# EFFECT OF SUN RADIATION EXPOSURE ON INDOOR AIR QUALITY OF CAR INTERIOR IN TROPICAL COUNTRY

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*Dedicated with much love and affection to my beloved parents and wife, who inspired me and sparked my interest in pursuing higher education, who are praying for me and provided me with support, help and encouragement every moment while studying Master of Mechanical Engineering that I have followed.*

*For my beloved mother Zakiah Angim  Binti Yussof, father Othoman Bin Mohd Pahang, and wife Siti Saleha Binti Abdul Azis*

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# ABSTRACT

Number of vehicle in Malaysia increasing rapidly and usually parked at open or un-shaded parking area due limited of roof parking facilities. Hot car interior after certain minutes or hours of parking due sun radiation exposure, forced car user to wait for a period of time to cool down the car interior temperature. Increase of car interior temperature caused heat stroke to living creature and degradation of material and finishes. The objective of this research are to determine air quality level in car interior due sun radiation exposure during a hot and sunny day in tropical country weather. The studies is focused to assess air quality parameters inside car interior such as temperature, particle matter ($PM_{10}$), relative humidity and carbon dioxide. Parameter data for indoor air quality has been analyzed in five different modes. Each modes data collection has been repeated for three days to reduce uncertainty. From experimental results, in sun radiation exposure car interior temperature can exceed 60% from ambient temperature. Sunshade installation and lowered 20 mm all windows caused reduction of interior temperature between 3% to 7%. Heat developed inside enclosed vehicle effected scattering of particle matter $PM_{10}$ in air. $PM_{10}$ concentration increased when circulation of air from outside have by windows gap. Relative humidity decreased when car interior temperature increased. $CO_2$ concentration is high at beginning of test but then gradually decrease to ambient concentration after certain period

**ABSTRAK**

Peningkatan jumlah kenderaan di Malaysia naik mendadak dan kebiasaanya kenderaan ini diletakkan di pakir terbuka disebabkan kurangnya kemudahan pakir kenderaan berbumbung. Suhu dalaman kereta yang tinggi setelah diletakkan pada tempoh masa tertentu dibawah sinaran matahari memaksa pengguna kereta menunggu pada sela masa tertentu sehingga suhu dalaman kereta turun. Sinaran matahari akan menyebabkan peningkatan suhu dalaman kereta seterusnya menyebabkan strok haba terhadap manusia dan haiwan yang ditinggalkan didalam kereta. Bahan yang digunakan untuk kemasan dalaman kereta menghasilkan reaksi kimia dan membentuk sebatian kimia apabila terdedah dengan suhu panas. Objektif kajian adalah untuk mengetahui tahap kualiti udara bahagian dalaman kereta di bawah sinaran penuh cahaya matahari di negara beriklim tropika. Kajian ini fokus kepada menilai tahap parameter-parameter kualiti udara di bahagian dalaman kereta seperti suhu, kelembapan, zarah dan gas karbon dioksida. Setiap parameter telah diukur dalam lima keadaan berbeza dan diulang sebanyak tiga kali untuk mengelakkan keraguan data. Dari hasil kajian yang telah dijalankan menunjukkan, pendedahan di bawah sinaran matahari, suhu dalaman kereta boleh melebihi 60% suhu ambien. Penggunaan pelindung cahaya matahari dan penurunan sebahagian tingkap hanya menyumbang 3% ke7% penurunan suhu maksimum. Bilangan zarah meningkat apabila terdapat pengaliran udara dan peningkatan suhu menyebabkan perawakan zarah yang meningkat. Peratus kelembapan udara menurun apabila suhu dalaman kereta meningkat. Kandungan gas carbon dioksida pada dalaman kereta agak tinggi pada permulaan dan menurun kepada nilai kandungan persekitaran.

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| | | |
|---|---|---|
| $CO_2$ | - | Carbon dioxide |
| IAQ | - | Indoor air quality |
| Max | - | Maximum |
| Min | - | Minimum |
| PM | - | Particle matter |
| ppm | - | Part per million |
| RH | - | Relative humidity |
| VOC | - | Volatile organic compound |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of study

Vehicle population in Malaysia rapidly increase due strong economy and income growth and hence most of people afford to buy their own vehicle. Malaysian drivers typically park the vehicles at open space or un-shaded parking area due lack of roof parking facilities. The problem that is faced by many car users today is a hot car interior after certain minutes or hours of parking in open space or un-shaded parking area. The car user is forced to wait for a period of time to cool down the car interior temperature either by lowering the window or switch on the air conditioner system at full that really affect the fuel consumption and other car parts or components due rapid cooling.

The climate in Malaysia is however, hot and humid. The data obtained by the Malaysia Meteorological Department (2015) for a ten-year period records relatively uniform outdoor temperatures with an average of between 23.7°C to 31.3°C throughout a day with highest maximum recorded temperature as 36.9°C with average relative humidity of between 67% to 95%.

Temperature, relative humidity, carbon dioxide and total concentration of air bone particulate matter is a part of indoor air quality components that used to determine how our air inside our buildings or space is in acceptance level. The rapid rise of car interior temperature inside static vehicles without nature or auxiliary ventilation in direct sun radiation exposure will damage property and harm human or pets left inside.

Excessive heat inside fully closed cabin temperature during hot sunny day will increase level of air bone chemicals in car interiors. The chemical mixture is consist of volatile organic compounds (VOCs), including formaldehyde; polybrominated diphenyl ethers (PBDEs), used as flame retardants; and phthalic acid esters (phthalates), which are emitted from materials and finishes used to make car interiors, such as plastics, leather, textiles, adhesive and sealants. Some car users lowering the driver or passenger windows when left the vehicle in un-shaded parking area to allow natural ventilation to reduce car interior temperature. These option will allow emission gases, solid particles and liquid droplets suspended in the air traps inside car interior.

## 1.2 Problem statement

Without any natural shading or roof in the parking area, the vehicle would be exposed to the sun radiation during the hot and sunny day at certain period of time. The sun radiation will strike directly the vehicle body and will also penetrate through the glass window. The heat from sun radiation will increase car interior temperature hence will caused heat stroke to human (frequently babies or children's) and pet after being left in hot vehicles. Material and finishes used to make car interiors will react to develop chemical substances or emission gases. Solid particles and liquid droplets suspended in the air will traps inside car interior when lowering the windows. Exposure to these substances will increase potential to get allergy and asthma symptoms and cause eye, nose and throat irritation.

## 1.3 Objective

The objective of this research is to determine indoor air quality level in direct sun radiation exposure in car interior during a hot and sunny day in tropical country weather.

## 1.4 Scope

The scopes of studies is focused to assess indoor air quality parameter inside car interior.

i. The test was carried on sunny day weather.
ii. The condition of testing vehicle is static (parking mode) in open air (un-shaded) and roof (shaded) parking area.
iii. A white sedan car with approximately 3 $m^3$ volume of size was used and the vehicle is originally manufactured specification.
iv. The car was located at same orientation and same place during entire experimental measurement session.
v. Four parameter of indoor air quality has been assessed which are temperature, carbon dioxide, particle matter ($PM_{10}$) and percent of relative humidity.
vi. Measuring devices were placed inside car compartment during observation time from 12.00 hrs to 14.00 hrs to record all parameter data.
vii. Data has been taken in five different modes for shaded and un-shaded condition.
viii. Each modes data collection has been repeated for three days to reduce uncertainty.

## 1.5 Significant of study

The finding of this study will contribute to develop of safety awareness guidelines about vehicle indoor air quality for car user. Safety awareness guidelines will reduce the health risk factor. Data from the findings it's quite useful as reference to design vehicle active climate and air quality control device.

# CHAPTER 2

# LITERATURE REVIEW

This chapter describes the principles and characteristics of indoor air quality standards, air quality variable which are temperature, relative humidity, particle matter and emission gasses carbon dioxide.

## 2.1 Indoor Air Quality

According to (ANSI/ASHRAE Standard 62.1-2007) indoor air quality (IAQ) define as air which are known contaminants at harmful concentrations as and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction. Indoor air quality problems in confined space primarily caused by internal pollution sources that release gases or particles into the air. Insufficient ventilation can increase pollutant levels by not bringing in enough fresh air to reduce emissions from internal sources and by not carrying indoor air pollutants out of the space. Excessive temperature and humidity levels also will increase level of pollutants.

Therefore indoor environment in car interior could be viewed as a kind of residential environment that is equipped with air conditioning system (Yokoyama, et. al, 2007). Study on the quality of vehicle air indoor has been very limited; e.g. by Yokoyama, et. al, (2007) and Nakagawa, et. al, (2007). On the other hand, there are a lot of reports available on study of indoor air quality in buildings; for example in the work by Sulaiman, et. al, (2013), and Harun, et. al, (2013). Table 2.1 shows recommended standard and guidelines for indoor air quality for office building from

Department of Occupational Safety and Health, Malaysia (2010) and Institute of Environmental Epidemiology, Singapore (1996).

Table 2.1: Recommended indoor air quality standard and guideline (Source: [1]Department of Occupational Safety and Health, 2010 and [2] Institute of Environmental Epidemiology, 1996)

| **Indoor air quality parameter** | **Malaysia[1] (Maximum limit)** | **Singapore[2] (Maximum Limit)** |
|---|---|---|
| Carbon dioxide, (ppm) | 1000 | 1000 |
| Carbon monoxide, (ppm) | 10 | 9 |
| Respirable particulates ($PM_{10}$), ($mg/m^3$) | 0.15 | 0.15 |
| Air Temperature, °C | 23 - 26 | 22.5 – 25.5 |
| Relative Humidity, % | 40-70 | 70 |

## 2.2 Temperature Variation

According to Hussain, et. al, (2010) solar irradiation increases with time to maximum values between 12.00 hrs to 14.00 hrs as shown in Figure 2.1. The mean value of 500±50 $Wm^{-2}$ depending on the cloud conditions. They also run experimental and numerical analysis effect of 20 mm window gap and sunshade on thermal accumulation inside a parked car cabin. The use of the sunshade and lowering windows on both sides reduced the heat accumulation due to fresh air exchange with the exterior environment.

Temperature level in car interior can be more 20 ºC above the ambient temperature when a car is parked and exposed to sun radiation as verified by Dadour, et. al, (2011). They build a simple ‘greenhouse’ model for predicting the daily interior vehicle temperatures of black and white vehicles. They also demonstrated car interior temperature can be reduce typically 3 ºC with lowering the driver's window by 25 mm as shown in Figure 2.2. Jan Null, CCM (2003) from Department of Geosciences, San Francisco State University has been demonstrate estimated vehicle interior air temperature vs elapsed time as shown on Table 2.2.

Kaynakli, et. al, (2005), measured temperature and humidity at a various points inside a sedan car during heating period. The instant and transient temperature distributions of all surfaces inside an automobile and investigate the thermal discomfort that was caused by those surfaces has been measured by Korukcu, et. al, (2009) using infrared thermography. Mezrhab, et. al, (2006), demonstrated a numerical model to study the performance of thermal comfort inside the car interior according to climatic conditions and materials that compile the vehicle.

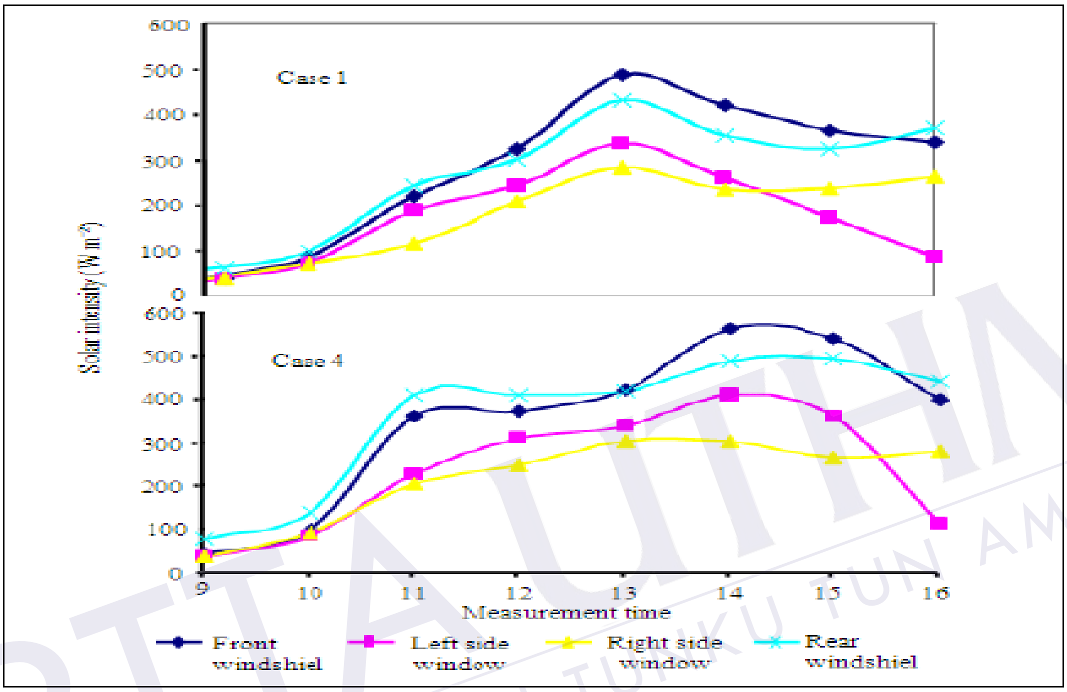


Figure 2.1: Solar intensity results of car interior (Source: Hussain, et al, 2010)

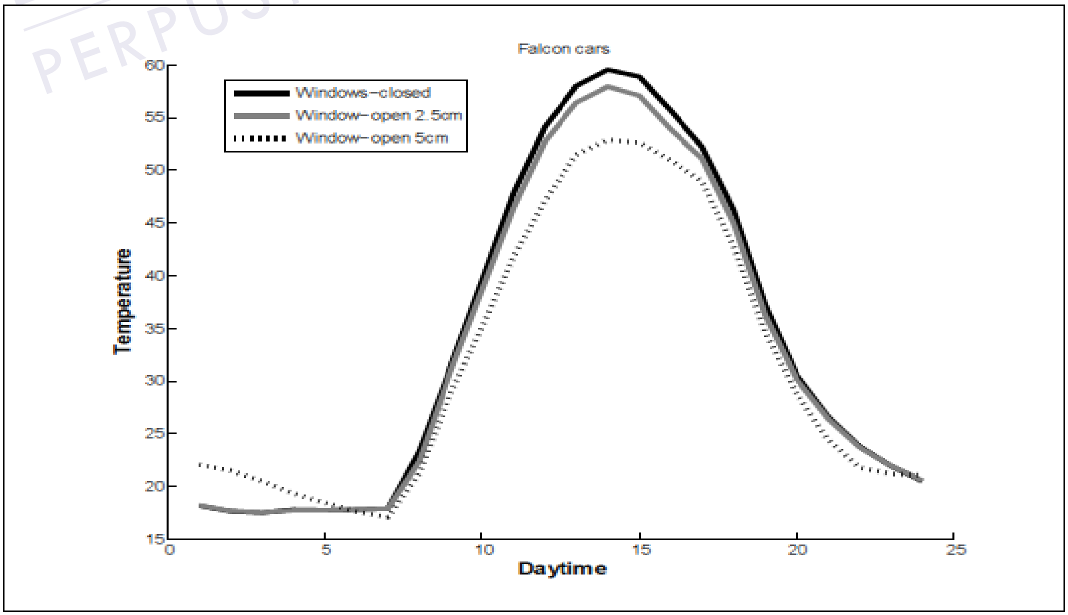


Figure 2.2: Ventilation effects to interior temperature (Source: Dadour, et. al, 2011).

Table 2.2: Estimated vehicle interior air temperature elapsed time (Source: Jan Null, CCM, 2003)

| **Elapsed time** | **Outside Air Temperature (ºF)** | | | | | |
|---|---|---|---|---|---|---|
| | 70 | 75 | 80 | 85 | 90 | 95 |
| **0 minutes** | 70 | 75 | 80 | 85 | 90 | 95 |
| **10 minutes** | 89 | 94 | 99 | 104 | 109 | 114 |
| **20 minutes** | 99 | 104 | 109 | 114 | 119 | 124 |
| **30 minutes** | 104 | 109 | 114 | 119 | 124 | 129 |
| **40 minutes** | 108 | 113 | 118 | 123 | 128 | 133 |
| **50 minutes** | 111 | 116 | 121 | 126 | 131 | 136 |
| **60 minutes** | 113 | 118 | 123 | 128 | 133 | 138 |
| **> 1 hour** | 115 | 120 | 125 | 130 | 135 | 140 |

## 2.3 Relative Humidity

According to the American Heritage Science Dictionary (2014) relative humidity is the ratio of the actual amount of water vapour present in a volume of air at a given temperature to the maximum amount that the air could hold at that temperature, expressed as a percentage. Warm air can hold more water vapour than cool air, so a particular amount of water vapour will yield a lower relative humidity in warm air than it does in cool air.

Relative humidity can influence comfortable feels of occupants in a certain space. The ASHRAE (1999) advises a relative humidity range of 30% to 60% in occupied spaces. The occupied spaces can relates to office or educational buildings, entertainment venues and medical facilities. Some medical facilities have different relative humidity requirements which are based on the condition and purpose.

Low relative humidity can have negative effects on human wellbeing and health. Arundel, et. Al, (1986) stated that low relative humidity cause eye irritation and may increase the occurrence of "infective aerosols produced by coughing or exhaling." People stay indoors for long time period during winter easy to get respiratory infection by weakening the defences provided by the mucous membranes. They also state relative humidity between 40% and 70% can minimize the infectivity of bacterial and viral organisms. Oak Ridge National Laboratory (2000) states, relative humidity below 30% can cause nosebleed, sinus and tracheal irritation and dry skin.

High relative humidity can considered when it is above 60%. Too high percentage of humidity can cause occupant discomfort, building and paper-based materials damage, mold and fungi growth, the existence of dust mites, and develop infectivity of bacteria and viruses. When humidity is increased, the human body has more complexity in cooling itself through perspiration. If the perspiration cannot disappear from the skin due to the increased relative humidity, then the people will become uncomfortable. Asthma can be triggered by allergens produced by dust mites.

High relative humidity can contribute problems to building materials. Moisture from air will absorbed by acoustical ceiling tiles, causing sagging. Wallboard can absorb enough moisture in a high humidity space to the extent that it supports mold or fungi growth, which itself can damage wallboard. High relative humidity also can contribute to the degradation of books and other paper-based materials as they become attractive place for mold and for house dust mites. House dust mites can increase in space where the relative humidity exceeds 50% and fine organic particles are readily available. These dust mites can be found in all types of indoor environments besides residential properties. Arundel, et. al, (1986) has been summarized the effect relative humidity on chemical and biological factor as shown in Figure 2.3

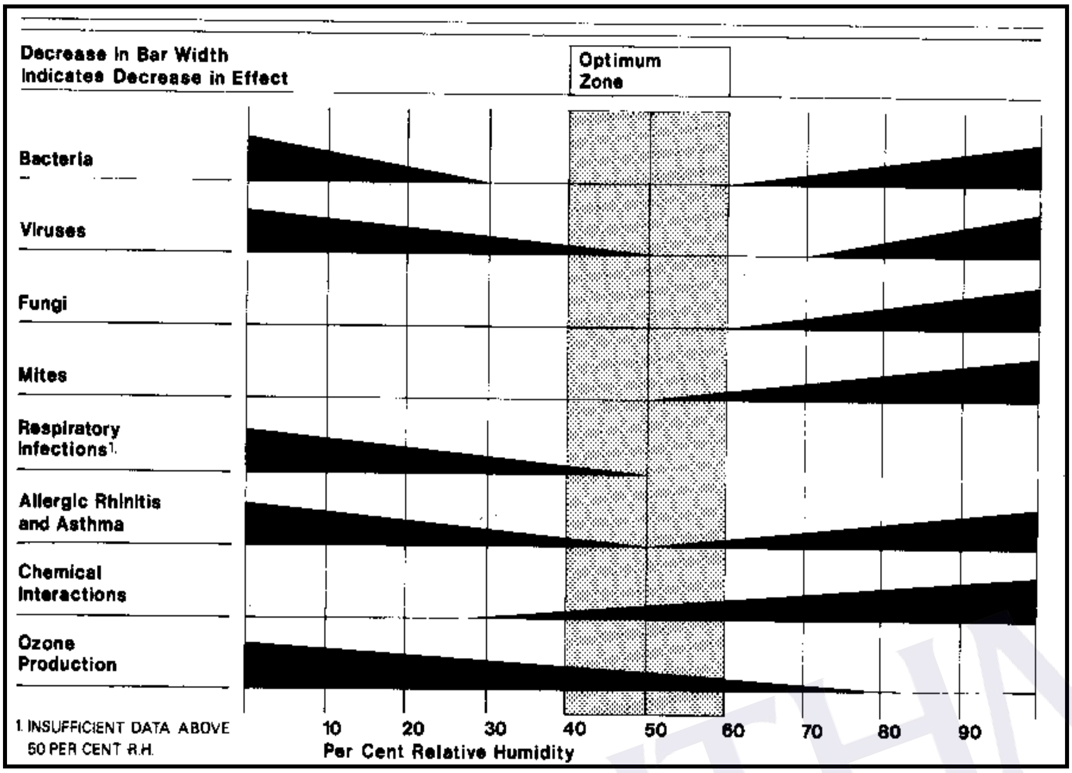


Figure 2.3: Optimum relative humidity range for minimizing health risk (Source: Arundel, et. al, 1986)

## 2.4 Carbon Dioxide

Carbon dioxide ($CO_2$) is the primary greenhouse gas released through human activities. Basically, when humans breathe out, $CO_2$ is one of the gases that are released. If there is limited ventilation within a confined space, $CO_2$ can build up. $CO_2$ is one of the parameters evaluated during a indoor air quality study. ASHRAE, (1999) recommends that the $CO_2$ concentration within an occupied space be no more than 700 parts per million (ppm) above the outdoor $CO_2$ concentration. Typically, outdoor $CO_2$ levels range between 300 and 400 ppm. If 700 ppm be added to these levels, then occupied space should not exceed 1,000 to 1,100 ppm of $CO_2$.

The National Institute of Environmental Health Science (NIEHS), (2012) demonstrated a findings “At 1,000 ppm $CO_2$, compared to 600 ppm, performance was significantly diminished on six of nine metrics of decision-making performance.” From this findings, it's a safe condition while maintaining $CO_2$ concentrations well-below the ASHRAE recommended level. Elevated $CO_2$ levels created from occupants' respiration inside car interiors can cause drowsiness and slow reaction times. If $CO_2$ concentration becomes too high, the air gets stale or ventilation in recycle mode and the occupants will not feel comfortable. Complaints usually begin when carbon dioxide concentrations reach about 800 ppm and become more common when carbon dioxide exceeds 1000 ppm. Praml, et. al, (2000) state if the level of carbon dioxide is too high, more fresh air would be required to dilute the $CO_2$ content. Mohd Sahril Mohd Fouzi, et. al, (2014), conducted a study of $CO_2$ concentration while a vehicle is driving with three occupants in intermittence mode (recirculation and fresh air). As shown in Figure 2.4 the $CO_2$ concentration increase when air conditioning ventilation in recirculation modes and decrease when in fresh air mode.

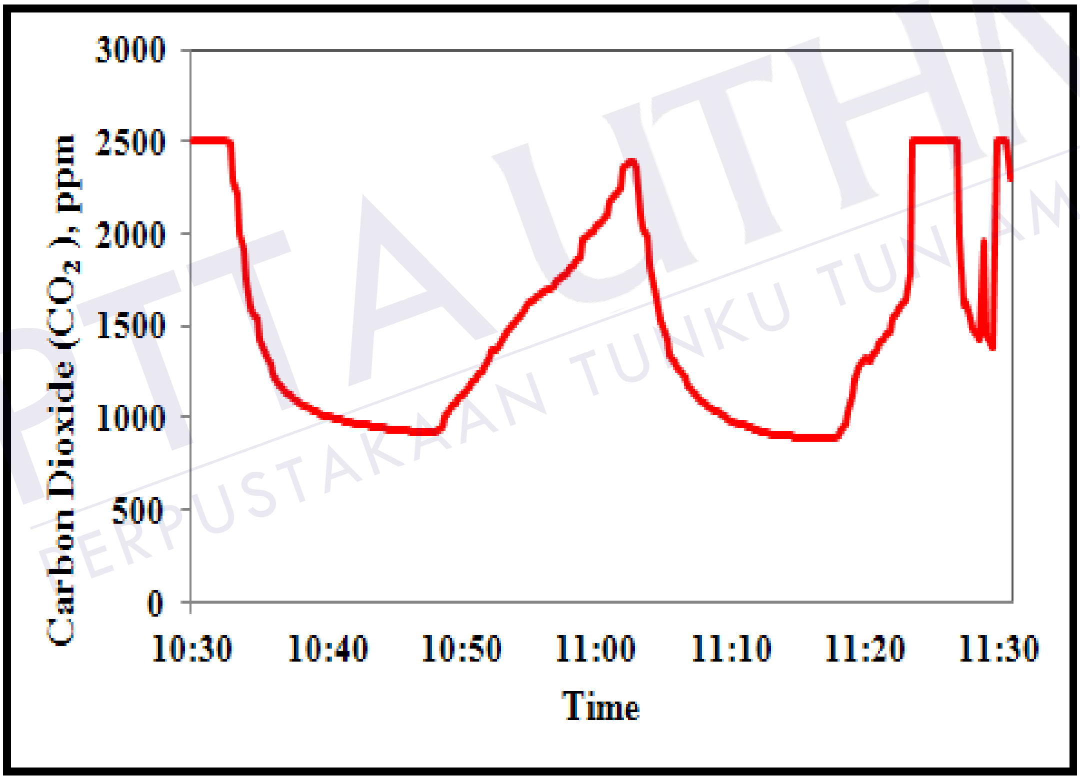


Figure 2.4: Variation of Carbon Dioxide ($CO_2$) in ppm with time for intermittence test (Source: Mohd Sahril Mohd Fouzi, et. al, 2014)

## 2.5 Particulate Matter

Particulate matter (PM) is the word used for a combination of very small solid particles and liquid droplets suspended in the air. These particles originated from a variety of activities, such as constructions, industrial, and transportations. Incomplete combustion from transportation engine and waste from industrial or construction then transformed to gaseous emissions hence suspended in the atmosphere as particulate matter. Particles can be carried over long distances by wind and then settle on ground or water. Particulate matter in a car compartment can be unhealthy. Particles are small enough to infiltrate nasal, sinus, and bronchial passages where they can affect passenger's health and comfort. Small particles less than 10 micrometers in diameter pose the greatest problems, because they can get deep into lungs, and some may even get into bloodstream and affect heart. Particulate matter can be divided in two categories, inhalable coarse particles and fine particles. Figure 2.5 shows how big pollution particle comparing to human hair and fine beach sand.

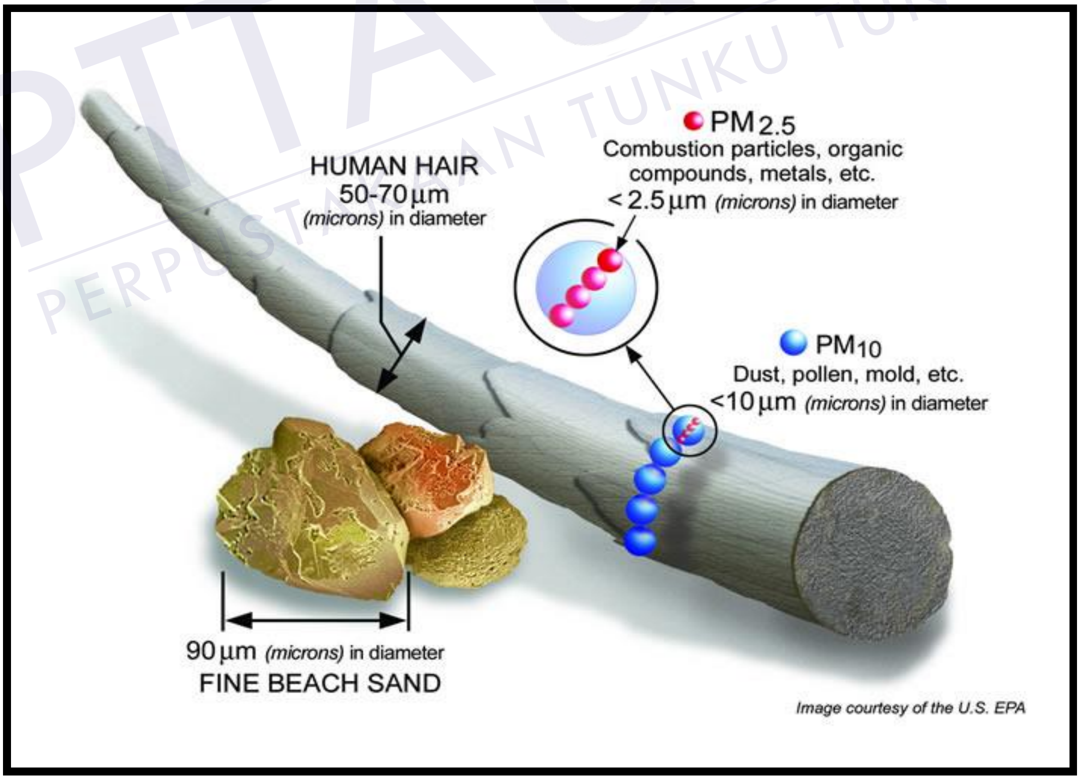


Figure 2.5: Size of particulate matter (Source: www.epa.gov.my, 2014)

Coarse particles ($PM_{10}$) have a diameter size between 2.5 micrometers and 10 micrometers. They are formed by mechanical interference such as crushing, grinding, abrasion of surfaces and also formed by evaporation of sprays, and suspended of dust. $PM_{10}$ is composed of aluminosilicate and other oxides of crustal elements, and major sources including dust from roads, industry, agriculture, construction and demolition, and fly ash from fossil fuel combustion. $PM_{10}$ travel distance varies from below 1 kilometer to 10 kilometer and its life time from minute to hours. Praml, et. al, (2000) signified that particulate matter concentration level inside vehicles comes from external sources. Mohamad Asyraf Othoman, et. al, (2014) demonstrated concentration level of $PM_{10}$ achieved maximum value when cars following heavy vehicle in fresh air ventilation mode and slightly stable when switch to recirculation mode.

Fine particles ($PM_{2.5}$) have diameter size less than 2.5 micrometers. These particles are formed from gas and condensation of high-temperature vapours during combustion, and they are composed of various combinations of sulphate compounds, nitrate compounds, carbon compounds, ammonium, hydrogen ion, organic compounds, metals (Pb, Cd, V, Ni, Cu, Zn, Mn, and Fe), and particle bound water. The major sources of $PM_{2.5}$ are forest fires, or they can form when gases emitted from power plants, industries and automobiles react in the air. $PM_{2.5}$ travel distance varies from 100 kilometer to 1000 kilometer and its life time from days to weeks. Figure 2.6 shows the size range and types or source of particulate matter.

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