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THE IMPORTANCE OF WINDOW POSITION IN EFFECTIVE NATURAL VENTILATION OF BUILDINGS

Master's Thesis

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2023

.ACCEPTANCE AND APPROVAL OF THE THESIS

The study entitled **"THE IMPORTANCE OF WINDOW POSITION IN EFFECTIVE NATURAL VENTILATION OF BUILDINGS"** prepared by **Wisam Hatem mohammed MOHAMMED**, and supervised by **Prof. Dr. Bahtiyar ÖZTÜRK**, was found successful and unanimously accepted by committee members as Master thesis, following the examination on the date 9.11.2023 .

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ÖZET

BİNALARIN ETKİLİ DOĞAL HAVALANDIRILMASINDA PENCERE KONUMUNUN ÖNEMİ

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Binaların iç hava kalitesini bozan kirleticilerin uzaklaştırılmasında ve temiz hava sağlanmasında etkin rol oynayan doğal havalandırma, yerden tasarruf sağlaması ve mekanik havalandırmanın enerji ve bakım maliyetlerini azaltması nedeniyle yeşil bina tasarımında özel bir yere sahiptir. Bu çalışma binaların farklı cephelerine konumlandırılan pencerelerin ve farklı havalandırma oranlarının bina içindeki kirleticilerin giderilmesindeki rolünü ortaya koymak amacıyla yapılmıştır. Deneyler 0,4x0,7x0,4 m (en, boy, derinlik) boyutlarında, yan ve üst yüzeylerinde 4 cm x 4 cm olmak üzere toplam 12 adet havalandırma açıklığı bulunan test odasında gerçekleştirilmiştir. Test odasında başlangıçta 5000 ppmv olan CO2 konsantrasyonunun 500 ppmv'ye düşürülmesini sağlayan, temiz havanın odaya girip çıktığı oda yüzeylerindeki pencere açıklıklarının konumunun etkinliği, üç farklı hava kullanılarak incelenmiştir. Çalışmadan elde edilen sonuçlar, iç ortama beslenen hava akışının arttırılmasının kirleticilerin uzaklaştırılması için gereken süreyi önemli ölçüde azalttığını ancak bu etkinin havanın giriş ve çıkış noktalarına bağlı olarak değiştiğini göstermektedir. Kirletici madde azaltım oranı en yüksek iken hava giriş ve çıkış noktaları odanın karşılıklı taraflarında bulunduğunda, gelen havanın odanın yan yüzeyinden veya üst tavanından dışarı atılması durumunda bu oranın yavaşladığı gözlemlenmiştir. Elde edilen sonuçlar, bina tasarımında doğal havalandırmanın etkili olabilmesi için pencerelerin hakim rüzgar yönünde ve binanın karşı tarafına yerleştirilmesinin faydalı olacağını göstermektedir. Pencerelerin bina cephelerine bu şekilde yerleştirilmesi, bina içindeki hava akışına direnç oluşturan türbülansı azaltacak ve kirleticilerin daha kısa sürede dışarı atılmasına olanak sağlayacaktır.

Anahtar Sözcükler: Kirlilik, Karbon Dioksit, Pencere Konumları

ABSTRACT

THE IMPORTANCE OF WINDOW POSITION IN EFFECTIVE NATURAL VENTILATON OF BUILDINGS

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Natural ventilation, which plays an active role in removing pollutants that deteriorate the indoor air quality of buildings and providing fresh air, has a special place in green building design as it saves space and reduces the energy and maintenance costs of mechanical ventilation. This study was carried out to reveal the role of windows positioned on different facades of buildings and different ventilation rates in removing pollutants inside the building. The experiments were carried out in a test room with dimensions of 0.4x0.7x0.4 m (width.length.depth) and a total of 12 ventilation openings of 4 cm x 4 cm on the side and top surfaces. The effectiveness of the position of the window openings on the room surfaces, through which the fresh air enters and exits the room, allowing the initial CO2 concentration of 5000 ppmv in the test room to be reduced to 500 ppmv, was examined using three different air flow rates. The results obtained from the study show that increasing the air flow fed to the indoor environment significantly reduces the time required for the removal of pollutants, but this effect varies depending on the entry and exit points of the air. When air inlet and outlet points are located on opposite sides of the room while the rate of pollutant reduction is highest, it has been observed that this rate slows down if the incoming air is expelled from the side surface or upper ceiling of the room. The results obtained show that in order for natural ventilation to be effective in building design, it would be beneficial to install windows in the direction of the prevailing wind and on the opposite side of the building. Placing windows on building facates in this way will reduce the turbulence that creates resistance to air flow within the building and allow pollutants to be expelled in a shorter time.

Keywords: Pollution, Carbon Dioxide, Windows Positions

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SYMBOLS AND ABBREVIATIONS

IAP	: Indoor Air Pollution
IAQ	: Indoor Air Quality
EPA	: Environmental Protection Agency
WHO	: World Health Organization
SO2	: Sulfur dioxide
PM	: Particulate Matters
NOx	: Nitrogen oxides
NO	: Nitrogen monoxide
NO2	: Nitrogen dioxide
O3	: Ozone
CO	: Carbon monoxide
CO2	: Carbon dioxide
PVC	: polyvinyl chloride
PAN	: peroxyacyl nitrates
SOA	: Secondary Organic Aerosols

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1. INTRODUCTION

With the massive growth of the economy, rapid population increase, and industrial development, civilization requires a large number of resources (such as energy, water, and food) to sustain life. Atmospheric pollution is an important environmental problem in cities because of its widespread nature, environmental problems, and potential health threat to individuals (Leung, 2015; Association, 2001).

Since people spend most of their daily lives in closed places such as homes, schools, shopping malls, vehicles, etc. pollutants in the inner atmosphere of closed environments are as important as the air pollution in the outer atmosphere. Sometimes indoor air pollution can be two to five times greater than outdoor air pollution, making it even more important than outdoor air pollution (Hinwood et al., 2003). For this reason, 3 billion people are exposed daily to indoor air pollution, which is a major contributor to the number of deaths and patients, with a huge negative impact on the environment and living organisms, including humans (Holgate, 2017).

Indoor air quality is mainly affected by indoor materials, human activities, building materials, and extraneous pollutants such as gases and solids. In the past few years, since the development of the construction of buildings to preserve the internal environment, energy, thermal insulation, and preventing air circulation between the internal and external environment of buildings, the increasing problems of air pollution have emerged over time (Firdhous et al., 2017). There are three basic strategies for controlling indoor air pollutants and improving indoor air quality. These; control at the source, use of ventilation system and use of air cleaners. Source control involves reasonable product selection, modification, or use restrictions that eliminate or reduce emissions of harmful substances into indoor air. For example; keeping cleaning products on the balcony, using personal care products in the bathroom, preventing the formation of a humid environment, connecting combustion systems such as stoves, stoves and fireplaces to the outside, keeping clothes in the closet and collecting them in a certain place where they will be washed, keeping animals such as cats, dogs and birds in the certain places of the house or not letting it in, taking precautions against radon gas entry on the building floor, not choosing flooring products that create too much dust, using vacuum cleaner frequently, choosing natural wood rather than compressed wood for furniture and flooring, not choosing paint and adhesive materials that contain too many VOCs, and not using asbestos building insulation materials.

Although there are systems that will remove moisture from the indoor atmosphere, eliminate dust and capture VOCs, they have not become widespread. One of the most commonly used methods to prevent indoor air pollution is natural or mechanical ventilation, which allows clean air to be fed in and the dirty air pushed out. Natural ventilation is the inflow of fresh air into the building through doors, windows, and other openings and the discharge of dirty air from the inside to the outside, depending on the pressure difference between the inside and outside of the building. It is the temperature or wind that creates the pressure difference. In mechanical ventilation, a fan, etc., driven by a motor, is used to feed air into the building and ensure air escape from inside to outside. The mechanical ventilation system generally consists of a fan that sucks air from or push to the outside, a filter, an air distribution duct and, in some cases, an air conditioner.

Natural ventilation is of particular importance in green building design because it saves space and reduces the energy, maintenance and noise problems of mechanical ventilation. Windows are one of the most used building elements in the natural ventilation of buildings. They improve indoor air quality as well as daylight, thermal comfort, aesthetic appearance and energy performance of buildings (Andersen et al., 2013 ;Rodrigues et al., 2019 ;Abdullah and Alibaba, 2022). Therefore, in building design, architects must determine the size and location of windows to ensure effective natural ventilation of the building as well as building aesthetics.

The aim of this study is to experimentally demonstrate the roles played by the position of the windows through which air enters and exits the indoor on the removal of pollutants in that indoor atmosphere. The experiments were carried out in a test room with dimensions of 0.4x0.7x0.4 m (width x height x depth) and a total of 12 ventilation openings of 4 cm x 4 cm on the side and top surfaces. The effectiveness of the position of the window openings on the room surfaces, through which fresh air enters and exits the room, which reduces the average 5000 ppmv CO_2 concentration in the test room at the beginning, was examined using three different air flow rates. The results obtained from the study are presented in terms of the effect of the entry and exit status of the air into the test room and the effect of the air flow rates on the removal of the pollutant.

2. FORM AND APPEARANCE FEATURES OF THE THESIS

2.1 Indoor air pollution definition

Rapid population growth, urbanization and industrial structuring play an important role in the intense spread of air pollutants into the atmosphere that can harm people and other living things and goods. The penetration of these air pollutants encountered in the ambient atmosphere into closed indoor environments and the air pollutant sources in indoor environments cause indoor air pollution as much as the outdoor environment, or even more (Davidson et al., 1986). Volatile organic compounds (VOCs), particulate matter (PM), inorganic compounds, gases, and chemical, physical, and biological agents are a few examples of types of indoor air pollution that can harm human health (Spengler et al., 2001).

2.2 Indoor air pollution sources

The most important indoor air pollutants are gases, insecticides, solvents, cleaning agents, fibers, cigarette smoke and molds resulting from human activities. Humans also create circumstances that enable the growth of millions of mold, fungi, pollen, spores, bacteria, viruses, and insects like roaches and dust mites. Pollutants such as carbon dioxide (CO_2), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and particulate matter (PM) are released into the indoor environments by combustion sources and cooking activities.

Humans also create circumstances that enable the growth of millions of mold, fungi, pollen, spores, bacteria, viruses, and insects like roaches and dust mites. Additionally, office supplies such as computers, printers, photocopiers, and other gadgets emit volatile organic compounds (VOCs) and ozone (O_3). Particle board, linoleum, parquet, rubber carpet, glue, lacquer, paint, polyvinyl chloride (PVC) floor covering, alkanes, aromatic compounds, 2-ethyl hexanol, acetophenone, alkylated aromatic compounds, styrene, toluene, glycols, and glycol esters, among others, are examples of common building materials that can release harmful gaseous substances (Linaker et al., 1996; Tran et al., 2020). Table 2.1 lists the indoor air pollution sources and the related health impacts.

Table 2.1 Indoor air pollutants, sources, and health impacts (Leung, 2015).

Type of indoor air pollutant	**Sources**	**Health impacts**
PM	Smoking; fireplaces; cooking stoves; outdoor air	Cardiovascular and respiratory diseases
SO_2	Fireplaces; cooking stoves; outdoor air	Deterioration of respiratory capacity
NO_x	Fireplaces; cooking stoves outdoor air	Reduced resistance to respiratory infections and irritate the lungs
CO	Fireplaces; water heaters; cooking stoves; outdoor air	highly lethal at a concentration of 700 ppm
CO_2	Smoking; fireplaces; cooking stoves; outdoor air	Irritant to the respiratory system detracts from attention
Ozone	High voltage air purifying apparatus; outdoor air	Causes for allergies and asthma
VOCs (such as terpenes and formaldehyde)	Paint and solvents, clothing that has been dry cleaned (which emits tetrachloroethylene or other dry cleaning chemicals), air fresheners, incense, and other scented goods, and some plants (which produce terpenes) are all examples of building materials that release formaldehyde.	Some can cause eye discomfort and are carcinogenic. They can also cause the production of photochemical oxidants including peroxyacetyl nitrates (PAN) and aldehydes.
Radon	Emitted from the ground and rocks like granite and gneiss in some places with poor ventilation and confined inside homes	The main factor causing lung cancer in non-smokers is radioactivity.

Biological air pollutants (airborne particulates and gasses)	Pets (dander), people (dust from tiny skin flakes and dead hair), dust mites (enzymes and m-sized feces), occupants (methane), and mold in the walls and air ducts	Heightened risk for those with weakened or underdeveloped immune systems, as well as those with breathing issues like asthma sufferers

2.2.1 Particulate Matters

According to the records of the World Health Organization, 800,000 premature deaths occur every year due to air pollution caused by particulate matter (PM). This is the thirteenth leading cause of mortality worldwide. However, numerous investigations show that the connection is deeper and more intricate than previously thought (Anderson et al., 2012).

PM can be obtained from both natural and artificial sources. Human-made sources of PM include combustion in mechanical and industrial processes, car emissions, and cigarette smoke. Volcanoes, fires, dust storms, and sea salt aerosol are examples of natural sources (Anderson et al., 2012).

Particulate matter (PM), a type of air pollution, is made up of carbonaceous particles with reactive metals and adsorbed organic molecules. PM typically contains metals like iron, copper, nickel, zinc, and vanadium as well as nitrates, sulfates, polycyclic aromatic hydrocarbons, endotoxins, and others (Hamanaka and Mutlu, 2018). According to particle size, PM is divided into (Hamanaka and Mutlu, 2018):

(a) Course (PM_{10}, diameter <10μm),

(b) Fine ($PM_{2.5}$, diameter <2.5μm), and

(c) Ultrafine ($PM_{0.1}$, diameter <0.1μm).

Larger particles are generally trapped in the upper respiratory tract and do not penetrate lower. Fossil fuel combustion produces fine and ultrafine particles, which are more hazardous to human health than coarse particles because they can go into the airways and alveoli. Even though the organic and metallic components contained in the particles vary by region, poor cardiovascular diseases are generally related to $PM_{2,5}$ (Hamanaka and Mutlu, 2018).

The two types of indoor PM sources are (i) outdoor particles that move indoors and (ii) indoor activity-related particles. The main sources of PM dispersal inside buildings are cooking, burning fossil fuels, smoking, operating machinery, and leisure activities. The ability of $PM_{0.1}$ to enter tiny airways and alveoli makes it a greater health danger than PM_{10} and $PM_{2.5}$ produced by burning fossil fuels (Van Tran et al., 2020; Miller et al., 2012).

According to studies on the concentration of major indoor pollutants, cooking, and smoking are the biggest sources of indoor particulate matter (PM) while cleaning activities often produce less indoor PM. The indoor $PM_{2.5}$ concentrations in smokers' houses are increased by an estimated 25 to 45 mg/m3, with wintertime concentrations being higher than midsummer concentrations (Ferro et al., 2004; Tran et al., 2020). Smoking is regarded as a significant contributor to indoor $PM_{2.5}$. The burning of food, wood, and oil while cooking has been proven to release millions of particles (106 particles/cm3), the majority of which are ultrafine particles. The occupants' health could also be harmed by these tiny particles if they enter not just the kitchen but also the living room and other parts of the building. The likelihood is that other common human activities like walking and sitting on furniture, which can resuspension household dust, account for about 25% of the interior PM concentrations. The values of $PM_{2.5}$ and PM_{10} induced by human activity varied from 0.03 to 0.5 mg/min and 0.1 to 1.4 mg/min, respectively (Ferro et al., 2004; Tran et al., 2020).

2.2.2 Sulfur Dioxide (SO_2)

Sulfur dioxide, also known as SO_2, is the sulfur oxide (SOx) that occurs most often in the environment. The primary source of SO_2 is the combustion of fossil fuels, which results in a complex mixture of aerosols and particulate matter. Among the sources of indoor SO_2 emissions include coal or wood stoves, oil furnaces, kerosene heaters, cigarette smoke, ventilated gas appliances, and oil furnaces. Additionally, it is thought that outside air is a substantial source of SO_2 in indoors. The levels of SO_2 in indoors are frequently lower than those outdoors. Interior surfaces quickly absorb reactivated SO_2, resulting in reduced indoor SO_2 emission. It is commonly known that the hourly SO_2 concentration in buildings is typically lower than 20 ppb. Only breathing exposes people to SO_2, which may harm their respiratory system (Tran et al., 2020).

The majority of sulfur released indoors originally exists as SO_2, but over time it transforms into molecules that include secondary sulfur, such as sulfate. Alterations in pulmonary function and respiratory symptoms are among the acute effects of SO_2 exposure, but chronic exposures at values of 20 g/m^3 have been associated with an increase in all-age mortality and pediatric respiratory illness. WHO established intermediate objective levels of 50 and 125 g/m3 and a 24-hour indoor cautious guideline threshold of 20 g/m^3 (Lam et al., 2012).

2.2.3 Nitrogen Oxides (NOx)

The two most common nitrogen oxides are nitric oxide (NO) and nitrogen dioxide (NO_2), and they are both produced by combustion devices like stoves and heaters. The ambient NO and NO_2 concentrations vary significantly depending on the sources and sinks in the area. However, when gas stoves and heaters are utilized, indoor concentrations frequently outperform outdoor ones. Because NO_2 is easily formed from NO under ambient conditions, it is frequently regarded as a major contaminant (Tran et al., 2020).

NO_2 is a reddish-brown gas that dissolves in water and has a strong, unpleasant smell. As an oxidizing agent, nitrogen dioxide can be particularly irritating to the lungs' mucous membranes. It is produced from the hot combustion of nitrogen and oxygen. It is very soluble in water, and the respiratory system eliminates a large portion of the NO_2 that is inhaled. It is thought to react with proteins and lipids to form nitrite anions and hydrogen ions in the lungs, where it mixes with water to form nitric acid (HNO_3). Using heterogeneous mechanisms involving water vapor, nitrogen dioxide in the airways is also converted to nitrous acid (HONO), a potent oxidant and common indoor pollution. HONO causes the production of free oxygen radicals and lipo-peroxidation. Although oxidative injury has been proposed as the main mechanism by which NO_2 damages the lung, there is still some uncertainty (Jones, 2002; Van Tran et al., 2020). Traffic constitutes an important source of atmospheric NO_2 emissions, especially in underdeveloped countries (Fu et al., 2001; Goyal et al., 2006)

As a result, high outdoor levels caused by combustion or surrounding traffic may have an effect on inside levels. It has been shown that indoor levels of NO_2 are a function of both external and indoor sources. The amount of NO_2 within buildings is thought to be significantly influenced by the distance between indoors and source and the roads. The flow of indoor and outdoor air has an impact on NO_2 levels inside buildings as well. Smoking and appliances that burn gas, wood, coal, oil, or kerosene, like ovens, stoves, water heaters, and fireplaces, are additional significant indoor sources (Kodama et al., 2002; Tran et al., 2020).

2.2.4 Carbon Monoxide (CO)

When not enough oxygen is present, incomplete combustion of organic matter produces the deadly, flavorless, odorless, colorless, and non-irritating gas known as carbon monoxide. In addition to being created indoors, CO is regarded as a non-reactive contaminant that can enter the external environment. Unvented kerosene and gas space heaters, chimney and furnace leaks, burning charcoal briquettes, and ambient tobacco smoke are the main indoor sources of carbon monoxide. Methylene chloride, a paint stripper, is also a source of the gas. It is converted by the reaction into carbon monoxide, and using it may result in considerable CO exposure even in well-ventilated spaces (Jones, 2002; Bernstein et al., 2008; Ridley, 2013; Van Tran et al., 2020). There are also studies showing that significant amounts of CO are emitted into the atmosphere from vehicles in traffic. It has been observed that motor vehicles constitute 90% of the atmospheric CO concentration in city centers (Hassan et al., 2000). Different mathematical models have been used to determine emissions of CO and other air pollutants from traffic in various countries (Ghose et al., 2004; Tippichai et al., 2005; Akinyemi et al., 2018; Azeez et al., 2019; Angatha and Mehar, 2020). Almost all of these models have prioritized CO.

A building without gas stoves typically has a carbon monoxide concentration of between 0.5 and 5 ppm, while the concentration in close proximity to a gas stove may be as high as 30 ppm. Exposure to CO can damage the cardiovascular system and neurobehavioral system at low concentrations, but at greater levels, it may result in unconsciousness or even death(Tran et al., 2020).

The primary reason for CO's toxicity is its high affinity for oxygen-carrying proteins like hemoglobin and myoglobin. Carbon monoxide displaces oxygen from hemoglobin because it has an affinity for hemoglobin that is around 200 times greater than that of oxygen. This results in carboxy-hemoglobin (COHb), which reduces the blood's ability to carry oxygen, and a left shift in the oxyhemoglobin dissociation curve (Jones, 2002).

According to general descriptions, COHb is the main health consequence of carbon monoxide and can cause headaches, nausea, dizziness, shortness of breath, tiredness, and in severe situations, coma, and death. The concentration, time spent exposed, and general health of the exposed person all affect how severe CO poisoning is. Long-term exposure to low concentrations of carboxy-hemoglobin may have considerable negative health effects due to the cumulative nature of these concentrations in blood. The three primary indoor gaseous pollutants NO_2, SO_2, and O_3 were not as effective at predicting congestive heart failure hospitalization in older people as CO (Burnett et al., 1997; Bernstein et al., 2008).

2.2.5 Carbon Dioxide (CO_2)

Humans continuously exhale CO_2, which is produced in the body during the metabolic process and is odorless, A renowned component of the atmosphere of the planet is a colorless gas. There are three main sources of carbon dioxide inside buildings: the background level of CO_2 in the outside air, CO_2 produced by human respiration inside the structure, and CO_2 produced by combustion inside space. Recently, a reference for assessing IAQ and managing ventilation has been the indoor CO_2 level (Offermann and Sextro, 1991; Jones, 2002; Tran et al., 2020).

When aiming to lower indoor CO_2 levels, source exclusion or removal should be your first consideration. The next step is to edit the source code if doing so is not practical. However, when it comes to carbon dioxide, source modification has a whole new meaning. The sole change to the building-combustion-device system that might cut carbon dioxide emissions does so by improving the building shell's thermal efficiency and, as a result, lowering the amount of fuel required to maintain the same degree of thermal comfort inside the space. Although this holds for all combustion-generated pollutants taken into account, it is the only change that will have an impact on CO_2 emissions from unvented combustion in space (Offermann and Sextro, 1991).

When using unvented appliances, indoor CO_2 concentrations can surpass 3000 ppm (5486 mg/m3) and typically vary between 700 and 2000 ppm (about 3657 mg/m3). Indoor CO_2 concentrations are advised to be fewer than 700 ppm by ASHRAE regulations to protect human health. Additionally, exposure to 3000 ppm of CO_2 in the air has been shown to intensify headaches, cause tiredness and weariness, and make it harder to concentrate (Jones, 2002; Van Tran et al., 2020).

2.2.6 Ozone (O_3)

Ozone is a strong oxidizer that is largely created by O_2, NOx, and VOC via photochemical reactions. Due to its delayed response to the bulk of airborne contaminants, it cannot be used to remove other indoor chemical pollutants. Ozone promotes quick chemical reactions with several indoor pollutants, but the byproducts of these reactions may irritate people and harm property. The functioning of electrical devices and the outside environment are the main contributors to indoor ozone. The most common indoor ozone emission technologies include laser printers, photocopiers, and room air purifiers. In research, According to the air rate of exchange, the interior ozone concentration varied from 20% to 80% of the outdoor ozone concentration (Van Tran et al., 2020; Rosário Filho et al., 2021).

Indoor ozone levels have been demonstrated to be influenced by several factors, comprising (i) the amount of ozone outdoors, (ii) the rate of indoor emissions, (iii) the rate of air exchange, (iv) the rate of surface removal, and (v) the relationships between ozone and other chemicals that enter the air (Weschler, 2000; Tran et al., 2020).

O_3 exposure may worsen asthma, aggravate lung problems, irritate the eyes and nose, reduce resistance to colds and other infections, and hasten the aging of lung tissue. A crucial point is that O_3 may encourage chemical interactions between the chemical species that are already there, resulting in secondary pollutants that could pose a greater health risk than primary pollutants (Zhang and Smith, 2003).

Rapid population growth, urbanization and industrial structuring play an important role in the intense spread of air pollutants into the atmosphere that can harm people and other living things and goods. The penetration of these air pollutants encountered in the ambient atmosphere into closed indoor environments and the air pollutant sources in indoor environments cause indoor air pollution as much as the outdoor environment, or even more (Davidson et al., 1986).

2.2.7 Volatile Organic Compounds (VOCs)

An organic compound is any chemical that has at least one carbon and one hydrogen atom in its molecular structure. Other categories of organic chemicals include very volatile organic compounds (VVOCs), volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and non-volatile organic compounds (NVOCs). Volatile organic compounds have boiling points that range from 50 oC to 260 oC. Because of their low boiling points, they quickly release vapors into the indoor environment. They are commonly employed in construction projects because the materials they are contained in have the necessary qualities of great insulation, economy, fire resistance, and ease of installation. Table 3.2 provides a list of some of the most typical construction sources and the VOCs they produce (Jones, 2002; Van Tran et al., 2020).

Generally, human activity including cooking, smoking, and the use of cleaning and personal care products, as well as interior chemical reactions, outdoor air infiltration through ventilation systems, indoor chemical reactions, and building materials are the four main causes of indoor VOC creation. Air exchange rates, housing age and size, building maintenance, external VOC levels, and door and window openings can all have an impact on the amount of volatile organic compounds

(VOCs)(Tran et al., 2020).

Formaldehyde is an odorless gas and one of the most prevalent volatile organic compounds (VOCs). It is released by a number of building supplies, including glues, particleboard, and plywood. In comparison to commercial buildings, residential buildings have higher formaldehyde concentrations because of the comparatively high number of pressed wood products in the air. Regardless matter where the building is, at least ten times more VOCs are present indoors than outside (Bernstein et al., 2008; Tran et al., 2020).

Inhalation, ingestion, and skin contact are typically the three main ways that VOCs enter to the body of a person who exposed to. Exposure to low levels of volatile organic compounds (VOCs) for a brief period of time generally has no negative effects on most people, but prolonged exposure to specific VOCs is thought to be harmful to human health and may even lead to cancer. Regarding SVOCs, direct transdermal absorption from the air has a more significant effect than inhalation (Tran et al., 2020).

Table 2.2 Lists the sources of VOCs (Bernstein et al., 2008).

Source	VOCs	Source	VOCs
Adhesives/ sealants	Propylene glycol, butyl ether, vinyl cyclohexane, 2-propenoic acid, and formaldehyde	**Paints**	Butyl propionate, methyl propanol, propylene glycol, ethylene glycol, and toluene
Carpet	Styrene, vinyl acetate, dodecanol, acetaldehyde, and 4-phenylcyclohexene	**Printers/copiers**	Styrene, 2-ethyl-1-hexanol, benzene, xylenes, and ethylbenzene
Cleaning chemicals	Butoxyethanol, 1,4-dichlorobenzene,	**Resilient/rubber flooring**	Vinyl acetate, cyclohexane, dodecane,

	isopentane, isopropane, and limonene		benzothiazole, and styrene
Linoleum	Hexanal, hexanoic acid, pentanoic acid, decane, and acetic acid	**Textiles**	Acetaldehyde, formaldehyde, acrylonitrile, decane, and tetradecane
Millwork	Benzaldehyde, formaldehyde, 2-pentyl furan, hexanal, and pentanal	**Wall covering**	Styrene, phenol, ethyl hexanoic acid, naphthalene, and methyl pyrrolidinone
Office furniture	Hexanal, acetaldehyde, butylacetate, formaldehyde, and cyclohexanone	**Window shades**	Naphthalene, decanol, dodecane, ethyl hexanol, and ethyl hexanoic acid
Building occupants	Tetrachloroethylene from dry-cleaned clothing, benzene from tobacco smoke (ETS) and attached garages, limonene (a terpene), different siloxane compounds, like decamethylcyclopentasiloxane, from personal care products like antiperspirants and deodorants, C12 to C16 alkanes from hand and body lotion, moisturizing soaps, and cosmetics.		

2.2.8 Radon

In granite locations, soil and rocks naturally produce radon, a radioactive gas. It causes issues in many homes built with rocky building materials or basements with inadequate ventilation because it is colorless, odorless, carcinogenic, and the second leading cause of lung cancer in many nations. Through structural cracks, radon can enter a building from the soil around the foundation. It can also enter through spring or well water, concrete, or other earth-derived building components (Offermann and Sextro, 1991). The primary indoor radon sources are drinking water, soil gas, and building materials. Small amounts of radium are found in soil, therefore it seems sensible that one of the gases filling those pores would be radon. Any materials with traces of radium have the potential to release radon when it comes to building materials. Since masonry materials like stone, concrete, and brick are utilized in such large quantities during the building process, they are the primary sources of indoor radon emission. If you use water from underground sources that contain granite or another type of rock rich in radium, radon may be released from the water itself; radon levels in these sources frequently exceed 10,000 pCi/L. Last but not least, radon can potentially enter a building from the outside air. The main source of radon exposure for people within buildings is the soil gas that is absorbed. Depending on the average radon level, epidemiological studies have revealed that indoor radon may raise the risk of lung cancer by three to fourteen percent (Tran et al., 2020).

These indoor air pollutants increase the risk for those with compromised immune systems and respiratory conditions, such as asthmatic patients. Isotopes that are discharged into the air as a result of radioactivity may cause cancer. Although radon gas doesn't cause much harm on its own (it may be blocked by relatively thin materials), the radioactively generated isotopes can cause cancer. To avoid the seepage of radon into structures in areas with high radon concentrations, additional precautions must be taken (Leung, 2015; Foundation, 2021).

2.2.9 Aerosols

While secondary aerosols are created by gas-to-particle interactions, primary aerosols come from a variety of indoor sources. Additionally, indoor aerosols are probably a result of outside particles that enter the indoor atmosphere. When volatile organic molecules are converted from gas to particle, secondary organic aerosols (SOAs) are created, whereas secondary inorganic aerosols (SIAs) are composed of inorganic components, such as anthropogenic or crustal origins and water-soluble ions. Additionally, carbonaceous aerosols, which are well-known $PM_{2.5}$ ingredients and are made up of SOAs and elemental carbon from incomplete combustion, are another type of aerosol. Microorganisms (bacteria and archaea), cellular components, and dispersion units (such as plant pollen and fungal spores) are all examples of biological aerosols. Aerosols can be thought of as dynamic systems due to the variety of their parts and phases (gas, liquid, or solid). This means that the nucleation mode (30 nm in vacuum cleaning settings), the accumulation mode (100 nm for indoor combustion aerosols from smoking, cooking, or incense burning), the fine and coarse modes (>1 m for resuspension aerosols), and the modes in between are all included in the range of their particle size distribution. The lungs (the entry to the human body) and other important target organs including the heart and brain have been associated to various adverse health impacts, in particular when aerosols are inhaled in confined spaces (Koivisto et al., 2019; Tran et al., 2020).

2.2.10 Heavy Metals

Both human activity and natural processes contribute to the atmospheric emission of heavy metals. Smoking, fuel-consuming products, construction materials, and outdoor pollutants (dust and dirt) are just a few of the things that might cause indoor air pollution from heavy metals. Metals in indoor dust that are ingested, inhaled, or touched by the skin by a person may have harmful health effects. IARC, an international organization dedicated to cancer research, there are two primary categories of heavy metals in indoor air based on how they affect people: Aluminum (Al), copper (Cu), nickel (Ni), iron (Fe), zinc (Zn), and cobalt (Co) are examples of non-carcinogenic elements. Other examples of heavy metals such as arsenic (As), chromium (Cr), and cadmium (Cd), as well as lead (Pb), are carcinogenic or are likely to result in cancer, whereas Cd, Pb, and a few others may have carcinogenic side consequences including cardiovascular disease, decreased expansion and harm to the nerves. The maximum values of As, Al, Cr, Cd, Co, Cu, Ni, Fe, and Zn are about 486.80, 7150.00, 254.00, 8.48, 43.40, 513.00, 471.00, 4801.00, and 2293.56 g/g, respectively, whereas Pb levels in indoor air have been observed to range between 5.80 and 639.10 g/g (Tran et al., 2020).

2.2.11 Pesticides

Inorganic and organic insecticides are frequently applied as surface coatings or impregnations to preserve wood construction components today. Pesticides are used to get rid of pests including controlling and preventing them, as well as things like insects, fungi, rodents, bacteria, and other animals. Insecticides are frequently semivolatile substances that can occur as gases or particles depending on factors including viscosity of the product, vapor pressure, and water solubility in the interior environment. Additionally, it has been hypothesized that fabrics and carpeting could act as lingering organochlorine pesticide reservoirs. It is hypothesized that polyurethane foam pads are pesticides in the fibers used in carpets, clothing, and padded furniture would move into them. As a result, carpets, textiles, and cushioned furniture may represent an integrated pesticide exposure throughout their lifespan. Additionally, pollutants may enter homes through the exterior. Since they are shielded from the sun, chilly temperatures, precipitation, and other environmental factors once inside, they may live for months or even years. Pesticide-containing particles or volatile chemicals can be exposed indoors by inhalation, ingestion, or skin absorption. Pesticide exposure is linked to negative health impacts, short-term negative effects, such itchy skin and eyes, nausea, headaches, and dizziness; and long-term negative effects, like cancer, asthma, and diabetes (Tran et al., 2020).

2.3 Factors Affecting the Quality of Indoor Air

The range of indoor air quality variations and their potential influences are extensive.

2.3.1 Outdoor Air Pollution

Through leakage, diffusion, and natural or artificial ventilation, air contaminants in the outside ambient air can enter indoor areas. The type of pollutant will determine the nature and extent of penetration; for example, particles are partially removed during penetration while carbon monoxide, an unreactive gas, penetrates readily (Stern, 1977).

2.3.2 Indoor Generation of Pollutants

Indoor pollutants are produced by a variety of activities, including moving about a lot and stirring up particulates, cooking, cleaning, smoking, painting, applying cosmetics, and more. According to leakage into the building, leakage out of the building of the same pollutant that is present in the outdoor space, and pollutant removal processes like absorption and adsorption on interior surfaces as well as atmospheric reactions, pollutants generated inside a building will diffuse throughout the enclosed space and accumulate to equilibrium concentrations (Stern, 1977).

2.3.3 Building Permeability

Building permeability, which allows for both the entry and existence of indoor and external contaminants, has a significant impact on the quality of indoor air. The number of windows and doors as well as how tightly the building is constructed are the primary considerations (Stern, 1977).

2.3.4 Ventilation and Air Conditioning System

An efficient ventilation system can significantly improve the indoor air quality inside a structure. In contrast to one that circulates interior air, one that provides outside ventilation will result in concentrations indoors that are comparable to those found outdoors. Use an air conditioning system that includes filtration, humidification or dehumidification, air washing, and activated carbon adsorption to lower the concentration of particles and reactive gaseous pollutants indoors (Stern, 1977).

2.3.5 Meteorological and Geographic Factors

Indoor air quality is impacted by a variety of variables, including the weather.

• The state of the weather in a particular area affects the quality of the outside air. For instance, temperature inversions might lead to higher concentrations outside. In these situations, external air entering the building will cause a drop in indoor air quality (Stern, 1977).

• The tenacity of outside contaminants' penetration can be predicted by indoor-outdoor temperature connections. In cold weather, a heated structure experiences a considerable stack effect, which causes a significant pressure differential between the interior and exterior. This phenomenon frequently causes the building's lower levels to pull in outside air and its upper levels to exhaust it (Stern, 1977).

• Wind may create pressure differences between interior and outdoor spaces, which may enhance the likelihood that indoor air pollutants may diffuse more quickly or that outdoor pollutants will enter structures (Stern, 1977).

2.3.6 Location Concerning Outdoor Sources

Inorganic Depending on where the building is located, the general ambient outdoor concentrations as well as nearby sources, whose effects on the generalized ambient air may not be well understood, could have a significant impact on the building's indoor air quality. An example of this would be the recirculation of combustion products from the building's heating system (Stern, 1977).

2.3.7 Energy Conservation Measures

Indoor air quality may be impacted by a variety of energy-saving measures.

• Tight construction and thick insulation may keep outside pollutants out, but they also let inside contaminants like carbon dioxide and moisture from human activity build-up (Stern, 1977).

• Maximum recirculation of heated or cooled air will reduce the impact of outdoor air quality and enhance the impact of indoor contaminants in the winter and summer (Stern, 1977).

• Making use of outside ventilation Replacement of recirculated heated or conditioned air with outdoor air will result in indoor air quality that is comparable to that of the outdoors when outside temperatures and humidity levels allow (Stern, 1977).

2.4 Health effects

Because of the people spent more time in indoor environments they face more pollutants in their daily time. Such pollutants cause some health problems, such as building-associated illness, upper and lower respiratory problems, school absenteeism, asthma etc. for people.

The World Health Organization estimates that 3 billion people still use dirty solid fuels (such as waste wood, charcoal, coal, dung, and crop waste) to cook and heat their homes on open fireplaces, cooking stoves, or kangas, which produces a lot of air pollutants (like SO2, CO, NOx, and PM) into the atmosphere (Leung, 2015).

The three main categories of indoor air pollution sources are organic air pollutants, inorganic air pollutants, and airborne particulate matter.

2.4.1 Building-Associated Illness

The relationship between poor indoor air quality (IAQ) and a variety of symptoms and diseases has gained more attention in recent years. While often present at low levels, inorganic, organic, physical, and biological pollutants are common and persistent in buildings and homes. As a result, the negative effects of indoor air pollution (IAP) on human health have drawn considerable interest and concern. Building-associated illnesses are any illnesses brought on by indoor environmental variables, which are typically divided into two groups by the World Health Organization (WHO): Building-related illnesses (BRI) and the sick building syndrome (SBS) (Gopalakrishnan et al., 2021).

Table 2.3 The common symptoms of the sick-building syndrome (SBS) and building-related illness (BRI) (Gopalakrishnan et al., 2021).

Sick Buiding Syndrome (SBS)

- Mucous membrane ittitation: eye, nose, and throat irritation.
- Neurotoxic effects: headaches, mental fatigue, reduced memory, nausea, tiredness, dizziness, and irritability.
- Asthma and ashtma-ike sysmtoms: cest tightness, and wheezing
- Skindryness and irritation, gastrointestinal complaints, and others.

Building Related Illness (BRI)

- Flue: fever, chills, cest tightness, muscale aches and cough.
- Legionnaires disease, hypersensitivity pneumonitis, humidifier, fever.

- Lung and respiratory problems.

2.4.2 Acute Respiratory Infection

Due to the fact that pollutants frequently enter the body through breathing, IAP primarily affects the respiratory system. Acute respiratory infections can be classified as upper respiratory infections (URIs) or acute lower respiratory infections (ALRIs) depending on which portion of the respiratory tract is affected (Simkovich et al., 2019), illnesses that primarily affect the upper respiratory tract are known as upper respiratory infections (URIs). Cough, sinusitis, and otitis media are among the symptoms that these illnesses frequently exhibit. The majority of the time, biological contaminants including viruses, bacteria, fungi, fungal spores, and mites are to blame for URIs, which are often moderate in nature, acute lower respiratory infections (ALRIs), on the other hand, are illnesses that are particularly directed at the lungs and are usually brought on by viruses or bacteria (Simkovich et al., 2019). Lung inflammation results from these infections. According to studies, indoor air pollution (IAP) significantly raises children's risk of developing ALRI by 78%. The tragic fact that one million children under the age of five die each year is a result of this increased danger. Children's relatively larger lungs, which make them more vulnerable to the negative effects of IAP, may be one explanation for this. Additionally, studies have shown that children who reside in structures that burn solid fuels have an ALRI risk that is 2-3 times greater than children who reside in homes that burn clean fuels (Kim et al., 2011), both the respiratory tract's particular and general defense mechanisms, which are crucial for warding off pathogens, are adversely affected by indoor air pollution (IAP). IAP also increases the risk of chronic bronchitis among moms who cook by making respiratory infections worse and making them more severe (Smith et al., 2000).

2.4.3 Pulmonary Diseases

Asthma, atopic dermatitis, and allergic rhinitis are just a few of the pulmonary and allergy disorders that can be brought on by breathing in air pollutants. Additionally, smoking is known to play a substantial role in the emergence of chronic inflammatory pulmonary disorders, such as lung cancer, asthma, and chronic obstructive pulmonary disease (COPD). Exposure to indoor air pollution (IAP) can have a major negative impact on achieving adequate lung function and eventually cause a reduction in lung function. Even before birth, harmful particles including particulate matter (PM) and carbon monoxide (CO) have the potential to have an impact on lung development (Kirkby et al., 2016).

Toxic particulate matter (PM) or indoor air pollution frequently cause COPD (chronic obstructive pulmonary disease), which is characterized by an intensified and persistent inflammatory reaction in the airways and lungs. According to research, women, especially those who live in undeveloped countries, are significantly more likely to get COPD as a result of being exposed to smoke from domestic cooking (Smith-Sivertsen et al., 2009). Fossil fuel burning produces particulate matter (PM), which can cause lung inflammation and drastically reduce pulmonary function. According to studies, domestic fuel smoke can result in COPD, which has clinical symptoms and mortality rates similar to those seen in tobacco smokers (Regalado et al., 2006). Fuel combustion results in chemical molecules with high oxidative potential, which leads to oxidative stress and DNA damage. These actions are thought to be the main mechanisms underlying the onset of COPD. In addition to these chemical factors, biological factors including allergens, viruses, and bacteria can also cause strong inflammatory reactions that result in chronic inflammation and immunological dysfunction, which eventually contributes to the development of COPD (Kim et al., 2007).

2.4.4 Cardiovascular Diseases (CVDs)

When solid fuels are used in homes, a number of pollutants are released that have been linked to cardiovascular illnesses (CVDs). These contaminants include carbon monoxide (CO), heavy metals, organic compounds, particulate matter (PM), and polycyclic aromatic hydrocarbons (PAHs) (Uzoigwe et al., 2013), The risk of some acute CVDs, including ischemic stroke, myocardial infarction, cardiac arrhythmia, heart failure, and atrial fibrillation, has been observed to increase with $PM_{2.5}$ exposure. According to reports, PM increases blood coagulability, causes systemic inflammation, causes oxidative stress, throws off the autonomic and vascular balance, and results in CVDs (Peters et al., 2000), A significant increase in fibrinogen levels, platelet activation, plasma viscosity, and the release of endothelins, potent vasoconstrictor molecules, are all caused by particulate matter (PM). Additionally, carbon monoxide (CO), which is abundant in indoor air, can have a major impact on cardiovascular function by influencing tissue oxygenation by producing car oxyhemoglobin (Peters et al., 2000),In addition, using cooking fuels exposes people to lead (Pb) and polycyclic aromatic hydrocarbons (PAH), which can cause oxidative damage, stimulate the renin-angiotensin system, and downregulate nitric oxide. These pathways may result in elevated peripheral vascular resistance and vascular tone, which may have further effects on cardiovascular health (Pan et al., 2008).

2.4.5 Asthma

Occupational or environmental asthma is a chronic respiratory condition that affects a significant portion of the population. This condition shares many similarities with classic asthma, primarily characterized by airway inflammation leading to breathing difficulties. However, what sets it apart is its intricate interplay with both genetic and environmental factors, particularly exposure to indoor air pollutants, which can act as potent triggers and exacerbate the symptoms of this condition (Athanazio, 2012).

Indoor air quality (IAQ) plays a pivotal role in the health of individuals, especially those with occupational or environmental asthma. Poor indoor air quality can significantly impact the frequency and severity of asthma symptoms, making it crucial to address this issue comprehensively (Krieger et al., 2002).

Indoor spaces can harbor a multitude of allergens and irritants capable of aggravating asthma symptoms. Common indoor allergens include dust mites, mold spores, pet dander, and cockroach droppings. These allergens are notorious for triggering asthma attacks, making it essential to implement effective measures for allergen control. Proper ventilation, regular cleaning routines, and the use of allergen-proof covers for bedding and mattresses are key strategies in mitigating these triggers (Ribeiro and Tarlo, 2012).

Furthermore, indoor environments often contain potentially harmful chemicals present in cleaning products, paints, and volatile organic compounds (VOCs) emitted from furniture and building materials. Prolonged exposure to these substances can irritate the airways and worsen asthma symptoms. Choosing low-VOC or VOC-free products and ensuring adequate ventilation are critical steps toward maintaining better indoor air quality (Ogbodo et al., 2022).

Indoor air can also become contaminated by outdoor pollutants such as particulate matter and ozone, which infiltrate indoor spaces and exacerbate respiratory diseases. Employing air purifiers with HEPA filters and sealing gaps in windows and doors can significantly reduce the infiltration of outside pollutants, creating a safer indoor environment for individuals with asthma (Rawat and Kumar, 2023).

Proper humidity levels within indoor spaces play a crucial role in managing asthma effectively. Excessively dry air can trigger symptoms, leading to discomfort and exacerbation of the condition. Conversely, high humidity can promote the growth of mold and dust mites, which are known asthma triggers. To strike the right balance, the use of humidifiers and dehumidifiers can help maintain an ideal indoor humidity range, typically between 30% and 50% (Kubba, 2016).

Exposure to secondhand smoke is a well-established trigger for asthma. Even brief exposure to tobacco smoke can lead to severe symptoms in individuals with asthma. Therefore, it is imperative to create and maintain smoke-free indoor environments, especially in homes and public spaces. Implementing strict no-smoking policies and providing designated smoking areas outdoors can help protect individuals with asthma from the harmful effects of secondhand smoke (Li et al., 2021).

In conclusion, occupational or environmental asthma is a complex condition influenced by both genetic and environmental factors, particularly indoor air quality. To manage this condition effectively, it is crucial to implement a comprehensive approach that includes allergen control, the use of low-VOC products, proper ventilation, the reduction of outdoor pollutants, humidity regulation, and the creation of smoke-free indoor environments. By addressing these factors, individuals with occupational or environmental asthma can better control their symptoms and improve their overall quality of life (Breysse et al., 2010).

2.5 Ventilation

Ventilation is described as "the process by which 'clean' air (usually outdoor air) is intentionally supplied to a place and stale air is removed" or "the supply of fresh outdoor air to a place for convective cooling of space, convection cooling and evaporation of people, and reduce the concentrations of unwanted pollutants that may be released as a result of occupation and use (ASHRAE, 1997; Liddament and Orme, 1998).

The deliberate entry of outside air into a structure is another definition of ventilation. Infiltration was not considered in the context of this study since it involves unintended openings, many of which cannot be regulated even though they can alter the effectiveness of interior airflow (ASHRAE, 1997; Liddament and Orme, 1998).

2.5.1 Ventilation Purposes

According to Givoni (1976), ventilation is meant to serve three purposes: giving building occupants comfortable temperatures indoors, cooling the structure of the building, and providing good indoor air quality. According to Awbi (1991), "A ventilation system's goal is to provide a suitable microclimate in the space being vented (1998). Allard Microclimate here refers to both the air quality and the heat environment."Ventilation is crucial for maintaining good interior air quality and giving building occupants comfortable temperatures. The ventilation functions for health (indoor air quality) and thermal comfort were divided into two categories by Van Straaten (1967). However, the topic of thermal comfort also covers the structure's heating and/or cooling. Indoor air quality and thermal comfort were similarly divided into two categories for this study's ventilation functions in buildings (Van Straaten, 1967; Gıvonı, 1976; Awbı, 1991; Gıvonı, 1998; Allard, 1998).

To provide building occupants with a healthy interior environment, ventilation for indoor air quality is crucial in all types of weather. Ventilation can enhance the quality of interior air by exchanging stale indoors with outdoor fresh air. Ventilation has an impact on thermal comfort in two different ways: by promoting sweat evaporation at the skin's surface (preventing discomfort from skin moisture), and by exchanging body heat through convection (giving a better thermal sensation) (Givoni, 1976).

To make sure that both ventilation roles are met, it is crucial to consider ventilation while designing a building. Important ventilation features include ventilation performance specifications including ventilation rate, air velocity, and ventilation distribution.

2.5.2 Mechanical Ventilation

Mechanical ventilation in buildings is a critical system designed to provide a controlled flow of fresh air while simultaneously removing stale air and contaminants. This technology plays a pivotal role in maintaining indoor air quality, ensuring occupant comfort, promoting energy efficiency (Sha and Qi, 2020), and even addressing broader sustainability concerns. In this extensive exploration, we delve deep into the world of mechanical ventilation, tracing its historical evolution, dissecting its key components, exploring its multifaceted benefits, and delving into its adaptation to emerging needs and challenges. In doing so, we aim to underscore its indispensable role in modern construction and the creation of healthier, more comfortable, and environmentally responsible indoor environments (Cooper et al., 2000).

Mechanical ventilation's roots can be traced back to ancient civilizations, where ingenious methods were used to channel fresh air into underground tunnels and homes. The Romans employed aqueducts and wind catchers, while ancient Chinese architecture incorporated "wind towers" for effective air circulation.

The Industrial Revolution marked a turning point as rapid urbanization led to densely populated cities with cramped living spaces and inadequate ventilation. This gave rise to health concerns and respiratory diseases, highlighting the importance of effective mechanical ventilation (He et al., 2022).

The 20th century witnessed significant advancements in mechanical ventilation technology, including electric fans, air conditioning systems, and advanced HVAC systems. These innovations revolutionized building design and construction, setting the stage for the development of modern ventilation systems (Narozny and Stevenson, 2015).

Key Components of Mechanical Ventilation Systems: Ventilation fans are the workhorses of mechanical ventilation systems. Exhaust fans expel stale air from areas like kitchens and bathrooms, while supply fans bring in fresh outdoor air. These fans are vital for circulating air throughout the building. Ductwork serves as the conduits for air distribution. It transports fresh outdoor air from the ventilation system to various rooms and expels indoor air outside after filtration (Alianto et al., 2022). Properly designed ductwork ensures even distribution of fresh air throughout the building. Filters are essential components of mechanical ventilation systems. They remove dust, allergens, and pollutants from incoming air, enhancing indoor air quality by ensuring that the air circulated within the building is clean and free from contaminants. Heat Recovery or Energy Recovery Ventilators (HRV/ERV): HRV and ERV systems contribute significantly to energy efficiency. They recover heat or energy from the outgoing air, pre-conditioning the incoming air and reducing energy consumption for heating or cooling. Advanced control systems enable precise regulation of airflow. These controls allow for adjustments based on occupancy levels, outdoor weather conditions, and specific requirements, ensuring that the ventilation system operates efficiently and effectively (Persily, 2006).

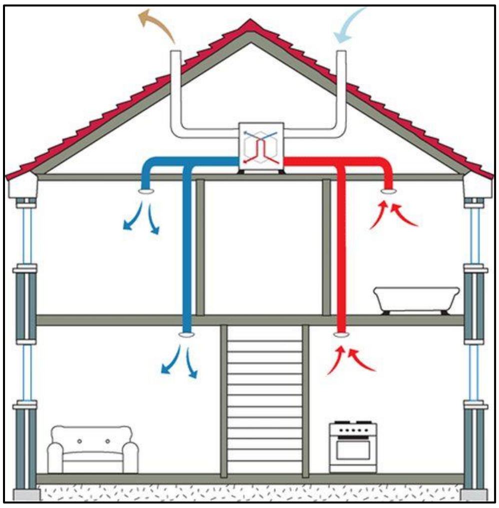

Figure 2.1 Mechanical ventilation system.

2.5.3 Natural Ventilation

Dynamic and static pressure differences are the main elements behind natural ventilation. As a result, greater pressure differences lead to greater ventilation rates. While the static pressure difference, also known as buoyancy or stack effect is caused by the temperature gradient, the dynamic pressure differential is caused by the incident wind. Additionally, a mix of static and dynamic pressure differences can be used to power natural ventilation (Institution, 1991).

Positive pressure is produced when the wind strikes a building's surface, while negative pressure is produced on the other side that is leeward and the side walls (Figure 2.1). As a result, the presence of apertures at outside walls allows outdoor air to pass through internal areas and into the negative pressure zone (Hunt and Linden, 1999). A bigger pressure differential causes a higher rate of airflow inside. The pressure distribution on the building frontispiece is influenced by factors including the design of the building, wind speed, wind direction, and surrounding environments (Hunt and Linden, 1999).

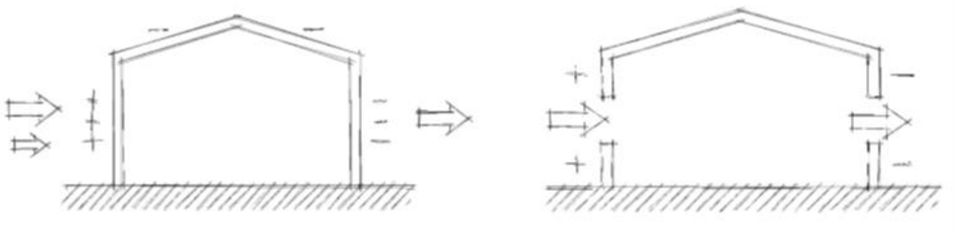

Figure 2.2 Due to wind force, there are areas of positive and negative pressure.

Due to buoyant forces brought on by temperature variations, air is pushed from high-density areas with low temperatures to low-density areas with high temperatures. Mixing ventilation and displacement ventilation are the two basic categories of buoyancy-driven ventilation (Linden et al., 1990). One opening that serves as both a supply and an exhaust is typically used in mixing ventilation, with heated air exiting from the upper section of the entrance and cool air entering the enclosure from the lower. However, The displacement ventilation method makes use of two holes that are separated by allowing cool air to enter through the lower opening and heated air to exit through the top opening, which usually faces the high ceiling (Cooper and Linden, 1996)(Figure 2.3).

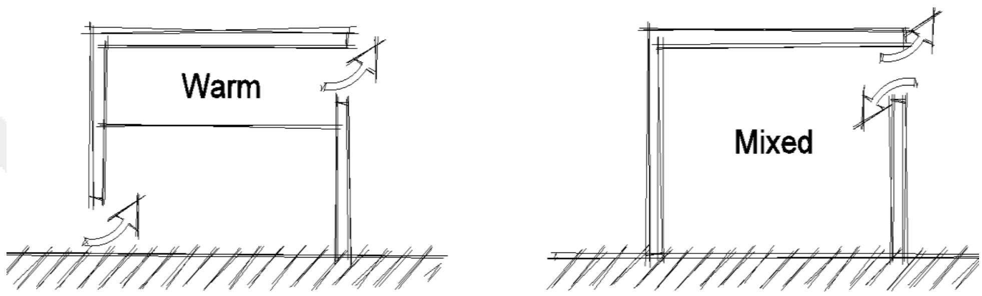

Figure 2.3 Displacement ventilation (left) and mixing ventilation (right) are examples of buoyancy-driven ventilation.

Additionally, a wind force and stack effect combination may be used to produce natural ventilation. Depending on the placement of the apertures and the direction of the incident wind, these forces may balance or augment one another (Hunt and Linden, 1999). The stack effect and buoyancy forces are produced in a room with openings at various heights by changes in indoor and outside temperature. The pressure difference caused by wind forces, as shown in Figure 2.3, incident wind direction, either be support (Figure 2.3-left) or counteract (Figure 2.3-right) the forces of buoyancy.

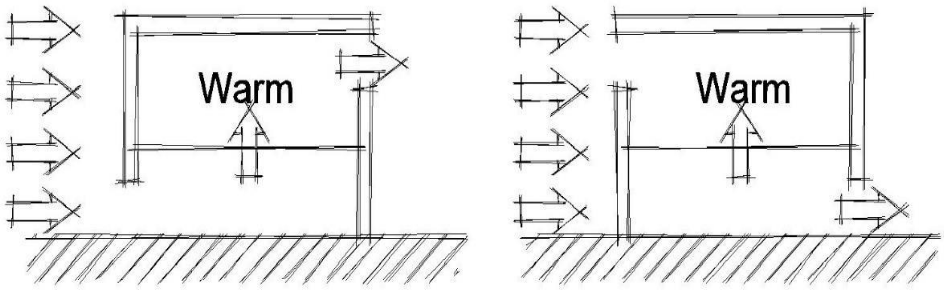

Figure 2.4 Combining the effects of wind and buoyancy when they interact (on the left) and when they conflict (on the right).

Although stack ventilation has the advantage of still being able to move air through space even in the absence of wind, wind-driven ventilation is far more effective (Wang and Malkawi, 2019).

2.5.4 Natural Ventilation Modes

The success of a natural ventilation system depends on the building's features, natural forces, air tightness, and occupant behavior (Chartier and Silva, 2009).

One of the factors associated with design that affects natural ventilation is the ventilation mode (Fung and Lee, 2015). Based on the ventilation mechanism and aperture placements, the natural ventilation mode can be identified. Therefore, there are three basic types of natural ventilation:

- Single-Sided Ventilation
- Cross-Flow Ventilation
- Stack ventilation

As shown in Figure 2.4, when air enters and leaves a space from the same side through one or more apertures, this is known as single-sided ventilation (Awbi, 1994; Linden, 1999). Single-sided ventilation systems that supply and exhaust air from the same side of the enclosure run the risk of not distributing it evenly throughout the space.

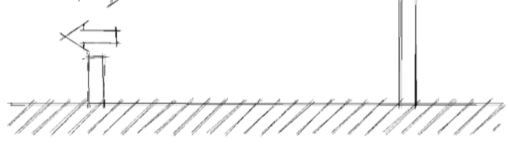

Figure 2.5 Single-sided ventilation.

Wind forces, buoyancy forces, or a combination of both can propel single-sided ventilation. There is a temperature difference between the inside and the outside when wind speed is low (up to 2 m/s), and buoyancy forces are dominant. Higher wind speeds, however, favor wind forces and scarcely register buoyant forces (Allocca et al., 2003).The result of the mean and pulsing components of the wind in the case of wind-driven single-sided ventilation is the overall flow rate, with mean flow serving as the primary driver of airflow in large apertures and pulsating flow predominating for small openings (Zhou et al., 2017).

When two or more apertures are erected on opposing walls, cross-flow ventilation occurs (Figure 2.5), where air enters through the windward side's aperture (inlet) and leaves through the opposite side's opening (outlet) (Ohba and Lun, 2010). Wind speed and the resulting pressure distribution around apertures have a significant impact on cross-ventilation (Awbi, 1994; Visagavel and Srinivasan, 2009; Fung and Lee, 2015). It has been demonstrated that cross-ventilation is substantially more efficient than single-sided ventilation. Because the pressure difference between the intake and output is higher.

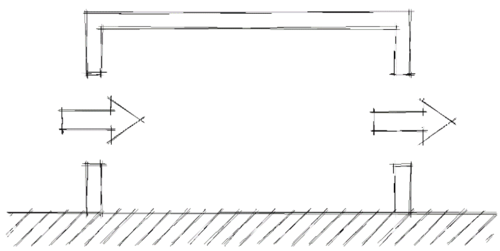

Figure 2.6 Cross ventilation.

Stack ventilation happens when there is a height difference between the input and exit (Figure 2.6-left), which causes hot air to climb and escape through the higher opening before being replaced by cold air entering from the lower opening (Szokolay, 2014).The height difference between the intake and outflow directly relates to how well the stack ventilates. Because of this, stack ventilation works better in rooms with high ceilings and/or when ventilation chimneys are used (Figure 2.6-right).

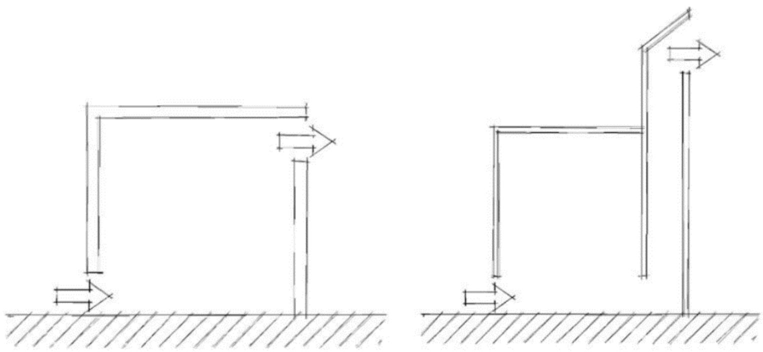

Figure 2.7 Stack ventilation with a ventilation chimney on the right and in a chamber with openings on the left.

Higher ventilation rates are the result of greater pressure differences. The difference in pressure brought on by wind is far greater than the pressure difference caused by variations in buoyancy and temperature (Evola and Popov, 2006). So, compared to stack ventilation, wind-driven ventilation is substantially more efficient. Especially in high-density residential apartments, a disadvantage of stack ventilation may also be the floor space required for the chimney. Therefore, the present study's main focus is on wind-driven ventilation, specifically single-sided and cross-ventilation.

2.5.5 Effects of Building Design on Natural Ventilation of Houses

2.5.5.1 Building Height

For both low-rise and high-rise buildings, wind and buoyancy are the two primary sources of natural ventilation. But because high-rise buildings are taller, these higher heights result in larger pressure differences generated by both wind and buoyancy. This is the primary challenge when constructing natural ventilation for high-rise structures (Etheridge, 2011).With the height of a building, both wind pressure and speed rise (Günel and Ilgin, 2014). Resulting in a greater pressure range across the facade of a structure. The atmospheric boundary layer is schematically depicted in Figure 2.7, which also shows the relationship between height and wind speed. This graphic clearly shows that a building's wind pressure loading varies dramatically with height, with higher wind pressure loads experienced at higher elevations than at lower elevations. As a result, the size and shape of the apertures on upper floors of high-rise structures are more difficult to design for natural ventilation due to the increasing wind pressure (Wood and Salib, 2013).

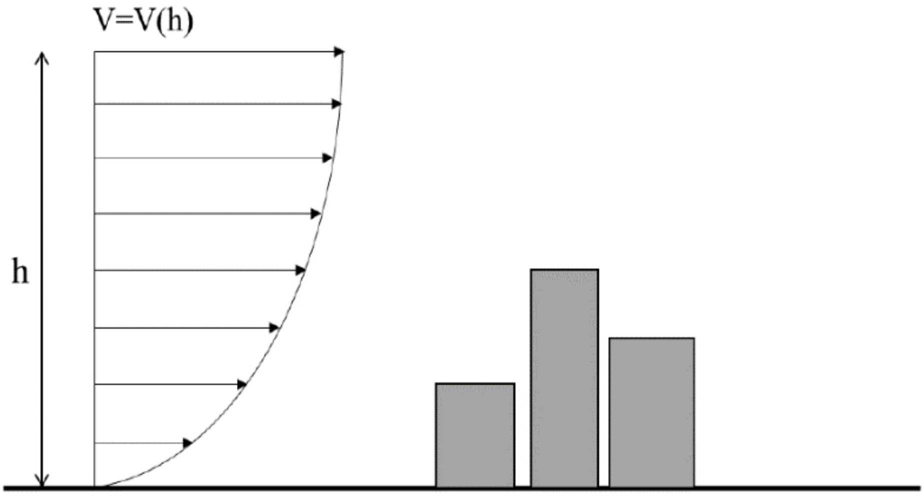

Figure 2.8 boundary layer of the atmosphere.

When inlets and outlets have different temperatures and heights, buoyancy forces are produced (Wood and Salib, 2013). The height of the space is the primary determinant of buoyancy-driven pressure oscillations in high chimney-like structures and floor-to-ceiling regions. Etheridge (2011) categorizes tall building natural ventilation systems into three groups (Figure 2.8). The pressure difference caused by buoyancy forces would behave similarly to those of low-rise buildings in type A (Figure 2.8-A) when each level's apertures are unconnected to vertical voids and the floor space is completely covered. The wind is typically the primary engine for natural ventilation in this situation. In high-rise structures of type B (Figure 2.8-B), which have large interior apertures and center voids, this pressure difference becomes an issue. In such circumstances, the thing would work like a single cell, and the pressure differential caused by buoyancy forces would depend on the overall height of the buildings. As a result, the lower units encounter a significant pressure drop, which could make it too difficult to open the windows. Liu et al. (2012) advocated segmentation (Figure 2.8-C) as a solution to the excessive pressure differential brought on by buoyancy forces in structures with center voids. Each part in this system is isolated from the others, similar to a low-rise building (Etheridge, 2011; Chun et al., 2012).

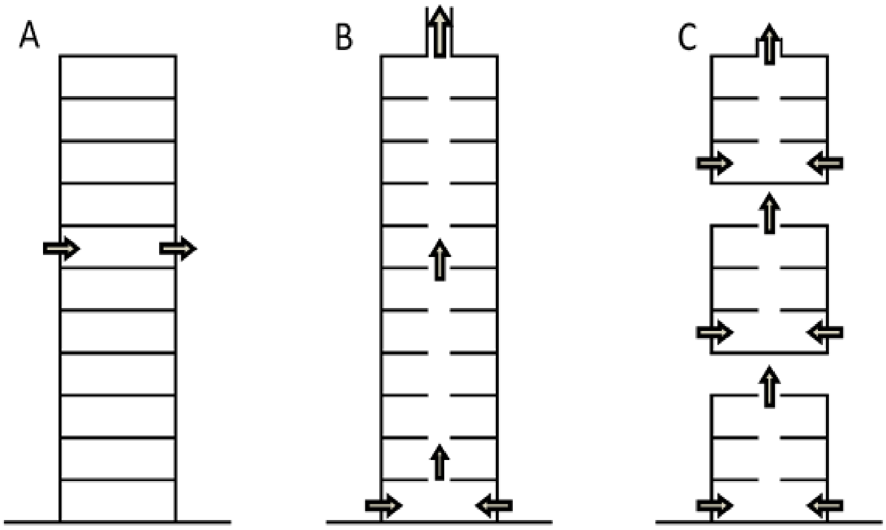

Figure 2.9 ventilation systems for tall structures.

2.5.5.2 Windows and Openings

The impact of apertures on natural ventilation is perhaps one of the most researched design-related aspects. According to their designs and classifications, studies have been done on apertures and how they affect natural ventilation.

The placement, size, and shape of openings on a façade are all examples of an opening's configuration (Lukkunaprasit et al., 2009). Placing the holes opposite or parallel to the other would improve airflow effectiveness, based on a study on how the layout of the apertures influences ventilation rate (Gao and Lee, 2011). It has been observed that having openings on one surface of the building does not provide very good ventilation (Im et al., 2012), but openings on surfaces far from each other provide better ventilation (Siew et al., 2011).

Yin et al (Vickers, 2017), Tantasavasdi et al.(Chalermwat et al., 2001), as well as Derakhshan and Shake (Derakhshan and Shaker, 2017) more recently explored the cross-ventilation opening arrangement, and stated that cross ventilation is a good arrangement for better indoor air quality. Yin et al., (2010) indicated that relative opening heights have a significant impact on ventilation performance. Their findings showed that, in most situations, having the same level of intake and output leads to greater ventilation. Chalermwat et al., (2001) discovered that contrary to Santamouris and Allard's suggestion in their design guide, The ventilation rate would be enhanced with a larger intake and a smaller output (ALLARD, 1998) where a larger or equal outlet is recommended. Smaller width-to-height ratio square windows would improve natural ventilation, according to Derakhshan and Shaker, (2017) research. Numerous research has looked into the different sorts of openings and their effects on the ventilation and airflow inside a space (Heiselberg et al., 2001; (Gao and Lee, 2011a; Grabe et al., 2014; Wang et al., 2015; O'Sullivan and Kolokotroni, 2017).

For single-sided and cross-ventilation modes, Heiselberg et al. (2001) and Gao and Lee (2011b) studied the impact of various opening types. Although the effect of window type on interior airflow is the subject of both of these research, Heiselberg et al. (2001) and Gao and Lee's (2011b) study focus on airflow as a cooling passively component while Gao and Lee's (2011b) study examines the topic more from the perspective of draught hazard. On side-hung and bottom-hung windows, laboratory tests were performed by Heiselberg et al. in 2001. They found that the bottom-hung window is the ideal choice for single-sided and cross-ventilation designs in the winter. However, in the summer a single-sided room would not receive enough air through bottom-hung windows. Gao and Lee (2011b) investigated the effectiveness of windows openings, such as top-hung, side-hung, half-end-slider, and full-end-slider (Figure 2.9), on ventilation performances using computational fluid dynamics (CFD) method and found that complete end-slider and side-hung windows performed better for cross ventilation, while side-hung windows were the best option for single-sided ventilation.

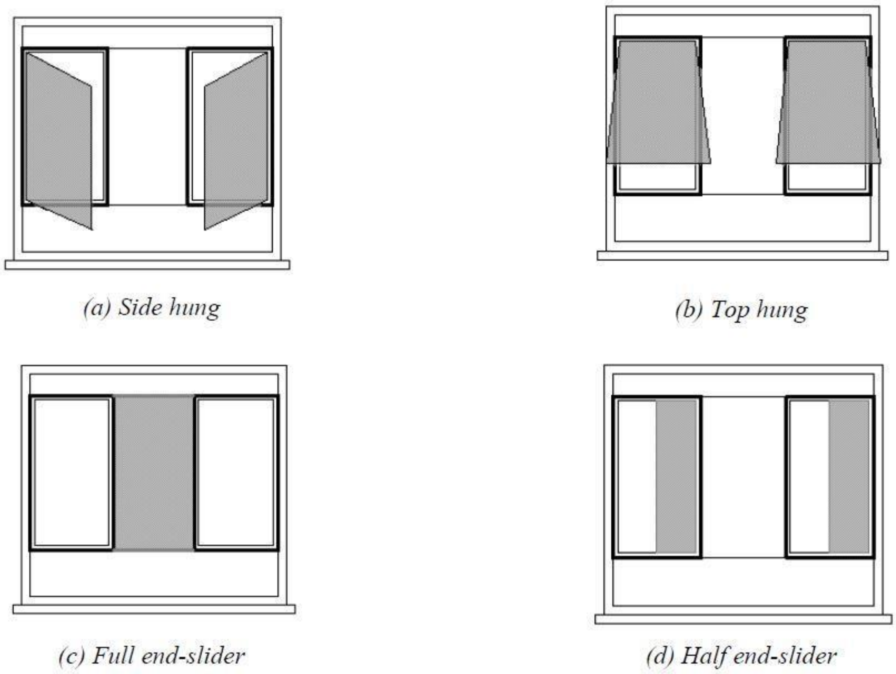

Figure 2.10 Gao and Lee (2011b) evaluated several window types.

Heiselberg et al. (2001) and Gao and Lee (2011b) focused on wind-driven ventilation, whereas Grabe et al. (2014) evaluated the buoyancy-driven ventilation effectiveness of six different window designs (Figure 2.10). Their experimental results showed that tilt windows had the weakest ventilation performance, while horizontal pivot windows had the best ventilation performance.

Recently, semi-empirical models for side-hung, top-hung, and bottom-hung ventilation prediction for single-sided ventilation mode were developed by Wang et al. in 2015. As part of their investigation, they assessed how well the aforementioned window styles performed in various wind directions. Their findings showed that bottom-hung windows functioned better overall whereas side-hung windows worked better for windward circumstances. A study showed that single-sided slot louvers have been shown to increase ventilation speed by 6.5% (Sullivan and Kolokotroni, 2017).

Figure 2.11 Windows opening types, A: duble vertical slide windows, b: turn windows, c: bottom-hung windows, d: awning windows, e: horizontal pivot windows, f: vertical pivot windows.

2.6 Literature Review Summary

Natural ventilation stands at the forefront of modern architectural design, especially within the context of sustainable and energy-efficient building practices. The strategic placement of apertures, such as windows and vents, within the built environment has emerged as a central focus in research and design-related studies.

The design and placement of windows in architectural settings play a pivotal role in shaping natural ventilation dynamics within buildings. The size, shape, and positioning of windows are critical factors influencing the flow of outdoor air into and throughout a structure. Larger windows, when strategically incorporated into the building's layout, can significantly enhance the ingress of fresh air, promoting effective natural ventilation. Additionally, the configuration and placement of openings, such as windows and apertures, can create airflow pathways that facilitate the movement of air within the interior space. This design approach not only contributes to improved indoor air quality but also enhances energy efficiency by reducing the reliance on mechanical ventilation systems.

Several architectural factors, including ventilation mode, building height, the design of apertures, balconies, and projections, have an impact on natural ventilation, and interior obstructions, in addition to climatically driven factors like the wind. Therefore, natural ventilation can be enhanced by properly integrating these design elements. The opening design has been thoroughly studied among the characteristics that affect the design, although further research is needed on ventilation mode and balconies. Additionally, there aren't many comprehensive models that link many design elements into a single diagram that may serve as a standard for the construction industry's usage of natural ventilation.

Given that one of the main purposes of natural ventilation is to cool down building occupants, thermal comfort is an appropriate criterion for assessing the efficacy of natural ventilation. Therefore, a relief model that uses air velocity as input and accurately forecasts thermal conditions in naturally ventilated buildings is required for assessing the performance of natural ventilation.

3. MATERIALS AND METHOD

The experiments were carried out in a lab-scale test room (or chamber) with dimensions width x length x height (WxLxH) of 0,4 m x 0,7 m x 0,4 m (Figure 3.1 and Figure 3.2). The test room is made from a glassy plastic and including total 12 square holes with the size of 4 cm x 4 cm. Air was supplied to the model test room at three different flow rates from each of three different inlet points (E1, E2 and E3) on the 40x40 cm surface. Air outlets from the room were carried out at nine points, three directly opposite the entrance (O1, O2 and O3), three on the side (O7, O8 and O9) and three on its upper surface (O4, O5 and O6). Also, in order to understand the effect of one sided ventilation on pollution discharge, sweeping air was fed into the chamber from E2 at three different flow rates and discharged from E1 and E3.

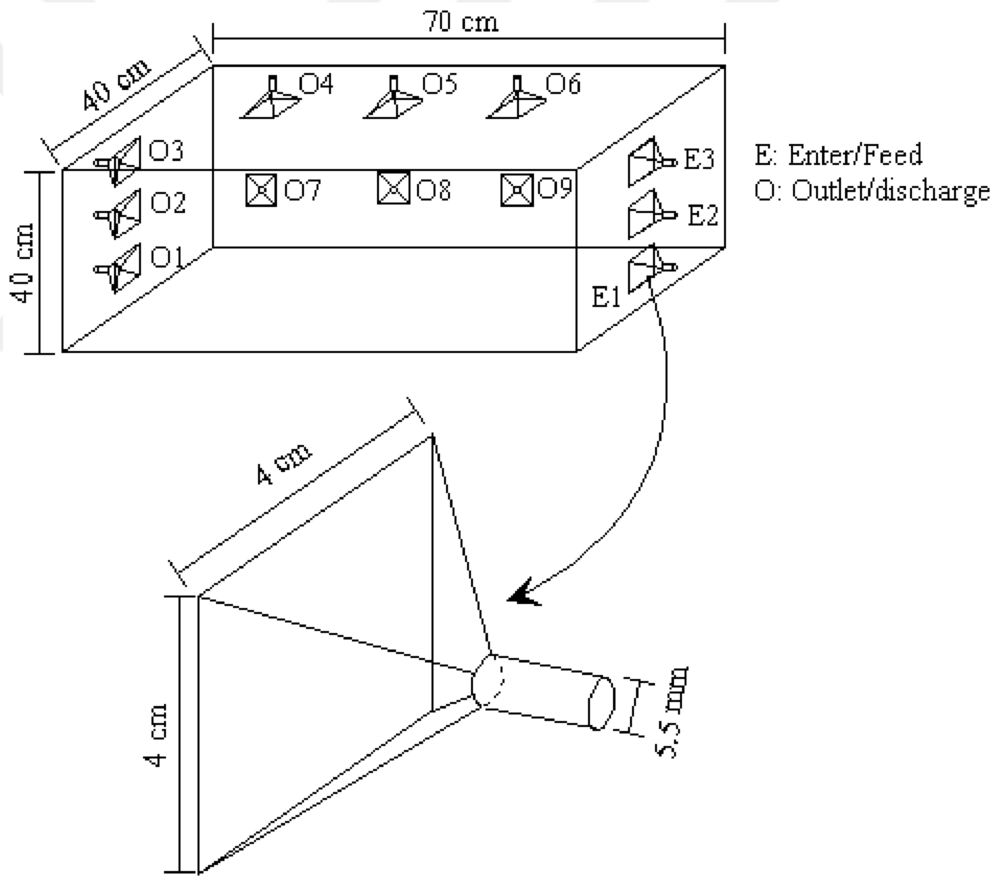

Figure 3.1 The model test room and schematic drawing of the enter/outlet point

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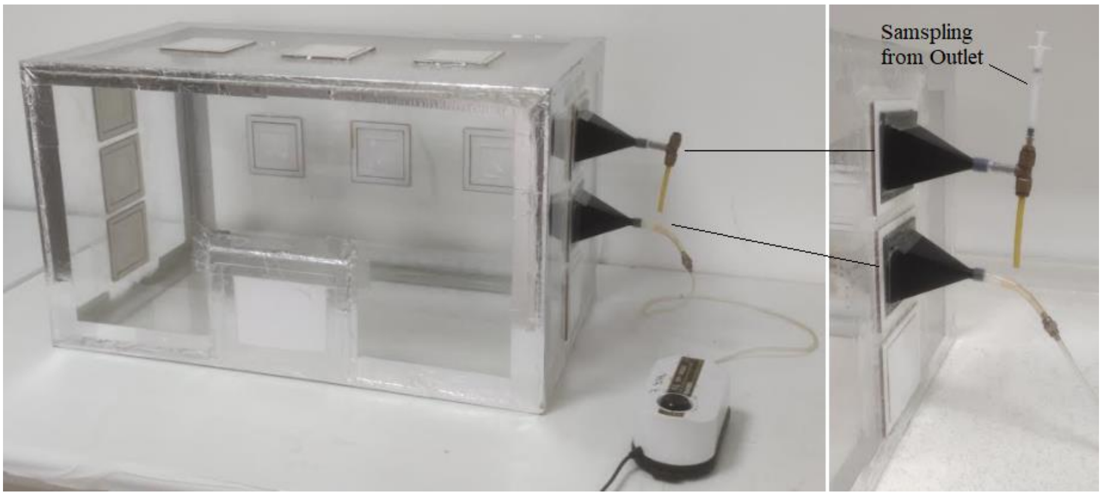

Figure 3.2 Picture of the lab-scale test room.

In order to determine the effectiveness of the windows and air flow rates on the surfaces of the test room, decreasing rate of pollutant concentration by the ventilation was examined. CO_2 was used as pollutant gas because it is accepted as a tracer gas in studies examining the effectiveness of ventilation on indoor air pollution (Kabirikopaei and Lau, 2020; Liang and Qiu, 2023; Reda et al., 2023).

A sufficient volume of pure CO_2 was fed into the test chamber to adjust the initial CO_2 concentration to about 5000 ppmv, and then the sweeping air was fed in continuously after waiting for about 20 minutes for the CO_2 + air mixture inside to become homogeneous. Then the sweeping gas started to be fed into the test chamber, and the change in CO_2 concentration inside the test chamber was determined by measuring the CO_2 concentration in the samples taken from the discharge point at regular intervals of 10 minutes. The CO_2 concentration was determined by a gas chromatography (Figure 3.3) (Shimadzu GC2010) equipped with TCD detector and capillary column (Supel-QTM Plot, 30 m x 0.32 mm ID x 30 μm) by taking gas sample from the discharge point in every ten minutes. The carrier gas (He) flow rate was 10 ml·min–1, and the injection, oven and detector temperatures were 473, 373, and 473 K, respectively (Figure 3.4). The amount of CO_2 in the discharge gas was determined using a previously prepared volume versus pressure calibration chart.

Figure 3.3 Gas chromatography (Shimadzu GC2010).

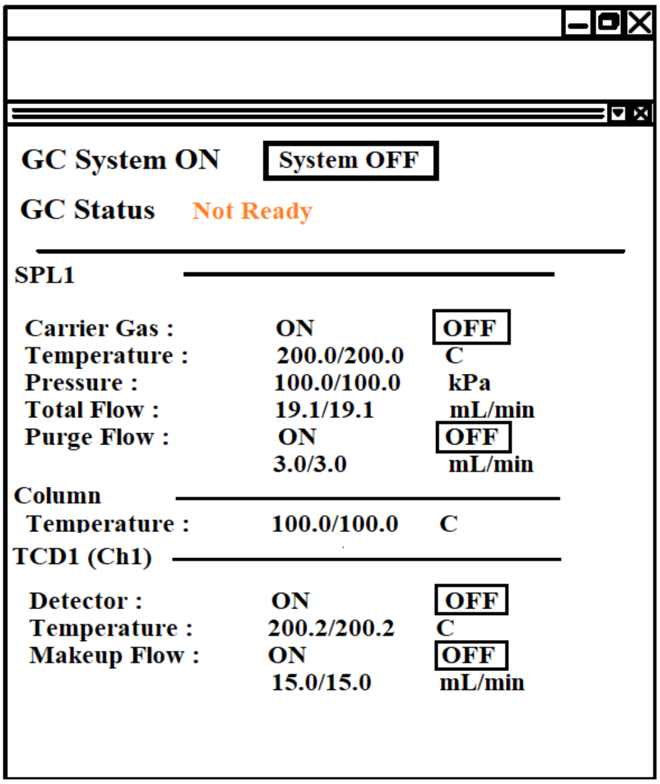

Figure 3.4 GC status.

3.1 Other Equipments and Materials

Table 3.1 The other equipments and materials used.

Equipment and Materials	Using	Figure
CO_2	Carbon dioxide is used as an indicator gas to assess indoor air quality. Therefore, CO_2 was also used as a tracer gas to assess the ventilation performance of the system. The CO_2 was in purity of 99,9% and used as it is (Figure 3.5).	 Figure 3.5 CO_2 cylinder.
Anemometer	An anemometer (TROTEC BA06, Germany) was used to measure the wind flow. The device must be parallel to the wind direction when measuring. The fan speed is measured by the number of revolutions, and by means of an electronic chip, the wind speed is calculated. In this thesis, the wind flow was measured by (anemometer) and then the wind speed was calculated by knowing the surface	 Figure 3.6 Anemometer .

	area of the outlet and the wind flow.	
Gas Storage Tank	Temporary gas storage tank used to supply CO_2 to the test chamber. The tank was first evacuated with a vacuum pump and then filled with enough CO_2 gas to adjust the CO_2 concentration in the test chamber to 5000 ppmv.	 Figure 3.7 Gas storage tank.

3.1.1 Flow Rate Calculation

In this study three different air flow rate were used to push the polluted air in the model room out, namely low, average and high. The diameter of the outlet opening was measured by a measuring tool through which the surface area of the outlet was known. The low, average, and the high speeds were measured by an anemometer, where the selected pump consists of three speeds that simulate the expected ventilation speed. By knowing the area and speed, the high, medium, and the low flows were calculated and adopted as the main flows in the experiment, where the test was conducted for each opening on three streams after checking and tightly closing the experiment room.

The radius of output: R

R = 5.5 mm = 0.0055m

$A = \pi \frac{R^2}{4}$ = $2.375835 * 10^{-5}$ m^2

The velocity of output:

Maximum gas flow rate = 1.09 $\frac{m}{s}$

Average gas flow rate = 0.94 $\frac{m}{s}$

Minimum gas flow rate = 0.75 $\frac{m}{s}$

Q=A.V

$$Q_{max} = 0.09323\ \frac{m^3}{h}, \quad Q_{average} = 0.0804\ \frac{m^3}{h}, \quad Q_{min} = 0.06415\ \frac{m^3}{h}$$

3.2 Experiment

Clean air was fed into the test room at three different speeds from an entry point (for example E1), and the change of pollutant concentration over time was monitored separately at 9 exit points for each of these feeding conditions. The experiment was repeated a total of 81 times for 3 entry points, 9 exit points and 3 feed rate cases. In addition, the change in the pollutant status in the room was examined for fresh air inlet and polluted air outlet on the same surface of the test room (single-sided ventilation). Here are the ventilation modes (Figure 3.8):

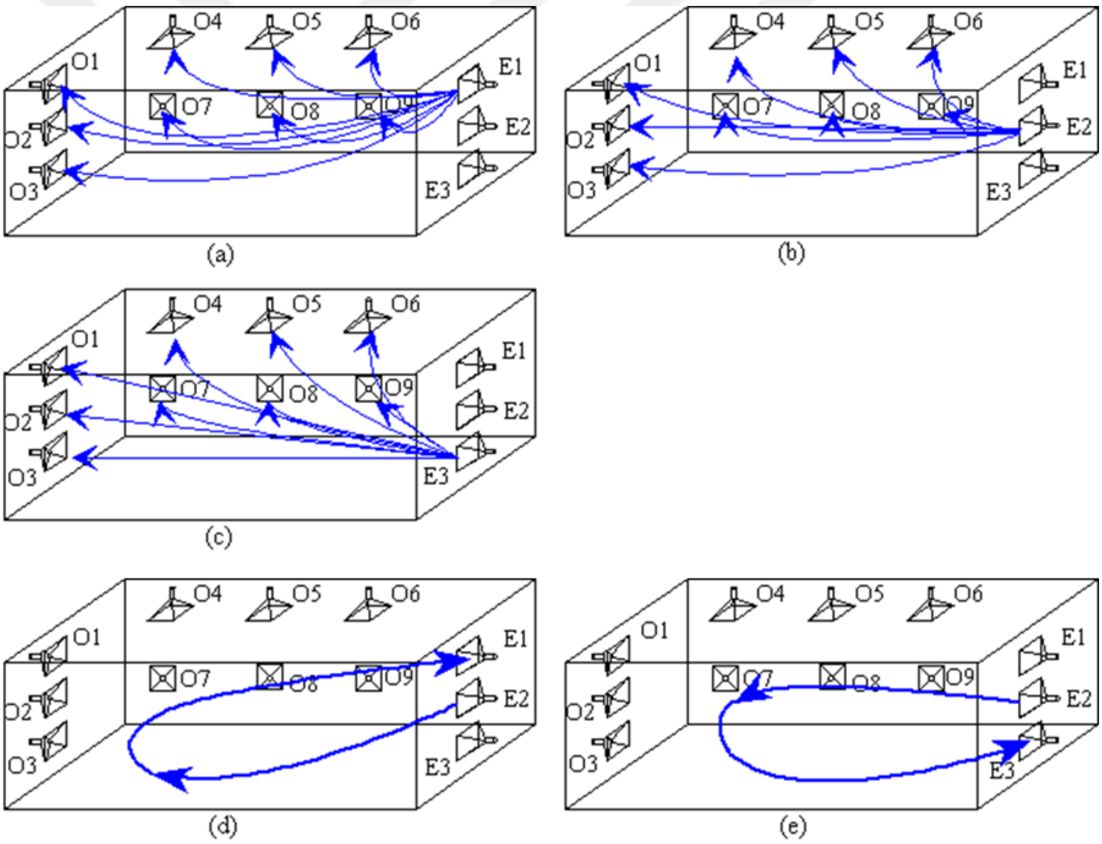

Figure 3.8 Ventilation modes used. Cross-flow ventilation modes (a, b, c)

Single-sided ventilation modes (d, e)

4. RESULTS AND DISCUSSION

4.1 The effect of windows position on natural ventilation

Properly located windows can assist with source control, including eliminating or reducing indoor pollutant emissions. Placing windows makes it easier to naturally ventilate interior spaces and allows pollutants to be expelled (Elshafei et al., 2017).

4.1.1 Cross-Flow Ventilation

The preliminary results from the maximum flow entry of the evaluation of different window configurations referred to as O1 to O9 have shown promising trends in reducing CO_2 levels within a controlled experimental environment. These observations represent a crucial step in understanding the dynamics of air flow rate and its impact on indoor air quality.

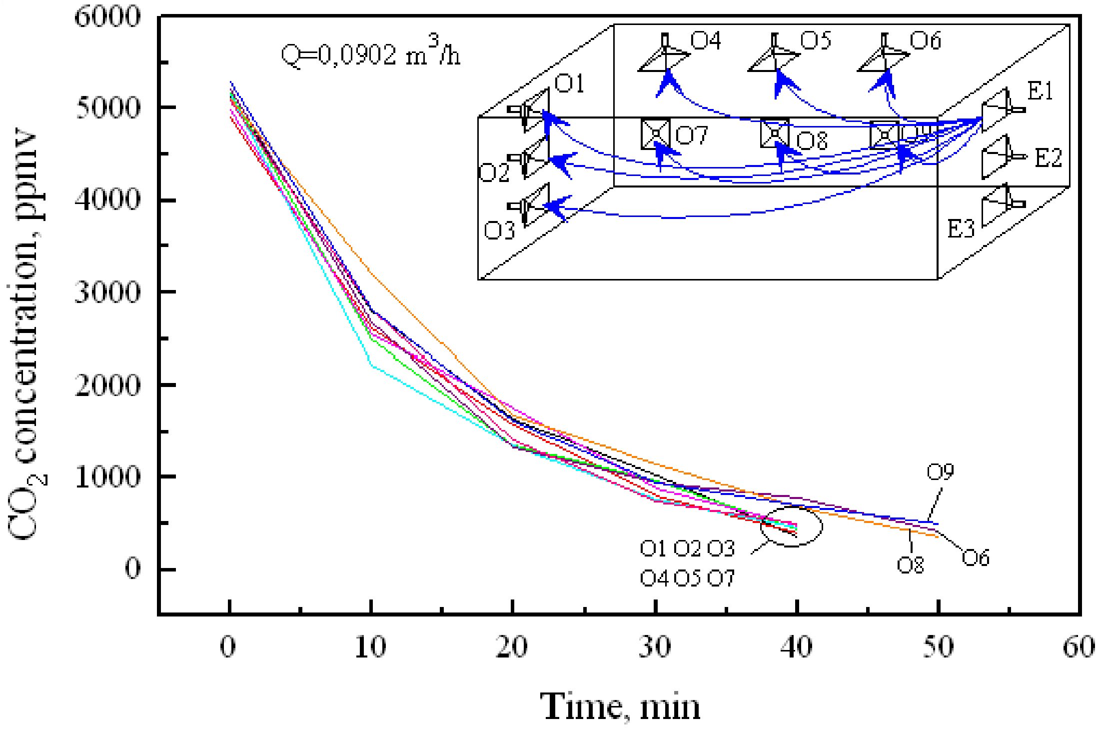

Figure 4.1 Results of decries carbon dioxide gas at the first inlet in the maximum flow rate for all outlets.

In the context of our experimental investigation, it is necessary to emphasize the noteworthy results obtained from windows O1, O2, O3, O4, O5, and O7 (Figure 4.1). These specific openings showed extremely promising results, characterized by significant reductions in carbon dioxide levels. These reductions were quantitatively substantial and achieved after a duration of 40 minutes.

On the contrary, clear deviations were observed for windows O6, O8, and O9. These specific outlet openings, which were examined over a slightly extended period of 50 minutes, revealed a distinct departure from this trend.

This evident variation in gas reduction rates, as mentioned by Wang et al., (2022), confirms the pivotal influence exerted by the strategic positioning of windows and their proximity to exit points on the effectiveness of indoor air exchange and pollutant removal. It is worth noting that these experimental observations undeniably affirm the profound importance of placing windows wisely within indoor spaces. This positioning critically affects the complex dynamics of airflow, leading to a noticeable and beneficial impact on overall indoor air quality. In fact, this research supports the scientific understanding of the subtle, multifaceted differences that govern indoor environmental conditions.

The investigation into average flow entry limits, assessing various window configurations denoted as O1 to O9, has yielded promising outcomes with regards to the mitigation of CO_2 levels within a controlled experimental setting (Figure 4.2). These findings mark a significant stride in comprehending the dynamics of air flow rates and their profound influence on indoor air quality. The exploration of diverse window setups and their effects on CO_2 concentration provides invaluable insights into the optimization of indoor environments, particularly in the context of environmental sustainability and occupant well-being.

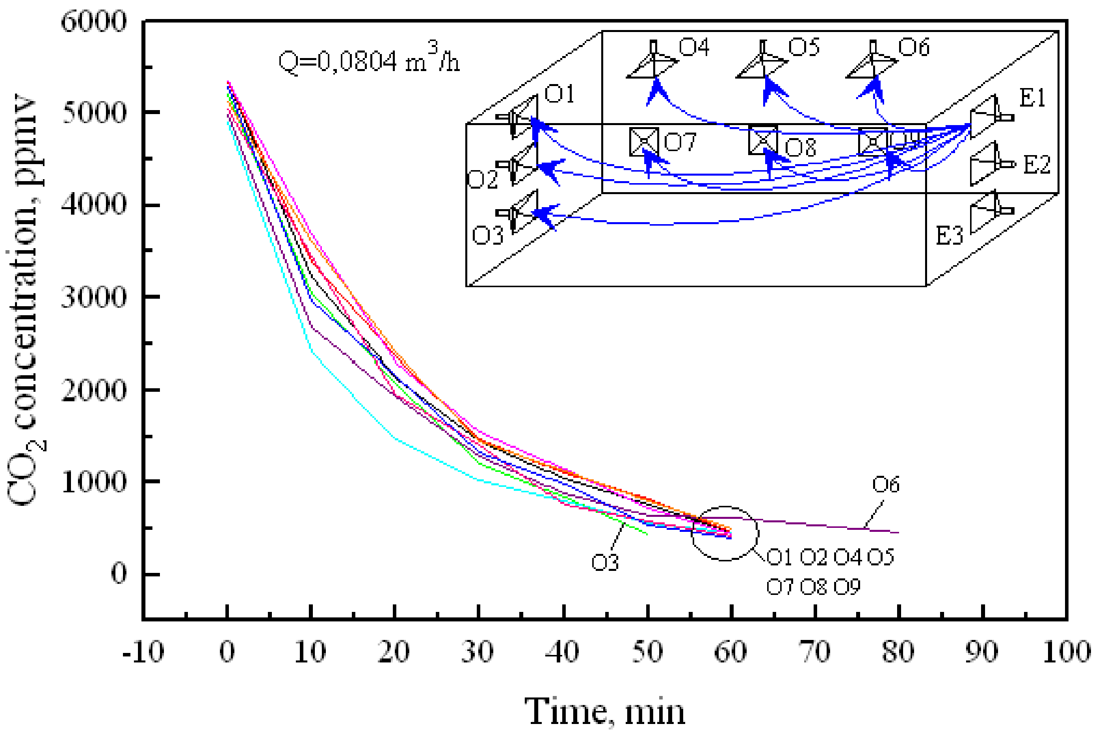

Figure 4.2 Results of decries carbon dioxide gas at the first inlet in the average flow rate for all outlets.

Such research contributes substantially to the overarching goal of creating healthier, more energy-efficient spaces, which is paramount in addressing contemporary environmental challenges.

In the initial observation, window O3 demonstrated commendable performance in maintaining low levels of carbon dioxide, as it recorded the desired concentration after 50 minutes. The distinctive feature of window O3 lies in its efficient air exchange mechanism, as highlighted by Zhou et al., (2021),which involves smooth extraction of outdoor air from the upper section and effective removal of pollutants from the lower part. The predominantly utilized vertical airflow pattern further contributes to enhanced infiltration of clean outdoor air. This innovative design principle, emphasizing the separation of inlet and outlet openings, significantly increases ventilation efficiency. Therefore, window O3 appears as an ideal choice for improving indoor air quality and comfort.

In contrast, windows O1, O2, O4, O5, O7, O8, and O9 exhibited similar trends in reducing carbon dioxide (Fig. 4.2), as they achieved the desired concentration after 60 minutes. The close time interval between these windows can be attributed to their strategic positioning, facilitating excellent airflow circulation. Additionally, we highlight the moderate speed that yields more consistent results and faster gas removal.

However, window O6 deviated from this trend, showing a relatively slower decrease in carbon dioxide levels after 70 minutes. This lower efficiency performance can be attributed to two key factors. Firstly, as mentioned earlier, the proximity of the window to the entrance has a constraining effect on its ability to effectively remove carbon dioxide. Secondly, the density of carbon dioxide, being heavier than air, hinders its dispersion, thereby impeding the window's capacity to maintain lower concentrations of carbon dioxide, as commonly known.

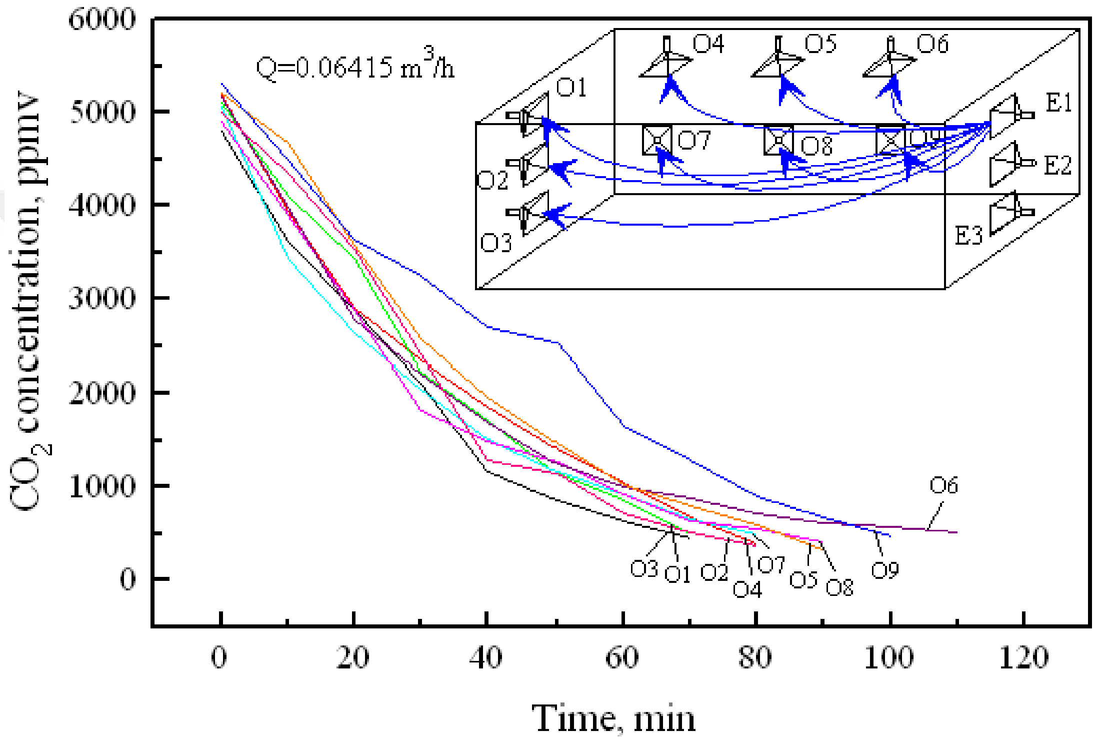

Figure 4.3 Results of decries carbon dioxide gas at the first inlet in the minimum flow rate for all outlets.

Detecting slow flow from the first inlet, in a study evaluating different window configurations referred to as O1 to O9, revealed distinct patterns in reducing carbon dioxide (CO_2) concentrations within a carefully controlled experimental environment.

As shown in Figure 4.3, window O3 exhibited a significant decrease in carbon dioxide levels, with a substantial reduction within 40 minutes. This achievement can be attributed to the window's distance from the entrance point, as window O3 was positioned farthest from entrance E1. Additionally, as mentioned by Lee et al., (2005), the depth of airflow from the top to the bottom of the room facilitates smooth airflow towards window O3, efficiently expelling the pollutant gas. This top to down airflow pattern enables maximum penetration of clean air, further solidifying its position as an ideal choice for improving indoor air quality and overall comfort.

Windows O1, O2, O4, and O7 demonstrated commendable performance, with noteworthy carbon dioxide reduction rates, especially after 50 minutes. Their efficient airflow distribution, which allows deeper air penetration towards the windows, and their optimal positioning in relation to the entrance window contribute to their effectiveness.

However, windows O5 and O8 required a longer timeframe of 60 minutes to demonstrate their effectiveness, resulting in delayed carbon dioxide reduction rates. This marginal performance delay can be attributed to their specific positioning within the experimental room.

On the other hand, windows O6 and O9 exhibited slower responses compared to the other windows, taking 70 minutes to reduce CO_2 levels. This difference in performance can be explained by Bernoulli's principle, which states that pressure decreases with an increase in fluid velocity. As air rises, its velocity increases, leading to a decrease in pressure. Thus, high-pressure zones form in the lower regions of the room, while low-pressure zones appear in the upper regions. Consequently, carbon dioxide-rich air accumulates in the upper part of the room. Additionally, as mentioned by Wang et al. (2022), the proximity of the windows to the entrance window primarily contributes to this slower response.

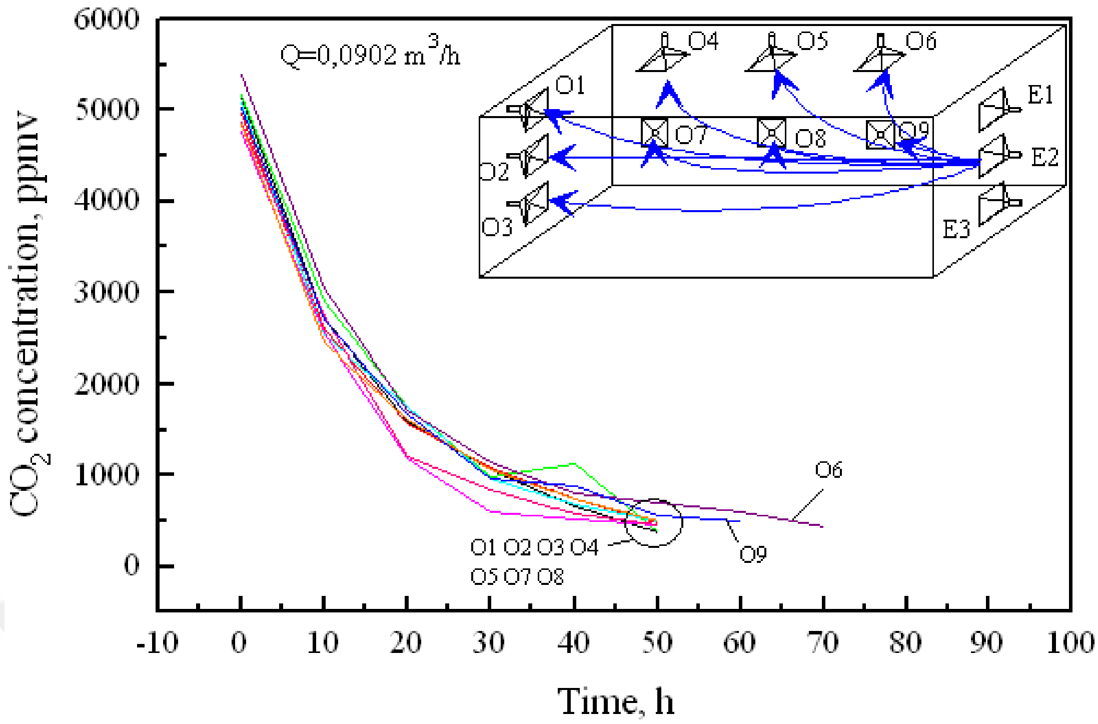

Figure 4.4 Results of decries carbon dioxide gas at the second inlet in the maximum flow rate for all outlets.

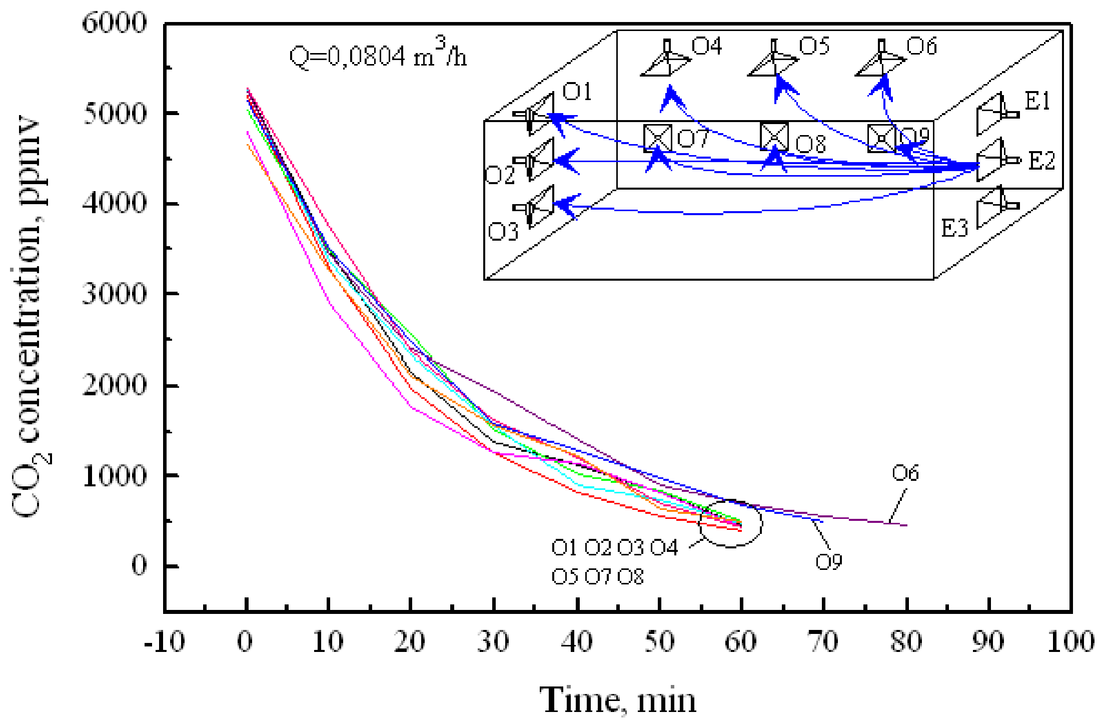

Figure 4.5 Results of decries carbon dioxide gas at the second inlet in the average flow rate for all outlets.

In the second data set, the maximum and average airflow remained constant in delivering results, as all windows maintained their capabilities in removing CO_2 gas. The only difference was the time factor, where the high flow rate was faster than the average flow rate. The observed results showed relatively small differences, as shown in Figure (4.4) and Figure (4.5). The recorded reductions in carbon dioxide (CO_2) levels for windows O1, O2, O3, O4, O5, O7, and O8 exhibited similar results, eliminating the pollutant gas within the same time period, with very slight variations. It is worth mentioning that the location and rate of these windows proved to be significantly effective in facilitating the removal of carbon dioxide from the surrounding air.

However, in the case of windows O9 and O6, the pace of carbon dioxide reduction was relatively slower, taking more time compared to the other windows. Several factors can be attributed to this slower removal. Firstly, the suboptimal location of these windows near the entrance played a pivotal role. Windows placed near the entrance usually experience higher initial pollutant concentrations, requiring more time to achieve significant reductions. Secondly, the density difference between carbon dioxide gas and ambient air exacerbated the slow removal process. Since carbon dioxide gas is denser than air, the upper position of window O6 intensified the challenge of efficient extraction.

In summary, the second data set demonstrated varying rates of carbon dioxide reduction across different windows, primarily influenced by window placement and the density characteristics of carbon dioxide gas. These results emphasize the importance of strategically determining the location of windows for effective ventilation and pollutant removal in indoor spaces.

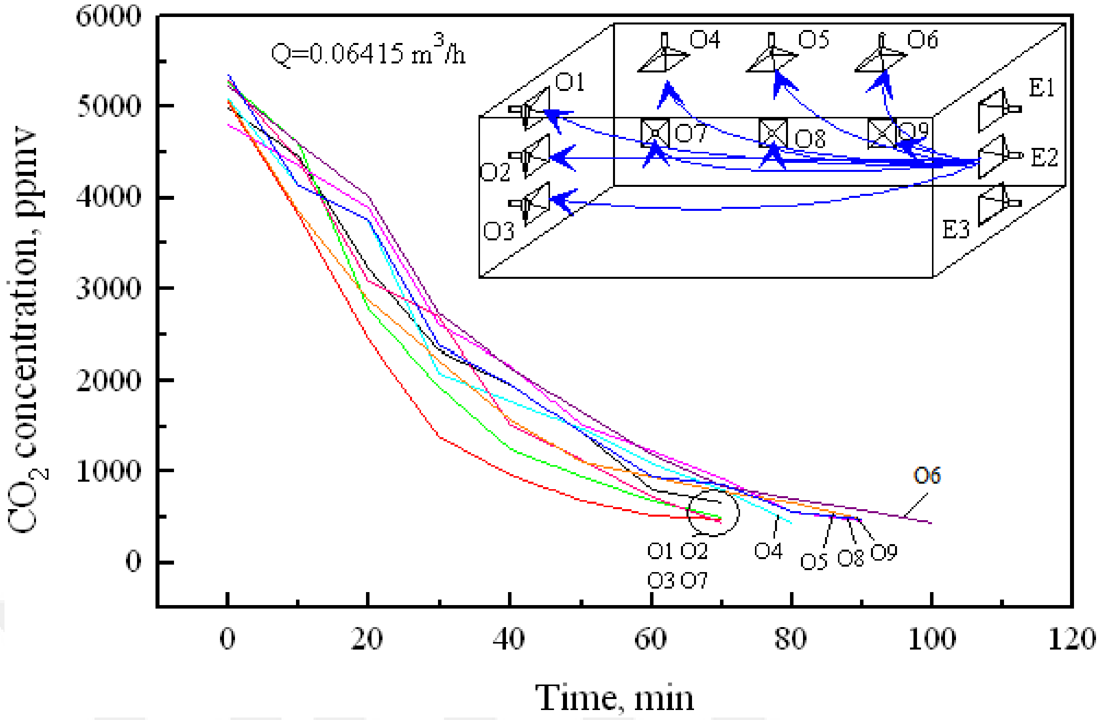

Figure 4.6 Results of decries carbon dioxide gas at the second inlet in the minimum flow rate for all outlets.

Firstly, it is important to mention the performance of the entrance window, E2. Its strategic placement effectively distributed indoor air and pushed out the polluted air, resulting in a significant impact on the exit windows. It provided good gas dispersion, as shown in Figure 4.6, and yielded relatively close results in CO_2 removal.

Windows O1, O2, O3, and O7 maintained their promising results in CO_2 removal, with significant reductions in levels within a duration of 70 minutes. This achievement can be attributed to their distance from the entry point, allowing for smooth removal of CO_2 by facilitating the infiltration of air deeper into the space.

The performance of window O4 slightly declined, as the CO_2 removal took longer, after 80 minutes. This indicates that the performance of the opposite and side windows was more effective compared to the upper windows.

Windows O5, O8, and O9 demonstrated commendable performance, exhibiting noteworthy rates of carbon dioxide reduction, particularly after 90 minutes. This can be attributed to the effective distribution of air entering deeper into the windows and the ideal location of the windows, especially for the entrance window.

On the other hand, window O6 showed a slower response compared to the other windows, taking 100 minutes to reduce CO_2 levels. This can be primarily attributed to its close proximity to the entrance window.

In summary, the performance of the windows varied in CO_2 reduction, with some windows exhibiting more effective removal capabilities. Factors such as window location, air distribution, and the characteristics of CO_2 density influenced the results.

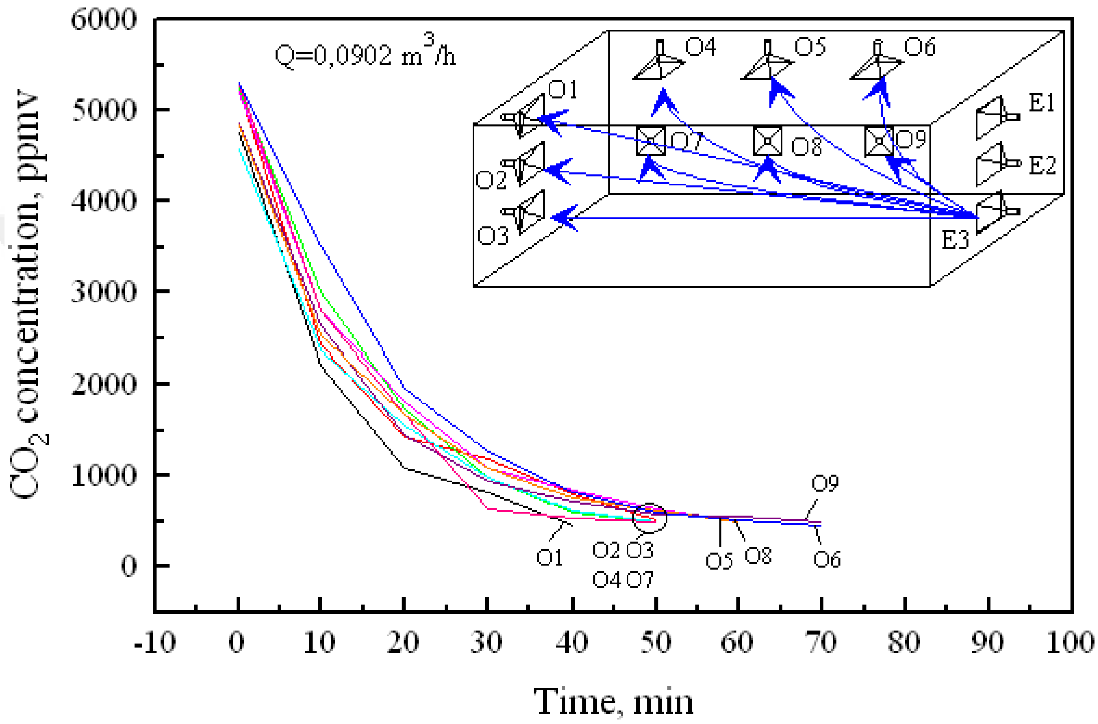

Figure 4.6 Results of decries carbon dioxide gas at the third inlet in the maximum flow rate for all outlets.

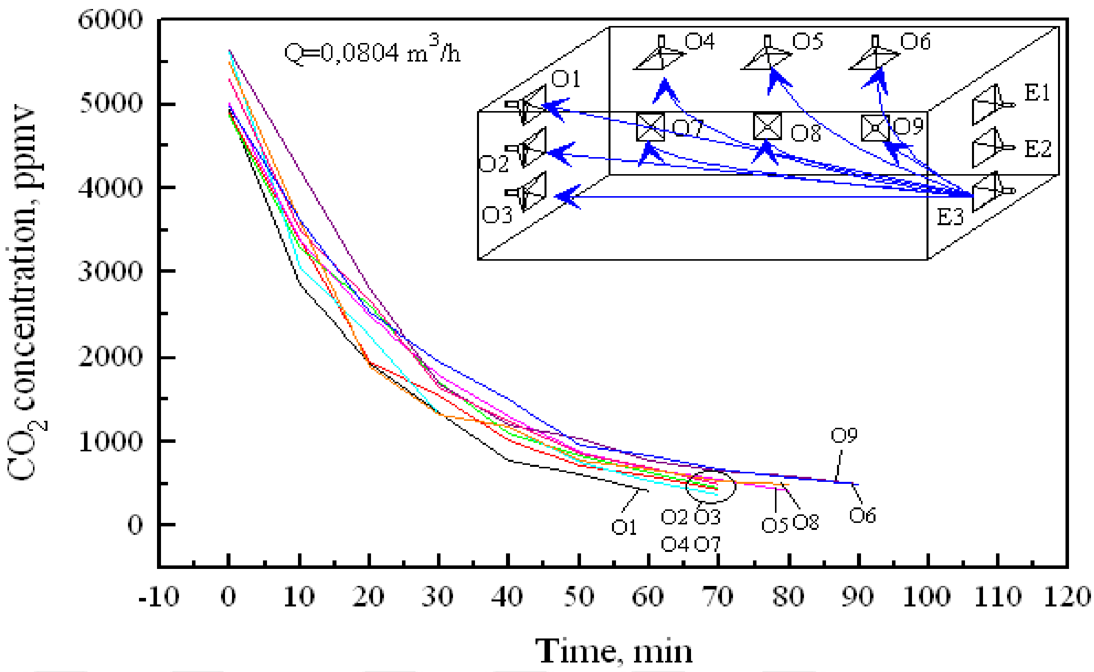

Figure 4.7 Results of decries carbon dioxide gas at the third inlet in the average flow rate for all outlets.

In the third data entry, the maximum and average flow rates remained constant in providing results, as all windows maintained their capabilities in removing CO_2 gas. The only difference was the time difference, where the high flow rate was faster than the average flow rate. The observed results showed relatively small differences, as shown in Figure (4.7) and Figure (4.8).

The preliminary results from evaluating the different window configurations referred to as O1 to O9 demonstrated promising trends in reducing carbon dioxide levels within a controlled experimental environment. These observations are a crucial step in understanding the dynamics of airflow and its impact on indoor air quality.

Initially, window O1 showed a significant decrease in carbon dioxide levels, with a substantial reduction. The change in the entry point and its redirection from bottom to top facilitated effective removal of the polluted air using the inflow air. This modification effectively directed the polluted air towards the exit, contributing to the overall success of this configuration. These findings align with Hooff et al., (2017), emphasizing the importance of bottom-to-top airflow.

Further investigations focused on windows O2, O3, O4, and O7. These windows demonstrated commendable performance, which is noteworthy considering their spatial distribution around the room's entrance. Their ability to extract and expel polluted air efficiently from the depths of the room indicates their effectiveness in reducing carbon dioxide levels effectively.

In contrast, windows O5 and O8 required a slightly longer period to demonstrate their effectiveness. This marginal delay in performance can be attributed to their specific location within the experimental environment.

Furthermore, windows O6 and O9 followed a distinct pattern, taking longer to reduce carbon dioxide levels. These results indicate that their effectiveness may be influenced by their proximity to the entrance window, allowing clean air to exit quickly without adequately addressing the removal of carbon dioxide.

These results highlight the variation in performance characteristics across different window configurations, prompting further investigation into the underlying mechanisms and effects behind these differences. It is worth mentioning that windows located higher inside the room exhibit slower airflow rotation compared to their counterparts at lower levels. This discrepancy can be attributed to differences in gas density, which plays a significant role in influencing airflow dynamics.

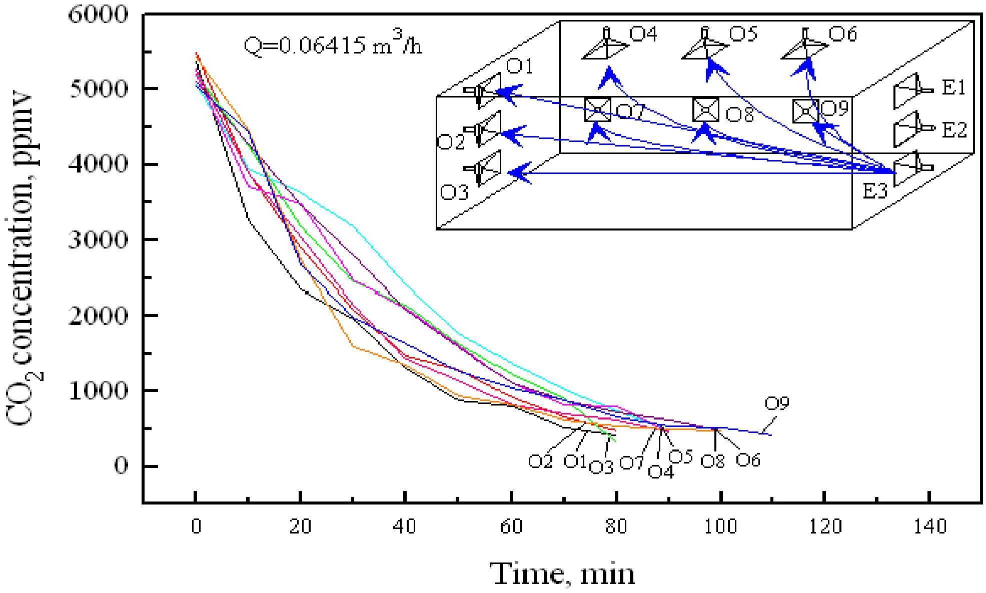

Figure 4.8 Results of decries carbon dioxide gas at the third inlet in the minimum flow rate for all outlets.

In the minimum flow scenario, an analysis of various windows, denoted as O1 through O9, was conducted to assess their efficiency in removing carbon dioxide gas from an indoor environment. Notably, windows O2 and O3 displayed a level of performance comparable to that of window O1 in the context of CO_2 gas removal8 (Figure 4.9). Furthermore, window O1 consistently maintained its effectiveness in mitigating this pollutant. A noteworthy observation was made concerning windows located opposite the entrance window; these demonstrated superior performance in CO_2 removal. This advantage was attributed to their positioning, distanced from the entrance window, as depicted in Figure (4.9).

Windows O4, O5, and O7 consistently exhibited promising results in CO_2 gas reduction, achieving significant reductions within a 90-minute timeframe. Their success can be attributed to their strategic location away from the entrance and the facilitation of efficient CO_2 removal due to the smooth airflow.

Windows O6 and O8 also delivered commendable performance, displaying noticeable reductions in CO_2 levels, particularly after 100 minutes. This can be attributed to their effectiveness in distributing incoming air deeper into the room and their optimal positioning concerning the entrance window.

In contrast, window O9 displayed a slower response compared to the other windows, requiring 110 minutes to achieve CO_2 level reduction. This delay can primarily be attributed to its proximity to the entrance window. In summary, these results underscore the variation in performance among different window configurations, with those opposite the entrance window demonstrating superior performance in CO_2 removal. The effectiveness of each window is influenced by factors such as its location relative to the entrance and the efficient airflow dynamics within the indoor space.

4.1.1.1 Opposite Side

Based on the comprehensive evaluation of the results, it is evident that the optimal window positioning strategy is to place the windows on the opposite sides of the room. This configuration yields the highest airflow values across various metrics, including maximum, average, and minimum airflow levels (Figure 4.10). This outcome can be ascribed to the strategic placement of the windows, which positions them at the furthest point within the experimental room in relation to the three entrances.

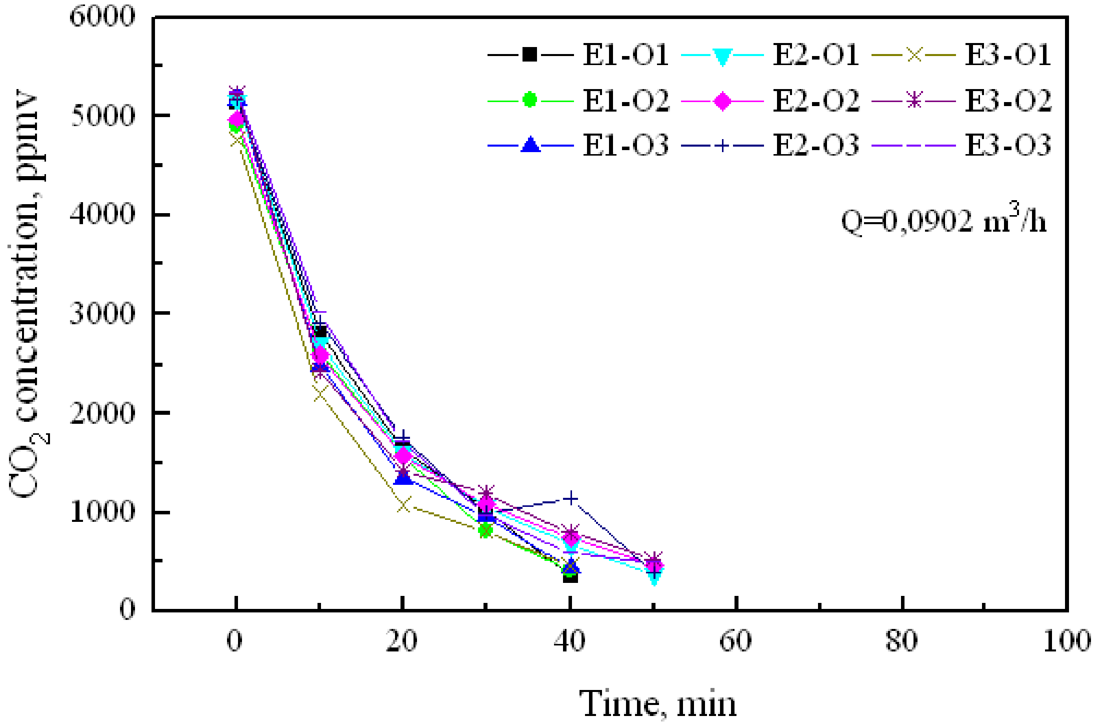

Figure 4.9 Results of decries carbon dioxide gas at the opposite side in the maximum flow rate

Furthermore, the direct orientation of these windows plays a significant role in effectively mitigating CO_2 gas buildup within the indoor environment. The combination of these factors ensures enhanced indoor environmental quality and ventilation performance. Consequently, the opposite-side window positioning approach emerges as a favorable choice for promoting occupant well-being and comfort..

The convergence of the results observed in the study can be ascribed to the maximum airflow generated through gas-sweeping mechanisms. In the case of the first entrance (E1), the outcomes across the three exits demonstrated a remarkable similarity, with all windows efficiently reducing CO_2 levels within a span of 40 minutes (Figure 4.10). Moving to the window situated at the second entrance (E2), it too yielded promising and optimal results, owing to its strategic placement in the central area. In this instance, all three windows achieved CO_2 gas elimination simultaneously after 50 minutes.

Now, considering the window in the third entrance (E3), a particular window denoted as O1 exhibited superior performance in comparison to its counterparts. This superiority was attributed to its distance from the entrance and its favorable positioning relative to the entrance window.

Furthermore, when comparing window E2-O1 with E1-O1 and E3-O1, a delay of 10 minutes became evident. This delay can be attributed to the influence of the entrance window, which exerted a general impact on the other windows due to its central location.

Notably, window E1-O2 excelled in comparison to windows E2-O2 and E3-O2, primarily due to the presence of a smooth downward airflow, which significantly contributed to the effective removal of CO_2 gas. Similarly, window E1-O3 outperformed its counterparts, benefiting from a smooth upward airflow that facilitated the substantial reduction of CO_2 levels.

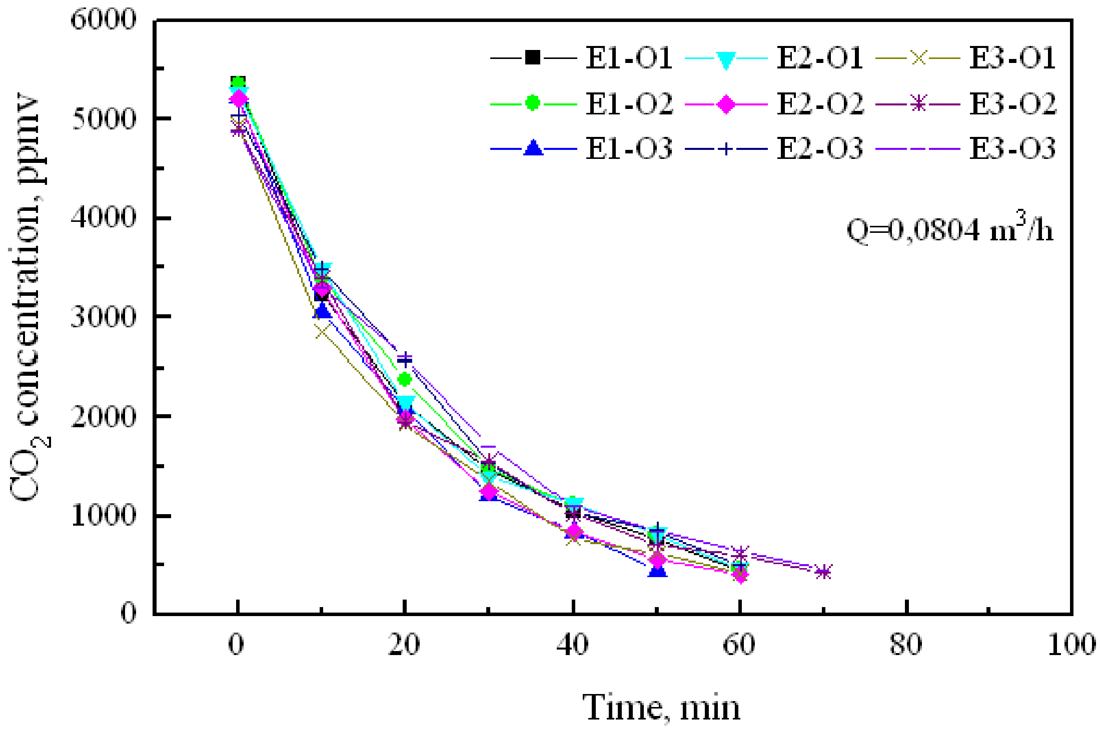

Figure 4.10 Results of decries carbon dioxide gas at the opposite side in the average flow rate.

In the average airflow, the data showed more variation in the elimination of CO_2 gas (Figure 4.11). The first entrance was ideal for effectively removing CO_2 gas and window O3 in the exit stood out by providing the shortest removal time. Meanwhile, the second entrance window maintained convergence in the results across all windows, as we previously mentioned, thanks to its ideal location in the middle. As for the third entrance window, window O1 stood out in particular. However, the overall performance of the third inlet was lower compared to the other inlets, mainly due to its proximity to the room floor, which made it more challenging for the gas to disperse indoors.

From another perspective, when comparing the windows of the exits E2-O1, E1-O1, and E3-O1, they yielded similar results, with all windows eliminating CO_2 gas simultaneously (Figure 4.11).

Window E1-O2 stood out from windows E2-O2 and E3-O2 due to the smooth downward airflow, which significantly aided in the elimination of CO_2 gas.

Similarly, window E1-O3 stood out from the other windows, as the smooth upward airflow facilitated the significant removal of CO_2 gas, giving it an advantage over the rest of the windows.

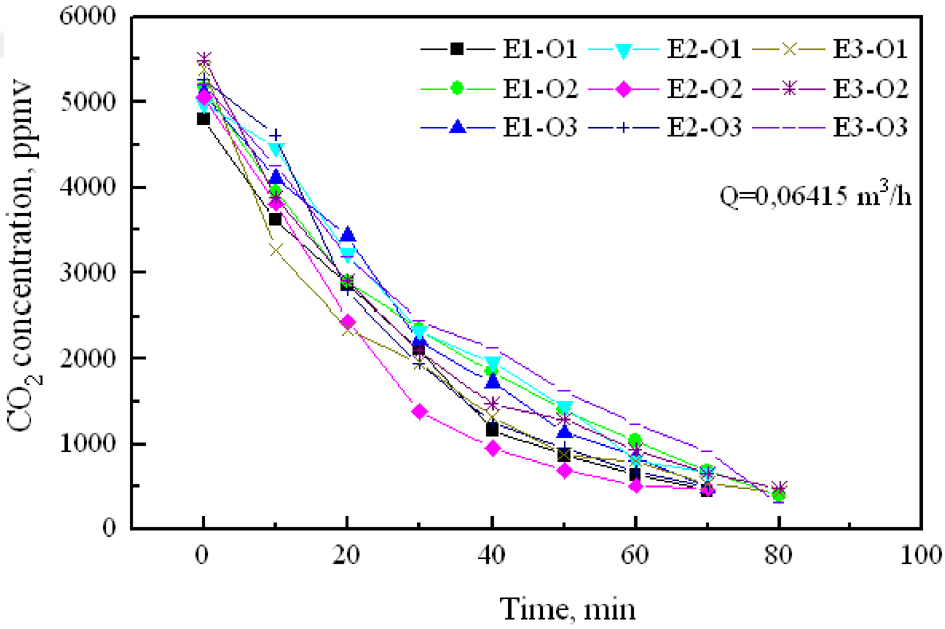

Figure 4.11 Results of decries carbon dioxide gas at the opposite side in the minimum flow rate.

In the minimum airflow conditions, the efficacy of various entrances and windows in removing CO_2 gas becomes evident (Figure 4.12). The first entrance, particularly for exits O1 and O3, demonstrates a significant role in achieving optimal results. Windows E2 and E3 exhibit consistent performance across all windows, effectively eliminating CO_2 gas. However, E3's overall performance is comparatively lower due to its proximity to the room floor, which hampers indoor gas dispersion.

A comparative analysis of window E3-O1 with its counterparts, E2-O1 and E1-O1, reveals a 10-minute delay, primarily attributed to the reduced impact of the entrance window resulting from its proximity to the room floor.

Window E2-O2 distinguishes itself from E3-O2 and E1-O2 due to its smooth airflow and strategic middle positioning, which accelerates the elimination of CO_2 gas.

Regarding window E3-O3, it outperforms E2-O3 and E1-O3 but experiences a 10-minute delay, attributed once again to the reduced impact of the entrance window due to its proximity to the room floor.

4.1.2 Single sided Ventilation

A comparison was made between the estimated ventilation rates from single-sided measurements of carbon dioxide (CO_2) levels and other experiments conducted on intermittent ventilation. It was found that all single-sided ventilation models were effective in eliminating CO_2 gas when wind tunnel experiments were used. However, they were less effective than intermittent ventilation in terms of pollutant removal rate (Figure 4.13). These results are consistent with those reported by Fan et al., (2021).

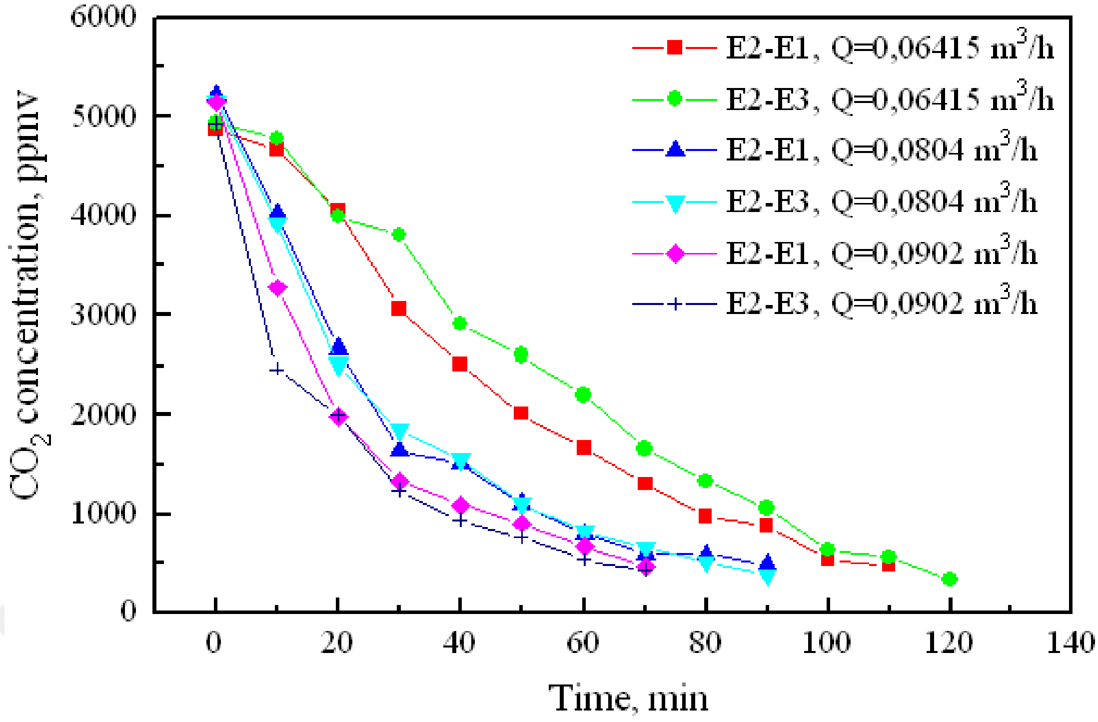

Figure 4.12 Single Sided Ventilation.

In this particular scenario, a ventilation experiment was conducted with the utilization of entrances E1 and E3 as outlets, while fresh air was introduced through entrance E2, situated in the middle section. The objective was to evaluate the efficacy of CO_2 gas removal. Notably, the outcomes indicated that the overall efficiency of this ventilation approach, in terms of CO_2 gas elimination, was notably slower when compared to cross ventilation techniques.

A closer examination of the results, as depicted in Figure 4.10, reveals that in scenarios involving both high and average airflow rates, the outcomes were quite consistent, with the removal of polluted air occurring within a similar timeframe. Interestingly, in the low flow scenario, entrance E1 demonstrated superior performance in contrast to entrance E3, primarily due to its lower placement. This discrepancy can be attributed to the disparity in the density of CO_2 gas in comparison to that of air, with CO_2 gas being denser.

To summarize, the findings from this experiment emphasize the importance of considering ventilation strategies, taking into account the density characteristics of CO_2 gas and the strategic placement of entrances for optimal indoor air quality.

4.2 The effects of air flow rate on natural ventilation

The airflow rate plays a significant role in determining the effectiveness of natural ventilation in a space. Higher airflow rates can lead to improved overall ventilation efficiency. Increasing air changes per hour means that old indoor air is replaced with fresh outdoor air at a faster rate, which is beneficial for maintaining indoor air quality (Zhou et al., 2021).

The airflow rate affects the regulation of cooling and temperature within the space. Higher airflow rates can help dissipate heat, making it more comfortable in warm conditions (Morrison et al., 2014).

Natural ventilation with higher airflow rates is also more effective in removing indoor pollutants, including odors, dust, and allergens, as it expels them at a faster rate (Wang et al., 2021).

Appropriate airflow rate is essential for passenger comfort and health. Insufficient airflow can result in stuffy and uncomfortable indoor environments, while well-regulated airflow rates can enhance well-being (Norrefeldt et al., 2021).

Designing a building with consideration for natural ventilation should take into account the desired airflow rate, which may vary depending on the purpose of the space and local climatic conditions (Emmerich et al., 2001).

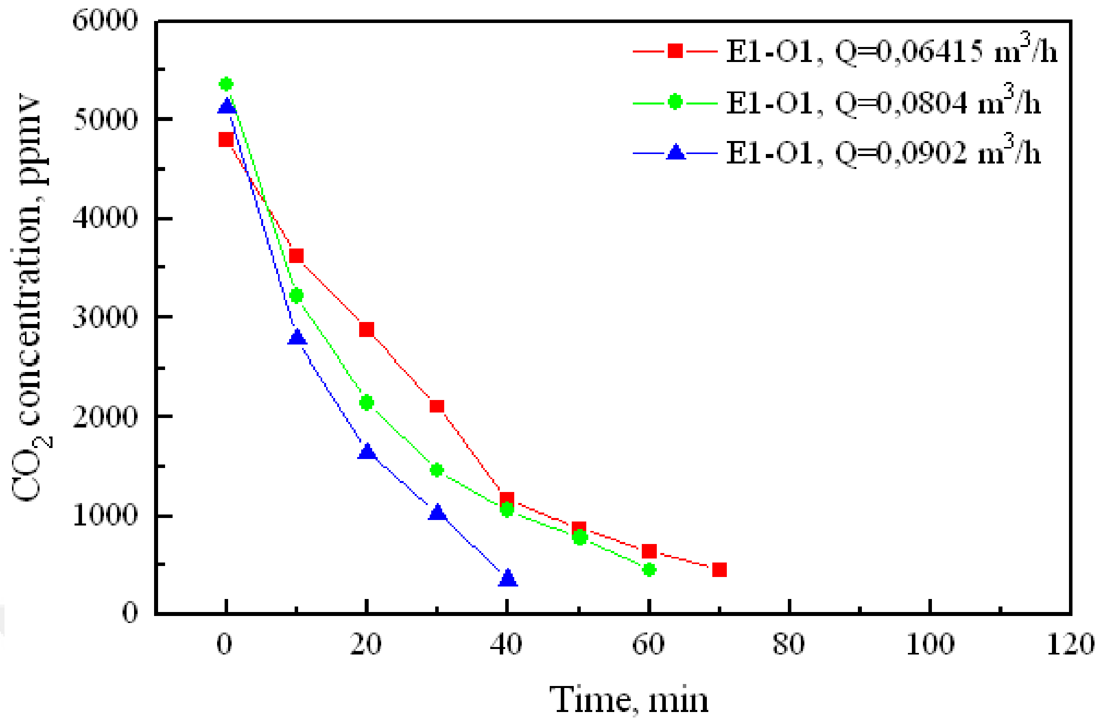

Figure 4.13 Effect of flow rate on windows E1-O1.

The airflow rate affects the direction and pattern of air movement within the space. Understanding these patterns is crucial for efficient design and operation of natural ventilation. Calculating and controlling airflow rate based on specific building and occupant needs is essential. Various techniques and tools are available to estimate and manage airflow rates in naturally ventilated spaces, depending on factors such as building design, wind patterns, and temperature differentials (Atkinson, 2009).

The impact of airflow on window E1-O1 yielded promising results at different airflow rates (Figure 4.14). The maximum flow rate demonstrated remarkable efficiency in removing CO_2 gas within a mere 40 minutes, whereas the average flow rate achieved the same outcome in a still commendable 60 minutes. In contrast, the minimum flow rate necessitated a longer duration of 70 minutes for CO2 elimination. This observation underscores the substantial influence of internal airflow on window performance, thereby highlighting the critical role of well-designed ventilation strategies in upholding and optimizing indoor air quality within a built environment. Such findings underscore the importance of considering airflow dynamics in building design and maintenance, particularly in the context of energy efficiency and indoor air quality.

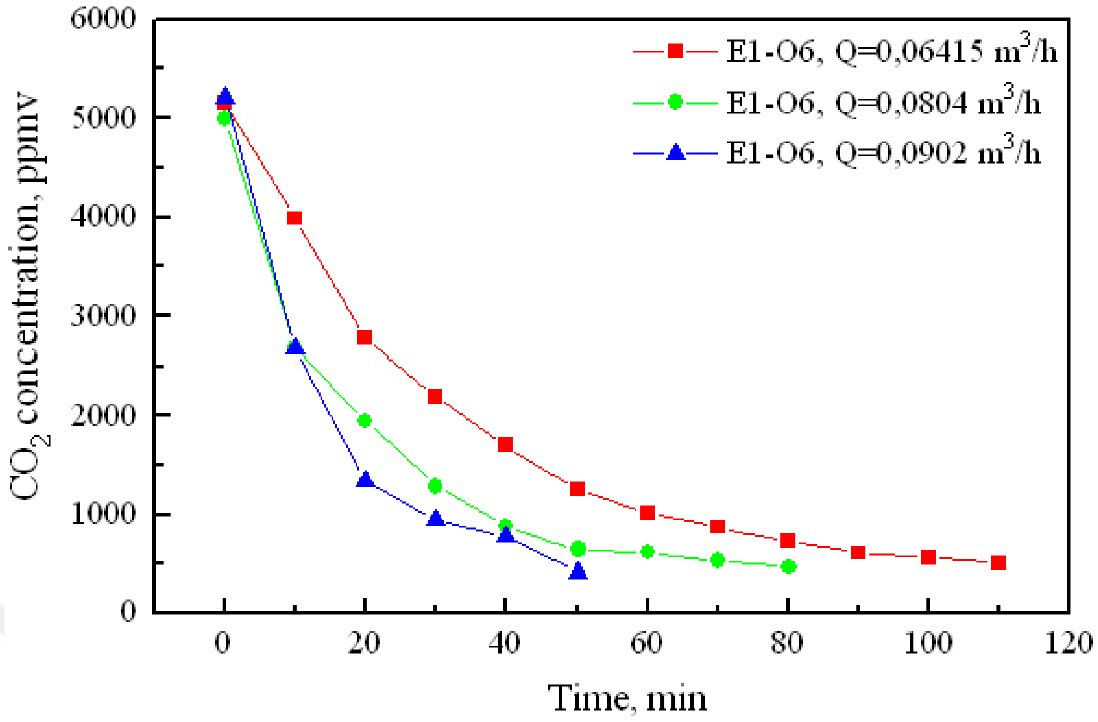

Figure 4.14 Effect of flow rate on windows E1-O6.

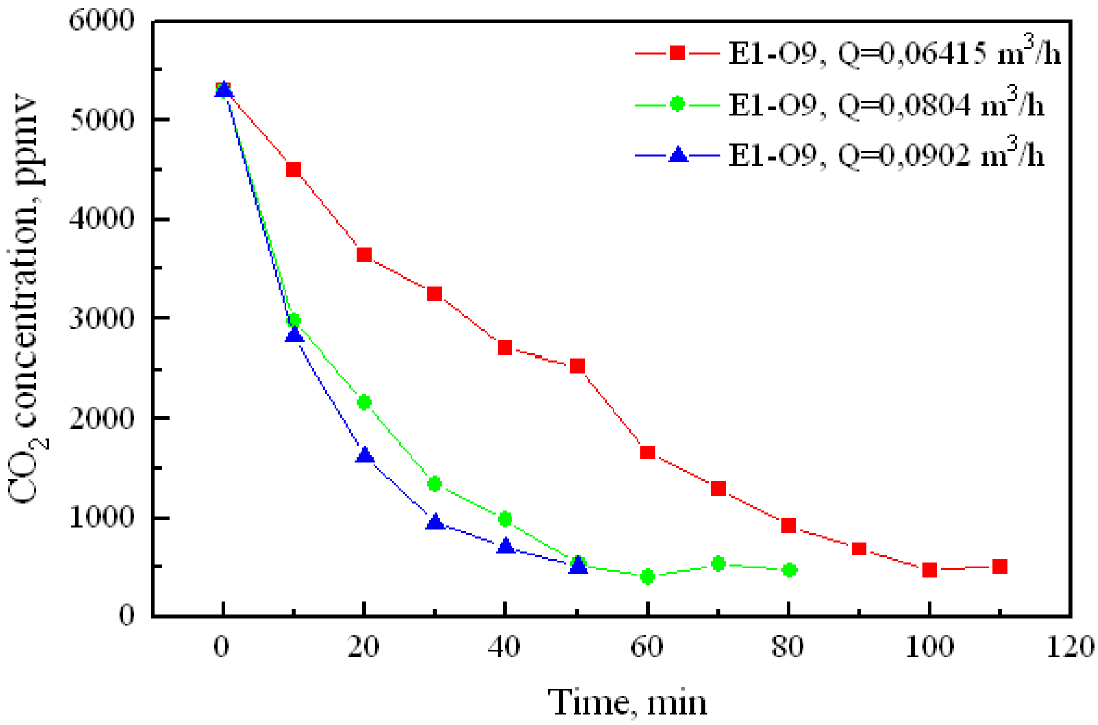

Figure 4.15 Effect of flow rate on windows E1-O9.

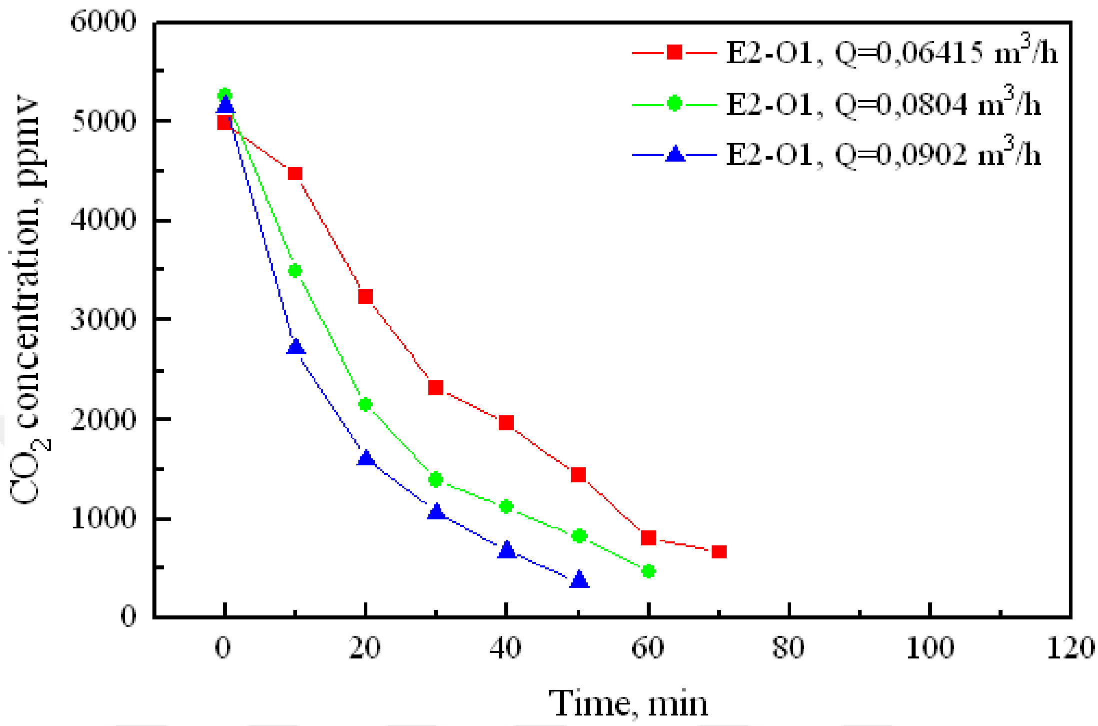

Figure 4.16 Effect of flow rate on windows E2-O1.

The impact of the three types of airflow was similar on windows E1-O6 and E1-O9, which can be attributed to the equal distance between the outlet and inlet windows. The high-flow airflow had an ideal effect on the aforementioned windows, as it was able to eliminate the pollutant gas within a duration of 50 minutes. On the other hand, the windows took 80 minutes to eliminate the pollutant gas in the average-flow airflow. The low-flow airflow had a longer effect on the windows, as it took 120 minutes to eliminate the CO_2 gas. This highlights the importance and effectiveness of the internal airflow and its impact on the windows.

The influence of airflow on window E2-O1 demonstrated promising outcomes across various airflow rates. Maximum flow rate efficiently removed CO_2 gas in 50 minutes, while the average flow rate achieved the same in 60 minutes. In contrast, the minimum flow rate required 70 minutes for CO_2 elimination. This observation underscores the significant impact of internal airflow on window performance, emphasizing the effectiveness of proper ventilation strategies in maintaining indoor air quality.

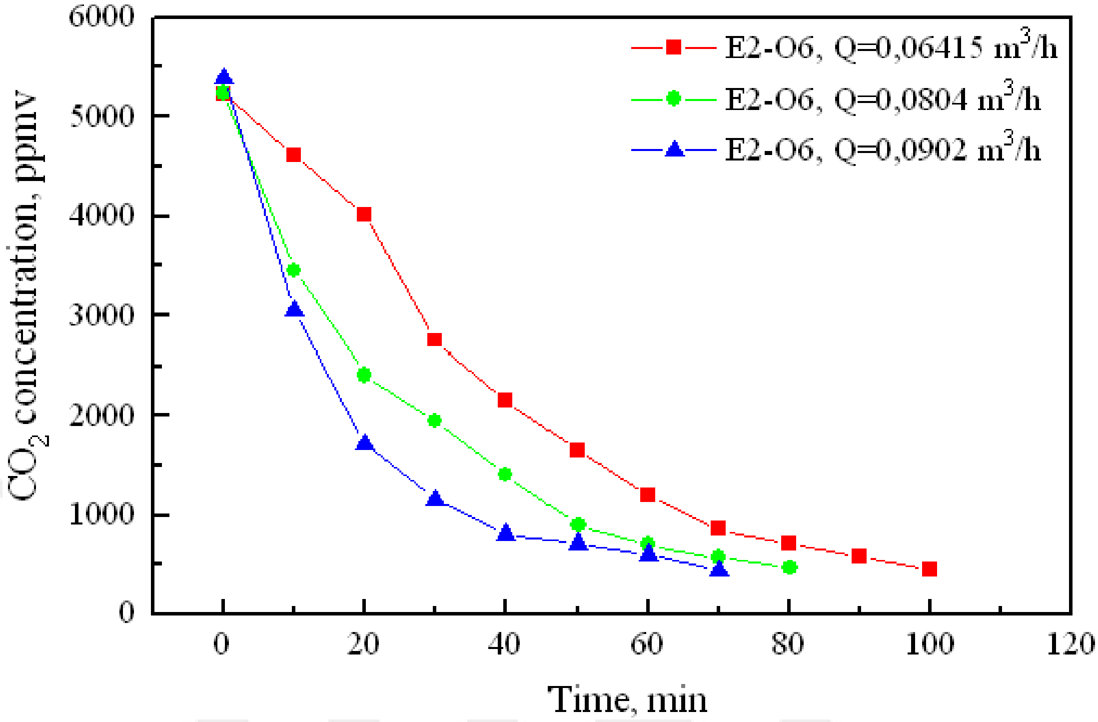

Figure 4.17 Effect of flowrate on windows E2-O6.

The influence of different airflow rates on window E2-O6 is evident, as depicted in Figure 4.18. Maximum flow rate ventilation demonstrated a substantial impact, effectively removing CO_2 gas in 70 minutes. Conversely, the average flow rate required 80 minutes to achieve the same level of removal, while minimum flow rate necessitated 100 minutes for complete elimination. This observation underscores the significance of airflow dynamics in determining the effectiveness of pollutant removal in a controlled environment. The results suggest that higher airflow rates contribute to more rapid indoor air quality improvement, emphasizing the importance of optimizing ventilation strategies for efficient pollutant dispersion and removal within a building environment.

The impact of the airflow on window E2-O9 was evident, as shown in Figure 4.18. The high-flow airflow had a significant effect on the window, achieving removal after 60 minutes. This indicates that high-flow air provides efficient ventilation and facilitates the expulsion of pollutants from the indoor environment.

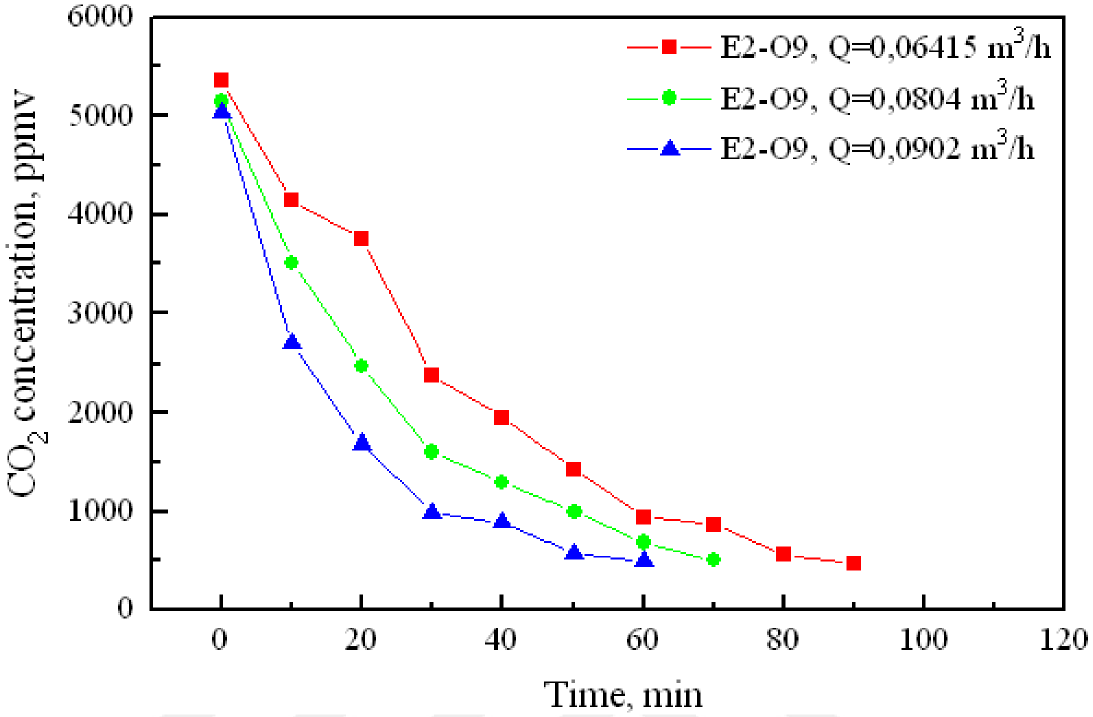

Figure 4.18 Effect of flow rate on windows E2-O9.

The average-flow airflow also had a noticeable effect on window E2-O9. It took slightly longer, around 70 minutes, to achieve the removal of CO_2 gas compared to the high-flow airflow. Nevertheless, it still demonstrated effective ventilation, albeit at a slightly slower rate.

The low-flow airflow had the longest duration for CO_2 gas removal from window E2-O9, taking approximately 90 minutes. This indicates that the low-flow airflow provides less efficient ventilation compared to the high-flow and average-flow scenarios. However, it still contributes to the gradual expulsion of pollutants from the indoor environment, albeit at a slower pace.

Overall, these findings demonstrate that higher airflow rates, such as high-flow and average-flow, result in more efficient and faster removal of CO_2 gas from window E2-O9, while the low-flow airflow is less effective but still contributes to the ventilation process over an extended period.

The primary emphasis was directed toward the central windows on both sides of the building. This preference stems from a common practice among designers during the architectural planning phase. Centered window placement serves multiple purposes beyond merely facilitating ventilation. Designers opt for this approach to achieve equilibrium and aesthetic cohesion within the building's overall design. Centralized windows offer a focal point that enhances the visual experience for occupants. Additionally, the strategic positioning of central windows aligns with various principles of architectural aesthetics, contributing to the overall appeal of the building design. This design choice underscores the meticulous considerations made by architects in harmonizing functionality and aesthetics in architectural projects.

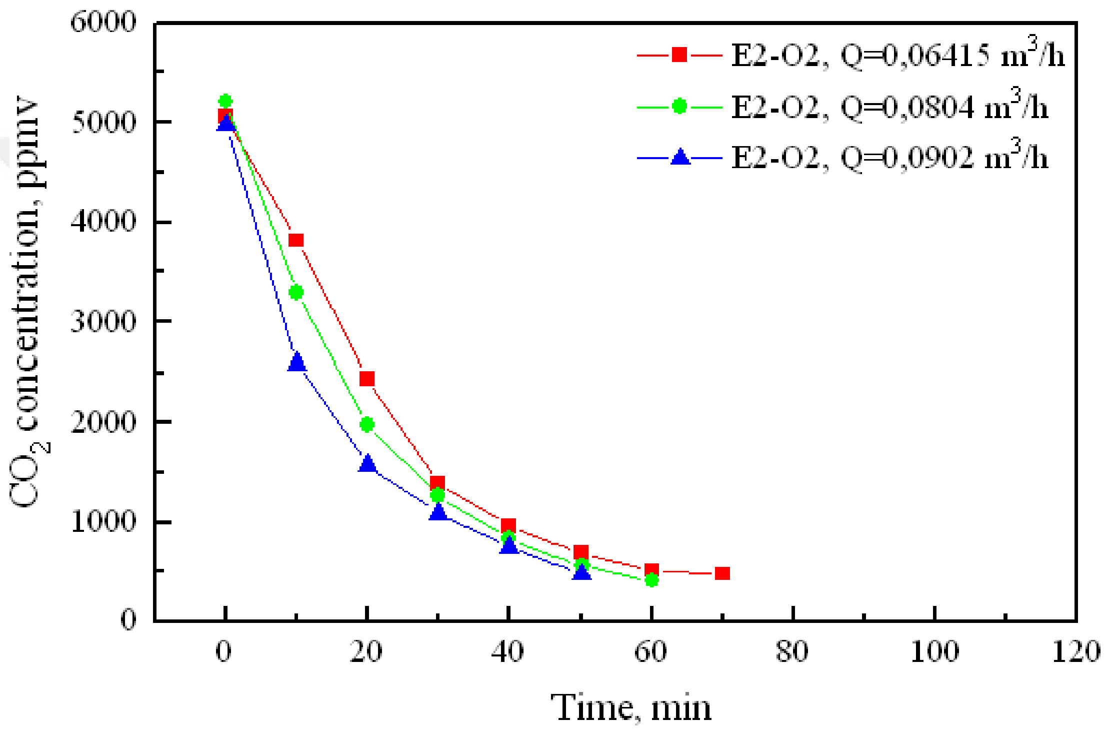

Figure 4.19 Effect of flowrate on windows E2-O2.

The influence of airflow on window E2-O2 demonstrated notable effectiveness across various airflow scenarios. Notably, the maximum flow rate exhibited a significant impact, successfully removing CO_2 gas within a 40-minute timeframe. Meanwhile, the average flow rate proved slightly less efficient, necessitating 60 minutes for CO_2 elimination. The minimum flow rate, while still effective, took 70 minutes to achieve the same removal result. These findings underscore the critical role of internal airflow in the context of indoor air quality and its implications for pollutant dispersion within a building environment.

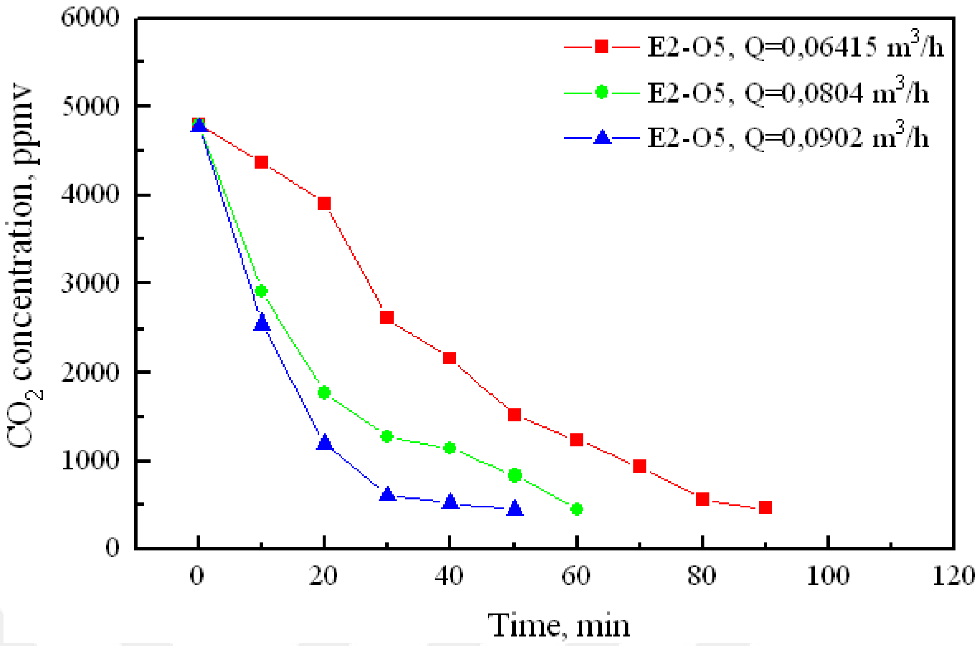

Figure 4.20 Effect of flowrate on windows E2-O5.

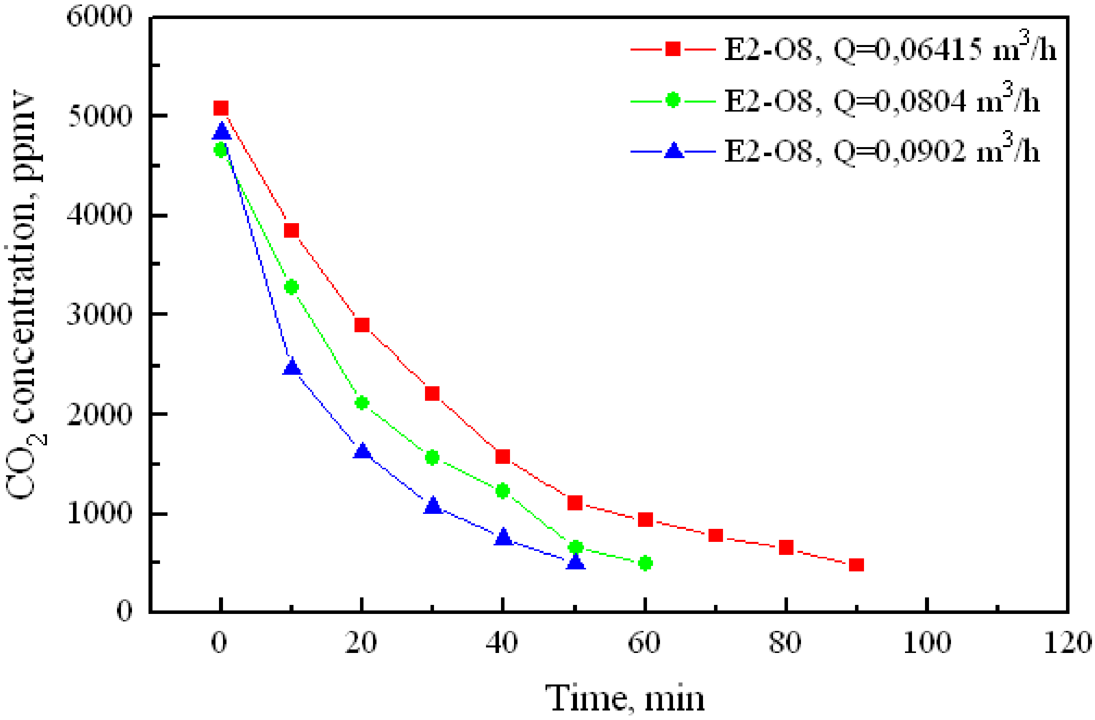

Figure 4.21 Effect of flow rate on windows E2-O8.

The study indicates that the influence of three distinct airflow types on the performance of windows E2-O5 and E2-O8 was found to be notably consistent. This consistency can be ascribed to the similar spatial distribution between the exit and entrance windows in question. Of the airflow types tested, the maximum flow rate demonstrated optimal efficacy, swiftly and efficiently eliminating the presence of pollutant gases from these windows within a mere 50-minute timeframe. In contrast, the average flow rate necessitated 60 minutes to achieve the same gas removal, and the minimum flow rate exhibited the most protracted impact, requiring a full 90 minutes for the mitigation of CO_2 gas. This observation underscores the pivotal role of internal airflow in influencing the performance of windows, revealing its significance in maintaining indoor air quality and energy efficiency in building environments.

5. CONCLUSION AND RECOMMENDATIONS

In this study, we conducted experiments in an environmental engineering laboratory to investigate the significance of window placement for enhancing natural ventilation in buildings. Our findings reveal that the location of windows on building façade plays a crucial role in determining air exchange rates and flow patterns within a room, particularly in the context of carbon dioxide (CO_2) reduction. Carbon dioxide, which is a common indoor air pollutant and can accumulate in indoors due to various sources including human respiration, was used as an indicator pollutant to describe the windows effectiveness. The study considered different window configurations and their impact on CO_2 concentration levels.

The results indicated that windows positioned strategically at different heights within the room can establish effective air circulation systems. In this design, fresh cool air enters the room near the ceiling and exits near the floor, thus carrying the CO_2 gas, which is heavier than air, out with it more easily. However, this may not be the case for gases whose density is lower than air, such as volatile organic compounds. Compared to the exit points located on the side and ceiling of the room, the ventilation type that allows the CO_2 in the room to be removed in the shortest time is the situation where the outlet is located opposite the entrance (cross-flow ventilation). Our findings align with previous research in this field, supporting the idea that greater penetration depth of fresh air into the room results in higher ventilation efficiency.

Recommendations for Thesis

Based on the research conducted in this study, we offer the following recommendations for further investigation and potential thesis topics:

1. Explore in-depth the specific optimal locations for windows within various types of buildings and under different environmental conditions to maximize natural ventilation and CO_2 reduction.
2. Investigate techniques for enhancing stack ventilation, such as using longer stacks or architectural features, to improve air flow and indoor air quality.
3. Delve into the development and implementation of advanced ventilation strategies that combine cross-ventilation, intermittent ventilation, and other

techniques to achieve superior indoor air quality with minimal energy consumption.

4. Utilize computational simulations and modeling tools to predict airflow patterns and CO_2 dispersion within buildings based on different window placements, aiding in the design and planning of energy-efficient and healthy buildings.
5. Develop comprehensive building design guidelines that incorporate the findings of this research to assist architects, engineers, and building designers in creating structures that prioritize natural ventilation and indoor air quality.
6. Investigate real-world applications of the research findings in existing buildings, assessing the feasibility of retrofitting windows and implementing ventilation strategies to improve indoor air quality.
7. Investigate the effect of interior design shape on ventilation.

The significance of window placement for enhanced natural ventilation in buildings is a vital aspect of sustainable and healthy building design. This research area holds substantial potential for further exploration and has the potential to significantly impact the way we approach building design and indoor air quality management in the future

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