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PERFORMANCE AND LEVELS ANALYSIS OF POLLUTANT EMISSIONS WHEN USING BIOFUELS IN THE PT6 ENGINE

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The Aircraft use jet engines, which have been op-timized over the years to be more efficient, silent, generate higher performance and emit lower levels of polluting emissions. However, there is still a high dependence on fossil fuels, for which high-lights the need to strengthen the study of alterna-tive fuels such as hydrogen and biofuels. To investigate the benefits of some biofuels, the different performances and emissions of biodiesel were theoretically studied in one of the most widely used engines in Colombia, the PT6-A. The results indicate that the use of this biofuel reduces NO_X levels and maintains engine performance at ac-ceptable levels. Analytical studies also indicate that the behavior of NO_X levels is approximately quadratic in the studied interval and CO_2 produc-tion is directly proportional to the percentage of biofuel in the blends.

Keywords: PT6, performance, pollutant emissions, reaction engine

1 INTRODUCTION

In Colombia, the air sector has been growing in supply and demand both in passenger transport and cargo transport, due to the implementation of new commercial and low-cost airlines [1] A report from the Sectorial Studies of Civil Aeronautics stated that in 2019, Colombia increased the mobilization of pas-sengers by air by 9.1% compared to 2018 [2] and in the first nine months of 2021, 16 million passengers transited through El Dorado, which represents 80 percent of air travelers, including domestic and in-ternational passengers, which totaled 20 million [3]. Additionally, according to data from the Civil Aero-nautics, in the last ten years, the country has doubled the number of routes to international destinations and has shown an increase of 168.4% in the number of passengers mobilized [4]. According to Unidad Administrativa Especial de Aeronáutica Civil (UAEAC), the increase in aviation in Colombia brings with it an increase in both air traffic and pol-luting emissions, highlighting the need for policies that promote the use and production of alternative fuels for aviation.

The aircraft currently operating in the different national airlines use Jet A1, Jet A and Avgas 100LL type fuel supplied by Terpel. Daily, Terpel mobilizes 455,000 gallons of fuel in Colombian airports, to supply 635 planes per day through the precise coor-dination of 85 supply vehicles [5]. These fuels have a significant environmental impact. For example, an economy class flight from London to New York emits approximately 0.67 tons of CO_2 per passenger, according to the International Civil Aviation Organi-zation (ICAO) [6].

In the last 20 years, environmental regulations have been created, implemented and strengthened in various sectors, to control the pollutant emission such as: particulate matter, carbon dioxide (CO_2), nitrogen oxides (NO_X), carbon monoxide (CO), lead, hydrocarbons (HC), among others. One of the sectors that generates the largest amount of polluting emis-sions is the air transport sector, due to the use of jet engines and the large number of aircraft that operate daily throughout the world. Aviation contributes about 2% of the world's global carbon emissions, according to the International Air Transport Associa-tion (IATA). This organization predicts that by 2037 the number of air passengers will double to 8.2 bil-lion [6]. The average for 2020 was 54.97 thousand barrels per day. The highest value was in the United States: 1076.44 thousand barrels per day and the lowest value was in Slovenia: 0.23 thousand barrels per day [7].

Biofuels will become a very promising alternative in the future, if we consider their sustainability and respect for the environment. The characterizations in these biofuels evaluate their physicochemical prop-erties such as their fluidity at low temperatures, thermal stability to oxidation, combustion properties, compatibility, volatility and energy density; the chemical composition is analyzed to determine its influence on its performance characteristics. It can be affirmed that biofuels meet the standards of the American Society for Testing and Materials, finding that the aromatic content has an important influence on the performance of biofuels. [8].

A possible solution to polluting emissions is be-ing sought in the automotive sector, through the de-velopment of new energy sources to face and reduce the massive use of fossil fuels. Among the alternative energy sources, hydrogen [9] and biofuels [10], that come from biological materials such as plants [11], agricultural waste, wastewater, wood pulp, animal fats, and garbage are being explored. Biodiesel can be obtained through the catalytic reaction of trans-esterification of triglycerides with short-chain alco-hols, generally at temperatures near the boiling point of the alcohol [12] [13]. Biofuels not only help re-duce the use of petroleum-derived fuels, but also emit fewer greenhouse gases; they are characterized by their ease of production, use, storage and poten-tial to reduce the levels of CO, CO_2 and HC [14].

The possibility of using biofuels for aviation has been evaluated as a potential replacement for con-ventional jet fuels. A study conducted in China ex-amined the use of a triglyceride biofuel in an aero-nautical piston engine to evaluate performance, economy, emissions, and heat release when com-pared to conventional fuels. The results showed that the biofuel did not have a significant impact on pow-er or economic performance, but it did increase hy-drocarbon (HC) emissions at moderate throttle open-ings. At larger throttle openings, power and economic performance decreased, while HC and nitrogen oxide (NOx) emissions increased, and carbon monoxide (CO) emissions decreased. Additionally, the study found that the biofuel was more prone to spontane-ous combustion than conventional fuel, and required additional cooling airflow to cool the cylinder due to the higher amount of heat released [15].

Growing environmental concerns, along with the search for renewable energies that emit less CO2, put biodiesel in a favorable position. The emissions re-duction index from the United States National Bio-diesel Board showed that the combustion of bio-diesel wholly as a transportation fuel decreased total hydrocarbons, polycyclic aromatic hydrocarbons, carbon, and sulfur emissions by 67%, 80%, 48%, and 100%, respectively [16].

The second-generation biodiesel obtained from waste vegetable cooking oil, which in most situations is considered garbage, is an energy product. Its mar-ket size was valued at $5.5 billion in 2020 and is pro-jected to reach $54.8 billion by 2030 [17]. For its part, synthetic fuels such as Fischer Tropsch [18], in addition to reducing polluting emissions, it also re-duces specific fuel consumption, due to its higher calorific value. However, it has the disadvantage of being more expensive.

Studies of the use of biofuels in military aviation also have a considerable impact; Research has been carried out on turbojet engines using 100% biofuel and aeronautical fuel, from the point of view of ener-gy, exergy, sustainability, exergoenvironment and thermoeconomics. Methyl oleate is used as a bio-diesel model, and it was found that the exergetic effi-ciency of the engine increases with the use of biofu-el, while the environmental effect factor also in-creases. However, the sustainability index decreases. The cost of biofuel is higher than jet fuel, as well as the specific exergetic cost. Despite this, it is con-cluded that biofuel can be a sustainable option for turbojet engines in military aviation. [19].

Unlike many other industries, the aviation sector has not made as much progress in the implementation and use of alternative fuels. Therefore, to reduce pol-lution, aircraft manufacturers have created lighter materials that reduce fuel consumption, such as the new Ultrafan engine by Rolls-Royce. They are also optimizing air traffic control to have much more effi-cient flights and, in parallel, have ventured into the use of biofuels to reduce air pollution due to green-house gas emissions [20]. At the international level, very few trials and tests are recorded, for example, the flight from Paris to Montreal in an Airbus A350 carried out by the company Air France. The plane takes off from Charles de Gaulle airport with a blend of 16% sustainable aviation fuel, produced from used cooking oil [21]. Similarly, the flight from Ma-drid to Washington utilizes fuel produced from waste at Repsol's Petronor refinery. The flight is operated with an Airbus A330-200, which has a capacity of 288 passengers and is one of the airline's most effi-cient aircraft. [22]. For their part, Boeing [23], Etihad Airways [24], Honeywell UOP and the SRBC have developed and commercialized sustainable aviation biofuels, made from plants grown in the desert and irrigated with seawater. These fuels can reduce car-bon emissions by between 50 and 80% compared to conventional fuels [25]. Boeing has teamed up with South African Airways to produce biofuels from to-bacco plants [26]. The China Petrochemical Corpora-tion predicts that 30% of aviation fuel will be biofuel soon [27]. In Spain, Iberia and Repsol used a 75% traditional kerosene and 25% carinata-based biofuel blend on a flight between Madrid and Barcelona in an A320. Carinata is an inedible oily plant. In the United States, the first commercial flight to use bio-fuel was a Continental Airlines B737 aircraft for a two-hour test flight hour test flight [28]. Reports indicate that a reduction in CO2 emissions of 1,500 kg was achieved achieved [29]. Currently, all Airbus aircraft are certified to fly on a 50% kerosene blend. Airbus' goal is to achieve certification for the use of 100% SAF by the end of the decade [30].

In Latin America, Mexico aims to reduce the CO2 emissions generated by air transport. To achieve this, it plans to increase its production of biofuels from 15% in 2020 to 50% in 2040 [31]. Argentina signed an agreement for the development of aeronautical biofuels between the Undersecretary of Air Transport, the National Civil Aviation Administra-tion, Argentine airlines, YPF, the National Institute of Industrial Technology (INTI), the National Institute of Agricultural Technology (INTA), the Secretary of Environment and Sustainable Development of the Nation, and the Argentine Chamber of Biofuels. The purpose of the agreement is to promote the use and development of aeronautical fuels [32]. In Chile, the Ministry of Transport and Telecommunications, through the Civil Aeronautical Board (JAC) and in conjunction with the Energy Sustainability Agency of the Ministry of Energy, formalized the incorpora-tion of the Catholic University of the Santísima Con-cepción (UCSC) into the Clean Flight program. The purpose is to use alternative fuels based on various raw materials, such as biomass and residual oils [33].

For their part, the three major aircraft manufac-turers, Airbus, Boeing and Embraer, signed an inten-tion and collaboration agreement to work together on the development of aviation biofuels. They hope that by this year, 4% of biofuel will be used in aircraft [34]. Regarding regulations, the ASTM method has been developed for the analysis of aviation biofuels. It serves as a verification tool to verify the accuracy of the amount of alternative fuel in the mixture [28]. In 2017, the first international flight from Beijing to Chicago was made, during which Hainan Airlines used biofuel based on cooking oil waste [35].

Colombia entered the biofuels sector at the be-ginning of the 21st century by specifying regulations for the production and commercialization of ethanol and biodiesel in the country. This has contributed to diversifying the energy basket, generating employ-ment, promoting agro-industrial development, im-proving environmental sustainability, and improving the quality of fuels. In 2013, the airline LAN Colom-bia, which is now known as Latam Colombia, made the first short-haul national flight on the Bogotá-Cali route in an A320-200 aircraft fueled with a mixture of 69% JET-A1 and 31% biofuel based on camelina oil. The purpose of this was to reduce CO_2 and other chemical components that affect the environment. The flight was a success, and the airline is now in the process of implementing such a biofuel blend in its aircraft. [36]. However, there was no evidence of the use of biofuels in the current fleet of airlines operat-ing in the country until 2020. Currently, the national airlines operating in the country have a variety of aircraft from different manufacturers such as Airbus, Boeing, Embraer, and ATR. All aviation companies use JET-A1 as fuel in all their aircraft. Taking the above into account, the tests carried out to date posi-tion biofuels as good substitutes for aviation fossil fuels. [37] [38]. One of the advantages of using this type of fuel in aircraft is that no further adaptation of the engines or their respective distribution network is required. The International Air Transport Association (IATA) has established that in the short term 6% of biojet should be used, that is, the equivalent of 8 bil-lion liters of biofuel for aircraft [39].

Despite the fact that Colombia is currently a high-ly productive country of alternative fuels [40] [41], rigorous projects have not yet been developed, in which the performance and levels of polluting emis-sions of a jet engine that works with various types and mixtures of both alternative fuels and fuels are compared. as traditional. Therefore, there is a need to promote projects in which the operation of these propulsion systems with alternative fuels is evaluat-ed to understand the operating parameters of the en-gines. These engines must be installed on test bench-es to obtain characteristic curves under different load levels and rotational regimes using different types of fuels.

One of the most important jet engines in the world due to its high reliability and the highest demand in Colombia, is the PT6 from the Canadian manufactur-er Pratt & Whitney (P&W). It is a propulsion system used in a wide range of aircraft for general and exec-utive aviation, military activities and agricultural tasks. AvioTechnology's main target is more than 400 PT6 turboprop engines, which operate in Central America and Panama [42]. At the national level, this engine is used by the Colombian Air Force (FAC) in training aircraft such as the T-6C Texan II, in attack aircraft such as the Embraer EMB 312 and 314 Tuca-no, in intelligence aircraft such as the King Air 300, and in transport aircraft such as the Embraer 110 Bandeirante, the IAI Arava, and the Beechcraft King Air. In total, around 63 aircraft use PT6 engines for their operation in Colombia. [43].

Based on all that has been discussed, it is proposed to evaluate the influence of using alternative fuels in the PT-6 jet engine theoretically. This will allow ob-taining knowledge of the engine's operational param-eters and the pollutant levels it produces.

2 METHODS

In accordance with the type of research that is intended to be developed, the proposed methodological proposal is purely theoretical in nature. For the correct execution of the project, 3 phases are established. In the first phase, a bibliographic review will be carried out, about tests in which mixtures of alternative fuels and conventional fuel have been used in jet engines, both nationally and internationally, and the various mathematical models to know the benefits and emissions. produced by a PT6 jet engine. In the second phase, the tools that will be used to develop the necessary calculations according to the characteristics of the engine are established.

In the last phase, three blends of biofuel and conventional fuel (JET-A1) will be established, with the aim of knowing their physical and chemical properties. Subsequently, the calculations of the engine will be carried out, evaluating the performance data and levels of polluting emissions, to later issue the main conclusions of the study.

3 RESULTS

As a starting point, it is necessary to know the composition and calculate the stoichiometric balance of each of the fuels and blends, for which the $C_{11}H_{21}$ is taken as the JET A1 formula.

$$C_{11}H_{21} + A(O_2 + 79/21N_2) \rightarrow BCO_2 + DH_2O + EN_2 \quad (1)$$

From the above formula, the stoichiometric balance (CHON) is performed and the following system of equations is obtained:

$$C: 11 = BH: 21 = 2DO: 2A = 2B + DN: (79/21)A \cdot 2 = 2E \quad (2)$$

whose solution is:

$$B = 11\,kmol,$$
$$D = 10.5\,kmol,$$
$$A = 16.25\,kmol,$$
$$E = 61.13\,kmol$$

For its part, the typical composition of Palm-based Biodiesel is presented in Table 1 [44]:

Table 1. Typical composition of Biodiesel from Palm

Fatty acid ester	Molecular formula	Mass composition (%)
Methyl palmitate	$C_{17}H_{34}O_2$	37.5
Methyl stearate	$C_{19}H_{38}O_2$	7.2
Methyl oleato.	$C_{19}H_{36}O_2$	46.4
Methyl linoleato	$C_{19}H_{34}O_2$	8.6
Methyl linolenate	$C_{17}H_{32}O_2$	0.3

and its formula is:

$$0.375(C_{17}H_{34}O_2) + 0.072(C_{19}H_{38}O_2) + 0.464(C_{19}H_{36}O_2) + 0.086(C_{19}H_{34}O_2) + 0.003(C_{17}H_{32}O_2) + A(O_2 + 79/21N_2) \rightarrow BCO_2 + DH_2O + EN_2 \quad (3)$$

Carrying out the balance (CHON) the system of equations is obtained:

$$B = 18.25\ kmol \quad D = 17.65\ kmol \quad A = 26.06\ kmol \quad E = 98.04\ kmol \quad (4)$$

As blends of Biodiesel and conventional fuel, three different concentrations were established: B10, B30 and B50. For each of these blends, the balance was also made according to the proportion of each of the fuels. The stoichiometric balance allowed knowing the levels of CO_2 produced, which are presented in Figure 1. Also, by means of equation 1 [45], NOx levels produced were calculated from the adiabatic temperature, whose values are 2578K for JET A1 and 2564K for Biodiesel [46].

$$EI\ NO_X = 2x10^{-83}T_f^{24.696} \quad (5)$$

Figure 1 shows the results found for NO_X and CO_2. Figure 1a shows that, by increasing the concentration of Biodiesel in the blends, the NO_X levels decrease. This reduction may be due to the lower temperature reached during the combustion process, which, as is known, contributes to the reduction of this pollutant. In Figure 1b a different behavior is observed for the CO_2 levels, because in this case when increasing the concentration of Biodiesel, said pollutant also increases. This behavior is because to produce the same thrust that the engine develops when using conventional fuel, a greater consumption of Biodiesel is necessary since they have a lower calorific value.

The results shown in Figure 1a can be explored more generally, by using equation 1 to study the behavior of NO_X production for different biofuel blends as illustrated in Figure 2. This figure shows an exponential growth (continuous red line) of NO_X levels as a function of adiabatic temperature; It also indicates that, at lower temperatures, the higher the percentage of biofuel in the blends and the lower the NO_X level, complementing the information in Figure 1.

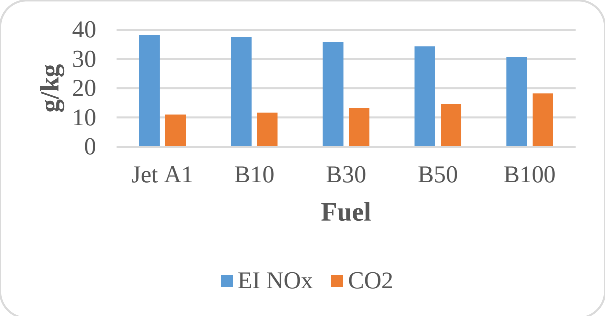

Fig. 1. NO_X y CO_2 levels

E In Figure 2 it is also observed that the behavior of the NO_X levels as a function of the temperature in the inspection window does not necessarily follow an exponential type behavior, but rather presents an approximately quadratic behavior (dashed blue line) for values between 2564.0 K and 2587.0 K, and whose equation is $0.00151546T^2$-7.47657T+9237.89.

In the case of CO_2 production, it was found that its behavior is linear, as shown in Figure 3, thus indicating that the growth in the number of moles of CO_2 is directly proportional to the percentage of biofuel in the blends. The function that governs this behavior is 11+7.253B, where B is the percentage of biofuel in the mixture and is shown in the figure by the red line.

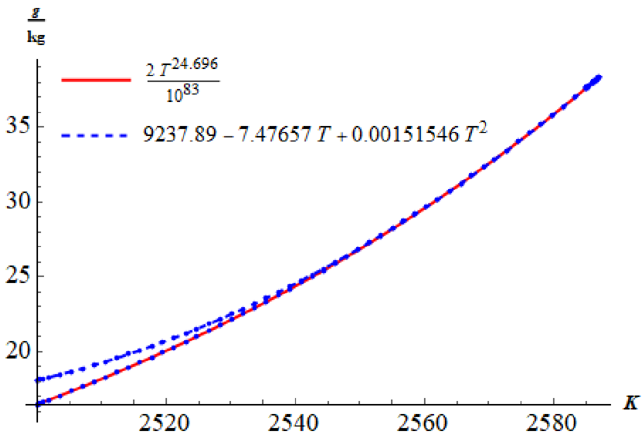

Fig. 2. NO_X levels. The red line shows an exponential growth of NO_X as a function of temperature, while the blue dashed line shows an approximately quadratic behavior

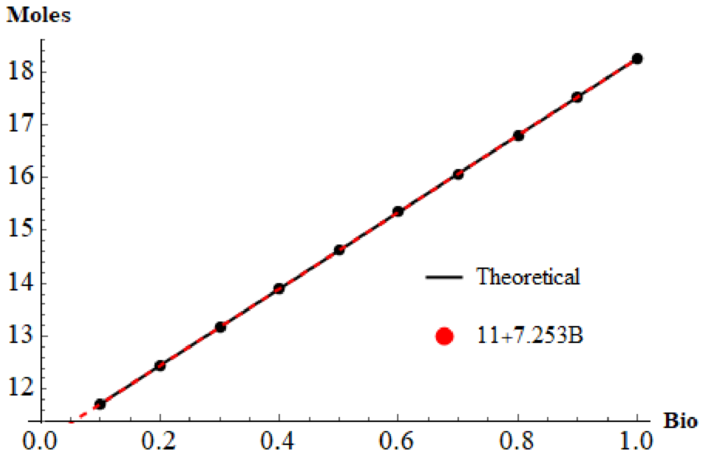

Fig. 3. CO_2 levels as a linear function of the percentage of biofuel

In terms of performance, the physical properties of the fuel influence the results. As is known, Biodiesel blends have a lower calorific power than conventional fuel and this power decreases as its concentration increases, as shown in Table 2, where there is evidence of an increase in CO_2 levels to keep performance constant, as shown in Figure 1.

Table 2. Fuel Properties

Fuel	Calorific Power kJ/kg	Density (kg/m^3) to 15ºC	v (cSt 40ºC)
Jet A1	46890,0	0,840	2,000
B10	46103,5	0,844	2,245
B30	44530,5	0,852	2,735
B50	42957,5	0,860	3,225
B100	39025,0	0,876	4,448

Table 2 is taken as a reference in terms of the calorific values, density and Kinematic viscosity (v) of Jet A1 fuel and Biodiesel blends, to calculate engine power, specific fuel consumption and injected fuel mass flow.

For the performance analysis, the standardized efficiencies of the components are used as a reference, within the design point of the turboprop engines [47] [48].

Figure 4 shows that the power of the low-pressure turbine (LPT), known as shaft power (SHP); It has a slight increase with the use of biofuels, almost negligible compared to the Jet A1. This indicates that using these mixtures does not influence the behavior of the SHP power, keeping the values within the operating ranges according to the engine manufacturer's manual, which are between 700 and 1650 SHP.

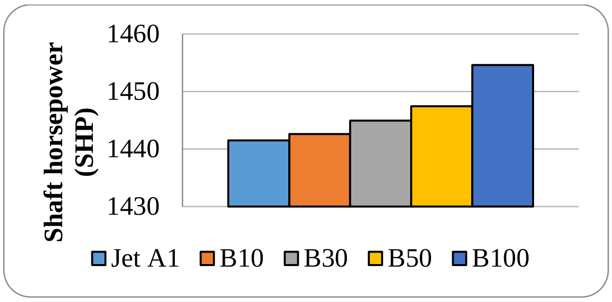

Fig. 4. Comparison of shaft horsepower

Figure 5 shows a behavior like the previous one, since the propeller power is the SHP power multiplied by the mechanical efficiencies of the motor gearbox and the low-pressure turbine (LPT), these values are the same for the blends. The blends also show a slight increase in this power, where the power for the B100 mixture is the highest of all, but said increase is not significant. Values within the established operating ranges are maintained.

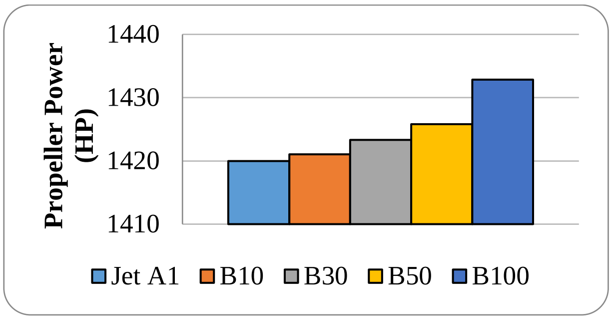

Fig. 5. Comparison of propeller power

Figure 6 shows the behavior of the engine in terms of specific fuel consumption (SFC), depending on the blends. It is possible to appreciate an increase in SFC within the ranges established by the engine manufacturer, which are between 0.509 a 0.680 LB/Hp·h. It is evident that biofuels have a higher specific consumption compared to Jet A1, but it remains in the range.

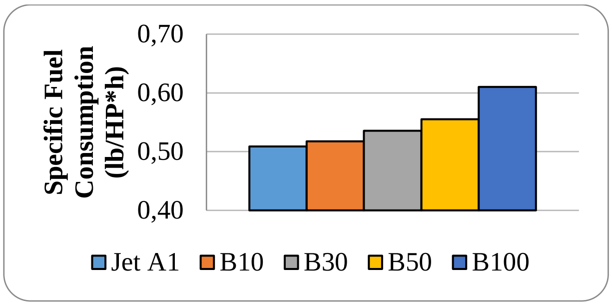

Fig. 6. Comparison of Specific Fuel Consumption

Figure 7 compares the injected fuel mass flow of the different biofuel blends with respect to Jet A1; in this it is observed that there is an increase in the amount of fuel used per hour of the blends compared to Jet A1; showing for example that the B100 blend consumes 68.66 kg more fuel than Jet A1 in one hour.

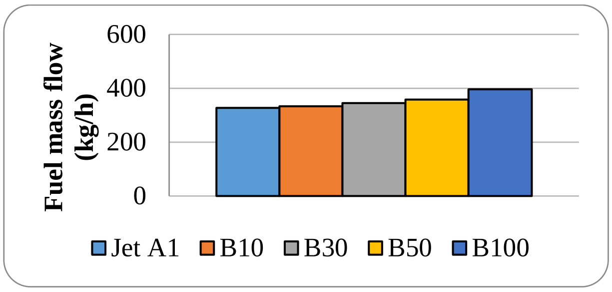

Fig. 7. Comparison of fuel mass flow

The theoretical results achieved in this work will serve as a reference for future experimental work in which it is possible to carry out real tests on a PT6 engine or another type of jet engine, using alternative fuels, thus allowing to demonstrate the advantages environmental benefits of these new forms of energy.

4 CONCLUSIONS

- Biodiesel has a lower calorific value than commercial JET A1, which can affect the power delivered by the engine and/or fuel consumption.
- In terms of density and viscosity, the variation is consistent with the literature. The density and viscosity of Biodiesel are superior in relation to commercial fuel. These small differences can affect the atomization process.
- The NO_X reduction becomes evident as the Biodiesel content in the fuel blends increases. On the other hand, the CO_2 levels increase since to maintain the performance of conventional fuel, a greater amount of fuel is required since the Biodiesel mixtures have a lower calorific value.
- It was found that the behavior of NO_X levels as a function of temperature in the interval [2564.0 K, 2587.0 K], is approximately quadratic.
- It was found that the production of CO_2 is linear, thus indicating that the growth of the number of moles of CO_2 is directly proportional to the percentage of biofuel in the mixture.
- The powers and specific fuel consumption calculated with the Biodiesel blends do not affect the nominal values given by the engine manufacturer, in addition to being within the ranges established by it; which indicates that the mixtures are optimal for use in terms of these parameters.
- There is an increase in the mass flow of engine fuel with the Biodiesel mixtures compared to Jet A1, which also indicates an increase in the amount of fuel used in one hour of operation, this would be reflected in an increase in costs in the time of use.

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