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Development of Mathematical Model for Aircraft LTO Emissions at Port Harcourt and Lagos International Airports, Nigeria

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Abstract:- The levels and trend gaseous emissions from aircraft landing and take-off operations and the resulting Air Quality Index (AQI) at the Lagos and Port Harcourt international airports have been investigated in this study for the years 2020-2022. Data for this study was collected from the Nigerian AIRSPACE MANAGEMENT AGENCY In Port Harcourt and Lagos.The levels of gaseous pollutants recorded at the Lagos airport were; CH4 (54190 - 60030 ppm), CO (9443.0 - 9510.9 ppm), CO2 (3162949.6 – 316309.7 ppm) and SO2 (92180 – 94190 ppm) while the Port Harcourt airport recorded levels of CH4 (562.6- 600.7 ppm), CO (822.3 - 942.0 ppm), CO2 (2963254.4 – 316309.7 ppm) and SO2 (11252.9 – 12019.4 ppm). The AQI at both airports showed that the air quality during the landing and take-off operations is hazardous and may pose occupational health risks, thus measures necessary to mitigate these risks should be put in place.

I. INTRODUCTION

➢ *Background to the Study*

Continuing rapid growth in aviation would provide economic benefits and allow greater mobility amongst the world's population. However, these benefits would come at a cost, most notably a significant increase in aviation greenhouse gas emissions. While aviation is not currently one of the main drivers of global warming, the growth trajectory of the industry suggests it could become a significant factor over the coming decades. A report prepared by the Intergovernmental Panel on Climate Change (IPCC) in 1999 at the request of the ICAO found that civil aviation carbon dioxide (CO2) emissions could rise by between 60 per cent and over 1000 per cent between 1992 and 2050 (IPCC, 1999). More recent research suggests that if strong global economic growth continues, aviation CO2 emissions are likely to experience a greater than three-fold increase between 2000 and 2050 (Berghof et al., 2005) Concerns about rapid growth in the industry and the associated threat to the climate system have prompted debate about the future of aviation.

According to the Air Transportation Action Group (ATAG2007), the global aviation industry, counting over 3 billion air passengers, produced 705 million tons of CO2 in 2013, accounting for 2% of the human-induced CO2 emissions and 13% of total transportation- related emissions. According to the 2016 European Aviation Environmental Report by European Aviation Safety Agency (EASA), there were 80% more European flights in 2014 compared with the number of flights in 1990. This environmental impact has increased regardless of possible technology improvements: in 2014, there was +5% more aviation- induced CO2 with respect to the level in 2005, and +44–53% more CO2 is estimated in 2035.

Politicians and regulators have agreed to limit CO2 emissions in response to public pressure on the issue of climate change. For instance, the 2015 Paris agreement established a temperature increase limit to 37°C above pre-industrial levels. In 1997, the Kyoto Protocol was signed, and the International Civil Aviation Organization (ICAO) was assigned to lead the establishment of global aviation CO2 regulation. Reaction to this regulation varied among countries. New Zealand and Australia initiated domestic aviation emission trading in 2010 and 2012 respectively, while the EU introduced the Aviation Directive in 2012 on both intra- EU and extra-EU flights as an extension of its already implemented Emission Trading Scheme (ETS) in other sectors in 2005. Extra-EU flights were then waived after legal action had been brought against the directive by some airlines and the International Air Transport Association (IATA)—the so-called ―stop the clock‖ decision that should have stayed enforced until 2016. However, to the best of our knowledge, the directive is still in force today.

After several meetings, during its 39th assembly, the ICAO approved a global market-based measurement (GMBM) scheme, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). This type of scheme will be enforced through different phases starting in 2020. CORSIA, which is different from the EU-ETS, will be applied to all flights, not only flights in the European Economic Area.

Thus, providing an econometric estimate of the sign and magnitude of some factors regarding CO2 aviation emissions is the first goal of this paper.

➢ *Statement of the Problem*

There are growing concerns about the emissions of particulates from aircrafts and other health impacts they may have. Fugitive particulate emissions from aircrafts are not well understood but are believed to be equal in magnitude to emissions from the engines.

Compilers of these emissions inventories need a practical methodology for estimating particulate emissions with a good evidence base.

- *Aim and Objectives*

The aim of this research is to develop mathematical formulas for aircraft emissions fromaviation operations in Port Harcourt and Lagos international Airports.

- *This will be Achieved Through the following Objectives:*

- To determine the trend of aircraft emissions (CO, NO2, CO2, SO2).
- To investigate the aircraft emissions on air quality.
- To investigate the amount of nonvolatile gases and methane emitted from aircraftsoperating into and out of these airports.

- *Scope and Limitation of the Study*

The scope of this research is limited to Port Harcourt International and Lagos Airports for thea few years.

The study intended to cover beyond LTO cycles and total flight emission data but was limitedto LTO cycles for both airports due to insufficient data.

Furthermore, the study intended to cover 20 years (2003-2023) but was limited to 3 years forinsufficient data due to record keeping and office bottleneck.

II. METHODOLOGY

- *The Study Areas*

The study areas of this research work are Murtala Mohammed International Airport, Lagos State, Nigeria (Fig 3.1) and Port Harcourt International Airport (Fig 3.4).

Lagos State is located on the south-western part of Nigeria on the narrow coastal flood plain of the Bight of Benin. Murtala Mohammed International Airport (MMIA) (IATA: LOS, ICAO: DNMM) is an international airport located in Ikeja, Lagos State, Nigeria, and is the major airport serving the entire country. The airport was initially built during World War II. Originally known as Lagos International Airport, it was renamed in the mid 1970’s, during construction of the new international terminal, after a former and fourth Nigerian military head of state, Murtala Mohammed. It lies approximately between latitude 6°22'N and 6°42'N of the equator and between longitude 2°42'E and 3°22'E of the Greenwich Meridian. It is bounded to the North and East by Ogun State of Nigeria, to the West by the Republic of Benin, and to the South by the Atlantic Ocean. Territorially, Lagos State encompasses an area

Port Harcourt International Airport (IATA: PHC, ICAO: DNPO) is an international airport located in Omagwa, a suburb of Port Harcourt city in Rivers State, Nigeria (Enete et al., 2015). The airport lies between latitude 04°49' 27"N and longitude 7°2'1"E and at attitude above 91ft (27.7m) mean sea level (coordinates; 4.824167N and 7.033611E). It has a areaof 2,700/km2 (7,100/sqm). At the 2006 census, Port Harcourt had a population of 2,000,000.

It is a public airport operated by the Federal Airports Authority of Nigeria (FAAN). Currently undergoing final phases of reconstruction to physical structures with two terminals for domestic and international flights. The single asphalt-surfaced runway at the airport has a length of 9,846ft (3, 00/m) and a width of 197ft(60m).

- *Data Collection for Aircraft Emissions*

An exploratory data analysis (EDA) on the relationship between aircraft emissions and flight operations at Port Harcourt and Lagos Airport.

- *Data Collection:*

Gathering of data on aircraft emissions (e.g., CO2, NOx) and flight operations (e.g., number of flights, flight duration) at Lagos and Port Harcourt Airports. Ensuring the data covers a significant time period.

- *Data Preprocessing:*

Cleaning the data for analysis. Handle missing values, formatinconsistencies, and outliers appropriately.

- *Descriptive Statistics:*

Calculated basic statistics such as mean, median, standard deviation,and range for both aircraft emissions and flight operations. This will provide an initial understanding of the data.

Mathematical Model for Aircraft Emissions

The aircraft total weight $w(t)$ is prepared as a sum of a fixed and a time varying term.

$$w(t) = w_0 + w_f(t) \tag{1}$$

Where the time fixed term w_0 includes in the general case, the operating empty and payload weight of the aircraft.

The time-varying term $w_f(t)$ refers to the fuel weight, which is the fuel mass $m_f(t)$ multiplied by the gravitational acceleration g.

$$w_f(t) = m_f(t)g$$

Fuel mass variation, also known as fuel flow rate/ burn is described by the fuel consumption relationship for a jet engineer aircraft.

$$\frac{dm_f}{dt} = -C_j f(t) \tag{2}$$

Being $\frac{dm_f}{dt}$ the fuel flow rate

C_j the thrust specific fuel consumption

$f(t)$ the aircraft thrust.

Hence a direct relationship can be obtained between equation (1) and (2) taking the time derivative of (3).

$$\frac{dw}{dt} = \frac{dm_f}{dt}g = -C_j f(t)g \tag{3}$$

The objective of this study is to determine whether it is possible to integrate and thereby find a close-form solution of equation (5) under the constraints established by the equation of motion of the cruising flight phase.

The equation of flight configuration can be reduced to the following expression:

$$W(t) = L(t) \tag{4}$$

$$F(t) = D(t) \tag{5}$$

Where the aerodynamics force, lift ($L_{(t)}$)

Drag $C_D(t)$ are defined by

$$L(t) - \ qAC_L(t) \tag{6}$$

$$D(t) - \ qAC_D(t) \tag{7}$$

Being q the dynamic pressure defined as $q = \frac{1}{2}\varsigma V^2$ in what

ς is the density of air

V is the time speed of the aircraft

A is total wing area is a known geometric parameter.

$C_L(t)$ is the lift coefficient

$C_D(t)$ is the drag coefficient

$$C_D(t) = C_{D,0} + K_{CL}(t)^2 \tag{8}$$

Where $C_{D,0} > 0$ is the zero – lift drag coefficient and $K > 0$ is the induced drag factor.

The latter is a function of the Oswald efficiency factor e and the aircraft aspect ratio AR

i.e. $K = 1(\pi AR_e)$

Aspect ratio is defined as the squared term of the aircraft wingspan b^2 divided by A.

Closed-form solution of the fuel consumption for the cruising flight phase

In the following section, the derivative for closed-form expression of the aircraft's weight as a function of time with $t\epsilon(0, t_{cr})$

Where $t = 0$, and $t = t_{cr}$ are the initial and final time instants of the cruising flight phase respectively from (7) and (9), we have

$F(t) = qAC_D(t)$

by combining (6), (8) and (10), we obtain

$$C_D(t) = C_{D,0} + K\left(\frac{w(t)}{qA}\right)^2 \tag{9}$$

and hence

$$F(t) = qA_{CD,0} + \frac{K}{qA}\left(w(t)\right)^2 \tag{10}$$

Equation (12) expresses the aircraft thrust as a function of weight, therefore the following differential equation is obtained from (5)

$$\frac{dw}{dt} = -C_j g\left(qA_{CD,0} + \frac{K}{qA}(w(t)^2)\right) = k_1 + k_2(w(t)^2) \tag{11}$$

Where k_1, k_2 are constant parameter defined as

$$\left.\begin{aligned} k_1 &= -C_j g A_{CD,0} \\ k_2 &= C_j g \frac{k}{qA} \end{aligned}\right\} \tag{12}$$

Observe that $k_1 \neq 0$ and $\frac{k_2}{k_1} > 0$

Integrating (13) lend to

$$\int \frac{w^1(t)dt}{1+\left(\frac{k_2}{k_1}\right)(w(t)^2)} = k_1 \int dt$$

Whose solutions is given by

$$\sqrt{\frac{k_1}{k_2}}\arctan\left(\sqrt{\frac{k_2}{k_1}}w(t)\right) = k_1 t + C \quad (13)$$

Where C is an arbitrary constant reordering terms

$$\arctan\left(\sqrt{\frac{k_2}{k_1}}w(t)\right) = k_1\sqrt{\frac{k_2}{k_1}}t + C' \quad (14)$$

Since $w(0)$ is the initial course weight

$$C' = \arctan\left(\sqrt{\frac{k_2}{k_1}}w(0)\right) \quad (15)$$

We obtain the implicit formula

$$\arctan\left(\sqrt{\frac{k_2}{k_1}}w(t)\right) - \arctan\left(\sqrt{\frac{k_2}{k_1}}w(0)\right) = k_1\sqrt{\frac{k_2}{k_1}}t \quad (16)$$

Applying the rule of a tangent of a sum:

$$\frac{\sqrt{\frac{k_2}{k_1}}(w(t)-w(0))}{1+\left(\frac{k_2}{k_1}\right)w(t)w(0)} = \tan\left(k_1\sqrt{\frac{k_2}{k_1}}t\right) \quad (17)$$

or equivalently,

$$w(t)\left(\sqrt{\frac{k_2}{k_1}} - \frac{k_2}{k_1}w(0)\tan\left(k_1\sqrt{\frac{k_2}{k_1}}t\right)\right) = w(0)\sqrt{\frac{k_2}{k_1}} + 1 \quad (18)$$

let

$$\beta = w(0)\sqrt{\frac{k_2}{k_1}} = \frac{w(0)}{qA}\sqrt{\frac{k}{C_{D,0}}} \quad (19)$$

Combining equation (14), (20) and (21), yields and explicit formula

$$w(t) = w(f)\cdot\frac{1-\left(\frac{1}{\beta}\right)\tan\left(C_{jg}\sqrt{C_{D,0}}kt\right)}{1+\tan\left(C_{jg}\sqrt{C_{D,0}}kt\right)} \quad (20)$$

Equation (21) provides the closed-form expression of the aircraft weight as a function of time.

From (1) and (9), we obtain

$$\frac{dm_f}{dt} = -C_j q A_{CD,0}\left(1 + \left(\frac{w(t)}{qA}\sqrt{\frac{k}{C_{D,0}}}\right)^2\right) = -C_j q A_{CD,0} \tag{21}$$

Substituting (22) in (23) being

$$\frac{dm_f}{dt} = -C_j q A_{CD,0}\frac{(1+\beta^2)(1+\tan^2(C_{jq}\sqrt{C_{D,0}kt}))}{(1+\beta\tan(C_{jq}\sqrt{C_{D,0}kt}))^2} \tag{22}$$

Equation (21) represent the closed-form formula of the aircraft. Fuel flow rate which enable further optimization and sensitivity analysis in order to evaluate the dependent on aerodynamic and enjoin parameter with the objective of reacting a more efficient fuel burn and emission note that the negation sign means that fuel is consumed in $t\epsilon[0, t_{cr})$.

This mathematical model to obtain a closed-form expression for the amount of aircraft emission of an aircraft during cruising time. Knowing the emission, during the cruising flight phase along with its associated cost index, would enable the estimation of the emission into our environment.

The calculation will be based on a constant value of the fuel flow rate. Considering the fixed values entails a loss of accuracy in the calculation of the emission. Hence this will propose closed-form expression based on equation (3) and (22), this provide a more account value of the aircraft emission.

This closed-form expression is as follow:

$$P_{ep} = A_{tk}\left(-\frac{dm_f}{dt}\right)dt = A_{tk}[m_f(0) - m_f(t_{cr})] = A_{tk}\frac{w(0)}{g}\left[1 - \frac{1-(1/\beta)\tan(C_{jq}\sqrt{C_{D,0}Kt_{cr}})}{1+\beta\tan(C_{jq}\sqrt{C_{D,0}Kt_{cr}})}\right]$$

(25)

Where

P_{ep} is the total emitted gases

A_{tk} is the emission index

I is the chemical component analyzed

$t\epsilon[0, t_{cr}]$ is fuel consumed

$\rightarrow$ is a negative insigner to show fuel was consumed

C_D = coefficient of Drag ratio

t_0/t_{cr} = initial and final time instants of the cruising flight phase

$\frac{dm_f}{dt}$ = fuel flow rate

C_j = thrust specific fuel consumption

g = gravitational acceleration

The closed-form expression of equation (21) of the fuel flow rate/fuel burn for an aircraft during the cruising flight phase also provides the closed-form formula for the emission.

Calculation for CO_2

$$P_{ep} = 3.16CO_2\left(-\frac{dm_f}{dt}\right)dt = 3.16[m_f(0) - m_f(t_{cr})]$$

Calculation for SO_2

$$P_{ep} = 0.8SO_2[m_f(0) - m_f(t_{cr})]$$

Calculation for NO_2

$$P_{ep} = 14NO_2[m_f(0) - m_f(t_{cr})]$$

Calculation for HC

$$P_{ep} = 14HC[m_f(0) - m_f(t_{cr})]$$

III. RESULTS

➢ *Gaseous Pollutants*

Results for the gaseous pollutants in the study areas for the period under study are presented in Figs. 4.17 – 4.28.

Methane (CH_4) levels at the Lagos airport fell between 54190 – 60030 ppm in the year 2020, 58960 – 60030 ppm in the year 2021 and 58770 – 60050 ppm in the year 2022 while at the Port Harcourt airport, CH_4 levels fell between 597.2 – 600.7 ppm in the year 2020, 562.6 – 600.7 ppm in the year 2021 and 599.5 – 600.7 ppm in the year 2022.

Carbon monoxide (CO) levels at the Lagos airport fell between 9443.0 – 9505.8 ppm in the year 2020, 9496.8 – 9510.9 ppm in the year 2021 and 9490.2 – 9510.1 ppm in the year 2022 while at the Port Harcourt airport, CO levels fell between 934.4 – 942.0 ppm in the year 2020, 822.3 – 942.0 ppm in the year 2021 and 941.2 – 941.8 ppm in the year 2022.

Carbon dioxide (CO_2) levels at the Lagos airport fell between 3162949.6 – 3163609.7 ppm in the year 2020, 3163464.3 – 3163609.7 ppm in the year 2021 and 3163499.5 – 3163618.1 ppm in the year 2022 while at the Port Harcourt airport, CO_2 level was 3163609.7 ppm in the year 2020, CO_2 levels fell between 2963254.4 – 3163609.7 ppm in the year 2021 and3163609.7 – 8063963.6 ppm in the year 2022.

Nitrogen dioxide (NO_2) levels at the Lagos airport fell between 11921.6 – 12013.7 ppm in theyear 2020, 11988.9 – 12078.4 ppm in the year 2021 and 12002.0 – 12013.2 ppm in the year 2022 while at the Port Harcourt airport, NO_2 levels fell between 9510.1 – 9510.9 ppm in the year 2020, 8908.5 – 9510.9 ppm in the year 2021 and 9510.2 – 9510.9 ppm in the year 2022.

Sulphur dioxide (SO_2) levels at the Lagos airport fell between 92180 – 94110 ppm in the year 2020, 92960 – 94010 ppm in the year 2021 and 93070 – 94190 ppm in the year 2022 while at the Port Harcourt airport, SO_2 levels fell between 12007 – 12013.7 ppm in the year 2020, 11252.9 – 12013.7 ppm in the year 2021 and 12013.7 – 12019.4 ppm in the year 2022.

Volatile Organic Compounds (NMVOCs) levels at the Lagos airport fell between 284700 – 304900 ppm in the year 2020, 301750 – 305290 ppm in the year 2021 and 302110 – 305020 ppm in the year 2022 while at the Port Harcourt airport, NO_2 levels fell between 3052.0 – 3053.4 ppm in the year 2020, 2860.0 – 3409.7 ppm in the year 2021 and 3052.4 – 3053.5 ppm in the year 2022.

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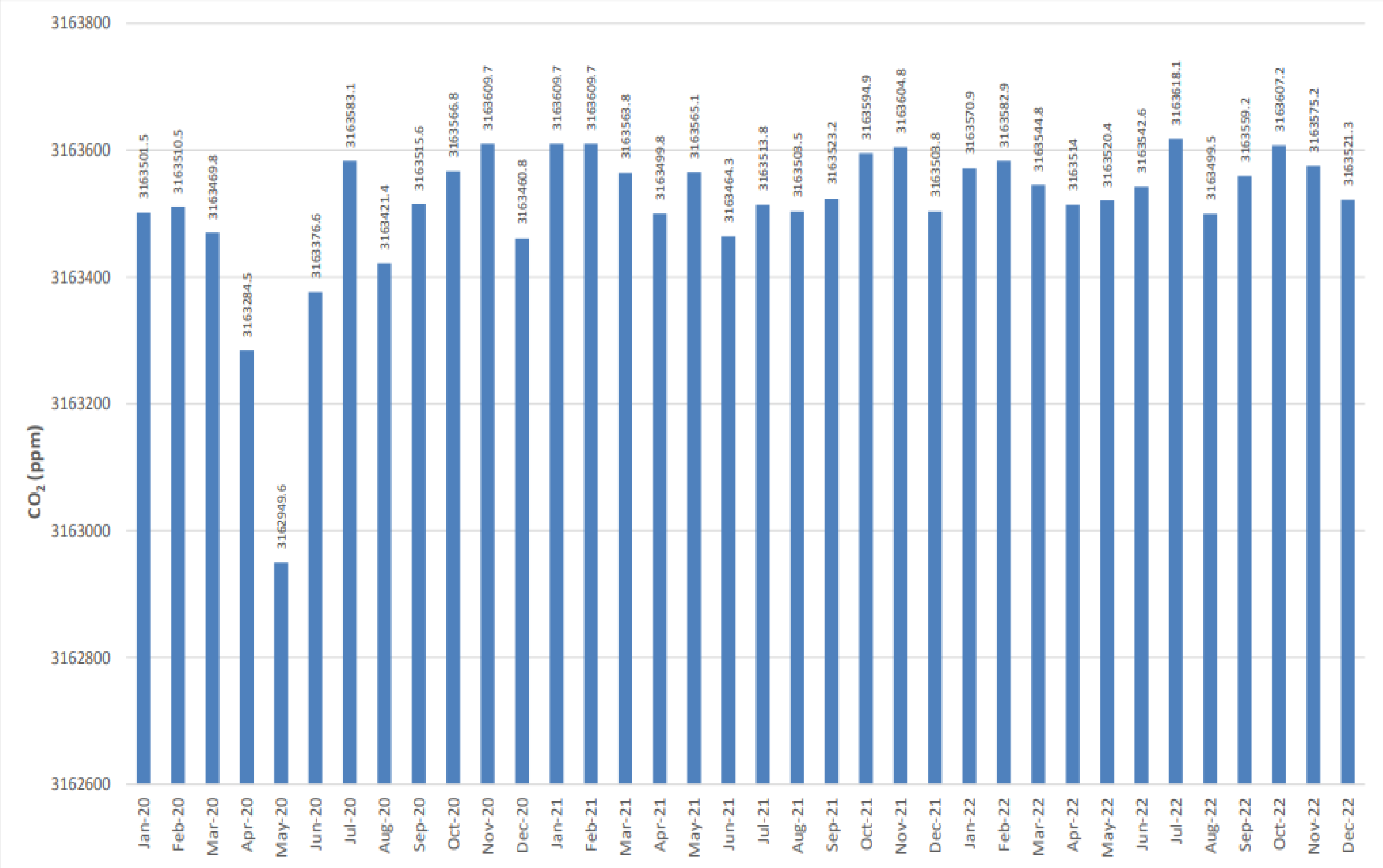

Fig 1 Carbon Dioxide (CO2) Levels at Lagos Airport

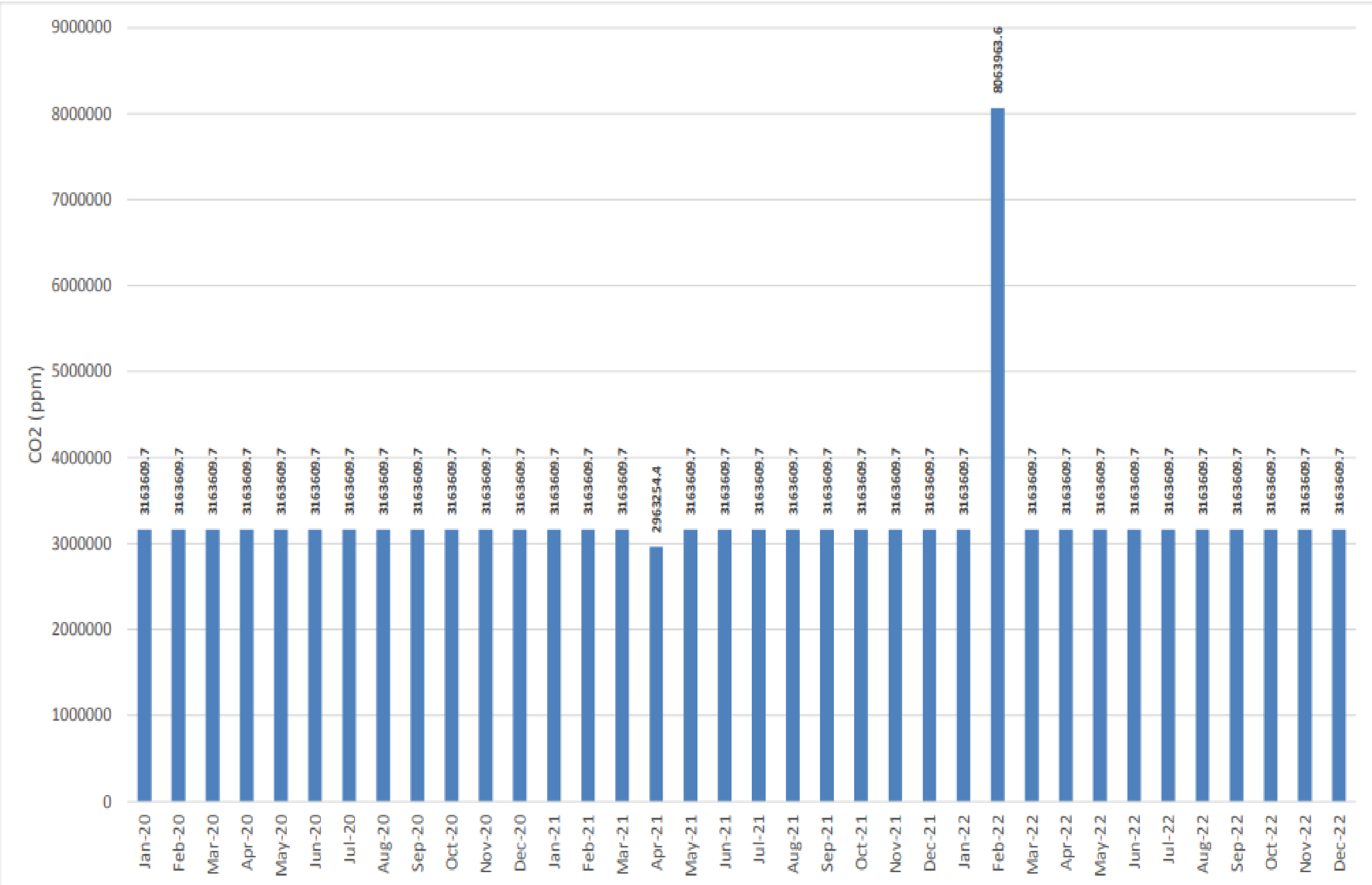

Fig 2 Carbon Dioxide (CO2) Levels at Port Harcourt Airport

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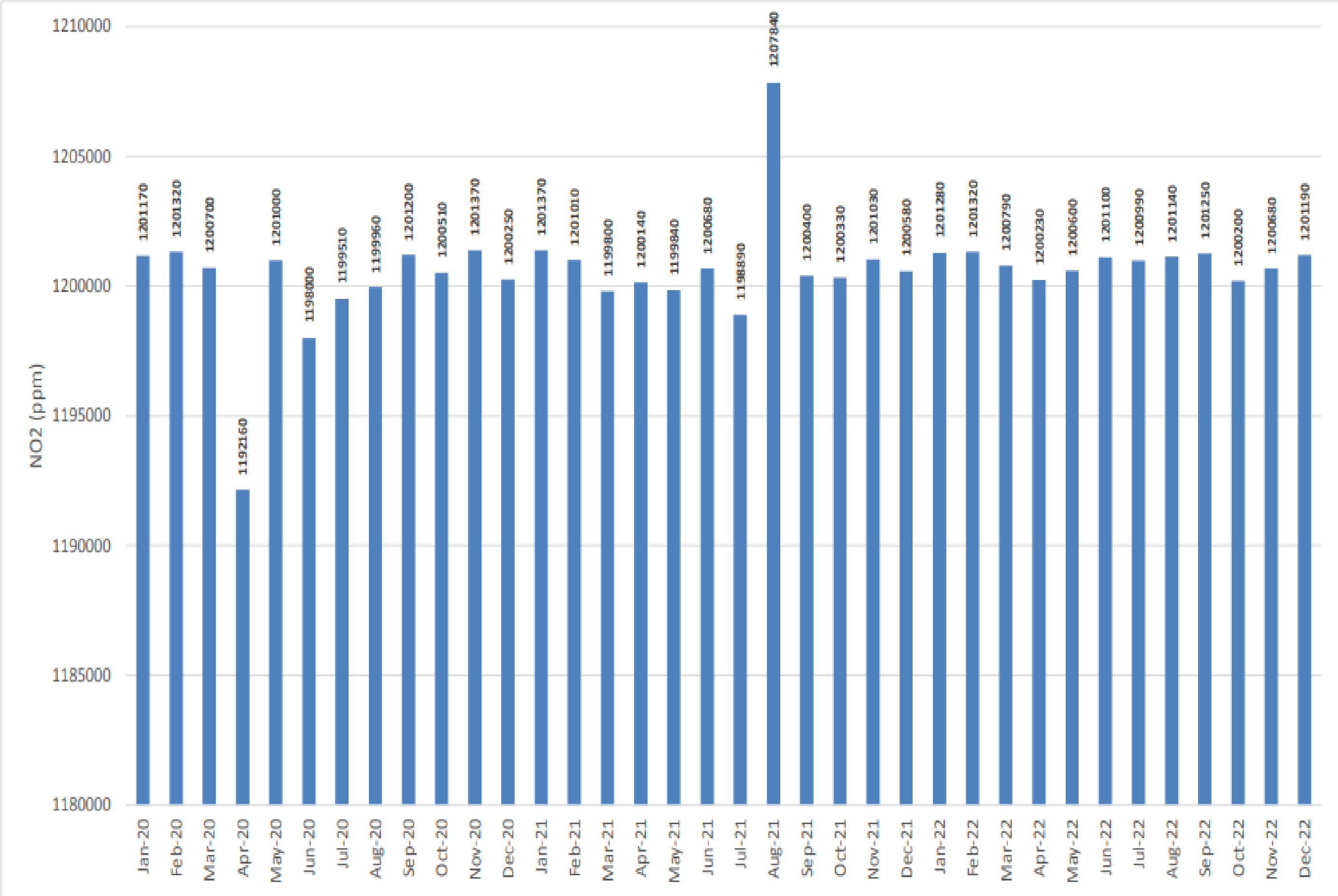

Fig 3 Nitrogen Dioxide (NO2) Levels at Lagos Airport

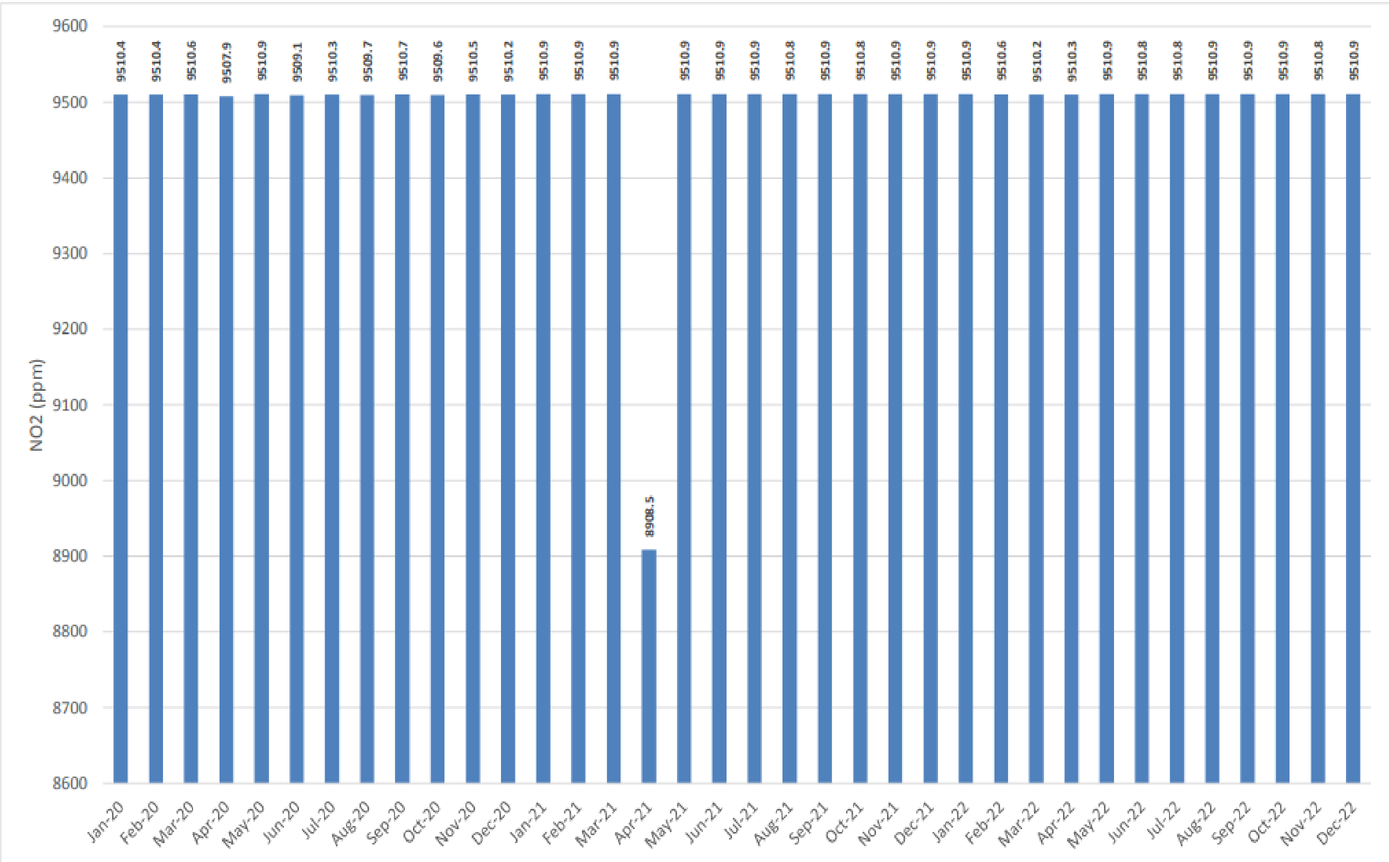

Fig 4 Nitrogen Dioxide (NO2) Levels at Port Harcourt Airport

IV. DISCUSSION

➢ *Trend of Gaseous Emissions*

A peak CH4 levels of 60030 ppm were reached at the Lagos airport in the three-year period under study. The lowest levels of 54190 and 55010 ppm were recorded in April, 2021 and May, 2022 respectively at the Lagos airport. At the Port Harcourt airport, peak CH4 level was 600.7 ppm within the three-year period. The lowest level of 562.6 ppm was recorded in April,2021.

A peak CO level of 951090 ppm was recorded at the Lagos airport 2021. The lowest level of 944300 ppm in the three-year period was recorded in May, 2020. Peak CO levels at the Port Harcourt airport was 942.0 ppm in the three-year period under study. The lowest level of 882.23 ppm was recorded in April, 2021.

At the Lagos airport, peak CO2 level of 3163609.7 ppm was recorded in May, 2020. Uniform CO2 levels were observed in all months of the year at the Port Harcourt airport except for February, 2022 which recorded the peak level of 8063961.6 ppm. The lowest CO2 level was recorded in April, 2021.

A peak NO2 level of 1207840 ppm was recorded at the Lagos airport in August, 2021 while the lowest level of 1192160ppm was recorded in April, 2020. NO2 emission levels at the Port Harcourt airport followed an almost uniform trend. In the three-year period, a peak level of 9510.9 ppm was recorded each year while the lowest level of 8908.5 ppm was recorded in April, 2021.

The SO2 emissions at the Port Harcourt airport were lower than those at the Lagos airport. A peak level of 94190 ppm was recorded in February 2022 during the three-year study period while the lowest level of 92180 ppm was recorded in October, 2021. SO2 emission levels at the Port Harcourt airport followed a uniform trend. Peak level of 12013.7 ppm was recorded each year while the lowest level of 11252.9 ppm was recorded in April, 2021.

A peak NMVOC level of 305290 ppm was recorded in April, 2021, during the three-year study period while the lowest level of 284700 ppm was recorded in August, 2020.NMVOCs emission levels at the Port Harcourt airport followed an almost uniform trend. Peak level of 3409.7 ppm was recorded in May, 2021 while the lowest level of 2860.0 ppm was recordedin April, 2021.

V. CONCLUSION AND RECOMMENDATION

➢ *Conclusion*

Aircraft gas emissions during landing and take-off operations investigated in this study were higher at the Lagos airport than the Port Harcourt airport. The air quality index also indicated that the air quality during the landing and take-off operations as the Lagos and Port Harcourt airports was hazardous and dangerous to human health.

With increased pressure from customers and regulators, Airline should be encouraged to embrace new methods and new technology using sustainable emission fuel which absorb CO2 up to 100% when burnt, using fuel efficient aircrafts and route optimization.

➢ *Contribution to Knowledge*

This study has established the trend of meteorological parameters, meteorological hazards, aircraft emissions and quality of air during landing and take-off operations at Lagos and Port Harcourt international airports.

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