PERFORMANCE TEST OF A SMALL-SCALE TURBOJET ENGINE RUNNING ON A PALM OIL BIODIESEL - JET A BLEND

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Abstract

The performance characteristics of an Armfield CM4 turbojet engine are investigated by running it on conventional kerosene fuel Jet A and on palm oil biodiesel fatty acid methyl ester (PME) 20% volumetric blend with Jet A. Values of thrust, fuel flow, temperature and pressure distribution along the engine and rpm are available from experimental measurements, whereas other values of merit are calculated using parametric cycle analysis and one-dimensional flow assumptions. Heating values of each fuel mixture are obtained and used to estimate changes in CM4 performance which are verified experimentally. It was found that the 20% PME blend with Jet A produced comparable results compared to the benchmark tests, particularly with thrust and thermal efficiency. Slight performance penalties occurred due to the lower energy content of the biodiesel blend. The efficiency of the combustor improved with the addition of biodiesel while the other component efficiencies remained collectively consistent.

Nomenclature

PME	Palm oil methyl ester biodiesel
*X*ME	Methyl ester biodiesel of feedstock *X*
B20	20% volume of PME blended with Jet A
rpm	Engine speed (revolutions per minute)
h_{pr}	Fuel heating value (FHV)
0	Free stream subscript
c	Sea level value corrected subscript
T_n	Temperature at station n
P_n	Stagnation pressure at station n
P_{tn}	Total pressure at station n
F	Net thrust
$\dot{m}_0$	Air mass flow rate
$\dot{m}_f$	Fuel flow rate
$\dot{m}_5$	Total mass flow rate
V_n	Velocity at station n
f	Fuel-air ratio
$F/\dot{m}_0$	Specific thrust
S	Thrust specific fuel consumption (TSFC)
a_n	Speed of sound at station n
M_n	Mach number at station n
c_{pn}	Specific heat capacity at station n
γ_n	Specific heat ratio at station n
τ	Temperature ratio between stations
π	Pressure ratio between stations
η	Efficiency
$w_{c,t}$	Specific work for compressor or turbine
$W_{c,t}$	Power produced by compressor or turbine
θ, δ	Sea level value temperature and pressure ratios

1 Introduction

There is a general consensus within the literature that fossil fuel feedstocks used for the production of aviation-grade kerosene fuel are dwindling. Koh and Ghazoul [1] expect a peak oil production scenario within the years 2010-2020, assuming that global oil consumption increases from 85 million barrels a day in 2006 to 118 million barrels per day in 2030. Nygren et al. [2] projected that civil aviation traffic growth will increase at a rate of 5% per year, while fuel consumption will increase at 3% per year. D.S. Lee et al. [3] projected that aviation traffic growth will increase by 4.5% to 6% per year over the next twenty years, with traffic doubling every 15 years. Despite the improvements in aircraft fuel efficiency since 1960 [2,4,5], further efforts need to be made in order to mitigate the dependency on traditional fuel sources and to replace current petrol-based fuels.

Biodiesel is produced through the transesterification of pure vegetable or organic oils by replacing the triglyceride molecules with lighter alcohol molecules such as methanol or ethanol. The reaction is carried out with a strong base catalyst, producing glycerol in addition to transesterified vegetable oils (biodiesel) [6–8]. Biodiesel carbon chains are typically 10% oxygen by weight [8]. The feedstock for biodiesel is highly varied, and includes soy bean oil, oil palm, jatropha, babassu nuts, sunflower oil, corn oil, canola oil, camelina, and olive oil [1–3,5,6,9–26]. Furthermore, any carbon dioxide CO_2 emitted during combustion is mitigated by its absorption during the production of the biodiesel; Canakci et al. claim that biodiesel CO_2 emissions are offset through photosynthesis [27]. In addition to its carbon offset, biodiesel is non-toxic, contains no aromatics or sulfur, has higher biodegradability, and is less polluting to water and soil upon spillage, as opposed to kerosene [16]. In addition, biodiesels do not contain trace metals, carcinogens like polyaromatic hydrocarbons and other pollutants that are directly detrimental to human health [8,28]. Anand et al. add that biodiesels biodegrade four times faster than petrol-based fuels [29].

A significant disadvantage of biodiesel is its significantly lower energy density compared with kerosene [11,16,25]. Furthermore, compared to aviation kerosene, biodiesel has poor lower temperature properties, and is susceptible to microbiological spoilage [4,12,30]. Biodiesel is also highly viscous compared to kerosene, and hence poses a challenge for fuel pump systems [4,11,26]. Assuming existing turbojet engine technology is utilized, larger fuel tanks would be required to match standard range and payload settings [10,12]. Gokalp reports that oxidation of biodiesels occured after a long storage period [28]. Another problem related to biofuels in general would be limited farmland and competition with food crops [1,3,4,25].

Algae is seen as the most viable future feedstock for biodiesel and is expected to alleviate concern over land usage and resource allocation [1,4,11,25]. Algae has a much higher yield than oil palm per hectare, which is the highest yielding land crop for biodiesel [4,26]. In the short term, palm oil biodiesel may be utilized as a prime source for biodiesel production. According to Sumathi et al., oil palm cultivation and processing requires little input of agrochemical fertilizers and fossil fuels to produce 1 ton of oil [26]. From 2007 data collected by Sumathi et al., the oil yield from oil palm was 3.74 ton/hectare/year, which is 10 times more than soybean during the same period (0.38 ton/hectare/year). This makes oil palm currently the highest yielding oil crop in the world [4,26], and hence an attractive biodiesel substitute or supplement to aviation kerosene.

French tested the performance of a Turbine Technologies SR-30 turbojet gas turbine engine using canola oil biodiesel [17]. No blends with the comparison fuel were tested. The benchmark fuel was Jet-A. It was found that the maximum thrust achieved by the biodiesel was less than Jet-A by 8% at maximum rpm. Ignition of biodiesel was not noticeably different from that of Jet-A. The exhaust gas temperature (EGT) was similar for all test fuels.

Using a gas turbine engine of the same model as French, Habib et al. tested a variety of biodiesels and biofuels in 50% and 100% (B50, B100) volumetric blends with Jet A [19]. The fuels tested were soy methyl ester (SME), canola methyl ester (CME), recycled rapeseed methyl ester (RRME) and hog fat biofuel

(HOG). In terms of thrust specific fuel consumption (TSFC), SME and CME B100 had slightly lower TSFC compared to Jet A at low rpm. At higher rpm, the TSFC of all test fuels were not significantly different from Jet A. All B100 fuels were found to have higher thermal efficiencies than Jet A. The thermal efficiencies of the B50 blends were not significantly different from Jet A. The turbine inlet temperature (TIT) for biofuels was higher than that of Jet A overall. The EGT was similar for all test fuels.

Chiang et al. tested a 150 kW Teledyne RGT-3600 micro gas turbine running on an unspecified biodiesel in volumetric blends of 10%, 20% and 30% with diesel [31]. The benchmark fuel was diesel, although no performance trend or data was presented for comparison. The fuel consumption was found to increase proportionally to increasing biodiesel content in the test fuels. All of the biodiesel blends had similar thermal efficiencies across all power loads. B30 was found to have the highest air mass flow rate and the highest compressor exit pressure. B30 also had the lowest turbine inlet temperature (TIT) at maximum load. The exhaust gas temperature (EGT) was similar for all blends. It was reported that after operating for 6 hours on biodiesel blends, carbon deposits were found on the fuel nozzle.

Krishna tested soy biodiesel (SME) in volumetric blends of 20%, 50% and 100% (B20, B50, B100) with ASTM #2 heating oil in a 30 kW Capstone CR30 gas fired microturbine [32]. It was found that the heating efficiencies of #2 heating oil, B20 and B100 were similar, at approximately 20%. B50 heating efficiency was higher by 7%.

A consensus between most of the related works is that smaller quantities of biodiesel blended with the benchmark fuel, be it diesel or aviation kerosene fuels, did not adversely affect the performance capabilities of the test engines. In this study, palm oil biodiesel is tested in 20% volume with Jet A in order to verify the findings of other gas turbine research tests on biofuel blends.

2 Description of Apparatus

In order to provide a functional turbojet engine for educational and research purposes, Armfield modified the Allied Signal JFS100-13A into the CM4 turbojet engine. The power recovery turbine and gear reduction unit were removed and replaced with an exhaust nozzle. The fuel control unit was also modified. A vernier throttle control was added to manually adjust the spool speed of the engine. A schematic of the engine is shown in Fig. 1.

In addition to the aforementioned modifications, sensors for temperatures, pressures, fuel-flow, shaft speed and thrust were installed. The engine is mounted on two 20 mm polished steel rods via four linear ball bearings, allowing a direct thrust reading to be obtained by a load cell. The CM4 turbojet engine can be broken down into five distinct main components:

1. Inlet
2. Centrifugal Compressor
3. Combustor (Burner)
4. Axial Turbine
5. Exhaust nozzle

The above components are simplified in Fig. 2. The manufacturer specifications for the JFS100 and by extension the CM4 are summarized in Table 1. Table 2 shows the range of sensors that came equipped with the CM4 turbojet as well as the properties measured.

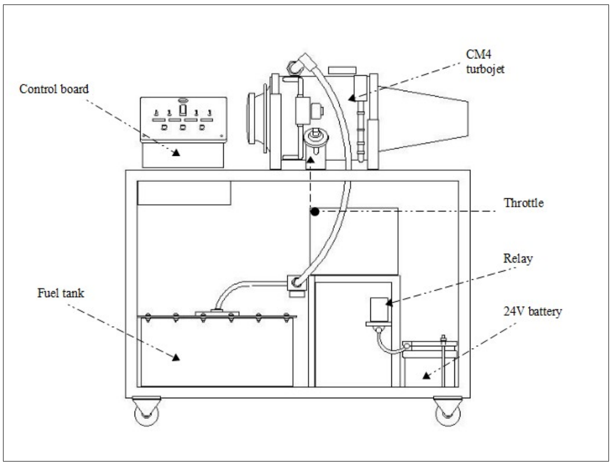

Fig. 1. Armfield CM4 Turbojet Engine

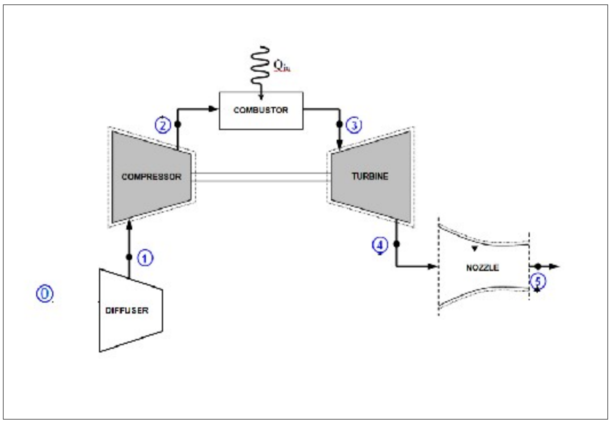

Fig. 2. Schematic layout of engine components

Table 1. Manufacturer and original equipment specifications

Model and type	JFS100-13A
Compressor	Air inlet in front of unit. Single stage radial outflow
Air Mass Flow	0.726 kg/s at 72,500 rpm
Compression Ratio	3.5:1
Combustor	Annular fuel manifold assembly Five simplex fuel nozzles
Turbine	1-stage axial flow turbine Maximum temperature 1000°C
Width and height	302.26 mm and 304.80 mm
Length	558.80 mm
Weight	37.195 kg dry 38.102 kg with lubricant
Fuel	K-1 Kerosene or Jet-A
Fuel Consumption	53.07 kg/hr or 14.74 g/s
Brake specific fuel consumption	1.3 lb/shp-hr or 0.22 kg/MJ
Power rating	67.11 kW at 60,400 rpm
Maximum thrust	300 to 400 N optimal
CM4 optimal shaft speed	70000 rpm
CM4 exhaust gas temperature	Maximum 800°C

Table 2. CM4 sensors and placements

Location	Sensor type	Measured parameters
Inlet	Type K Thermocouple	Inlet temperature T_1
Compressor	Type K Thermocouple	Entry temperature T_1
	Pitot tube	Entry pressure P_1
	Type K Thermocouple	Exit temperature T_2
	Pitot tube	Exit pressure $P_2 = P_3$
Turbine	Type K Thermocouple	Entry temperature T_3
	Type K Thermocouple	Exit temperature T_4
	Pitot tube	Exit pressure P_4
Nozzle	Type K Thermocouple	Exit temperature $T_5 = T_4$
	Pitot Tube	Exit pressure P_5
Starter gear	Magnetic pickup optical sensor (0-100,000 rpm)	Shaft Speed
Between front of engine and frame of test rig	Load Cell (± 800 N)	Thrust F

3 Preparation of Test Fuels

Palm oil biodiesel is a fatty acid methyl ester that is amber in color and is noticeably viscous in comparison with Jet A fuel, which is straw and less opaque in color. The odors of the two fuels are also distinct from each other, with Jet A being highly sharp and offensive in odor. Palm oil methyl ester (PME) in comparison smells almost like palm oil cooking oil. The Jet A fuel used in this research project was obtained from Petronas Malaysia, whereas the PME fuel was supplied by Sime Darby. Fuel samples were made in volumetric blends of 20% (B20) biodiesel. It was found that, similar to what was reported in the reviewed literature, biodiesel, regardless of source feedstock, mixes readily with any petroleum-derived fuel; in this case, Jet A. Each volume of fuel was mixed in a glass beaker with the aid of a glass stirring rod. It was found that not much stirring was necessary to blend the biodiesel and Jet A. The mixtures that were formed were found to retain their structure and no separation was visible for all blends. This remained true for the entire duration of the research project for samples that were kept for several months. Furthermore, there was no visible water retained in the fuel blends, which would have caused separation. This also tallies with the observations reported in the various literature sources.

Each fuel was also tested for their fuel heating or calorific values (FHV). This was done using an IKA C200 oxygen bomb calorimeter with the cooperation of the Faculty of Science and Technology of Universiti Kebangsaan Malaysia (UKM). Each test was performed three times to obtain a mean FHV for each fuel. Table 3 shows the range of FHV for the test fuels.

Table 3. Fuel heating values for Jet A and PME blends

Fuel	Jet A	B20
FHV (MJ/kg)	46.190	44.905

4 Experimental Procedure

The tests conducted for the CM4 engine were all cold starts. This means that no fuel switching occurred during operation, nor was there a quick restart of the engine after a test run was complete; each test was at least one day apart. This was due to the slow recharge process for the aircraft batteries as well as preserving the integrity of the starter gear motor. Similar to the experiments of French, Habib et al. and Krishna, no modification to the internal turbomachinery of the test engine was made [17,32,33].

Upon ignition, the engine was given approximately one minute to reach a steady state whereby the engine speed remained constant at a minimum rpm. This was found to be at approximately 48000 rpm. Data sampling is begun at this point. The throttle is slowly raised from 48000 rpm to approximately 66000 rpm. The engine maximum rpm was found to be within 68000 rpm running on Jet A fuel. However, it was found that running on B20, the highest achievable engine speed was 66000 rpm, and hence this remained as the maximum point for data sampling.

At each 1000 rpm interval, a sampling period of 10 seconds was allowed to ensure more reliable average readings for each sensor. Once the maximum rpm was achieved and the relevant data was measured, the throttle was slowly closed in a similar, decremental fashion back to 48000 rpm. Sampling was then halted once the minimum rpm was achieved. Tests for Jet A and B20 were repeated at least three times each.

The Armfield CM4 is equipped with a PC interface for its various sensors. The values of temperature, pressure, engine speed, and measured thrust are displayed in the user interface. An automatic sampling rate of every 2 seconds was set. Fig. 3 shows the CM4 engine stations as identified by the Armfield software and is used throughout the following analysis. Because of sensor limitations, the burner inlet and exit pressures P_2 and P_3 were assumed to be equal, as were the turbine exit and nozzle exit temperatures T_4 and T_5.

All of the Armfield CM4 tests were conducted in the Propulsion Laboratory at the Faculty of Engineering, Universiti Putra Malaysia. In all cases, the larger shutter doors of the laboratory were opened such that the engine's exhaust would travel outwards of the laboratory.

The ambient pressure was found to be 101.0 kPa on average. However, the variation of temperature depending on the time of day had to be taken into account. For the majority of the tests involving Jet A fuel, the engine tests were performed after sundown, leading to a lower ambient temperature. For the tests using biodiesel fuel, the engine was mostly operated during daylight hours due to the lower number of students on campus during the semester holidays. Thus the average ambient temperatures for both test fuels vary slightly, from 300 to 305 K.

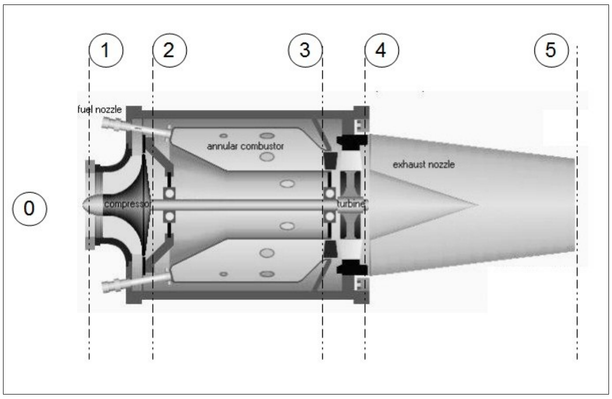

Fig. 3. Station numbering for Armfield CM4

4.1 Jet Engine Cycle Analysis

The basis of the calculation of performance parameters is the cycle analysis of gas turbines as demonstrated by Mattingly [34]. The primary measure of a turbojet engine is its thrust F, which is represented by Eq. 1.

$$F=\dot{m}_5 V_5-\dot{m}_0 V_0+A_5(P_{t5}-P_0) \quad (1)$$

where $\dot{m}_5$ is the total mass flow exiting the exhaust nozzle, V_5 is the nozzle exit velocity, $\dot{m}_0$ is the airflow ahead of the engine inlet, V_0 is the free stream air velocity, and the term $A_5(P_{t5} - P_0)$ refers to the thrust contribution from the pressure difference at the nozzle exit.

The next performance parameters for the turbojet engine to be calculated are the specific thrust $F/\dot{m}_0$, fuel-air ratio f and thrust specific fuel consumption S. Eqs. (2)~(4) show the equations used to obtain the aforementioned parameters. The FHV is represented as constant h_{PR}.

$$\frac{F}{\dot{m}_0}=a_0\cdot\frac{\dot{m}_5}{\dot{m}_0}\left(\frac{V_5}{a_0}-M_0\right)+\frac{A_5 P_5}{\dot{m}_0}\left(1-\frac{P_0}{P_5}\right) \quad (2)$$

$$f=\frac{1}{h_{PR}}(c_{p3}\cdot T_3-c_{p2}\cdot T_2) \quad (3)$$

$$S=\frac{f}{F/\dot{m}_0} \quad (4)$$

Following the above calculations, the engine thermal, propulsive and overall efficiencies η_T, η_P and η_O are obtained as shown in Eqs. (5)~(7).

$$\eta_T=\frac{a_0^2\cdot(1+f)\left[\left(\frac{V_5}{a_0}\right)^2-M_0^2\right]}{2\cdot f\cdot h_{PR}} \quad (5)$$

$$\eta_P=\frac{2V_0\left(\frac{F}{\dot{m}_0}\right)}{a_0^2\left[(1+f)\left(\frac{V_5}{a_0}\right)^2-M_0^2\right]} \quad (6)$$

$$\eta_O=\eta_T\times\eta_P \quad (7)$$

The individual component figures of merit are then calculated, beginning with the inlet, with diffuser efficiency η_d in Eq. (8)

$$\eta_d=\frac{\tau_r^{\left(\frac{\gamma_0-1}{\gamma_0}\right)}}{\tau_r-1} \quad (8)$$

where τ_r is the free stream temperature ratio:

$$\tau_r=1+\frac{\gamma_c-1}{2}M_0^2 \quad (9)$$

The compressor figures of merit are its efficiency η_c, specific work w_c and compressor power $\dot{W}_c$, as shown in Eqs. (10)~(12).

$$\eta_c=\frac{\pi_c^{\frac{(\gamma-1)}{\gamma}}-1}{\tau_c-1} \quad (10)$$

$$w_c=c_{p2}T_2-c_{p1}T_1 \quad (11)$$

$$\dot{W}_c=\dot{m}_0(c_{p2}T_2-c_{p1}T_1) \quad (12)$$

After the compressor section is the combustor or burner section, with burner efficiency η_b obtained from Eq. (13):

$$\eta_b=(\tau_b\cdot f+\tau_b-1)\times\frac{c_{p2}T_2}{h_{PR}f} \quad (13)$$

where the term τ_b refers to the ratio of burner exit and inlet temperatures T_4/T_3. Similar to the compressor figures of merit, the turbine is judged in terms of efficiency η_t, specific work w_t and power $\dot{W}_t$, as shown in Eqs. (14)~(16). The term e_t in Eq. (14) refers to the turbine efficiency coefficient, which is assumed to be 0.8, the lowest value specified by Mattingly with respect to the level of technology of the turbine.

$$\eta_t=\frac{1-\tau_t}{1-\tau_t^{\frac{1}{e_t}}} \quad (14)$$

$$w_t=|c_{p5}T_5-c_{p3}T_3| \quad (15)$$

$$\dot{W}_t=\dot{m}_5(|c_{p5}T_5-c_{p3}T_3|) \quad (16)$$

Finally the mechanical efficiency η_m, which represents the effectiveness of the link between the engine's turbine and compressor sections, is the ratio of the compressor power and turbine power.

$$\eta_m=\frac{\dot{W}_c}{\dot{W}_t} \quad (17)$$

In order to normalize the results from the experiments due to the differing ambient temperature T_0, corrections to the performance parameters with respect to standard sea level conditions were made. These corrections are listed below from Eqs. (18)~(21). The remaining performance parameters were then calculated as previously based on the corrected values. The dimensionless variables δ_n and θ_n refer to the station pressure or temperature ratios in relation to standard sea level pressure and temperature 101.3 kPa and 288.2 K.

$$F_c=\frac{F}{\delta_0} \quad (18)$$

$$\dot{m}_{c0}=\frac{\dot{m}_0}{\frac{\sqrt{\theta_0}}{\delta_0}} \quad (19)$$

$$\dot{m}_{cf}=\frac{\dot{m}_f}{\delta_1\cdot\sqrt{\theta_1}} \quad (20)$$

$$S_c=\frac{\pi_d\cdot\dot{m}_{cf}}{F_c} \quad (21)$$

5 Results

As stated prior, the fuels that were tested experimentally were Jet A and B20. The results from these tests were averaged for each fuel and presented against each other. Because the only factor taken into account that directly affected thrust is the throttle, most of the results are shown against the engine speed or rpm.

During operation, a clear change in the Armfield CM4 performance was the time for ignition of the B20 fuel. As opposed to the time of ignition for Jet A, which was less than 5 seconds after starting the ignition plug, the ignition of B20 took more than twice as long, at over 10 seconds. In addition, Fig. 4 shows the changes that occurred in the cooling oil temperature for both fuels. The lubrication oil outlet temperature for B20 is clearly higher than Jet A from 55000 rpm onwards. The largest rise in lubrication oil temperature is from 343.2 K to 368.6 K at 61000 rpm, an increase of 7.4%. This would imply that more stress is placed on the turbomachinery when using B20 fuel. The higher lubrication oil temperatures may also be attributed to the higher turbine temperatures during the B20 tests, shown in Fig. 5.

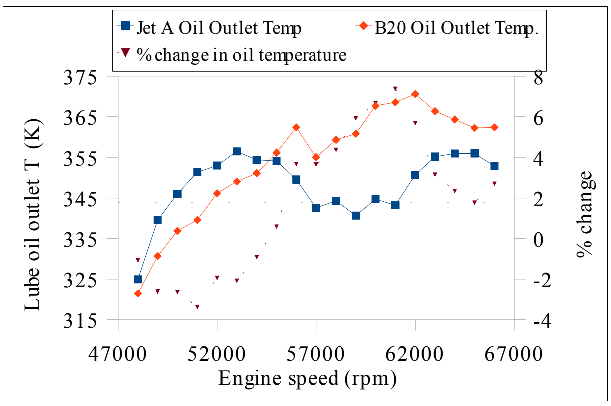

Fig. 4. Lubrication oil temperatures for B20 and Jet A

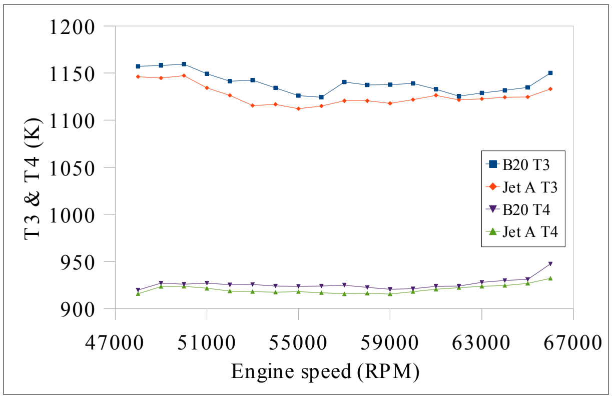

Fig. 5. Turbine inlet and exit temperatures for B20, Jet A

An important indicator of change in the CM4 engine performance is the increase in turbine inlet temperature T_3 and turbine exit or exhaust gas temperature T_4. This tallies with the literature findings which indicate that the higher oxygen content of biodiesel leads to better combustion and thus higher combustion temperatures. The higher temperatures are further supported by Fig. 6, which shows the energy balance of the test fuels' combustion as demonstrated by Pourmovahed et al. [35].

$$\dot{m}_f\cdot h_{PR}=\dot{m}_5\cdot\frac{V_5^2}{2}+\left(\dot{m}_5\cdot h_5-\dot{m}_0\cdot h_{air}\right)+\dot{Q}_{loss} \quad (22)$$

At maximum rpm, a marginally higher percentage of the B20 fuel FHV is converted into a change in enthalpy (the second term in Eq. 22), and thus a higher temperature rise.

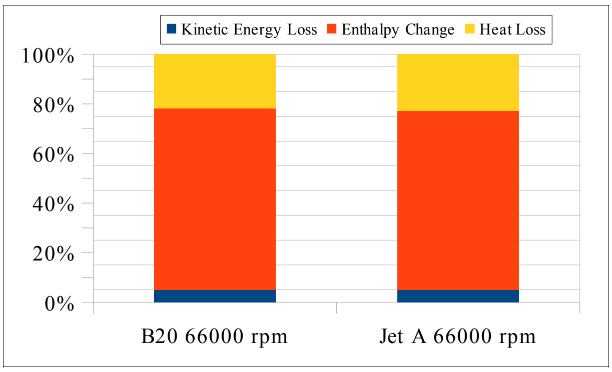

Fig. 6. Energy balance for B20 and Jet A

The change in thrust for B20 from Jet A is shown in Fig. 7. It can be seen that barring a 2% to 4% drop in thrust at the midrange of engine speed, B20 performs comparably with Jet A, to the point that from 61000 rpm onwards the difference in thrust is less than 1.5%.

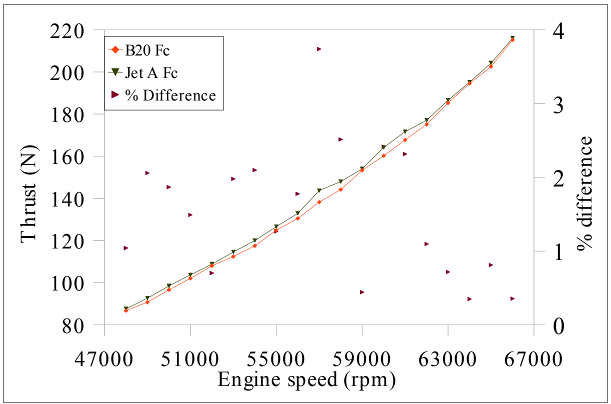

Fig. 7. Corrected thrust lines for B20 and Jet A

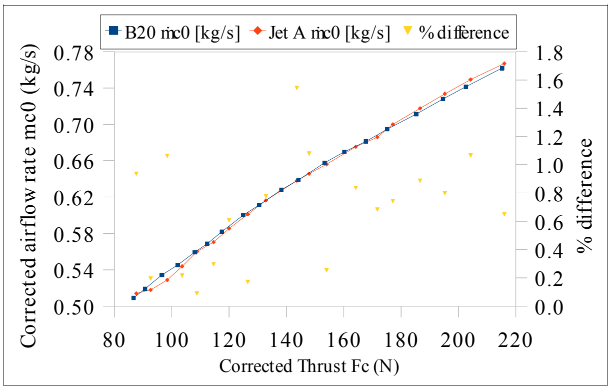

Fig. 8. Corrected airflow rate for B20 and Jet A

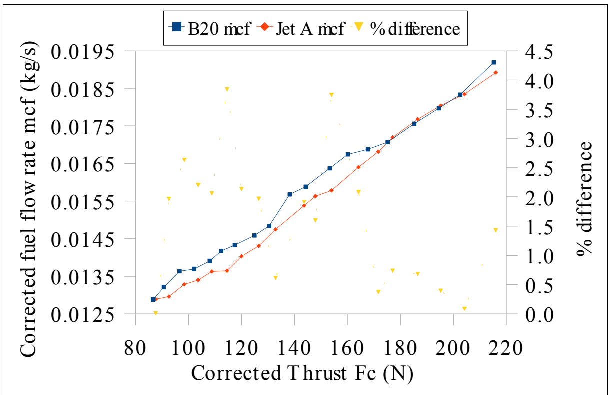

Fig. 9. Corrected fuel flow for B20 and Jet A

Figs. 7~12 show an interesting trend for the performance of the CM4 running on Jet A and B20. The percentage differences between the two fuels' impact on thrust is very small, at most about 4%, with increasing similarity at the high rpm range. This tallies with the literature [32], whereby smaller quantities of biodiesel in the benchmark fuel did not lead to a significant drop in performance. The trend of converging parameters towards maximum rpm continues for air- and fuel flow, specific thrust, and thrust specific fuel consumption. This suggests that a 20% mixture of PME with Jet A is viable, particularly at higher rpm. However, the CM4 still saw a small increase in fuel-air ratio and specific fuel consumption before reaching 60000 rpm. This can only be attributed to the slightly lower FHV of B20.

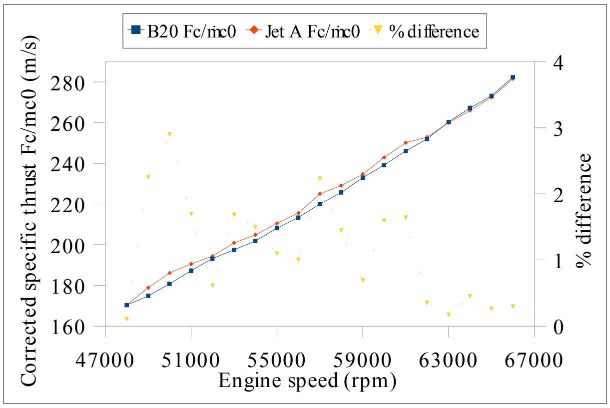

Fig. 10. Corrected specific thrust for B20 and Jet A

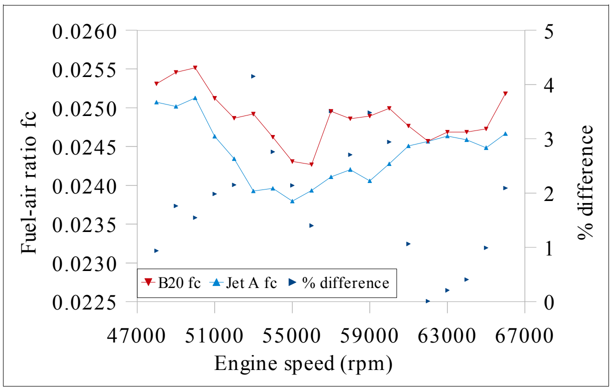

Fig. 11. Fuel-air ratio for B20 and Jet A fuels

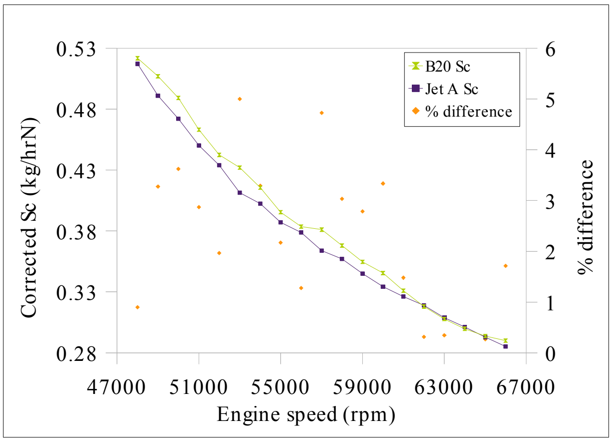

Fig. 12. Corrected thrust specific fuel consumption for B20 and Jet A

As with the earlier performance indicators, B20 performed comparably to Jet A for thermal efficiency (Fig. 13); however, the differences in propulsive efficiency are clearer, with Jet A having better propulsive efficiency at the higher engine speeds as shown in Fig. 14. This leads to a similar percentage difference for overall efficiency (Fig. 15). The higher propulsive efficiency for Jet A is due to its lower fuel-air ratio (Fig. 11) as well as its marginally better specific thrust.

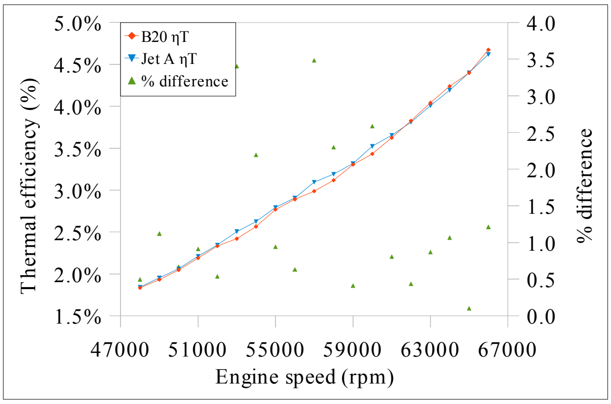

Fig. 13. Thermal efficiency for B20 and Jet A

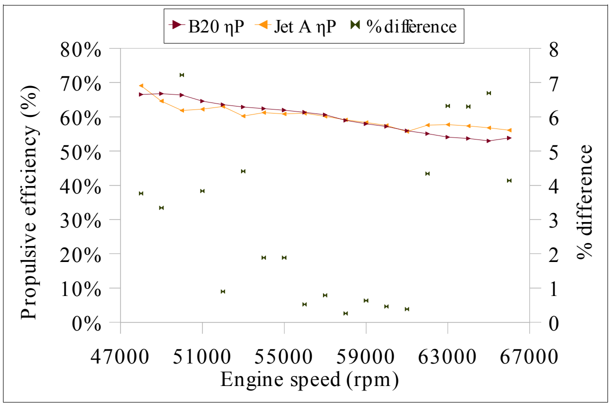

Fig. 14. Propulsive efficiency for B20 and Jet A

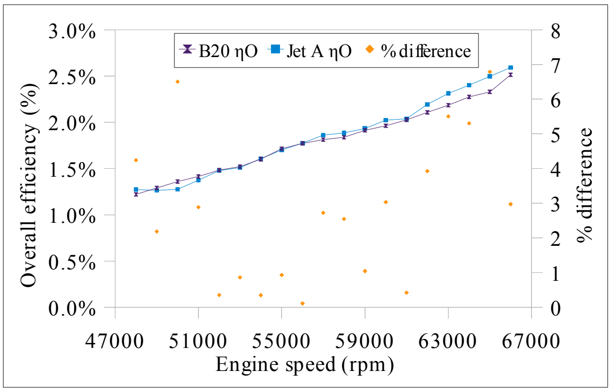

Fig. 15. Overall efficiency for B20 and Jet A

The component efficiencies of the CM4 turbojet are compiled in Fig. 16. The diffuser efficiencies for B20 and Jet A are highly similar, decreasing with increasing rpm and thrust. The free-stream temperature ratios and diffuser efficiencies for B20 and Jet A are very similar with little variation; the mean percent differences are only 0.09% and 0.032% respectively. Fig.16 shows a slightly higher line for η_c for B20 than Jet A, particularly at 48000 rpm, 52000 rpm, 57000 rpm and 66000 rpm. However, the compressor efficiencies remain very close to each other, with a mean percentage difference of 1.5%. The efficiency of the turbine section of the CM4 is not seen to change significantly with the change in fuel. The turbine efficiency was actually marginally higher using B20, but only by 0.07%. Hence no real change is apparent there, as with the inlet and compressor sections.

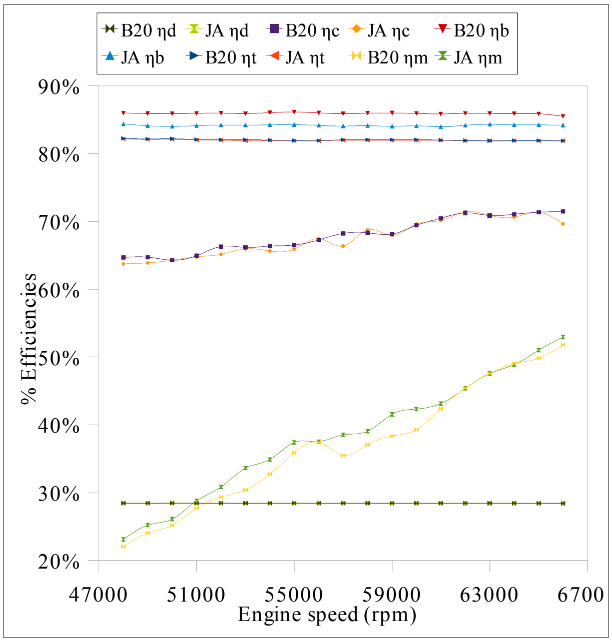

Fig. 16. Component efficiencies for B20 and Jet A

A more apparent change in component performance is seen in the burner section, which is made clearer in Fig. 17. By burning B20, the combustor efficiency rose by approximately 2% on average. The higher burner efficiency is due to the completeness of the combustion process, which is due to the oxygen content of the biodiesel.

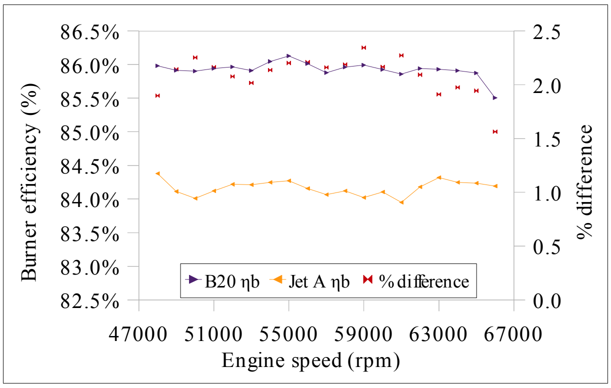

Fig. 17. Burner efficiency for B20 and Jet A

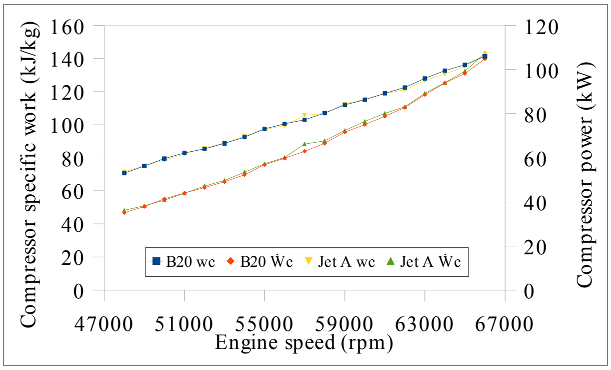

Fig. 18. Compressor specific work and power for B20 and Jet A

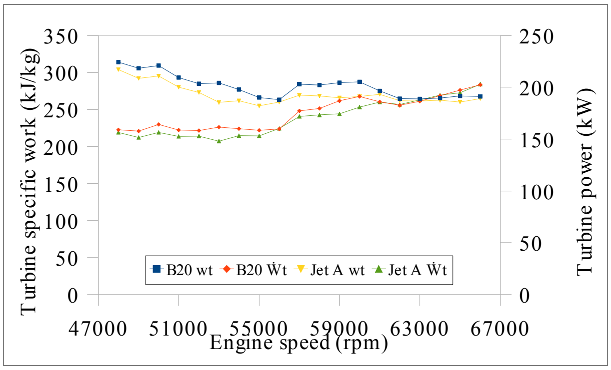

Fig. 19. Turbine power and specific work for B20 and Jet A

Figs. 18 and 19 show the specific work and power generated by the compressor and turbine sections. The compressor work and power for B20 and Jet A are similar; however, there is a slightly more noticeable rise in turbine specific work and power for B20. Because the turbine power is linearly affected by the difference between T_5 and T_3, the higher temperatures associated with B20 may have influenced the rise in turbine work and power. However, because the compressor performance of the two fuels were of similar values, the higher turbine output for B20 actually led to a drop in mechanical efficiency, particularly at the midrange of engine rpm. The mechanical efficiency lines for B20 and Jet A are shown in Fig. 16; the mechanical efficiency for B20 is only comparable to Jet A from 60000 rpm onwards.

6 Conclusion and Recommendations

The aim of this experimental work was to determine the performance of the Armfield CM4 turbojet running on a blend of palm oil biodiesel and Jet A. It was found that B20 produced similar amounts of thrust as Jet A, particularly at the higher range of rpm. The trade-offs from the usage of biodiesel include slightly higher fuel flow, fuel-air ratio and specific fuel consumption, but from the B20 data the increase in these values was minimal, within a range of 0 – 5%. In addition, the thermal efficiency for B20 was of similar caliber to that of Jet A, while the propulsive and overall efficiencies underwent a slight drop at maximum rpm. However, the largest dip in propulsive and overall efficiency was less than 8%, suggesting a minimal penalty.

In terms of component efficiency, the inlet, compressor and turbine sections of the CM4 were not overtly affected by the change in fuel, with very little difference between the two. However, the burner efficiency actually improved with the combustion of B20, due to its higher oxygen content.

The compressor produced similar amounts of specific work and power for both fuels, while the increase in turbine temperatures led to a small increase in turbine work for B20. However, the mechanical efficiency of the CM4 for B20 was slightly less than that of Jet A, up until the engine approached 60000 rpm, after which the differences were marginal.

In all, the drawbacks for B20 were higher turbine inlet and exit temperatures as well as its inherently lower calorific value. Future work would include further testing of different blends of PME in Jet A, including increasing the PME content. The long term effects of biodiesel testing in turbojet engines have not yet been studied, particularly in terms of combustor and turbine lining as well as fuel delivery systems. Currently, simulation work for Jet A, B20 as well as other volumetric blends of PME is underway.

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