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The Impact of Altitude, Mach Number And Relative Humidity Towards Aircraft Engine Emission

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ABSTRACT

Background: The growth of air travel has a significant impact towards the environment. A lot of researches have been conducted in order to address issues that are related to the environment impacts. Before further improvement or action can be taken to address these issues, further understanding on the relationships between the emission, engine performance and the flight operating condition are required. Objective: To evaluate the impact of altitude, relative humidity and Mach number towards the emission produced by the aircraft engines. Results: The results show that altitude, relative humidity and Mach number have influence on the amount of emission of HC, CO and NOx. The emission index for HC and CO is inversely proportional to the emission index for NOx for three of the factors. Conclusion: The method used in this study is able to provide a good assessment on how altitude, relative humidity and Mach number can affect gas turbine's emission. Comparison analysis between different aircraft engines on its emission can also be conducted using this approach.

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INTRODUCTION

Aviation industry has grown drastically and this is reflected in the increase in air traffic, which has rose at an average annual rate of around 5%. As the trend is projected to continue in future, considerable economic benefits can be expected by the industry. However, an increase in aviation emissions is also associated with its growth. The aviation emissions are known to have a significant impact towards airport's local air quality and climate change through radiative forcing or global warming.

Aircraft emissions from combustion process includes carbon dioxide (CO_2), water vapor (H_2O), sulfur dioxide (SO_2), sulfur oxide (SO_x), nitrogen dioxide (NO_2), nitrous oxide (NO), carbon monoxide (CO) and unburned hydrocarbon (UHC). At present, aviation industry is responsible for 2.5 to 3% of global anthropogenic CO_2 emissions. Meanwhile nitrogen oxide (NO_x), a term used to refer to NO_2 and NO, plays an important role in increasing ozone concentrations at cruise altitude which directly contributes to global warming. Through a report published by International Panel of Climate Change, it is anticipated that the ozone increased will rise up to 13% by 2050 (IPCC, 1999). Hence, various efforts have been directed in addressing this issues in local and global scale through atmospheric research, regulatory activities, enhancement in aircraft and engine designs, introduction of alternative fuels and improvement of operational aspects (IATA, 2009, 2013; Wulff & Hourmouziadis, 1997).

With the purpose of enhancing the current state of knowledge on aviation emissions, this paper presents a study that explains the relationship between engine performance and flight operations with emissions. It was conducted by analyzing the impact of altitude, Mach number and relative humidity towards common emissions (CO, NO_x and HC) from aircraft engine combustion. The amount of emission was quantify using an emission index from ICAO Engine Exhaust Emissions Data Bank using Boeing's Fuel Flow Method 2.

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Emission Prediction Models:

In order to estimate the amount of emissions produced by the aircraft engine, several emission prediction models have been introduced namely empirical models, semi-empirical models, simplified physic-based models and high fidelity simulations. A comparison of each method in estimating emissions have been discussed comprehensively by Chandrasekaran and Guha (2012) and Allaire (2006).

A rather complex approach can be observed from high fidelity simulations which offer the most accurate method among the available models. However it requires complete details of the combustor geometry, designs and operating conditions to accurately model the combustor. In order to produce more accurate estimations, it tends to be very computationally expensive.

Amongst the available prediction models, the empirical model tends to be the least computationally extensive. The implementation of this model can be realized in two ways: 1) using engine thermodynamic parameters and 2) using the fuel flow during landing and take-off (LTO) operations defined by ICAO. The fuel flow method was developed and derived from the P3 – T3 semi-empirical method which requires engine proprietary information for its estimation. Using fuel flow at altitude, Boeing Fuel Flow Method 2 (Dubois & Paynter, 2006) and DLR Fuel Flow Method (Dopelheuer & Lecht, 1998) managed to provide an acceptable estimation of aircraft emissions.

Icao engine exhaust emissions data bank:

ICAO's Committee for Aviation Environmental Protection (CAEP) sets emission certification standards for certified commercial aircraft engines. The standard, Annex 16 Volume II: Aircraft Engine Emissions to the Convention on International Civil Aviation (ICAO, 2008) was initially designed to address growing concerns on aviation impact towards local air quality around airport vicinity. Hence, details of approved tests and emission measurement procedures are also included in the standard.

At present, limits for emissions of CO, NO_x and HC and maximum smoke number from turbojet and turbofan aircraft engine for a reference landing and take-off cycle below 3000 feet at standard power setting of 7% (idle), 30% (approach), 85% (climb out) and 100% (take off) have been established. These limits also help to restrict the amount of emissions produced by aircraft at altitude.

Meanwhile, the existing ICAO Aircraft Engine Emission Databank was first issued in 1995 and contains comprehensive database of jet engine emissions certification data provided by engine manufacturers (ICAO, 2014). Each emission is represented by an emission index (EI) at a corresponding fuel flow rate and power setting.

Boeing fuel flow method:

Boeing Fuel Flow Method 2 (BFFM2) has been used in estimating engine emissions in this study due to its simplicity and inexpensive computational time using publicly information. This method was developed by Boeing to model engine emissions at non-reference conditions. It has been widely used as it also allows emissions estimation without depending on proprietary data which is not always publicly available. Successful implementations of this method have been reported in numerous studies (Bonnefoy *et al.*, 2011; Kim & Rachami, 2008; Sridhar, Chen, Ng, & Morando, 2011; Wilkerson *et al.*, 2010).

In this method, data from ICAO emission databank are utilized by considering engine installation effects on an airframe toward fuel flow. Fuel flows from the database are corrected using Eq. 1 at which RW_{ff} is the fuel flow at reference condition for installation effect, $RW_{ff,u}$ is the fuel flow at reference condition from the ICAO database and r is the fuel flow correction factor with values given in Table 1.

$$RW_{ff} = RW_{ff,u} \times r \quad (1)$$

Table 1: Correction factor for ICOA fuel flow values (Dubois & Paynter, 2006).

LTO Cycle	Throttle Setting	Correction Factor
Take-off	100%	1.010
Climb	85%	1.013
Approach	30%	1.020
Taxi/Landing	7%	1.100

Reference values for oxides of nitrogen (NO_x), carbon monoxide (CO) and hydrocarbon (HC) emission indices (EI) can be found in ICAO emission databanks which provides information for various types of engine that can be fitted to many types of aircraft. Using the corrected fuel flow determined by Eq. 2, the corresponding emission indices can be obtain through a simple empirical approach which will be discussed in later section. In Eq. 2, W_{ff} is the actual fuel flow at reference condition, W_f is actual fuel flow at a given altitude, and M is Mach number. In Eq. 2, both δ and θ are calculated using Eq. 3 and Eq. 4 with P_{amb} and T_{amb} are ambient pressure and temperature respectively.

$$W_{ff} = \frac{W_f}{\delta_{amb}} \times (\theta_{amb})^{3.8} \times \exp(0.2 \times M^2) \tag{2}$$

$$\delta_{amb} = \frac{P_{amb}}{101.3} \tag{3}$$

$$\theta_{amb} = \frac{T_{amb}}{288.15} \tag{4}$$

Engine Models

The engine model was constructed using GasTurb. Four engine models were modelled in accordance with ICAO emission databanks and also from the data obtained from open literatures. The important design point data for engine model construction are given in Table 2.

Table 2: Input data for engine model construction.

	JT9D-7R4G2	CF6-50E2	GEnX-2B67	CFM56-7B24
Airflow, kg/s	768.84	669.50	970.5	342.01
Bypass ratio	4.8	4.3	8	5.2
Relative humidity, %	60	60	60	60
Altitude, m	0	0	0	0
Mach Number	0	0	0	0
Power Off-Take	0	0	0	0

An approach explained by Chandrasekaran & Guha (2012a) has been used to model the engine at design point. Firstly, outer fan pressure ratio was adapted to ideal jet velocity ratio which is given as a product of low pressure turbine efficiency and fan efficiency. Meanwhile, turbine entry temperature was iterated to achieve the value of the fuel flow reported in ICAO emission databanks as shown in Table 3. The compressor pressure ratios were adapted to the overall pressure ratio while the isentropic efficiency for fan, compressor and turbine were adapted to achieve the output given in the same table. It is important to note that the adaptation and iteration were carried out to ensure that the engine model performance simulation is accurate at the design point.

Table 3: Engine rated output, fuel flow and overall pressure ratio.

Type of engine	Output, kN	Fuel Flow, kg/s	Overall Pressure Ratio
JT9D-7R4G2	243.5	2.429	26.3
CF6-50E2	230.4	2.487	29.8
GEnX-2B67	299.8	2.451	42.4
CFM56-7B24	107.65	1.103	25.78

Based on the developed, off-design performance simulations were carried out at different altitude, relative humidity and Mach number to study their impact towards engine emission. This was done by recording the fuel flows for each simulated operating conditions for subsequent analyses.

Emission Index Calculations:

Data from ICAO emission databanks are used to plot the log-log graphs of emission indices (HC, CO and NO_x) against fuel flow. By adding a trend line for each plot, an empirical relation is generated hence the emission index for each engine model developed can be obtained for its respective design point. Figs. 1 to 4 provide the log-log graphs of emission indices (HC, CO and NO_x) against fuel flow for the selected engines.

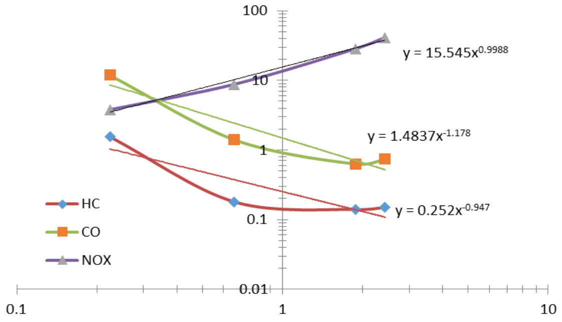

Fig. 1: Log-log graph of emission indices (HC, CO and NO_x) against fuel flow for JT9D-7R4G2.

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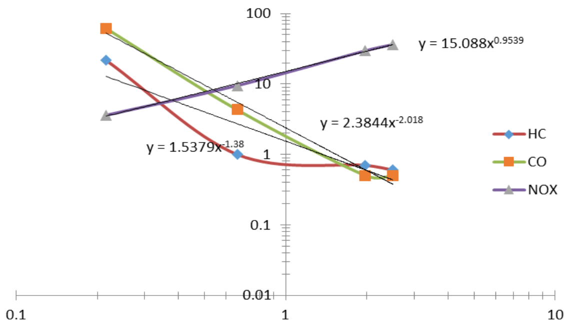

Fig. 2: Log-log graph of emission indices (HC, CO and NO_x) against fuel flow for CF6-50E2.

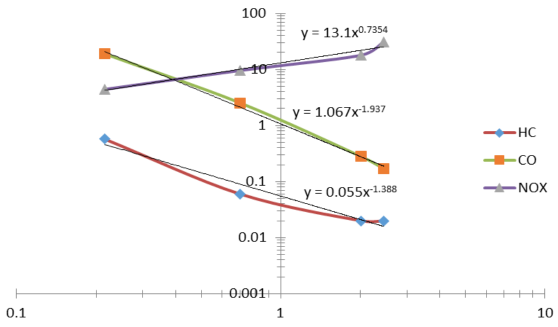

Fig. 3: Log-log graph of emission indices (HC, CO and NO_x) against fuel flow for GEnX-2B67.

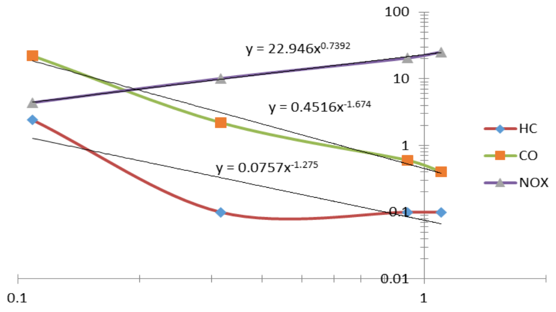

Fig. 4: Log-log graph of emission indices (HC, CO and NO_x) against fuel flow for CFM56-7B24.

The emission index can be calculated using a reference emission index at sea level, corrected ambient temperature and pressure. In addition, relative humidity is also needed for the calculation of NO_x. It is important to note that based on BFFM2, relative humidity is not involved in the calculation of HC and CO because both depends only on ambient condition. However, the engine performance simulations consider the change of relative humidity in investigating its impact towards aircraft emissions.

To calculate the emission indices, Eq. 5 to Eq. 7 can be used where in these equations EIHC, EICO and $EINO_x$ are the emission index for HC, CO and NO_x at any given altitude or flight condition while REIHC, REICO and $REINO_x$ are the emission index for HC, CO and NO_x at the reference condition.

$$EIHC = REIHC \times \frac{\theta_{amb}^{3.3}}{\delta_{amb}^{1.02}} \quad (5)$$

$$EICO = REICO \times \frac{\theta_{amb}^{3.3}}{\delta_{amb}^{1.02}} \quad (6)$$

$$EINO_X = REINO_X \times \sqrt{\frac{\delta_{amb}^{1.02}}{\theta_{amb}^{3.3}}} \times EXP(H) \quad (7)$$

Note that H in Eq. 7 is the humidity correction factor and can be calculated using Eq. 8 with ω is the specific humidity.

$$H = -19.0 \times (\omega - 0.0063) \tag{8}$$

Specific humidity given in Eq. 8 can be determined using Eq. 9 where RH is the relative humidity and P_{sat} is the saturated pressure at a given T_{amb} calculated using Eq. 10.

$$\omega = \frac{0.62189 \frac{RH}{100} P_{sat}}{P_{amb} - P_{sat}} \tag{9}$$

$$P_{sat} = 0.1 \times 6.107 \times 10^{\left(\frac{7.5\times(T_{amb}-273.15)}{273.15+(T_{amb}-273.15)}\right)} \tag{10}$$

Effects Of Altitude Towards Hc, Co And Nox Emissions:

For this investigation, altitude was varied from sea level to 10,000 m while both Mach number and relative humidity were fixed at 0.4 and RH = 60% respectively. Figs. 5 to 7 depict how altitude affects HC, CO and NO_x emission for the four engines. Note also that the plot depicted in Fig. 7 provides results of RH = 60% for all engine.

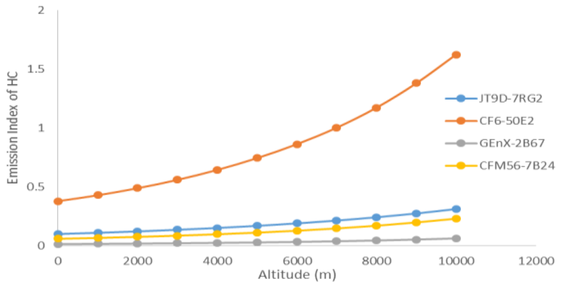

Fig. 5: Emission index of HC at various altitudes.

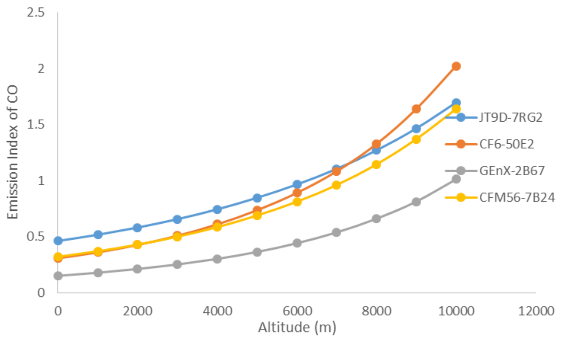

Fig. 6: Emission index of CO at various altitude.

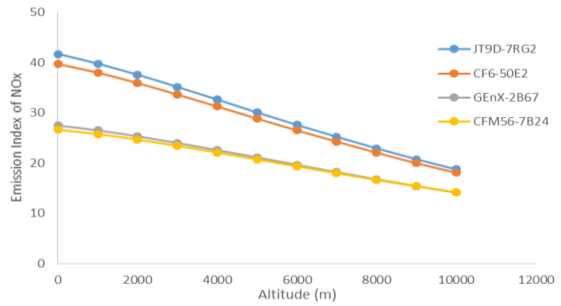

Fig. 7: Emission index of NO_x at various altitudes

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From the figures, it can be seen that the emission index of HC and CO is increasing with an increment in altitude. The results are in contrast with NO_x where a reduction in NO_x is observed when altitude increases. As the altitude increases, both ambient temperature and pressure drop. To maintain a same pressure differential in the engine, the temperature and pressure must be reduced and this is consequently achieved by reducing inlet airflow and amount of fuel for combustion process. Hence less fuel is consumed by the engine.

By referring to the ICAO emission data plotted in the log-log plot for the reference engine cycles (Figs. 1 to 4), NO_x emission index is higher at high engine fuel flow (high engine power setting) compared to HC and CO. Through this understanding, it is expected that more NO_x emission is produced at lower altitude unlike emissions produced by HC and CO. Based on the values presented by the engine models, lower altitudes could produce up to 50% more emissions compared to higher altitudes.

Effects of relative humidity towards hc, co and nox emission:

Using the performance of JT9D-7R4G2 as reference, effect of relative humidity was studied by varying its value from 0 to 100% while Mach number and altitude were fixed at 0.4 and 10000 m, respectively. The relationships between relative humidity and the emissions are given in Figs. 8 to 10. From the results, emission of HC and CO increased linearly with the relative velocity. However, the production of NOx emission is reduced at higher relative humidity. As NO_x emission contributes to a significant amount of pollution, flying at a region with a higher content of water vapor helps to reduce the amount of emission. However, it is interesting to note that at the highest relative humidity, HC and CO emissions increase up to 60% and 70%, respectively but at a relatively small value compared to NO_x.

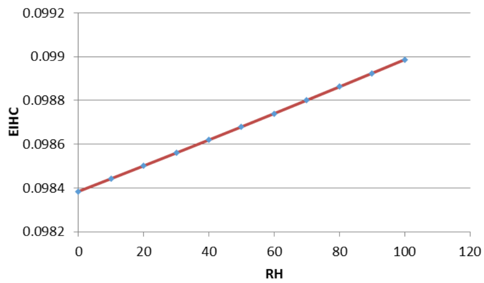

Fig. 8: Emission index of HC at various RH.

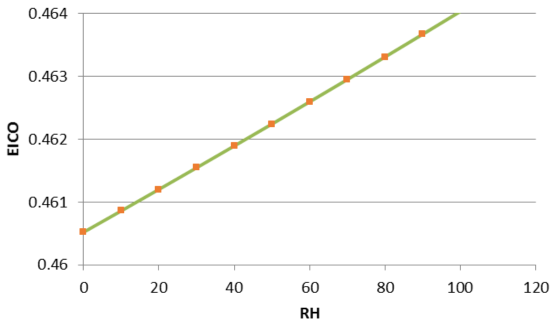

Fig. 9: Emission index of CO at various RH.

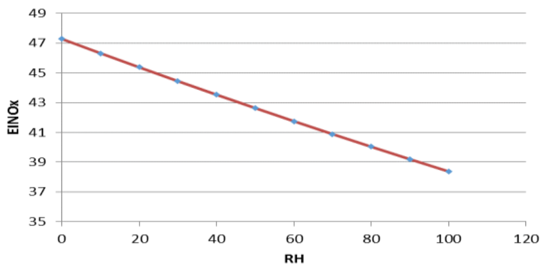

Fig. 10: Emission index of NO_x at various RH.

Effects Of Mach Number Towards Hc, Co And Nox Emission:

To evaluate the effect of Mach Number towards emissions, Mach number was varied from 0 to 0.8 while both altitude and relative humidity are fixed at 10000 m and RH = 60%, respectively. The results are presented in Figs. 11 to 12. As the speed increases, NO_x emission increased exponentially due to the increment in fuel flow. Contradictory results can be observed for HC and CO emissions. The results suggest that an aircraft could fly at a lower speed to reduce the amount of harmful emissions.

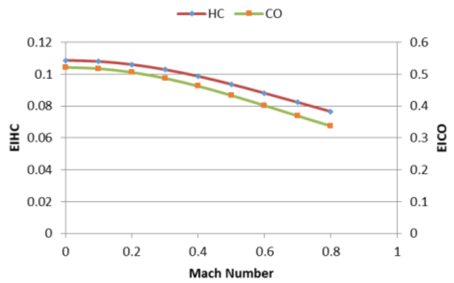

Fig. 11: Emission index of HC and CO at various Mach Number.

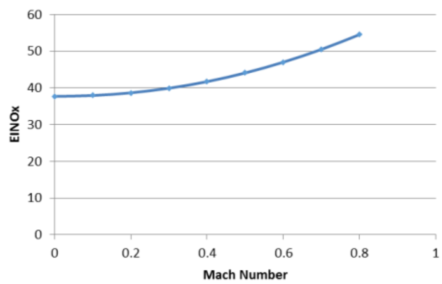

Fig. 12: Emission index of NO_x at various Mach Number

Conclusions:

The effects of altitude, Mach number and relative humidity towards aircraft emission have been captured in this study. The amount of emission was predicted through its relationship with fuel flow using BFFM2 which provides a mean to estimate emissions at various operating condition without depending on proprietary information. From the study, flying at lower altitude with a higher speed at a region with lower relative humidity will help in reducing the amount of HC and CO emissions. On the other hand, reduction of NO_x emission is possible by flying at higher altitude and lower speed with higher humidity. Overall, it can be observed that a small change in altitude, Mach number and relative humidity give a considerable impacts towards HC, CO and NO_x emission. Moreover, as the current environmental concerns are directed towards NO_x emissions, the results of this study can be used in emission reduction strategies by considering the effect of the presented parameters towards emissions.

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