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Original article

Biodiesel substitution in a J69 aeronautic turbine engine: An experimental assessment of the effects on energy efficiency, technical performance and emissions

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ABSTRACT

Biodiesel has been widely considered as an alternative fuel for aircraft and power generation turbine engines, but experimentation in literature is mostly limited to microturbines and technological challenges remain open regarding its sustainability. The present study publishes the experimental methodology and the obtained results of testing a full-scale turbojet engine J69-T-25A using blends of JetA1 and palm oil biodiesel with volume contents from 0% to 50%. An increased biodiesel FAME substitution and extended data analysis yields new findings. Biodiesel substitution up to 50% v/v drops the thrust force by 26,6% and raises the fuel consumption by 10,8%, causing a detriment in the efficiency near 76,3%. Albeit poor atomization is noticed, the rise in the excess air of combustion diminishes the CO and HC emissions. An optimum trade-off value of 15,8% of biodiesel volume content is found to avoid a significant reduction of efficiency and acceleration time, driving to a slight reduction in the GHG-emissions and a raise of 25% in the fuel costs. The employment of a biodiesel content above 30% harms the ignition at the start-up procedure of the engine and fosters cloudiness development at the exhaust gases during the shutdown.

Introduction

Aviation is one of the foremost energy-consuming sectors that strongly contributes to global Greenhouse Gas - GHG emissions and that is largely vulnerable to the availability and cost of fossil fuels. During 2017, the domestic and international aviation transport consumed almost 12,8% of the transport energy in the world [1] and exhaled globally over 170 million tons of CO_2 [2]. This mode of transport depends almost entirely on fossil fuels such as jet/kerosene, diesel, and gasoline, which is translated into a global oil consumption of 340 million tons of equivalent oil in 2018 with an expected increase in 3,5% per year by 2030 [3]. Remarkably, the increasing freight-transport activities throughout the world contrast with the low utilization of renewable energies in the aircraft powertrain splits.

Fortunately, a variety of alternatives to ensure a sustainable operation of the industry are to be disclosed, such as those including new modifications to the engine designs or the substitution of conventional fuels with alternative fuels [4]. Most efforts in recent years have been focused on the promotion of fossil fuel substitution by biomass-derived fuels and the study of new bio-jet fuels production pathways [5,6]. However, the participation of biofuels in the global transport fuel market is scarce and it still represents < 3% of fossil fuel consumption [1]. A greater effort on the promotion of partial or total substitution of petroleum by-products in this sector becomes necessary, in the sense of new technological developments that make it feasible for the aviation industry. Indeed, the aviation biofuels are economically and ecologically sustainable since the feedstock for biofuels is available worldwide (with an expected contribution of 30% consumption arising from bio-jet fuels by 2030) [4]. Furthermore, most biofuels fit the technical specifications of the properties of conventional fuels [7], allowing the operation of engines with reduced particle emissions and similar performance when using biofuels blends [8,9].

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Nomenclature

Symbol	Definition (Units)
$\%EA$	Percent excess combustion air (% g/g)
A_t	Air inlet duct cross-sectional area (m^2)
P_f	Fuel pressure (kPa)
X_{CO_2}	Carbon dioxide volume content in flue gas (% v/v_e)
X_{CO}	Carbon monoxide volume content in flue gas (% v/v_e)
$\dot{m}$	Mass flow (g/s)
t_{ac}	Acceleration time (s)
w_{BD}	Biodiesel volume content in fuel blend (% v/v)
θ_{atom}	Atomization angle with fuel blend (°)
ρ_0	Density of intake air (kg/m^3)
ω_{shaft}	Main shaft rotational speed (RPM)
AFR	Air/Fuel Ratio (g/g)
EGT	Exhaust gas temperature (-)
HC	Hydrocarbons volume content in flue gas (% v/v_e)
HHV	Higher heating value (MJ/kg)
M	Moisture content in fuel (% g/g)
MW	Molar mass (g/mol)
OAT	Outer Air Temperature (°C)
SOC	Specific Operating Cost per year (USD/N•year)
SGE	Specific GHG-Emissions per year ($kg_{CO_{2,eq}}$/N•year)
T	Thrust force (N)
$TSFC$	Thrust specific fuel consumption (g/Nh)
u	Stream velocity (m/s)
η	Engine global energy efficiency (% J/J)
ν	Kinematic viscosity of the fuel blend (m^2/s)
Subscript	**Definition**
0	Intake air
C	Carbon
a	Air
ad	As determined basis
e	Exhaust gas
f	Fuel
$norm$	Normalized value for optimum trade-off
st	Stoichiometric

Biodiesel is the preferred biofuel to use in a partial substitution mostly in terms of its chemical compatibility, considering that aviation Jet Fuels are mainly an intermediate distillate from petroleum, and due to its high worldwide availability [10]. Biodiesel has been widely studied as an alternative fuel for gas turbine engines, not only for thrust generation in aircraft [11–13] but also, for power generation systems [14–16]. Conventional biodiesel is a mixture of Fatty Acid Methyl Esters – FAME, derived mainly from vegetable oils that have shown advantages of miscibility with fossil fuels, high flash point, and no content of sulfur or aromatic compounds [4]. Former studies of biodiesel blends used in gas turbine engines have shown minor detrimental effects on the engine performance when testing blends of biodiesel FAME from different feedstocks and Jet A1 or JP-8 [13]. Its effects include a raise of the Thrust Specific Fuel Consumption - *TSFC* [11], a higher thermal efficiency [8] and a slight decline in the engine acceleration time [17]. One of the main concerns is linked to the density and viscosity of the biodiesel FAME, which can be 1,2 and 4 times higher than the regulated limits in the aviation fuel standards, respectively. This adversely affects the atomization of fuel by reducing almost 50% of the spray angle when using a mixture of 50% of soybean biodiesel [7].

Furthermore, the effects of the biodiesel viscosity have been appreciable on the exhaust gas emissions of turbine engines operating with biodiesel blends, showing a significant rise in CO emissions related to larger fuel droplets in the atomization and incomplete combustion [12,18]. Nonetheless, Rehman et al. [19], Kimble et al. [20], and Chiaramoniti et al. [13] noted a possible reduction in the evolved CO when increasing the atomization pressure of the biodiesel blend from 0,3 bar to 1,1 bar, leading to better flame stability within the combustion chamber. This reduction also occurred by raising the injection temperature above 120 °C, since the fuel viscosity is reduced when increasing the temperature, thus improving the atomization and volatilization process. A slight reduction in SO_2 was obtained at idle and high-power operating regimes in the same tests [21]. There is no unanimity concerning the NOx and HC emissions of gas turbine engines operating with biodiesel blends. French et al. [17] detected cloudiness of the exhaust stream at low engine power and Corporan et al. [11] reported an increase in the particle emissions near 20% at idle, but a 15% drop at cruise and take-off. The results reported by Nascimento et al. [12] and Habib et al. [8] indicate a lower evolution of NOx and a rise of HC, linked to the higher cetane number and poor atomization of the biodiesel. Lupandin et al. [22], Panchasara et al. [23] and Wang et al. [3] reported a reduction of HC and CO emissions associated with an improved combustion process. Raju et al. [24], studied black carbon emissions when testing a J-85 aviation turbine with blends of catalytic hydro-processed Camelina oil and Jet A1. The authors reported a reduction in the soot particle size when increasing the Camelina oil content due to the lower aromatic concentration. The drawback is related to the dependence of soot formation upon the fuel pyrolysis of Camelia oil.

Some properties of the biodiesel blends do not fulfill the requirements of international aeronautic regulations – such as the current ASTM D1655-19a (for aviation jet fuels) and ASTM D7566-19b (for aviation fuels containing synthesized hydrocarbons as hydro-processed esters and fatty acids – HEFA and biodiesel/FAME) [20]. For instance, the freezing point and waxy particles formation at high altitudes hinder the use of biodiesel in aircraft engines, since the cloud point of biodiesel ranges from −25 °C to 26 °C, which is far from the −40 °C temperature limit given in the standard [18]. Waxy particles formation can be corrected by the mixture of the jet fuel with a biodiesel content below 20%, or even by implementing a pre-heater within the fuel tanks or the injection systems [25]. Also, rapid oxidation of biodiesel was reported in the literature caused by the high total acid number of this biofuel (typically 4 times the limit of ASTM D1655 standard) and its high reactivity with metals (like brass, bronze, copper, and zinc), which promote fuel gelling, solvent problems, and corrosion of many components of the engine. The chemical incompatibility with the fuel systems also causes a degradation effect on rubber seals and hoses, resulting in a malfunction of the control systems and a more severe maintenance routine [26].

Despite the positive benefits of biodiesel utilization, the previously mentioned challenges remain regarding the aeronautic operational safety. Chiefly associated with the mechanical malfunctions and the need to adjust biodiesel properties to aviation standards. Another issue has to do with the high production costs and the low energy density of biodiesel compared to conventional jet fuels [26]. Unfortunately, technical knowledge arising from experimentation on full-scale aeronautical turbines is expensive and complex, limiting most of the research reported in the literature to small size turbojets [27]. For instance, experimental results performed by Nascimento et al. [12], Chiaramoniti et al. [13], French et al. [17] and Habib et al. [8] are limited to micro-turbines with a power rating below 50 kW. Experimentation using full-size turbines with a power rating above 100 kW is only reported in few studies like the ones by Corporan et al. [11], Lupandin et al. [22], Brem et al [28], and the recent publications of Raju et al. [24] and Talero et al. [29]. In that last study, results of testing of a full-scale turbojet engine J69-T-25A (power rating of 640 kW) using blends of Jet A1 and palm oil biodiesel up to 10% of volume content have been presented by the authors of this article [29]. The results revealed no substantial impacts of biodiesel in the engine operation with that substitution volume. Thereupon, a technical discussion approved testing the gas turbine with up to 50% of biodiesel content in the fuel blend, argued by on-field measurements of the Exhaust Gas Temperature - EGT, Thrust, and Mechanical Wearing of the engine parts. The experimental results of the higher-biodiesel content operation are published in the present article, being obtained using parallels in the experimental bench and methodology (safety procedures, mixing facility, and measurement systems) with those former publications [29,30].

Extended analyses are motivated by the lack of experimental information and validation in real aeronautic turbines operating with a relevant content of biodiesel in the fuel blend, including the major absence of information regarding the effects on the energy performance, emissions, and the mechanical wearing of components. Therefore, the main purpose of the current study is to analyze the experimental results of testing a full-scale turbojet engine J69-T-25A with a power rating of 640 kW, operated at a mean sea level of 2554 m using blends of Jet A1 with palm oil biodiesel volume contents. The focus of the present article is on the thermal, mechanical, and economic feasibility analysis of achieving a 50% biodiesel substitution in aircraft turbojet engines without any mechanical adjustments. The inclusion of experimental methods such as the fuel characterization, atomization analysis in the fuel nozzle injectors, and thrust force and exhaust gas measurements expands the technical knowledge necessary to make the biodiesel substitution for commercial aviation feasible. An optimum trade-off between the economic and environmental impacts against the technical drawbacks of this technology is researched in the full-size aviation turbojet engine, which has been traditionally devoted to commercial aircrafts. Special attention has been paid to thermal efficiency at all engine operation regimes and the interaction between the fuel blend and the auxiliary systems of the aircraft. The main findings are related to the overall engine performance and the exhaust emissions by measuring the Thrust force – T, fuel mass flow – $\dot{m}_f$ and volume fractions of O_2, CO_2, CO and HC; and by calculating the Thrust Specific Fuel Consumption – $TSFC$, engine global efficiency – η, Air/Fuel Ratio – AFR and percent Excess combustion Air – $\%EA$.

The remainder of this article is organized as follows. In the Materials and methods section, the methodology and experimental facility of the gas turbine engine are described. Simultaneously, the experimental planning and data processing are explained in that same section. The measured results of different operation scenarios are presented in the Results and discussion section, involving the engine operation with blends of biodiesel and power loads. The discussion about the influence of the biodiesel content in the engine performance, evolved emissions, and the environmental and economic impacts is addressed in that section too, determining some outstanding findings of the deterioration of the engine hot section. Finally, in the last section some conclusions close the article.

Materials and methods

Fuels characterization

Two fuels are used in the present study: a commercial kerosene-based Jet A1 and a Colombian palm oil biodiesel with a commercial reference BioD – Premium 360. The experimental plan on the J69 engine is conducted with fuel blends of Jet A1 and biodiesel using the following Biodiesel Volume Contents - w_{BD}: 0% (B0), 10% (B10), 20% (B20), 30% (B30), and 50% (B50). The blends are prepared in a tank trailer (nominal capacity of 4 m^3), using a transfer pump and a flow meter Tuthill Fill-Rite model 820 (accuracy of 0,1%). An initial volume $V_{i,B0} = 1762 \pm 8$ L of Jet A1 is filled in the tank trailer and consumed in the baseline experiments B0 until a final volume $V_{f,B0}$ is obtained. Thereafter, a volume of biodiesel is added to the tank trailer to increase the biodiesel volume fraction to 10%. The new volume $V_{i,B10}$ is used in the experimental levels B10 until a final volume $V_{f,B10}$ is accomplished. This procedure is repeated for the experimental levels B20, B30, and B50, successively. The accuracy of the volume contents of biodiesel is always kept below 2,5%.

The characterization of the Jet A1, the palm oil biodiesel, and the fuel blends are presented in Table 1, including a compilation of

Table 1
Characterization of biodiesel and Jet A1 fuels used in this study. Measured and gathered values from the literature [11,13,14,21,31], including the aviation fuel standards: ASTM D1655-19a (for fossil fuels), ASTM D7566-19b (for fuels containing synthesized hydrocarbons), and DIN EN 14,214 (for FAME).

Properties	Unit	Current study						Literature		Aviation fuels standard		
		B0 Jet A1	B10	B20	B30	B50	B100 biodiesel	JetA1	Biodiesel	ASTM D1655	ASTM D7566	DIN EN 14,214
Density 15 °C	kg/m^3	809,5 ± 1,8	823,2	827,1	832,3	835,1	841,1 ± 3	807	881	775–840	730–772	860–900
νat 40 °C	mm^2/s	1,42 ± 0,01	1,61	1,76	1,99	2,52	4,53 ± 0,11	1,2	3,7	1,9–6,0	< 8,0	3,5–5,0
Pour point	°C	3	n.m.	n.m.	n.m.	n.m.	12	−45	−12	n.r.	n.r.	n.r.
Flash point	°C	60	n.m.	n.m.	n.m.	n.m.	181	39,5	173	> 38	> 38	> 101
Cloud point	°C	n.d.	n.m.	n.m.	n.m.	n.m.	14	−53,4	−19	< −47	< −40	n.r.
Cetane number	–	> 45	n.m.	n.m.	n.m.	n.m.	58	46	53	n.r.	n.r.	> 51
Acid value	mg$_{KOH}$/g	n.d.	n.m.	n.m.	n.m.	n.m.	0,323	n.r.	n.r.	< 0,1	< 0,015	< 0,5
HHV_{ad}	MJ/kg	45,41 ± 0,07	44,8*	44,3*	43,7*	42,6	39,70 ± 0,02	42,9	39,9	> 42,8	> 42,8	n.r.
AFR_{st}	g$_{air}$/g$_{fuel}$	21,64	20,98	20,34	19,72	18,55	15,98	n.r.	n.r.	n.r.	n.r.	n.r.
C_{ad}	% g/g$_{fuel}$	82,79 ± 1,57	82,2*	81,6*	80,9*	79,7*	76,74 ± 0,51	86,4	77,3	n.r.	n.r.	n.r.
H_{ad}	% g/g$_{fuel}$	13,01 ± 0,23	12,9*	12,9*	12,8*	12,7*	12,38 ± 0,03	13,6	12,1	n.r.	n.r.	n.r.
N_{ad}	% g/g$_{fuel}$	1,26 ± 0,08	1,24*	1,21*	1,19*	1,14*	1,02 ± 0,18	n.r.	n.r.	n.r.	n.r.	n.r.
O_{ad}**	% g/g$_{fuel}$	1,90 ± 0,51	2,70	3,49	4,29	5,88	9,86 ± 0,72	n.r.	10,6	n.r.	n.r.	n.r.
S_{ad}	mg/kg$_{fuel}$	< 350	n.m.	n.m.	n.m.	n.m.	1,1 ± 0,01	50,3	10	< 300	< 15	< 10
Moisture (M_{ad})	mg/kg$_{fuel}$	n.d.	n.m.	n.m.	n.m.	n.m.	102	n.r.	n.r.	< 250	< 75	< 500
Methyl palmitate	% g/g$_{fuel}$	n.d.	3,13*	6,25*	9,38*	15,6*	31,26 ± 1,17	n.d.	42,5	n.r.	n.r.	n.r.
Methyl oleate	% g/g$_{fuel}$	n.d.	4,84*	9,7*	14,5*	24,2*	48,42 ± 1,97	n.d.	41,5	n.r.	n.r.	n.r.
Methyl steate	% g/g$_{fuel}$	n.d.	0,39*	0,78*	1,16*	1,94*	3,88 ± 0,1	n.d.	4,2	n.r.	n.r.	n.r.
n-dodecane	% g/g$_{fuel}$	3,05 ± 0,2	2,75*	2,44*	2,14*	1,53*	n.d.	3,57	n.d.	n.r.	n.r.	n.r.
n-alkanes	% g/g$_{fuel}$	19,67 ± 2,02	17,7*	15,7*	13,8*	9,8*	n.d.	19,35	n.d.	n.r.	n.r.	n.r.

n.d. – Not detected.
n.r. – Not reported.
n.m. – Not experimentally measured.
*Calculated considering a linear response in terms of the biodiesel content and with mass balance of the elements and the CG components.
**Determined by difference.

experimental values reported in the literature [11,13,14,31] and the regulated limits in the aviation fuel standards. The density, kinematic viscosity – ν, pour point, flash point, cloud point, cetane number, and acid value are determined for both biodiesel and Jet A1, according to the ASTM D4052-16, ASTM D445-15, ASTM D97-17b, EN 2719, ASTM D2500, EN 15195, and EN 14104 standards, respectively. The ultimate analysis – CNHO of both fuels is performed according to the EN 15104 standard in a Thermo Scientific Flash 2000 organic elemental analyzer. The sulfur content – S_{ad} is determined according to DIN EN 20884 and the oxygen content – O_{ad} is measured by calculating the mass difference in the products. The moisture content – M_{ad} of both biodiesel and Jet A1 is measured by applying a Karl-Fisher titration according to the ASTM D6304-16 standard.

The Higher Heating Value – HHV_{ad} is determined experimentally for three samples (Jet Fuel, Biodiesel FAME, and 50% volume mixture of the previous two), according to the standard ASTM D240-14 by Bomb Calorimeter. Additionally, chromatographic analysis is carried out to determine the content analysis of hydrocarbons in the Jet Fuel A1 and the FAME in the biodiesel by gas chromatography – GC in an Agilent 6820 equipment. A Flame Ionization Detector – FID, fused silica (0,3 m × 0,53 mm) precolumn and a Supelco SGE HT-5 fused silica capillary column (12 m × 0,53 mm × 0,15 mm) are used. To perform the GC, tricaprine is added as internal standard, and hexane is used as a solvent for preparing samples, manually injecting 1 µL. For hydrocarbons, after 1 min of stabilization at 70 °C, the oven temperature is programmed to increase from 70 °C to 380 °C at 25 °C/min. For FAME, the oven temperature is stabilized at 140 °C for 1 min, then, the temperature increases from 140 °C to 380 °C in 12 min, and it is retained for 5 min. The carrier gas is nitrogen with a flow rate of 4 mL/min and a 50:1 split ratio for hydrocarbon determination, while the flow rate is 6 mL/min for FAME. The flows of H_2 and dry air are 40 mL/min and 360 mL/min, for both hydrocarbons and FAME, respectively.

For the fuel blends (B10, B20, B30, and B50), only properties like density, ν, HHV_{ad}, ultimate composition, and content of hydrocarbons are reported in Table 1, as they are relevant during the ground testing of the turbine. However, the pour point, flash point, cloud point, and the acid value are excluded from the characterization of the fuel blends, as they are pertinent only for flight tests. The density and ν are experimentally determined for all the fuel blends. The HHV_{ad} is experimentally measured only for B50 and is calculated for the remaining blends (B10, B20, and B30) considering a linear interpolation in terms of the biodiesel content. The last approach has a deviation of 0,06% with respect to the measured values of HHV_{ad} (achieved for the B0, B50 and B100), thus they can be estimated without significant error. The ultimate analysis – CHNO and the content of hydrocarbons of all the fuel blends are calculated with a mass balance, considering a linear response in terms of the biodiesel content. Indeed, the GC and the CHNO characterization are not mandatory for all fuel blends since the hydrocarbons of Jet A1 are chemically inert to esters of FAME under standard conditions and no chemical reactions are presented during the preparation of the blends [32,33]. Also, the effects of antioxidants in the biodiesel suggest that fossil fuels have a negligible effect on the mixture stability [34]. Finally, a linear response of the ultimate composition and the content of hydrocarbons against the biofuel content is also reported in the literature [32–36], where a R-squared above 95% concerning experimental data is reported. Hence, the linear estimation can be carried out without significant error.

In general, similar values in the literature have been reported to the ones obtained in the present study [11,13,14,21,31]. Remarkably, the pour point significantly differs in both fuels from the values reported in the literature [37]. The GC analysis for Jet A1 (B0) shows that about 37% corresponds to linear hydrocarbons, while the rest is composed mainly of branched hydrocarbons and some aromatics. About 3% corresponds to n-dodecane, which is one of the typical components [14]. Due to the high proportion of linear alkanes, the Jet Fuel has both a lower average boiling temperature than that of diesel and a higher-octane number than that of gasoline [38]. The GC analysis for the biodiesel sample (B100) indicates that 84% corresponds to methyl oleate, methyl stearate, and methyl oleate, which are the main FAME components whose values are similar to those reported in literature [32,39,40]. The methyl oleate and methyl palmitate are found in a greater proportion, and the composition of these three methyl esters

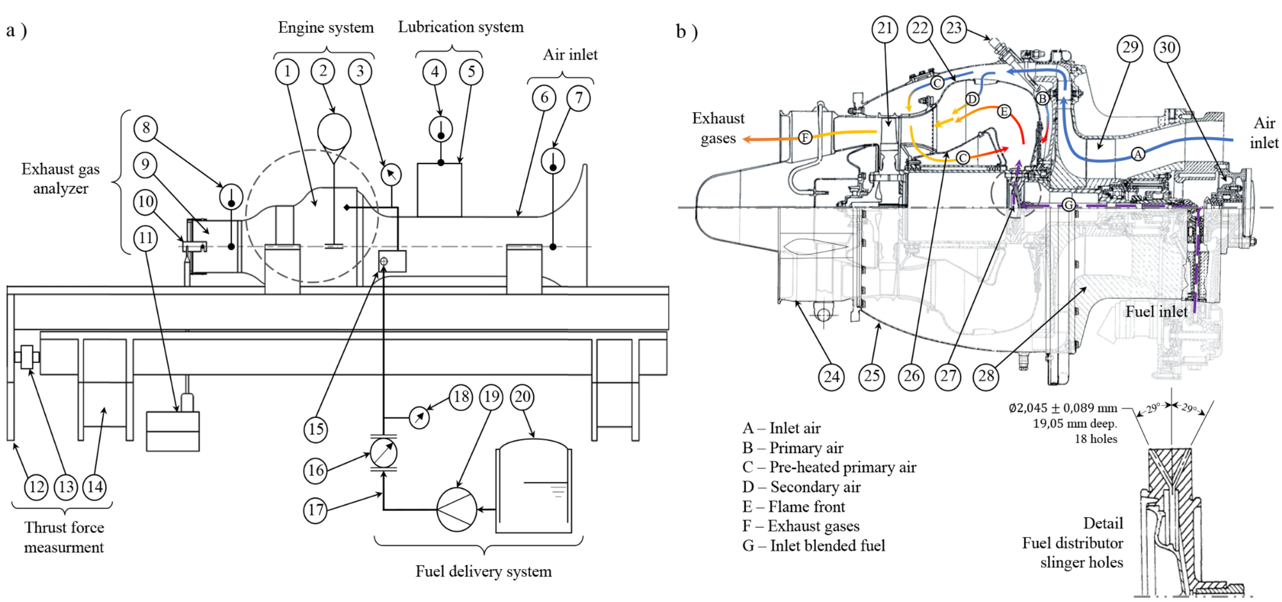

Fig. 1. (a) General J69 engine experimental facility detailing peripheral components and instrumentation: (1) turbojet engine model J69T-25A, (2) tachometer, (3) fuel pressure manometer, (4) oil supply temperature thermocouple, (5) oil supply tank, (6) air inlet duct, (7) air inlet temperature probe set, (8) EGT thermocouple set, (9) outer tailpipe, (10) exhaust gas sampling rake, (11) exhaust gas analyzer, (12) testing platform of horizontal movement, (13) thrust force load cell, (14) fixed testing platform, (15) fuel pump group and fuel control unit, (16) fuel flow meter, (17) fuel supply line, (18) fuel inlet pressure manometer, (19) fuel supply pump, and (20) fuel tank. (b) Detail of the J69 engine including its main components and the steams of air and exhaust gas: (21) turbine rotor, (22) outer combustion shell, (23) starting igniter plug and fuel nozzle, (24) exhaust duct, (25) turbine housing, (26) inner combustion shell, (27) fuel distributor, (28) compressor housing, (29) compressor rotor and (30) starter-generator drive. Source: The Authors.

indicates the palm oil origin of this biodiesel. The presence of oxygen in the fuel blends (corresponding to the ester group of the added FAME biodiesel) is the fundamental cause of the variations in the physico-chemical and functional properties, like the HHV_{ad} reduction [7]. Indeed, when adding FAME biodiesel to the Jet A1, the HHV_{ad} is practically reduced linearly due to the low value of the FAME biodiesel HHV_{ad} (by 12,6%). As a result, the HHV_{ad} is supposed to portray a linear response in terms of the biodiesel content, as experimentally verified in the present study and in [7]. Although the HHV_{ad}, ultimate composition, and the content of hydrocarbons are calculated assuming a linear response in terms of the biodiesel content, the calculated results are not linear as it will be discussed in Section 3.

Experimental facility

Fig. 1 presents the experimental facility employed in the current study. It consists of a ground test bench for the Teledyne CAE – J69 turbojet engine used by the Colombian Air Force in the military aircraft Cessna T-37. The engine is equipped with a dual fuel injection system including slinger holes and fuel nozzles that allows a wide range of fuel operation without breaching the manufacturer specifications. It is used in the present study since its operation using blends of biodiesel has been tested and described in former publications [29], also integrating a more general experimental framework. The engine is installed on a testing bench built following the standard MIL-E-5007D (2) from the Department of Defense of the United States of America and the Teledyne CAE engine manufacturer T.O. 2 J-J69-72 technical manual [41]. Fig. 1a depicts the main components of the experimental facility: the turbojet engine, the control and instrumentation sets, the thrust force measurement system, the fuel delivery system, the exhaust gas temperature measurement, the vibrations control of the compressor and turbine, the exhaust gas sampling stand, and the lubrication system.

The Teledyne CAE – J69 is a single spool turbojet engine of the model variant J69-T-25A with the main technical specifications as indicated in the specific literature of the engine [29,41]. This engine is equipped with a single-stage centrifugal compressor and a single-stage axial turbine that operates at a maximum shaft rotational speed of 21,730 RPM and generates 640 kW and a maximum thrust of 4450 N at ISA conditions. The combustion system is designed to operate with kerosene-based fuels like the Jet A and Jet A-1, and naphtha-type fuels like the JP-4, delivering maximum fuel consumption of 0,143 kg/s. Experimentation is carried out in the operating environment of Madrid, Colombia with a mean sea level of 2554 m, the barometric pressure of 1017 hPa, atmospheric temperature ranging from 16 °C to 26 °C, and relative moisture from 25% to 56%. Considerable differences exist between the engine performance under International Standard Atmosphere (ISA) conditions and at the current study location.

Fig. 1b presents the inner assembly of the J69 engine with the streams of air, exhaust gas, and fuel. The inlet air stream – A is pressurized in the compression housing to a maximum pressure ratio of 3,9 and then propelled into the turbine housing where it is separated into three different flows: the primary airflow – B (5% of total airflow volume); the pre-heated primary airflow – C (70% of total airflow volume); and the secondary airflow – D (25% of total airflow volume). The inlet fuel flow – G is pumped from the Fuel Control Unit – FCU into the starting fuel nozzle only during the start-up procedure of the engine. This flow is mixed with the airstream B to start the combustion, and then pumped into the fuel distributor during steady-state operation. The streams C and D are mixed with the fuel coming from the distributor once the flames reach steady-state conditions. The fuel distributor is a hollowed shaft joined to the turbine main shaft and is responsible for injecting fuel into the combustor chamber through 16 slinger holes. The streams C and D are also used to cool down the combustion chamber. The exhaust gas stream – F expands at the turbine and is cooled down later below 663 °C when it reaches the outer tailpipe.

The instrumentation used in the testing bench is presented in Table 2, which fits with the indications of the engine technical manual - T.O. 2 J-J69-72 [41]. The Outer Air Temperature – OAT and Exhaust Gas Temperatures – EGT are measured with a set of 6 thermocouples installed at the air inlet duct and at the outer tailpipe, respectively. An exhaust gas sampling rake is installed at the outer tailpipe with a design that meets the standards of the International Civil Aviation Organization [42] and according to the experimental facility proposed by Talero et al. [29]. The fuel blends stored in the tank trailer is then pumped with an external transfer pump (345 kPa of max. pressure and flow ranging from 20 L/min to 120 L/min) into the Fuel Control Unit – FCU. The FCU is a hydro-mechanical component that controls the dosing of fuel by modifying the opening of a set of needles valves as a function of the ω_{shaft}, EGT, acceleration control, and the sensed pressure of the pre-heated primary air. Note that no mechanical adjustments of the engine or the inclusion of external components to assure its functionality are involved in the experiments.

Experimental planning and procedure

In order to evaluate the effect of the biodiesel substitution in the engine performance a full factorial experimental design is build [43,44]. For the independent parameters, a set of 5 levels of biodiesel contents – w_{BD} described in the previous section together with 4 levels of engine load (in terms of a percentage ratio of the maximum ω_{shaft} of 21,730 RPM) are tested and codified with the acronym "B" and "RPM", respectively. The engine regimes are selected to evaluate the most frequently operating power loads during a flight, as follows. The Idle – 38% RPM (8257 ± 165 RPM) regime is selected to test the stabilization condition after the start-up of the engine with no acceleration. The Cruise – 80% RPM (17384 ± 347 RPM) and 70% RPM (15211 ± 305 RPM) regimes are used to evaluate the performance of the engine at

Table 2
Instrumentation used in the testing bench of the J69 engine fitting the indications of the engine technical manual - T.O. 2 J-J69-72 [41] and according to the experimental facility proposed by Talero et al. [29].

Variable	Instrument	Range	Accuracy
Fuel mass flow –$\dot{m}_f$	Flow meter Tuthill Fill-Rite model 820	7,6 L/min to 75,7 L/min	± 0,5%
Rotational speed of the main shaft –ω_{shaft}	Tachometer generator ref. AAE and model MS25038-4	0 RPM – 4200 RPM, speed ratio of 6:1	± 1%
Thrust force –T	2 load cells Toroid model Corp. 3965	0 kg–11,340 kg	± 1%
Volume fractions at te exhaust gas of O_2, CO_2, CO, HC	Gas analyzer Hanatech ref. IM2400 Ultra 4/5	0–23%, 0–20%, 0–10% and 0–10,000 ppm for the O_2, CO_2, CO, and HC, respectively	± 1%
Exhaust Gas Temperature – EGT	6 thermocouples Ref. 700, 530	−270 °C to 1260 °C	± 1%
Air Inlet Temperature – OAT	6 thermocouples Ref. 700, 530	−270 °C to 1260 °C	± 1%
Temperature of ambient air	Thermo-hygrometer Omet ref. C3121	−30 °C to 105 °C	± 0,4 °C
Relative humidity of ambient air	Thermo-hygrometer Omet ref. C3121	0% to 100% RH	± 2,5% RH
Barometric pressure	Barometer Wallace and Tiernan ref. FA 112, 170	64 kPa to 108 kPa	± 0,1%