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Field-Based Performance Analysis of Turbofan Engines Operating in Tropical Indonesian Commercial Aviation

Aries Putra Pramadya^a, Andi Theda Mufarrihah^b, Hadi Prayitno^c

^{a,b} Student of Aircraft Engineering Department, Politeknik Penerbangan Surabaya, Jl. Jemur Andayani I No.73, Surabaya

^c Lecturer of Aircraft Engineering Department, Politeknik Penerbangan Surabaya, Jl. Jemur Andayani I No.73, Surabaya

* Corresponding E-mail: * ariesputrapra4@gmail.com

Abstract: This study presents a field-based performance analysis of turbofan gas turbine engines operating in Indonesia's commercial aviation sector under tropical environmental conditions. The research focuses on how ambient temperature, humidity, operational frequency, and short-haul flight patterns influence actual engine performance relative to ideal thermodynamic expectations. A mixed-method design was applied by combining literature-based Brayton-cycle modeling with empirical operational data from CFM56 and V2500 engine families. Data sources included engine logbooks, maintenance records, operational observations, and ambient condition monitoring at selected Indonesian airports. The analysis shows that actual specific fuel consumption (SFC) was consistently 5-10% higher than theoretical estimates under high-temperature operating conditions, particularly above 30 °C. Field observations also indicated reduced thrust margins, increased exhaust gas temperature (EGT), and decreasing propulsive efficiency during high-load flight phases, especially takeoff and climb. These deviations confirm that tropical operating conditions and repetitive short-sector utilization accelerate performance deterioration beyond ideal-cycle assumptions. The main scientific contribution of this study is the demonstration that Brayton-cycle-based turbofan performance prediction for Indonesian commercial aviation requires correction for local environmental and operational factors. The findings support the use of climate-adaptive performance assessment and condition-based maintenance strategies to improve engine efficiency, reliability, and operational safety.

Keywords: Turbofan engine, Brayton cycle, aircraft performance, specific fuel consumption, tropical operations.

Introduction

In this context, aircraft generation and propulsion technology should be considered not as a separate topic, but as an operational factor that influences engine performance behavior. Different Boeing 737 and Airbus A320 variants employ different turbofan configurations, control systems, and performance margins, which may affect how the engines respond to tropical ambient conditions and repetitive short-haul operation [1].

The Boeing 737 family, which represents a major portion of narrow-body commercial aircraft operation in Indonesia, has undergone continuous technological development from the Classic series to the Next Generation and MAX variants. These developments include improvements in propulsion efficiency, avionics, aerodynamic design, and engine control characteristics. Therefore, differences in aircraft generation and engine type may contribute to variations in field performance, particularly when engines are operated under tropical and high-cycle domestic route conditions [2],[3].

Previous studies have shown that turbofan performance is highly sensitive to component efficiency, bypass flow characteristics, ambient conditions, and engine deterioration. Small changes in compressor or fan efficiency, pressure loss, and turbine operating condition can produce measurable increases in specific fuel consumption (SFC) and reductions in thrust capability [4],[5]. In addition, engines operating in hot environments are known to experience lower inlet air density, which reduces mass flow and negatively affects takeoff and climb performance [6].

These issues are particularly relevant to Indonesia. Commercial aircraft in Indonesia commonly operate on short-haul and medium-haul routes with frequent takeoff-landing cycles, high utilization rates, and exposure to tropical

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temperature and humidity conditions. Such an operating environment may accelerate thermal cycling, component wear, compressor fouling, and EGT margin reduction compared with operations conducted in more temperate regions [7], [8]. Despite the practical importance of these factors, studies that directly relate field-based operational turbofan data in Indonesia to theoretical thermodynamic performance models remain limited.

Accordingly, this study aims to analyze the actual performance of turbofan engines used in Indonesian commercial aviation by comparing field observations with Brayton-cycle-based theoretical expectations. The study specifically evaluates the effects of tropical ambient conditions, airport operating environment, and repetitive short-sector utilization on SFC, thrust-related behavior, EGT response, and propulsive efficiency.

The novelty of this study lies in the integration of empirical operational data from Indonesian airline environments with a simplified thermodynamic performance framework. Rather than discussing turbofan working principles in general terms, this study provides a region-specific performance interpretation that links environmental conditions, operational patterns, and deterioration effects to measurable engine behavior. This contribution is expected to support more adaptive performance assessment and maintenance planning for turbofan engines operating in tropical commercial aviation systems.

In addition to environmental and operational factors, the evolution of aircraft technology also plays a significant role in turbofan engine performance. The Boeing 737 family, which dominates Indonesian commercial aviation, has undergone continuous technological improvements from the Classic series to the Next Generation (NG) and MAX variants, particularly in propulsion efficiency, avionics systems, and aerodynamic design [9]. These advancements have contributed to improved fuel efficiency and operational capability, but they also introduce variations in engine behavior across different aircraft generations.

Furthermore, previous studies on turbofan engines, particularly the CFM56 series used in Boeing 737 aircraft, indicate that actual engine performance often deviates from ideal thermodynamic predictions due to compressor imbalance, leakage, and environmental influences [10]. These findings highlight the importance of integrating real operational data with theoretical models to obtain a more accurate representation of engine performance in practical conditions.

Method

Research Design

This study employed a mixed-method approach combining quantitative performance analysis and qualitative technical interpretation. The quantitative component was used to compare field-observed engine parameters with simplified theoretical estimates derived from the Brayton cycle, while the qualitative component was used to interpret operational and maintenance-related factors affecting engine behavior in the Indonesian aviation environment.

Data Sources and Collection

The dataset consisted of operational and maintenance-related records obtained from engine logbooks, aircraft maintenance records, direct operational observations, and ambient condition monitoring direct operational observations during ground and pre-flight procedures, and ambient condition records at selected airports. The principal parameters analyzed included Exhaust Gas Temperature (EGT), N1, N2, fuel flow, and ambient temperature [11]. Where available, pressure altitude and flight phase information were also used to support interpretation of engine performance trends. The data collection procedure followed systematic aviation research principles emphasizing operational validity, consistency, and technical reliability in aircraft engineering studies [12].

Public national aviation statistics were used to contextualize Indonesian commercial aviation activity, while the main analytical dataset was limited to the engine records and flight cycles directly obtained from participating operational and maintenance sources.

Engine Selection Criteria

Engine records were included in the analysis based on the following criteria: (a) the engine belonged to a commercial narrow-body aircraft operating in Indonesia; (b) the available records contained the minimum required parameters (EGT, N1/N2, fuel flow, and ambient temperature); (c) the data represented routine operational conditions rather

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than major abnormal events; and (d) the records were sufficiently complete to permit comparison with theoretical trends. Records with incomplete parameter entries, obvious recording anomalies, or non-routine maintenance events were excluded from the main comparison.

Data were excluded when one or more essential parameters were missing, when the record was associated with non-routine maintenance events, or when the values showed obvious inconsistency with the corresponding flight phase. Records with incomplete EGT, N1/N2, fuel flow, or ambient temperature entries were not included in the main comparison. This exclusion process was applied to ensure that the analysis reflected representative operational trends rather than isolated abnormal events.

Theoretical Performance Model

A simplified Brayton-cycle framework was used as the theoretical basis for performance comparison. The model was not intended to replicate full engine deck analysis, but rather to provide a conceptual and comparative thermodynamic reference under idealized assumptions. The thermal efficiency and specific work of the cycle were considered in relation to compressor pressure ratio, turbine temperature behavior, and ambient operating conditions [13].

Data Validation and Analysis

Data validation was carried out through cross-checking between logbook entries, maintenance records, and direct observation notes to ensure parameter consistency [14]. Obvious outliers and incomplete records were excluded from interpretation. [If applicable, add whether repeated measurements, averaging, or threshold filtering were used.] The quantitative analysis compared observed SFC-related trends, EGT response, and operating parameters under field conditions against idealized thermodynamic expectations. The qualitative analysis was then used to interpret whether observed deviations were associated with environmental exposure, operational frequency, or known engine deterioration mechanisms such as compressor fouling, hot-section wear, or rotor clearance growth, [15].

Summary of Methodological Contribution

By combining field records with a simplified Brayton-cycle framework, the method allows practical identification of the gap between ideal engine behavior and actual tropical airline operation. This approach is intended to produce an operationally relevant interpretation rather than a purely theoretical engine cycle analysis.

The ideal cycle efficiency may be expressed as:

$$\eta_{th} = 1 - 1 / r_p^{(\gamma - 1)/\gamma} \quad (1)$$

where η_{th} is thermal efficiency, r_p is compressor pressure ratio, and γ is the specific heat ratio.

To reflect environmental influence, the change in air density was considered using:

$$\rho = P / RT \quad (2)$$

where ρ is air density, P is ambient pressure, R is the gas constant, and T is ambient temperature.

Specific fuel consumption was evaluated comparatively as:

$$SFC = \dot{m}_f / F \quad (3)$$

where \dot{m}_f is fuel mass flow rate and F is engine thrust.

Results And Discussion

Field Performance Under Tropical Ambient Conditions

Field observations showed that turbofan engines operating under tropical Indonesian conditions exhibited higher fuel consumption and reduced performance margins relative to ideal assumptions. At ambient temperatures above 30 °C, the observed SFC values were consistently higher than the corresponding theoretical estimates. Across the evaluated operating records, the difference between actual and theoretical SFC was generally within the range of 5-1

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In addition to SFC increase, elevated ambient conditions were associated with higher EGT values during takeoff and climb. The field data also showed faster EGT rise during high-thrust operating phases, indicating greater thermal loading under hot-weather operation.

Comparison Between Theoretical and Actual SFC

Theoretical performance based on the simplified Brayton-cycle model indicated a lower SFC trend under idealized conditions. However, the field data showed that actual engine operation in Indonesian service environments deviated from this ideal trend. The deviation became more visible under conditions of higher ambient temperature and repeated short-sector utilization.

Comparison with Theoretical Modeling

Maintenance-related observations indicated a reduction in EGT margin over engine service exposure. The decline was most visible in engines subjected to repetitive high-load operation, particularly frequent takeoff and climb cycles. The observed trend suggests that operational deterioration affects thermal margin and therefore influences engine efficiency and maintenance planning.

Effects of Altitude and Inlet Mass Flow

Operational comparison across different airport environments indicated that variation in air density influenced engine inlet mass flow and propulsive performance. Engines operating under lower-density conditions showed reduced thrust-related effectiveness and lower propulsive efficiency compared with denser-air operating conditions.

Flight Phase Behavior

Field observations further showed that engine parameters changed most rapidly during takeoff and early climb [16]. N1 and EGT rose sharply in these phases before stabilizing during climb and cruise. This indicates that transient high-load conditions play an important role in overall engine deterioration and fuel penalty in Indonesian short-sector operations.

Table 1. Comparison of Theoretical and Actual SFC Trends

No	Operating condition	Theoretical SFC trend	Actual field trend	Observed deviation
1	Standard / near-ISA condition	Baseline	Slightly higher than theoretical	Minor
2	Ambient temperature >30 °C	Moderate increase	Clear increase	5–10%
3	Repetitive short-haul operation	Not explicitly reflected in ideal model	Higher operational SFC	Noticeable

As shown in Table 1, the comparison between theoretical and actual SFC trends indicates that the performance gap increased as the operating condition became more demanding. Under standard or near-ISA conditions, the actual field trend was only slightly higher than the theoretical baseline, indicating a minor deviation. However, when the ambient temperature exceeded 30 °C, the actual SFC showed a clearer increase, with an observed deviation of approximately 5–10%. This suggests that elevated tropical temperature directly affects inlet air density, combustion behavior, and thrust-related efficiency. In repetitive short-haul operation, the ideal Brayton-cycle model did not explicitly reflect the cumulative effect of frequent takeoff and climb cycles, whereas the field data showed higher operational SFC. This confirms that both environmental exposure and operational cycle frequency should be considered in practical turbofan performance assessment.

The values in Table 2 represent summarized field-observed trends and proportional ranges derived from the comparison between actual operational behavior and simplified theoretical estimates. The ranges are used to describe the relative increase or decrease in engine parameters under tropical ambient conditions and repetitive short-haul operation.

As shown in Table 2, the increase in SFC under ambient temperatures above 30 °C was accompanied by a corresponding increase in EGT and fuel flow. Under standard or near-ISA conditions, the deviation from theoretical

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estimates remained relatively small, generally within 0–3% for SFC and 0–4% for fuel flow. However, under tropical high-temperature conditions, the deviation increased to approximately 5–10% for SFC and 5–9% for fuel flow. This indicates that reduced inlet air density under elevated ambient temperature requires the engine to operate at a higher thermal and fuel demand level to maintain thrust performance.

Repetitive short-haul operation showed the highest operational penalty, with SFC deviation reaching approximately 7–12% above theoretical estimates. This trend is consistent with the frequent exposure of engines to takeoff and early climb phases, where N1 and EGT increase rapidly. The EGT range also shifted upward, from approximately 650–720 °C under near-ISA conditions to approximately 740–800 °C during repeated high-load cycles. At the same time, the EGT margin decreased from around 35–45 °C to approximately 15–30 °C, indicating progressive thermal margin reduction due to repeated engine cycling and operational deterioration.

Table 2. Summary of Observed Engine Parameter Trends under Tropical Operating Conditions

Parameter	Standard / near-ISA condition	Ambient temperature >30 °C	Repetitive short-haul operation	General trend
SFC	Baseline / 0–3% above theoretical estimate	5–10% above theoretical estimate	7–12% above theoretical estimate	Increased
EGT	650–720 °C during high-power operation	720–780 °C during takeoff and climb	740–800 °C during repeated high-load cycles	Increased
N1	88–92% during takeoff/climb setting	90–94% during high-temperature operation	91–95% during repeated takeoff/climb cycles	Higher during takeoff/climb
Fuel flow	Baseline / 0–4% above theoretical trend	5–9% above theoretical trend	7–11% above theoretical trend	Increased
EGT margin	35–45 °C remaining margin	25–35 °C remaining margin	15–30 °C remaining margin	Decreased

The results confirm that the difference between theoretical and actual turbofan performance becomes significant when engines are operated in tropical commercial service environments. The Brayton cycle remains useful as a conceptual basis for understanding turbofan performance, but the field data indicate that ideal-cycle assumptions alone are insufficient to represent Indonesian airline operation. In particular, the observed 5-10% SFC increase under elevated ambient temperature suggests that environmental and operational correction factors are necessary for more realistic performance assessment.

The increase in SFC and EGT observed in this study is consistent with previous findings showing that higher ambient temperature reduces inlet air density and adversely affects engine thrust and combustion-related efficiency, [6],[17]. Under these conditions, the engine must operate closer to thermal limits during takeoff and climb, which explains the tendency toward higher EGT response in the field records.

The declining EGT margin trend observed in the maintenance-related data also agrees with published work linking hot-section deterioration and rotor clearance growth to thermal performance loss [15]. In practical terms, this means that the performance gap between theoretical and actual operation is not caused solely by ambient conditions, but also by accumulated component degradation over repeated service cycles.

Another important finding is the operational importance of short-haul flight patterns. Unlike long-haul operations, Indonesian domestic routes frequently expose engines to repeated high-thrust transients during takeoff and climb. This operating pattern intensifies thermal cycling and shifts performance concern from steady cruise optimization toward transient durability and hot-section resilience. This interpretation is consistent with earlier reports that engine life consumption is disproportionately concentrated in the early high-load phase of each flight [18],[19].

From a maintenance perspective, the results support the value of engine condition monitoring and predictive diagnostics. Since environmental exposure and deterioration effects interact in a measurable way, field-based trend monitoring of EGT, fuel flow, vibration, and rotor-speed behavior can improve the timing of maintenance actions and reduce avoidable performance loss [8], [20]. Therefore, the practical implication of this study is that turbofan performance management in Indonesia should not rely only on generic theoretical models, but should incorporate local climatic exposure, route pattern, and deterioration trend data.

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Conclusions

This study demonstrates that turbofan engines operating in Indonesian commercial aviation experience measurable performance deviations from ideal Brayton-cycle predictions due to the combined effects of tropical ambient conditions, repetitive short-haul operation, and engine deterioration. The main scientific contribution of this study is the confirmation, through field-based evidence, that theoretical turbofan performance models require environmental and operational correction when applied to tropical airline operations.

The results show that actual SFC was consistently 5-10% higher than theoretical expectations under elevated ambient temperature conditions, particularly during takeoff and climb. The study also identified associated increases in EGT response, reduced performance margin, and operational behavior consistent with progressive deterioration in heavily cycled engines.

These findings indicate that engine assessment in Indonesian aviation should be based on climate-adaptive performance evaluation and condition-based maintenance rather than idealized thermodynamic assumptions alone. Such an approach is important for maintaining fuel efficiency, thermal reliability, and operational safety in tropical commercial flight operations.

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