



Delft University of Technology

A review of gas turbine engine with inter-stage turbine burner

Yin, F.; Gangoli Rao, A.

DOI

[10.1016/j.paerosci.2020.100695](https://doi.org/10.1016/j.paerosci.2020.100695)

Publication date

2020

Document Version

Final published version

Published in

Progress in Aerospace Sciences

Citation (APA)

Yin, F., & Gangoli Rao, A. (2020). A review of gas turbine engine with inter-stage turbine burner. *Progress in Aerospace Sciences*, 121, Article 100695. <https://doi.org/10.1016/j.paerosci.2020.100695>

Important note

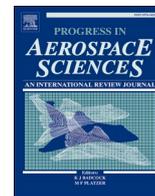
To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.



A review of gas turbine engine with inter-stage turbine burner

Feijia Yin^{*}, Arvind Gangoli Rao

Faculty of Aerospace Engineering, Delft University of Technology, the Netherlands

ARTICLE INFO

Keywords:

Inter-stage turbine burner
Sustainability
Energy transition
Fuel flexibility
Energy mix

ABSTRACT

Society is going through transformations at a rate that is unprecedented in human history. One such transformation is the energy transition, which will affect almost every facet of our society. Gas turbine engines are state of the art machines, a backbone of modern society, and used in various applications, right from power generation to propelling aircraft and ships. This paper reviews the possibilities offered by the Inter-stage Turbine Burner (ITB) configuration for both aviation and power generation with a view on sustainability and fuel flexibility.

First, the thermodynamic characteristics of a Brayton-Joule cycle with ITB is elaborated, followed by discussions on the design and the off-design performance characteristics of such a gas turbine architectural variation. Finally, the viability of ITB architecture in reducing emissions and enabling “Energy Mix” in aviation is elaborated. The paper concludes with an outlook on the technological readiness ladder that the engineering community will have to address in the future.

1. Introduction

Driven by a continuous increase in the world population and a strong development in the economy, a significant increase in energy demand is anticipated in the future. On the other hand, the society is committed to mitigating its environmental impact through various transformations. The energy transition is one of such transformations, which will affect the energy sector, industrial processes, and mobility, including aviation. Increasingly, the selection of energy sources and fuels will be strongly influenced by their emissions and environmental impacts.

Gas turbines play an essential role in stationary power generation and remain a critical part of the foreseeable future for multi-fold reasons. So far, a vast effort has been made to improve the gas turbine efficiency because of operational cost and greenhouse gas emissions (mainly CO₂). Fig. 1 illustrates the significant increase in terrestrial gas turbine efficiency over the last decades (roughly 15% for the Simple Cycle (SC) and around 20% for the Combined Cycle (CC)). The improvements have been possible mainly due to increased Overall Pressure Ratio (OPR), maximum Turbine Inlet Temperature (TIT), and turbo-machinery component efficiencies enabled by a combination of technology efforts:

- Improved materials with high thermal resistance;
- The development of thermal barrier coatings;

- Improved cooling technique;
- More advanced aerodynamic design for blades;
- Improved sealing technique;

The emissions from gas turbines are relatively low as compared to other power plants. A complete comparison for emissions of CO₂, SO₂, NO_x, and Particulate Matter (PM) between various power plants is presented in Fig. 2 [2]. For instance, a Gas Turbine Combined Cycle (GTCC) reduces CO₂ emissions by more than 50%, NO_x emissions by approximately 80%, and eliminates sulfur dioxide (SO₂) compared to the power plants burning coal. The fact that gas turbines produce low emissions is due to low carbon fuels, e.g., natural gas, improved cycle efficiency, and superior combustion technology.

Furthermore, in the aviation sector, technological advancements have managed to reduce fuel consumption (and thereby the CO₂ emissions) per passenger-km by around 75%. About 50% of this reduction is due to improved gas turbine efficiency (seen from Fig. 3). Means of enabling such improvements are mainly directed at increasing the thermal and propulsive efficiency of conventional aero engines. Next to the efficiency improvement, ambitious emission reduction goals have been set by the Advisory Council for Aeronautics Research & Innovation in Europe (ACARE) to reduce CO₂ emissions significantly by 75%, NO_x emissions by 90%, and the perceived noise emission by 65% by the year of 2050 relative to the technology introduced in the year of 2000 [3].

^{*} Corresponding author. Kluyverweg 1, 2629HS, Delft, the Netherlands.

E-mail address: F.yin@tudelft.nl (F. Yin).

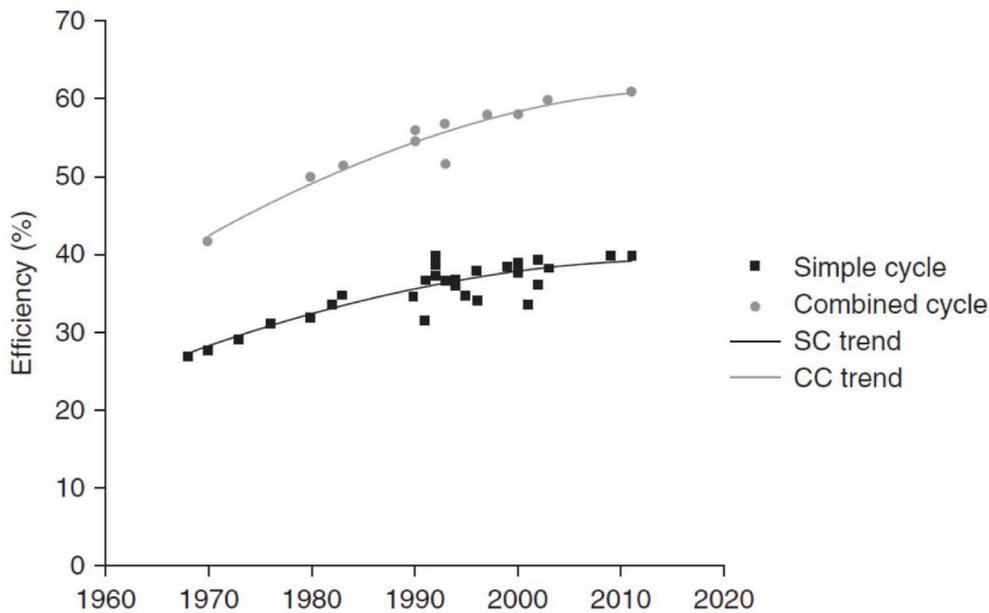


Fig. 1. Efficiency improvement of gas turbines since 1960 [1]. SC: Simple Cycle; CC: Combined Cycle.

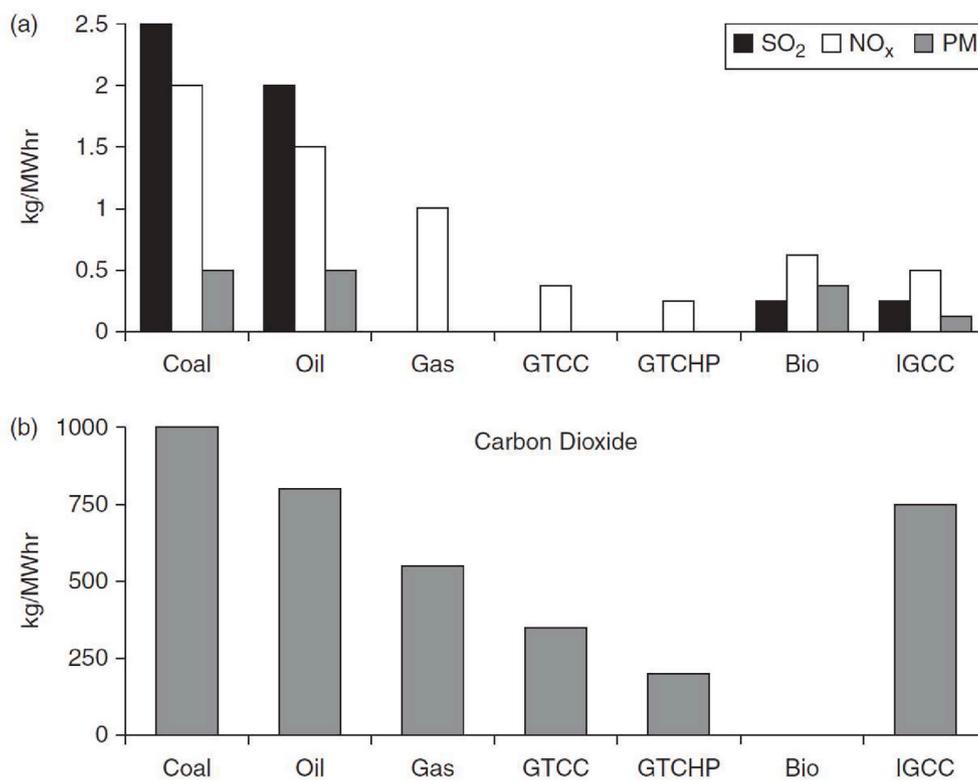


Fig. 2. Comparison of emissions from various power plant configurations: a) emissions of SO₂, NO_x, and PM; b) CO₂ emissions. Coal, Oil, and Gas: steam boiler Rankine cycles; GTCC: gas turbine combined cycle; GTCHP: gas turbine combined heat & power; Bio: wood waste biomass; IGCC: coal gasification combined cycle. Figure obtained from [2].

The thermal efficiency is principally a function of OPR, TIT, component efficiencies and pressure losses in the ducts. Whereas, the propulsive efficiency is a function of Fan Pressure Ratio (FPR) and BPR. Fig. 4 shows the Thrust Specific Fuel Consumption (TSFC) of aero engines related to thermal and propulsive efficiency. The current high bypass ratio engines reach thermal efficiencies in the region of 0.45 and propulsive efficiencies in the area of 0.8. With the further increase of cycle parameters, the envisaged very high bypass ratio engines in the

future are expected to reach the thermal efficiency of 0.55 and the propulsive efficiency of 0.825–0.85.

Considering the theoretical limits imposed by developing material technologies, which allow a further increase of TIT and OPR, thermal efficiency of 0.6 might be possible. Nevertheless, the NO_x emissions tend to increase with the increased combustion temperature, especially when the temperature in the combustor is beyond 1800K; one would expect an exponential increase of NO_x. For environmental issues, it would be

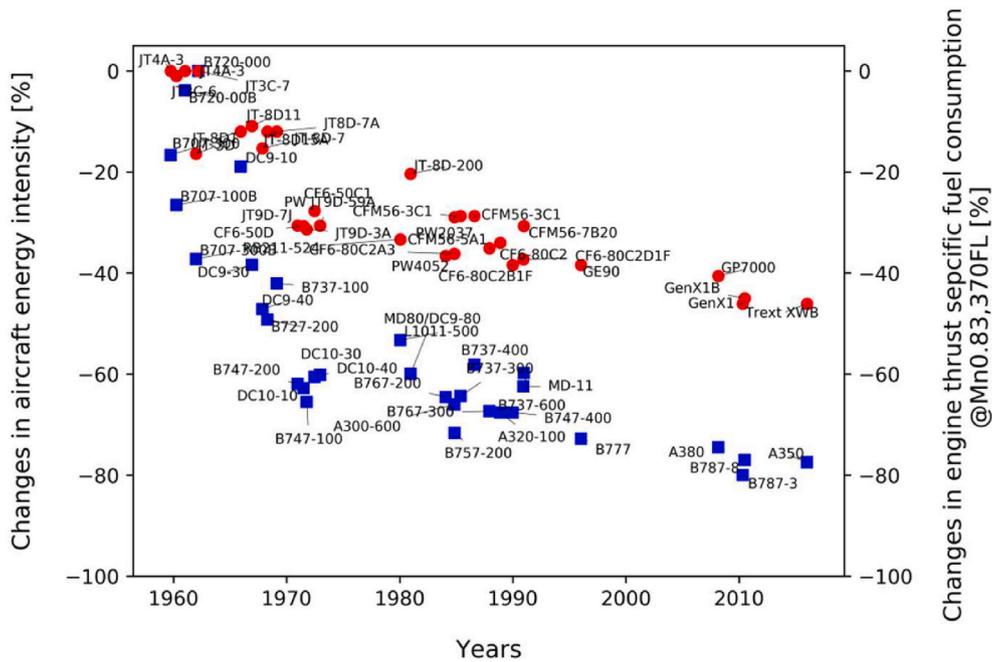


Fig. 3. Variation in the Fuel efficiency of air transportation over the years. Figure adapted from Figs. 9-3 of the IPCC Special Report on Aviation and the Global Atmosphere [4].

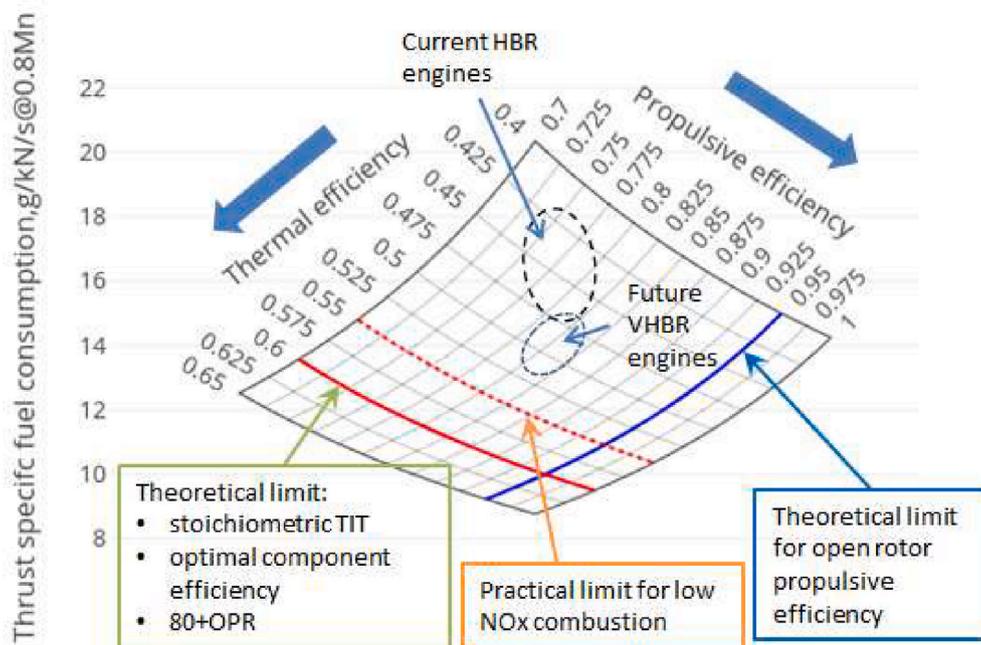


Fig. 4. Variation of the specific fuel consumption versus thermal and propulsive efficiency. HBR: High Bypass Ratio; VHBR: Very High Bypass Ratio. Figure reprinted from Ref. [5].

necessary to limit the TIT to a value of approximately 2000 K at take-off. Therefore, the thermal efficiency improvement via OPR and TIT is expected to approach its practical limits of 0.55 imposed by NO_x emissions represented by the dashed line in Fig. 4.

The other question is how much increases in propulsive efficiency can still be possible via increasing the engine BPR. As BPR increases, the overall engine diameter increases, which increases drag and weight that eventually would offset the benefits of having higher propulsive efficiency. A possible future engine configuration could then be the open rotor configuration. Thus, the open rotor's propulsive efficiency is

considered a theoretical limit for propulsive efficiency of about 0.95, as indicated by the solid blue line in Fig. 4. Overall, improving the engine efficiencies to reduce fuel consumption and the consequent CO₂ emissions is facing diminishing returns.

Gas turbines with conventional Brayton-Joule cycle appear to be reaching their performance and capacity limits. As a result, novel cycles with the perspective of better performance or larger operating capabilities are under investigation [6–9]. The concept of adding heat in the turbine expansion process, known as sequential combustion (reheat) through the turbine, is one of the cycle variations.

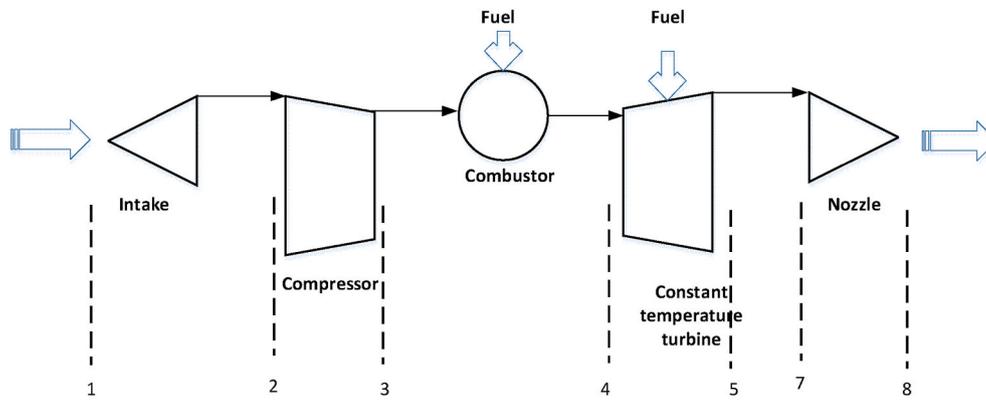


Fig. 5. Schematic representation of a turbojet engine with a constant temperature turbine burner. Figure adapted from [11].

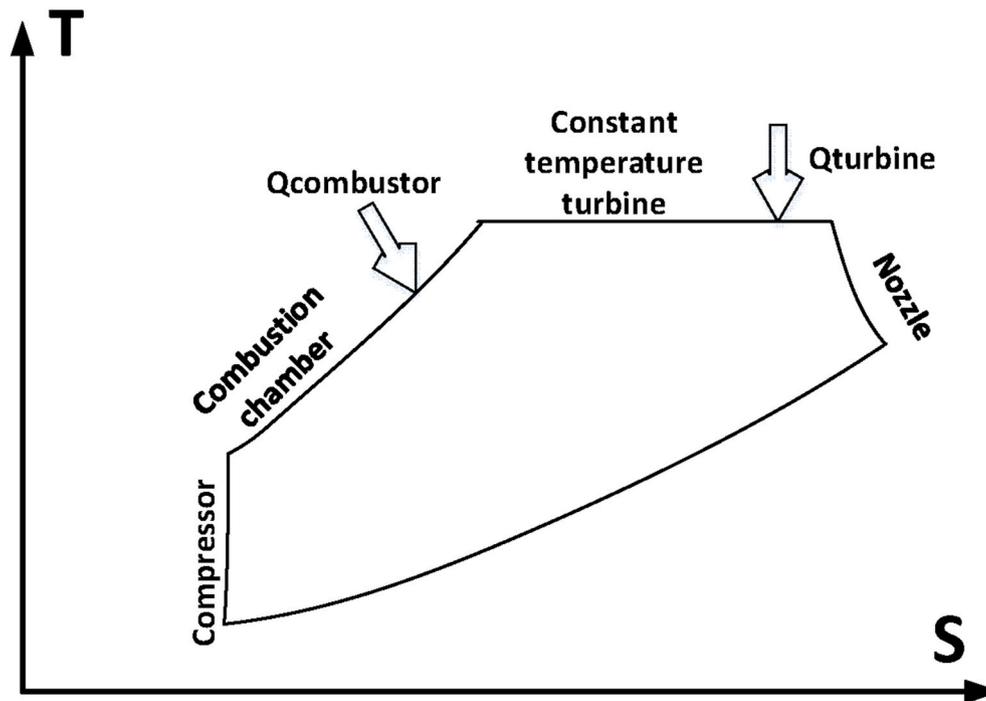


Fig. 6. Thermodynamic cycle of a turbojet engine with a constant temperature turbine burner in Fig. 5. Figure adapted from Ref. [11].

2. Thermodynamic variation of reheat through turbine expansion

The world's first industrial gas turbine plant unit with a sequential combustion system dates back to the 1940s. This application was initiated to increase the cycle efficiency when the technology readiness did not facilitate high turbine operating temperature [10]. Up to now, research on reheat cycles has been conducted widely for both industrial and aero applications. The research interests are mainly divided into two streams: Constant Temperature Turbine Burner (CTTB) and Constant Pressure Turbine Burner (CPTB).

2.1. Constant temperature turbine burner

The working principle of the CTTB follows that combustion takes place in the turbine passage simultaneously while work is being extracted to drive the compressor or other auxiliary units [11–14]. By balancing heat addition and energy extraction, the operating temperature through the turbine remains constant. Such a process is considered close to a Carnot cycle (isothermal heat addition), allowing maximum

thermodynamic efficiency.

Previous research mainly focused on the effects of CTTB on aero-derived gas turbine engines. One example is to apply the CTTB in turbojet studied by Andriani et al. [11,12]. The engine scheme, shown in Fig. 5, comprises an intake, a compressor, a constant pressure combustion chamber, the turbine in which the constant temperature combustion process happens, and a nozzle. The corresponding thermodynamic cycle is depicted using a well-known temperature (T)-entropy (S) diagram in Fig. 6. The CTTB engine's performance was compared to a simple turbojet and a turbojet equipped with an afterburner. It was evident that the CTTB turbojet could produce comparable Specific Thrust (ST) as the afterburner turbojet while maintaining the fuel consumption at nearly the same level as the simple turbojet engine. A further study by Sirignano et al. [15,16] showed that the CTTB could increase the ST by 20% compared to a simple turbojet at the expense of a 10% increase in the engine thrust specific fuel consumption (TSFC). In contrast, the afterburner turbojet would increase the TSFC by 50%. In these studies, the simplification in the modeling approach of not adequately considering the possible changes in turbine cooling might overestimate the efficiency gains.

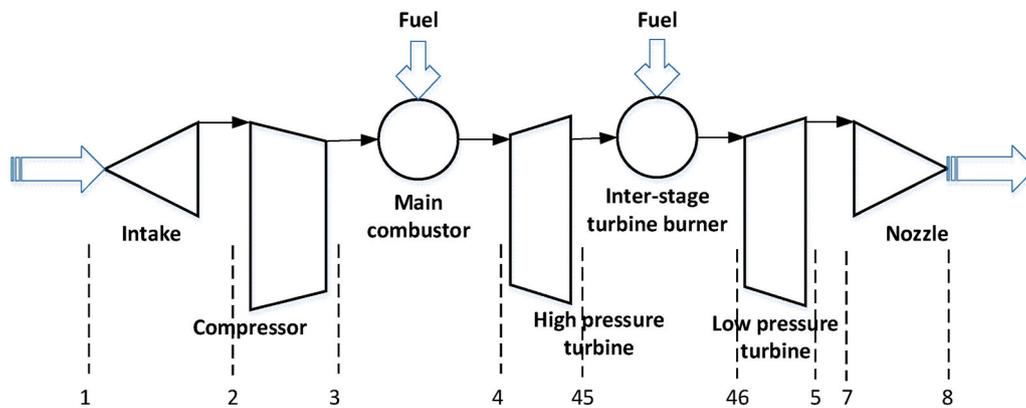


Fig. 7. Scheme of a simplified ITB engine with the station numbers.

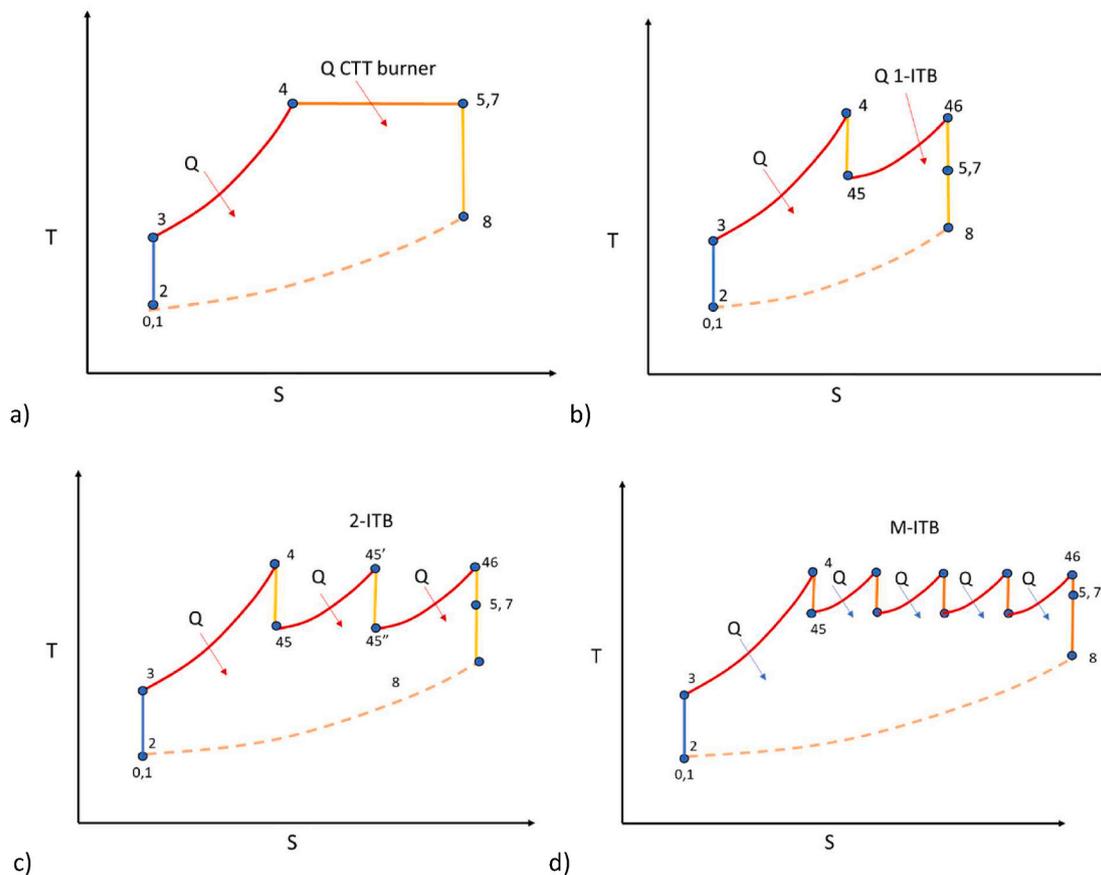


Fig. 8. a) CTTB engine; b) 1 stage ITB engine; c) 2 stages ITB engine; d) multi-stages ITB engines [27]. In figure d), when M is close to infinite, the M-ITB becomes a constant temperature turbine burner as indicated in a).

Later on, Chiu et al. [14] applied a more sophisticated approach incorporating a turbine cooling model. The analysis confirmed that replacing the afterburner with the CTTB significantly increased the turbine cooling. The authors recommended thoroughly analyzing the effects of the increased turbine cooling on the cycle efficiency. Nevertheless, using the CTTB allowed a smaller and more efficient engine for a supersonic aircraft than the traditional afterburner engines.

From the previous research, we understand that the CTTB engine qualitatively produces more specific power than the simple engine and is more efficient than the afterburning engine. The absolute performance gain remains arguable due to simplifying assumptions in the analytical approach used in most research, e.g., without explicitly considering the turbine cooling. Moreover, the understanding of the CTTB gas turbine so

far has been mainly from various theoretical studies, as the application of CTTB is practically challenging. Transferring heat within an expansion process in a gas turbine is not straightforward. Nevertheless, the CTTB engine cycle itself represents the limits that the reheat through turbine expansion can reach.

2.2. Constant pressure turbine burner

Unlike the CTTB, the working process of a CPTB involves a nearly constant pressure combustion process in an additional combustor located between turbine stages, for which a CPTB is also known as “Inter-stage Turbine Burner (ITB)” [17–25]. For illustration purposes, Fig. 7 presents a simplified CPTB engine scheme and the station numbers

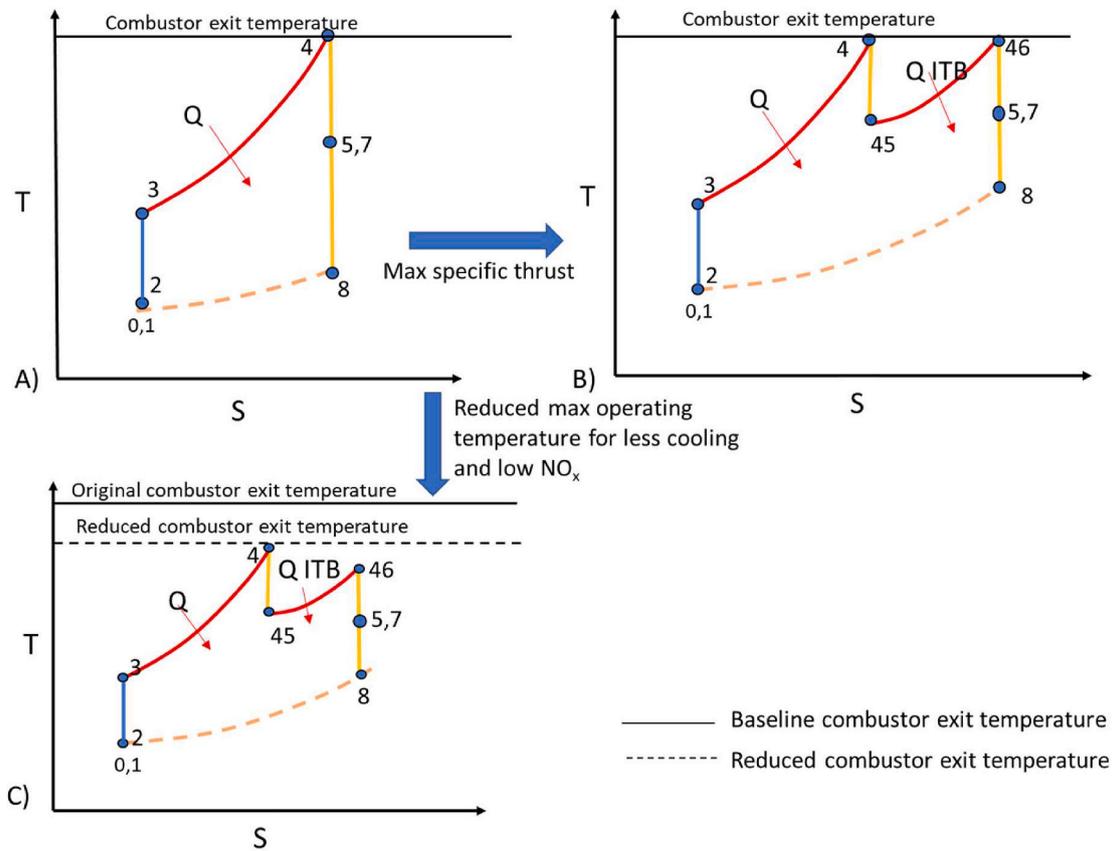


Fig. 9. Temperature (T)-entropy (S) diagram of ITB engine concepts for different purposes. A) The original single combustor engine (baseline); B) the baseline engine is extended with an ITB operated at the same combustor exit temperature; C) the baseline engine is extended with an ITB optimized for the same specific thrust.

used in an ITB (CPTB) engine. Station 46 indicates the exit of the ITB. Unlike the structure of CTTB in Fig. 5, the ITB (CPTB) is explicitly separated from the expansion process in the High-pressure Turbine (HPT) and the Low-pressure Turbine (LPT) stages. The ITB is more like an afterburner in such configuration, but occurring at a relatively high pressure environment.

As the ITB is separated from the turbine competent, one could accumulate multiple ITB stages infinitely to get as close to a CTTB cycle [26]. Fig. 8 attempts to demonstrate such a process. The T-S diagram in Fig. 8 a) represents a CTTB engine cycle identical to the cycle presented in Fig. 5, whereas Fig. 8 b) is the T-S diagram of a single-stage ITB engine cycle. In a single-stage ITB engine, the heat is added in the main burner (the process 3–4) and the ITB (the process 45–46), respectively. The hot gas at the ITB exit expands further through the LPT (the process 46–5) and the nozzle (the process 7–8). As the ITB stages increase (Fig. 8 c-d)), the expansion through the turbine happens more discretely with the continuous heat addition in between. As the ITB stages increase infinitely, the gas temperature is close to a constant value, which behaves like a constant temperature expansion. Therefore, the T-S diagram’s shape in Fig. 8 d) approaches the CTTB engine cycle as in Fig. 8 a). Such a similarity implies that the CTTB engine’s performance is the theoretical maximum achievable for an ITB engine. In other words, an ITB engine is a concept that lies in between a CTTB engine and a conventional engine.

Despite the possibilities of adding multiple ITB stages, most of the previous research was focused on one stage ITB [11,26,28,29], possibly because it is technically more feasible. In this paper, our focus of interest is, therefore, on the features of a single-stage ITB engine configuration, if not mentioned in the following sections.

3. Characteristics of gas turbines with one stage ITB

In this section, the effects of an ITB on the characteristics of gas turbines are discussed. We focus on three aspects: on-design condition, off-design condition, and as an enabler to alternative fuels for aero applications, where the mass and volume of the fuel storage are critical.

3.1. On-design condition

At the on-design condition, the impacts of an ITB on gas turbine design flexibility, cycle efficiency, NO_x emissions, and turbine cooling requirements are considered.

3.1.1. Design flexibility

Because of the two combustion chambers, the ITB engine is flexible in its design for various purposes. Fig. 9 shows two example ideas. Fig. 9 A) is the T-S diagram of a conventional engine cycle where the heat (Q) is added in a single combustion process. Based on this simple cycle, one can make two types of transformations. The first option (as shown in Fig. 9 B)) is to maintain the exit temperatures of two combustors identical to the baseline engine [30,31]. Such a design philosophy delivers high specific power, which might be of great interest to military applications or supersonic flights [20]. The high specific power feature is especially useful for having the supersonic cruise capability in modern fighter aircraft. It is noticeable that in such an engine concept, the turbine cooling air would increase substantially, which introduces an additional penalty to the engine cycle efficiency.

Alternatively, the operating strategy presented in Fig. 9 C) produces the same amount of the specific power as the baseline engine in Fig. 9 A). This way, the exit temperatures of both combustors are significantly lower than the baseline engine. Such an engine cycle has three

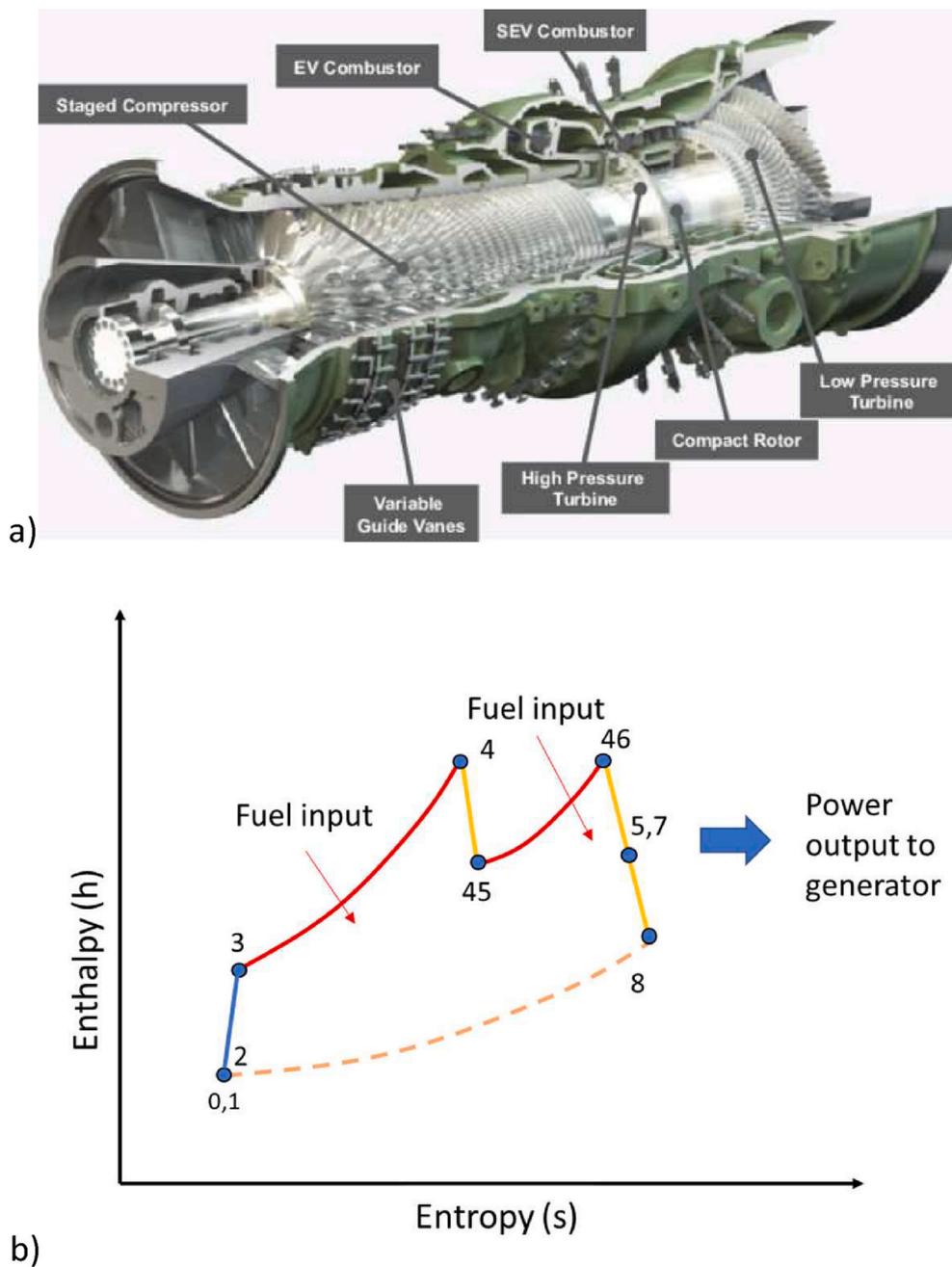


Fig. 10. a) Architecture of GT24/GT26 gas turbine [33]; b) the thermodynamic cycle of GT24/GT26 [21].

advantages: 1) the lower TIT is beneficial in reducing/eliminating the turbine cooling air and the associated penalty on engine performance; 2) combustion at low pressure is thermodynamically inefficient; limiting the heat addition in ITB can minimize the efficiency penalty due to ITB. 3) the thermal NO_x emissions decrease [32]; In the following sections, we will elaborate on these three features.

3.1.2. Cycle efficiency

In ITB, the fuel is burnt at relatively low pressure, limiting the further expansion of the hot gas; hence, an ITB engine's exhaust temperature is expected to be higher than a conventional engine. The effects of such a phenomenon on the cycle efficiency differ for industrial gas turbines and aero engines.

3.1.2.1. Industrial application. In power generation, combined-cycle gas turbines are popular due to their high thermal efficiency, lower

emissions, lower ground footprint, lower maintenance, and running cost. The working principle is that after completing the first engine cycle, the exhaust flow is still hot enough such that a second heat engine can extract energy from the exhaust. In such a process, the higher exhaust gas temperature due to ITB is not detrimental to the overall efficiency. The GT24/GT26 from ABB power generation Ltd (currently GE power) is one recent industrial gas turbine featuring an ITB configuration. Fig. 10 presents the architecture and the thermodynamic cycle of the GT24/GT26, respectively. The first combustion chamber is the environmental combustor (EV combustor), and the ITB is the sequential environmental combustor (SEV combustor). The analysis by Joos [21, 22] confirmed that compared to a single combustor gas turbine, the GT24/GT26 produced high specific power.

Moreover, the exhaust temperature of GT24/GT26 is ideal for combined cycle operation, which can further improve the cycle efficiency. Eventually, the achievable cycle efficiency of GT24/GT26 is around

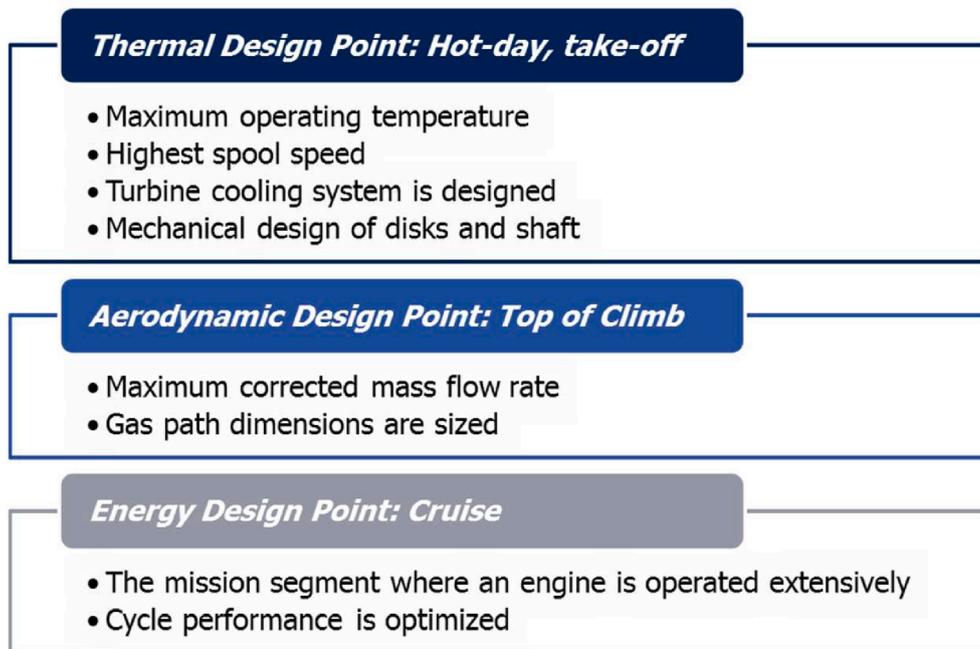


Fig. 11. Various engine design conditions for a commercial turbofan engine [37].

58%. The EV combustor and SEV combustor system enable a significant reduction in emissions, which will be discussed later in this paper.

3.1.2.2. *Aero application.* From earlier research [27,34,35], we observe that an ITB engine can have benefits at high OPR, high BPR, and increased flight speed than a conventional engine. The modern gas turbines are mostly favoring high OPR and high BPR to attain high cycle efficiency. Accordingly, we expect that the efficiency penalty associated with using ITB will be less prominent. One example is the study by Voegler [34], where the research was focused on a preliminary concept of using ITB in a single spool geared fan system, like a turboprop. Thanks to ITB’s additional power, this concept attained a substantial reduction in engine fuel consumption while guaranteeing the specific thrust. Furthermore, research in Ref. [27,36] suggested optimizing the power ratio between turbine segments separated by ITB can improve an ITB engine’s performance.

Furthermore, in aeronautical applications, the engine operates under a broader range of ambient and operating conditions. Depending on the specific working condition, different requirements, as summarized in Fig. 11, have to be satisfied. For instance, the thermal and mechanical design mostly happens at a hot-day take-off condition or hot and high take-off condition. In these conditions, the engine operates at its maximum operating temperature and the highest spool speed. Hence, the thermal system should fulfill the maximum cooling requirement, and the mechanical design should sustain the high stress of the disks and shafts. The aerodynamic design is at the Top of the Climb (TOC) where the gas paths are sized based on the maximum corrected mass flow rate. The energy design point is then at cruise conditions, where the cycle efficiency is of great importance.

Research-oriented design philology is mostly directed at optimizing the cruise cycle efficiency while taking the take-off and TOC requirements as constraints. The engine thrust lapse rate (decreasing thrust with increasing flight speed), especially for turbojet or low BPR turbofan engines, is smaller than that of aircraft. Therefore, to meet the thrust requirement at take-off, the engine cycle at cruise is often oversized. Hence, the engine is operating at off-design at cruise. With the modern UHBR engine, such a mismatch of the thrust lapse rate between engines and aircraft reduces; nevertheless, the thrust requirement at extreme working conditions like hot-day/high altitude take-off

Table 1

Comparison of cycle performance between a single combustor engine and an ITB engine [37]. The operating condition is on-design cruise level. The off-design performance requirements are constraints to derive the optimized cycle.

Parameters	Baseline GTF engine (Oversized to meet all requirements)	ITB turbofan engine with 15% energy provided by ITB
BPR	12.3	15
FPR	1.5	1.44
OPR	59	70
HPT inlet temperature [K]	1806	1606
LPT inlet temperature [K]	1093	1184
FN [kN]	47	47
TSFC [g/kN/s]	14.4	13.8

constrains the engine cruise performance. For an ITB engine, the extra power required at non-cruise conditions can be provided by flexibly switching on the ITB. This way, the engine cycle can be optimized for maximum cruise efficiency, reducing the overall mission fuel burn.

Research in Ref. [37] addresses the effects of ITB on engine design partly. A virtual geared turbofan (GTF, baseline) engine and a GTF ITB engine at cruise (design condition) are optimized respectively within the same design space and constraints imposed by the off-design requirements, including thrust, surge margin, and flat rating at hot-day take-off. Table 1 presents the two engine designs. It is noticeable that to meet the off-design requirements, the baseline GTF engine had to be oversized, meaning the actual fuel burn during the cruise is higher than the ITB engine for the same thrust. A further mission analysis based on these two engine cycles in Ref. [37] showed that the ITB GTF engine fuel consumption is around 4% lower at cruise, 2% lower at TOC, 5% lower at take-off, and about 7% lower at the maximum static thrust condition. That is to say, using an ITB relaxes the constraints of engine design to allow a reduction in the total block fuel consumption.

3.1.3. *NO_x emissions*

The technological limits are challenging the conventional approach of reducing engine emissions. For instance, increasing the operating

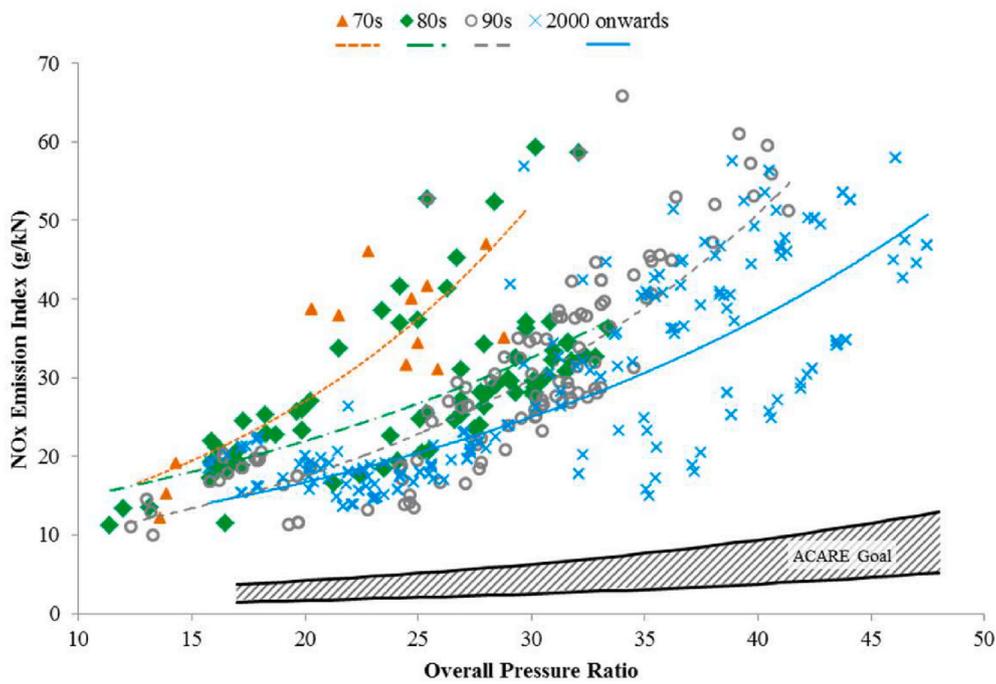


Fig. 12. Variation of overall pressure ratios and NOx emissions index for aero engines over time [38].

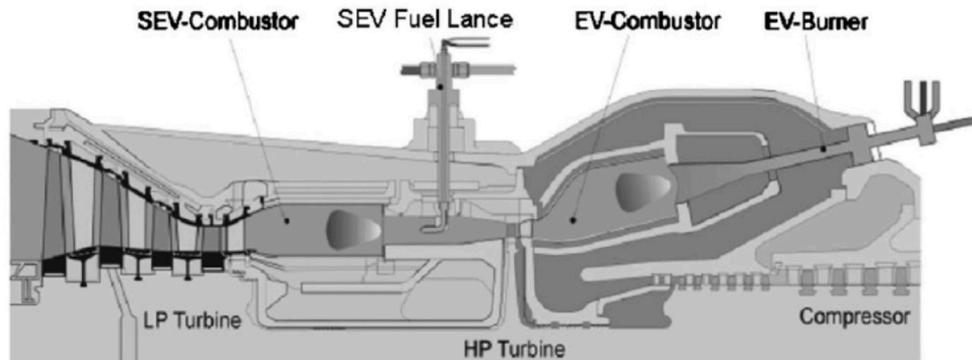


Fig. 13. GT24/GT26 sequential combustion system [39].

pressure and temperature to increase thermal efficiency increases NO_x emissions. Fig. 12 shows that for a given combustion technology level, the NO_x emissions (gram per kilo newton thrust) have increased substantially with the engine OPR. Though the data is for aero engines, the effect is expected to be similar in industrial gas turbines.

The low level of NO_x emissions achieved with an ITB engine cycle is a combined effect of three mechanisms. First, the dual combustors' operating flexibility allows lowering the peak flame temperatures in both combustion chambers, leading to a significant decrease in NO_x emissions. This feature makes ITB a means of addressing the paradox between CO₂ reduction and NO_x reduction, as shown in Fig. 12. Secondly, the vitiated air that enters the ITB has less oxygen concentration reducing the NO_x formation in the ITB. Thirdly, the re-burning process in the ITB helps to dissociate some of the NO_x emissions formed in the primary combustor.

3.1.3.1. ITB combustor characteristics. An excellent example of the ITB engine's low NO_x feature is the sequential combustion system of GT24/GT26. A schematic of this gas turbine engine is given in Fig. 10. Fig. 13 is a cross-section of the combustion system comprising the main burner (EV combustor) and the ITB (SEV combustor).

Fig. 14 presents a part of the simulation results of this reheat combustion system presented by Güthe et al. in Ref. [39]. The figure shows the NO_x contributions versus the flame temperature (T_{flame}) of three situations: a single EV combustor at 30 bars (EV premixed-kinetics), a single SEV combustor at 15 bars (SEV premixed-kinetics), and the combination of two combustors with fixed T_{flame} for EV combustor (Reheat NO_x EV-Const). The NO_x emissions are normalized to the single EV combustor's NO_x emission value at a referent temperature (T_{ref}). For further information on the simulation setup, please refer to Ref. [39].

From the figure, we observe that the single SEV combustor produces less NO_x than the single EV combustor would have for the same flame temperature. The full reheat engine's NO_x emissions, a summation of the two combustors' absolute values, are also lower than the single EV combustor. The possible reason is that the SEV burner worked at a reduced O₂ level and increased H₂O in the reactants. Research in Ref. [40] showed a similar feature.

3.1.3.2. Reduction in peak flame temperature. The turbine inlet temperature of an ITB engine reduces significantly compared to a conventional engine architecture for a given thrust requirement. This feature is beneficial in reducing thermal NO_x emissions. ITB's effects on the

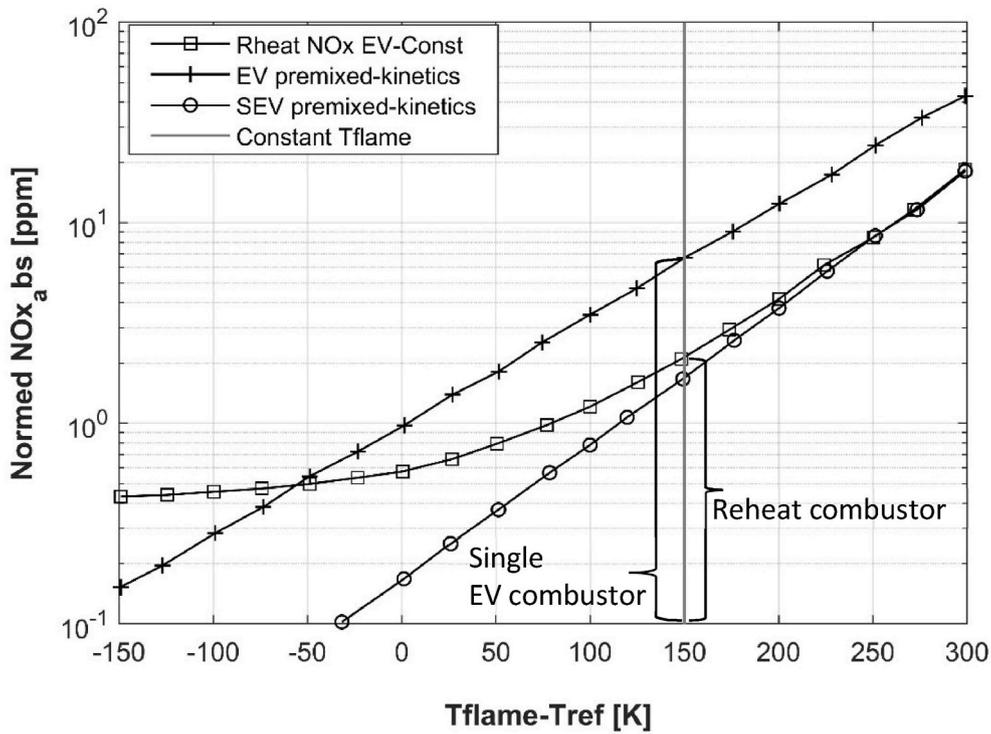


Fig. 14. NO_x emissions on the log scale (normalized, non-calibrated) for a single combustor (EV), the SEV combustor, and a reheat combustion system. Adapted from Fig. 3 in Ref. [39].

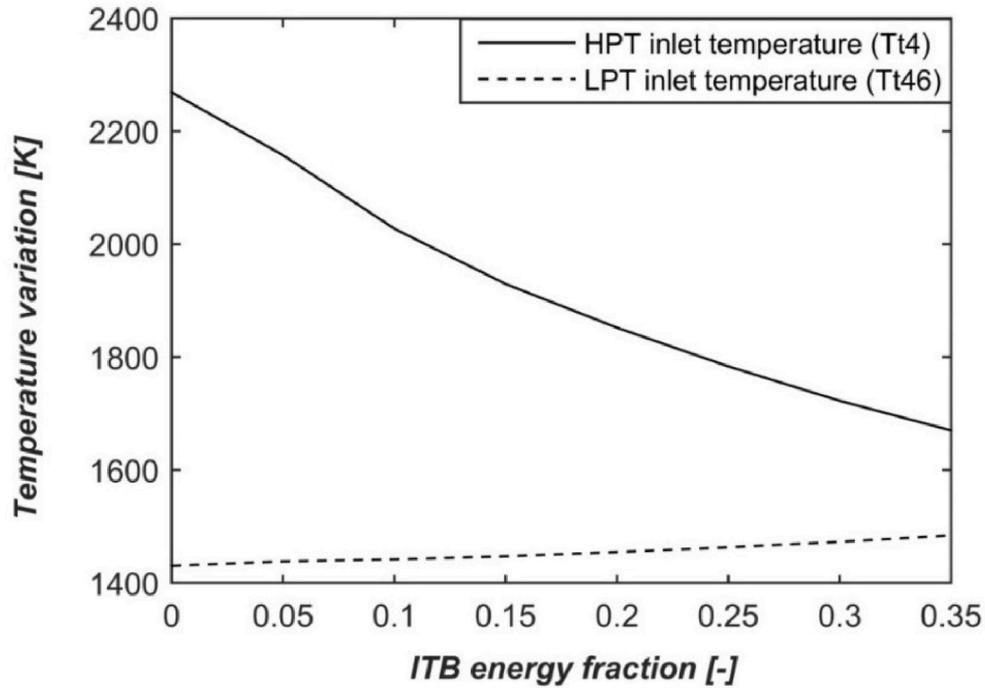


Fig. 15. Variation of turbine inlet temperatures versus ITB energy fraction at Sea Level Static hot day (ISA+15K) [41].

temperature reduction inside the combustor and the consequent NO_x emissions have been discussed in Refs. [24,41]. Fig. 15 shows, at hot-day (ISA+15K) Sea Level Static (SLS) condition, the variation of HPT and LPT inlet temperatures concerning the interpretation of ITB energy fraction, a ratio of the amount of heat added in ITB to the amount heat added to both the main combustion chamber and the ITB, as defined in Eqn. (1). We can conclude that increasing the ITB energy fraction

decreases the HPT inlet temperature substantially from about 2300 K to 1700K to deliver the same thrust while meeting the same constraints. Meanwhile, the LPT inlet temperature is increased slightly from 1400 K to 1500K.

$$ITB \text{ energy fraction} = \frac{\dot{m}_{f2} \cdot LHV_{f2}}{\dot{m}_{f2} \cdot LHV_{f2} + \dot{m}_{f1} \cdot LHV_{f1}} \quad (1)$$

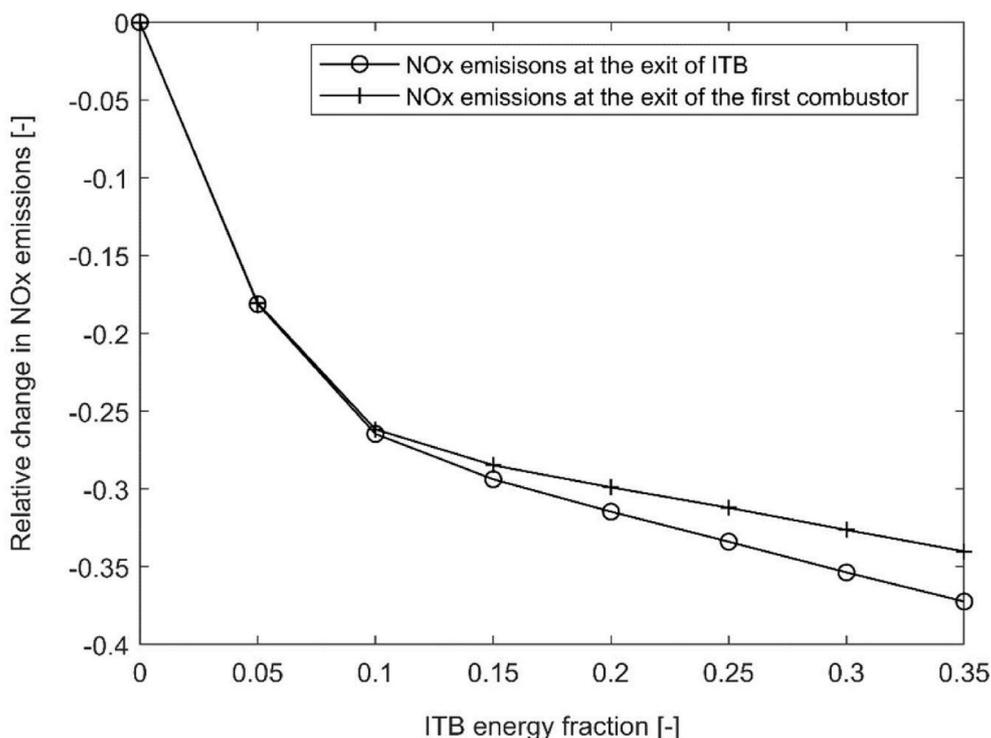


Fig. 16. Normalized reduction in NO_x emission as the energy provided by ITB increases, i.e., the rise in ITB energy fractions.

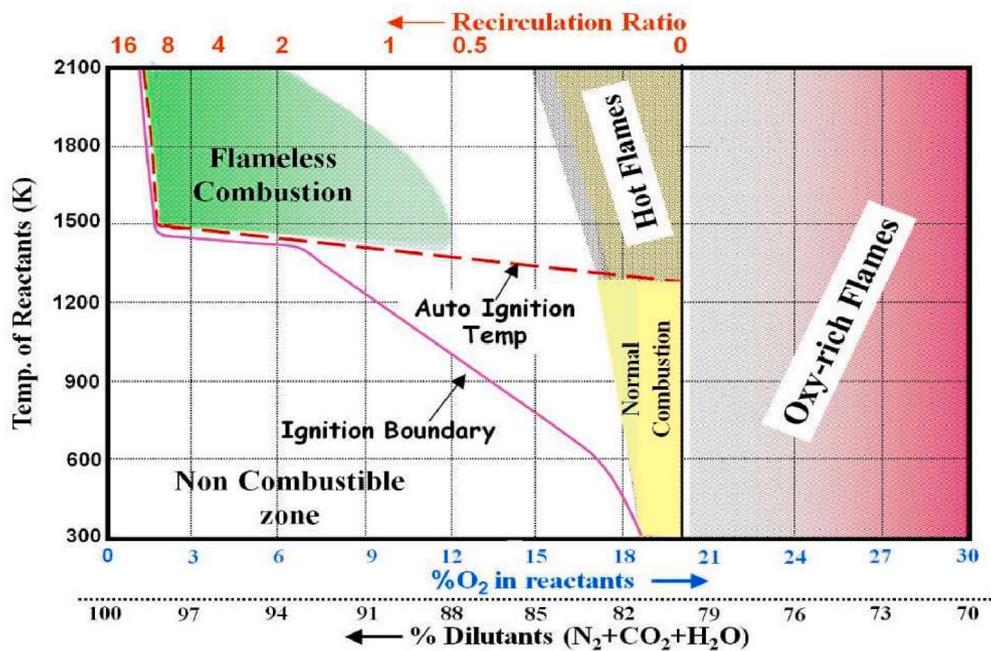


Fig. 17. Schematic of different combustion regimes [46].

Where f_1 and f_2 are fuel flow rates in the first combustor and ITB, LHV is the lower heating value (J/kg) of a given fuel.

Fig. 16 demonstrates the corresponding normalized reduction in NO_x emissions versus the ITB energy fraction. The NO_x emissions at the exit of the first combustion chamber and the ITB are presented separately. As the ITB energy fraction increases from 0 (baseline single combustor engine) to 0.35 (roughly 35% thermal energy provided by ITB), the NO_x at the exit of the first combustion chamber decreases by approximately 35%. In contrast, the total NO_x reduction at the exit of ITB is slightly

more. There are two reasons for this variation pattern. First, the decrease of HPT inlet temperature reduces the combustion temperature in the main burner, hence reduces the NO_x emission substantially. Secondly, some of the NO_x from the first combustion chamber is re-burnt in the ITB, meaning a fraction of NO_x formed in the first combustor dissociates in the ITB, reducing the total NO_x emissions at the exit of ITB further. Such a NO_x re-burning process has been observed by Perpignan et al. in Ref. [42]. What is interesting to see from Fig. 16 is that even a small fraction of ITB energy fraction, around 0.15, can reduce NO_x emissions

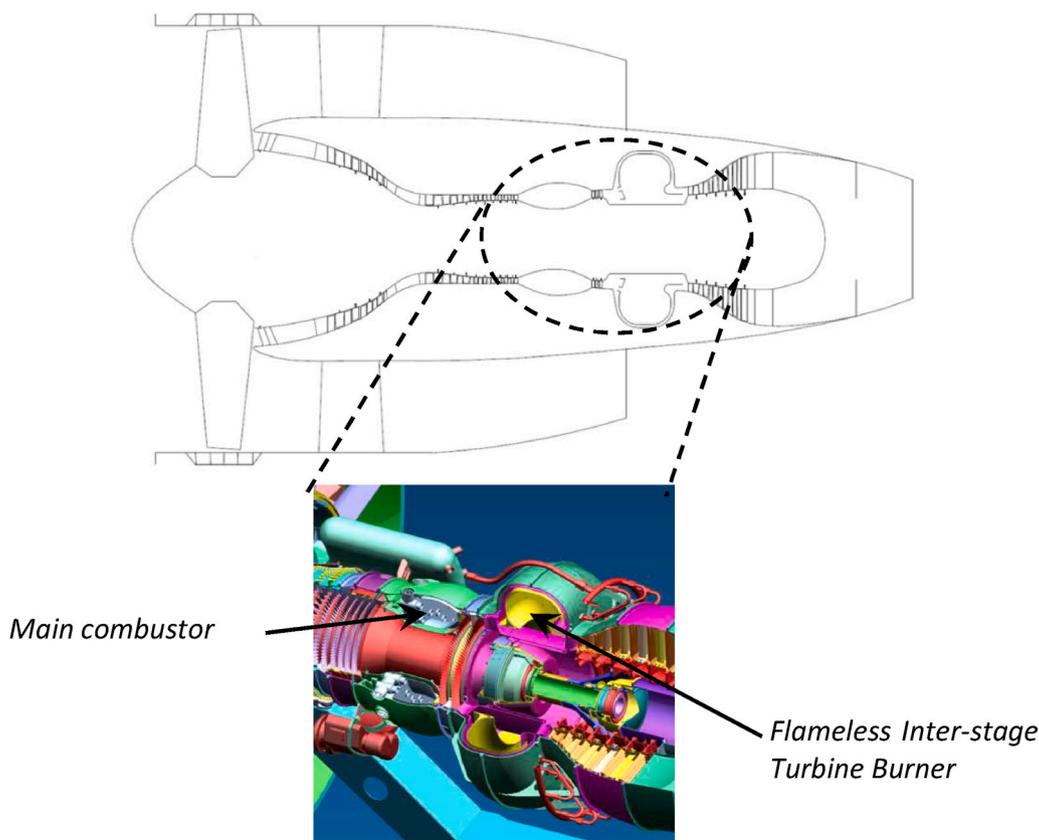


Fig. 18. Overview of the hybrid sequential combustion chamber (Courtesy: Pratt & Whitney Rzeszów, The AHEAD team).

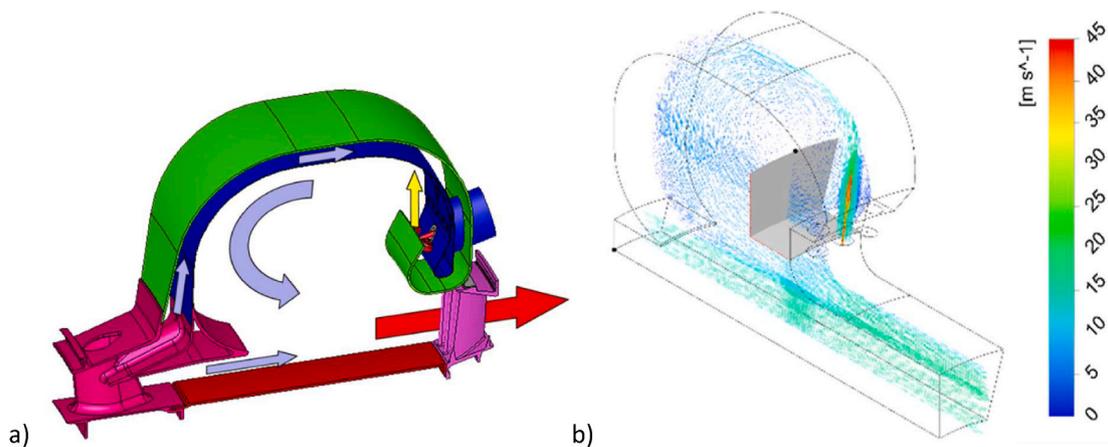


Fig. 19. a) Flow pathway and b) the velocity distribution of the flameless combustion within the ITB in Fig. 18.

by approximately 30%.

3.1.3.3. *Low NO_x combustion technique in ITB.* The ITB's operational environment provides a good opportunity to use low NO_x combustion techniques like Flameless Combustion (FC) for gas turbines. The FC has been widely used in industrial furnaces [43,44]. FC's favorable conditions are low O₂ concentration and high inlet temperature (above the fuel's auto-ignition temperature), as shown in Fig. 17. A large recirculation volume is required to achieve low O₂ concentration and provide sufficient residence time. This large volume requirement is challenging in a conventional aero engine. As the ITB is downstream of the first combustion chamber, the combustion in the main burner increases the concentration of flue gases such as CO₂ and H₂O (vapour) in the inlet

stream of ITB. It also reduces the O₂ concentration, thereby creating a high temperature vitiated environment at the ITB inlet. This is ideal for the FC to take place [45].

There are very few attempts made in the literature to design an ITB combustor for an aero engine. There are several constraints in designing an ITB for an aero-engine such as minimizing pressure losses and providing enough residence time to complete combustion while minimizing the volume required. Fig. 18 shows an example of an ITB design for a multi-fuel aero-engine [47,48]. One can notice that the ITB has a toroidal shape to enhance the recirculation ratio within the combustor to facilitate flameless combustion [49].

Correspondingly, Fig. 19 a) displays the flow stream, and Fig. 19 b) shows the velocity distribution within the flameless ITB in Fig. 18. The

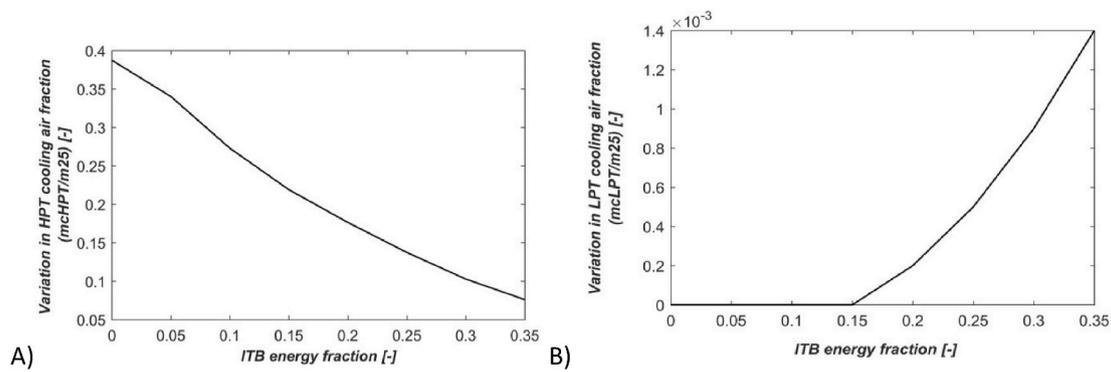


Fig. 20. Variation in turbine cooling to the ITB energy fraction: A) the HPT cooling; B) the LPT cooling.

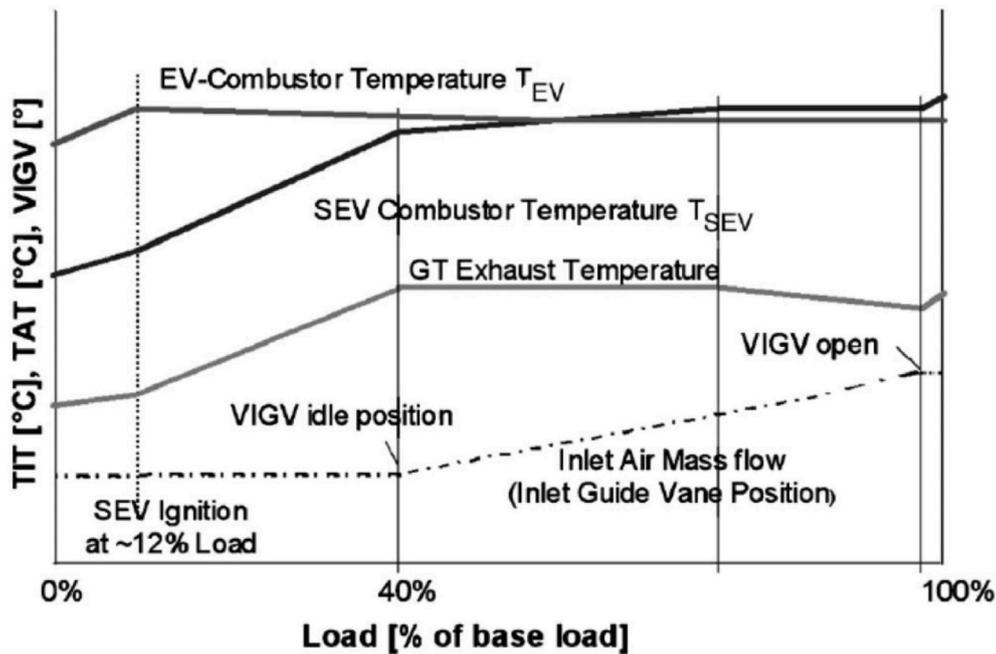


Fig. 21. schematic of the operating concept of GT24/GT26 with load variation adjusted by ITB fuel flow rate [39]; EV-combustor is the primary combustor, and the SEV combustor is the ITB.

chemical mechanism in such a combustor is quite different from a normal combustor. Perpignan et al. [50] showed that the prompt NO_x formation mechanism of flameless combustion was the dominant pathway and determined the overall NO_x emissions behavior. The thermal path has a relatively low contribution, being less critical than the NNH and N₂O-intermediate pathways.

3.1.4. Turbine cooling

In modern aircraft engines, a substantial portion of the core flow is extracted for cooling the HPT blades and vanes, in the order of 20% [25]. Using such a significant amount of cooling penalizes the HPT efficiency substantially [25]. Furthermore, as the engine core becomes smaller in the future UHBR engine, the engine off-design performance, such as the compressor surge margin, would become more sensitive to the amount of bleed air.

Using an ITB reduces the turbine-cooling requirement, provided if the main-burner and the ITB exit temperatures are managed well. Such an example is presented in Fig. 15. Given the same engine design space and constraints, the HPT inlet temperature reduces substantially as the ITB energy fraction increases (at the expense of a marginal increase in the LPT inlet temperature). Correspondingly, the HPT cooling requirement reduces by half while the LPT cooling is not required until 15% of

the ITB energy fraction, as indicated in Fig. 20 A) and B). This turbine cooling reduction can compensate for the penalty of using an ITB on engine efficiency.

3.2. Off-design performance

The application of ITB improves the performance of a gas turbine engine under off-design conditions. The actual effects differ between the industrial and aeronautical applications.

3.2.1. Part-load performance of industrial gas turbines

The combined gas turbine cycle plays a vital role in the energy structure because of its high design efficiency, fuel flexibility, operational flexibility, low emissions, and low ground footprint. However, the performance of such a system drops significantly when the load decreases. Therefore, optimizing the gas turbine's performance under part-load conditions is an important issue, especially with the incorporation of intermittent renewable energy sources like wind energy and solar energy. Using ITB could be a practical approach to improve part-load efficiency. An example of the operational strategy for a reheat cycle in GT24/GT26 can be seen in Fig. 21 [39]. From the load range of 0–12%, the operating temperature of the EV-combustor and the SEV-combustor

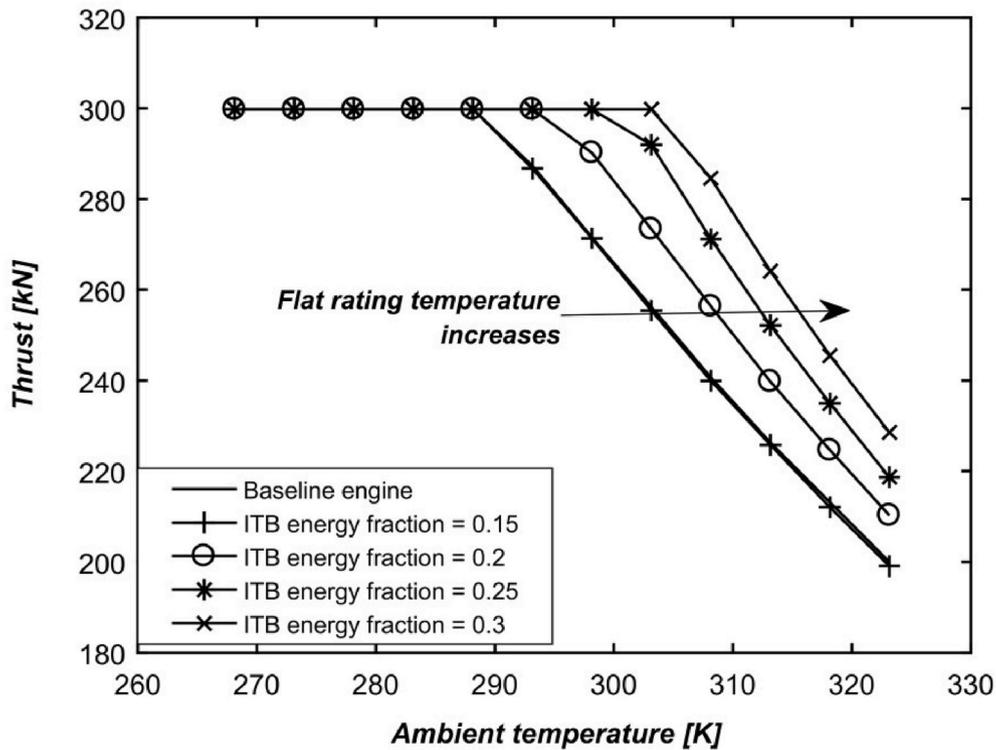


Fig. 22. Engine flat rating at SLS condition for various ambient temperatures [37]. The increase of ITB energy fraction indicates the increase in the fuel flow rate in ITB.

increase. Afterward, the operating temperature of the EV-burner decreases negligibly until the 100% based load is reached. This way, the efficiency of the bottoming Rankine cycle is not deteriorating as much as in a configuration with a conventional gas turbine.

In contrast, the SEV burner’s operating temperature increases further sharply until up to 40% of the baseload and remains almost constant. When beyond 80% of the baseload, the SEV-burner works at a constant temperature equal to the maximum temperature of the first burner. This operating strategy allows the maximum specific power output. As a result, the gas turbine (GT)’s exhaust temperature first increases (up to 40% based load) and then is nearly constant (up to 80% of the baseload),

followed by a slight reduction until 100% based load is reached.

The associated benefits are:

- The variation of the ITB operations allows avoiding the start-stop cycles due to the varying loads, hence reducing the thermal stress;
- The nearly constant temperature of the main burner maintains the cycle efficiency of the bottoming cycle;

3.2.2. Relaxation of design constraints

As mentioned in the earlier section, using ITB allows the relaxation of some design constraints imposed by the off-design requirements. The

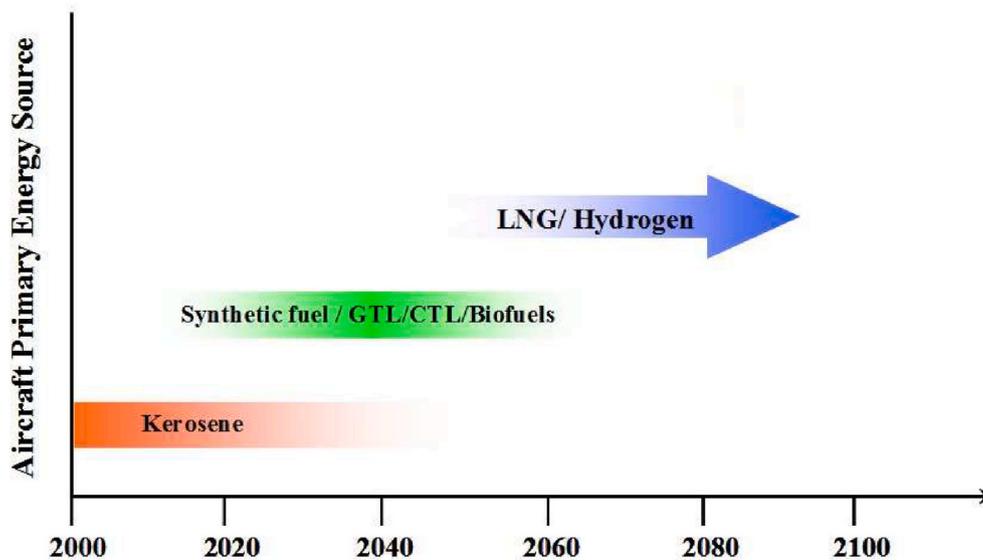


Fig. 23. A possible future energy scenario for long-range commercial aircraft [56].

Tanks for LH2

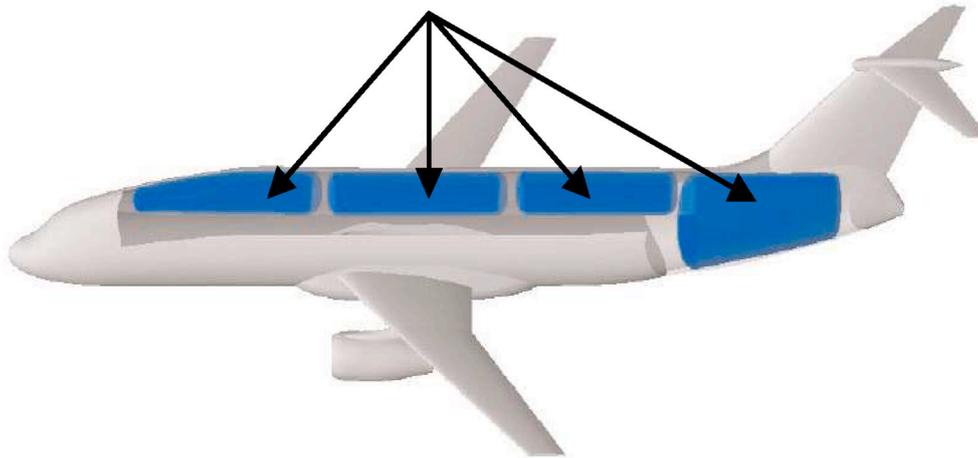


Fig. 24. LH2 tanks storage scheme of “Cryoplane” project [64].

engine can work at its optimum condition as much as possible to minimize the mission fuel burn.

An example of ITB’s effects on engine thrust rating (a process of maintaining the thrust output uniform until the ambient conditions do not allow the engine to operate) is illustrated in Fig. 22 [37]. The baseline engine and the ITB engine are designed at cruise conditions (shown in Table 1), whereas the engine thrust rating is studied at the SLS condition. Again, the ITB energy fraction, defined in Eqn. (1), is used to change the power split ratio of ITB over the total power output: ITB energy fraction of 0 is a single combustor working mode. It is noticeable that, for the same thrust rating, the achievable ambient temperature is much lower for the baseline engine with one combustion chamber than the ITB engine. A 30% power split by ITB enables the flat rating temperature of ISA+15K without affecting the engine design performance. The baseline engine has to be redesigned if the same flat rating temperature were to be achieved.

3.3. Fuel flexibility-enabler of the energy transition in aviation

The current technological limits are preventing the aviation industry from reducing its environmental footprint. Furthermore, corresponding to the increase of air traffic, the jet-fuel demand is expected to increase by about 2–3% annually despite improved aircraft fuel efficiency [51]. On the other hand, the oil reserves are depleting. The discrepancy in supply and demand will lead to a significant increase in fuel costs.

Fig. 23 provides insight into future energy scenarios for short medium to long-range commercial aircraft. “Drop-in” fuels, e.g., biofuels or synthetic aviation fuels, are a part of the solutions in the short term, as they can be implemented directly into the existing airplanes without incurring significant changes to the aircraft nor the airport infrastructure. Some commercial flights have been successfully operated with

biofuels [52,53]. To achieve aviation’s carbon-neutral growth, alternative fuels, like Liquid Natural Gas (LNG) and Liquid Hydrogen (LH2), are the most attractive [47].

Note that Fig. 23 does not include electricity power as an energy option. With the limited power density of batteries, the fully electric flight seems only feasible for small regional aircraft. The hybrid-electric propulsion system might be an option for short and medium-range missions [54,55], with marginal fuel savings (1.8% for a mission range of 1000 km and the projected 2030 technology level [56]). Furthermore, it will not be feasible to fly a long-range mission with any form of an electric propulsion system.

As hydrogen-rich fuels, LH2 and LNG are certainly favorable from a long-term perspective. One of the challenges to use the LNG and LH2 in a conventional aircraft is the large volume required to carry the energy needed. The LNG and LH2 have to be stored in cylindrical tanks with a well-insulated system to prevent the fuel from leaking and boiling off. Therefore, the required volume to keep cryogenic fuels, especially LH2, is more than four times that of kerosene. This volume increase would cause additional aerodynamic drag, increasing energy consumption [57–59]. The Cryoplane project [58,60–62] is a well-known example of implementing LH2 for a conventional tube wing aircraft configuration. Fig. 24 demonstrates the proposed design, where the LH2 fuel tanks are located on top or at the rear of the fuselage. The analysis reported that replacing the kerosene with LH2 increases the mission energy consumption by approximately 10% due to the increased aircraft wetted area caused by LH2 storage [63]. From the previous research, we can conclude that retrofitting the existing aircraft for pure LH2 is not feasible.

One promising solution to introduce LNG/LH2 for aviation is to use them in the form of the “energy mix” concept, namely, burning two types of fuels simultaneously. An example of such a multi-fuel aircraft



Fig. 25. The AHEAD multi-fuel blended wing body aircraft [65].

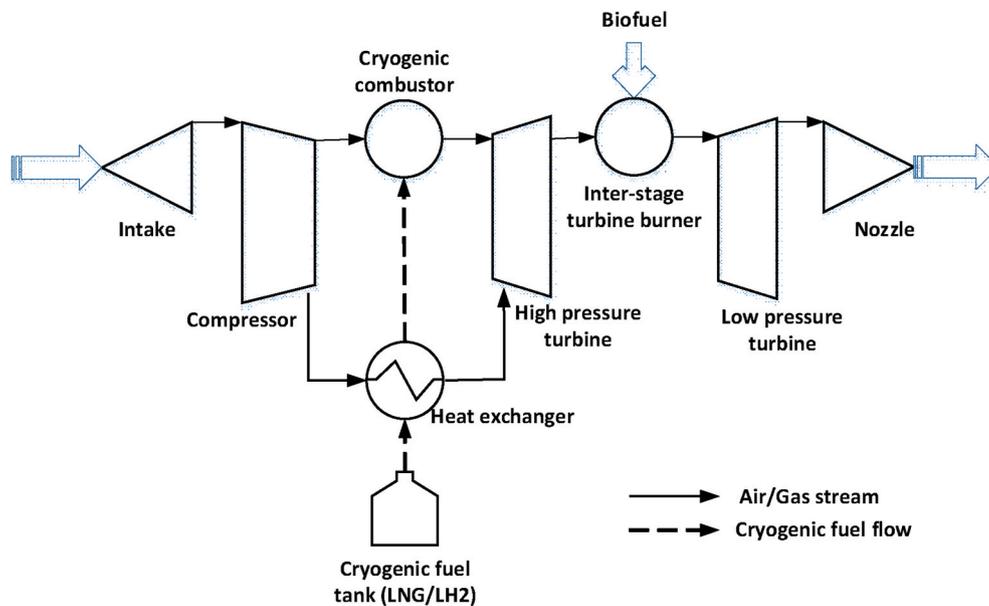


Fig. 26. Scheme of a multi-fuel hybrid engine concept.

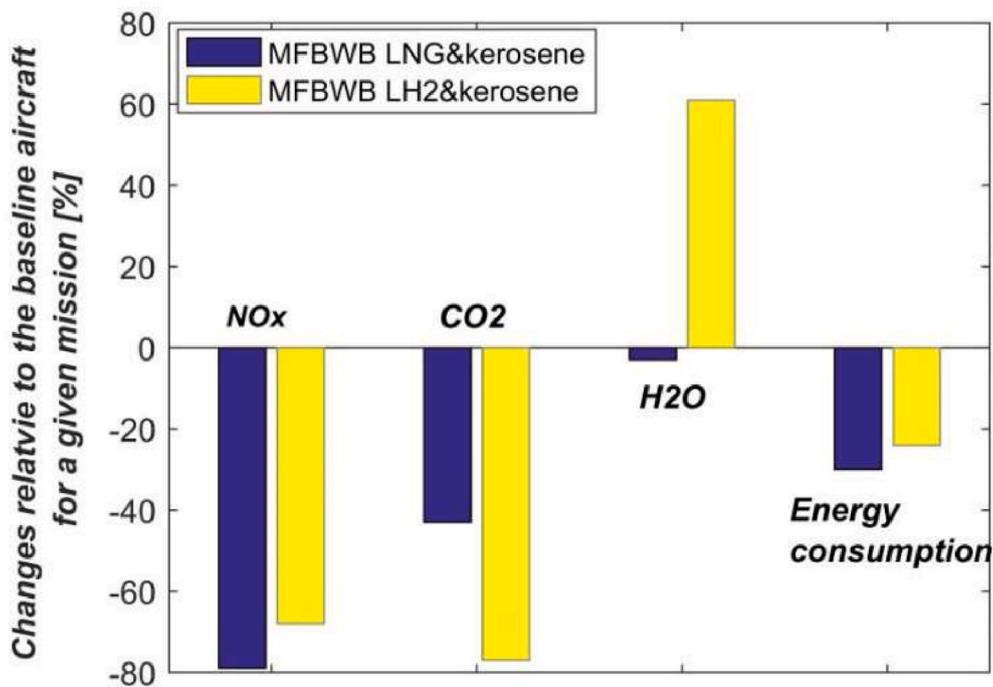


Fig. 27. The changes in emissions and energy consumption for the MFBWB aircraft compared to the baseline B787 aircraft [48].

design is a Multi-Fuel Blended Wing Body (MFBWB). Fig. 25 shows the schematic of the MFBWB [65]. The Blended Wing Body (BWB) aircraft itself has been investigated widely [66–69]. MFBWB is one of these radical concepts. The inherent feature of the BWB aircraft offers a large amount of space, which makes it competitive in transporting payload. In the MFBWB design, the central fuselage is reserved as the passenger compartment. Space at both sides can perfectly accommodate the cryogenic fuel tanks. The wings' internal volume is still used to store normal liquid fuels (Kerosene/Biofuels).

Such an aircraft requires a different propulsion system as two types of fuels need to be burnt simultaneously. Accordingly, a multi-fuel hybrid engine that originated from the ITB turbofan concept was proposed. A simplified engine scheme is shown in Fig. 26. The hybrid

engine has many unique features, like contra-rotating fans [70–72], a cryogenic bleed air cooling system to cool the bleed air, and a dual combustion chamber system to reduce the emissions. Details on this engine concept are discussed in Ref. [48]. On top of all features, the energy mix concept is highlighted in this section. The dual combustion chambers of the ITB engine burn two types of fuels (cryogenic fuels and biofuels) simultaneously such that the thrust power is provided in a hybrid manner. This way, the volume required to store cryogenic fuels reduces, which provides a possibility for cryogenic fuels in aviation.

The emissions (mainly NO_x, CO₂, and H₂O) of the MFBWB are compared to the current state-of-the-art aircraft B787 for a given mission, as seen in Fig. 27 [48]. The MFBWB using LNG/kerosene or LH₂/kerosene can reduce both the CO₂ and NO_x emissions substantially.

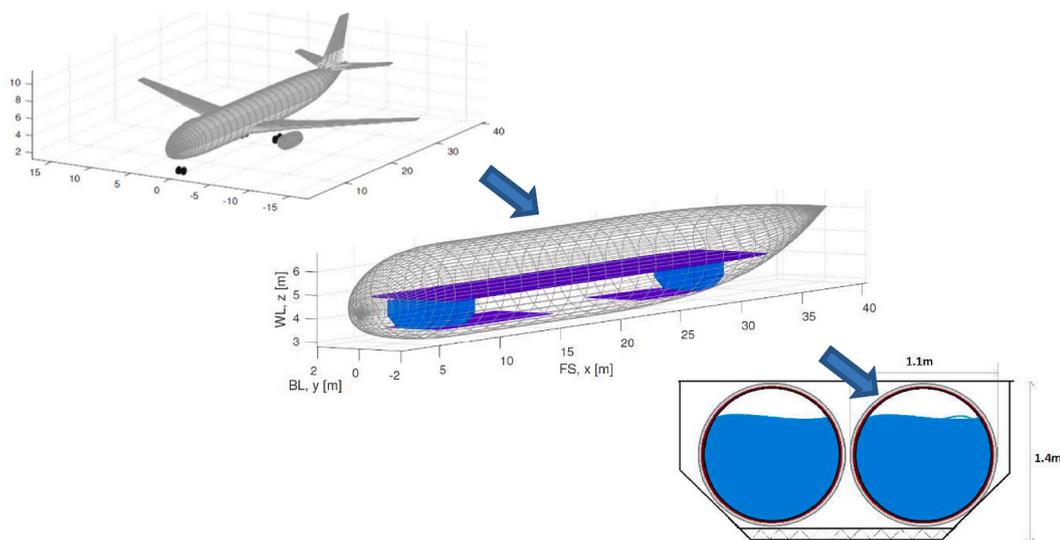


Fig. 28. A possible configuration of storing H_2 tanks within LD3 containers in a single-aisle aircraft. Adapted from Ref. [73].

While the example mentioned above is dedicated to a long-range aircraft, the multi-fuel philosophy in aviation is not necessarily restricted to long-range aircraft. In Ref. [73], Jebbawi has initiated the study on retrofitting Airbus A320 to work on LNG. The design of the aircraft fuselage and fuel tanks are presented in Fig. 28. This study shows that an A320 type single-aisle aircraft's cargo compartment can be modified to store cryogenic fuel tanks. While the study is on LNG, it provides an idea for using LH₂ in single-aisle aircraft. That is to keep some of the mission energy requirement (around 25–30%) from LH₂ in the aircraft cargo compartment. The rest of the mission energy is provided by kerosene in a conventional way. An ITB engine would facilitate such a multi-fuel design. The ITB engine enables using dual fuels and can change engine emissions for various mission segments offered with a proper power management plan. The emissions of such configurations have yet to be investigated in detail.

4. Opportunities and challenges to enable the ITB for future civil aviation

4.1. Opportunities

- As the constraints imposed by off-design conditions restrict the conventional turbofan engines' design performance, using an ITB provides an opportunity to decouple the design and off-design conditions and allows the engine to work at its optimal cruise condition as much as possible, simultaneously meeting the off-design performance requirements.
- As we will move towards a hydrogen-based society, fuel flexibility in aeronautical applications will become essential. In this context, an ITB engine allows future aviation to adapt itself to multiple energy sources, which is far superior compared to conventional aero-engine architecture.
- Even though it is known that NO_x re-burning occurs in the ITB, the reaction mechanisms for re-burning have to be validated and tested. Subsequently, the effect of NO_x re-burning in the ITB on the total NO_x emission of the gas turbine should be investigated further.

4.2. Challenges

- Low emission ITB design: The ITB is positioned downstream of the HPT, where the inlet operating temperature and the flow velocity are much higher than the inlet of the main burner. If the same combustion volume were considered, the residence time available for the

flow in the ITB is low, not allowing the combustion to complete. This might increase CO and UHC emissions. Therefore, designing an ITB with low emissions would be one challenge for future research.

- Incorporation of an ITB increases the engine complexity substantially with multiple fuel lines and fuel controls.
- The introduction of an ITB to a normal turbofan engine will increase the engine length and weight. This negates some of the fuel savings advantages that ITB might provide. Therefore designing an ITB for an aero-engine is an extremely challenging task. Research in Ref. [74] has focused on the integration of an ITB to a jet turbine engine. The ultra-compact combustor studied in this research shows a large potential in reducing the additional weight of the ITB. The research in the AHEAD project also confirms that using ITB appropriately can minimize the resulting weight penalty. Since the weight and volume constraints for industrial gas turbines are not that stringent, incorporating ITB in land-based gas turbines is beneficial.

5. Conclusions

In this paper, a review of the gas turbine with an inter-stage turbine burner has been presented. The potentials of using ITB for future green aviation are summarized from three aspects:

- Using an ITB relaxes some of the constraints imposed on the gas turbine design by the off-design requirements. Accordingly, the engine can work optimally at all operating conditions to reduce the total mission fuel consumption.
- Using an ITB can reduce the turbine inlet temperature substantially such that the turbine cooling requirements and NO_x emissions are significantly lower.
- The prompt NO_x formation mechanism is the dominant pathway in the ITB using flameless combustion and determines the overall NO_x emissions behavior. The thermal pathway has a relatively low contribution.
- The ITB engine configuration provides a perfect architecture to use non-drop in fuels such as liquefied hydrogen for future civil aviation to achieve a substantial reduction in CO₂ emissions without contradicting the reduction of NO_x emissions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

(NWO) numbered 17367.

Acknowledgement

One of the authors is partly funded by the Dutch Research Council

Nomenclature

ACARE	Advisory Council for Aeronautics Research in Europe
AHEAD	Advanced Hybrid Engines for Aircraft Development
BPR	Bypass Ratio
CTTB	Constant Temperature Turbine Burner
CPTB	Constant Pressure Turbine Burner
CC	Combined Cycle
EV	Environmental
FC	Flameless Combustion
FPR	Fan Pressure Ratio
GTF	Geared Turbofan
GTCC	Gas Turbine Combined Cycle
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
ITB	Inter-stage Turbine Burner
LH2	Liquefied Hydrogen
LHV	Lower Heating Value J/kg
LNG	Liquefied Natural Gas
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
LTO	Landing Take-off
MFBWB	Multi-fuel Blended Wing Body
\dot{m}	mass flow rate kg/s
OPR	Overall Pressure Ratio
PM	Particulate Matter
S	Entropy
ST	Specific Thrust kN.s/kg
SEV	Sequential Environmental
SC	Simple Cycle
SLS	Sea Level Static
T	Temperature K
TIT	Turbine Inlet Temperature K
TSFC	Thrust Specific Fuel Consumption g/kN/s
T_{t4}	HPT inlet temperature K
T_{t46}	LPT inlet temperature K
TOC	Top of the Climb
UHBR	Ultra High Bypass Ratio

References

- [1] A.J.A. Mom, 1-Introduction to gas turbines, in: *Modern Gas Turbine Systems*, Woodhead Publishing, 2013, pp. 3–20.
- [2] V. McDonell, M. Klein, Ground-based gas turbine combustion, in: *Gas Turbine Emissions*, Cambridge University Press, Cambridge, 2013, pp. 24–80.
- [3] ACARE, Flightpath 2050 Europe's Vision for Aviation, European Commission, 2011, <https://doi.org/10.2777/50266>.
- [4] IPCC, Aviation and the global atmosphere, Cambridge University Press, Intergovernmental Panel on Climate Change, Cambridge, UK, 1999.
- [5] J. Kurzke, Aeroengine design: from state of the art of turbofans towards innovative architectures., in: *von Karman Institute for Fluid Dynamics Lecture Series 2013-2014*, 2013.
- [6] H. Gao, Z.-x Wang, Effects of intercooling and recuperation on turbofan engine performance, in: *Proceedings of 2011 International Conference on Electronic & Mechanical Engineering and Information Technology*, 2011, <https://doi.org/10.1109/EMET.2011.6023545>. Harbin, China.
- [7] K.G. Kyprianidis, T. Grönstedt, S.O.T. Ogaji, P. Pilidis, R. Singh, Assessment of future aero-engine designs with intercooled and intercooled recuperated cores, *J. Eng. Gas Turbines Power* 133 (1) (2011) 11701, <https://doi.org/10.1115/1.4001982>.
- [8] S. Boggia, K. Rud, Intercooled recuperated gas turbine engine concept, in: *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2005 (Tucson).
- [9] C. Riegler, C. Bichlmaier, The geared turbofan technology—opportunities, challenges and readiness status, in: *Proceedings of the 1st CEAS European Air and Space Conference*, Berlin, Germany, 2007.
- [10] B. Gellert, 8-Turbogenerators in gas turbine systems, in: *Modern Gas Turbine Systems*, Woodhead Publishing, 2013, pp. 247–326.
- [11] R. Andriani, U. Ghezzi, L.F.D. Antoni, Jet engines with heat addition during expansion - a performance analysis, in: *37th Aerospace Sciences Meeting and Exhibit*, 1999, <https://doi.org/10.2514/6.1999-744>. Reno, NV, U.S.
- [12] R. Andriani, U. Ghezzi, Off-design analysis of constant temperature turbine jet engine, in: *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference&Exhibit*, 2002, <https://doi.org/10.2514/6.2002-3766>. Indianapolis, Indiana.
- [13] W.A. Sirignano, F. Liu, Performance increases for gas-turbine engines through combustion inside the turbine, *J. Propul. Power* 15 (1) (1999) 111–118, <https://doi.org/10.2514/2.5398>.
- [14] Y.-t. Chiu, P. King, W. O'Brien, A performance study of a super-cruise engine with isothermal combustion inside the turbine. 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Arizona, DOI, Tucson, 2005, <https://doi.org/10.2514/6.2005-4197>.
- [15] W. Sirignano, J.-P. Delplanque, F. Liu, W. Sirignano, J.-P. Delplanque, F. Liu, Selected challenges in jet and rocket engine combustion research, in: *33rd Joint*

- Propulsion Conference and Exhibit, 1997, <https://doi.org/10.2514/6.1997-2701>. Seattle, WA, U.S.
- [16] W. Sirignano, F. Liu, Performance increases for gas-turbine engines through combustion inside the turbine, *J. Propulsion Power* 15 (1) (1999) 111–118.
- [17] F. Liu, W.A. Sirignano, Turbojet and turbofan engine performance increase through turbine burners. 38th AIAA Aerospace Sciences Meeting and Exhibit, Nevada, DOI, Reno, 2000, <https://doi.org/10.2514/2.5797>.
- [18] K.H. Liew, E. Urip, S.L. Yang, Parametric cycle analysis of a turbofan engine with an interstage turbine burner. *Journal of propulsion and power* 21 (3) (2005) 546–551, <https://doi.org/10.2514/1.2546>.
- [19] K.H. Liew, E. Urip, S.-I. Yang, J. Mattingly, C. Marek, Performance cycle analysis of a two-spool, separate-exhaust turbofan with interstage turbine burner, in: 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2004.
- [20] K.H. Liew, E. Urip, S.L. Yang, J.D. Mattingly, C.J. Marek, Performance cycle analysis of turbofan engine with interstage turbine burner, *J. Propulsion Power* 22 (2) (2006) 411–416, <https://doi.org/10.2514/1.13394>.
- [21] F. Joos, P. Brunner, B. Schulte-Werning, K. Syed, A. Eroglu, Development of the sequential combustion system for the ABB GT24/GT26 gas turbine family, in: ASME 1996 International Gas Turbine and Aeroengine Congress and Exhibition, 1996, <https://doi.org/10.1115/96-gt-315>.
- [22] F. Joos, P. Brunner, M. Stalder, S. Tschirren, Field experience of the sequential combustion system for the GT24/GT26 gas turbine family, in: ASME 1998 International Gas Turbine and Aeroengine Congress and Exhibition, 1998, <https://doi.org/10.1115/98-gt-220>.
- [23] C.-Y. Chen, M.H. Waters, D. Mavris, An Evaluation of the Geometry and Weight of a Mixed Flow Low Bypass Ratio Turbofan Engine with an Intermediate Turbine Burner, 2005, pp. 85–94, <https://doi.org/10.1115/GT2005-68379>, 46997.
- [24] T. Grönstedt, R. Avellan, Mission analysis of an inter-turbine burning turbofan engine, in: 20th International Symposium on Air Breathing Engines 2011 (ISABE 2011), 2011 (Gothenburg, Sweden).
- [25] R. Jakubowski, Study of Bypass Ratio Increasing Possibility for Turbofan Engine and Turbofan with Inter Turbine Burner, 2019, p. 61, <https://doi.org/10.2478/kones-2019-0033>, 26(2).
- [26] G. Chen, M.A. Hoffman, R.L. Davis, Gas-turbine performance improvements Through the Use of multiple turbine interstage burners, *J. Propulsion Power* 20 (5) (2004) 828–834, <https://doi.org/10.2514/1.2886>.
- [27] F. Liu, W.A. Sirignano, Turbojet and turbofan engine performance increases through turbine burners. *Journal of Propulsion and Power* 17 (3) (2001) 695–705.
- [28] G. Chen, M. Hoffman, R. Davis, Improvements in gas-turbine performance Through the Use of multiple turbine inter-stage burners, in: 42nd AIAA Aerospace Sciences Meeting and Exhibit, 2004.
- [29] R.M. Abd El-Maksoud, Gas turbine with heating during the expansion in the stator blades, *Energy Convers. Manag.* 78 (2014) 219–224, <https://doi.org/10.1016/j.enconman.2013.10.054>.
- [30] D.E. Gray, Study of unconventional aircraft engines designed for low energy consumption, NASA CR-135065 (1976).
- [31] B. Sheikhbeigi, M.B. Ghofrani, Thermodynamic and environmental consideration of advanced gas turbine cycles with reheat and recuperator, *Int. J. Environ. Sci. Technol.* 4 (2) (2007) 253–262, <https://doi.org/10.1007/BF03326282>.
- [32] F. Yin, A.G. Rao, Performance analysis of an aero engine with inter-stage turbine burner, *Aeronaut. J.* 121 (1245) (2017) 1605–1626, <https://doi.org/10.1017/aer.2017.93>.
- [33] G. Cuccu, S. Danafar, P. Cudré-Mauroux, M. Gassner, S. Bernero, K. Kryszczuk, A data-driven approach to predict NO_x-emissions of gas turbines, in: 2017 IEEE International Conference on Big Data (Big Data), 2017, <https://doi.org/10.1109/BigData.2017.8258056>.
- [34] K. Liew, E. Urip, S. Yang, Parametric cycle analysis of a turbofan engine with an interstage turbine burner, *J. Propulsion Power* 21 (3) (2005) 546–551.
- [35] K. Vogeler, The potential of sequential combustion for high bypass jet engines, in: ASME 1998 International Gas Turbine and Aeroengine Congress and Exhibition, 1998, <https://doi.org/10.1115/98-gt-311>.
- [36] A. Pellegrini, T. Nikolaidis, V. Pachidis, S. Köhler, On the performance simulation of inter-stage turbine reheat, *Appl. Therm. Eng.* 113 (2017) 544–553, <https://doi.org/10.1016/j.applthermaleng.2016.10.034>.
- [37] F. Yin, A.G. Rao, Off-design Performance of an interstage turbine burner turbofan engine, *J. Eng. Gas Turbines Power* 139 (8) (2017), <https://doi.org/10.1115/1.4035821>.
- [38] A.A.V. Perpignan, A. Gangoli Rao, D.J.E.M. Roekaerts, Flameless combustion and its potential towards gas turbines, *Prog. Energy Combust. Sci.* 69 (2018) 28–62, <https://doi.org/10.1016/j.pecs.2018.06.002>.
- [39] F. Güthe, J. Hellat, P. Flohr, The reheat concept: the proven pathway to ultralow emissions and high efficiency and flexibility, *J. Eng. Gas Turbines Power* 131 (2) (2008), <https://doi.org/10.1115/1.2836613>.
- [40] A.G. Rao, A. Bhat, Hybrid combustion system for future aero engines, in: Proceedings of the 2nd National Propulsion Conference, 2015 (IIT Bombay, Powai, Mumbai).
- [41] F. Yin, A.G. Rao, Performance analysis of an aero engine with inter-stage turbine burner, *Aeronaut. J.* 121 (1245) (2017) 21, <https://doi.org/10.1017/aer.2017.93>.
- [42] A.A.V. Perpignan, Gangoli Rao, A., Effects of chemical reaction mechanism and NO_x formation pathways on an inter-turbine burner, *Aeronaut. J.* 123 (1270) (2019) 1898–1918, <https://doi.org/10.1017/aer.2019.12>.
- [43] J. Wüning, J. Wüning, Flameless oxidation to reduce thermal NO-formation, *Prog. Energy Combust. Sci.* 23 (1) (1997) 81–94.
- [44] J. Wüning, Flameless Combustion and Its Applications, Natural Gas Technologies, Orlando (USA), 2006, p. 30.
- [45] Y. Levy, V. Sherbaum, P. Arfi, Basic thermodynamics of FLOXCOM, the low-NO_x gas turbines adiabatic combustor, *Appl. Therm. Eng.* 24 (11–12) (2004) 1593–1605, <https://doi.org/10.1016/j.applthermaleng.2003.11.022>.
- [46] G. Rao, Y. Levy, A new combustion methodology for low emission gas turbine engines, in: 8th HITACG conference, Poznan, 2010.
- [47] A.G. Rao, F. Yin, J.P. van Buijtenen, A hybrid engine concept for multi-fuel blended wing body, *Aircraft Eng. Aero. Technol.* 86 (6) (2014).
- [48] F. Yin, A. Gangoli Rao, A. Bhat, M. Chen, Performance assessment of a multi-fuel hybrid engine for future aircraft, *Aero. Sci. Technol.* 77 (2018) 217–227, <https://doi.org/10.1016/j.ast.2018.03.005>.
- [49] Y. Levy, V. Erenburg, V. Sherbaum, I. Gaissinski, Development of Combustor for a Hybrid Turbofan Engine, 2019, <https://doi.org/10.1515/tij-2019-0042>, 0.
- [50] A.A.V. Perpignan, M.G. Talboom, Y. Levy, A.G. Rao, Emission modeling of an interturbine burner based on flameless combustion, *Emission Fuels* 32 (1) (2018) 822–838, <https://doi.org/10.1021/acs.energyfuels.7b02473>.
- [51] B. Cheze, P. Gastineau, J. Chevallier, Forecasting air traffic and corresponding jet-fuel demand until 2025, IFP Energies Nouvelles (2010).
- [52] History - KLM corporate, Available from: <https://www.klm.com/corporate/en/abo-ut-klm/history/>, 2017 August 22.
- [53] Finnair's scheduled commercial biofuel flight marks a step towards more sustainable flying, says airline, Available from: <http://www.greenaironline.com/news.php?viewStory=1300>, 2017 August 22.
- [54] Gladin, J.C., Perullo, C., Tai, J.C., and Mavris, D.N., A parametric Study of hybrid electric gas turbine Propulsion as a Function of aircraft size Class and technology level, in 55th AIAA Aerospace Sciences Meeting.
- [55] M.K. Bradley, C.K. Droney, Subsonic Ultra Green Aircraft Research: Phase II Volume II Hybrid Electric Design Exploration, NASA, California, 2015. NASA/CR-2015-218704/vol. II.
- [56] F. Yin, Modeling and Characteristics of a Novel Multi-Fuel Hybrid Engine for Future Aircraft, Delft University of Technology, Delft, the Netherlands, 2016.
- [57] J. Brand, S. Sampath, F. Shum, R.L. Bayt, J. Cohen, Potential use of hydrogen in air propulsion, in: AIAA/ICAS International Air and Space Symposium and Exposition: the Next 100 Y., 2003 (Dayton, Ohio).
- [58] H.W. Pohl, V.V. Malychev, Hydrogen in future civil aviation, *Int. J. Hydrogen Energy* 22 (10–11) (1997) 1061–1069, [https://doi.org/10.1016/S0360-3199\(95\)00140-9](https://doi.org/10.1016/S0360-3199(95)00140-9).
- [59] M. Janic, Is liquid hydrogen a solution for mitigating air pollution by airports? *Int. J. Hydrogen Energy* 35 (5) (2010) 2190–2202, <https://doi.org/10.1016/j.ijhydene.2009.12.022>.
- [60] M. Ponater, S. Pechtl, R. Sausen, U. Schumann, G. Hüttig, Potential of the cryoplane technology to reduce aircraft climate impact: a state-of-the-art assessment, *Atmos. Environ.* 40 (36) (2006) 6928–6944, <https://doi.org/10.1016/j.atmosenv.2006.06.036>.
- [61] H.G. Klug, R. Faass, CRYOPLANE: hydrogen fuelled aircraft—status and challenges. *Air & Space Europe* 3 (3) (2001) 252–254.
- [62] M. Ponater, S. Marquardt, L. Strom, K. Gierens, R. Sausen, G. Hüttig, On the potential of the CRYOPLANE technology to reduce aircraft climate impact, in: AAC conference, 2003 (Friedrichshafen, Germany).
- [63] Airbus-Deutschland-GmbH, Liquid hydrogen fuelled aircraft-system analysis fianl technical report, 2003.
- [64] H.G. Klug, R. Faass, CRYOPLANE: hydrogen fuelled aircraft — status and challenges, *Air Space Eur.* 3 (3–4) (2001) 252–254, [https://doi.org/10.1016/S1290-0958\(01\)90110-8](https://doi.org/10.1016/S1290-0958(01)90110-8).
- [65] Multifuel Blended Wing Body, Design Synthesis Exercise Report, Delft University of Technology, Delft, the Netherlands, 2012.
- [66] R.H. Liebeck, Design of the blended wing body subsonic transport, *J. Aircraft* 41 (1) (2004) 10–25, <https://doi.org/10.2514/1.9084>.
- [67] N. Qin, A. Vavalle, A. Le Moigne, M. Laban, K. Hackett, P. Weinerfelt, Aerodynamic considerations of blended wing body aircraft, *Prog. Aero. Sci.* 40 (6) (2004) 321–343, <https://doi.org/10.1016/j.paerosci.2004.08.001>.
- [68] J. Hileman, Z. Spakovszky, M. Dreha, M. Sargeant, Airframe design for 'silent aircraft', in: 45th AIAA Aerospace Sciences Meeting and Exhibit, 2007, <https://doi.org/10.2514/6.2007-453>. Reno, Nevada.
- [69] P. Li, B. Zhang, Y. Chen, C. Yuan, Y. Lin, Aerodynamic design methodology for blended wing body transport, *Chin. J. Aeronaut.* 25 (4) (2012) 508–516, [https://doi.org/10.1016/S1000-9361\(11\)60414-7](https://doi.org/10.1016/S1000-9361(11)60414-7).
- [70] M.V. Jérôme Talbotec, Sncema counter rotating fan aerodynamic design logic & tests results, in: 27th International Congress of Aeronautical Sciences, 2010.
- [71] T. Lengyel, C. Voß, T. Schmidt, E. Nicke, Design of a counter rotating fan. an aircraft engine technology to reduce noise and CO₂-emissions, in: ISABE Conference on Air Breathing Engines, Montreal, Canada, ISABE Paper No. 2009-1267, 2009.
- [72] T. Lengyel-Kampmann, A. Bischoff, R. Meyer, E. Nicke, Design of an economical counter rotating fan: comparison of the calculated and measured steady and unsteady results, in: ASME Turbo Expo 2012: Turbine Technical Conference and Exposition, American Society of Mechanical Engineers, 2012.
- [73] E. Jebbawi, Retrofitting Airbus A320 to Work on Liquefied Natural Gas, Delft University of Technology, Delft, 2019.
- [74] M.M. Conrad, Integration of an inter turbine burner to a jet turbine engine, in: Air Force Institute of Technology: Wright-Patterson Air Force Base, Ohio, US, 2013.