EVALUATION ON ALTERNATIVE JET FUELS APPLICATION AND THEIR IMPACT ON AIRPORTENVIRONMENTAL CHARGES

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ABSTRACT

Air transportation continues to grow positively over the years, and the growth is accompanied by the increase in aviation's environmental impact, particularly the pollutant emissions. Alternative jet fuels have been introduced as a substitute with the aim to reduce the emissions as well as the industry's high dependency on conventional jet fuel. In this study, the application of alternative jet fuel, specifically Bio-SPK from jatropha and camelina, as well as their blends have been evaluated in terms of their impact towards engine performance and the environment. Further evaluations have been emphasized on environmental performance at landing and take-off cycle. The potential benefit of using alternative jet fuels in terms of aircraft emission charges is also discussed.

Keywords: alternative fuel, engine performance, environmental charges, airport charges, LTO cycle.

INTRODUCTION

Aircraft engine exhaust emission has been identified to have a notable impact towards both local air quality and climate change. From the perspective of local air quality of an airport, the primary emittants of concern are nitrogen oxides (NOx) and hydrocarbon (HC). These emissions, along with carbon monoxide (CO) and smoke are currently regulated by ICAO. Initially, a certification standard for aircraft engines has been introduced in 1981 by ICAO and since then it has been made 50% more stringent [1]. This standard has put more emphasis on the aircraft emissions at landing and take-off (LTO) cycle as it aimed to improve the local air quality in areas in the vicinity of airports. Some of the airports have also taken an aggressive approach by introducing a charge for aircraft emission. Widely known as emission-related charge, it is charged to the aircraft landing or taking off from those airports. This approach was first initiated by some Swedish and Swiss airports in the late 1990s and subsequently followed by several other airports in Europe. From observation, the impositions of this charge are not restricted to airports with high air traffic and aircraft movement only. Its implementation is currently limited to 23 airports in Europe. However, all airlines flying to these airports are subjected to this charge which added to the aircraft direct operating charges [2]. Furthermore, a study conducted by ICAO shows that airlines from developing countries are facing increased landing fee as they tend to operate with older and more emitting aircraft compared to the developed countries [3].

In another perspective, a lot of improvements in engine designs have been introduced, and they have helped to gradually reduce the emissions. However, demand for air travel has been projected to continuously increase for the next 20 years [4]. The increase in demand is accompanied by a rise in aircraft movement at the airport and as a result, it has also raised a huge concern on the increment of aviation emission. Pressure to further reduce the emissions will be constantly faced by the aviation industry due to increasing public awareness on the environmental impact of aircraft emissions. Due to this reason, together with efforts to reduce the dependency on fossil fuels, it is imperative for the industry to consider alternative fuels as the possible solution.

Currently, a lot of efforts have been directed towards promoting, developing and deploying the use of alternative fuels in aviation. The central focus has been the use of 'drop-in' fuels, which can be translated into the types of fuels that can be applied in existing aircraft/engine infrastructure with no modifications. Presently, there are two promising alternative jet fuels that have been certified to be used in aviation: bio-synthetic paraffinic kerosene (bio-SPK) and Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK) [1]. Bio-SPK is also known as hydrotreated renewable jet (HRJ) or hydroprocessed esters and fatty acids (HEFA), produced from feedstock similar to biodiesel and undergo hydrogenation to improve its hydrogen content and calorific value. Meanwhile, FT-SPK is produced from carbon source such as methane, coal or biomass by first forming a synthetic gas (syngas) which is a mixture of hydrogen and carbon monoxide before being converted to a hydrocarbon that is suitable as a jet fuel.

In this paper, the application of the alternative fuels, particularly bio-SPK fuel and its blends has been evaluated. The paper aims to provide an understanding on the effect of alternative fuels usage on the engine performance as well as the environmental impact of burning these fuels. The evaluation also emphasized on LTO cycle to respond to the community concerns over local air quality surrounding the airport area. Further investigation was also conducted in exploring the possible benefit towards the airline operating cost specifically in terms of aircraft emission charges.

METHOD

Alternative jet fuel characteristics

The evaluation was conducted on two drop-in, bio-synthetic paraffinic kerosene (SPK) fuels: jatropha

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SPK and camelina SPK. These fuels have been recognized to be compatible with the existing aircraft/engine infrastructure and have been tested on actual flights [5]. The fuel characteristics were prepared using NASA CEA[6] and defined in Gasturb [7] by utilizing the available information on the hydrocarbon composition and the heat of combustion, ΔH_c of the respective fuels. NASA CEA calculates chemical equilibrium composition and properties for a given mixture and it is accessible from Gasturb Detail, a utility program by Gasturb.

A summary of the fuel properties is given in Table-1. A result of Jet A is also given for a comparison. The molecular formula and heat of formation, ΔH_f were calculated following a method explained by [8].In addition, several fuel blends were prepared by mixing the fuel with Jet A at an increment of 20% of alternative fuel. This step was executed to investigate the impact of different fuel blends towards the performance of the engine. The simulated heat of combustion for the fuel blends is shown in Figure-1.The figure indicates that a higher heat of combustion can be obtained by blending a higher percentage of alternative fuels with Jet A.

Table-1. Properties of the selected fuels.

Parameter	Jet A	Jatropha SPK	Camelina SPK
Carbon mass, %		85.4[1]	85.4[1]
Hydrogen mass, %		15.5[1]	15.1[1]
Molar mass, g/mol	167.3	170.3	169.3
Molecular formula	$C_{12}H_{23}$	$C_{12}H_{26}$	$C_{12}H_{25}$
ΔH_c , MJ/kg	43.0	44.3[1]	44.0[1]
ΔH_f, kJ/mol	-303.4	-319.4	-294.5

[1]Ref. [9]

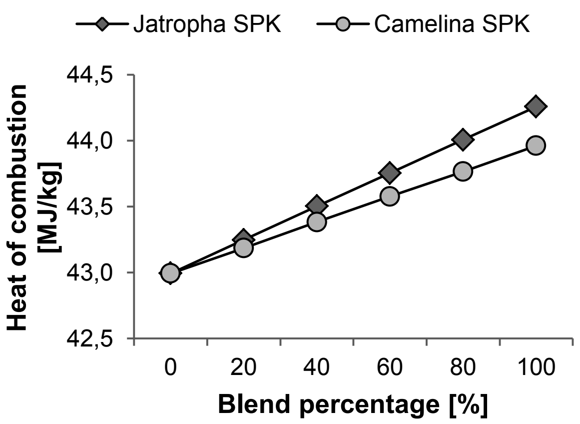

Figure-1. Heat of combustion for various fuel blends.

Engine performance setup

A specific aircraft and engine pair has been selected as a reference for performance simulation. An engine model that imitates the performance of CFM56-7B26 turbofan engine which powered a Boeing 737-800 aircraft was constructed in Gasturb [7] using specification data from the open literature. Based on the available data, engine performance at take-off has been chosen as the design point. Table-2 shows the engine characteristics at sea level static take-off conditions as well as its comparison with the publicly available data.

Table-2. Engine design and performance specifications at design point.

Design and performance parameters	Simulated model	Public data	% diff.
Design point (Alt = 0m, Mach number = 0)			
Mass flow [kg/s]	353.348	353.348[1]	0
Fan pressure ratio	1.768	-	-
Overall pressure ratio	27.61	27.61[2]	0
Bypass pressure ratio	5.1	5.1[2]	0
TET [K]	1617.44	-	-
Fuel Flow [kg/s]	1.221	1.221[2]	0
Thrust [kN]	116	116.99[2]	0.85
SFC [g/kN-s]	10.526	10.8[1]	2.6
Ambient condition			
Temperature [K]	288.15		
Pressure [kPa]	101.325		
Relative humidity [%]	60		

[1]Ref. [10]
[2]Ref. [11]

Initially, the performance of using Jet A has been simulated at the design point so as to provide a reference for further analysis and comparison with the selected alternative fuels. Various operating conditions were then simulated by running the engine model at off-design condition. The effect of using alternative fuels and variation in their blends can be observed by running the simulation using the similar engine setup. Note that only the fuel type is changed at the design point condition.

Emission prediction method

An empirical method known as Boeing Fuel Flow Method[12] has been employed to predict the amount of emissions produced by the engine. This method has been widely recognized to provide as estimation of NOx, CO and HC emissions without depending on proprietary information.

Engine emission data at LTO cycle from ICAO Aircraft Engine Emission Databank [11], specifically the emission indices, have been utilized to find the emission relationship with the amount of fuel flow at four power settings. The emission indices (EI) have been used to quantify the emission data. This information is given in

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Table-3. They represent the amount of emission for an engine running on a conventional jet fuel; and given on the basis of grams of emission for a kilogram of burnt fuel.

Table-3. Emission indices from ICAO databank for CFM56-7B26[11].

Mode	Power setting [$\%F_{00}$]	Fuel flow [kg/s]	EI CO	EI NOx	EI HC
Take off	100	1.221	0.2	28.8	0.1
Climb	85	0.999	0.6	22.5	0.1
Approach	30	0.338	1.6	10.8	0.1
Idle	7	0.113	19.8	4.7	1.9

A log-log plot as shown in Figure-2 was constructed to relate the amount of emissions with their respective fuel flow. A set of correlation that relates these two parameters has been established in [13] and was further applied in this study. The correlations and their coefficient of determination (R^2) are given in Table-4. It consists of a polynomial, linear and bilinear fitted curve for the estimation of EINOx, EICO and EIHC respectively. The presented fittings produce smoother and higher coefficient of determination compared to other fitting method. In order to generate a similar type of information for different types of fuels, the engine model was run at a similar power setting at off-design to observe its effect on the engine fuel flow. By using the method presented above, the amount of emissions can then be estimated.

Table-4. Correlations to determine emission indices.

Correlations for emission index [g/kg]	R^2
$EINOx = 21.403(m_f)^3 - 43.11(m_f)^2 + 44.10(m_f) - 0.156$	1
$EICO = 0.373(m_f)^{-1.80}$	0.95
For $m_f \leq 0.345$ kg/s: $EIHC = 0.004(m_f)^{-2.88}$	1
For $m_f > 0.345$ kg/s: $EIHC = 0.1$	1

m_f= fuel flow in kg/s

Emission charges

Data on the NOx emission indices at the four operating modes were required to calculate the emission value. The emission value is determined by applying an Emission Related Landing Charges Investigation Group (ERLIG) formula introduced by ECAC [14]. The aircraft emission value is the equivalent amount of NOx emitted by an aircraft in the standardized LTO cycle explained in ICAO Annex 16, Volume II [15]. This cycle was introduced for an aircraft engine certification process and has been widely used in modeling airport emissions. The emission value was used to determine the charge per landing or per take-off depending on the airport procedures and policies. To estimate this value, the absolute amounts of NOx need to be calculated as:

$$NOx_a = n_e \times \frac{\sum_{LTOmode}(t \times m_f \times EINOx)}{1000} \quad (1)$$

NOx_a = NOx emission of an aircraft [kg]
n_e = number of engine
t = time [s]
m_f = fuel flow [kg/s]
$EINOx$ = emission factor in g/kg

Next, the aircraft emission value can be calculated as:

$$EV_a = a \times NOx_a \quad (2)$$

EV_a = emission value of an aircraft
a = HC emission factor

The standardized time for each operating mode is given in Table-5.

Table-5. LTO cycle power setting and time in mode [15].

Mode	Power setting [$\%F_{00}$]	Time in mode [min]
Take off	100	0.7
Climb	85	2.2
Approach	30	4
Idle	7	26

The aircraft emission value is subjected to the amount of engine emission for HC per LTO cycle. As stated in Equation.2, it will be multiplied with a factor a according to the following conditions

For $Dp_{HC}/F_{00} \geq 19.6$ g/kN:

$$a = 1 \quad (3)$$

For $Dp_{HC}/F_{00} < 19.6$ g/kN:

$$a = Dp_{HC}/F_{00}/19.6 \quad (4)$$

The charge for the aircraft engine emission is equivalent to

$$C_{ef} = EV_a \times f_e \quad (5)$$

C_{ef} = emission charge of an aircraft
f_e = emission fee per kg of NOx emission

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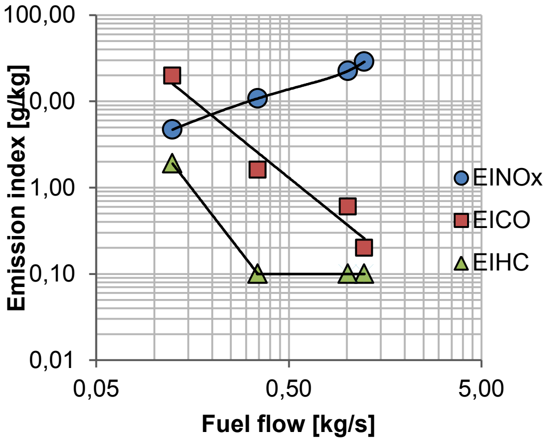


Figure-2. Logarithmic plot of the engine emission and fuel flow.

In this study, the emission fee was determined based on the average emission fee of all airports with emission charges. Due to different charging procedures at these airports, some of the airports are charging NOx emission at both landing and take-off operations. For the purpose of estimating the emission fee, the study only considers emission charge at either landing or take-off as the rate per kg emission is similar for both operations.

RESULTS AND DISCUSSIONS

Engine performance of alternative jet fuels blends

The evaluation of engine performance was done at cruise condition as the aircraft spends most of its operating time at this condition. The performance of an engine running using 100% Jet A was used as a reference. The results of thrust, specific fuel consumption and fuel flow at different fuel blends can be observed in Figure-3.

The blend percentage refers to the amount of alternative fuel in the mixture. It is important to note that the performance of 0% blend is expected to be equal as 100% Jet A. Hence, comparison with Jet A can be observed by observing performance value at 0% blend.

As presented in the previous section, the heat of combustion is increased linearly with an increment in blend percentage. As a result, an improvement up to 0.2% and 0.3% in thrust for camelina-SPK and jatropha-SPK can be observed at higher blend percentage with a higher heat of combustion.

Besides, the application of alternative fuels leads to a reduction in the fuel flow rate of up to 2.1% and 2.7% for camelina-SPK and jatropha-SPK respectively. Consequently, as the fuel consumption is directly affected by the fuel flow, less fuel is consumed. The results show about 2.3% to 3% fuel can be saved when the engine runs with 100% alternative fuel. A similar observation for 50% and 100% fuel blends have been reported by [8].

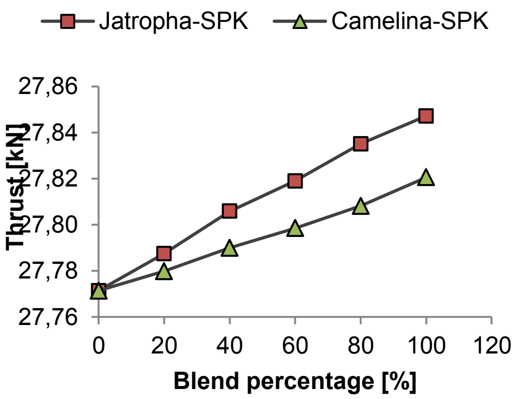
Engine emissions of alternative jet fuels blends

The engine emissions for various fuel blends have been evaluated at cruise condition. Based on the information of the fuel flow rate at this condition, the amount of emission produced by the two alternative jet fuels can be quantified and compared with Jet A as shown in Figure-4.

A significant difference can be seen for both NOx and CO emissions. For example, at 100% jatropha-SPK, the alternative fuel application managed to reduce the amount of NOx by up to 5.3% in relative to Jet A due to the lower fuel flow rates, but at an expense of 5.1% increase in CO emissions. Further investigation in the amount of CO will reveal that it is relatively lesser compared to NOx (Figure-5). Meanwhile, the effect of burning alternative jet fuels towards the emission of HC shows no significant difference in relative to Jet A. Based on the data on the fuel flow (Figure-3) and emission prediction in Figure-2, the small changes in fuel flow did not provide notable impact towards the emission of HC. Hence, the amount of HC emission will be similar irrespective of the fuel used.

Performance and emission at LTO cycle

Investigation on the application of the alternative fuel was conducted on their effect towards fuel flow and emission at four thrust settings that represent the operating mode at LTO cycle recognized by ICAO. The NOx emission value used in estimating emission charge is highly depended on the emission index at these modes. This investigation was conducted at a similar power setting so that the variation in fuel flow for all fuels can be observed. Results of fuel flow rate improvement for the 100% alternative fuels are presented in Table-6.



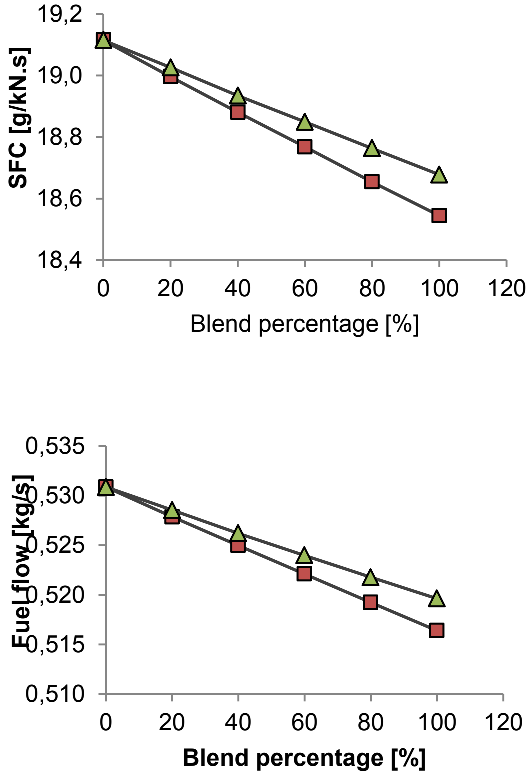


Figure-3. Variation of engine net thrust, specific fuel consumption and fuel flow with different fuels and blends at cruise condition (Alt = 10668m, Mach number = 0.8).

Meanwhile, total emissions at the four operating modes are summarized in Table-7 and the details can be observed in Figure-5. Evidently, the reduction in fuel flow rates on engines running using jatropha-SPK and camelina-SPK helps to reduce the amount of NOx emissions at LTO cycle by 355 g and 274 g. Although an opposite impact can be observed for CO and HC emissions, based on the result of jatropha-SPK, the increase in emissions (up to 66 g for CO and 17 g for HC) is still justifiable compared to the improvement in NOx.

Further observation also shows that emissions at higher power setting are highly dominated by NOx. By letting the engine run using 100% alternative fuel, this helps to reduce the amount of emissions particularly during climb and take off. Observations on CO and HC emissions show an opposite result as both are the highest while running at the low power settings (7% F_{00}). The results are consistent with the findings by [5] but it has been highlighted that the burning of the alternative fuels could also lead to a reduction in CO and HC due to the effect of aromatic content [16] which is not addressed in this study.

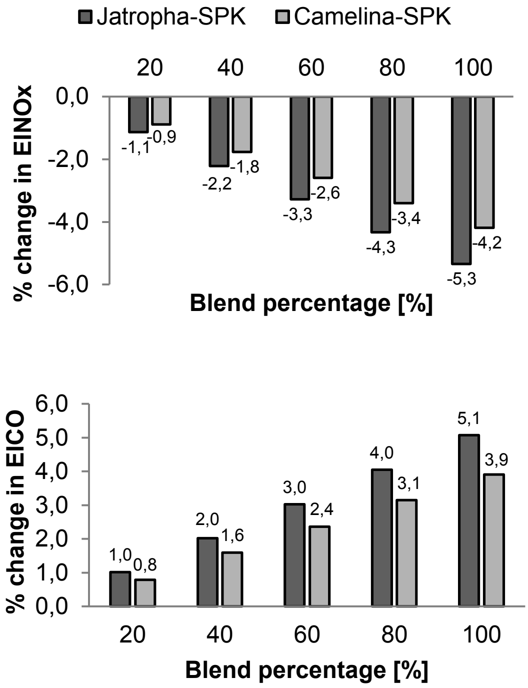


Figure-4. Difference of NOx and CO emissions at cruise (Alt = 10668m, Mach number = 0.8) for various alternative fuel blends compared to Jet A.

Table-6. Comparison of engine fuel flow at fixed power setting between Jet A and alternative fuels.

Power setting [%F_{00}]	Fuel flow [kg/s]				
	Jet A	Camelina SPK	% diff.	Jatropha SPK	% diff.
100	1.221	1.193	-2.3	1.184	-3.0
85	0.999	0.951	-2.3	0.945	-3.0
30	0.338	0.324	-2.3	0.322	-3.0
7	0.113	0.114	-2.3	0.113	-2.9

Table-7. Comparison of total emission at the LTO operating mode for various fuels.

Fuel	NOx [g]	CO [g]	HC [g]
Jet A	6029	3015	340
Jatropha SPK	5674	3081	357
Camelina SPK	5755	3066	352

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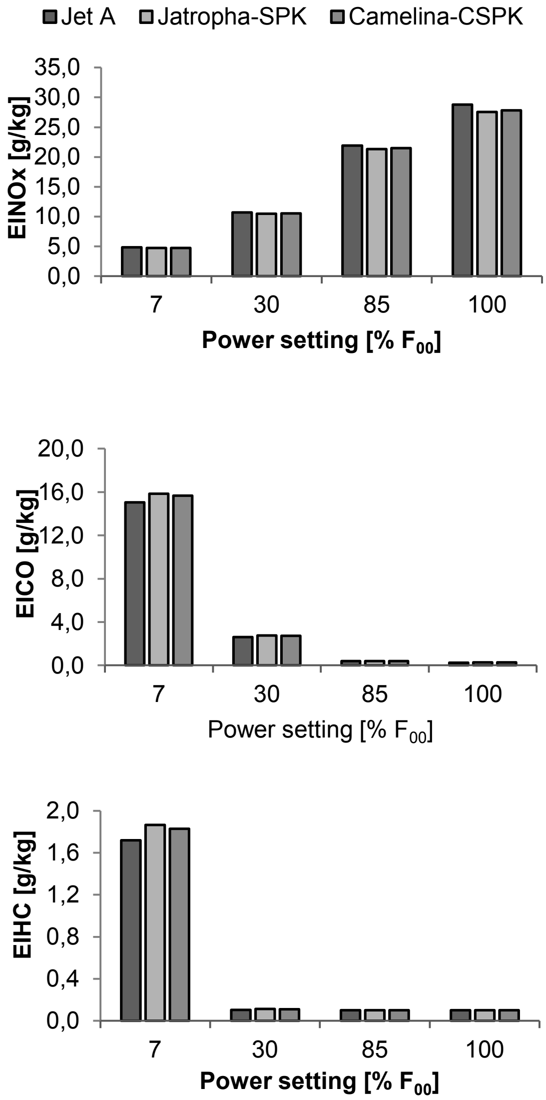

Figure-5. Comparison of EINOx, EICO and EIHC for different fuels at 4 power settings.

Impact of fuel usage towards emission charges

As aircraft emission has been recognized as one of the contributors to the amount of pollution at airports, some airports have introduced an emission-related charge which is charged to the aircraft landing or taking off from those airports. Although it is also often seen as an ineffective mean in reducing the aircraft emission, the charge does add an additional cost to the airline operation.

To estimate the amount of charge imposed to the aircraft, an emission fee for all airports with such charges for the year of 2015 has been reviewed, particularly emission charge for the reference aircraft/engine pair used in this study. According to the ERLIG-formula, the emission value of two CFM56-7B26 engines for B737-800 is 12.3 kg. This figure was calculated based on the ICAO data presented in Table-3. However, the emission charge is not identical for different airports, mainly due to the amount of fees charged per emission value. The value is also not similar for Swedish airports due to adjustments made for taxi times in ICAO's LTO cycle. The results for all 23 airports are given in Table-8. The average emission charge for flying using two CFM56-7B26 engines is found to be USD 56.2 or USD 4.6 per kg of emission value (based on 12.3 kg emission value).

Table-8. List of23 airports with emission charges for the reference aircraft/engine pair in 2015.

Airport name	Emission value [kg]	Emission charge[2] [USD]	Ref.
Basel-Mulhouse[1]	-	25.0	[17]
Bern-Belp	12.30	41.8	[18]
Bromma	11.42	68.5	[19]
Copenhagen	12.30	28.6	[20]
Dusseldorf	12.30	19.9	[21]
Frankfurt	12.30	40.9	[22]
Gatwick	12.30	51.0	[23]
Geneva	12.30	17.7	[24]
Hamburg	12.30	19.9	[25]
Heathrow	12.30	156.0	[26]
ÅreÖstersund	11.18	67.1	[19]
Ronneby	11.04	66.2	[19]
Kiruna	11.30	67.8	[19]
Landvetter	11.26	67.6	[19]
Lugano	12.30	43.1	[27]
Luleå - Kallax	11.38	68.3	[19]
Luton	12.30	92.8	[28]
Malmo	12.30	73.8	[19]
Munich	12.30	39.9	[29]
Stockholm-Arlanda	11.60	69.6	[19]
Umea	11.28	67.7	[19]
Visby	11.10	66.6	[19]
Zurich	12.30	31.7	[30]

[1]Emission charge is calculated as 0.2% of basic landing fee,
amount of surcharge depends on aircraft classification
[2]Charges imposed at either landing or takeoff at a given airport

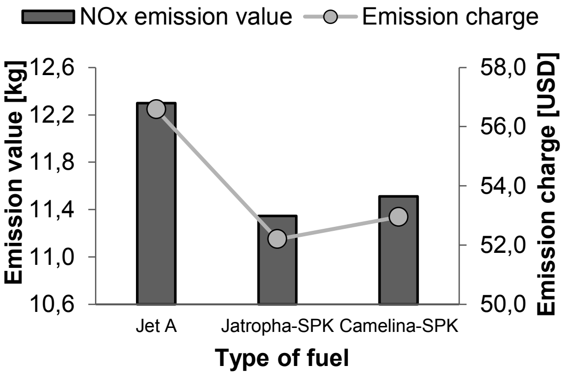

Figure-6. Variation of NOx emission and emission charge for different fuel.

The emission value of jatropha-SPK and camelina-SPK were calculated using the information given in Figure-5 and the results are presented in Figure-6. From the result, it can be concluded that up to 6.4% and 7.7%reduction in emission charges can be achieved if 100% camelina-SPK and jatropha-SPK were to be used instead of Jet A. This is in line with the reduced amount of NOx emissions at the LTO cycle. Overall, alternative jet fuels offer higher heat of combustion, produce less NOx emissions and contribute to a reduction in emission fees charged to the aircraft.

CONCLUSIONS

This paper presents the performance and emission evaluations on two types of bio-SPK fuel in relative to Jet A in order to identify the potential gains in terms of environment and economic perspective. By performing the evaluations on a reference engine modeled from CFM56-7B26 data, the results show that a higher percentage of alternative fuel blends in a mixture can produce higher heat of combustion as seen in jatropha-SPK. The fuel offers a significant effect in improving the engine performance by up to 0.3% while reducing specific fuel consumption and fuel flow rates by 3% and 2.7% respectively compared to Jet A. Investigations conducted on LTO cycle also show the local air quality can be benefited from running alternative jet fuels on the engine due to a significant reduction in NOx emission. In this study, the application of jatropha-SPK at 100% blend on the selected aircraft has proven to reduce up to 1 kg of NOx emissions at the LTO cycle. Considering hundreds of aircraft movement per day at an airport, a greener environment can be achieved with the usage of alternative jet fuels. Furthermore, airlines can save up to 7.7%in terms of the amount charged to them for NOx emission. However, the amount is considered small compared to the other costs in operating the aircraft and yet to play an important role to motivate the aviation industry to reduce their pollutant emissions.

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