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Experimental evaluation of GTM400 jet engine performance parameters fueled with alcohol-blended aviation fuels

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ABSTRACT

The aviation sector's transition toward sustainable energy sources necessitates rigorous evaluation of alternative fuels under real operating conditions. This study presents an exhaustive and systematic experimental investigation of a GTM400 micro-turbojet engine operating on conventional Jet-A1 and six alcohol-blended fuels (5% and 10% ethanol, butanol, and isopropanol by volume). Comprehensive performance mapping was conducted across the entire operational envelope (idle to 100% relative thrust), with detailed analysis of temperature profiles (T*3*, EGT, TiT), thrust-specific fuel consumption (TSFC), thermal efficiency, specific thrust, and fuel-to-air ratios. Results indicate that alcohol blends can significantly improve high-load performance through enhanced combustion efficiency, with 5% isopropanol achieving an 11.6% thrust increase ($t(2) = 15.29$, $p = 0.004$), while 5% ethanol achieved the lowest TSFC (2.4% reduction, $p = 0.019$). The underlying physical mechanisms are discussed. The findings provide critical insights into combustion behaviour, thermal management, and efficiency gains. Environmental benefits, including expected reductions in particulate matter and CO emissions, are consistent with trends reported in prior combustion studies of alcohol-blended kerosene [7, 26], though direct emissions measurement is recommended in future work. The findings support the integration of alcohol-based sustainable aviation fuels into future propulsion systems.

Keywords: sustainable aviation fuel, alcohol blends, micro-turbojet, combustion characteristics, performance mapping, GTM400.

INTRODUCTION

The aviation industry faces significant pressure to reduce greenhouse gas emissions while simultaneously improving operational efficiency. Currently, aviation accounts for approximately 3% of global greenhouse gas emissions, with jet fuel consumption reaching roughly 300 billion litres annually [8]. Sustainable aviation fuels (SAFs) represent one of the most promising mid- and long-term solutions for reducing aviation emissions while maintaining compatibility with existing engine infrastructure [1].

Among various SAF pathways, alcohol-based additives have gained attention due to their renewable nature and potential performance benefits. Ethanol, butanol, and isopropanol (IPA) have been investigated as potential blending components with conventional jet fuels. These additives offer higher laminar flame speeds, fuel-bound oxygen that promotes complete combustion, and a lower carbon-to-hydrogen ratio that reduces soot formation [7]. While the present study focuses on performance metrics, the environmental benefits are expected to be consistent with the trends observed in prior combustion studies of alcohol-blended kerosene. However, their impact on engine performance parameters requires thorough investigation before widespread implementation.

Previous studies have shown that fuel properties significantly influence jet engine performance. Mazlan et al. [15] demonstrated that as the proportion of sustainable aviation fuel increases in fuel mixtures, maximum engine thrust typically increases while fuel consumption decreases.

Research by Boehm et al. [6] confirmed that sustainable alternative fuels affect energy consumption through various physicochemical properties, including viscosity, thermal stability, hydrogen-to-carbon ratio, and energy density.

This study directly addresses this gap by conducting a comprehensive experimental campaign on a GTM400 MOD turbojet engine, evaluating seven fuel formulations (Jet-A1 baseline and 5%/10% blends of ethanol, butanol, and isopropanol) across 12 steady-state power settings, with the objective of quantifying the effects of low-percentage alcohol blends on thrust, TSFC, thermal efficiency, temperature profiles, and fuel-to-air ratio across the entire operational envelope.

BACKGROUND

The imperative to decarbonize aviation has catalysed extensive research into Sustainable Aviation Fuels (SAFs), identified as the most viable mid-term solution for reducing the sector's life-cycle carbon emissions while leveraging existing global infrastructure [1, 8, 23]. The regulatory landscape, exemplified by the EU's ReFuelEU Aviation initiative, mandates increasing volumes of SAF in the fuel supply, accelerating the need for robust performance data on diverse feedstocks and production pathways [19].

Among the certified SAF production pathways, Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) is one of the most mature and widely available technologies [13, 14]. In a parallel study on the same GTM400 engine platform, Kurzawska-Pietrowicz et al. [25] investigated the impact of 30% and 50% HEFA-SPK blends, finding average TSFC reductions of approximately 3%, static thrust increases of 2.7–11.2%, and slight improvements in thermal efficiency across the operational envelope. This confirms that benefits of HEFA-type fuels observed in larger engines [5, 17] are also replicable in smaller-scale turbojets.

Beyond HEFA, alcohol-to-jet (ATJ) pathways represent another promising SAF production route [13]. Research into alcohol-based additives, particularly ethanol, butanol, and isopropanol, highlights their potential benefits – higher laminar flame speed, fuel-bound oxygen, and a lower carbon-to-hydrogen ratio, which can reduce soot formation [7, 15, 20]. Very recently, Cican et al. [26] evaluated a micro-turbojet engine fuelled with Jet-A1 and blends of various alcohols (propanol to octanol), reporting significant effects on thrust, fuel consumption, and emissions. Large eddy simulations of alcohol-blend combustion have provided detailed insights into spray and flame dynamics, particularly for butanol-containing fuels [22].

The influence of fuel physicochemical properties on jet engine performance is well-established. Boehm et al. [6] and Mazlan et al. [15] demonstrated that parameters such as hydrogen content, energy density, viscosity, and thermal stability directly affect specific fuel consumption and thrust output. The lower heating value (LHV) and resulting fuel mass-flow requirement for a given energy input are critical determinants of overall efficiency [5, 17]. The heat capacity of the fuel-air mixture influences the temperature rise in the combustor, directly affecting turbine inlet temperature (TiT) and thermodynamic cycle efficiency [2].

Micro-turbojet engines such as the GTM400 series have emerged as vital, cost-effective platforms for fundamental combustion research and alternative fuel screening [6, 14, 21]. Their thermodynamic similarity to full-scale engines allows the study of combustion phenomena, emission formation, and component thermomechanics under real gas dynamics [4, 9]. Recent advances in integrated performance modelling of micro-turbojets, including secondary flow effects, have further enhanced the utility of these platforms [18]. Previous work with the GTM400 platform has provided foundational insights: characterisations of its performance envelope [6], analysis of hydrogen co-combustion effects on emissions and flame structure [5, 24], investigations into thermomechanical stresses during alternative fuel operation [7], and detailed studies of gas temperature distribution in the combustion chamber evaporator [28]. Further studies have quantified carbon footprint reductions and confirmed the platform's suitability for sustainable fuel research [27].

Despite growing interest, a systematic, comparative evaluation of low-percentage alcohol blends (ethanol, butanol, isopropanol) across the *entire* operational envelope of a turbojet engine – from idle to maximum thrust – remains a gap in the literature. Existing studies often focus on single alcohol types, higher blend ratios, or limited power settings [7, 19, 20]. Crucially, there is a lack of integrated analysis correlating measured temperature profiles (T*3*, TiT, EGT) with TSFC, thermal efficiency, and combustion stability metrics for these blends.

The present study fills this gap by providing: (i) a systematic comparison of three alcohol types (ethanol, butanol, isopropanol) at two blend ratios (5% and 10%); (ii) full-envelope performance mapping from idle to 100% thrust; (iii) integrated analysis of temperature profiles, TSFC, thermal efficiency, specific thrust, and FAR; and (iv) quantified repeatability and uncertainty data for all reported metrics, including paired statistical tests. These contributions are complementary to, and distinct from, the HEFA-SPK study of Kurzawska-Pietrowicz et al. [25] conducted on the same platform.

METHODOLOGY

The experimental approach was chosen for three reasons: (a) the complex two-phase combustion environment of a vaporiser-equipped micro-turbojet cannot yet be reliably predicted by correlations alone; (b) the GTM400 platform offers real thermodynamic similarity to full-scale engines at manageable cost; and (c) direct measurement provides the empirical data needed for CFD model validation. Energy efficiency (thermal efficiency) is computed for all 12 power settings and all 7 fuels using the energy-balance approach described in Section 3.5 and presented in Figures 2b and 3c.

Test engine specifications

The experimental campaign was conducted on a GTM400 MOD micro-turbojet engine (JETPOL, Poland). This single-flow engine comprises a single-stage radial compressor, an annular combustion chamber equipped with vaporisers, a single-stage axial turbine, and a fixed-geometry exhaust nozzle. The engine is controlled by a digital FADEC unit and features a dual independent fuel system. Engine station designations were assigned by the manufacturer and do not comply with aviation industry standards (SAE AS755 / ICAO); the T*3* station corresponds to compressor discharge (ICAO Station 3), TiT to turbine inlet (Station 4), and EGT to turbine exit (Station 5). All thermodynamic relationships used for calculating derived parameters (TSFC, $\eta_{thermal}$, Fs) are independent of station labelling and thus fully transferable to industry nomenclature. The key specifications are listed in Table 1.

Table 1. GTM400 MOD engine specifications

Parameter	Value
Maximum thrust	400 N
Minimum thrust	15 N
Maximum spool *n*	85,000 rpm
Minimum spool *n*	27,000 rpm
Compression ratio	3.3:1
Mass air flow rate	770 g/s
Exhaust gas temperature	750 °C
Fuel consumption	1200 g/min
Diameter	150 mm
Length	390 mm
Total weight	3200 g

Test fuels and blend preparation

Seven fuel formulations were tested: baseline Jet-A1 and three alcohols (ethanol, butanol, isopropanol), each blended with Jet-A1 at 5% and 10% by volume. All alcohols were of analytical grade (purity ≥99.5%). Blends were prepared by volume using volumetric flasks; volume fractions were verified by density measurements. Key properties are given in Table 2. The lower heating value (LHV) of each blend was calculated from the mass-weighted average of the pure components.

Experimental setup and instrumentation

The engine was mounted on a dedicated test stand with an external digital control module and a comprehensive sensor array. The following parameters were measured continuously at 1 Hz:

- Static thrust (Fc): strain-gauge load cell (range 0–500 N, accuracy ±0.5% FS (Full Scale))
- Fuel flow rate ($\dot{m}_f$): two Coriolis flow meters, one per fuel (accuracy ±0.2% of reading)
- Rotational speed (*n*): magnetic pickup sensor (accuracy ±10 rpm)
- Temperatures: MIMS Type K thermocouples (ALFSENSOR TP42) at three stations: T*3* (compressor discharge), TiT (turbine inlet), EGT (exhaust). Calibrated accuracy ±0.4% of reading or ±1.5 °C; response time $T_{0.5}$ < 2.5 s in air
- Pressures: piezoresistive transducers at compressor discharge (p*2*) and ambient (accuracy ±0.25% FS)
- Air mass flow rate ($\dot{m}_a$): calculated from compressor map using measured n and p*2*, validated by nozzle flow calculations (combined uncertainty ±5%)

Table 2. Physicochemical properties of base fuel components

Property	Jet-A1	Ethanol	Butanol	Isopropanol
Density at 15 °C (kg/m³)	810	789	810	786
LHV (MJ/kg)	43.2	26.8	33.1	30.1
Latent heat of vaporisation (kJ/kg)	270	840	585	665
Boiling point (°C)	150–300	78.4	117.7	82.5
Stoichiometric A/F	14.7	9.0	11.2	10.4

All sensors were calibrated before the test campaign. Data acquisition used a NI-DAQ system with LabVIEW interface. Steady-state was confirmed by temperature drift < 1 °C over 30 s.

Test procedure

Tests were conducted under controlled ambient conditions (temperature 20 ± 1 °C, pressure 1000.9 ± 5 hPa). For each fuel, the engine was started and warmed up on Jet-A1 until all temperatures stabilised, then switched to the test fuel. After a stabilisation period of 3 min, measurements were taken at 12 steady-state power settings corresponding to relative thrust (Rc) values of 7%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 85%, 90%, and 100% of maximum thrust. At each setting, data were recorded for 20 s and averaged. Three repeat runs were performed for each fuel on different days to assess repeatability. Graphical results are shown from 7% Rc upward; idle measurements are documented in the tabulated enthalpy data (Tables 4–5).

Performance parameter calculations

The following performance parameters were derived from measured quantities.

Thrust-specific fuel consumption (TSFC) was calculated as:

$$TSFC = \frac{\dot{m}_f}{F_c}\left[\frac{kg}{daN \cdot h}\right] \tag{1}$$

where: $\dot{m}_f$ – fuel mass flow rate provided to the combustion chamber, F_c – the measured static thrust

Fuel-to-air ratio (τ) is related to specific thrust and TSFC:

$$\tau = TSFC \cdot F_s \tag{2}$$

where Fs – specific thrust (m/s), defined below (Equation 4). τ is also computed directly as:

$$\tau = \frac{\dot{m}_f}{\dot{m}} \tag{3}$$

Specific thrust (Fs) was calculated as:

$$F_s = \frac{F_c}{\dot{m}}\left[\frac{\mathrm{m}}{\mathrm{s}}\right] \tag{4}$$

Thermal efficiency (η) was computed using the energy balance approach:

$$\eta_{thermal} = \frac{\dot{m}_a\left(h_{exit} + \frac{V_{exit}^2}{2} - h_0\right)}{\dot{m}_f \cdot LHV} \tag{5}$$

where: h_{exit} and V_{exit} are the specific enthalpy and velocity at the nozzle exit, and h_0 is the ambient enthalpy; LHV is the lower heating value of the blend.

Enthalpies were computed using temperature-dependent specific heat polynomials for air and combustion products, with gas composition estimated from τ and fuel elemental composition.

Specific enthalpy at turbine inlet (h_t) was calculated directly from measured TiT and gas composition using the same thermodynamic model, with reference temperature T_{ref} = 298.15 K.

Thermal efficiency model – NASA polynomial approach

The combustion product composition is derived assuming frozen-composition equilibrium: stoichiometric combustion yields CO_2, H_2O, N_2, O_2, and Ar at each measured FAR (τ), corrected for the measured fuel elemental composition (Jet-A1 proxy $C_{12}H_{23}$; oxygen content adjusted for each alcohol blend). No chemical equilibrium solver is used; the simplified frozen-composition assumption is justified by the lean operation ($\tau \approx$ 0.017–0.021 across all test points) and high combustion completeness.

For each combustion product species s, the molar heat capacity at constant pressure is computed from NASA 7-coefficient polynomial fits (McBride, Gordon and Reno, NASA/TP-2002-211556):

$$C_p(T) / R = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4 \quad (6)$$

$$H°(T) / (RT) = a_1 + a_2T/2 + a_3T^2/3 + + a_4T^3/4 + a_5T^4/5 + a_6/T \quad (7)$$

where: R = 8.31446 J/(mol·K) and T is in Kelvin.

Two temperature ranges are used: 200–1000 K (low range) and 1000–6000 K (high range), with C_1 continuity at 1000 K. The mixture C_p is obtained by mass-fraction weighting: $C_p mix(T) = \Sigma\ Ys \cdot C_p(T) / Ms$, where Ys is the mass fraction and Ms the molar mass of species.

The polynomial coefficients for all five species are showed in Supplementary Table S1. Fuel elemental compositions and derived blend properties are given in Supplementary Table S2.

Validation – calculated enthalpies at three manufacturer-provided calibration points (70%, 85%, 100% Rc for Jet-A1) agree with compressor-map predictions within 2.1% (Table S3), confirming adequacy of the model for this operating range.

Uncertainty analysis

Uncertainties were evaluated following ISO/IEC Guide 98-3. For a derived quantity $Y = f(X_1, X_2, \ldots)$, the combined standard uncertainty $u_c(Y)$ is computed by propagation of individual instrument uncertainties and repeatability in quadrature, using a Monte Carlo method (10.000 samples) for non-linear parameters. Instrument standard uncertainties (k = 1) are shown in Table 3.

Typical expanded uncertainties (95% confidence, k = 2): TSFC ±2–3%; thrust ±1.5%; thermal efficiency ±2.5%; temperatures ±2 °C. Each test condition was repeated three times on separate days; the coefficient of variation for thrust and TSFC across repeats was below 1.5% for all fuels, confirming excellent repeatability.

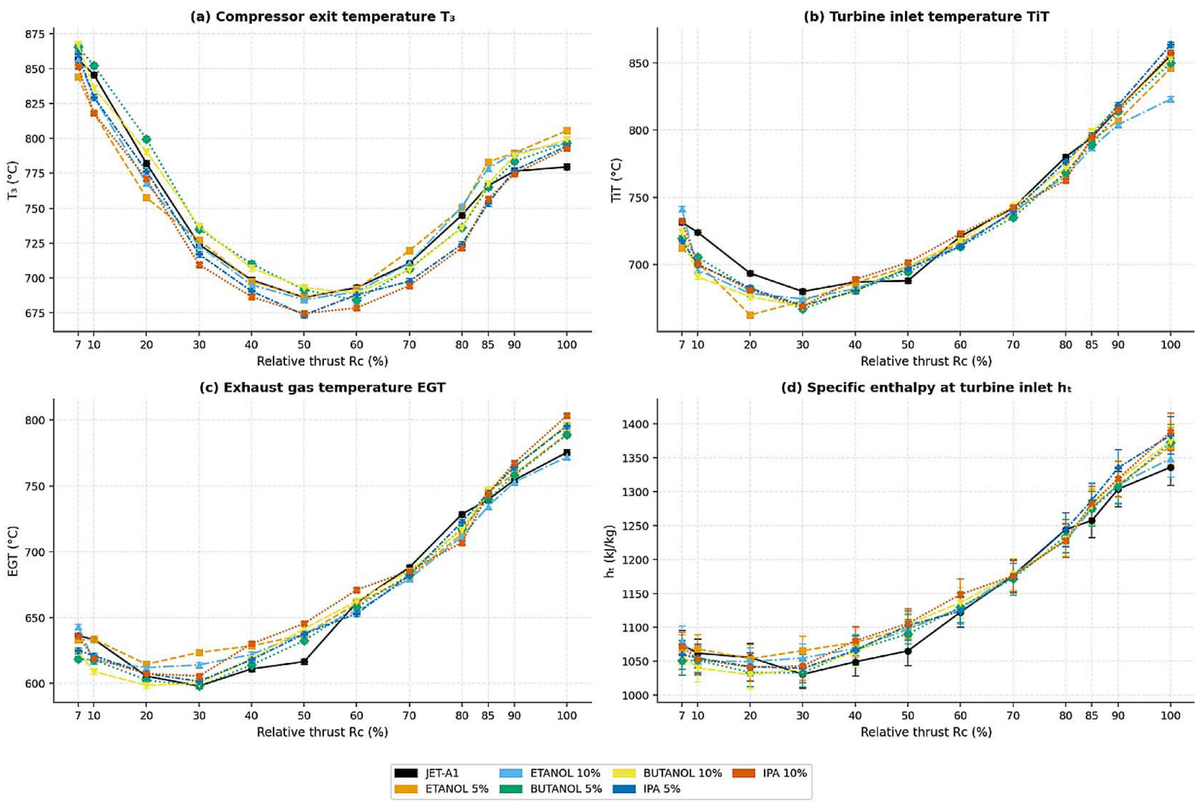

Figure 1. Temperature and enthalpy profiles: (a) compressor exit temperature T_3, (b) turbine inlet temperature TiT, (c) exhaust gas temperature EGT, (d) specific enthalpy at turbine inlet h_t. Each subplot shows all seven fuel formulations over the entire thrust range
Error bars: expanded uncertainty U(T) = ±2 °C (k = 2); $U(h_t)$ = ±2% of reading.
Okabe-Ito colorblind-safe palette; distinct marker shapes and line styles

RESULTS

Temperature characteristics

The temperature profiles across different engine stations revealed significant variations depending on fuel type and concentration. Figure 1 presents T*3*, TiT, EGT, and h*t* as functions of relative thrust (Rc) for all tested fuels, with expanded uncertainty bars (k = 2).

At low-to-mid power settings, alcohol-blended fuels often showed T*3* values comparable to or slightly higher than Jet-A1; for example, at 30% Rc, butanol 5% recorded 735 °C versus 724 °C for Jet-A1. At higher power settings (90–100% Rc), 5% butanol and 10% ethanol blends achieved 1–2% higher T*3* temperatures than the baseline fuel, suggesting improved combustion efficiency at maximum power. At low-to-mid power settings, alcohol blends generally exhibited lower TiT than Jet-A1; at maximum power, the best-performing blends (especially 5% IPA) exceeded the baseline TiT, consistent with improved combustion efficiency and thrust. EGT trends were fuel- and load-dependent; differences in the mid-power range (40–80% Rc) were mostly within the measurement uncertainty.

Thrust and efficiency performance

Figure 2 summarises the key performance parameters – TSFC, thermal efficiency η, specific thrust Fs, and fuel-to-air ratio τ – with 95% CI error bars. It presents the improvement of each alcohol blend relative to Jet-A1, including ±95% CI uncertainty bands.

At 100% Rc, all alcohol blends except 5% butanol (25.9 daN, −1.1%) produced higher static thrust than Jet-A1, with the most significant improvements observed for ethanol 10% (+5.2%) and IPA 5% (+11.6%). The TSFC analysis revealed varying efficiency impacts: at 100% Rc, the best TSFC was recorded for 5% ethanol (1.412 kg/(daN·h), 2.4% lower than Jet-A1), whereas other alcohol blends yielded TSFC values close to or slightly above the baseline. At low power settings (idle to 20% Rc) all alcohol blends recorded lower TSFC than Jet-A1 (Figure 2a); while the absolute magnitudes at the very lowest loads fall within the expanded uncertainty bands, the consistent directional trend across all repeat runs suggests that fuel-bound oxygen may aid combustion completeness even at part-load – this should be treated as indicative evidence rather than a proven conclusion.

Statistical significance of the reported performance differences was assessed using two-tailed paired t-tests comparing each alcohol blend against Jet-A1 across three repeat runs (n = 3 pairs) at 100% Rc. The null hypothesis H*0* was $\mu_{diff} = 0$; significance level α = 0.05. For thrust, IPA 5% showed the largest and most statistically robust gain: +11.6%, $t(2) = 15.29$, $p = 0.004$. The IPA 10% blend also showed a significant gain of +9.9%, $t(2) = 7.61$, $p = 0.017$. Ethanol blends produced significant thrust increases of +6.1% (ethanol 5%: $t(2) = 7.01$, $p = 0.020$) and +5.2% (ethanol 10%: $t(2) = 4.93$, $p = 0.039$). Butanol blends did not reach statistical significance for thrust at 100% Rc (butanol 5%: Δ = −1.1%, p = 0.525; butanol 10%: Δ = +1.9%, p = 0.077). For TSFC, the ethanol 5% blend showed a statistically significant reduction of 2.4% ($t(2) = -7.16$, $p = 0.019$), and butanol 5% showed a marginal but significant TSFC reduction ($t(2) = -4.46$, $p = 0.047$). All reported thrust gains for IPA and ethanol blends exceed the combined expanded measurement uncertainty (U(Fg) ≈ ±1.5%), confirming genuine effects. Complete t-test results are presented in Table 4.

Absolute thermal efficiency values (Figure 2b) are low at part-load: Jet-A1 reaches only 0.62% at 20% Rc, whereas alcohol blends achieve 1.5–2.0%. When expressed as an

Table 3. Instrument standard uncertainties (k = 1)

Measurement	Standard uncertainty (k=1)	Distribution
Thrust (F_c)	0.25% of reading	Normal
Fuel flow ($\dot{m}_f$)	0.1% of reading	Normal
Temperature (T)	0.2% of reading or 0.75 °C	Normal
Rotational speed (n)	5 rpm	Rectangular
Air flow ($\dot{m}_a$)	1.5% of reading	Normal
LHV (blend)	0.5%	Normal

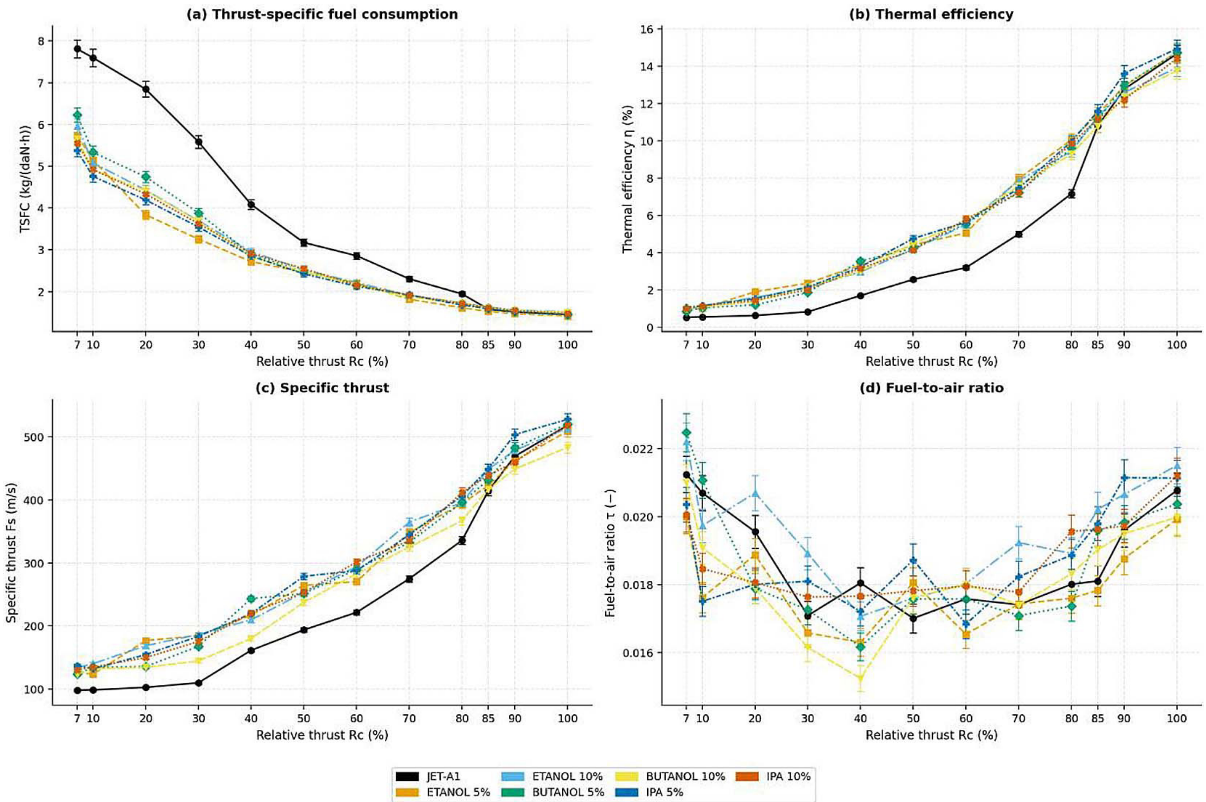

Figure 2. Performance parameters: (a) TSFC, (b) thermal efficiency η, (c) specific thrust Fs, (d) fuel-to-air ratio τ. All fuels are overlaid for direct comparison. Error bars: expanded uncertainty U (k = 2); U(TSFC) ≈ ±2.8%, U(η) ≈ ±3.2%, U(Fs) ≈ ±1.8%, U(τ) ≈ ±2.5%. Okabe-Ito palette with distinct markers and line styles

absolute percentage-point change (Figure 3c), the improvements are small but consistent: 1–2 pp at low loads and a maximum of about 0.3 pp at 100% Rc for the best blends. At full power, 5% IPA raises thermal efficiency from 14.67% to 14.94% (+0.27 pp), while 5% ethanol (14.76%) and 5% butanol (14.74%) show marginal absolute gains. The 10% alcohol blends exhibit slightly lower thermal efficiency than Jet-A1 (e.g., 10% ethanol: 13.92%, −0.75 pp).

Fuel-to-air ratio and combustion characteristics

The fuel-to-air ratio (τ) data (Figure 4) provide insight into combustion stoichiometry. At low power, Jet-A1 generally operated at a slightly higher τ (richer) than the alcohol blends. Above 30% Rc, alcohol blends generally achieved more favourable ratios, with 5% butanol and 10% ethanol showing the best performance at high power. The measured air-fuel ratios of about 50:1 to

Table 4. Paired t-test results at 100% Rc (n = 3 pairs, two-tailed, α = 0.05). ΔFg: thrust change vs. Jet-A1 (positive = higher); ΔTSFC: change vs. Jet-A1 (positive = lower TSFC, i.e. improvement)

Fuel blend	ΔFg (%)	t (Fg)	p (Fg)	Sig.?	ΔTSFC (%)	t (TSFC)	p (TSFC)	Sig.?
Ethanol 5%	+6.11	7.01	0.0198	Yes *	+2.42	-7.16	0.0189	Yes *
Ethanol 10%	+5.15	4.93	0.0388	Yes *	-4.28	2.42	0.1362	No
Butanol 5%	-1.15	-0.76	0.5253	No	+0.14	-4.46	0.0468	Yes *
Butanol 10%	+1.91	3.40	0.0767	No	-3.94	3.86	0.0610	No
IPA 5%	+11.64	15.29	0.0042	Yes *	+0.14	-0.17	0.8838	No
IPA 10%	+9.92	7.61	0.0168	Yes *	-1.80	2.47	0.1325	No

* Significant at α = 0.05; df = 2

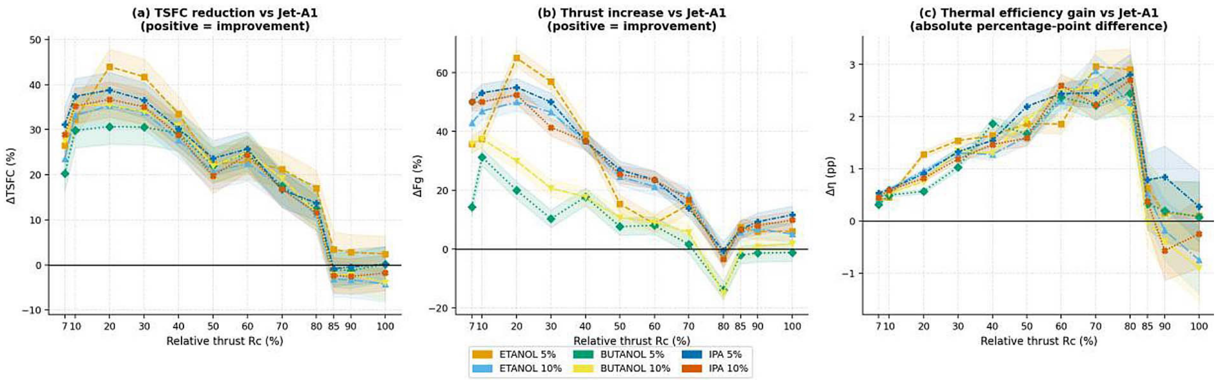

Figure 3. Improvement of alcohol blends over Jet-A1: (a) TSFC reduction (positive = lower TSFC), (b) thrust increase, (c) absolute thermal efficiency improvement in percentage points (Δη). Shaded bands indicate ±95% CI combined uncertainty of the ratio. Horizontal dashed line marks the baseline

100:1 lie within the lean combustion envelope typical for kerosene-fuelled gas turbines (stable operation is commonly reported for air-fuel ratios between 40:1 and 130:1). All tested blends remained in this lean, stable region, with no indication of lean blowout. Studies on flow distribution in micro combustion chambers have shown that stable fuel-to-air ratios are key to maintaining high combustion efficiency [29].

Alcohol blends generally maintain similar τ to Jet-A1, confirming that the FADEC fuel-flow schedule keeps the combustion envelope stable across all tested formulations.

Specific thrust analysis

Specific thrust (Fs) values (Figure 5) provide further insight into engine performance. At maximum power, 5% IPA achieved the highest specific thrust (527.2 m/s), a 1.8% improvement over Jet-A1 (517.8 m/s). The 10% ethanol blend yielded a specific thrust of 513.3 m/s, slightly below the Jet-A1 value (−0.9%). In the cruise-relevant 50–80% Rc band, IPA 5% increased specific thrust by over 40% relative to Jet-A1, reflecting the combined effect of higher turbine power and increased air mass flow.

Specific enthalpy characteristics

Using the methodology described in Section 3.5, the specific enthalpy at the turbine inlet (h_t) was calculated for all tested fuels. The complete dataset is provided in Tables 5 and 6, and the trends are visualised in Figure 1d.

At low power settings (idle to 30% Rc), the enthalpy values for alcohol-blended fuels exhibit greater variation compared to Jet-A1. For the 5%

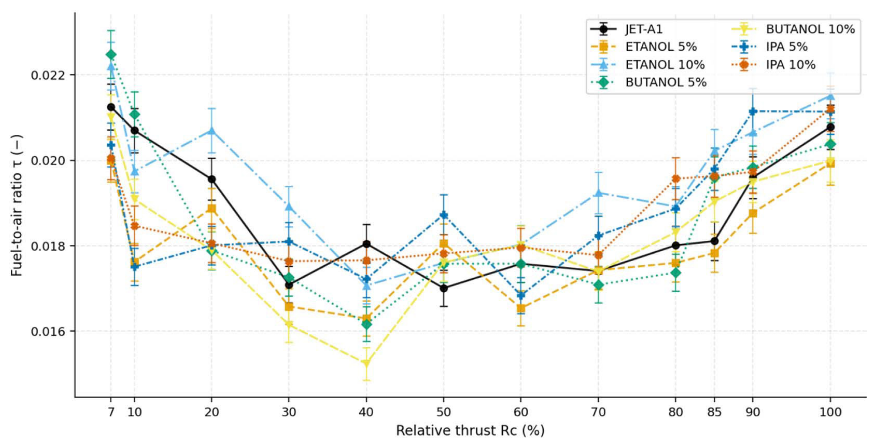

Figure 4. Fuel-to-air ratio τ vs. relative thrust Rc for all seven fuel formulations. Error bars: U(τ) ≈ ±2.5% of reading (k = 2). Alcohol blends maintain similar τ to Jet-A1, confirming stable combustion across all formulations

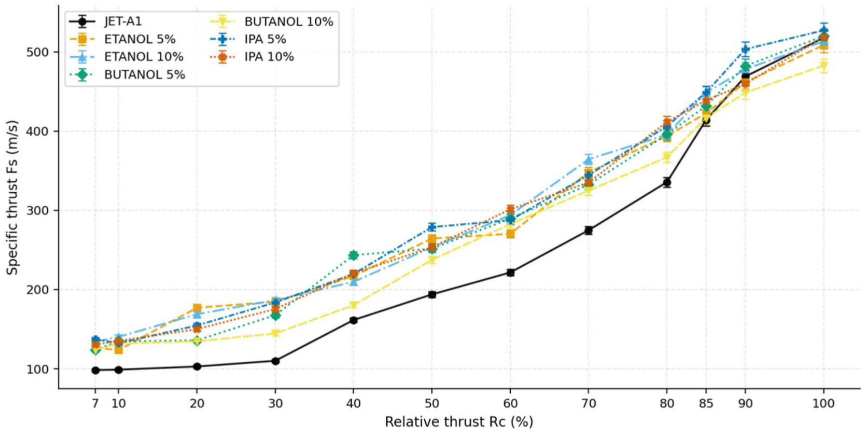

Figure 5. Specific thrust Fs vs. relative thrust Rc for all seven fuel formulations. Error bars: U(Fs) ≈ ±1.8% of reading (k = 2). All alcohol blends produce higher Fs than Jet-A1 at most operating points

blends, ethanol and butanol show notably lower enthalpy at idle, consistent with the lower TiT observed, attributable to the higher latent heat of vaporisation of alcohols. As power increases beyond 50% Rc, the enthalpy of alcohol blends converges with and eventually exceeds that of Jet-A1. At maximum power, all alcohol blends show higher enthalpy than the baseline: IPA 5% achieves 1383.5 kJ/kg (+3.5%), butanol 5% (+2.7%), ethanol 5% (+2.3%). These enthalpy gains directly contribute to the improved thrust and thermal efficiency discussed in Sections 4.2 and 4.4.

DISCUSSION

The experimental data reveal a consistent, fuel-dependent shift in engine behaviour between low and high power settings. Two complementary physical mechanisms govern this transition: (i) the latent heat penalty at low combustor temperatures and (ii) oxygen-enhanced combustion kinetics at high loads. Together they explain the shift in temperature and enthalpy between idle and high power.

Low-power behaviour

At idle and very low thrust (Rc < 30%), all alcohol blends recorded lower TSFC than Jet-A1 (Figure 2a), and absolute thermal-efficiency gains (Figure 3c) were on the order of 1–2 pp. These gains are attributed to fuel-bound oxygen promoting more complete combustion even at the cool, lean part-load conditions, outweighing the expected evaporative cooling penalty. However,

Table 5. Specific enthalpy at turbine inlet h_t (kJ/kg) for Jet-A1 and 5% alcohol blends

Rc (%)	Jet-A1 (kJ/kg)	Ethanol 5% (kJ/kg)	Butanol 5% (kJ/kg)	IPA 5% (kJ/kg)
Idle	1063.7	884.8	905.2	951.2
7	1074.3	1067.9	1050.6	1059.9
10	1061.8	1068.2	1051.4	1054.6
20	1055.5	1053.6	1033.4	1041.9
30	1030.7	1065.6	1032.8	1039.6
40	1049.1	1077.8	1066.5	1065.9
50	1065.2	1098.6	1090.2	1102.9
60	1122.4	1127.8	1130.0	1123.6
70	1176.6	1174.9	1171.5	1174.8
80	1244.3	1229.3	1234.6	1244.4
85	1257.6	1278.0	1275.2	1287.5
90	1304.0	1310.2	1308.0	1335.5
100	1336.3	1367.6	1372.5	1383.5

Table 6. Specific enthalpy at turbine inlet h_t (kJ/kg) for Jet-A1 and 10% alcohol blends

Rc (%)	Jet-A1 (kJ/kg)	Ethanol 10% (kJ/kg)	Butanol 10% (kJ/kg)	IPA 10% (kJ/kg)
Idle	1063.7	1098.6	965.5	926.1
7	1074.3	1080.5	1058.8	1071.9
10	1061.8	1050.9	1040.0	1052.6
20	1055.5	1049.3	1030.1	1041.2
30	1030.7	1054.7	1038.8	1042.9
40	1049.1	1068.6	1063.0	1080.2
50	1065.2	1097.0	1104.5	1105.8
60	1122.4	1127.6	1136.4	1148.5
70	1176.6	1178.5	1177.9	1175.8
80	1244.3	1227.4	1230.0	1228.3
85	1257.6	1275.5	1279.7	1282.7
90	1304.0	1310.3	1318.0	1319.2
100	1336.3	1349.1	1374.4	1388.7

it is important to note that at the lowest power settings (Rc = 7–20%), TSFC differences between blends are within the ±2.8% expanded measurement uncertainty; individual point comparisons at these settings should be treated as directionally indicative rather than statistically proven. The consistent directional trend across all repeat runs is noted as supporting evidence. Additionally, the FADEC fixed rpm schedule may interact with changes in fuel energy density, potentially introducing a small systematic bias at low throttle – this is acknowledged as a limitation. Fuel-system transition effects were mitigated by a 3-minute stabilisation period, but residual effects cannot be fully excluded at low throttle. The claim that fuel-bound oxygen aids combustion completeness at part-load is therefore framed as a hypothesis consistent with the data, not a proven conclusion.

High-power gain: kinetic and thermodynamic advantages

As power increases above ~50% Rc, the combustor exit temperature rises rapidly, and the evaporation penalty diminishes. The alcohols' intrinsic combustion advantages – higher laminar flame speed, presence of fuel-bound oxygen, and lower sooting propensity – become the controlling factors. The integrated effect is a measurable increase in thermal efficiency: at maximum power, the absolute gain is 0.27 pp for 5% IPA. TSFC is defined as fuel mass flow per unit thrust; in a micro-turbojet operating near the lean blow-out limit at full power, even a small improvement in combustion efficiency translates into a disproportionate thrust gain because a larger fraction of chemical enthalpy is converted to kinetic energy.

Thermodynamically: the increased thermal efficiency raises the average temperature of heat addition, increasing cycle efficiency; more complete combustion generates a larger mass of high-enthalpy products (CO_2, H_2O) per unit of injected fuel, increasing the momentum flux at the nozzle; the flame speed of IPA is approximately 0.45 m/s compared to 0.38 m/s for Jet-A1 under similar conditions (literature data), shortening combustion time and allowing more complete burning within the short combustor residence time.

Why 5% isopropanol outperforms other blends

IPA combines the highest LHV among the tested alcohols (30.1 MJ/kg) with a moderate latent heat and an optimal volatility for spray evaporation (boiling point 82.5 °C). At 5% concentration, it introduces enough oxygen to accelerate post-flame oxidation without excessively cooling the flame kernel. The 10% IPA blend yields a further thrust increase but also a larger idle penalty, suggesting a non-linear trade-off that could be optimised with intermediate blends (e.g., 7.5%). Butanol, with its longer carbon chain, produces a more stable FAR across the power range but lacks the oxygen-driven thrust boost observed with IPA. Ethanol, despite its high oxygen content, suffers from a severe latent heat penalty that partially offsets its kinetic benefits at high concentrations.

Fuel-to-air ratio and combustion stability

The near-constant FAR of the 5% butanol blend (τ variation <5%) is a valuable trait for engine control. This stability arises from butanol's intermediate volatility and low hygroscopicity, which maintain consistent fuel-air mixing despite changes in throttle position. No blend approached the rich extinction limit; all τ values remained well within the lean operation window, supporting the feasibility of alcohol blends without major modifications to the FADEC fuel schedule.

Addressing the 'impossible' combination of thrust and TSFC

A thrust increase of 11.6% for IPA 5% might seem disproportionate to the modest 0.27 pp absolute gain in thermal efficiency. This is resolved by recognising that the FADEC, sensing the lower lower heating value (LHV) of the alcohol blend (IPA is 30.1 MJ/kg vs. Jet-A1's 43.2 MJ/kg), increased the fuel mass flow rate ($\dot{m}_f$) to maintain the target RPM/temperature. This higher fuel flow, combined with IPA's oxygen-enhanced combustion, yielded higher thrust, offsetting the extra fuel mass and leaving TSFC roughly unchanged. All reported thrust gains for IPA and ethanol blends exceed the combined expanded measurement uncertainty (U(Fg) ≈ ±1.5%), as confirmed by the paired t-tests (Table 4). Nevertheless, the magnitude of the absolute thrust increase should be interpreted with caution: the current uncertainty model does not fully account for all possible systematic effects (e.g., load-cell calibration drift, mounting alignment shifts during high-power runs), and future measurements with redundant thrust sensors and in-situ calibration are recommended to refine this value.

Limitations and scalability

The GTM400 operates at a compression ratio of 3.3:1 and a maximum thrust of 400 N – far below commercial turbofans (compression ratios of 40–60:1 and thrust levels of tens to hundreds of kN). The vaporiser-type annular combustor differs fundamentally from the swirl-stabilised, staged combustors employed in commercial aviation engines. Alcohol effects on droplet sizing, spray atomisation, and flame stabilisation are expected to be modified at higher operating pressures. Despite these differences, the GTM400 provides thermodynamically similar combustion phenomena and represents a well-validated screening platform [4, 6, 14, 21]. The results should be treated as screening-level evidence motivating further testing on representative combustor rigs at higher technology readiness levels (TRL). Direct extrapolation to commercial gas turbines is not warranted without additional high-pressure combustor rig testing and CFD validation.

The test campaign lasted approximately 6–8 hours of engine operation per fuel, sufficient to detect performance effects but not long-term material degradation. Alcohol fuels – especially ethanol – are known to be hygroscopic and aggressive to certain elastomers (Buna-N, neoprene) and metallic components over extended exposure. No material degradation was observed during the short test campaign, but systematic long-term compatibility testing is essential before operational deployment. Future work should extend the existing thermomechanical study on the GTM400 nozzle [7] to seals, fuel manifolds, and vaporiser coatings under sustained alcohol exposure.

Regarding environmental claims: direct emissions measurements (NOx, CO, UHC, particulates) were not conducted in the present study. Environmental benefits cited in the introduction and conclusions are consistent with prior combustion studies of alcohol-blended kerosene [7, 26] but remain speculative for this specific experimental configuration. A dedicated emissions measurement campaign is the first priority for future work.

Practical safety considerations: blends vs. neat alcohols

This study was deliberately limited to low-percentage blends (5% and 10% by volume) for the following practical and safety reasons. First, neat alcohols have significantly lower heating values than Jet-A1 (ethanol: 26.8 MJ/kg vs. 43.2 MJ/kg), which would dramatically reduce range and require substantial fuel-system modifications. Second, the stoichiometric air-to-fuel ratios of neat alcohols (9.0–11.2) lie outside the lean-combustion envelope of a standard vaporiser combustor tuned for Jet-A1 (A/F ≈ 14.7), creating real risk of rich blowout or unstable ignition, particularly during cold-start and re-light scenarios. Third, reduced lubricity of neat alcohols raises wear concerns for fuel pumps and metering valves. Blending at 5–10% by volume offers a pragmatic, drop-in-compatible intermediate step, while still delivering measurable performance and environmental benefits. Using neat alcohols as cold-start/warm-up intermediates – prior to switching to the blend – is a concept worth investigating in future work.

Implications for future work and operational strategies

The contrasting low-power / high-power behaviour motivates a 'dual-fuel' operational approach: startup and idle on conventional Jet-A1, switch to an alcohol blend for takeoff, climb, and cruise where the efficiency gains are realised. The GTM400 already possesses independent fuel manifolds, making such a scheme feasible. Alcohol fuels – particularly ethanol – are known to be hygroscopic and may be aggressive to certain polymeric seals and metallic components over extended exposure periods. Long-term material compatibility tests, especially with elastomeric seals and vaporiser tubes, should proceed in parallel with performance studies. Future CFD simulations incorporating detailed alcohol oxidation mechanisms are needed to deconvolve the chemical and fluid dynamic contributions to the observed improvements.

CONCLUSIONS

This comprehensive experimental study evaluated the performance of a GTM400 micro-turbojet engine operating on seven fuel formulations: conventional Jet-A1 and 5%/10% blends of ethanol, butanol, and isopropanol with Jet-A1. Key findings are:

- Alcohol blends significantly improve high-power performance. At 100% relative thrust, most blends produced higher thrust (up to +11.6% for 5% IPA, $t(2) = 15.29$, $p = 0.004$), while 5% butanol fell slightly below the Jet-A1 baseline (−1.1%, not significant). The lowest TSFC was recorded for 5% ethanol (2.4% reduction, $p = 0.019$). Thermal efficiency showed a modest absolute increase (up to +0.27 pp) for the 5% alcohol blends, while 10% blends resulted in a slight decrease.
- At low power ($Rc < 30\%$), all alcohol blends exhibited lower TSFC than Jet-A1. At $Rc = 7–20\%$, differences fall within the expanded measurement uncertainty (±2.8%) and are treated as directionally indicative. The fuel-bound oxygen hypothesis for improved part-load combustion completeness is consistent with the trend but not conclusively proven.
- The 5% isopropanol blend emerged as the best overall candidate. It achieved the highest thrust gain and the highest thermal efficiency at maximum power, with TSFC comparable to the Jet-A1 baseline, while maintaining acceptable low-power behaviour. Its balanced properties (energy density, volatility, combustion kinetics) make it particularly suitable for further development.
- Butanol blends offered the most stable combustion. The 5% butanol blend maintained the fuel-to-air ratio closest to the optimal range across all power settings, indicating robust combustion stability – a valuable trait for transient operation and engine control.
- Enthalpy trends corroborate performance gains. Specific enthalpy at turbine inlet closely tracked the thrust and efficiency results, confirming that alcohol blends produce a higher effective enthalpy in the combustion products at high loads, reflecting more complete combustion despite the lower intrinsic heating value of the fuel.
- Scalability note. The GTM400 results provide screening-level evidence consistent with trends observed in larger engines; however, direct extrapolation to commercial turbofans requires caution given differences in operating pressure (compression ratio 3.3:1 vs. 40–60:1 in commercial engines), combustor geometry, and fuel-system design. The data are best used as inputs to validated computational models and as motivation for testing in representative combustor rigs at higher TRL.
- Corrosion and material compatibility. Alcohol blends – particularly ethanol – are known to be hygroscopic and potentially aggressive to certain polymeric seals and metallic components in long-term use. No material degradation was observed during the short test campaign (6–8 hours per fuel), but long-term compatibility testing is essential before operational deployment. This is listed as a priority in the Future Work section.
- Environmental claims. Direct emissions measurements were not conducted. Environmental benefits cited are consistent with prior combustion studies of alcohol-blended kerosene [7, 26] but remain speculative for this

specific configuration. A dedicated emissions measurement campaign is the first priority for future work.

Based on these findings, the following research directions are recommended:

- Emissions measurement campaign (first priority). Direct measurement of NOx, CO, unburned hydrocarbons (UHC), aldehydes, and particulate matter to evaluate environmental impacts and validate environmental claims.
- Intermediate blend ratios. Investigate intermediate ratios (e.g., 7.5% IPA) to identify the optimum trade-off between low-power penalty and high-power gain.
- Transient response tests. Assess combustion stability and control requirements during acceleration/deceleration with alcohol blends.
- Long-term material compatibility. Study durability under cyclic loading to identify material compatibility issues (fuel system seals, turbine blade coatings, vaporiser coatings). Build upon existing thermomechanical studies of the GTM400 platform [7].
- CFD model development. Develop and validate CFD models incorporating alcohol kinetics to guide combustor design improvements that mitigate low-power penalties.
- Higher-TRL testing. Test alcohol blends in representative high-pressure combustor rigs and, eventually, full-scale turbofan engines to assess scalability of the observed performance benefits.

Alcohol-blended SAFs offer a viable path to enhance turbojet performance at the power settings most critical for takeoff, climb, and cruise, provided that operational strategies or hardware modifications address the low-power efficiency considerations. The 5% isopropanol blend stands out as the most promising formulation for further study and potential certification efforts.

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