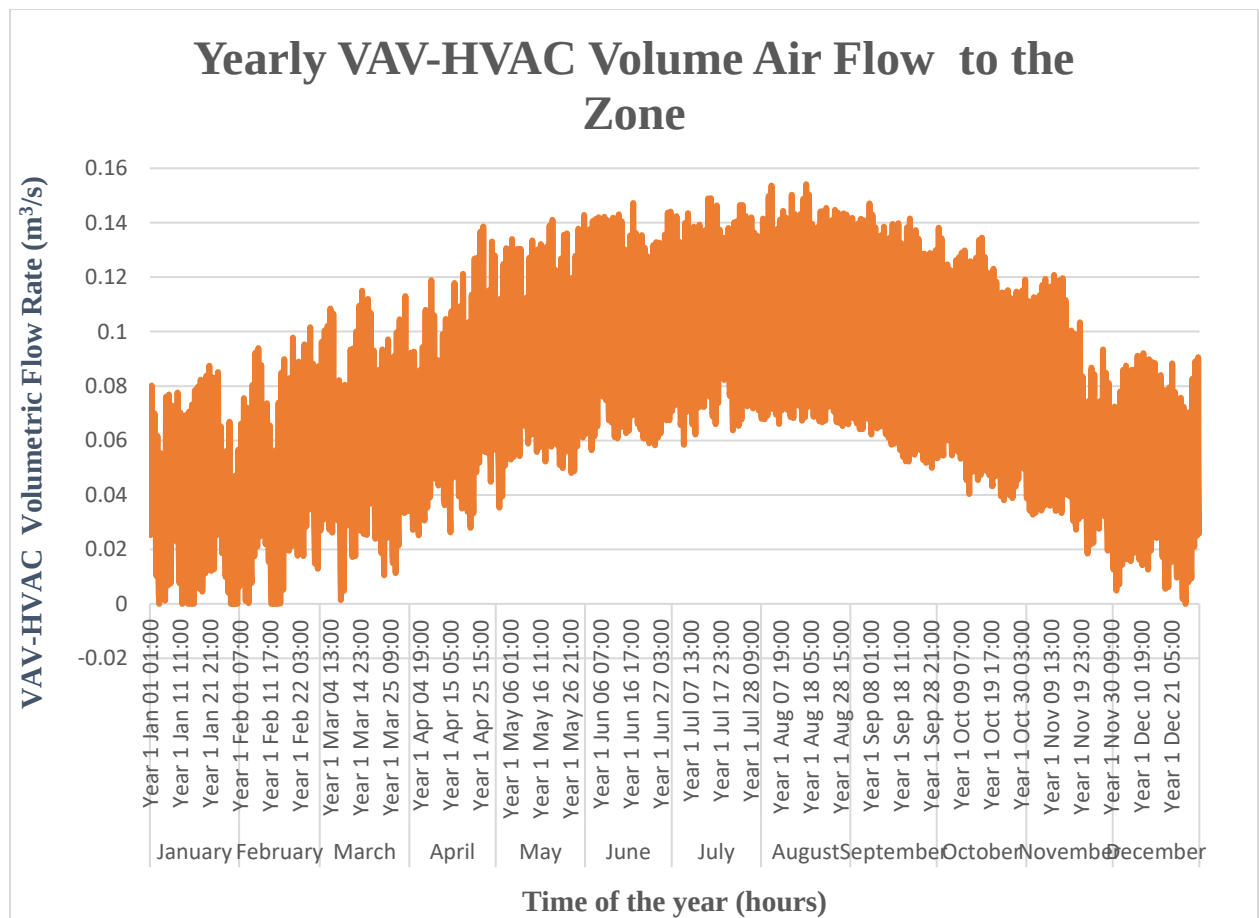


Figure 59: Yearly VAV-HVAC Volume Air Flow to the Zone

The graph in Figure 60 below shows the CO₂ concentration levels within the office zone throughout the year. Despite only two occupants in the office, the CO₂ concentration curve

mirrors the outdoor temperature and HVAC airflow pattern (Figures 59, 60 and 61). This correlation likely results from the HVAC system's response to thermal conditions, which impacts the ventilation rate. As outdoor temperatures rise, the HVAC system increases airflow to cool the space, simultaneously affecting CO₂ dilution. Thus, the seasonal variation in CO₂ concentration reflects the HVAC system's ventilation adjustments in response to temperature changes rather than fluctuations in occupancy, and this is why another specialized software, CONTAM-W will be used in subsequent sections to determine the actual CO₂ generated within the space and how it moves.

However, the intense summer heat can influence occupant behavior (generating more carbon dioxide, especially in the summer), with many individuals adjusting indoor thermostats or relying on shading devices and insulation to mitigate heat ingress (Asimakopoulos et al., 2012). This change in occupant behavior can be argued as what happens, as the rate of CO₂ within the zone increases in consonance with the outdoor air temperature despite a non-increment in the number of people in the zone (office).

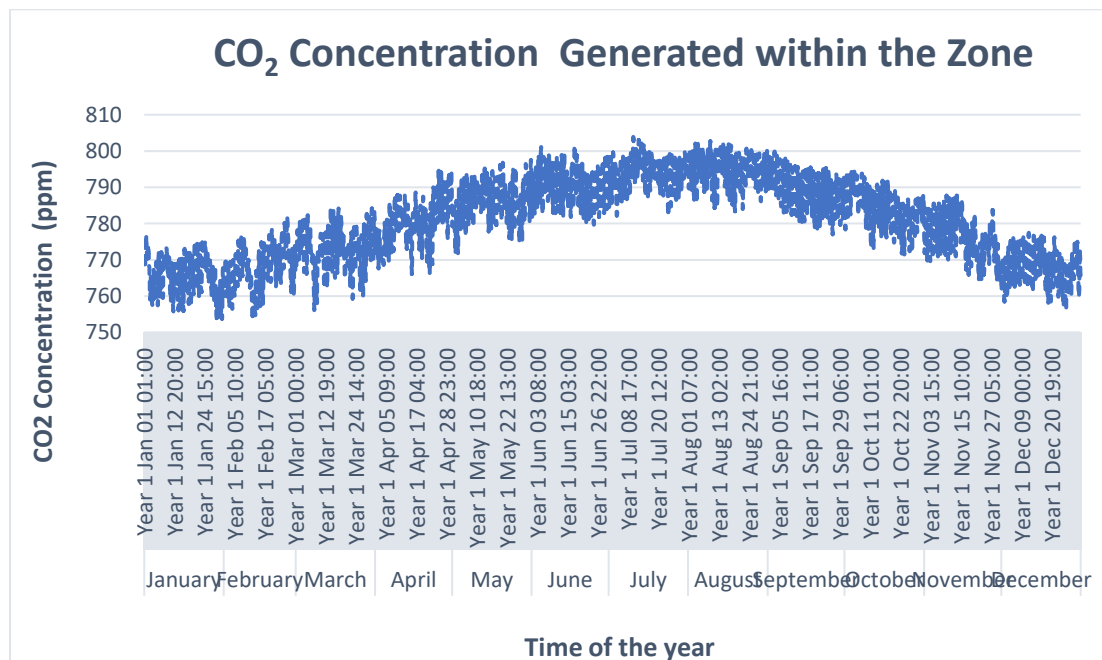


Figure 60: CO₂ Concentration Generated within the Zone

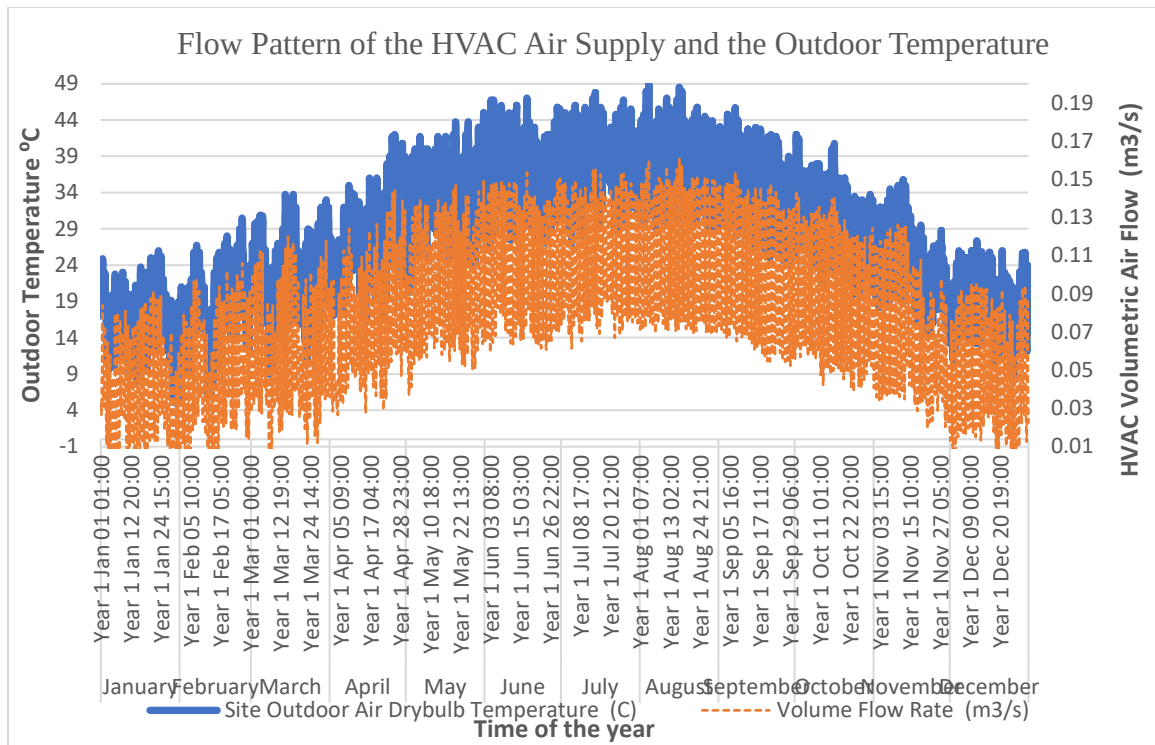


Figure 61: Flow Pattern of the HVAC Air Supply and the Outdoor Temperature

Despite the limitation in the use of Design Builder software in the modeling and simulation of indoor air quality modeling, Design Builder software as shown in Figure 62 (below) the rise in CO₂ concentration in the zone, which parallels the seasonal increase in outdoor temperature and the airflow supply to the zone, below are some of the justifications that might have led to this:

- a. **Reduced Ventilation Effectiveness During Warmer Months:** During hot summer months, although the HVAC system increases the airflow to provide cooling, the HVAC system does not necessarily increase fresh air intake proportionally. It appears that the ventilation strategy is more focused on recirculating indoor air rather than bringing in fresh outdoor air, then CO₂ from the occupants accumulates

despite higher airflow. This recirculation-based cooling can result in slightly higher CO₂ concentrations even as temperature-driven airflow increases.

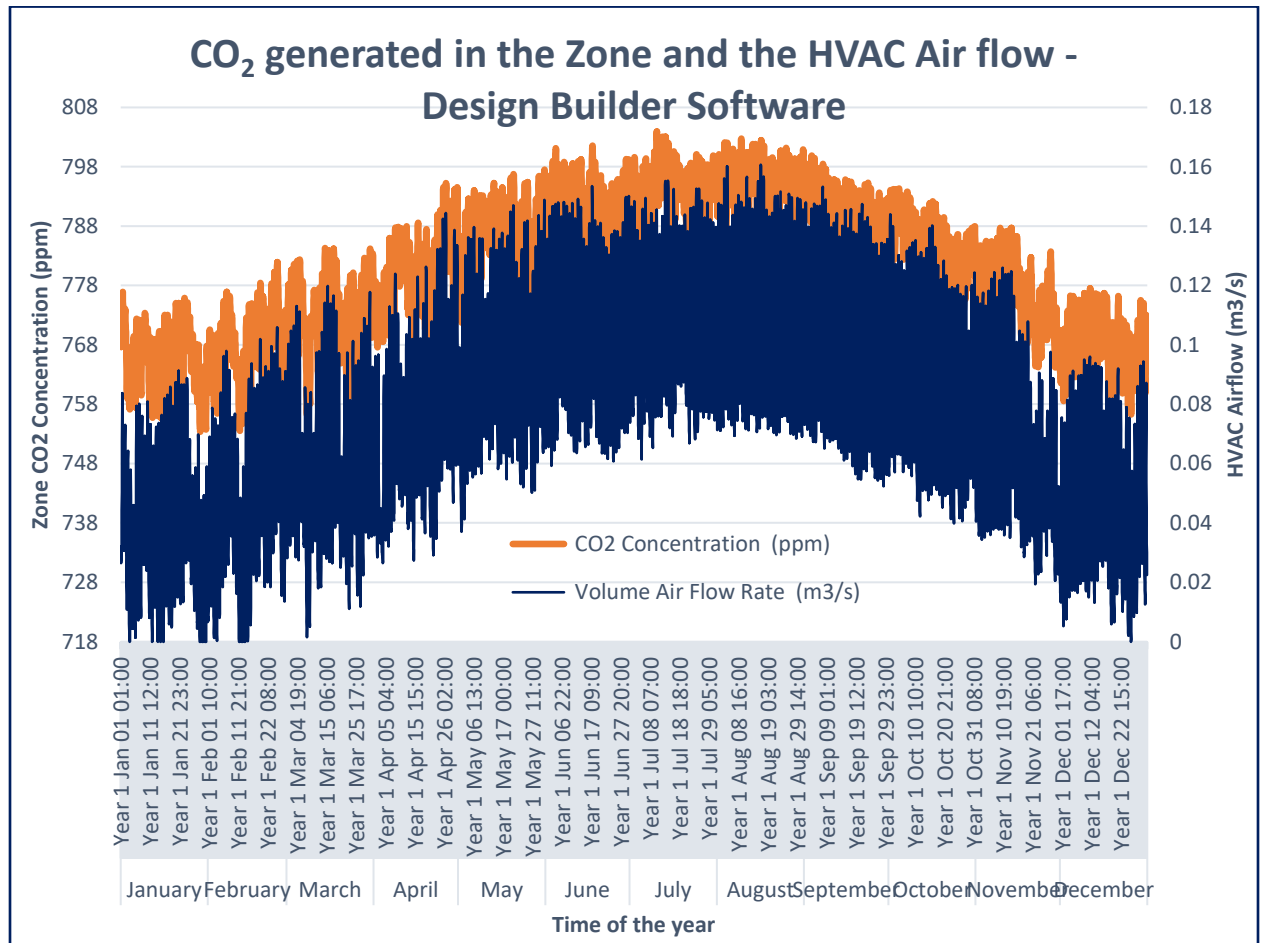


Figure 62; CO₂ generated in the Zone and the HVAC Airflow

- b. Temperature's Influence on Air Density and Ventilation Performance:** Warmer air is less dense than cooler air. As outdoor temperatures rise, the HVAC system's cooling strategy might alter airflow patterns within the room, affecting how CO₂ disperses and ventilates out. This temperature effect can sometimes reduce the efficiency of air mixing, leading to pockets of higher CO₂ concentration or slower removal rates.

c. Potential Seasonal Differences in Air Exchange Rates: HVAC systems in warmer climates like Dhahran, often operate in ways that vary fresh air intake rates seasonally. In summer, some systems minimize the intake of hot outdoor air to reduce cooling loads, relying more on recirculated air. This lower rate of fresh air intake can cause CO₂ to build up slightly more during summer than in cooler months, where outdoor air intake might be more balanced with recirculation.

d. Thermal Stratification and CO₂ Build-up in Warm Weather: Thermal stratification can occur in warmer weather, where cooler air (from the HVAC) tends to settle near the floor while warmer air (including occupant-generated CO₂) stays higher. This stratification might reduce the effectiveness of CO₂ concentration near occupant level, contributing to increased measured concentrations in the zone.

In summary, while the HVAC system is responding to temperature changes with higher airflow, this increase may not be purely fresh air, and factors like air density, recirculation rates, and thermal stratification all contribute to the observed seasonal CO₂ variation. For a more stable CO₂ concentration, the model would need a dedicated outdoor air supply device for a constant rate of fresh air ventilation that isn't influenced by cooling demand.

5.2.1 Energy Consumptions in Summer Months

In hot-arid regions like Dhahran, Saudi Arabia, summer temperatures present the most extreme conditions for building energy performance, indoor thermal comfort, and occupant health. The months of May through September are particularly significant, as daily temperatures consistently rise above 40°C, with high solar radiation and minimal

precipitation, placing considerable demands on indoor cooling systems to maintain acceptable comfort levels (Monahan & Powell, 2011); (Purohit, 2009), and this is evident in Figure 62 (outdoor dry bulb temperature). Extreme temperatures increase both cooling loads and energy consumption, creating a critical period for assessing building performance and energy efficiency in hot climates (Al-Hemiddi & Megren Al-Saud, 2001).

Moreover, the intense summer heat can influence occupant behavior, with many individuals adjusting indoor thermostats or relying on shading devices and insulation to mitigate heat ingress (Asimakopoulos et al., 2012). By concentrating on the summer months, this research aims to capture the highest levels of thermal stress on building systems, providing insights into how architectural designs and HVAC systems can better adapt to high temperatures and improve energy efficiency. Studies on building energy performance in hot climates typically recommend focusing on summer months, as they reveal the "peak load" demands, which are essential for designing sustainable and resilient buildings in arid climates (Attia et al., 2013). Table 16 below shows the maximum and minimum HVAC volumetric airflows alongside their average. This data in Table 16 shall be used on the ANSYS-CFD simulation.

Table 14: Summer Data Extracted from the yearly Data:

S/N		Volumetric Air Flow (from Energy Plus) (m ³ /s)
1	Maximum	0.1608
2	Average	0.0963
3	Minimum	0.0370

5.3 ANSYS – CFD - Simulation

This section started with the validation of the ANSYS model, to the physics of the main study, as discussed in section 2.9 of this thesis. Two people are placed in the computational domain (office room) to generate carbon dioxide to effectively study how the generated contaminant behaves under the varying loads of the VAV-HVAC system.

5.3.1 ANSYS Model Validation Process

Having understood the reason behind having a validated model as elucidated in section 4.3.5 of this thesis, to have a validated C F D Model, the CFD set-up, approximations and simplifications of the actual problem are needed, which allows for analyzing the problem with reasonable effort. The following assumptions are made in this study:

- (1) No leakage in the model office.
- (2) The flow in the model room is turbulent.
- (3) No heat transfer during the procedure and the wall and air temperatures are constant (Adiabatic condition).
- (4) The gravity influence on CO₂ is not considered.
- (5) The introduction of CO₂ will not influence the final steady state of the airflow.

5.3.1.1 Grid Independency Test

As earlier mentioned, the grid independence test was the first exercise that was conducted. Three (3) meshes were used. From figure 63 (below), it appears that there are not many differences between the meshes, they all follow the same path with little record of air change rate. Hence Mesh B in Table 4 can be adopted for this study.

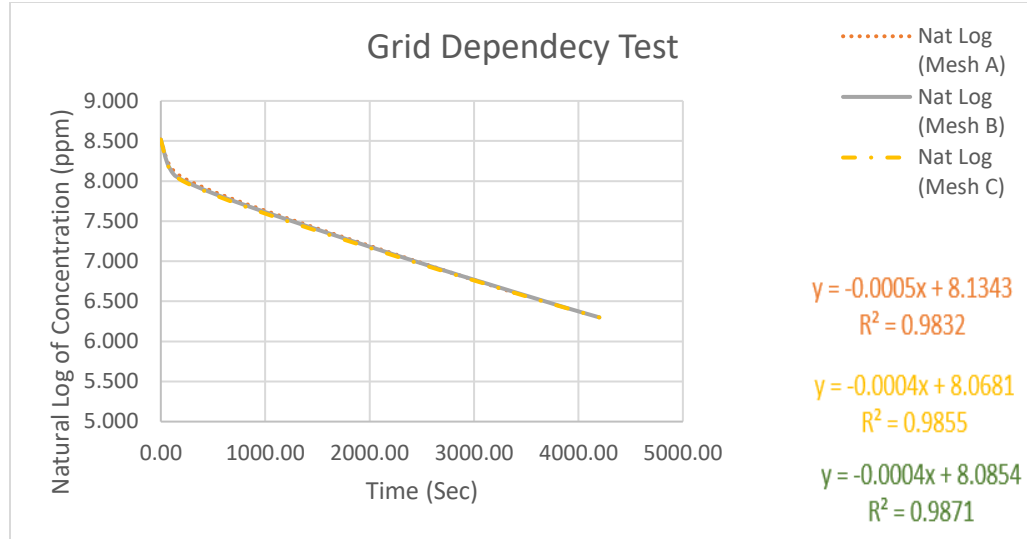


Figure 63: Grid dependency test

5.3.1.2 Sensitivity Analysis

As explained in Sec 4.3.3 above, this study confirms that K- ϵ realizable was optimal, having the closest graph slope with the highest R^2 value. While Table 13 shows the details of the model types, Figure 58 shows how the cube mesh looks and Figure 59 shows Sensitivity Analysis on different turbulence models alongside experimental results.

Table 15: Sensitivity Analysis with K - Epsilon turbulence models

S/N	Model	Model Types	No of Element	Slope	R^2
1	Experimental	-----	----	0.0005	0.9968
2	Numerical Simulations	Cube_Mesh_K - ϵ _ Realizable	323,544	0.0004	0.9867
3		Tetrahedral K - ϵ _ Realizable	308,141	0.0004	0.9993
4		Tetrahedral K - ϵ _ RNG	308,141	0.0003	0.9989
5		Tetrahedral K - ϵ _ Standard	308,141	0.0004	0.999

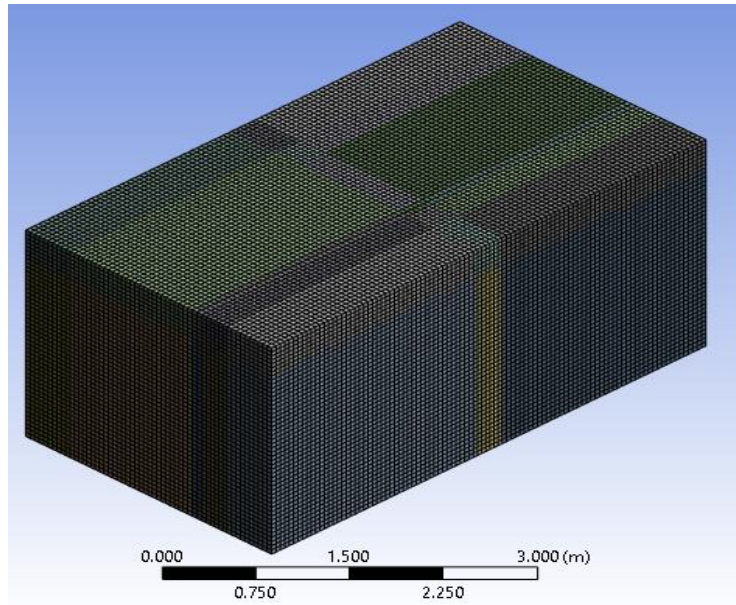


Figure 64: Cube-meshed (Realizable $k-\epsilon$ model) simulated along other meshes

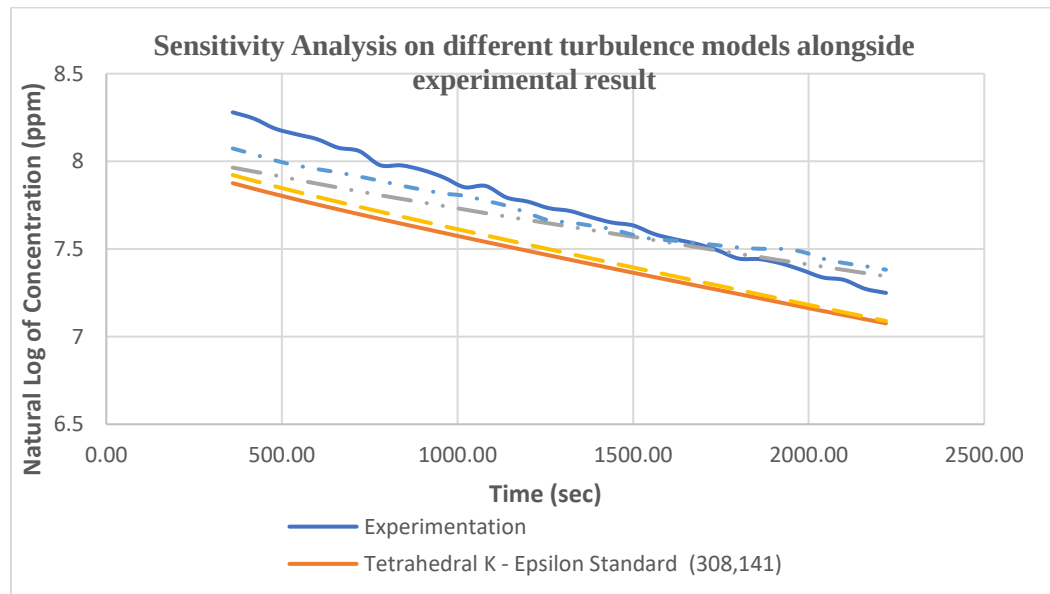


Figure 65: Sensitivity Analysis on different turbulence models alongside the experimental result

Just as having it done with the experiment, the contaminant in the computational domain (in red color) was also being displaced gradually by the fresh air within the software. Figure 60a below shows the domain (experimental room) and how the contaminant is gradually pushed by the fresh air (in blue color), other colors in the spectrum (from light

blue, green, and yellow) show the loss of strength by the red (contaminants) in the room.

Figure 60b shows a gradual downward exponential curve which represents a dissipation pattern on how the contaminants escape the room.

a.

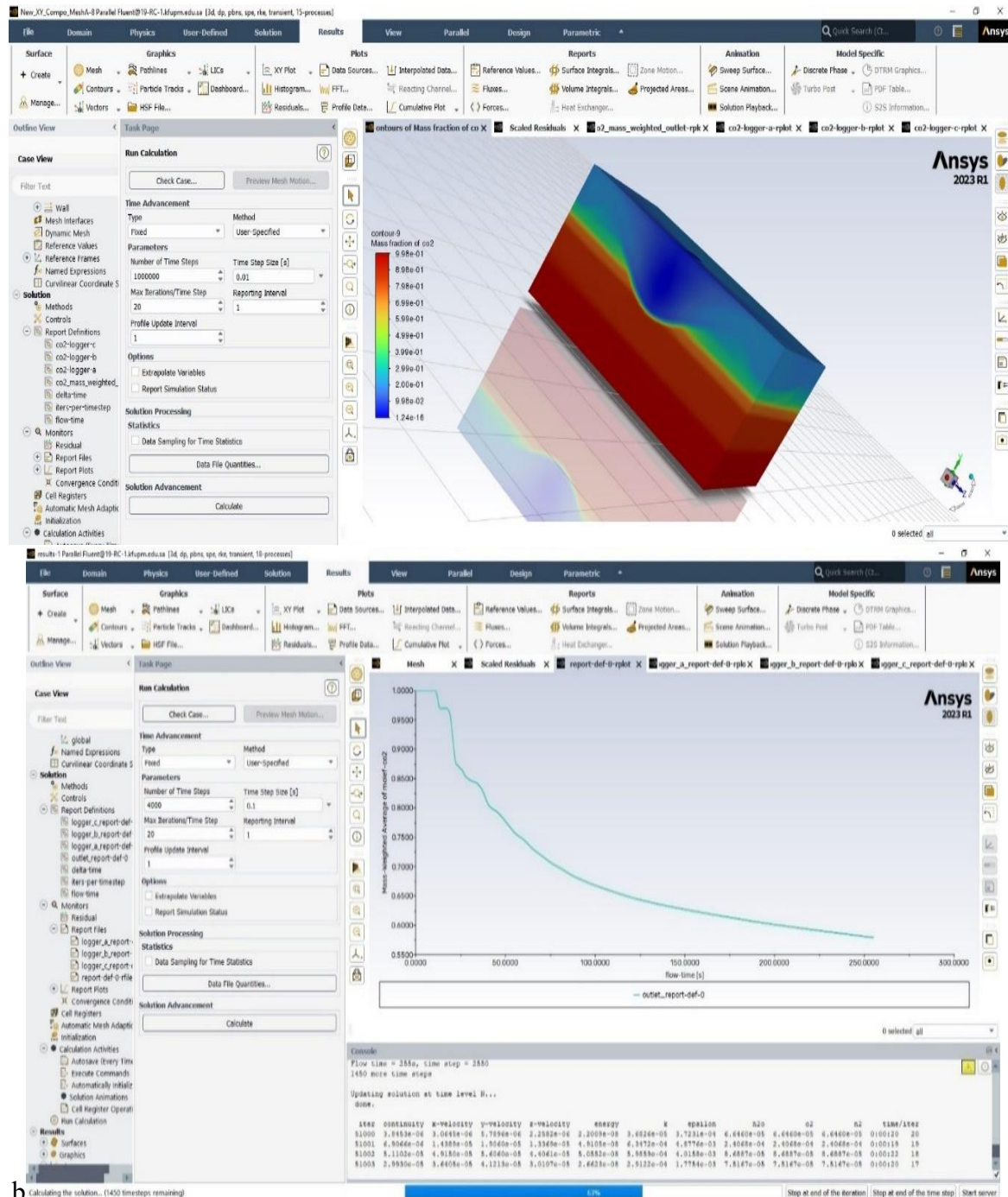


Figure 66 (a-b) : ANSYS-CFD Simulation

5.3.1.3 Validation of Air Change Rate

Having performed the tracer gas experiment physically and with the CFD software, it is pertinent to compare the results. This process is known as the validation process. As explained earlier, the calculation of the air change rate was the metric used to compare the two exercises. Table 16 and Figure 61 below show the validation results.

Table 16: Validation Table				
Scenario	Experimentation		Simulation	
	R ²	ACH ⁻¹	R ²	ACH ⁻¹
Strategy 1	-	-	-	-
Strategy 2	0.9935	1.08	0.9758	1.44
Strategy 3	0.9927	1.44	0.9742	1.44
Strategy 4	0.9885	1.44	0.9871	1.44

The comparison of the experimentally measured air change rates and the results obtained from the CFD simulation, as illustrated in the graph in Figure 67, demonstrates a strong agreement between the two. Across all four cases, the air change rates from the experiment and simulation were effectively identical, confirming the accuracy of the CFD model.

Consistency Across All Cases

For each strategy (1 to 4), the CFD simulation results closely matched the experimental data. This consistency indicates that the model can reliably replicate the physical conditions and dynamics observed during the tracer gas experiment.

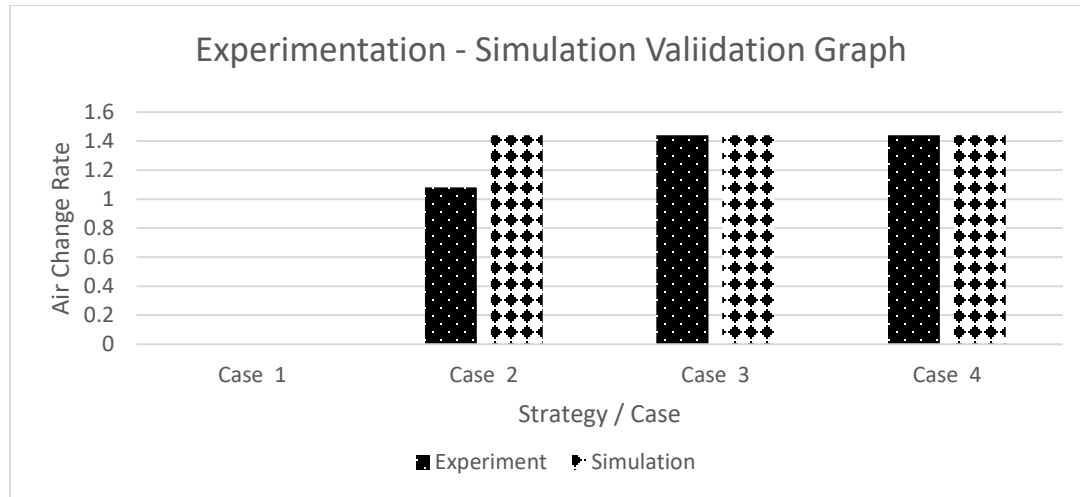


Figure 67: Study validation graph

Accuracy of the CFD Model

The alignment between the experimental and simulation results suggests that the input parameters, boundary conditions, and assumptions used in the CFD model were correctly defined. This highlights the robustness of the model in capturing the airflow behavior and air change rates under varying scenarios.

Validation Criteria Met

Validation of CFD models typically requires a comparison with experimental data, with the expectation that deviations between the two should be minimal. In this study, the close agreement between the two sets of results satisfies this criterion, confirming that the CFD model is validated.

Implications for Main Simulations

With the established validation, the CFD model can now be confidently applied to other scenarios either to predict air change rates in similar setups or other scenarios involving ventilation analysis. This ensures that the model can be used as a reliable tool for further

research or practical applications. In summary, the results from this section confirm the reliability and accuracy of the developed CFD model. The successful validation enhances its applicability for the next phase of this study, where a source term shall be in the fluid domain and the principle of mass balance equation shall be applied and studied.

5.3.2 Physical Model Characteristics of the Study - ANSYS – Simulation

5.3.2.1 Linking Design Builder Output to the ANSYS CFD Software

Since the same experimental room was modeled for both energy simulation (using Design Builder) and CFD simulation (using ANSYS), it was crucial to ensure consistency between the two simulations by transferring key data from the Design-BUILDER software to the ANSYS CFD software. One of the most critical parameters to be transferred was the volumetric airflow rate supplied by the VAV-HVAC system, as determined in Energy Plus (via Design Builder) and presented in Table 14. However, ANSYS CFD does not directly provide where the volumetric airflow data in units of m^3/s as an inlet boundary condition can be inserted, instead, it requires the airflow to be specified in terms of its velocity (m/s). To bridge this gap, it became necessary to calculate the velocity of the volumetric airflow, ensuring that the input data provided to ANSYS accurately represented the airflow conditions modeled in Design Builder. This approach ensured a seamless integration of data between the two software platforms, improving the reliability and consistency of the CFD simulation results. By converting the volumetric airflow to velocity, the boundary conditions in ANSYS closely aligned with the real-world operating conditions simulated in the energy model, strengthening the overall validity of the study.

5.3.2.2 Estimating the Velocity of the Volumetric Flow Rate

In estimating the velocity of the volumetric flow rate, the fundamental equation in fluid dynamics which has overtime be used in HVAC operations shall also be adopted, and the equation is given below:

$$V = \frac{Q}{A} \quad \dots\dots\dots (22)$$

where:

- Q represents the volumetric airflow rate (m³/s),
- V is the velocity of airflow (m/s), and
- A denotes the cross-sectional area through which the airflow passes (m²).

This equation establishes the relationship between the amount of air flowing through a given space and its velocity, based on the geometry of the inlet or duct.

In this study, the volumetric airflow rate (Q) was obtained from the Design-Builder simulation. To input the data into ANSYS CFD, the airflow velocity (V) was calculated by rearranging the equation as:

$$V = \frac{Q}{A} \quad \dots\dots\dots (23)$$

The cross-sectional area (A) of the supply vent or duct was measured from the room's physical dimensions, allowing for an accurate conversion. This calculation ensured that the inlet boundary conditions in ANSYS CFD matched the real-world operating conditions modeled in Design Builder, improving the consistency and reliability of the simulation results. The estimation of the effective area A is done below. Figure 68 shows the air inlet diffuser from the experimental room.

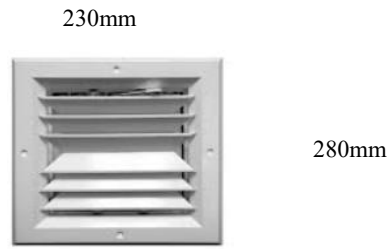


Figure 68: Air inlet Diffuser from the Experimental Room

The dimensions of the strips that air passes through are 190mm x 16mm (well visible from the back of the diffuser), and there are four (4) trips on the air inlet diffuser. Hence the effective cross-sectional area (A) becomes:

$$\begin{aligned}
 A &= 190\text{mm} \times 16\text{mm} \\
 &= 0.19\text{m} \times 0.016\text{m} \\
 &= 0.00304 \times 4 \text{ strips} \\
 &= 0.012\text{m}^2
 \end{aligned}$$

Effective Area of Inlet = **0.012m²**

After getting all the parameters required, Table 15 above will now be transformed into Table 16, showing the volumetric airflow, the calculated effective area of the supply inlet, and the corresponding velocity of the volumetric flow rate, and the later shall be used as part of the boundary conditions for the inlet in the ANSYS CFD simulation.

Table 17: HVAC volumetric airflow (summer time), to be used for ANSYS simulation

S/N		Volumetric Air Flow (from Energy Plus) (m ³ /s)	Effective Area of Supply Inlet (Physical office) (m ²)	Velocity of the Volumetric Airflow (m/s)
1	Maximum	0.1608	0.012	13.40
2	Average	0.0963	0.012	8.02
3	Minimum	0.0370	0.012	3.08

The histogram in Fig 69 below represents the skewness distribution of the elements used in an ANSYS Fluent simulation mesh, with a significant number of elements falling below

a skewness of 0.3. Skewness is a critical metric in mesh quality, affecting the stability, convergence, and accuracy of computational fluid dynamics (CFD) simulations. Skewness measures how much an element deviates from an ideal shape (e.g., an equilateral triangle or a square in 2D meshes, or a tetrahedron in 3D meshes). For optimal mesh quality, it is recommended that most elements have a skewness value below 0.25, as higher skewness can lead to numerical inaccuracies (ANSYS, 2021). In this histogram, the majority of elements have a skewness within an acceptable range, supporting the stability and reliability of the simulation results. Furthermore, the skewness threshold set to 0.25 in this case ensures that only high-quality elements are retained, improving computational efficiency and reducing potential errors (Roache, 1998).

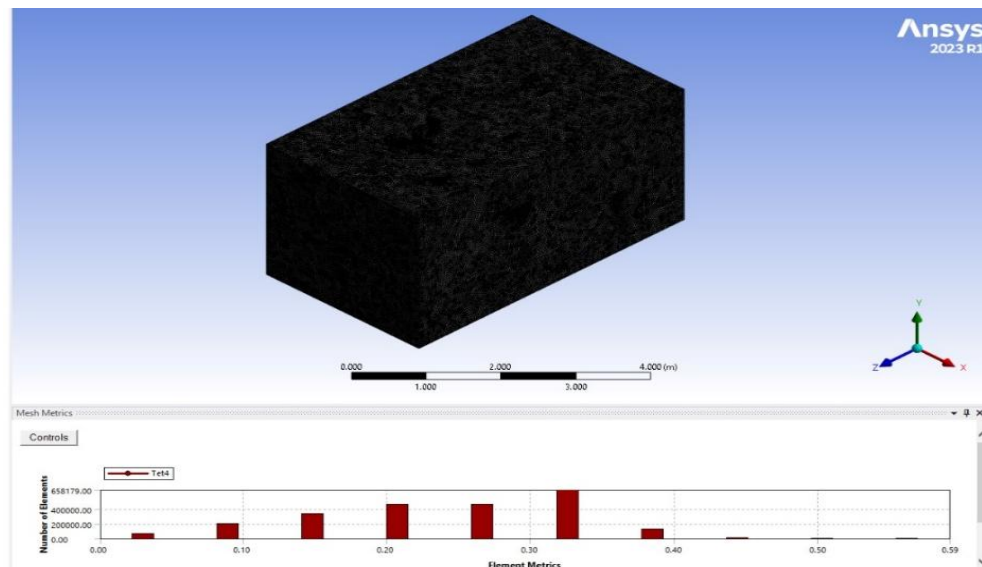


Figure 69: The mesh and its skewness

The graph in Figure 70 below demonstrates the relationship between air velocities and the mass average of CO₂ concentration within the room over time, based on the summer weather data obtained from Design Builder and simulated in ANSYS. The three air velocities analyzed correspond to the minimum (3.0850 m/s), maximum (13.4039 m/s), and average (8.0256 m/s) volumetric airflow rates as shown in Table 16 above.

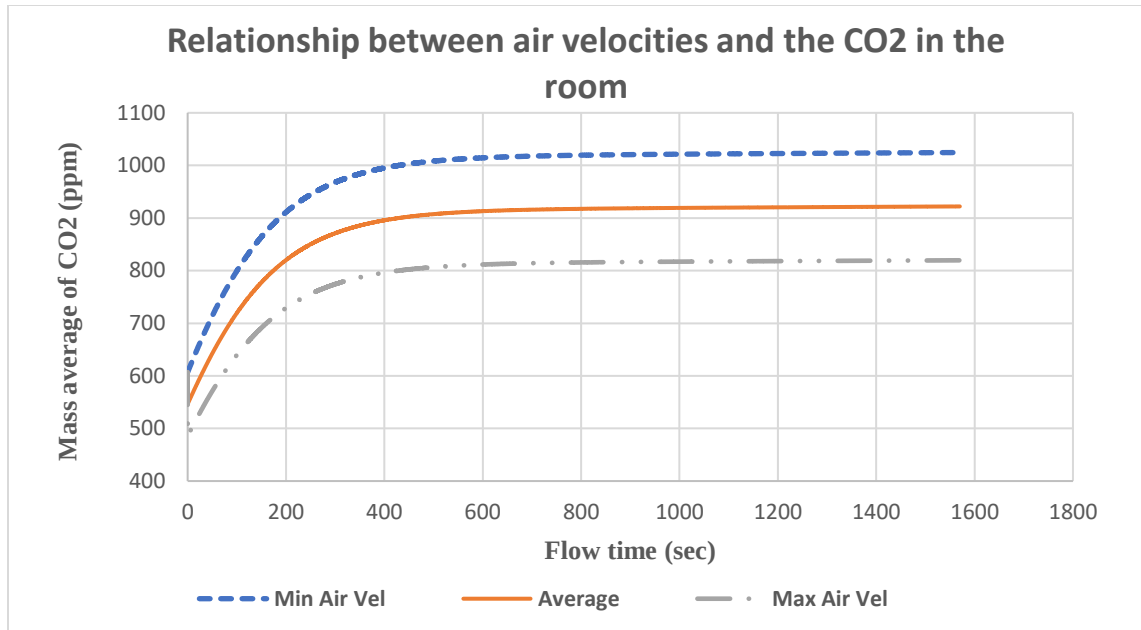


Figure 70: Relationship between air velocities and the CO₂ in the room

Observations:

Initial Behavior

For all three air velocities, the CO₂ concentration starts low and rapidly increases during the first 200 seconds of the simulation. This rapid rise indicates the initial stabilization of air mixing and CO₂ distribution in the room. Simply put, the CO₂ concentration increases with low air velocity and vice versa.

Maximum Air Velocity (13.4039 m/s)

- The curve corresponding to the maximum air velocity stabilizes significantly faster than the others, reaching equilibrium around 300–400 seconds.
- This implies that higher air velocities enhance air mixing efficiency, enabling quicker dilution of CO₂ concentrations to a steady-state value.

Minimum Air Velocity (3.0850 m/s)

- The curve for the minimum air velocity stabilizes more slowly, taking approximately 1000–1200 seconds to approach equilibrium. This indicates that lower velocities lead to reduced mixing effectiveness, resulting in slower dispersion and dilution of CO₂.

Average Air Velocity (8.0256 m/s)

- The curve for the average velocity lies between the maximum and minimum air velocities in both behavior and stabilization time, taking roughly 600–800 seconds to reach equilibrium. This reflects a moderate rate of air mixing and CO₂ dilution compared to the extremes.

Steady State Concentration

- The steady-state CO₂ concentration is highest for the minimum air velocity (~1100 ppm) and lowest for the maximum air velocity (~900 ppm), with the average velocity curve settling at ~950 ppm. This suggests that higher air velocities stabilize faster and maintain lower CO₂ levels due to enhanced ventilation performance.

Implications:

The findings underscore the importance of selecting appropriate air velocities in HVAC system design to achieve optimal indoor air quality (IAQ). High air velocities ensure efficient pollutant removal and rapid stabilization of CO₂ levels, which is crucial in

maintaining healthy indoor environments, especially during critical summer months when ventilation demands are higher.

Validation with Literature:

These results align with findings in ventilation and indoor air quality research. For example: (A. Persily & de Jonge, 2017), in their work titled “Carbon dioxide generation rates for building occupants”, emphasize that increased ventilation rates (linked to higher air velocities) reduce indoor CO₂ concentrations and improve IAQ. More so, (L. Yang et al., 2014) in their work titled, “thermal comfort and building energy consumption implications” demonstrated that airflow dynamics significantly influence pollutant dispersion and mixing times, similar to the trends observed in the simulation.

5.3.2.3 Contour Visualization of CO₂ Distribution:

The contour plots shown below in Figure 71 represent the simulated distribution of CO₂ concentration within the room. The color gradients indicate variations in CO₂ concentration, with higher concentrations represented by warmer colors (red and yellow) and lower concentrations by cooler colors (blue and green). The visualization demonstrates the effectiveness of the ventilation system in dispersing and diluting CO₂ throughout the space. The uniformity of the contours in certain regions highlights areas of efficient mixing and pollutant removal, while variations in other regions reflect localized CO₂ accumulation or slower dilution. These results are consistent with the airflow patterns generated by the VAV-HVAC system and emphasize the critical role of air velocity and distribution in

maintaining indoor air quality. This analysis corroborates the findings from the CFD simulation, showing compliance with ASHRAE Standard 62.1 recommendations for acceptable indoor CO₂ levels, even under the minimum airflow velocity conditions.

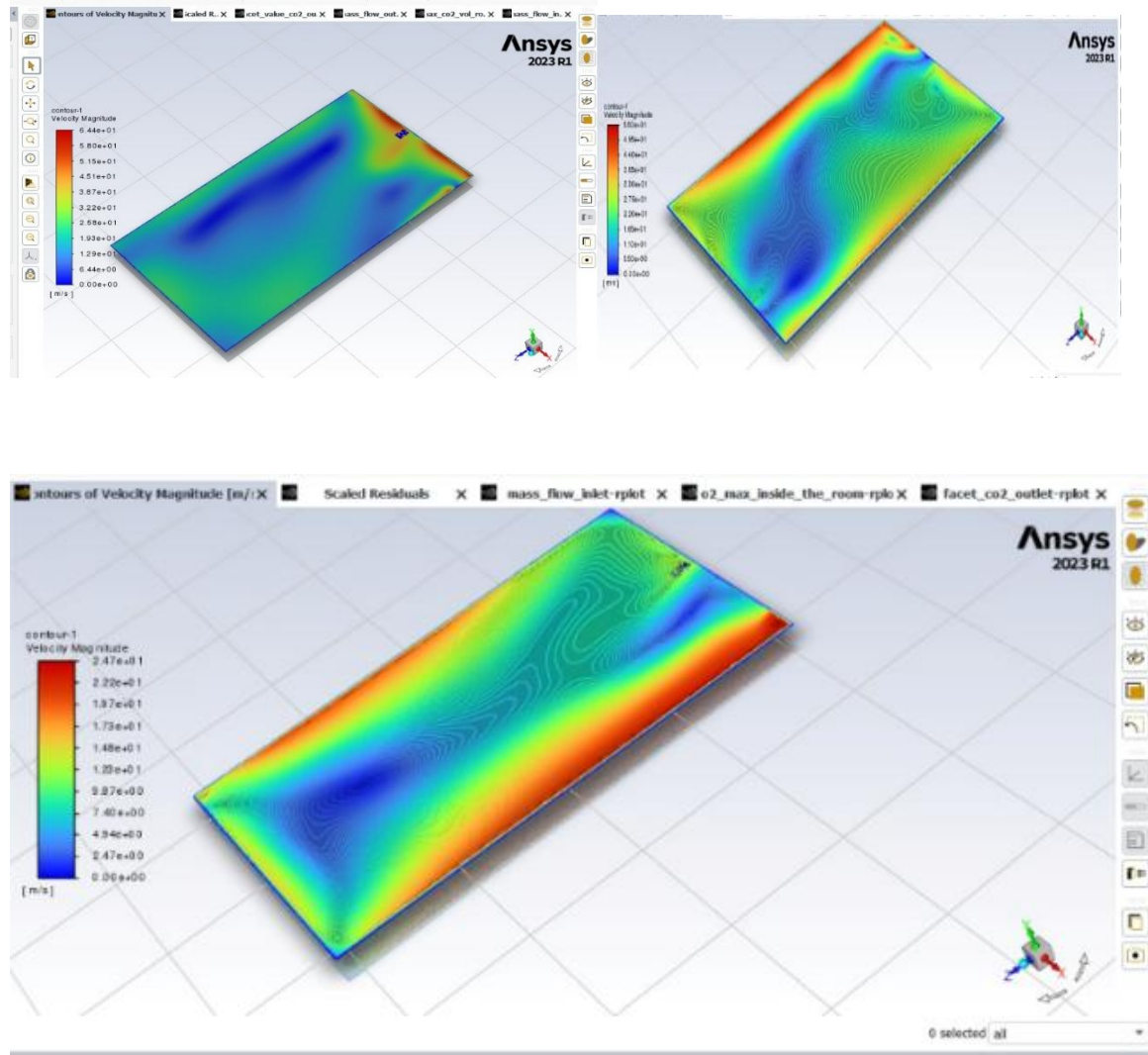


Figure 71: Contour Visualization of CO₂ Distribution

5.4 CONTAM (W) - SIMULATION

Similar to the ANSYS software, this section shall start with the validation of the indoor air quality model., to address the physics of the main study, as discussed in section 2.9 of this thesis. Two people are placed in the computational domain (office room) to generate carbon

dioxide to effectively study how the generated contaminant behaves under the varying loads of the VAV-HVAC system.

5.4.1 CONTAM Validation Study

Figure 72 below illustrates the relationship between experimental data and numerical simulations conducted using CONTAM to model the decay of CO₂ concentration within the room environment over time. This comparison validates the simulation model against physical measurements, ensuring its reliability in predicting CO₂ concentration dynamics. The x-axis represents time, expressed in hours, while the y-axis indicates CO₂ concentration, measured in parts per million (ppm).

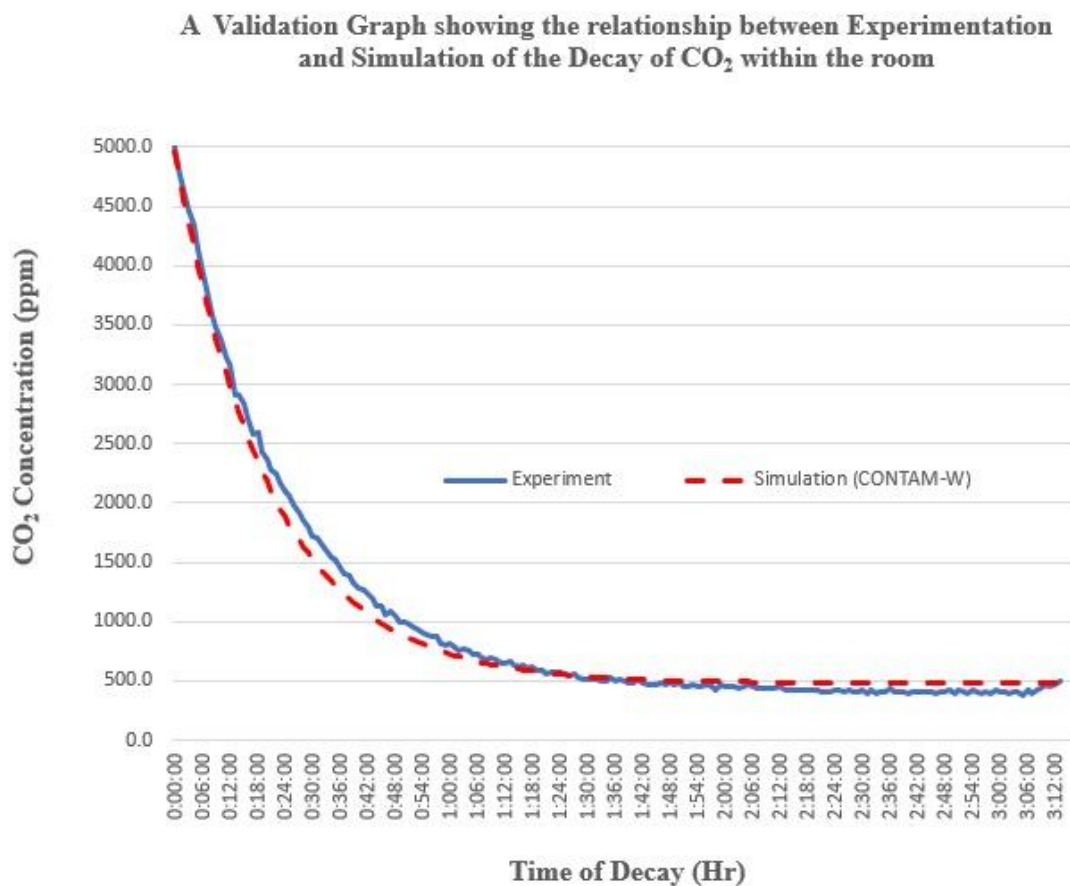


Figure 72: CONTAM Validation graph and the experimental graph

The graph illustrates a steep decay in CO₂ concentration within the first few hours, suggesting the rapid removal of CO₂ by the mechanical ventilation system. The experimental and simulation results converged as the concentration approached the indoor ambient CO₂ level of approximately 480 ppm, maintained consistently throughout the test. The close alignment of the experimental and simulated data confirms the robustness of the CONTAM model in accurately predicting contaminant decay in a controlled environment. The absence of significant deviations between the two datasets highlights the validity of the modeling assumptions, including the ventilation rate, boundary conditions, and the exclusion of infiltration. These findings reinforce the reliability of CONTAM for simulating the performance of mechanical ventilation systems in managing indoor air quality under well-defined conditions. This agreement between simulation and experimental results serves as a critical foundation for using CONTAM to model more complex scenarios involving varying ventilation strategies and pollutant dispersion patterns.

5.4.1.2 Error Estimations

Given the absence of a perfect (100%) match between the simulation and experimental results, it became necessary to quantify the potential errors (i.e., divergences) between the two scenarios. Several error estimation criteria were employed to evaluate the degree of discrepancy and validate the accuracy of the simulation model. These criteria include:

- **Mean Absolute Percentage Error (MAPE):** To express the average deviation between the experimental and simulated values as a percentage of the observed data.

- **Mean Square Error (MSE):** To quantify the average squared difference between the simulated and experimental results, highlighting significant deviations.
- **Root Mean Square Error (RMSE):** To measure the magnitude of errors in the same units as the data, offering a clear interpretation of the divergence.

Table 18 (below) presents the calculated error metrics, demonstrating the extent of divergence between the two scenarios.

Despite the observed discrepancies, the errors were determined to be minimal, indicating that the simulation model provides a reliable representation of the experimental conditions. This validation confirms that the model is fit for further analysis and can be confidently used for predictive and optimization purposes in subsequent studies.

Table 18: Calculated error margin between the Experiment and the CONTAM simulation

S/N	Criteria	Error Margin
1	Mean Absolute Percentage Error	10.5%
2	Mean Square Error	10009.4
3	Root Mean Square Error	100.04 ppm

5.4.2 Physical Model Characteristics of the Study – CONTAM-W - Simulation

In section 2.9, the physics of the main study was discussed, where two individuals are allowed to generate CO₂ in the office model while realizing airflow from the VAV-HVAC system from the design-builder software. Figure 73 below illustrates the relationship between the **CO₂ concentration (after emission of the individuals) within the room (in ppm)** and the **volumetric airflow of the HVAC system (in m³/s)** across different months of the year. It provides insights into how indoor air quality and ventilation vary with

temperature changes and VAV-HVAC volumetric flows throughout the year. The CO₂ concentration is based on the assumption that two occupants are present in the office room.

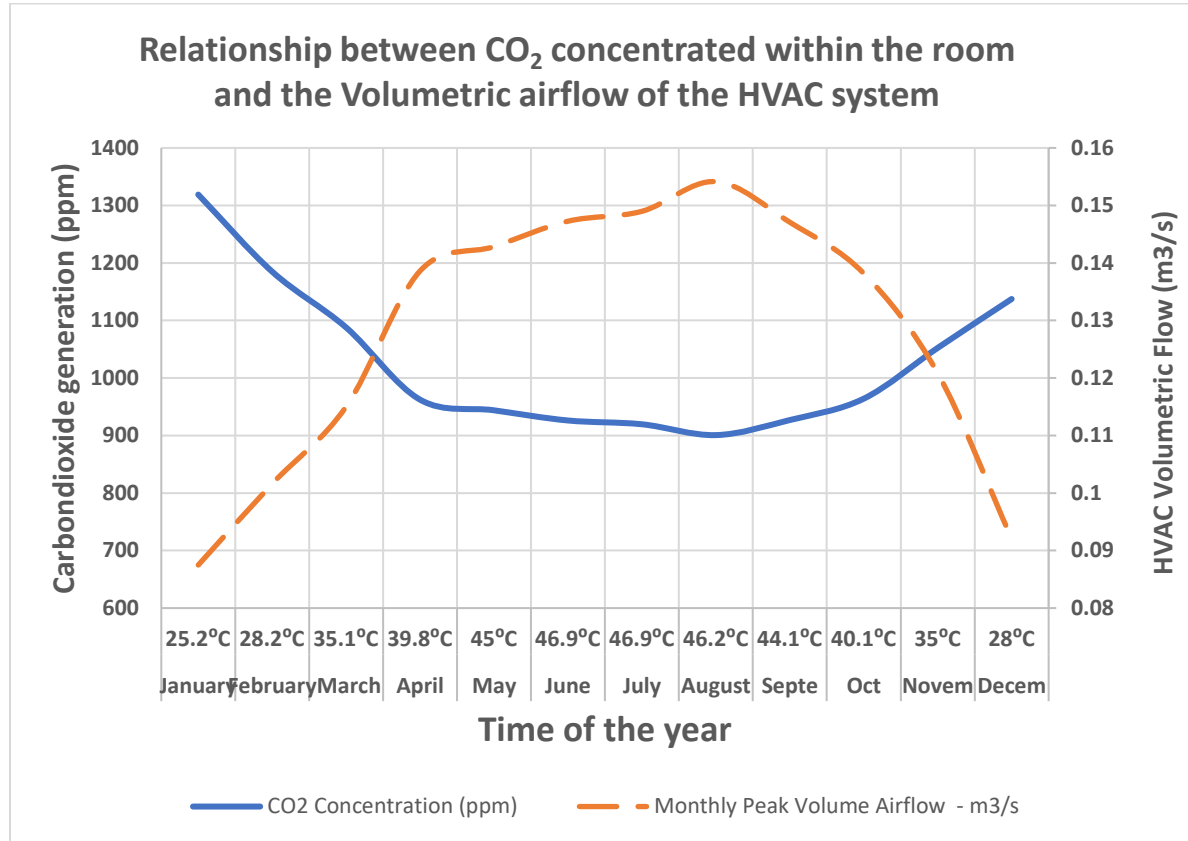


Figure 73: Relationship between the CO₂ concentrated within the zone and the supply volume flow of the HVAC system

5.4.2.1 Main Observations from the Graph:

1. CO₂ Concentration Trend (Blue Line):

CO₂ concentration starts high in January at approximately **1300 ppm** when the ambient temperature is **25.2°C**. As the temperature increases toward the middle of the year (peaking at **46.9°C** in July), the CO₂ generation steadily declines, reaching its minimum value of around **800 ppm**. From September onward, as the temperature decreases, the CO₂ generation gradually increases again, reaching **1100 ppm** by December.

This pattern suggests that CO₂ generation decreases with increasing temperatures, possibly due to enhanced HVAC ventilation rates in warmer months, which dilute the indoor CO₂ concentration.

2. HVAC Volumetric Airflow Trend (Dashed Orange Line):

The HVAC volumetric airflow increases steadily from January (**0.10 m³/s**) to its peak in **July and August** at approximately **0.15 m³/s**. After August, the airflow begins to decline as temperatures drop, reaching its lowest value of around **0.09 m³/s** in December.

This trend aligns with HVAC systems' operational strategy, which typically increases ventilation rates during hotter/summer months to maintain thermal comfort and air quality and reduces airflow in cooler months to conserve energy.

3. Crossing Point:

In **April**, the CO₂ generation and HVAC volumetric airflow intersect. At this point, the indoor air quality (CO₂ level) and ventilation system seem to balance, suggesting that the ventilation rate is optimized for the room's occupancy and activity level.

4. Seasonal Influence on Ventilation and CO₂ Levels:

During the summer months (May to August), high HVAC volumetric airflow correlates with reduced CO₂ concentration. This indicates effective ventilation in maintaining low CO₂ levels despite potential increases in metabolic activities or external pollutant infiltration. Conversely, in the cooler months (November to February), reduced HVAC airflow corresponds with higher CO₂ concentrations, likely due to lower ventilation rates leading to reduced air exchange.

Interpretation and Implications:

The observed variation in CO₂ concentration highlights the critical role of HVAC systems in maintaining indoor air quality. Increased ventilation rates during warmer/summer months effectively reduce indoor CO₂ levels, ensuring a healthier indoor environment.

The seasonal adjustment of HVAC airflow appears to align with energy-saving strategies, but it also suggests a potential trade-off with indoor air quality during cooler months. Higher CO₂ levels in these months may require periodic adjustments to ventilation settings to avoid compromising occupant comfort and health. Or as earlier suggested a DOAS can be introduced during these periods.

The crossing point in April may represent an optimal scenario where ventilation and occupancy are well-matched. This can serve as a baseline for determining the most energy-efficient and health-conscious HVAC operation, and since the threshold of the CO₂ concentration is just about 1000 ppm, which is often the maximum allowable limit of CO₂ in indoor space by relevant standards like ASHRAE (Asif & Zeeshan, 2020).

In summary, the graph underscores the importance of dynamic HVAC operation tailored to seasonal variations in temperature and occupancy. While the system effectively reduces CO₂ levels during high-temperature summer periods, attention should be given to potential indoor air quality issues during low ventilation periods in cooler or winter months. These findings can inform future improvements in HVAC system design and operation, ensuring both energy efficiency and occupant well-being.

In order to analyze the behavioral pattern of the contaminant further, it is necessary to investigate what happens at different times of the year. Figure 74 below illustrates the behavioral pattern of the contaminant at the four different times of the year, winter, summer, spring, and autumn; using a typical day simulation (and arranged in series) in each of these seasons.

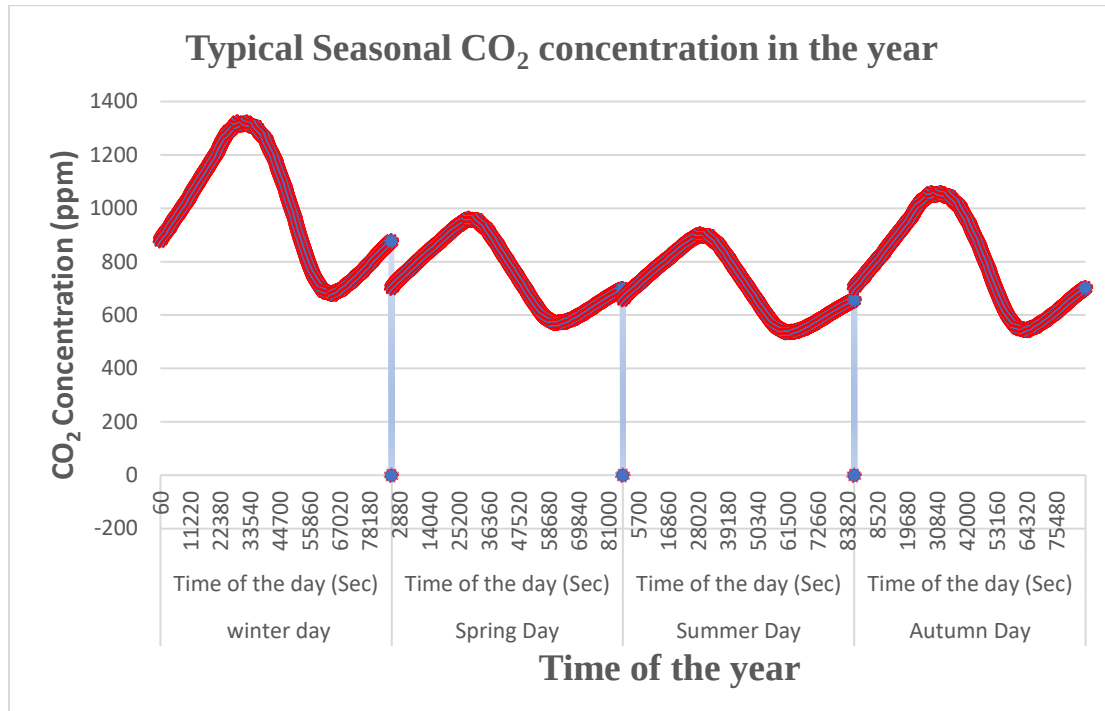


Figure 74: Typical Seasonal CO₂ concentration in the year (a)

In the **Winter Season**, the CO₂ concentrations are highest, peaking above 1200 ppm, going above the ASHRAE recommendation of below 1000 ppm for indoor spaces (Asif & Zeeshan, 2020). This could be due to limited ventilation supplied by the HVAC system.. In the **Spring Season**, the CO₂ concentration decreases slightly compared to winter, indicating better air exchange or reduced indoor emissions. In the **Summer Season**, the CO₂ levels reach their lowest, averaging around 600 - 800 ppm, simply because of the high ventilation rate by the HVAC system during the day. For the **Autumn Season**, the CO₂

concentrations rise again, though not as significantly as during winter, indicating a transitional period between the low concentrations of summer and the high concentrations of winter. The cyclical pattern in the graph suggests a direct correlation between indoor ventilation behavior and seasonal climatic conditions.

To better understand these behavioral patterns, the output by CONTAM software was arranged as shown in Figure 75 below. The diurnal cycles show that the CO₂ concentrations generally peak during midday and gradually decrease toward the evening. This trend corresponds to outdoor temperatures (as explained earlier), in which the HVAC operation was based; more so typical human activity patterns could also contribute to the trend, where peak occupancy and activity coincide with higher emissions.

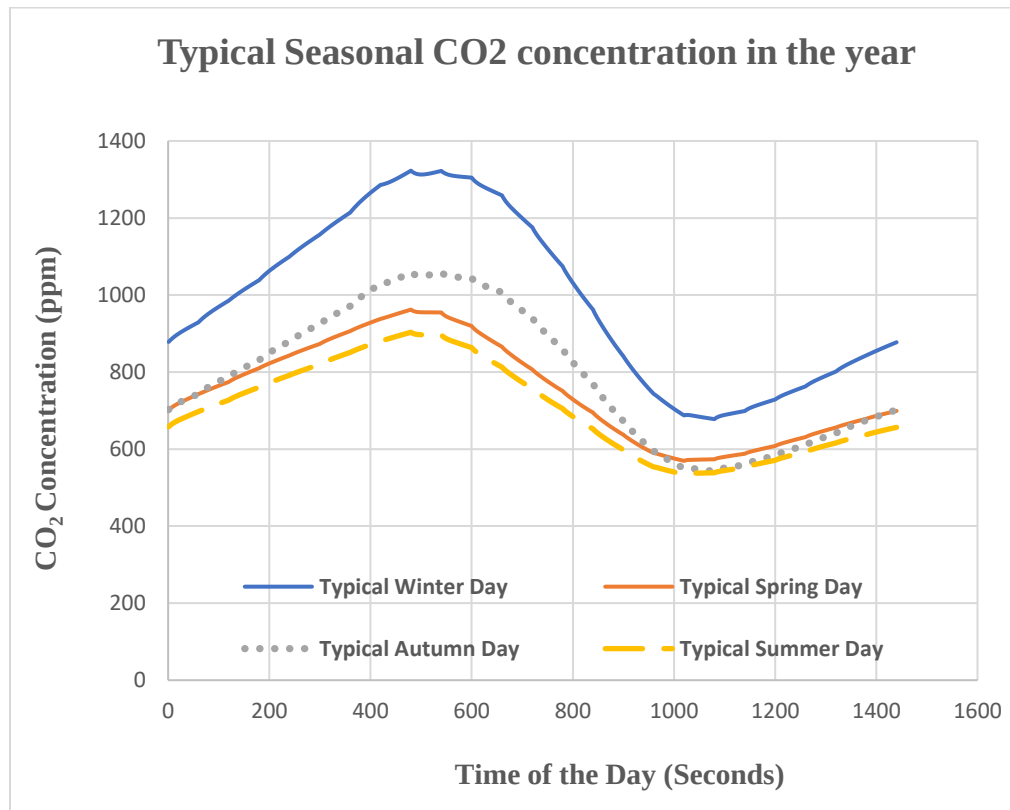


Figure 75: Typical Seasonal CO₂ concentration in the year (b)

For a combined analysis of figures 74 and 75, this study has grouped the implications on seasonal influences, occupancy patterns, and simulation insights; and they are discussed below:

1. Seasonal Influences:

Seasonal weather conditions influence ventilation rates by the HVAC system, which significantly affects CO₂ concentrations. For instance, colder winter months typically result in lower ventilation rates, leading to higher CO₂ levels, while warmer / summer months, such as summer, promote better ventilation and outdoor activity, reducing indoor CO₂ levels.

2. Occupancy Patterns:

Peaks in CO₂ concentrations during the day are consistent across all seasons, indicating a relationship between outdoor temperature, human activity, and emission rates. The rate of decline in the evening likely reflects reduced outdoor temperatures and human activity indoors.

3. Simulation Insights:

The CONTAM simulation effectively captures the interaction between climatic conditions, ventilation, and CO₂ emissions. These findings can inform building design strategies, such as optimizing ventilation schedules or implementing automated systems to regulate indoor air quality seasonally and diurnally.

5.5 Guideline for the Operation & Control of VAV-HVAC Systems to Achieve Indoor Air Quality

5.5.1 Introduction

5.5.1.1 Purpose and Scope:

This guideline provides building owners, facility managers, architects, and engineers with actionable insights to achieve optimal energy efficiency and maintain excellent indoor air quality (IAQ). Drawing from field experimentation research and simulations conducted on building performance, such as CFD modeling of CO₂ emissions and ventilation efficiency in office spaces, this guideline highlights practical methods to balance energy use with occupant health and comfort. The guideline shall be based on five (5) phases; Phase 1 is tagged the system selection which focuses on defining the region upon which any design is based, for this study, the area is Dhahran, the eastern province of Saudi Arabia; aside from the region, this phase narrows down to the building/room/zone that interest the designers, and up to the ventilation systems adopted. Phase 2 is the energy simulation, where after the appropriate simulation tool was selected, parameters like the building envelope systems, activity within the building, number of occupants, etc are well defined. Phase 3 is the Indoor Air Quality simulation, where yearly data from the building energy simulation are modeled. Phase 4 is the result analysis & findings of the simulation, while Phase 5 is either to specify the minimum air velocity required to keep the air at an acceptable level or to optimize the VAV-HVAC system when the system supplies low ventilation incapable of removing the air contaminant. Figure 76 below illustrates the framework on which this guideline follows.

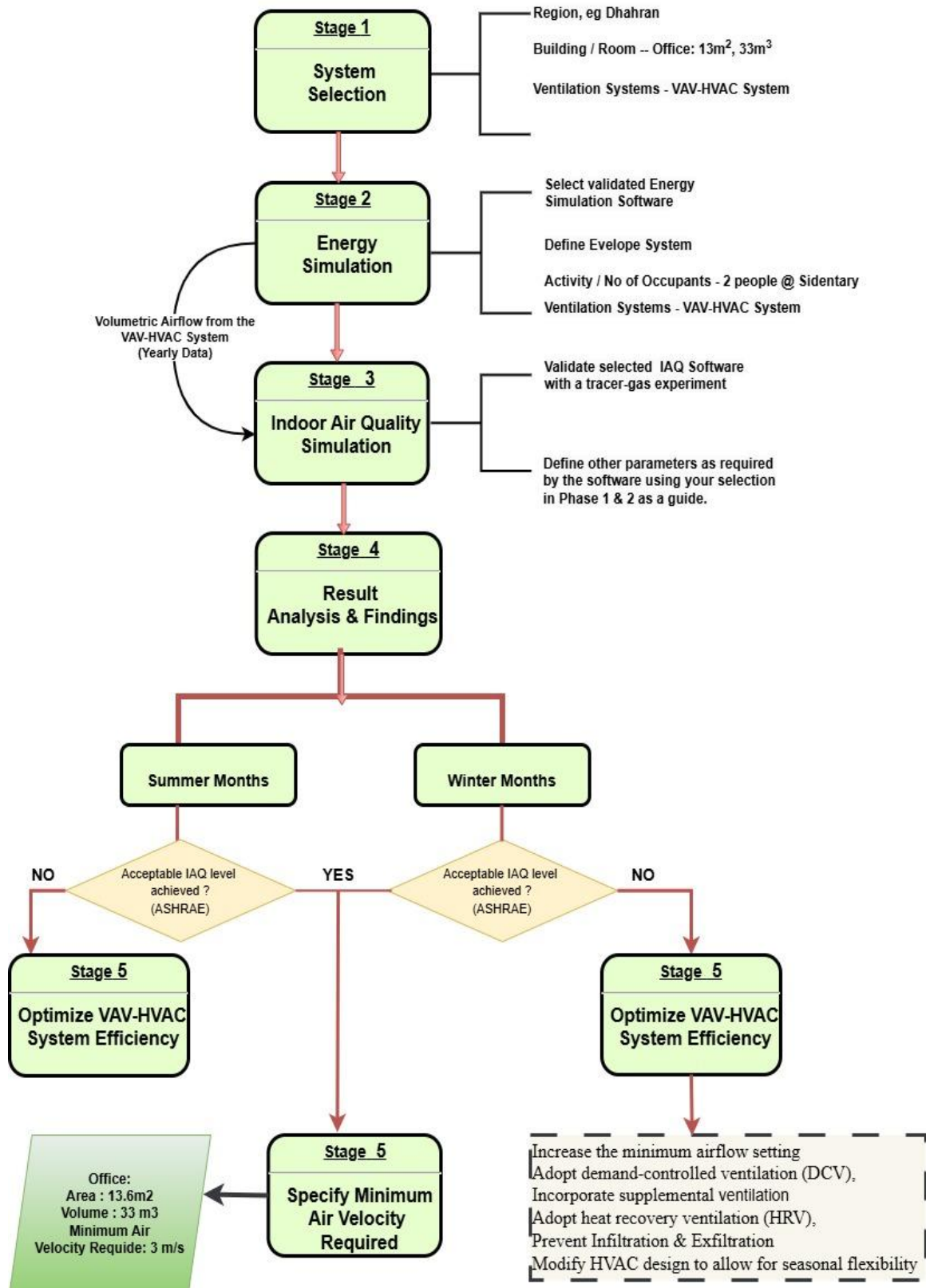


Figure 76: Framework for the guideline for the operation & control of VAV-HVAC systems to achieve indoor air quality & energy efficiency

5.5.1.2 Importance of Energy Efficiency and IAQ:

Energy efficiency is critical to reducing operating costs, minimizing environmental impacts, and meeting global sustainability goals by combating climate change by lowering carbon emissions. At the same time, IAQ directly impacts occupant health and productivity. This research on CO₂ simulations in ANSYS Fluent and tracer gas experiments to validate ventilation models illustrates the necessity of balancing IAQ with energy performance in modern buildings.

5.5.1.3 Key Definitions:

- Energy Efficiency: Minimizing energy use while maintaining required performance levels.
- Indoor Air Quality (IAQ): The quality of air within and around a building, measured by the presence of contaminants like CO₂, VOCs, and particulate matter.
- Ventilation: Introducing outdoor air into a building to dilute indoor air contaminants. Air exchange methods that help maintain good IAQ, including natural and mechanical systems.
- Thermal Comfort: A state of mind where individuals are satisfied with their thermal environment.
- HVAC Systems: Heating, Ventilation, and Air Conditioning systems responsible for maintaining indoor environmental conditions.
- Thermal Comfort: A state where occupants feel neither too hot nor too cold, influenced by temperature, humidity, and airflow.

- CFD Modeling: Computational Fluid Dynamics, a simulation technique used to analyze airflow and pollutant dispersion, as utilized in my work on office ventilation.

5.5.2. Stage 1 – System Selection

The foundation of any building performance design, modeling, and simulation lies in the careful selection of the system, starting with the location. Identifying the study's location is critical as climatic and environmental conditions heavily influence energy requirements, thermal comfort, and indoor air quality (IAQ). This study focuses on Dhahran, a city in Saudi Arabia's eastern province, characterized by its hot and humid climate. Such conditions demand a robust approach to cooling, which forms the primary focus of HVAC design in this region. The computational domain chosen for this research is an office space within an academic building in KFUPM. The office has a floor area of 13.6 m² and an internal volume of 33 m³, serving as a representative space for the simulations. The decision to focus on this space allows for precise analysis of airflow dynamics, thermal comfort, and energy efficiency. Given Dhahran's hot climate, natural ventilation was ruled out as an option due to its inability to consistently provide sufficient cooling. Instead, the study adopts a mechanical ventilation system, essential for maintaining thermal comfort and IAQ in such an environment. To address the dual goals of energy efficiency and IAQ, a Variable Air Volume (VAV) HVAC system was selected. This system is widely recognized for its ability to dynamically regulate airflow based on occupancy levels and cooling demand, thereby reducing energy consumption without compromising occupant comfort.

The choice of a VAV system aligns with sustainable building practices, as it:

Optimizes Energy Use: Adjusting airflow to match cooling loads, it minimizes unnecessary energy consumption. **Supports Zonal Control:** Ensures localized control of airflow, catering specifically to the needs of the selected office space. In summary, the system selection phase establishes a solid framework for energy-efficient HVAC design and IAQ optimization, which will guide subsequent modeling and simulations in this study.

5.5.3. Stage 2 – Energy Simulation

This phase focused on utilizing advanced computational tools to simulate the energy performance of the selected zone. A state-of-the-art, validated software, Design Builder, was chosen for this purpose due to its robust capabilities in modeling building energy dynamics. The software required detailed input parameters to reflect the actual conditions of the study accurately. These inputs included:

Building Envelope Systems: Information about thermal insulation, glazing properties, and airtightness of the walls, roof, and windows.

Activity Type: The nature of activities occurring within the space, which influences heat loads and ventilation requirements.

Occupancy Details: The number of occupants (two people in this study) and their sedentary activity levels, which affect internal heat and CO₂ generation.

HVAC System Details: Characteristics of the VAV-HVAC system, which regulate airflow and thermal comfort.

Unlike conventional energy simulation studies that focus on building energy consumption, the primary goal here was to extract the volumetric airflow rate supplied by the HVAC system to the office space. This parameter is pivotal for evaluating the system's capacity to maintain acceptable indoor air quality (IAQ) and displace airborne contaminants effectively. The volumetric airflow data derived from Design Builder formed the backbone of subsequent analyses in this study. As a validated simulation tool, Design Builder ensured high accuracy and reliability, reducing the need for additional manual calculations or corrections.

- **Main contributions of this phase:**

Tailored Input Parameters: Customizing the simulation to the specific characteristics of the selected office ensured realistic airflow data.

A baseline for IAQ Assessment: The volumetric airflow rate served as a baseline for determining the effectiveness of air supply in contaminant removal and ventilation.

Energy-Efficient Operations: Insights from the simulation guided decisions about optimizing energy use without compromising IAQ, aligning with sustainable building practices.

By focusing on airflow dynamics rather than energy consumption alone, this phase bridged the gap between energy efficiency and IAQ performance, laying the groundwork for subsequent indoor air quality simulations.

5.5.4. Stage 3 – Indoor Air Quality- Modelling & Simulation

Building on the inputs from Phase 1 and Phase 2, the indoor air quality (IAQ) within the computational domain was modeled and simulated. The domain, representing an office space with two sedentary occupants, required an accurate representation of both the contaminant source and airflow dynamics. The two individuals were modeled as CO₂ emission sources using specialized software, specifically CONTAM-W and ANSYS Fluent, each chosen for their complementary strengths in IAQ analysis.

- **Validation Process**

Before conducting the IAQ simulations, both CONTAM-W and ANSYS Fluent were validated using a tracer gas experiment employing the concentration decay method. This experiment measured how quickly a known concentration of CO₂ (used as a tracer gas) dissipated in the domain, providing experimental data to confirm the accuracy of the simulations. Validation was critical to ensure the reliability of the results, particularly given the high level of precision required for IAQ modeling.

- **Role of Each Software**

CONTAM-W: This software provided insights into the behavior of the contaminant (CO₂) within the domain. It modeled how the contaminant dispersed, accumulated, or was removed over time, accounting for the ventilation rate and occupant emissions. CONTAM-W is particularly adept at predicting long-term pollutant distribution and IAQ levels.

ANSYS Fluent: As a computational fluid dynamics (CFD) tool, ANSYS Fluent offered detailed simulations of airflow patterns, turbulence, and the interaction between air velocities and the contaminant. By modeling the intricate dynamics of air movement,

ANSYS Fluent captured localized effects that CONTAM-W could not, such as regions of stagnation or high turbulence near the occupants and ventilation outlets.

- **Integration of Results**

The results from both software platforms were integrated to provide a comprehensive understanding of IAQ within the office. While CONTAM-W revealed the overall pollutant concentration levels over time, ANSYS Fluent added a layer of detail by showing how airflow patterns influenced these concentrations. Together, these simulations enabled a detailed assessment of the effectiveness of the VAV-HVAC system in maintaining acceptable IAQ levels as defined by ASHRAE standards.

- **Main Contributions of this phase:**

Validated Modeling Tools: The tracer gas experiment ensured the robustness of the simulation outputs.

Behavioural Insights: CONTAM-W revealed the contaminant dispersion trends, enabling a macroscopic view of IAQ.

Detailed Airflow Analysis: ANSYS Fluent provided microscopic insights into the interaction of airflow with contaminants, identifying areas for optimization in the HVAC system.

Benchmarking Against Standards: Simulation outputs were compared with ASHRAE IAQ guidelines to evaluate system performance.

By combining the strengths of both CONTAM-W and ANSYS Fluent, this phase provided a detailed, validated assessment of IAQ, setting the stage for optimization efforts in the subsequent phases

5.5.5. Stage 4 – Result Analysis & Findings

The analysis of simulation results reveals key insights into the performance of the VAV-HVAC system in maintaining acceptable indoor air quality (IAQ) under varying seasonal conditions.

- **Summer Performance**

During the summer months, the volumetric airflow supplied by the VAV-HVAC system was sufficient to maintain CO₂ concentrations below the 1000 ppm threshold recommended by ASHRAE standards. This indicates that the cooling-oriented airflow settings were adequate not only for thermal comfort but also for effective contaminant displacement within the office space.

- **Winter Performance**

Conversely, during the winter months, the airflow supply was notably reduced. This reduction, typical of energy-saving measures in cooling-dominated conditions, proved inadequate for maintaining acceptable IAQ during winter months. CO₂ concentrations exceeded the 1000 ppm limit, highlighting a critical gap in the system's ability to ensure sufficient ventilation and pollutant removal during this period.

- Summary of Findings

Seasonal Discrepancies: The system performed well in summer but failed to maintain adequate IAQ in winter due to insufficient airflow supply.

Optimal Air Velocity: For an office space with an area of 13.6 m² and a volume of 33 m³, an air velocity of 3.08 m/s was found to be sufficient to displace contaminants in the summer.

Need for System Optimization: The findings underscore the necessity of calibrating the VAV-HVAC system for both IAQ and energy efficiency, particularly during winter months, to ensure consistent compliance with IAQ standards.

- Implications

The study demonstrates that while the VAV-HVAC system is effective in certain conditions, its seasonal performance variability can compromise occupant health and productivity. The findings advocate for a dual focus on energy efficiency and IAQ during system design and operation.

5.5.6. Stage 5 – Optimisation of the Ventilating System

It has been established that during the continuous operation of mechanical ventilation systems, especially the VAV-HVAC ventilation system, some control measures will need to be implemented to optimize the system. In the winter, when the VAV-HVAC system supplies low volumetric airflow and fails to effectively displace the CO₂ emitted by humans

in the room (as we have in this study), the following technical advice could be considered to improve indoor air quality:

- Increase Minimum Airflow Setting for Winter

Adjust the VAV system's control settings to increase the minimum airflow rate during winter, ensuring a sufficient supply of fresh air to displace CO₂ even during low heating demands. This approach may increase energy consumption (a little) for heating, so balancing airflow and heating energy efficiency is key.

- Utilize Demand-Controlled Ventilation (DCV)

Installing CO₂ sensors to implement DCV will go a long way to ensure adequate ventilation. This system monitors CO₂ levels in real time and adjusts the airflow rate to maintain acceptable indoor air quality. The benefit here is that energy efficiency is preserved by increasing airflow only when CO₂ concentrations exceed a threshold.

- Supplemental Ventilation

Localized or supplemental ventilation systems, such as exhaust fans or air purifiers, can be added to enhance air exchange in the space during winter. They use small air purifiers with CO₂ absorption capabilities or direct outdoor air supply to the room.

- Heat Recovery Ventilation (HRV)

Integrating a heat recovery ventilation system to bring in fresh air without losing significant heat. The benefit of HRV is that it recovers heat from the exhaust air, maintaining energy efficiency while improving indoor air quality.

- Evaluate Room Insulation and Sealing

Checking for excessive insulation or airtight sealing that may trap CO₂ indoors. If necessary, allow for controlled infiltration of outdoor air. This prevents CO₂ accumulation while minimizing heat loss.

- Modify HVAC Design for Seasonal Flexibility

Redesigning or upgrading the HVAC system to incorporate seasonal flexibility in airflow rates, ensuring adequate air displacement in both summer and winter. For example, adding specialised variable speed fans that can respond to seasonal and occupancy needs

5.5.5. Conclusion Notes (Guideline)

Optimizing building designs using tools like **CFD modeling** and Design Builder for energy and IAQ performance is necessary before and during a building's lifespan. Adopt renewable energy systems such as solar PV to support **net-zero goals**. Advanced ventilation strategies like VAV systems ensure IAQ without excessive energy consumption. Emerging trends include **AI-driven building management systems**, real-time IAQ monitoring, and advanced materials for insulation and filtration, which align with my research focus on improving building performance.

CHAPTER 6

SUMMARY, CONCLUSION & RECOMMENDATIONS

6.1 Summary

This study, which assesses air contaminant behavior in a VAV-HVAC air-conditioned space under varying thermal loads, successfully achieved its objectives:

Objective 1: To evaluate the behavior of air contaminants in a VAV-HVAC air-conditioned space under varying thermal load conditions.

This objective was addressed through the use of Design Builder, a validated energy simulation software, by developing a digital model of an existing office space in Building 19, College of Design and Built Environment, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. The model simulated real-world conditions in a 13.6 m² office room occupied by two individuals, with "number of people" selected as the occupancy method and mechanical ventilation set to "room ventilation", ensuring that the influence of human presence on the indoor air dynamics was captured. The software dynamically calculated thermal loads over a year, providing outputs that varied with time and external conditions. The results, including annual contaminant dispersion patterns and behaviors, were documented in earlier sections. Despite the idea of allowing the Design Builder software to generate contaminants within the experimental domain (room) alongside the volumetric flow, this study employed the use of CONTAM-W, an indoor air quality software to model how CO₂ contaminants are generated within the room effectively; ANSYS Fluent, a computational fluid dynamics (CFD) software, was

employed to visualize and understand how contaminants dispersed and were displaced within the room. This tool enabled detailed analysis of airflow patterns and contaminant interactions, offering valuable insights into the room's ventilation effectiveness under the influence of varying thermal loads.

Objective 2: To evaluate different VAV system strategies for improving indoor air quality and ventilation effectiveness.

To address this objective, a tracer gas experiment was conducted using carbon dioxide (CO₂) as a surrogate for indoor contaminants. The room was initially filled with 5000 ppm of CO₂, and four (4) different ventilation strategies were assessed by varying the air supply rates. The experiment evaluated how changes in ventilation rates influenced the removal of CO₂ and its dilution within the space, thereby providing insights into ventilation effectiveness. Additionally, the impact of sensor/logger placement on the decay rate and decay time was investigated. It was observed that the positioning of the sensor significantly influenced the recorded decay time but had minimal effect on the calculated air change rate. The findings highlighted that placing the sensor/logger near the return grill was optimal, while heights below 0.75 m should be avoided to ensure accurate decay measurements. The experimental results demonstrated the effectiveness of different ventilation strategies in enhancing indoor air quality. Furthermore, the data obtained from the tracer gas experiment were used to validate the ANSYS Fluent computational fluid dynamics (CFD) model and CONTAM – W software, which was employed to achieve Objective 1. This validation confirmed the reliability of the simulation softwares used in the prediction of airflow patterns and contaminant dispersion within indoor spaces.

Objective 3: To develop guidelines for the operation and control of VAV-HVAC systems to achieve indoor air quality.

The successful completion of Objectives 1 and 2 provided valuable insights into the interaction between varying thermal loads, ventilation effectiveness, and indoor air quality in VAV-HVAC systems. Leveraging these findings, a comprehensive set of guidelines for the operation and control of VAV-HVAC systems was developed to ensure a balance between energy efficiency and acceptable indoor air quality. These guidelines serve as a framework for facility managers and HVAC designers to optimize VAV-HVAC systems, enabling sustainable building operations while maintaining indoor air quality standards.

6.2 Conclusion

The way air flows through a structure or individual rooms can significantly affect how energy-efficient a ventilation system is. Furthermore, airflow behavior affects general circumstances, the thermal environment, and the spread of airborne pollutants. Building airflow behavior and mixing features are receiving more attention in an effort to optimize the design and guarantee a healthy interior. This study has accessed air contaminant behavior in a VAV-HVAC air-conditioned space under varying thermal loads, following a structured sequence of analyses aimed at achieving model validation and integration through the use of experimentation and simulation.

The study underscores the pivotal role of tracer gas experiments in determining ventilation effectiveness in indoor spaces. By employing CO₂ as the tracer gas, this experiment has shown that sensor positioning significantly influences the decay time of the tracer gas, but it has a minimal impact on the calculated air change rate (ACH) within the room. Notably,

placing the sensor near the return grill proved to be optimal for capturing accurate ventilation data. However, the analysis highlighted that sensor placement at heights below 0.75 meters should be avoided, as it may introduce inconsistencies due to stratification or insufficient air mixing at lower levels. This insight is crucial for future ventilation studies and standards in indoor air quality (IAQ) research.

For the Design and Assessment of Indoor Air Quality Systems, a validated CONTAM model can simulate various indoor scenarios, helping designers optimize ventilation strategies for improved air quality and energy efficiency. The software provides a sensitivity analysis by varying key parameters in the simulation, such as ventilation rates or occupancy levels, the model can provide insights into their impact on CO₂ dynamics, aiding in the development of robust air quality management plans.

The integration of ANSYS Fluent as a computational fluid dynamics (CFD) tool demonstrated its robustness and reliability also in simulating indoor airflow and ventilation scenarios. The CFD simulations aligned well with experimental findings, reinforcing ANSYS Fluent's capacity to model complex ventilation processes accurately. The rule of thumb observed in the study, that increasing the supply of fresh air improves air dilution and displacement while reducing contaminants, was validated both experimentally and numerically. This reinforces the importance of sufficient ventilation rates for achieving healthier and cleaner indoor environments, particularly in spaces with human occupancy.

On the energy simulation front, Design Builder software played a pivotal role in complementing the CFD analysis. The software's dynamic modeling capabilities provided insights into the interaction between HVAC systems and outdoor environmental conditions. Specifically, during summer months, the VAV-HVAC system showcased its adaptability in

handling outdoor air. Overall, this study highlights the synergy between experimental methods, numerical simulations, and energy modeling tools in understanding and optimizing indoor ventilation. The findings emphasize that integrating tools like tracer gas experiments, air quality modelling, CFD simulations, and dynamic energy modeling can offer comprehensive insights into indoor air dynamics, enabling better design and operation of HVAC systems. The conclusions drawn from this work are instrumental for improving ventilation practices, ensuring energy-efficient building operations, and advancing IAQ standards in diverse indoor environments. These insights contribute to the growing body of knowledge on the design and operation of sustainable and high-performance HVAC systems

Despite achieving 7%–38% energy savings, the VAV-HVAC system has notable disadvantages, particularly in providing adequate ventilation during winter. To address this issue, as earlier stated in section 5.5 of this thesis (guidelines), homeowners, engineers, and builders should consider the following strategies: increase the minimum airflow setting during winter, adopt demand-controlled ventilation (DCV), incorporate supplemental ventilation and heat recovery ventilation (HRV), evaluate and improve room insulation and sealing, modify HVAC design to allow for seasonal flexibility. These measures aim to enhance ventilation performance and maintain energy efficiency throughout the year.

6.3 Recommendations

This study hereby recommends the following : **Real-Time Monitoring:** Incorporating CO₂ sensors can enable dynamic control of ventilation rates, ensuring compliance with ASHRAE guidelines under varying occupancy conditions, especially during the winter

seasons **Design Optimization:** To achieve rapid pollutant stabilization, air velocities above 3.0850 m/s are recommended for a room area of 13.6m² and a volume of 33.2m³, while rates closer to 8.0256 m/s (especially for summer periods) offer a practical trade-off between IAQ and energy use. **Validation of Modeling Approaches:** The use of simulation tools such as Design Builder and ANSYS aligns with ASHRAE's advocacy for advanced modeling techniques in IAQ assessment.

6.4 Areas For Further Studies

While this study focuses on a typical office room in a university, similar studies need to be carried out on other indoor spaces to establish the minimum airflow from a VAV-HVAC system and enhance further design. More so, this study used tetrahedra mesh based on previous studies, further studies should also work on other mesh types, especially Polyhedral Mesh (tipped for better convergence and accuracy) and Prism (Wedge) Layers mesh, which some experts argue that it is good, especially for significant wall interactions, when resolving turbulence issues.

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CURRICULUM VITAE

AFOLABI Oladayo Popoola

A member of the Nigeria Institute of Building (NIOB) *since Dec. 2013*

HND (Bldg), BTECH (Bldg), MSc (Arch_Engr)

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WATCHWORD

I want to be a researcher, who uses research to solve real-life problems, thereby bridging the gap between classrooms and industry.

RESEARCH INTEREST

- High Performance Buildings
- Human - Building Interactions
- Building Envelope Optimisation
- Occupant health and well-being
- Artificial Intelligence for Attainment of Building Performance Assessment / Building Management Systems
- Sustainability in (Building) Construction / Green Buildings / Net Zero-Energy Building
- Building Energy Simulation & Modelling
- Ventilation & Indoor Air Quality Studies
- Carbon Capturing in HVAC Systems
- Sustainable Construction Materials

EDUCATION

MSc **Architectural Engineering** **(3.313 /4.0)** June, 2024
King Fahd University of Petroleum & Minerals, Saudi - Arabia
Dissertation: Assessment of Air-Contaminant Behavior In VAV-HVAC Air Conditioned Space Under Varying Thermal Loads
Supervisor: Prof. Ismail Budaiwi Muhammad

Professional Diploma **Project, Quality, Safety, Environment, Risk & Sustainability Management**
 QHSES Leadership Academy – Lagos Nigeria
Project Presentation: An Analysis of Oppau Explosion of 1921 August 2023
Supervisor: Engr. Jamiu Badmus

MSc	Construction Engineering (Management) American University in Cairo Program Suspended (after a year) Due to COVID – 19 Restrictions	(3.28 / 4.0)	N/A
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BTech **Building** (4.25 / 5.0) November, 2017
 Federal University of Technology Minna - Nigeria
Dissertation: Splitting Tensile Strength of Mortar (Using the mixture of Millet Husk Ash and Calcium Carbide Waste as Binder)
Supervisor: Associate Prof. Babatunde James Olawuyi

HND **Building Technology** (2.66 /4.0) February, 2009
 Yaba College of Technology – Lagos Nigeria
Dissertation: Maintenance of Millennium Classrooms in Lagos State
Supervisor: Bldr. Siraj Bokini

ND **Building Technology** (2.81 /4.0) December, 2005
 Federal Polytechnic Ede, Osun State Nigeria
Dissertation: Perimeter Survey of FPE - Phase II
Supervisor: Surv. T. G Akinola

RESEARCH & TEACHING EXPERIENCE

- Senior Class 1 – Physics Teacher (Taught face-to-face)
 [08/2009 - 07/2010]
 NYSC Scheme - Nigeria
 Army Day Secondary School, Port Harcourt Rivers State Nigeria
- Research / Teaching Assistant
 [25/08/2021 – 10/06/2024]
 Architectural Engineering & Construction Management Department
 King Fahd University of Petroleum & Minerals

➤ MSc – Research - Thesis

My MSc thesis titled, Assessment of Air-Contaminant Behaviour in VAV-HVAC Air-Conditioned Space under Varying Thermal Loads; tends to ease the trade-off between Building (Operational) Energy and achieving acceptable Indoor Air Quality. A tracer gas experiment (concentration decay test) was conducted, using a CO₂-filled room to determine the air change rate; This experiment was used to validate a CFD model using ANSYS-Fluent & CONTAM (W). Design-builder software was used to generate the varying supply airflows that were later used on the validated CFD & CONTAM (W) Model. While the ANSYS CFD shows the turbulence of the contaminated air, CONTAM (W) was used to access the behaviour of the contaminant within the computational domain (office room).

➤ BTech – Research - Thesis

To reduce building embodied energy, limit the rate of CO₂ - GHG emissions, and reduce environmental outdoor pollutants, **I used the combination of agricultural waste (millet husk ash-MHA) and industrial waste (calcium carbide waste -CCW) to generate a pozzolanic binder for construction works.** The XRF result shows that the ashes of MHA contain SiO₂ and CCW contain Ca (OH)₂, and these form the basis of my research, which was aimed at an outright displacement of Portland cement for construction works.

PUBLICATIONS & CONFERENCES [Link](#)

- ✚ Abdulkabir, O. B ; Aliyyu A. A; Shamsideen A.A; **Afolabi, O** "Factors Influencing the Adoption of Distributed Ledger Technology in Developing Countries: An Examination of Nigerian Construction Industry" submitted to **International Journal of Construction Education and Research** <https://doi.org/10.1080/15578771.2024.2384375> (Taylor & Francis)
- ✚ Abdulkabir, O. B ; Aliyyu A. A; **Afolabi, O** ; Adefemi A; Precious O. G. (2024) "Assessing the underlying factors affecting trust and transparency in the construction industry: a mixed method approach" **Construction Economics and Building** - <https://doi.org/10.5130/AJCEB.v24i1/2.8906>
- ✚ Abdulkabir, O. B.; Isa, R.B; **Afolabi, O.**; Khan, A. A.; & Arogundade, S; (2023), Drivers for the Implementation of Circular Economy in the Nigerian Construction Industry: A Structural Equation Model Approach **Journal of Engineering, Design & Technology**– <https://doi.org/10.1108/JEDT-09-2023-0434>
- ✚ Abdulkabir, O. B.; Ayegba, C.; Ibrahim, O. O.; **Afolabi, O.**; & Ihedigbo, K. S. (2022). A review on the awareness and challenges of Building Information Modelling for Post Construction Management in the Nigerian Construction Industry. 5th International African Conference on Current Studies., (pp. 137-142.). Cairo
- ✚ Ihedigbo, K. S; Idris A.; **Afolabi, O.**; & Mudasiru, S. A; (2022). Effect of Time Performance on Educational Building Projects in Nigeria. 5th International African Conference on Current Studies, (p. 151). Cairo

✚ **Afolabi, O** & Muhammad, A (PhD) - **Ongoing – Manuscript** - “Evaluation of Particulate Matters Dispersion in Religious Buildings (Mosques) in Saudi Arabia”

✚ **Afolabi, O** -**Ongoing – Manuscript**- “Study of Indoor Air Quality in Student Restaurant”

CONSTRUCTION WORK EXPERIENCES

DATE	COMPANY	PROJECT	POSITION	RESPONSIBILITIES
August 2019 – Oct. 2020	Stallion Group of Companies	Construction of Warehouses, Offices ...	Engineer	- Client Representative/ Clerk of Works - Resident Engineer - Quality Control Officer - Ensuring adherence to site health and safety plan - Site Measurement for Contractors' Valuations - Keep updates of Site Notes / Change orders for necessary use. - Produce BOQ and Budgets, supervise and execute in-house jobs that are not assigned to contractors
February 2019 – July 2019	Centre Base Consult Limited	Construction of Buildings	Engineer (Senior Staff)	- Site Manager (Planning, Organizing, Staffing, ...) - Quality Control Officer - Ensure Site Safety (Implementing Site Safety plan, giving talks during toolbox meeting, ...)
Jan 2018- July 2018	BrickHouse Construction Company Limited (Contract Staff)	Construction of Residential apartments at Victoria Island and Banana Island Lagos	Assistant Site Engineer	- Programming/Scheduling of Construction Activities - Implementation of Planned schedules - Application of Quality Control Measures - Giving Safety Briefs & Ensuring a Safe Working Environment - Negotiate Contract Sum with small Contractors - Always liaise with the Consultant

April 2016 - November 2016	EXPEDITE ENGINEERING LIMITED Plot 407, Kubwa Extension, Arab road, Kubwa Abuja	Design Office	Building/Structural Engineer	-Learning and working with CSC Orion for Building Structures. Visiting the Site to oversee Structural Element -Giving appropriate advice to the Contractors
March 2013 - Oct 2013. Oct. 2013 - Jan 2014	ZAINA NIG. LTD 8, Kinshasa Street Wuse Zone 6 Abuja - Nigeria	Construction of Central Bank of Nigeria (C.B.N) Damaturu branch, Yobe State. MDG PROJECT- Construction of Primary Health care Centre, Shuey Duku LG Gombe State.	Building Engineer II SITE ENGINEER	- Maintain cordial relationships with consultants & other client representatives - Producing a Program of Works with Microsoft Project Professionals - Interpretation of Designs (Architectural, Structural, ...) for Artisans - Ensuring proper shuttering of forms - Quality Control Officer - Ensuring Site safety - Attend Site Technical meetings. - Carrying out tests on concrete for Structural Elements (Rebars, Concrete, ...)
Oct., 2011 Nov., 2012	Concrete Wood & Glass Limited (Contract Staff)	Construction of High-rise Buildings (7 Floors each) consisting of 340 Luxury Apartments for Prime Water Views Gardens II Lekki Lagos (Finishes-only)	Site Engineer	-Ensuring good finish application (Plastering, Tiling , Painting, Plumbing etc) -Taking physical measurements for payment purposes -Preparation of Site Activities Report for *Management Decisions *Consultants * Proposed Buyers
Feb.-July 2011	Adunmed Nigeria Ltd, Kamarise House, Academy Monotan Ibadan Oyo State.	Rehabilitation of Outpatient Department & Construction of 2 NOs Prototype gatehouses of OYO state Hospital Ring Road Ibadan.	Site Supervisor 11	-Interpretations & Implementation of Production Documents (Designs) -Distribution of Work activities to Artisans on each day -Taking Physical Measurements for cost purposes -Always Ensuring Site Safety. -Preparation of Site activity reports (fortnightly) -Attending site meetings as the need arises

SOFTWARE INTERACTED WITH

- Python Programming (Beginner)
- Design Builder (Energy Plus) – Building Energy Modelling & Simulation
- ANSYS Fluent (CFD Analysis) – Air flow movement
- CONTAM (W) – Indoor Air Quality Modelling & Simulation
- Microsoft Project – Construction Planning & Scheduling
- CSC ORION - Structural Analysis and Design (of Concrete Buildings)
- AutoCAD (2D)
- Microsoft Office (Word, Excel, PowerPoint)

PROFESSIONAL AFFILIATIONS

- Nigerian Institute of Building (NIOB) *_ Corporate Member _* December, 2013 - Present
- Nigeria Institute of Management (NIM) *_ Graduate Member _* November, 2011 - Present
- American Society of Civil Engineers (ASCE) *_ Student Member _* January, 2021 - Present
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)
March, 2022 – Present
(_ Student Member _)

AWARDS & FELLOWSHIP

- King Fahd University Masters Scholarship for International Students 08/2021 – 06/2024
- African Graduate Fellowship – American University Cairo 01/2020 – 07/ 2021
- Laboratory Fellowship – American University Cairo 09/2020 – 12/2020
- 3rd Best Graduating Student (Uncelebrated) @ Building Department, F.U.T Minna Nigeria
2017

EXTRACURRICULAR ACTIVITIES

- Volunteering Activities
 - KFUPM Volunteers Day 2022
 - KFUPM Volunteers Day 2023
- Leadership Activities
 - National Secretary General _ National Association of Building Students _ 2007
 - Vice President _ National Association of Osun State Students (Yabatech Chapter) _ 2007

- Organizing Secretary _ Muslim Students Society of Nigeria (FPE Branch) _2005
- Library Prefect _Abibat Mogaji Mill. Senior Secondary School Agege (AMMSSS) _ 2003
- President (Amir) _ Muslim Students Society of Nigeria (AMMSSS) _ 2003

REFeree

Shall be forwarded on request

APPENDIX

Table 19: Table showing the relationship between Sensor/Logger positions and their corresponding Air Change Rates

Relationship between Logger Positions and its corresponding Air Change Rate			
	Heights		
	2.2m	1.65m	0.75m
Strategy 1	0.36	0.36	0.36
Strategy 2	1.08	1.08	1.08
Strategy 3	1.44	1.8	1.44
Strategy 4	1.44	1.8	1.44

Table 20: Table showing CO₂ concentrations & the monthly peak volumetric airflow

Months of the year	Temperature	CO ₂ Concentration (ppm)	Monthly Peak Volume Airflow - m ³ /s
January	25.2°C	1318.9195	0.087485502
February	28.2°C	1184.849	0.101613954
March	35.1°C	1087.7365	0.115028953
April	39.8°C	962.2765	0.138617048
May	45°C	943.857	0.142851782
June	46.9°C	926.1345	0.147259451
July	46.9°C	919.5725	0.148982657
August	46.2°C	900.745	0.1541453
September	44.1°C	926.925	0.147079395
October	40.1°C	964.0445	0.138176095
November	35°C	1052.368	0.120823122
December	28°C	1137.368	0.092077222

Table 21: Table showing different peak airflows at different months

	Monthly Design Temperature	on 21st - Average Volume Airflow of 24hrs	on 21st - Peak Volume Airflow (within 1 hr)	Monthly Average Volume Airflow	Monthly - Peak Volume Airflow (in 1hr)
	°C	m ³ /s	m ³ /s	m ³ /s	m ³ /s
January	25.2	0.0399	0.0875	0.0310	0.0875
February	28.2	0.0438	0.0890	0.0395	0.1016
March	35.1	0.0479	0.0861	0.0515	0.1150
April	39.8	0.0605	0.1036	0.0653	0.1386
May	45	0.0882	0.1227	0.0839	0.1429
June	46.8	0.0890	0.1308	0.0941	0.1473
July	46.9	0.0956	0.1324	0.0974	0.1490
August	46.2	0.0969	0.1442	0.0973	0.1541
September	44.1	0.0861	0.1415	0.0887	0.1471
October	40.1	0.0760	0.1183	0.0769	0.1382
November	35	0.0439	0.0701	0.0566	0.1208
December	28	0.0427	0.0883	0.0387	0.0921

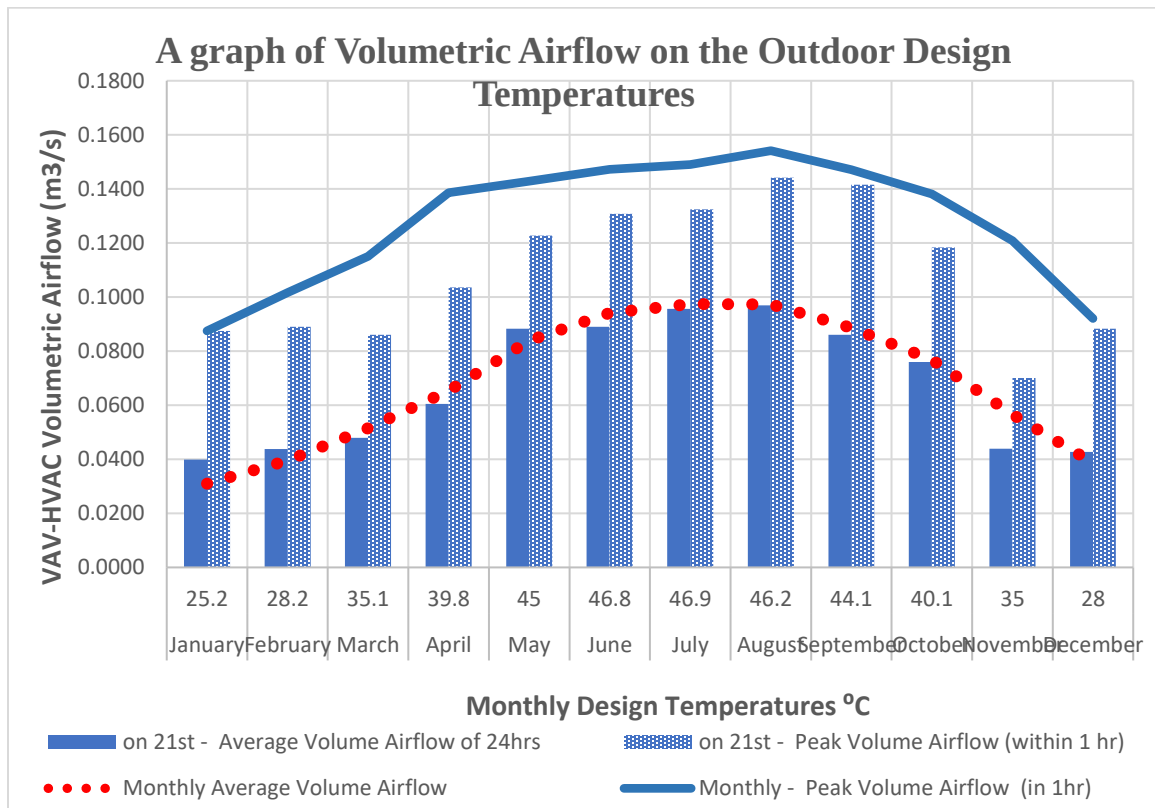


Figure 77: A graph of Volumetric Airflow on the Outdoor Design Temperatures depicting Table 21