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High Power Density Work Extraction from Turbofan Exhaust Heat

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Abstract

Integration of steam and air bottoming cycles with a conventional transport category turbofan is discussed. A conceptual design of a turbofan with a steam bottoming cycle yielded a 5% efficiency improvement for realistic component performance, but the weight eliminated in principal all gain on an aircraft level. For an air bottoming cycle simplified core cycle simulations showed the potential for up to 8% efficiency improvement. A novel Exhaust Heated Bleed engine where the bottoming cycle is integrated with a conventional turbofan turbo machinery is proposed. Simulation of this engine for take-off, climb and cruise conditions shows a 3-7% efficiency benefit. A concept for an exhaust heat exchanger and a conceptual turbine design for the Bleed Turbine to convert the exhaust heat to shaft power are illustrated.

Nomenclature

ε_x	exhaust heat exchanger effectiveness
BPR	ByPass Ratio
BT	Bleed Turbine
BTPR	Bleed Turbine Pressure Ratio
DTISA	temperature over standard atmospheric conditions
EHB	Exhaust Heated Bleed engine
EOR	End-Of-Runway
H	altitude
EHEX	Exhaust Heat EXchanger
IRA	Intercooled Recuperated Aero-engine
OPR	Overall Pressure Ratio
klbf	thousands of pounds thrust
LPT	Low Pressure Turbine
M	flight Mach number
P	total pressure
SFC	Specific Fuel Consumption
T	temperature
TOC	Top-Of-Climb

Subscripts

21	booster exit
4	combustor outlet
5	low pressure turbine outlet
b	bleed
l	low pressure side of EHEX
h	high pressure side of EHEX

Introduction

The high fuel prices and environmental concern of this century has spurred a new phase of development of more fuel economic engines for transport category aircraft.

Considerable effort has gone into improving the propulsive efficiency both by optimizing the conventional configurations resulting in e.g. the GEnx and the RR TRENT XWB engines, and by innovative geared turbofans such as the PW1000G series. Further, new large scale research into high speed propeller propulsion has been initiated [1].

In order to also improve the thermal efficiency the core pressure ratios have been rising, with 60 applied to engines under development and even higher values proposed. The trend is supported by improved heat resistant materials and cooling. Although the record thermal efficiencies, on the order of 55%, are much lower than the best propulsive efficiencies, it will be very hard to reach beyond what is now on the drawing board. The complexity of a very high pressure core requires advances on a large number of technologies. Moreover, raising pressure further reduces the size of the turbomachinery airfoils, which increases tip and sealing leakage losses.

Accordingly there is a strong incentive to research other ways to improve thermal efficiency. A formal breakdown of losses by e.g. exergy methods[2], provides some guidance – and points to combustor losses and exhaust heat losses (apart from jet kinetic energy = propulsive losses). The combustor losses are associated with not using the fuels ability to burn at higher temperatures and to provide a pressure rise. Direct attack on these is difficult due to the high temperatures involved.

For exhaust heat, on the other hand, there are readily available technologies for extracting work. For stationary power plants the combined cycle uses high pressure (water) steam, whereas in transport applications thermo-electric cells and Organic Rankine Cycles are under development.

However, in stationary applications the secondary system is many times larger than the gas turbine itself. For an aircraft application, weight increases fuel consumption and there is therefore a need to radically increase the power density of the bottoming cycle.

The innovative IRA (Intercooled Recuperated Aero engine) [3,4] integrates the energy extraction into the main cycle by heating the compressor output with the exhaust gas. The integration provides advantages in terms of power density but it also requires transfer of high pressure air from the core to the exhaust end and back.

The project EVÅF was set up in 2013 to study alternatives to the IRA in the form of classical bottoming cycle solutions to work extraction from turbofan engines. The paper discusses EVÅF´s initial findings.

The recuperated turbofan

The most obvious way to modify the conventional turbofan engine to use the exergy in the exhaust is to use it to heat the compressor delivery air, thereby reducing the needed fuel flow to achieve the design turbine inlet temperature. Superficially the thermodynamic cycle is quite similar to the conventional Brayton (non-recuperated cycle) turbofan as the compressor and turbine functions may be left unchanged. The integration will obviously lead to a minor effect on the compressor and turbine pressure ratios as caused by the pressure drop in the heat exchanger. There is also some loss of thrust from the lower exhaust temperature.

However, as recuperation only can be used to raise the compressor delivery temperature towards the turbine exhaust temperature, the amount of heat that can be transferred is minimal for a modern, optimized engine. This is because modern engines have exhaust temperatures quite similar to compressor delivery temperatures. Thus, in practice, the pressure ratio should be decreased from ~40 to around half and an intercooler be inserted between the low and high pressure compressor. In a study using fixed flow paths [3], the fuel burn of an IRA was reduced by about 5% compared to a conventional turbofan, but the estimated weight and cost of the heat exchangers did not provide a reduction of operating cost.

Boggia and Rud [4] showed the improvement possible using a variable low pressure turbine, allowing the core flow and pressure to be lowered in cruise, while keeping the exhaust temperature at around 850 K. Although design parameters overall are different it can be compared with the 786K for the fixed LPT design in [3]. The high level of recuperation then possible provides for additional fuel savings at the cost of high temperature operation during cruise. The high temperature exhaust, in some cases reaching 900 K, is a particular challenge for the design of a long life minimum maintenance recuperator.

One problem with the recuperated engine is the transfer of the high pressure air from the compressor to the rear of the engine for heating and the return of the heated gas to the combustor. Any failure causing leakage in this long path, including in the heat exchangers would cause loss of thrust or possibly spin down of the engine.

The steam bottoming cycle turbofan

Searching for alternatives to the complications of recuperation two of the authors in 2012 studied steam cycles applied to aircraft propulsion. In this study (hitherto unpublished), energy recovery with a boiler – piston expander – condenser – pump engine was used to provide power from waste heat in military and transport category aircraft engines.

For a 70 klbf thrust turbofan of 2020 technology level with a cruise exhaust temperature of 656 K from which 2400 kW heat could be extracted. Based on previous experience the Rankine cycle efficiency was estimated at 25%. The resulting 610 kW shaft power provided a potential 3.5% specific fuel consumption reduction. However the steam engine added 42% to the baseline turbofan weight. Half of the weight was due to the condenser located in the turbofan bypass channel, which achieved a heat transfer of 1.5 kW/kg. The boiler which works at higher pressure was lighter and transferred 2.8 kW/kg.

When the engine performance was applied to an aircraft model and rescaling the wing and engines to allow the same payload and mission range, it was found that no gain of fuel burn could be achieved. The conclusion was that the air velocities at 40 m/s selected in the heat exchanger drove the matrix size and weight to too high values. Although it is possible that a net positive gain can be achieved by increasing the heat exchanger power density, the 3.5% efficiency increase limits the potential for the system.

The air bottoming cycle

For an aircraft engine the use of water is not ideal, due to the risk of freezing both during operation at high altitude and non-operating on the ground. However, water handling in aircraft engines has been shown to work for combustor injection for thrust augmentation in early jet engines into the 70s, but was made obsolete by the higher temperatures possible from improved materials and cooling employed in turbines.

A natural consequence of the above is the investigation of air in the low temperature cycle. Air requires significant compression work and provides lower power densities than steam and thus is more sensitive to the turbomachine flow rates and efficiency. It is possible to raise the power density by employing a high pressure closed or semi-closed cycle, but the weight of the recirculation cooler is going to be similar to the condenser for a steam cycle. While impractical for a turbofan it may be possible for smaller flow rates such as those in APUs and helicopter engines. Although using a recuperated rather than a bottoming cycle, a high pressure semi-closed cycle using recirculation cooling has been demonstrated on an APU [5].

In order to avoid the limitations of a cooler it was decided to investigate the simpler open air bottoming cycle. Apart from using exhaust heat supplied from the main core in lieu of combustion it is essentially the same as the standard Brayton gas turbine cycle. However, to match the lower heating temperature, the optimal pressure ratio is much lower, typically in the range 2-10.

The exhaust heated bleed turbofan

In a pre-study a large number of heat exchanged thermodynamic cycles were simulated on a simplified cycle level. This included conventional intercooled, recuperated and intercooled engines as well as air bottoming cycle engines. The first conclusion was that the optimum cycle pressure ratio decreases by about 20% as the air bottoming cycle is utilized. This is due to that the lower pressure ratio increases the exhaust temperature, thus leaving more energy to be recovered by the bottoming cycle. The lower pressure ratio removes some of the limitation on the engine in terms of the compressor exhaust temperature.

The second conclusion was that the fuel consumption was reduced by an amount increasing with turbine inlet temperature, reaching an 8% advantage at 2000 K turbine inlet temperature, while the compressor outlet temperature was limited to 1000 K. Moreover, for typical temperature limitations the efficiency was higher than for an intercooled recuperated cycle. It should be stressed that due to the simplifications in these early studies, they are not estimates of what can be achieved in actual engines.

With the main cycle limited by the turbine temperature at 1800 K, the optimal pressure ratio for the air bottoming cycle was found to be of the order 4.

The requirement for a second thermodynamic process to provide the air bottoming cycle is a complexity disadvantage relative to a conventional recuperated engine.

However, a practical configuration was found in which the bottoming cycle function was integrated in a turbofan by using the low pressure compressor to provide the bottoming cycle air flow. Part of the flow is bled into an annular duct inside the fan bypass duct. This flow is ducted to the rear of the engine where it is heat exchanged with the exhaust. The heated flow is expanded in a turbine and exhausted in parallel with the turbine exhaust. Figure 1 describes the basic features of the Exhaust Heated Bleed (EHB) engine.

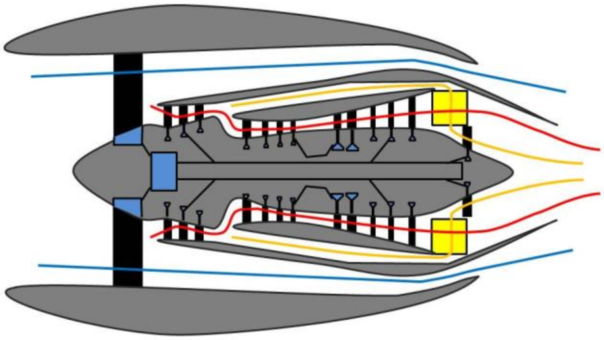

Figure 1. Conceptual cross section for an Exhaust Heated Bleed (EHB) turbofan, with the EHEX behind the LPT and the bleed turbine (BT) inside the EHEX. Blue: fan bypass flow, red: core flow, yellow: bleed flow.

A further refinement is to expand the heated bleed flow in the low pressure turbine driving the fan, see figure 2. Here a cross flow heat exchanger has been used to provide the heated bleed flow to the inner part of the turbine. The lower temperature is an advantage both mechanically and aerodynamically as the tangential Mach number for the blade is increased.

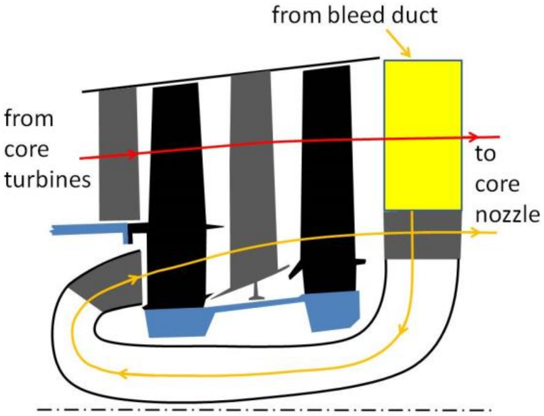

Figure 2. Confluent bleed turbine. Black: turbine blades, grey: stators, blue: low pressure spool, yellow: exhaust heat exchanger.

The integration of the air bottoming cycle with the main gas turbine, while reducing the part count, makes the bleed reheat engine more sensitive to failures of the heat exchanger. While even a large leakage of the exhaust exchanger cannot cause spin down of the core, the power provided to the fan will be significantly reduced. The reduction stems both from the reduced pressure delivered by the booster, when its operating line drops, and by the loss of bleed flow fed to the turbine.

Detailed studies of effects of failures have not been carried out, but the fact that the heat exchanger is not integrated in the high pressure flow path in the manner of recuperated engines should decrease the impact of failures.

Exhaust heat exchanger

The main challenge when introducing a bottoming cycle for a flying application is the weight of the heat exchangers. While the power density for an aircraft engine core gas turbine is over 25 kW/kg, steam boilers and condensers heat exchangers in ground based applications are many times larger and heavier than the engine.

As an example of a high efficiency gas turbine recuperator, Solar uses 0.1 mm 347SS stainless corrugated steel sheet in the MERCURY 50 primary surface recuperator with an effectiveness of 92% [6].

Based on the available data the authors estimated that the heat transfer density of this is 5-10 kW/kg. This number is quite impressive and has been demonstrated in field use for a stationary application. In an aircraft engine it is likely that the material thickness needs to be higher due to the:

- higher levels of vibration
- higher aerodynamic forces due to higher Mach numbers

- possibly higher and variable cycle temperatures increasing corrosion and low cycle fatigue.

In a cycle level study of heat exchanged aircraft engines [3] circular tubes with 3.5 mm inner diameter and a rather conservative 0.35 mm thickness for the nickel alloy tubes was assumed. In that study, a recuperator optimized to minimize aircraft operating cost weighed 29% of the engine, which had a significant effect on the aircraft fuel burn. The same study found that the cost optimized recuperator had only 56% effectiveness, but for the current higher fuel prices the optimal value would increase to about 65-70%.

In the current project a microtube Exhaust Heat EXchanger (EHEX) developed by RANOTOR AB is studied. The exchanger concept was originally developed as a steam (flash) boiler, and was used in the steam bottoming cycle discussed above. The heat exchanger leads the denser medium (steam or compressed air) in conical tube stacks, while the less dense medium (combustor or turbine exhaust gas) travels in the conical volume between the tube stacks, see figure 3.

The stacks are spirally wound of tubes about 1 mm in inner diameter. The wall thickness has in high pressure (25 MPa) steam applications been 0.5 mm. The small diameter yields high temperature gradients in the flow which allows a high heat transfer coefficient, while the laminar flow reduces flow losses. Somewhat larger diameters and/or reduced wall thickness should be possible at the lower pressures in the EHB and reduce the EHEX weight.

The flow direction in the spiral is arranged so that the multiple pass cross flow heat exchanger achieves close to the same efficiency as a counter flow heat exchanger.

Small turbine dimensions pose additional challenges for blockage. The inlet to bleed system must be located to avoid this. In any case the bleed extraction after the booster compressor is one of the best possible to exclude ingested debris from the flow path.

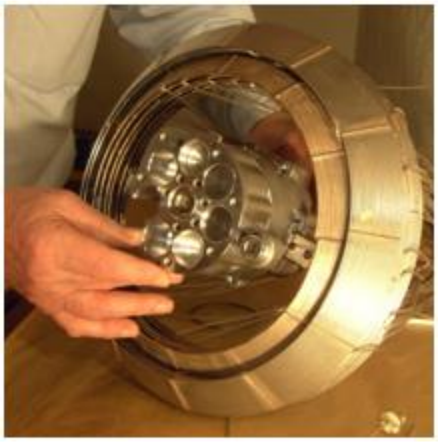

Figure 3. Ranotor heat exchanger configuration. (The piston engine in the center of the picture is not part of the current project.)

Bleed turbine

To generate work from the heated bleed flow, it is expanded through a Bleed Turbine (BT), providing additional power to the fan shaft. This flow will typically have a relatively low pressure and temperature.

In addition to providing high efficiency, the most critical requirement is to fit both the core flow and the bleed flow in a reasonable diameter inside the bypass flow, see figure 1. As seen from figure 2, the confluent path turbine also requires the bleed flow to flow outside and the reversed bleed flow on the inside through the same cross section.

The high pressure turbine exit pressure will typically be significantly higher than that of the bleed flow, requiring this flow path to have a larger number of stages than the bleed flow (not shown in figure 2)

Due to the complications mentioned above, in the initial studies presented here, the turbine was assumed to be separate, i.e. not confluent.

Engine performance

Based on previous experience a reference turbofan in the 70 klbf thrust class of 2025 technology level was designed and optimized for low fuel consumption in the Chalmers performance tool GESTPAN [7]. Thrust requirements corresponding to a 250 passenger medium range aircraft were estimated at End-Of-Runway, Top-Of-Climb and Cruise.

The key features of this engine are high component efficiencies and pressure ratio, a large fan driven by a gearbox giving a low fuel consumption. This allows for a reasonably fair estimate of the benefit of a future Exhaust Heated Bleed engine. Key parameters for the reference engine at the three operating points are listed in table 1.

Table 1. Performance requirements and key data for the reference turbofan engine.

Parameter	EOR	TOC	Cruise
M	0.25	0.82	0.82
H(m)	0	10668	10668
DTISA (K)	15	10	0
Thrust (kN)	248	67.3	51.1
T_4 (K)	1950	1767	1585
OPR	53.2	68.2	55.9
BPR	12.6	11.3	12.6
Inlet mass flow (kg/s)	1289	554	529
Specific thrust(m/s)	192	122	97
SFC (mg/Ns)	9.66	14.48	14.19

In a similar way the EHB engine was modeled in the GESTPAN tool.

The sizing of the heat exchanger is determined by the bleed bypass ratio BPR_b, the design heat exchanger effectiveness ε_x and the target pressure drops for the bleed (high pressure) $\Delta P_h/P_{21}$ and turbine exhaust (low pressure) side $\Delta P_l/P_5$.

To minimize the fuel consumption a high value of ε_x and BPR_b as well low pressure drops are needed. However, as shown for recuperators in [3] each of these goals will increase the weight of the EHEX, driving aircraft drag and the installed fuel burn. As the heat exchanger design is not yet completed the first designs was calculated based on that a 300 K temperature rise for the bleed was assumed at take-off, and the pressure losses set to 7% on each side. Based on an initial parameter study the bleed bypass ratio was set to unity. The variation of ε_x for other operating points was calculated using the GESTPAN standard heat exchanger correlations.

The fan pressure ratio was set to the same value as for the reference engine at take-off and the booster and high pressure compressor were set to minimize the specific fuel consumption at cruise while satisfying the thrust requirements and temperature design constraint. The main parameters for this engine are shown in table 2.

Table 2. Performance requirements and key data for the reference turbofan engine.

Parameter	EOR	TOC	Cruise
M	0.25	0.82	0.82
H(m)	0	10668	10668
DTISA (K)	15	10	0
Thrust (kN)	248	67.3	51.1
T_4 (K)	1950	1767	1585
T_5 (K)	841	710	635
OPR	51.8	65.4	53.9
BPR	14.4	13.4	14.8
Inlet mass flow (kg/s)	1334	581	554
BPR_b	1.00	1.05	1.09
$\Delta P_h/P_{21}$	0.07	0.07	0.07
$\Delta P_l/P_5$	0.07	0.07	0.07
ε_x	0.82	0.77	0.73
Specific thrust(m/s)	186	116	92
SFC (mg/Ns)	9.04	13.78	13.67
SFC vs ref.	-6.4%	-4.8%	-3.7%

The bypass ratio (BPR) above is calculated as the ratio of flow entering the high pressure compressor to that going into the bypass and bleed ducts. The increase compared to the reference engine shows the reduction of high pressure core size made possible by the extra power provided by the bleed turbine.

The mass flow of the EHB is slightly higher than for the corresponding data for the reference turbofan. This is believed to be an artifact of setting the FPR at Take Off to the same value as the reference engine. Resizing the fan to that of the reference is estimated to cost about 1% on the fuel consumption. However, as the fan pressure ratio has not been optimized it may be possible to eliminate some of this.

Bleed turbine configuration

Two BT designs were generated to directly drive on the same shaft as the low pressure turbine, which powers the booster and via a 3 to 1 planetary gear box drives the fan. The design is made with the intention to fit this turbine radially inwards from the EHEX, which in turn covers the exit area of the LPT. As the hub diameter of the last stage of conventional LPT for a geared turbofan in the 70 klbf class is estimated at 800 mm, the flow may have to be routed diagonally outwards from the LPT to the EHEX to provide room for the BT.

Table 3. Design condition for the bleed turbine. The Cruise condition was used as the design point.

Parameter	EOR	TOC	Cruise
BTPR	3	3.72	3.65
n_{LPT} (rps)	116	119	109
Mass flow (kg/s)	87.8	42.4	38.5
Inlet pressure (kPa)	393	175	149
Inlet temp (K)	595	647	414

The geared turbine section is based on either a high radius single-stage or a lower radii twin-stage design, as seen in table 4. The single stage offers a simple lightweight solution that has to be fitted under the last turbine stage (figure 4). The lower-radii twin-stage design is shown in figure 5.

Table 4. Aerodynamic design data for the bleed turbine. The Cruise condition was used as the design point.

	Twin-stage	Single-stage
Loading coefficient	1.0/1.5	1.15
Flow coefficient	0.68/0.52	0.72
Blade speed (m/s)	243/273	341
Max tip radius (m)	0.399	0.497

The very high Mach number levels for the single-stage, renders the usage of conventional design loss models questionable. Instead, the design was analyzed with course CFD. The results indicates that the single-stage design is far from optimum with e.g. relative super-sonic speeds into the rotor.

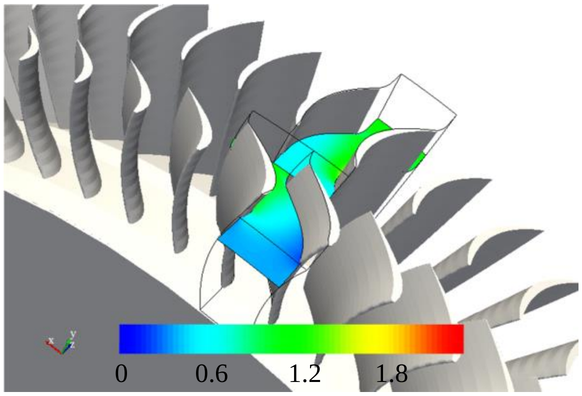

Figure 4. The single stage turbine illustrating high relative Mach numbers.

The twin-stage design indicated sub-sonic relative Mach numbers over the entire blade spans. The height of the first stage is controlled by the actual blade heights whilst the second is arbitrarily set according to the figure. The selected radii for the first stage is maximized limited by the minimum loading of unity in order to provide space for discs. This would also be an advantage to fit the bleed duct inside for a confluent turbine.

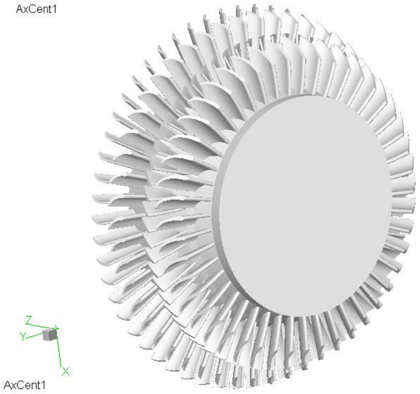

Figure 5. The two-stage turbine viewed from the inlet side.

Discussion

The initial studies of an exhaust heated bleed engine shows encouraging results.

The potential for increase of efficiency is significant even when comparing to an advanced ultra high bypass and pressure ratio engine. The 8% efficiency advantage observed in initial experiments of turbo shaft cycles was reduced to 3-7% for a turbofan. This could be a result of the reduced thrust from cooling the core turbine exhaust, requiring a higher pressure in the core nozzle to achieve the desired exhaust velocity.

The reduction of specific fuel consumption would give 4-5% reduction of fuel burn for a short range aircraft before the weight penalty is considered. For a long range aircraft the saving would be similar, since although it would spend longer time at cruise where the saving is less, it should be possible to scale down the aircraft more due to the reduced fuel weight.

The reduction of the optimal pressure ratio is about 5% compared to the reference engine. This is driven by the increased amount of heat available in the exhaust when the pressure ratio is reduced. Thus the combined effect of increased bypass ratio and reduced pressure ratio means that the corrected high pressure compressor outlet flow will be similar to the reference. Thus, in contrast to an optimized intercooled engine the last stage will not suffer from a reduced blade height causing increased tip leakage and reduced efficiency.

It can be noted that the temperature may allow the turbine to be at least partially manufactured in titanium which would help limit its weight, although the take-off inlet temperature at 501°C is somewhat above design temperatures for standard titanium (450°C).

Previous experience of the IRA [3] makes it probable that a tube exhaust heat exchanger with effectiveness of 73-82% will add 30% or more to the engine weight. This clearly poses a risk that the EHB will not provide a net installed fuel burn improvement. Typically it is estimated that 10% on engine weight costs 1% on fuel burn. The proposed heat exchanger design and lighter construction compatible with the relatively modest temperatures and pressures may allow the weight to be reduced relative to recuperators for an IRA.

One of the concerns of heat exchanged engines is its sensitivity to blockage and leakage. The exhaust bleed engine has a significant advantage here as the heat exchanger is not present in the path from the fan to the LPT. Thus in principle an EHB should be able to provide thrust even after failure of the EHEX. The 100-200 K lower heat exchanger temperature compared to the IRA especially in cruise should also allow for a durable design.

Conclusions

The application of steam and air bottoming cycles to transport turbofans was discussed.

It was shown that 5-8% efficiency gain may be possible, but that practical configurations will suffer from the increased weight of these engine configurations. As for the intercooled and recuperated engines, the remaining gain must be judged against first cost and operating costs.

The integration of the air bottoming cycle with the turbofan leading to the Exhaust Heated Bleed engine looks promising from a configuration standpoint. The resulting engine is significantly simpler than the intercooled recuperated engine and even avoids the diversion of the main core flow typically required in intercooled turbofans.

The EHB also yields core compressor and turbine sizes close to conventional future engines, which shows that conventional turbomachinery designs can be employed. A further advantage is that it is less sensitive to leakage and is therefore expected to more easily be able to adhere to the current high flight safety level.

Significant work remains in the EVÅF project including the adaption and optimization of the heat exchanger concept for the calculated operating conditions. This work should also provide a better estimate of the effectiveness and pressure losses, as well as a weight estimate. Life estimates relative the selection and thickness of the tube material is of interest.

The engine geometrical configuration will be developed for the heat exchanger and for the separate and confluent exhaust bleed turbines.

A comparative analysis of leakage and blockage effects for the recuperated, intercooled and EHB engines may provide further insight.

A system optimization calculating the installed fuel burn over a flight mission including the effect of the engine weight will provide a more reliable indication of preferred design parameters and also an indication of the overall viability of the concept.

Acknowledgements

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