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Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 2013 227: 1701
originally published online 16 October 2012
DOI: 10.1177/0954410012462183

Original Article

Proc IMechE Part G:
J Aerospace Engineering
227(11) 1701–1719

DOI: 10.1177/0954410012462183
uk.sagepub.com/jaero

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Abstract

Current rapid growth of the aviation transport sector is deemed to be unsustainable because of the large quantities of greenhouse gas the aircrafts emit at sensitive altitudes. To prevent growth limits on this sector being imposed, the airlines must become cleaner. In the present study, a sustainable engine concept – based on intercooled recuperated turbofan, fuelled by liquid hydrogen, and using water injection for take-off and climb-out – is developed. This concept is intended to provide airlines a clean, efficient alternative to conventional engines. A commercially available computer program is used for modeling the sustainable turbofan concept. The optimization scheme of Guha has been applied for the new engine concept for minimizing fuel consumption and the performance of the sustainable turbofan engine in the possible design space has been determined. Comparisons with an existing conventional engine (of same thrust) revealed the significant improvement in overall efficiency (44%), reduction of emissions surpassing the demanding ACARE 2020 goals, improved longevity of the engine, and simplification in turbo-machinery components trying to offset the increase in weight due to the heat exchangers.

Keywords

ACARE goals, optimization, gas turbine cycle, NOx emission, alternative fuel

Date received: 22 December 2011; accepted: 28 August 2012

Introduction

One of the greatest challenges to face the human race at present, and in the near future, comes from the need to reach a condition of 'sustainable development'. Sustainable development is defined as the 'Development which meets the needs of the present without compromising the ability of future generations to meet their own needs'.[1]

In the majority of the countries, the needs of the people are not met to the current standard of the developed world, and hence these economies must be allowed to grow. Economic development and transport are highly interdependent i.e. an increase in development increases the transport demand, and the availability of various transports in turn increases the opportunity to grow by means of trade and economic specialization. Globally, civil aviation is one of the fastest growing transport means. A forecast by the International Civil Aviation Organization (ICAO) for the annual growth in air passenger traffic has set it at 4.3% up to 2020.[2] Similar forecast by industries such as Airbus, Boeing and others predict the growth percentage of global average passenger traffic at around 5% per year.[2]

But the airlines emit large quantities of greenhouse gases into the atmosphere at sensitive altitudes. Studies are predicting that aviation emissions would get doubled or tripled by 2050 and the emissions from aircraft would become a significant contributor to global warming by then.[3] Therefore global warming is one of the significant challenges to be tackled for sustainable development. In order to restrict the effect of aviation emissions on global warming, the regulations or legislations for engines and aircrafts are expected to be made more stringent. Aircraft engine design is currently

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driven by the ACARE 2020 goals (Advisory Council for Aeronautics Research in Europe).[4] ACARE 2020 goals were set up in order to achieve the sufficient reduction in aircraft emissions to maintain sustainable air transport for the future. More stringent emission standards are set by Committee on Aviation Environmental Protection (CAEP, a technical committee formed by ICAO to assist the council in making new policy and standards for aircraft emissions and noise level) to avoid climate change due to global warming. Besides the regulations and goals, rising operating costs force the airlines to reduce emissions from the aircraft, which drives the aeroengine design further to look for alternative engine concepts (which may involve new designs, configurations and alternative fuels).

Another drive for exploring alternative fuels comes from the depletion of the fossil fuel reserves. A difference of opinion exists about how long fossil fuel reserves will last, but they will definitely be obsolete one day. Moreover, the prospect of meeting the environmental constraints through the development of the current conventional aeroengines is modest and it will not have any bearing in meeting the carbon reduction targets. In short, the aviation sector is not sustainable in its present form and will have to cut back if preserving the environment becomes the society's first priority. This circumstance can only be avoided by coming up with a technological innovation (by using an alternative engine thermodynamic cycle and/or by using an alternative fuel) and intelligent government pressures.

In this context, the present study explores the thermodynamic merit of a sustainable engine concept. The objectives of this article are: (i) to propose a sustainable concept for a turbofan with an alternative fuel, which could surpass the ACARE 2020 goals (engine contribution) for carbon dioxide (CO_2) and nitrogen oxide (NOx) emissions (the ACARE goals envisage 50% reduction in CO_2 and 80% reduction in NOx), (ii) to use an optimization scheme developed by Guha[5] to determine an optimum configuration for the new concept which minimizes fuel consumption, and (iii) to compare the performance and emissions from the new engine (derived from the optimization study) with those of an existing engine that produces the same net thrust.

Though significant works have been carried out separately on intercooled recuperated turbofans, liquid hydrogen fuel in aircrafts and water injection in aircraft engines, they have not been put together previously. In this article, the option of synergizing the three technologies stated above has been explored, which makes the thermodynamic cycle sustainable. In the following section the details of the above-mentioned technologies are studied individually before developing the cycle for the sustainable development of the aviation sector.

Details of a sustainable turbofan concept

The sustainable turbofan concept proposed in this study is an InterCooled, ReCuperated, three spool, high bypass TurboFan engine (ICRCTF), fuelled by liquid hydrogen (LH_2) and using water injection at take-off and climb-out. In this section, all the aspects of this engine concept are detailed.

Intercooled recuperated turbofan

For the conventional aircraft engines, the scope of improvement in thermal efficiency (η_{th}) (and hence the overall efficiency (η_o) as the propulsive efficiency (η_p) can be fixed if the specific thrust is fixed for the given speed of aircraft) due to higher overall pressure ratio (OPR) and higher turbine entry temperature is small with the existing level of technology in cooling and components.[6] Advancements in the technology for cooling and components may not increase the thermal efficiency appreciably.[6] Therefore many European Union technology programs like NEW Aero engine Core concepts (NEWAC),[7,8] Component validator for environmentally friendly aero engine (CLEAN),[9] and EnVIronmenTALly friendly aero engine (VITAL)[10] have been working for years to come up with a breakthrough technology, which would make an efficient and environmentally friendly aeroengine. Some of the new engine technologies being explored in recent times by many European Union programs mentioned above are simple intercooled turbofan, simple recuperated turbofan, intercooled recuperated turbofan (ICRCTF), etc.

Performance of the simple intercooled cycle is attractive at a higher OPR level than that of a simple Brayton cycle.[11] As the NOx emissions are higher at higher OPR level intercooled core will not be a proper choice as one of the objectives of the present study is to meet the ACARE goals. Recuperation, while compensating the heat removed by intercooling, increases the combustor inlet temperature (T_{35}) thus reducing the amount of fuel required to achieve a given combustor outlet temperature (COT). In the intercooler, the bypass air cools down the compressor exit temperature (T_3) thus transferring energy to the bypass stream and enhancing high heat transfer by recuperation. This synergy of intercooling with recuperation eliminates the disadvantage of having lower specific thrust due to recuperation alone. Also, the core efficiency of intercooled recuperated cycle is higher than the simple Brayton cycle and simple recuperated cycle.[12] Therefore the configuration which can give the promising benefits in reducing fuel consumption and meeting ACARE goals would be intercooled recuperated cycle.

The presence of heat exchangers adds to the weight and drag. Despite having these disadvantages this engine configuration has the potential to reduce *sfc* and NOx emissions (See Appendix 2 for details). In Plohr et al.,[13] it is concluded that though intercooled recuperated turbofan gives about 16% reduction in *sfc*, it may not meet the ACARE 2020 target. 50% reduction in the CO_2 emission is a prime target of the ACARE goals, it would be difficult to achieve such a large reduction in CO_2 emission if the use of fossil fuel is continued. Since a primary objective of the present study is to develop an optimized sustainable turbofan concept that meets the ACARE 2020 goals, it is decided to use an unconventional fuel – hydrogen – in addition to the unconventional engine configuration (ICRCTF).

Hydrogen fuel and its effect on the environment

As the price of crude oil rises and the cost of operating kerosene-fuelled aircraft increases (due to political pressure upon airlines to lower their operating emissions) the option of using hydrogen as a fuel will become more affordable. The emissions from combustion of hydrogen are water vapor and NOx eliminating all other emissions like CO_2, carbon monoxide (CO), sulphur oxides (SOx), unburned hydrocarbons (UHC) and soot. This makes hydrogen an environment-friendly fuel. The significant increase in water vapor emissions with hydrogen as a fuel over a conventional fuel is, however, a concern as there shall be an increase in contrail formation (which can add to the global warming effect). Reduction of cruise altitude to 10 km has been suggested by the Cryoplane project to reduce the impact of the water vapor emissions due to the use of hydrogen.[14]

Hydrogen-fuelled engine versus fossil-fuel-based engine

Hydrogen fuel can operate over a wider flammability range.[15] The stoichiometric flame temperature of hydrogen is higher than that of kerosene. Despite having higher stoichiometric flame temperature, operating limit for leaner combustion of hydrogen fuel is considerably lower than that of kerosene. This factor allows the combustor of hydrogen to operate towards the leaner limit and hence the combustor flame temperature can be significantly reduced as compared to that of kerosene, resulting in significant reduction in NOx formation.[15]

The Cryoplane project (in which LH_2 fuel for aircraft applications is being researched in depth[16]) predicts that the hydrogen fuel will enhance the net thrust of an engine at fixed COT by 3.2%.[15] If the increase in net thrust is not intended, *sfc* can be improved by reducing COT which also enhances the turbine blade life.[15] It is claimed that a hydrogen-fuelled conventional engine will run approximately 40 K cooler than kerosene-fuelled engine depending on the cycle parameters.[17]

Hydrogen onboard storage and heating

Liquid hydrogen is normally stored in tanks at a temperature of 23 K. At such a low temperature it is not suitable for injection into the combustion chamber. The density and the viscosity vary greatly with temperature at the critical temperature of hydrogen ($\sim$60 K) leading to combustion instability. In addition, pressure drop across the injection nozzle may lead to re-liquefaction of hydrogen. These problems can be avoided by preheating the liquid hydrogen prior to its entry into the combustion chamber to a minimum temperature of 150 K.[18]

High energy density per unit mass of hydrogen fuel (equivalent to its lower heating value) results in one-third reduction of fuel mass, for a flight, compared to a conventional carbon-based fuel.[16] However, low energy per unit volume of hydrogen results in approximately four times larger fuel tanks which would increase the structural weight of the aircrafts.[16] The technical challenges regarding the use of hydrogen like liquid hydrogen storage and its weight impact on the aircraft performance are explained in Appendix 3. As these are not the subject-matter of this article, only the thermodynamic aspects of the engine have been studied here.

Water injection to reduce NOx emission

Having employed LH_2 as the propulsion fuel and reduced cruise altitude to minimize the impact of water vapor emissions, NOx remains the only emission to be controlled for the sustainable turbofan engine. It is possible to implement changes in the combustor design specifically for the hydrogen fuel that could significantly reduce the NOx emission.[19,20] However, such detailed design is beyond the scope of the present study, and therefore the results on NOx emission for hydrogen in the conventional combustor have been presented here.

In order to reduce the NOx formation, both the O_2 concentration and the combustor flame temperature should be reduced. Injection of water into either the compressor or the combustor can achieve both of the requirements mentioned above. Water injection which was initially used as one of the methods for augmenting thrust[21,22] is now directed at reducing NOx emissions. This simple, low cost and low risk technology is used during critical flight stages of a landing and take-off cycle (LTO cycle – Figure 1), i.e. take-off and

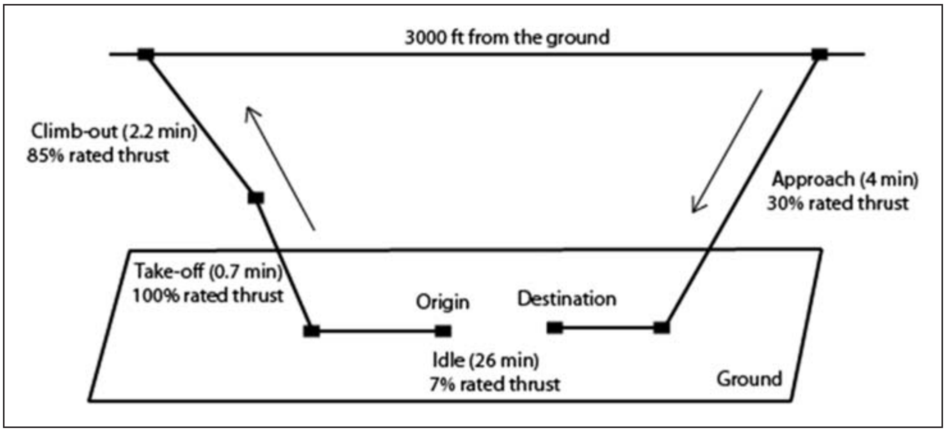

Figure 1. Typical LTO cycle for ICAO engine certification.

climb-out, for a conventional turbofan.[23] Water injection during all other phases of aircraft does not seem to be feasible due to weight issues. In Appendix 4, impact of water injection system on an aircraft and the necessity of water injection in meeting ACARE goals are discussed.

Location of water injection within the engine

Water injection in aircraft engines to reduce NOx emission has been studied in the recent past.[22,24,25] It is observed from these studies that the possible locations for water injection in aircrafts are: (i) combustor and (ii) compressor. When water is injected into the combustor more fuel is required to be injected to achieve a given COT.[24] Injection into the compressor requires more water than injection into the combustor to achieve a given NOx reduction.[22,25] However, due to the associated reduction in compressor temperature rise (and hence in the required compressor work) a larger reduction in COT can be achieved and a slight reduction in fuel burn if no increase in thrust is required.[19]

As the augmentation in thrust is not intended in this study it is decided to use water injection ahead of intermediate pressure (IP) compressor during take-off and climb-out to get the benefits of reduction in *sfc* and NOx emission.

A new prediction tool for NOx emission

In a recent study by the present authors,[26] major prediction tools for NOx emission from a gas turbine engine have been systematically analyzed and a new prediction method called the 'NOx – *generic*' method has been developed. The prediction of 'NOx – *generic*' compares well with the $P_3 - T_3$ method (a preferred method by the industries). But unlike the $P_3 - T_3$ method, the 'NOx – *generic*' method is a generic prediction technique, as the name implies, and does not require any proprietary information. The equation of 'NOx – *generic*' for NOx Emission Index (EINOx) prediction is

$$\mathrm{EINO}x_{\mathrm{NOx}-generic} = C_1 \cdot S_{NOx} + C_2, \tag{1}$$

where S_{NOx} is the NOx severity index, and C_1 and C_2 are constants which are to be estimated for a particular engine using EINOx values of ICAO engine emissions databank.[27] C_1 and C_2 are determined from the data for LTO cycle but it has been established in Chandrasekaran and Guha[26] that the same values of the constants and the same equation (1) can be used for other phases of the flight such as the cruise. S_{NOx} is obtained by simulating the thermodynamic cycle with GasTurb-11,[28] a commercially available program to compute gas turbine performance.

Development of sustainable turbofan concept

Configuration of the present concept

Based on the discussions in section 'Details of a sustainable turbofan concept', a turbofan concept is developed in the present study. The layout of the proposed turbofan concept is shown in Figure 2. This concept is based on intercooled recuperated turbofan configuration with liquid hydrogen as the fuel. In addition, water will be injected ahead of an intermediate pressure (IP) compressor during take-off and climb-out (the critical phases of the flight). The proposed engine cycle is equipped with two intercoolers which are arranged in such a way that a fraction of bypass-flow cools the core initially in the first intercooler (IC-1) and then the LH_2 takes over in a separate reverse flow heat exchanger

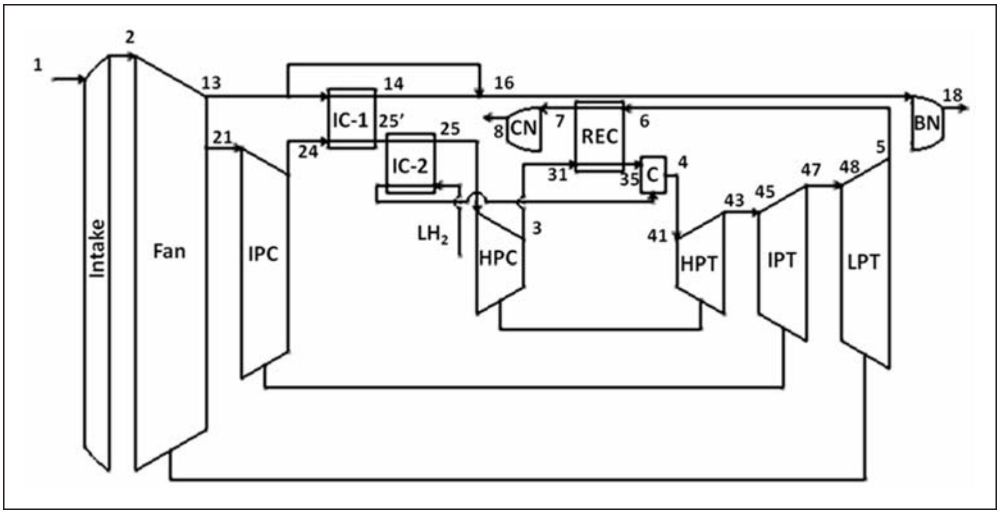

Figure 2. Layout of the proposed sustainable turbofan concept.
C: combustor; HPC: high pressure compressor; HPT: high pressure turbine; IC: intercooler; IPC: intermediate pressure compressor; IPT: intermediate pressure turbine; LPC: low pressure compressor; LPT: low pressure turbine; CN: core nozzle; BN: bypass nozzle; REC: recuperator.

(IC-2). The reason for using LH_2 as one of the coolants is to get the dual benefit: (i) to heat LH_2 up to a temperature of 300 K (the limit imposed by GasTurb, which also fulfills the condition for stable combustion), and (ii) to get further benefit of recuperation with its superior cooling properties (high latent heat).

Modeling methodology

In this section, the modeling methodology for the development of a sustainable turbofan concept has been explained. The description can be divided into four parts: (i) an optimization study based on the method of Guha,[5] (ii) selection of overall parameters for the design point (cruise) from the optimization study and thermodynamic modeling of the engine at the design point, (iii) modeling of the LTO cycle, and, (iv) simulation of water injection during take-off and climb-out. For these simulations, GasTurb-11 computer program[28] is used in general; however, GasTurb does not have certain features required for the present study. As an example, there is no facility within GasTurb for water injection in an ICRCTF engine. Separate computational programmes were written for this study to enhance the capability of GasTurb; these have been described in appropriate places.

GasTurb-11 is able to model an ICRCTF with hydrogen as a fuel which is injected at 300 K. The inbuilt configuration in GasTurb can deal with only one intercooler where a fraction of the bypass flow is used as a coolant. However, in the present concept shown in Figure 2, there are two intercoolers, the second using LH_2 as the coolant. The inability of GasTurb to model the use of two intercoolers and a cryogenic fuel was overcome in the present application by running GasTurb twice at each design point, with separate calculations by an in-house program in between.

1. Initially, for a particular design point, GasTurb is run in its normal configuration, by setting a realistic value (0.85) of effectiveness of an intercooler, and the value of the core flow exit temperature ($T_{25'}$) is noted.
2. Next, an energy balance on the second intercooler, for LH_2 as the coolant, is performed. The analysis is based on the simple principle that the enthalpy gain of the fuel (ΔH_f) equals the enthalpy loss of the core flow (ΔH_a)

$$\begin{aligned}\Delta H_f &= W_f \cdot c_{p,f} \cdot \Delta T_f + W_f \cdot h_{fg,f} \\ &= \Delta H_a = W_{21} \cdot c_{p,a} \cdot (T_{25'} - T_{25})\end{aligned} \tag{2}$$

   In equation (2), the change in temperature (ΔT_f) of the liquid hydrogen fuel is specified by the difference between its storage temperature (23 K) and its injection temperature (300 K). For each design point, the fuel flow (W_f) will vary as will the core mass flow (W_{21}). Therefore, $T_{25'} - T_{25}$ can be determined.
3. GasTurb is then run again in its normal configuration, but this time the intercooler effectiveness is iterated to achieve the same final T_{25} that was determined in step 2 above.

In this manner, the two-intercooler arrangement proposed here can be analyzed by GasTurb, without making changes to the software.

Optimization. According to Guha,[5] concurrent optimisation of the main parameters is needed to exploit the full benefits of the thermodynamic cycle selected for any engine. It is clearly evident from equation (3) that the overall efficiency (η_o) governs the fuel economy for a given aircraft speed

$$\eta_o = \frac{V_a}{Q_{CV} \cdot sfc} \tag{3}$$

Therefore, it is the overall efficiency that is to be maximized (instead of the usual dealing with thermal and propulsive efficiencies separately).

In the optimization method of Guha,[5] the specific thrust is taken as a basic design parameter since it indicates the overall picture of an engine: mean jet speed (propulsive efficiency and jet noise), fan diameter (size of the engine), weight, cost and drag. The possibility of aircraft integration issues of an engine can also be indicated by the specific thrust of the engine. The optimization is thus carried out by finding concurrently a combination of fan pressure ratio (FPR), OPR, bypass ratio (B) and COT which maximizes η_o (or minimizes *sfc*) subject to the constraint that the specific thrust is kept fixed at a predetermined level.[5] The value of the specific thrust at which the optimization is performed is determined by an economic analysis. The performance and optimization of gas turbines with real gas effects are given in Guha.[29,30]

The above optimization method is very different from the usually employed parametric studies, which involve the numerical calculation of engine performance as a single parameter is varied each time, while keeping all other parameters fixed – therefore not at their optimum values. Parametric studies with a single variable are inadequate in finding true optimum conditions in jet engine design (even if they produce the typical 'U-shaped' curves). Moreover, such parametric studies may be associated with large excursions in the value of the specific thrust which is not acceptable for real design. (It has been shown in Guha[5] from a careful compilation of the existing engine data that the values of cruise specific thrust of modern engines lie within a very narrow range.) The above optimisation scheme, in contrast to previous studies, is also able to establish true thermodynamic optimums for the bypass ratio and turbine entry temperature.

In the ICRCTF concept proposed in this study (Figure 2) two intercoolers are placed in between IP and high pressure (HP) compressors hence there could be an optimum position of them which would minimize *sfc*. However, it became evident from this analysis that the change in *sfc* for other positions of the intercoolers is very meager from the usual optimum position of equal pressure ratios across the IP and HP compressors (which is the case for an intercooled-land based gas turbine). Therefore it is decided to choose equal pressure ratio as the intercooler position for the ICRCTF engine concept proposed here. With a recuperator, the *sfc* of the turbofan concept decreases monotonically with increasing effectiveness of the recuperator which is an indication of having no optimum effectiveness value. Hence the new features of the sustainable turbofan engine do not alter the optimisation procedure that was developed for a conventional turbofan engine.[5]

Using the suggested reduction in cruise altitude (section 'Hydrogen fuel and its effect on the environment'), design point altitude has been chosen 1 km lower than the one currently being used by engine manufacturers. The optimization in this work is therefore carried out for an engine running at Mach (Ma) 0.82 at 10 km altitude and under International Standard Atmosphere (ISA) conditions.

In the proposed turbofan concept the working fluids used for cooling the core flow in IC-1 and IC-2 are bypass air and liquid hydrogen, respectively. It is established from the current research that the core flow temperature at the exit of the intercooler (T_{25}) decreases with an increase in B, until the value of B reaches 5 (Figure 3). The present studies also show that the relevant optimum bypass ratio is usually greater than 6, hence the calculation of T_{25} becomes simplified.

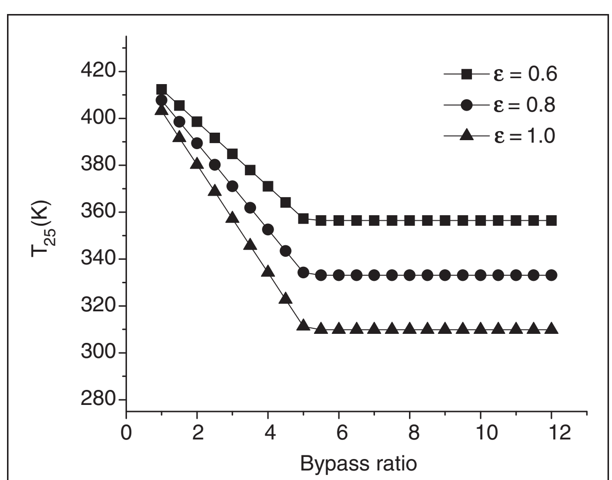

Figure 3. Effect of the amount of cooling flow on T_{25} (for constant COT and FPR).

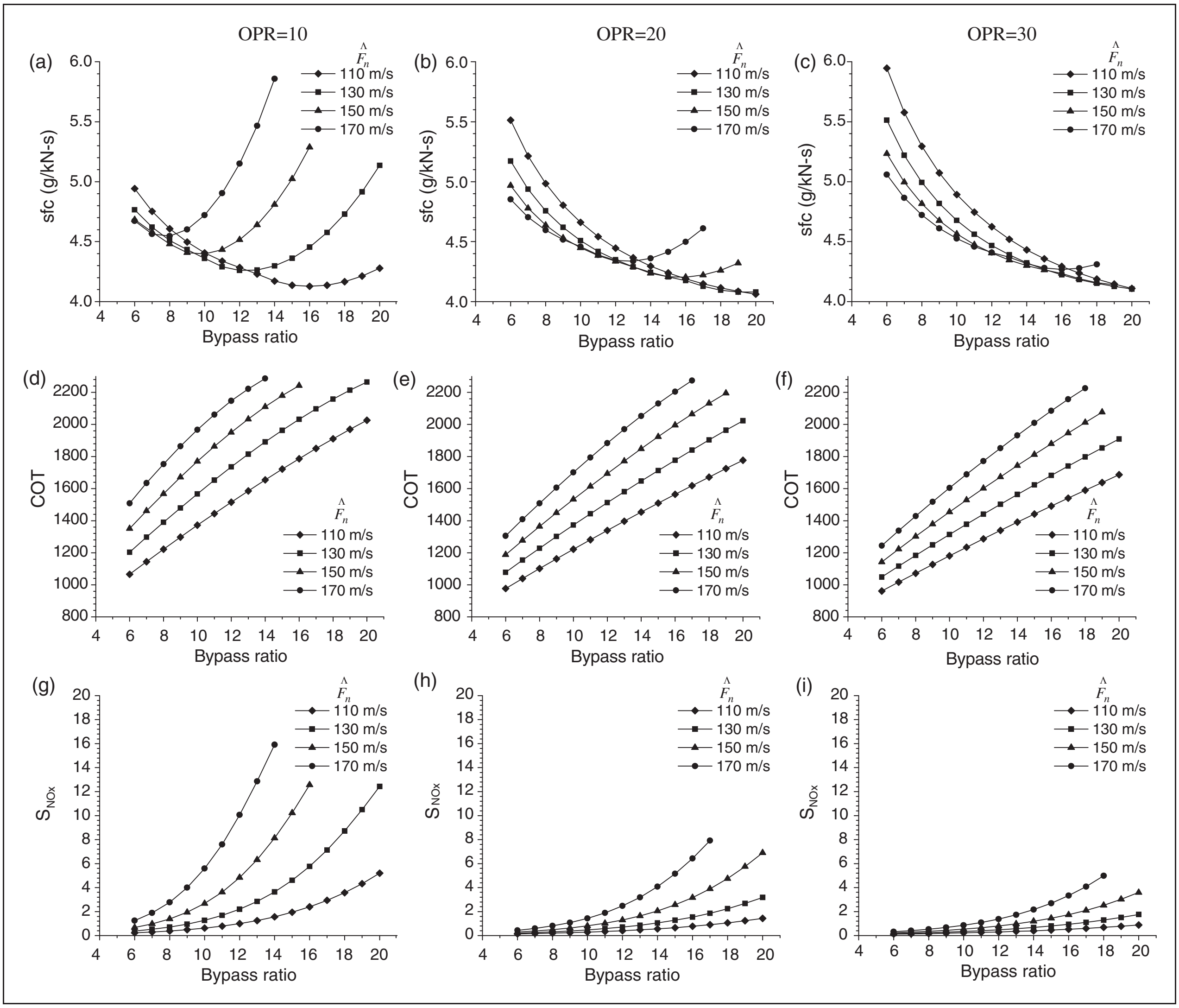

Figure 4. Optimization of ICRCTF with liquid hydrogen as a fuel and with bypass air and liquid hydrogen as the coolants in the intercoolers at fixed values of the specific thrust. (The optimization theory and technique of Guha[5] has been used).
COT: combustor outlet temperature; OPR: overall pressure ratio.

Figure 4 shows the effect of OPR and *B* on *sfc*, COT and NOx emissions for a fixed specific thrust. GasTurb[28] is used for the numerical computation. At every operating point shown in Figure 4, the corresponding optimum FPR is used; this is consistent with the objective of minimizing the *sfc*.[31] The results are set out in a series of graphs, arranged in columns of constant OPR. The four specific thrusts chosen represent broadly the past, present, near-future and distant-future. Hence the optimization results shown in Figure 4 represent the possible design space of an aero-engine based on the turbofan cycle developed here. (As the OPR would rise in the future, one may need to add another column of curves in Figure 4 corresponding to a higher pressure ratio.)

One can conclude the following from Figure 4

I For each value of the specific thrust, there is a bypass ratio that gives the minimum specific fuel consumption. This is the optimum bypass ratio.
II The optimum bypass ratio increases with decreasing values of specific thrust. It depends only weakly on the overall pressure ratio.
III The value of COT corresponding to the optimum bypass ratio represents the optimum COT. (The value of COT obtained by this method would be different from that determined from consideration of thermal efficiency of the core engine alone.)
IV At low specific thrust level, the *sfc* versus *B* curves are sufficiently flat near the optimum value. One

can therefore use significantly lower value of B than optimum, without appreciably increasing the *sfc*. This results in the use of lower COT, which allows the thrust growth potential of the engine in the future with the minimum change. A lower bypass ratio reduces the number of low pressure (LP) turbine stages and may avoid the use of a gear drive.

V The *sfc* versus B curves for various specific thrusts cross each other indicating that there is an optimum specific thrust if bypass ratio were kept fixed at a particular value. This topic has been discussed in detail in Guha.[5]

Selection and modeling of design point (cruise) for the sustainable turbofan concept. To select the design point from the optimization results shown in Figure 4, a trade-off between NOx emissions and *sfc* may have to be made. The design point to be chosen must also comply with other engineering constraints. The following points are considered: (i) a low OPR is chosen to have lighter and fewer turbomachinery components,[13] (ii) the value of B is restricted to such a value so as to have a plausible number of LP turbine stages[13] and to avoid the requirement of gearbox, (iii) a low value of specific thrust is chosen which is consistent with the design trend, (iv) having chosen a combination of main parameters defining the design point, the engine is simulated under off-design conditions to find the NOx emissions for the LTO cycle (section 'Modeling of LTO cycle for sustainable turbofan concept'), ensuring that the emissions satisfy the ACARE 2020 goal (section 'LTO NOx').

Taking all of these factors into account, basic parameters for the design point (cruise) chosen for this study are: OPR = 20, $\hat{F}_n = 130\,\text{m/s}$, $B = 13$. The value of optimum FPR is not shown explicitly in Figure 4, but can be calculated from the analytical formula derived by Guha[31]

$$(\text{FPR})_{op}^{\frac{\gamma-1}{\gamma}} = 1 + \frac{\gamma-1}{2+(\gamma-1)Ma^2} \left[\frac{(1+B)^2}{1+1/\eta_{KE}} \left\{ \frac{\hat{F}_n}{\sqrt{\gamma R T_{amb}}} + Ma^2 \right\}^2 - Ma^2 \right] \tag{4}$$

The cruise thrust for the turbofan engine is set equal to that of an existing engine (GE-90-85B has been taken here as the comparator engine). With $Ma = 0.82$, altitude = 10 km, the above-mentioned basic design parameters from the optimization study, the design point is modeled in GasTurb using the design mode. In GasTurb, the COT is iterated to obtain the required specific thrust at cruise and the inlet mass flow of air through the engine is iterated to obtain the specified cruise thrust.

Modeling of LTO cycle for sustainable turbofan concept. The schematic of a typical LTO cycle is shown in Figure 1. The characteristics of the ICRCTF concept for the different phases of LTO cycle can be obtained from the engine modeled in the previous section, using an off-design mode of GasTurb. Performance results corresponding to a particular input parameter (e.g. thrust/fuel flow/air flow) can be obtained if the value of the parameter is given as an input in 'Limiters' option available in the off-design mode of GasTurb.[28] Here the maximum rated thrust at sea level static (SLS) condition has been chosen as the Limiter parameter since the standard thrust settings for each phase of LTO cycle are specified in terms of maximum rated thrust in ICAO engine testing procedure (take-off – 100% of maximum rated thrust, climb-out – 85% of maximum rated thrust, approach – 30% of maximum rated thrust and idle – 7% of maximum rated thrust). The maximum rated thrust assumed here will be the same as that of an existing engine (GE-90-85B) whose performance is compared, in the present study, with that of the sustainable turbofan concept.

Simulation of water injection (take-off and climb-out). It has been mentioned in section 'Location of water injection within the engine' that, for the turbofan cycle, water injection is used ahead of the IP compressor during take-off and climb-out. Generally, the absolute speed of the compressor (N) is kept constant, and therefore, water injection at the inlet of the compressor increases the corrected speed (N_C) by decreasing the effective temperature of the fluid passing through the compressor (θ_{eff}),[21] as shown in equation (5)

$$N_c = \frac{N}{\sqrt{\theta_{eff}}} \tag{5}$$

The increase in total mass flow of the working fluid, associated with this increase in N_C, results in thrust augmentation. This is what is normally adopted in ICRCTF engines when water injection is used.

However, in the present study, there is no requirement for an increase in thrust. Hence it is proposed here: (i) to reduce the absolute speed of an IP compressor (N) such that corrected speed (N_C) is held constant with the reduction in θ_{eff} (which is a function of IP compressor inlet temperature) to maintain nearly a constant operating point of the IP compressor, and (ii) to reduce the HP compressor speed to produce the same thrust as that of the dry condition.

As the work required to drive the compressor is reduced, the amount of work extraction from the turbine will also be reduced which allows the engine to run with reduced COT than that of the dry condition. The reduction of COT increases the life of the engine.

As mentioned above at the beginning of section 'Modeling methodology', GasTurb does not have the capability of water injection in an ICRCTF engine. However, it does have the option of water injection (ahead of booster) in the off-design mode for an Intercooled Recuperated Turboshaft (ICRCTSHFT) engine. Though ICRCTSHFT engine is widely different from the ICRCTF, it is the only engine configuration available in GasTurb 11 with intercooler and recuperator apart from ICRCTF. Therefore a detailed study of water injection in ICRCTSHFT engine has been made here to formulate a quantitative understanding of the performance based on which the simulation of water injection in ICRCTF for take-off and climb-out became possible.

The systematic procedure followed in GasTurb to obtain the accurate results for the effect of water injection into the ICRCTF engine (ahead of IP compressor) using ICRCTSHFT configuration is as follows.

I It is observed that the core of an ICRCTF is similar to an ICRCTSHFT up to the station corresponding to compressor exit (Station 3), i.e. just before the starting of recuperation. Therefore it is decided here to simulate water injection in ICRCTSHFT engine and all the results at Station 3 will be obtained. Prior to obtaining these results it is necessary to ensure that the conditions of the working fluid of ICRCTSHFT engine, from the entry of the LP compressor (where water would be injected) to the exit of the HP compressor, are same as the conditions of the ICRCTF engine from the entry of the IP compressor to the exit of the HP compressor. The methodology followed in GasTurb to achieve the required conditions in various stations (2, 24, 25 and 3) is explained in Appendix 5.

II The proposal of maintaining nearly the constant operating point of the IP compressor and reducing the HP compressor speed of ICRCTF (as discussed above) is achieved through GasTurb (details explained in Appendix 6) using the ICRCTSHFT configuration.

III The Station 3 results thus obtained are given as the input to a program specifically written for ICRCTF in this research work using Engineering Equation Solver (EES).[32] The performance equations used for writing the program are taken from Walsh and Fletcher.[11] The values for the properties of air and combustion products (used in the program) are taken from GasTurb Details 5 – a sub package of GasTurb 11.[28] The properties of combustion products can also be obtained from Guha.[33]

The two programs written by the authors in EES, in effect, represent performance packages for ICRCTF and ICRCTSHFT engines. The two programs are validated for both dry (no water injection) and wet simulation (with water injection) using the available engine configurations in GasTurb; the dry simulation is validated with ICRCTF results and wet simulation is validated with the results for ICRCTSHFT – an engine with the capability of wet simulation in off-design mode. The results are summarized in Tables 1 and 2.

Performance and emission characteristics of the sustainable turbofan concept

The benefits of the sustainable turbofan concept proposed here can be well established only when the results are compared with the performance of an existing engine with same thrust. GE-90-85B, being one of the largest modern engines with excellent performance figures, is chosen to be the comparator engine for the present study. It has already been pointed out that there are technical challenges regarding the use of hydrogen that need to be resolved through research and development; however these are not the subject-matter of this article. Here, only the thermodynamic aspects of the engine have been studied.

The modeling of GE-90-85B in GasTurb has been discussed below in section 'Modeling of GE-90-85B (an existing engine)', the procedure for estimating blade temperature is explained in section 'Estimation of blade temperature', a comparison of the performance and emission characteristics of the sustainable turbofan with GE-90-85B at design point (cruise) is presented in section 'Engine characteristics at the design point (cruise)'. The assessment of benefits in performance and emissions during take-off and climb-out phases of LTO cycle due to water injection are covered in section 'Engine characteristics at take-off and climb-out'. Finally, LTO NOx emissions for the sustainable turbofan are quantified and compared with ACARE 2020 goals in section 'LTO NOx'.

Modeling of GE-90-85B (an existing engine)

Based on the details from ICAO databank[27] and the data given by Meier[34] at SLS take-off condition, GE-90-85B is reconstructed in GasTurb design mode (details of the procedure are given in Appendix 7). The details of GE-90-85B engine are as follows: cruise

Table 1. Validation of the results of EES program for dry simulation using GasTurb with ICRCTF configuration.

	ICRCTF (Dry simulation)		
Engine characteristics	GasTurb	EES	% Deviation
Net thrust (kN)	395.24	395.00	0.00
Fuel flow (kg/s)	0.8850	0.8535	3.55
Thrust *sfc* (g/kN-s)	2.2390	2.1594	3.56
Combustor inlet pressure (kPa)	1712.92	1713.00	0.00
Combustor inlet temperature (K)	991.62	984.80	0.69
NOx severity index	2.0908	2.0246	3.16
COT (K)	1737.83	1727.63	0.59

ICRCTF: intercooled recuperated turbofan; EES: Engineering Equation Solver; NOx: nitrogen oxide; COT: combustor outlet temperature.

Table 2. Validation of the results of EES program for wet simulation using GasTurb with ICRCTSHFT configuration.

	ICRCTSHFT (Wet simulation)		
Engine characteristics	GasTurb	EES	% Deviation
Power (kW)	65933	64492	2.19
Fuel flow (kg/s)	0.8708	0.8750	−0.48
Power *sfc* (kg/kW-h)	0.0475	0.0488	−2.74
Combustor inlet pressure (kPa)	1657.27	1680.00	−1.37
Combustor inlet temperature (K)	790.21	796.60	−0.81
NOx severity index	0.5732	0.5962	−4.01
COT (K)	1470.71	1474.00	−0.22

ICRCTSHFT: intercooled recuperated turboshaft; EES: Engineering Equation Solver; NOx: nitrogen oxide; COT: combustor outlet temperature.

thrust – 77.87 kN[34]; engine maximum rated thrust (F_{oo}) – 395.31 kN; B_{to} – 8.4; OPR_{to} – 38.1; $W_{f,to}$ – 3.91 kg/s; fuel – Jet A[27]; take-off engine air flow – 1378 kg/s.[34] For the simulation in GasTurb, the design point of GE-90-85B is taken to be the take-off condition since most of the details available are for the take-off condition. Therefore its performance at cruise condition can be obtained by specifying the cruise-thrust in the 'Limiter' option available in the off-design mode of GasTurb.

Estimation of blade temperature

In this section, blade temperature is estimated for both GE-90-85B and the sustainable turbofan concept. Blade temperature is not an output variable in GasTurb. Therefore, the following procedure is used for its determination. Firstly, the cooling effectiveness on blade due to bleed air (η_{cool}) is calculated from Figure 5 corresponding to the relative cooling air used for the high pressure turbine for a particular value of cooling air constant. Then from the definition of η_{cool}, the blade temperature (T_b) can be calculated if the gas temperature (T_g) – here T_g is the same as COT – and the bleed temperature (T_{bleed}) are known. η_{cool} has

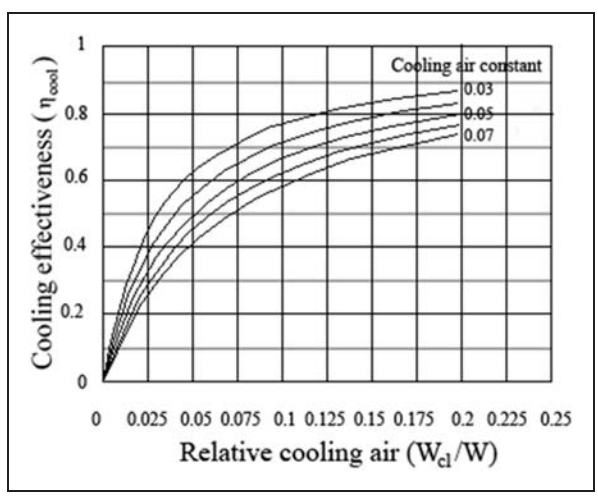

Figure 5. Cooling effectiveness vs relative cooling air (data taken from Kurzke[28]).

been defined in GasTurb[28] as follows

$$\eta_{cool} = \frac{T_g - T_b}{T_g - T_{bleed}} \tag{6}$$

For the turbofan, the amount of cooling flow in the HPT is determined iteratively such that the same COT as that of GE-90-85B is obtained. The relative cooling air value being known, η_{cool} and T_b for the turbofan are determined.

Engine characteristics at the design point (cruise)

A comparison of the important overall parameters of the turbofan engine and the comparator engine is shown in Table 3. The comparator engine chosen here is one of the finest examples of the existing conventional engines (GE-90-85B is chosen here, but there are similar engines available from other manufacturers also). Table 3 shows that the engine concept, developed in the present work, outperforms the GE-90-85B almost in all categories; the improvement in the overall efficiency η_o (43.76%) is particularly substantial. The decrease in blade temperature of about 78 °C, due to the turbofan concept, will increase the life of the turbine to a great extent. From Table 3, it is observed that the percentage cooling air required for the present engine is less than that of GE-90-85B. The lower OPR would result in lighter and fewer turbo-machinery components.[13]

Here, the NOx emission index (EINOx) for both the sustainable engine concept and GE-90-85B is calculated using the 'NOx – *generic*' method (equation (1) – developed by the authors of the present study) explained in section 'A new prediction tool for NOx emission'. It is clear from equation (1) that the values of C_1 and C_2 are to be found. Here the combustor of ICRCTF engine is assumed to be of a conventional engine (GE-90-85B) since there is no reference available for a hydrogen-fuelled aeroengine in ICAO engine emissions databank. Therefore C_1 and C_2 can be found by plotting EINOx values of LTO cycle for GE-90-85B (from ICAO engine emissions databank[27]) with corresponding NOx severity index (obtained from GasTurb after reconstructing GE-90-85B in it using the data available from public domain – explained in Appendix 7). It is to be noted that EINOx value calculated for the engine will be a conservative estimate since the actual EINOx of a hydrogen-fuelled engine would be less. The reason for this can be explained through the NOx formation mechanisms for the combustion of a fuel. Generally, NOx formation during combustion of a fuel occurs through thermal NOx, prompt NOx and fuel NOx. However, for hydrogen fuel, NOx formation would be due to thermal NOx and fuel NOx (if the fuel contains nitrogen impurity) only since prompt NOx is absent due to the non-availability of carbon in the fuel.[35]

If the reference aeroengine with hydrogen fuel is available, the 'NOx – *generic*' method[26] described in

Table 3. Parameters and performance of the sustainable engine cycle versus those for a conventional engine producing the same net thrust.

Engine characteristics	Sustainable engine cycle (1)	GE-90-85B (2)	% Change = ((1) − (2))/(2)
Net thrust (kN)	77.87	77.87	0.00
Specific thrust (m/s)	130.00	133.00	−2.26
sfc (g/kN-s)	4.42	17.50	−74.74
Bypass ratio	13.00	8.28	57.00
OPR	20.00	43.89	−54.43
FPR	1.56	1.76	−11.36
Inlet mass flow (kg/s)	599.00	585.51	2.30
Thermal efficiency	0.5932	0.4141	43.25
Propulsive efficiency	0.7910	0.7879	0.39
Overall efficiency	0.4691	0.3263	43.76
COT (K)	1652.70	1652.70	0.00
Total Cooling air system (%)	9.42	14.00	−32.71
Blade temperature (K)	1037.38	1115.42	−7.00
NOx severity index	0.8169	0.8110	0.73
EINOx (g/kg)	29.15	28.95	0.72
EICO (g/kg)	0	0.3527	−100
$EICO_2$ (g/kg)	0	3155.45	−100
EIHC (g/kg)	0	0.19	−100

OPR: overall pressure ratio; FPR: fan pressure ratio; COT: combustor outlet temperature; NOx: nitrogen oxide; EINOx: NOx emission index; EICO: emission index of carbon monoxide; $EICO_2$: emission index of carbon dioxide; EIHC: emission index of hydrocarbons.

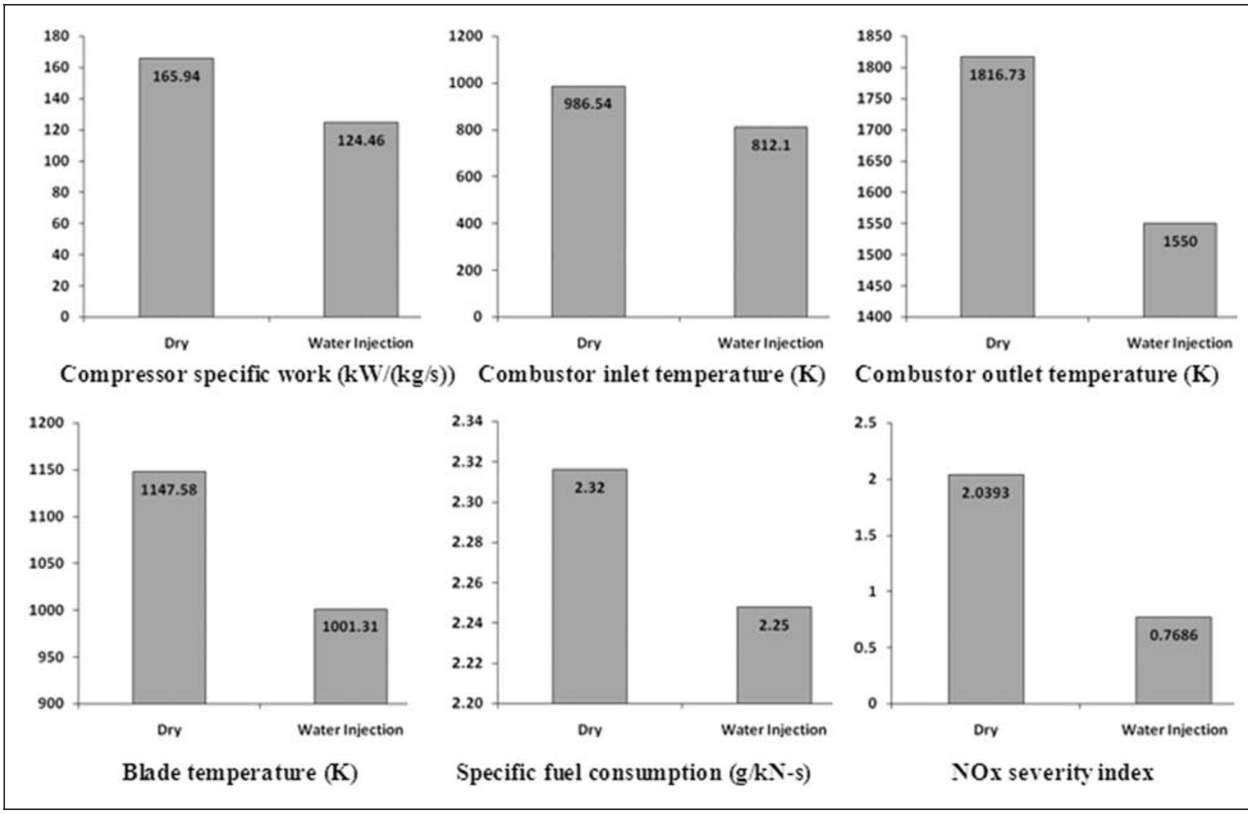

Figure 6. Effects of water injection at take-off for the sustainable turbofan engine (*war* = 0.081 estimated using GasTurb based on IP compressor temperature rise during dry operation).
NOx: nitrogen oxide.

section 'A new prediction tool for NOx emission' can be used to predict the EINOx value of the sustainable engine accurately. It is so since the constants of equation (1), C_1 and C_2 (can be estimated using data from ICAO[27]), would capture the trend of EINOx variation from the combustor for various phases.

The conservative EINOx estimate for the sustainable turbofan concept is very slightly higher than that of GE-90-85B (Table 3). It is to be noted here that the combustor of hydrogen-fuelled ICRCTF engine is assumed to be same as that of a conventional engine. However the combustor for LH_2 fuel could be significantly redesigned to reduce NOx emissions. Studies[19,20] predict about 80% reduction in NOx if the combustor is redesigned. This reduction is possible from lean burn techniques, improved fuel–air mixing and reduced residence time in the combustor. If this 80% reduction is applied in the present study, the final value of EINOx comes out to be 5.87 g/kg, which is substantially lower than that of the conventional engine.

The emission indices of carbon monoxide (EICO) and hydro-carbon (EIHC) for GE-90-85B are calculated using the Boeing fuel flow method[36] for CO and HC, respectively. These values are shown in Table 3. The emission index of carbon dioxide ($EICO_2$) is calculated accurately by using the relation[37]

$$\mathrm{EICO_2} = \mathrm{EICO}_{2,ideal} - \frac{44}{28} \cdot \mathrm{EICO} \quad (7)$$

where $\mathrm{EICO}_{2,\mathrm{ideal}} = 3156$ g/kg for a jet fuel and, 44 and 28 are respective molar masses of CO_2 and CO. EICO in equation (7) is calculated by the Boeing fuel flow method. Equation (7) has been used to determine the $EICO_2$ of GE-90-85B; this value is shown in Table 3. The sustainable turbofan engine does not emit CO_2, CO or HC.

Engine characteristics at take-off and climb-out

As discussed in section 'Development of sustainable turbofan concept', water is injected only during the two critical modes of LTO cycle; take-off and climb-out. The benefit of this technology is very much apparent from the take-off and climb-out results, which are shown in Figures 6 and 7, respectively and in Table 4. It is observed here that the water injection significantly reduces the COT at take-off and climb-out (making them even lower than the value at cruise). According

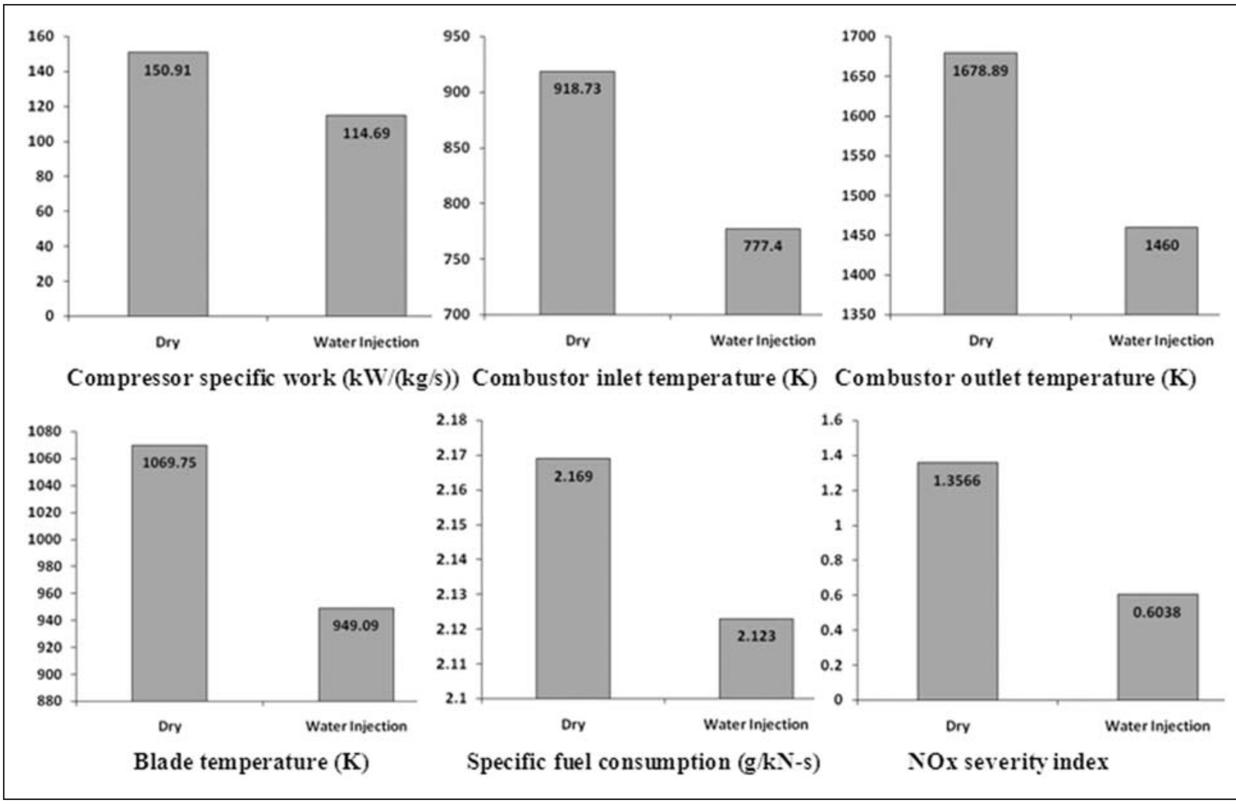

Figure 7. Effects of water injection at climb-out for the sustainable turbofan engine (*war* = 0.074 estimated using GasTurb based on IP compressor temperature rise during dry operation).
NOx: nitrogen oxide.

Table 4. Effect of water injection in ICRCTF during take-off and climb-out phases of LTO cycle.

	Take-off			Climb-out		
Engine characteristics	Dry (GasTurb)	Wet (EES)	% Change = (Wet−Dry)/Dry	Dry (GasTurb)	Wet (EES)	% Change = (Wet−Dry)/Dry
Compressor specific work kW/(kg/s)	165.94	124.46	−25.00	150.91	114.69	−24.00
Combustor inlet temperature (K)	986.54	812.10	−17.68	918.73	777.40	−15.38
COT (K)	1816.73	1550.00	−14.68	1678.89	1460.00	−13.04
Blade temperature (K)	1147.58	1001.31	−12.75	1069.75	949.09	−11.28
sfc (g/kN-s)	2.32	2.25	−2.94	2.17	2.12	−2.12
NOx severity index	2.0393	0.7686	−62.31	1.3566	0.6038	−55.49

EES: Engineering Equation Solver; COT: combustor outlet temperature; NOx: nitrogen oxide.

to Daggett et al.,[22] take-off consumes about 36% of the HP turbine life in a conventional engine. Due to the water injection into the compressor of the turbofan concept, the blade temperature of HP turbine reduces by 146.27 °C for take-off and by 120.66 °C for climb-out. Therefore, there would be a great improvement in the life of the HP turbine. In addition, less advanced cooling technology can be used since the COT is reduced considerably. Similarly, due to water injection, the NOx severity index reduces by 62.31% at take-off and by 55.49% at climb-out.

LTO NOx

The primary objective of using water injection is to reduce the LTO cycle NOx emissions. In order to

Table 5. LTO cycle NOx emissions (water injection during take-off and climb-out in ICRCTF engine resulted in surpassing of ACARE 2020 goals for LTO cycle NOx emissions).

Sustainable engine concept (LTO cycle)	D_p/F_{oo}	D_p/F_{oo} – ACARE 2020 goals
ICRCTF-Dry	25.09	15.06
ICRCTF-Water injection	13.49	15.06

LTO: landing and take-off; NOx: nitrogen oxide; ICRCTF: intercooled recuperated turbofan; ACARE: Advisory Council for Aeronautics Research in Europe.

achieve the ACARE 2020 goals, LTO NOx emissions from an aircraft engine must be reduced to the level defined by CAEP2 – 80%.[4] LTO cycle NOx emissions are calculated by

$$\left(\frac{D_p}{F_{oo}}\right)_{\mathrm{NO}x} = \sum \left(\frac{\mathrm{EINO}x \cdot W_f \cdot \mathrm{TIM}}{F_{n,to}}\right) \tag{8}$$

where D_p is the mass of NOx emitted during the LTO cycle (g), F_{oo} is the rated output of the engine (kN), EINOx is the NOx emission index (g/kg), W_f is the fuel flow rate (kg/s), TIM is the time in mode (s), and $F_{n,to}$ is the take-off thrust (kN).

EINOx (required for calculating D_p/F_{oo} of ICRCTF engine) is to be estimated using the 'NOx – *generic*' method (see sections 'A new prediction tool for NOx emission' and 'Engine characteristics at the design point (cruise)'). The time in each mode of the LTO cycle is the standard value used by industry; the time for take-off, climb-out, approach and idle are 0.7 min, 2.2 min, 4 min and 26 min respectively.

The ACARE 2020 goals, corresponding to the take-off overall pressure ratio of 20.04 that is used for the sustainable turbofan engine, show that the D_p/F_{oo} has to be limited to 15.06. However, the D_p/F_{oo} value for ICRCTF dry (no water injection) is 25.09. But, with water injection, it can be reduced to 13.49, which surpasses the ACARE 2020 goals for NOx emissions (Table 5). Further reduction in LTO NOx, by 80% or so, would be possible if the combustion chamber is redesigned for LH_2 fuel.[19,20]

Conclusions

A sustainable thermodynamic cycle – an intercooled recuperated turbofan with Liquid hydrogen fuel and water injection during take-off and climb-out – is developed and analyzed, which eliminates the CO_2, CO and HC emissions completely and surpasses the demanding ACARE 2020 goals for LTO cycle NOx emission.

Following Guha,[5] an optimization scheme is devised for the sustainable turbofan concept to minimize the fuel consumption. The optimization results shown in Figure 4 represent the possible design space of an aero-engine based on the sustainable turbofan cycle developed here, the four specific thrusts chosen representing broadly the past, present, near-future and distant-future. A comparison (Table 3) for the design point (cruise) of the engine (derived from the optimization study) with an existing conventional engine with the same thrust capacity shows a significant improvement (43.76%) in overall efficiency, a large increase in the engine life due to the reduction in blade temperature by about 78 °C during cruise (the longest phase of a mission), and simplification in turbo-machinery components due to the lower overall pressure ratio. The water injection during take-off and climb-out reduces the NOx emission and increases the life of the HP turbine. In contrast with the conventional engines, the take-off and climb-out no longer remain the critical phases of the flight in terms of the combustor outlet temperature (Table 4).

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

1. Bruntland G. Report of the world commission on environment and development: our common future. World Commission on Environment and Development A/42/427, Geneva, Switzerland.
2. Metz B, Davidson OR, Bosch PR, et al. *Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge; New York: Cambridge University Press, 2007.
3. Global warming forecasts. http://www.global-warming-forecasts.com/2050-climate-change-global-warming-2050.php (accessed 18 April 2011).
4. ACARE. European aeronautics: a vision for 2020. Report of the Group of Personalities, European Commission, 2001.
5. Guha A. Optimisation of aero gas turbine engines. *Aeronaut J* 2001; 105(1049): 345–358.
6. Cumpsty NA. Preparing for the future: reducing gas turbine environmental impact-IGTI scholar lecture. *ASME J Turbomach* 2010; 132: 041017-1–041017-17-.

7. Bock S, Horn W and Sieber J. "Active core" – a key technology for more environmentally friendly aero engines being investigated under the NEWAC program. In: *26th congress of International Council of the Aeronautical Sciences including the 8th AIAA aviation technology, integration, and operations (ATIO) conference*, ICAS 2008-4.2.1, Anchorage, Alaska, USA, 2008.
8. Parker R and Lathoud M. Green aero-engines: technology to mitigate aviation impact on environment. *Proc IMechE, Part C: J Mechanical Engineering Science* 2010; 224(3): 529–538.
9. Wilfert G, Kriegl B, Wald L, et al. CLEAN - Validation of a GTF high speed turbine and integration of heat exchanger technology in an environmental friendly engine concept. In: *17th ISABE*, Munich, Germany, 2005.
10. Korsia J and Spiegeler G. VITAL, An European R&D program for greener aero-engines. In: *25th congress of International Council of the Aeronautical Sciences*, ICAS 2006-5.6.1, Hamburg, Germany, 2006.
11. Walsh PP and Fletcher P. *Gas turbine performance*. 2nd ed. Blackwell: Oxford, 2004.
12. Boggia S and Rüd K. Intercooled recuperated aero engine. In: *Programme Deutscher Luft- und Raumfahrtkongress*, Dresden, Germany, 20–23 September 2004, DGLR-Paper 2004-179.
13. Plohr M, Lecht M, Otten T, et al. Aero-engine technology to cope with ACARE goals. In: *25th congress of International Council of the Aeronautical Sciences*, ICAS 2006-5.4.5, Hamburg, Germany, 2006.
14. Haglind F, Hasselrot A and Singh R. Potential of reducing the environmental impact of aviation by using hydrogen Part III: Optimum cruising altitude and airport implications. *Aeronaut J* 2006; 110(1110): 553–565.
15. Haglind F, Hasselrot A and Singh R. Potential of reducing the environmental impact of aviation by using hydrogen Part II: Aero gas turbine design. *Aeronaut J* 2006; 110(1110): 541–552.
16. Haglind F, Hasselrot A and Singh R. Potential of reducing the environmental impact of aviation by using hydrogen Part I: Background, prospects and challenges. *Aeronaut J* 2006; 110(1110): 533–540.
17. Corchero G and Montanes JL. An approach to the use of hydrogen for commercial aircraft engines. *Proc IMechE, Part G: J Aerospace Engineering* 2005; 219(1): 35–43.
18. Haglind F and Singh R. Design of aero gas turbines using hydrogen. *ASME - J Eng Gas Turb Power* 2006; 128: 754–764.
19. Dahl G and Suttrop F. Engine control and low NOx combustion for hydrogen fuelled aircraft gas turbines. *Int J Hydrogen Energy* 1998; 23(8): 695–704.
20. Cryoplane. Liquid hydrogen fuelled aircraft – system analysis. Airbus Deutschland GmbH, and Airbus partners in Europe. Project funded by the European Community under the 'Competitive and Sustainable Growth' Programme (1998-2002), 2003.
21. Lundin BT. Theoretical analysis of various thrust augmentation cycles for turbojet engines. Report 981, NACA TN 2083, 1950.
22. Daggett DL, Ortanderl S, Eames D, et al. Revisiting water injection for commercial aircraft. SAE International, 2004-01-3108, 2004.
23. Balepin V and Ossello C. NOx emission reduction in commercial jets through water injection. NASA/TM-2002-211978, AIAA-2002-3623, 2002.
24. Daggett DL. Water misting and injection of commercial aircraft engines to reduce airport NOx. NASA/CR-2004-212957, 2004.
25. Daggett DL, Hendricks RC, Mahashabde A, et al. Water injection - Could it reduce airplane maintenance costs and airport emissions? NASA/TM-2007-213652, ISABE-2005-1249, 2007.
26. Chandrasekaran N and Guha A. Study of prediction methods for NOx emission from turbofan engines. *AIAA J Propul Power* 2012; 28(1): 170–180.
27. ICAO. ICAO aircraft engine emissions databank. 1st ed. ICAO Doc 9646-AN/943. Quebec, Canada: International Civil Aviation Organization, 1995.
28. Kurzke J. GasTurb 11 - A program to calculate design and off-design performance of gas turbines, 2007.
29. Guha A. Performance and optimisation of gas turbines with real gas effects. *Proc IMechE, Part A: J Power and Energy* 2001; 215: 507–512.
30. Guha A. Effects of internal combustion and non-perfect gas properties on the optimum performance of gas turbines. *Proc IMechE, Part C: J Mechanical Engineering Science* 2003; 217: 1085–1099.
31. Guha A. Optimum fan pressure ratio for bypass engines with separate or mixed exhaust streams. *AIAA J Propul Power* 2001; 17(5): 1117–1122.
32. Klein SA. *Engineering equation solver version 8* 2008.
33. Guha A. An efficient generic method for calculating the properties of combustion products. *Proc IMechE, Part A: J Power and Energy* 2001; 215: 375–387.
34. Meier N. Jet engine specification database, http://www.jet-engine.net/civtfspec.html (2005, accessed 17 September 2010).
35. Shudo T and Mizuide T. NOx emission characteristics in rich–lean combustion of hydrogen. *JSAE Rev* 2002; 23: 9–14.
36. DuBois D and Paynter GC. "Fuel flow method2" for estimating aircraft emissions. SAE Technical Paper Series, 2006-01-1987, 2006.
37. Eyers CJ, Addleton D, Atkinson K, et al. AERO2K Global aviation emissions inventories for 2002 and 2025. Technical Report QinetiQ/04/01113, QinetiQ, UK, 2004.
38. Greitzer EM, Slater HN, Aurora Flight Sciences, and Pratt & Whitney Team. Volume 2: Appendices - Design methodologies for aerodynamics, structures, weight, and thermodynamic cycles. Report Submitted to NASA Glenn Research Center, Cooperative Agreement Number NNX08AW63A, 2010.
39. Kyprianidis KG, Grönstedt T, Ogaji SOT, et al. Assessment of future aero-engine designs with intercooled and intercooled recuperated cores. *ASME - J Eng Gas Turb Power* 2011; 133: 011701-1–011701-5.
40. McDonald CF, Massardo AF, Rodgers C, et al. Recuperated gas turbine aeroengines. Part III: Engine

concepts for reduced emissions, lower fuel consumption, and noise abatement. *Aircraft Eng Aerosp Technol Int J* 2008; 80(4): 408–426.
41. Corchero G, Montañés JL, Pascovici D, et al. An insight into some innovative cycles for aircraft propulsion. *Proc IMechE, Part G: J Aerospace Engineering* 2008; 222(1): 731–747.
42. Wilson J and Paxson DE. Jet engine performance enhancement through use of a wave-rotor topping cycle. NASA TM-4486, 1993.
43. Verstraete D. *The potential of liquid hydrogen for long range aircraft propulsion*. PhD Thesis, Cranfield University, 2009.
44. Guha A, Boylan D and Gallagher P. Determination of optimum specific thrust for civil aero gas turbine engines: a multidisciplinary design synthesis and optimisation. *Proc IMechE, Part G: J Aerospace Engineering*. Epub ahead of print 14 March 2012. DOI: 10.1177/0954410011435623.

Appendix 1

Notation

B	bypass ratio
c_p	specific heat (J/kg-K)
D_p	mass of NOx emitted during the LTO cycle (g)
F_{Nt}	net thrust (kN)
F_n	specific thrust (m/s)
F_{oo}	rated output of the engine (kN)
h_{fg}	latent heat of vaporization (J/kg-K)
H	enthalpy (J)
$\dot{m}_{core}$	mass flow rate through the core engine (lbm/s)
Ma	Mach number
N	spool speed (r/min)
N_c	corrected spool speed (r/min)
P	pressure (Pa)
Q_{cv}	fuel heating value (J/kg)
R	specific gas constant of air (J/kg-K)
S_{NOx}	NOx severity index
sfc	specific fuel consumption (g/kN-s)
T	temperature (K)
T_{25}	intercooler exit temperature (K)
T_{35}	combustor inlet temperature (K)
T_4	burner exit temperature (K)
V_a	speed of an aircraft (m/s)
V_{jc}	fully expanded jet speed of the cold bypass stream (m/s)
V_{jh}	fully expanded jet speed of the hot core stream (m/s)
W	mass flow rate (kg/s)
W_{21}	mass flow rate at intercooler inlet (kg/s)
W_e	bare engine weight (lb)
W_{cl}	mass flow rate of coolant (kg/s)
ε	effectiveness of an intercooler
η_{cool}	cooling effectiveness on blade due to bleed air
η_f	isentropic efficiency of the fan
η_{KE}	efficiency of energy transfer between the core and bypass flow
η_{LPT}	isentropic efficiency of the low pressure turbine
η_{th}	thermal efficiency
η_p	propulsive efficiency
η_o	overall efficiency
γ	isentropic index of air
θ_{eff}	effective temperature of the fluid passing through the compressor

Subscripts

a	air
amb	ambient air
b	blade
f	fuel
g	gas
op	optimum
to	take-off

Appendix 2

Estimation of the impact of heat exchangers of the sustainable ICRCTF engine (weight and drag) on aircraft performance

In Greitzer et al.,[38] a correlation for estimating the weight for conventional turbofan engines (using operating parameters at sea level static conditions like OPR, B, core mass flow) has been derived by regression analysis on various engines whose operating parameters are available in the open literature.

Weight of conventional engine[38] is given by

$$W_e(\text{lb}) = a\left(\frac{\dot{m}_{core}}{100\text{lbm/s}}\right)^b \left(\frac{OPR}{40}\right)^c \tag{9}$$

For the current technology level (late 1990 through mid 2000)

$$a = (1.809 \times 10^1)B^2 + (4.769 \times 10^2)B + 701.3$$
$$b = (1.077 \times 10^{-3})B^2 - (3.716 \times 10^{-2})B + 1.19$$
$$c = (-1.058 \times 10^{-2})B + 0.326$$

For the future technology level (Advanced materials including carbon composites, CMC, MMC, TiAl)

$$a = (1.538 \times 10^1)B^2 + (4.011 \times 10^2)B + 631.5$$
$$b = (1.057 \times 10^{-3})B^2 - (3.693 \times 10^{-2})B + 1.171$$
$$c = (-1.022 \times 10^{-2})B + 0.232$$

Table 6. Estimated weight with current technology versus published weight.[38]

Engine	Estimated weight (1)	Published weight (2)	% Error = [(1)−(2)]/(2) × 100
GE90-85B[a]	18406	17250	6.7
V2530A5	4810	5210	−7.7
PW2037	6519	7300	−10.7
PW4462	10279	9332	10.2
PW4168	11628	11400	2.0
PW4090	16429	15585	5.4

[a]GE90-85B considered in Greitzer et al.[38] is DAC-II whereas the comparator engine considered in the present study is DAC-I.[27]

Table 6 shows the comparison of weight estimated by equation (9) with the weight published in the open literature.[38] Using equation (9), weight of the comparator engine (GE90-85B) used in the present study is estimated to be 18,110 lbs (current technology) and 15,130 lbs (advanced materials). Similarly, the weight of the sustainable turbofan engine excluding heat exchangers estimated from the above equation (using corresponding OPR, B and core mass flow) is 16,720 lbs (current technology) and 14,870 lbs (advanced materials). In Kyprianidis et al.,[39] weight of the additional components (an intercooler, a recuperator and a gear) on geared ICRCTF entering into service in the year 2020 is estimated as 25.4% of engine dry weight. But in sustainable turbofan engine with liquid hydrogen fuel there are two intercoolers, one recuperator and no gear. Therefore it is assumed here that the weight of the gear in the geared turbofan configuration is approximately of similar magnitude as the small additional heat exchanger required to heat the liquid hydrogen to 250 K. After including the impact of heat exchangers into the sustainable turbofan engine, weight of the engine is 20,967 lbs (this value is estimated from 16,720 lbs by considering current technology for ICRCTF engine).

In McDonald et al.,[40] a breakeven analysis for adoption of heat exchanged aeroengines in place of conventional aeroengines was carried out using Brequet Range equation. For this study, a virtual reality aircraft similar to Boeing 737 powered by two turbofan engines fuelled by kerosene is considered. Moreover, aircraft flight range of 2000 miles with flight time of 4 h having same maximum fuel weight at take-off and same percentage fuel margin upon landing is assumed. This analysis was carried out for cruise as it is the longest phase of a mission.

For a particular weight ratio of heat exchanged engine to non-heat exchanged engine (with conventional fuel) approximate percentage reduction in *sfc* needed for breakeven can be found from Table 7. Heat exchanged to non-heat exchanged weight ratio in the present study is 1.16 (20,967/18,110). From Table 7, it is estimated that breakeven of heat exchanged engine with 1.16 weight ratio is at least 3.6% *sfc* reduction. By taking the technical advancement in the near future into consideration further 15% reduction needs to be added. It implies that for breakeven of heat exchanged engines at least 18.6% reduction in *sfc* is needed.

Table 7. Breakeven analysis *sfc*/engine weight for heat exchanged turbofan (values extracted from the graph of McDonald et al.[40]).

Sl. No	Heat Exchanged/ Non-heat exchanged weight ratio	Approximate % reduction in *sfc* needed
1	1.0	0.0
2	1.1	2.2
3	1.2	4.6
4	1.3	6.9
5	1.4	9.2
6	1.5	11.6
7	1.6	13.8

As the ICRCTF engine proposed here is with liquid hydrogen fuel, *sfc* could not be directly compared with a conventional non-heat exchanged engine. Therefore, the sustainable engine in the present study is modeled in GasTurb with conventional fuel for the fair estimation of breakeven. *sfc* of sustainable ICRCTF with conventional fuel is 12.19 g/(kN-s) whereas the *sfc* of comparator non-heat exchanged engine in the present study (GE90-85B) is 17.5 g/(kN-s) which shows ~30% *sfc* reduction (which is greater than the estimated minimum requirement of 18.6% mentioned in the previous paragraph). This comparison clarifies the potential benefits of heat exchanged turbofans as aeroengines.

Also, in Plohr et al.,[13] a detailed analysis of intercooled recuperated aeroengines, in addition to ultra high bypass ratio engines, was performed to evaluate the capabilities of the engines in meeting ACARE2020 goals. In this study, the analysis was carried out for the entire mission with the current technology level by including various critical parameters like engine weight and drag. According to this study, potential *sfc* benefit of ~16% was estimated for the aircraft mounted with intercooled recuperated turbofan engine. Similar detailed study was also performed by Corchero et al.[41] with intercooled recuperated aeroengines (in addition to the other engine concepts) by including engine weight and drag. According to this study, all the benefits of intercooled recuperated engine would be nullified if the heat exchangers are not efficient. Minimum regenerative efficiency required for the heat exchangers to get the *sfc* benefit on the intercooled recuperated engine is 70%.[41] An alternate way of increasing the performance of the engine by having wave rotor as a topping cycle was explained in Wilson and Paxson.[42]

Appendix 3

Estimation of the impact of liquid hydrogen fuel system on aircraft performance

Many previous studies have used hydrogen as the aviation fuel; these have been described in the main text. Hydrogen offers promises as well as challenges: all technological challenges in using hydrogen have not yet been solved. The present contribution which focuses on the thermodynamic aspects of the proposed sustainable turbofan engine should be considered in this context of conceptual evolution.

According to the study of Verstraete,[43] large long range aircraft category (similar to Airbus A340 or Boeing 777) seems to be the promising class for conversion of kerosene to hydrogen. In this study a kerosene-fuelled aircraft is compared with hydrogen-fuelled aircraft with conventional turbofan engines for the same mission. The details of aircraft and flight conditions used for comparison are: aircraft capacity – 380 passengers (with First class, Business class and Tourist class); Ma – 0.85; design range – 7500 nm; no. of decks – 1 (for kerosene); 2 – (for hydrogen). It is to be noted here that the storage of hydrogen fuel is also considered in deciding the fuselage dimensions for hydrogen-fuelled aircraft.

Guha[5] has established a methodology for choosing the engine design point based on direct operating cost (DOC), details of this method are given by Guha et al.[44] Adopting this approach, the figure of merit in Verstraete,[43] chosen for selecting the engine design point for both kerosene- and liquid-hydrogen-fuelled aircraft was DOC of the aircraft. In the study of Verstraete,[43] size and shape of the wing is optimized for each of the fuels by a parametric study with wing area and wing aspect ratio as parameters whereas in Cryoplane[20] study constant wing area was assumed for both the aircrafts. Conclusions from this study are: (1) take-off weight of hydrogen-fuelled aircraft is 25% lower than that of conventional aircraft, (2) operating empty weight increases slightly (around 3%) compared to conventional aircraft, (3) fuel weight for hydrogen-fuelled aircraft reduced approximately by 70% compared to conventional aircraft. These results are different from the conclusions of Cryoplane[20] study as the wing area used in the later study was not optimized for hydrogen fuel.

The main take away from the study of Verstraete[43] is that the optimum configuration for hydrogen-fuelled aircraft, which performs as competitive as the conventional aircraft can be achieved by optimizing wing area and other parameters. This conclusion might not change appreciably if the conventional engine is replaced with an unconventional engine like intercooled recuperated turbofan engine.

Appendix 4

Impact of water injection system on aircraft performance and emissions

According to a study by Daggett,[24] the maximum water-to-air (*war*) tried out in aeroengines till date, is 2.2% with the current technology level. In the same study, weight added to the aircraft due to the water injection system including the weight of water is estimated as 2865 lbs.[24] However, in the present study, water injection ahead of IP compressor at take-off and climb out greater than 2.2% is considered to meet the stringent goals of NOx emissions during LTO cycle i.e. the maximum possible *war* ratio (which is derived based on the LP compressor temperature rise in the present ICRCTF engine) of 8% for take-off and 7% for climb out are considered for the performance calculations. Though *war* used here is higher than the current technology level it would be possible to reduce the weight of the water injection system with the technological advancement and thus decrease the fuel consumption and NOx emissions. Moreover, in the years to come it would be necessary to meet the stringent LTO NOx emission goals (say ACARE) to reduce the operating cost by avoiding high penalties. It is to be noted from the LTO results of the present study that even with the usage of maximum possible *war*, ACARE 2020 goals for LTO cycle are just met which might mandate the airliners to use water injection technology in the future.

Appendix 5

Methodology to obtain the conditions of core of the ICRCTF (at Stations 21, 24, 25 and 3) in ICRCTSHFT configuration (at Stations 2, 24, 25 and 3)

The simulation of water injection in the core of an ICRCTF engine is to be carried out in the ICRCTSHFT engine. It is to be noted here that an IP compressor of an ICRCTF is equivalent to the booster of an ICRCTSHFT and the HP compressor of an ICRCTF is same as the HP compressor of an ICRCTSHFT when water injection in ICRCTF is simulated in ICRCTSHFT configuration. Prior to the simulation, the dry conditions (before water injection) of ICRCTSHFT engine from the inlet of booster to the exit of the HP compressor have to be maintained same as that of the dry conditions of ICRCTF engine from the inlet of the IP compressor to the exit of the HP compressor.

The aforementioned conditions in ICRCTSHFT (at Stations 2, 24, 25 and 3) are achieved from GasTurb by iterating the following variables: (i) intake pressure ratio, (ii) ΔT from ISA, (iii) inlet corrected flow, (iv) booster pressure ratio, (v) isentropic booster efficiency, (vi) intercooler design pressure ratio, (vii) HP compressor pressure ratio and (viii) isentropic HP compressor efficiency to match the following values of ICRCTF engine: (i) P_{21}, (ii) T_{21}, (iii) W_{21}, (iv) P_{24}; (v) T_{24}, (vi) P_{25}, (vii) P_3, (viii) T_3, respectively.

Finally, the hot side intercooler exit temperature (T_{25}) for ICRCTSHFT engine is obtained by giving corresponding T_{25} value of ICRCTF engine as an input in the intercooler tab of ICRCTSHFT engine.

Appendix 6

Maintaining constant operating point for IP compressor and reducing HP compressor speed in GasTurb

When the water is injected at the inlet of the booster of an ICRCTSHFT (equivalent to water injection at the inlet of the IP compressor of an ICRCTF) there will be a change in operating point for booster (equivalent to IP compressor) which is not intended since the change of operating point results in an increase in thrust. The change in operating point is due to the increase in corrected speed of the booster for ICRCTSHFT (equivalent to corrected speed of IP compressor). In GasTurb, operating point of booster can be maintained same by reducing the 'low pressure spool speed' option available in the off-design input window such that the 'relative corrected booster speed' is equal to 1. Similarly HP compressor speed can be reduced by varying the 'HPC spool speed ZXN' option available in the off-design input window. It has to be reduced till the same power (ICRCTSHFT) as that of dry simulation is achieved.

Appendix 7

Reconstruction of GE-90-85B using GasTurb

All the values used here are for GE-90-85B and they are taken from the ICAO engine emissions databank[27] and from the data given by Meier.[34]

Steps to be followed to reconstruct an engine cycle for GE-90-85B are as follows.

I Take-off engine air flow – 1378 kg/s,[34] B – 8.4,[27] OPR – 38.1[27] and relative humidity – 60% (from ambient conditions and *war*[27]) are given as input in GasTurb.

II For GE-90-85B, mechanical efficiency and burner efficiency are assumed to be 100% efficient, and intake and burner pressure ratio are assumed to be 1. Since cooling airflow rates, burner part load constant, and power off-take are not known, they are fixed at the default value of GasTurb.

III In GasTurb, outer fan pressure ratio is set to iterate to reach the condition of optimum jet velocity ratio given by $(V_{jc}/V_{jh})_{op} \approx \eta_{LPT}\eta_f$.[31] Inner fan pressure ratio is assumed to be same as that of outer fan pressure ratio. The compressor pressure ratio can then be obtained from the value of OPR. Concurrently, burner exit temperature (T_4) is iterated to get W_f – 3.91 kg/s,[27] while the isentropic efficiencies (fan, compressor and turbines) are varied over sensible ranges until the computed value of thrust (i.e. the output of GasTurb simulation) reaches (F_{oo}) – 395.31 kN[27] as closely as possible.

Now the results corresponding to take-off mode can be obtained.

Similarly, results for other modes of LTO cycle of GE-90-85B can be obtained from GasTurb by giving the corresponding fuel flow values[27] as an input in the 'Limiter' option of GasTurb.