Design and Analysis of an Intercooled Turbofan Engine

Lei Xu
e-mail: lei@chalmers.se

Tomas Grönstedt[1]
e-mail: tomas.gronstedt@chalmers.se

Department of Applied Mechanics,
Division of Fluid Dynamics,
Chalmers University of Technology,
Gothenburg 41296, Sweden

The performance of an intercooled turbofan engine is analyzed by multidisciplinary optimization. A model for making preliminary simplified analysis of the mechanical design of the engine is coupled to an aircraft model and an engine performance model. A conventional turbofan engine with technology representative for a year 2013 entry of service is compared with a corresponding intercooled engine. A mission fuel burn reduction of 3.4% is observed. The results are analyzed in terms of the relevant constraints such as compressor exit temperature, turbine entry temperature, turbine rotor blade temperature, and compressor exit blade height. It is shown that the gas path of an intercooled engine for medium range commercial transport applications, having an overall pressure ratio greater than 70 in top of climb, may still be optimized to fulfill a compressor exit blade height constraint. This indicates that a state of the art high pressure compressor efficiency can be achieved. Empirical data and a parametric computational fluid dynamics (CFD) study are used to verify the intercooler heat transfer and pressure loss characteristics.
[DOI: 10.1115/1.4000857]

1 Introduction

A range of questions must be addressed to establish a high performance engine-intercooler system. Apart from selecting optimal cycle parameters, the intercooler flow configuration has to be defined. In the process, conflicting requirements on pressure losses, heat transfer, and weight have to be met. In particular, the high overall pressure ratio (OPR) cycles resulting when optimizing intercooled engines may require a novel approach for optimizing gas paths. A common tradition for one stage high pressure turbine (HPT) turbofans has been to tilt the combustor radially in order to create a variation between the high pressure compressor (HPC) exit hub radius and the HPT entry hub radius. This has allowed an HPC with a pressure ratio greater than 10.0 to be driven by a single stage HPT. In this work, the radially tilted combustor design approach is explored in conjuntion with a two stage HPT and a three spool engine architecture to allow full optimization of the intercooled engine cycle.

2 Intercooler Design and Modeling

2.1 Intercooler Engine Integration. Several design considerations of the aeroengine-intercooler relate to its external flow conditions. The intercooler is mounted inside the bypass channel, as illustrated in the upper half in Fig. 1. The diffuser of the intercooler splits the bypass flow into an internal bypass flow and an external bypass flow. The static pressure on the up- and downsides of the diffuser trailing edge must match each other. Thus, the larger the pressure loss is on the internal flow side, the smaller the flow speed and the mass flow rate will become. Here, we introduce the intercooler bypass ratio Φ as the ratio of the mass flow on the external side of the diffuser to the mass flow on the internal side. A 1% external pressure loss over the heat exchanger may lead to a Φ of 1.0, whereas a 10% pressure loss may lead to a Φ in the range of 10.0–20.0, depending on other design parameters. Thus, care must be taken to avoid excessive pressure losses on the intercooler external side, and thus, to guarantee that enough air passes through the internal bypass channel.

2.2 Intercooler Analysis. At the start of the design process, several common heat exchanger surface types were considered such as fin plate surfaces, tube fin surfaces, and tubular surfaces. A tubular heat exchanger was selected in this study since it was expected to suffer less from the problem of thermal stresses. Two tubular configurations have been analyzed. The analysis of the initial configuration has been presented in Ref. [1].

One problem identified during the evaluation of the initial configuration was the large pressure losses occurring on the external surfaces. From the test results of Kays and London [2], it can be seen that the staggered tube bank used for the initial configuration has a larger friction factor than most other configurations. Combined with a relatively high flow speed in the bypass channel, this configuration generates high pressure losses on its external surfaces. As mentioned in Sec. 2.1, this will greatly reduce the amount of air passing over the external intercooler surface, and hence, limit the heat exchange. To improve the design and resolve some of the problems mentioned above, a refined configuration was conceived. First, the tube shape is changed from the circular cross section to an elliptic one. Due to the streamlined shape, the total drag force on the elliptic tubes is greatly reduced compared with tubes with circular cross section. As explained earlier, this will allow more air to pass through the internal bypass channel for heat exchange. A second advantage of the elliptic tubes is the larger wetted surface it has compared with the round tubes having the same cross-sectional area. Additionally, the elliptic shape reduces vortex shedding tremendously. This alleviates problems associated with flow induced vibrations, which could be a serious problem in real applications. Also, the overall arrangement of the refined configurations is more regular in its shape, which enables a more accurate assessment of the performance using CFD tools. The refined configuration features a standard shape multi pass overall counterflow heat exchanger. Considerably more useful validation information could therefore be found in the literature. Details of the design configuration can be found in Ref. [3].

2.3 Intercooler Performance Modeling. Before the impact of the intercooler on the engine and the flight mission can be studied, a model based on correlations is created to predict the pressure loss and heat transfer of the flow through the intercooler. This model is then incorporated into the engine system evaluation tool GESTPAN [4].

Correlation based methods exist that relatively accurately model the internal side performance. The selected methods have been described previously in Ref. [1]. In contrast to the internal side, no correlation or test data with the suitable range of Reynolds number for the external side could be found in open literature. To have a reasonably accurate assessment, a CFD study was carried out to evaluate the pressure loss and heat transfer.

The commercial softwares ICEM-CFD and CFX are used to generate the mesh and compute the flow on the external side of the heat exchanger. Preliminary computations show that the flow pattern does not change much after passing through three to four tube rows; hence, five tube rows are meshed. The whole domain consisted of about 700,000 hexagonal cells, and the mesh was concentrated around the tubes to resolve the boundary layers. The

[1]Corresponding author.

Contributed by the Aircraft Engine Committee of ASME for publication in the Journal of Engineering for Gas Turbines and Power. Manuscript received: June 22, 2009; final manuscript revised: November 4, 2009; published online August 10, 2010. Editor: Dilip R. Ballal.

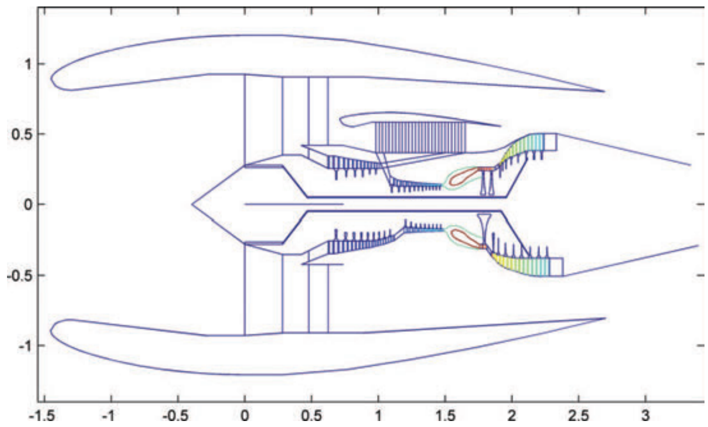

Fig. 1 Cross sectional drawings of optimal engines

SST $k-\omega$ turbulence model was used in the computation since it is generally believed that it can predict the separation better than the $k\epsilon$ model. The resulting friction factor f and Colburn J-factor $StPr^{2/3}$ are given in Table 1. The friction factor f is calculated from the equation

$$\Delta P = \frac{(\rho V_{max})^2 v_i}{2}\left[(1+\tau^2)\left(\frac{v_o}{v_i}-1\right)+f\frac{A}{A_c}\frac{v_m}{v_i}\right] \quad (1)$$

where v_i and v_o are the fluid inlet and outlet specific volumes, v_m is the average of the above two quantities, τ is the ratio between the minimum flow cross-sectional area A_c and the heat exchanger frontal area, and A is the total heat transfer area.

3 Simulation Results and Discussion

Details about engine performance modeling have been published in previous work [4]. Preliminary design data for the intercooled and conventional turbofan engines will be given below. The aircraft model has been described in Ref. [5]. Although the aircraft design code is general and may be used to model any subsonic aircraft of conventional type, the particular Boeing 737-800 model definition analyzed in Ref. [5] is re-used here. The only difference being that the cruise phase length is shortened so that the total mission length is now 925 km.

3.1 Optimal Engines. A baseline engine for a medium range commercial transport application is established and optimized for the given mission. The engine design parameters are set up to reflect year 2013 technology. The component efficiencies and optimization constraints are given in Table 2. The blade material temperature has been selected to be representative for a fourth generation single crystal alloy. The constraint defining the compressor exit blade height is imposed to limit the deteriorating effect of high pressure compressor tip leakage. Thermal expansion during engine transients makes it very difficult to design high efficiency compressors with blade heights less than the given value. An intercooled engine is then set up, subject to the same constraints and is optimized for comparison with the conventional cycle.

3.1.1 Conventional Engine. The optimal conventional turbofan is determined by carrying out a search in fan pressure ratio (FPR), bypass ratio (BPR), and OPR, subject to the constraints imposed in Table 2. The minimum mission fuel burn was found to be 3633 kg. The optimal cycle parameters are found in Table 3.

3.1.2 Intercooled Engine. As for the conventional engine, FPR, BPR, and OPR are key optimization variables. Due to the introduction of the intercooler into the engine, additional optimization parameters are available for the designer. For example, the pressure ratio split between the intermediate pressure compressor (IPC) and HPC has a strong influence on the engine performance.

Table 1 Friction factor and J factor for elliptic tube banks

Re	$StPr^{2/3}$	f
3000.0	0.00300	0.0120
16,000.0	0.00229	0.0079
24,000.0	0.00209	0.0064
28,000.0	0.00205	0.0061
32,500.0	0.00200	0.0060
37,500.0	0.00194	0.0059
42,500.0	0.00190	0.0058
53,500.0	0.00185	0.0056

Table 2 Engine design parameters and constraints

Parameter	Value
η_{FAN}	91.0
η_{IPC}	91.0
η_{HPC}	91.5
η_{HPT}	90.0
η_{IPT}	91.0
η_{LPT}	91.5
$h_{blade\ exit,HPC}$ (m)	0.012
$T_{blade,rotor}$ (K)	1196
T_{30} (K)	900
T_{40} (K)	1850
$F_{Net,TO}$ (lbf)	27,300

Table 3 Conventional engine parameters: take-off (TO), top-of-climb (TOC), and mid-cruise (MC)

Parameter	TO	TOC	MC
OPR	37.25	47.01	43.32
BPR	11.83	11.50	11.97
FPR	1.463	1.575	1.529
π_{IPC}	5.000	5.421	5.231
π_{HPC}	5.091	5.507	5.416
G_2 (kg/s)	460.8	212.4	206.6
T_{30} (K)	900.0	798.3	779.0
T_{40} (K)	1850.0	1641.1	1580.4
SFC (mg/N s)	7.444	14.72	14.58

Table 4 Intercooled engine parameters: take-off (TO), top-of-climb (TOC), and mid-cruise (MC)

Parameter	TO	TOC	MC
OPR	57.15	71.99	66.48
BPR	12.17	11.69	12.15
FPR	1.478	1.591	1.544
π_{IPC}	3.301	3.478	3.389
π_{HPC}	11.71	13.01	12.70
G_2 (kg/s)	457.7	210.3	204.65
T_{30} (K)	900.0	796.2	776.5
T_{40} (K)	1850.0	1631.5	1573.0
SFC (mg/N s)	7.191	14.23	14.11

Table 5 Comparison of key module weight breakdowns: nacelle (Na); thrust reverser (TR)

Parameter	Conventional	Intercooled
FAN	841.56	841.58
IPC	89.86	72.15
HPC	30.19	38.42
HPT	62.59	75.51
IPT	19.20	13.85
LPT	412.23	358.47
Na+TR	906.44	909.62
IC	-	114.76
Total	2932.9	2969.3

Furthermore, the design parameters of the intercooler can also be tuned to reduce the engine fuel consumption. As was done for the conventional engine optimization, a multidimensional search is carried out to minimize the fuel burn for the given mission. The optimal engine and intercooler parameters determined here are summarized in Table 4.

The number of intercooler tubes were determined to be 5621, and the intercooler weight was estimated at 114 kg. Temperature change on the hot side was 53 K, and the inside pressure loss was 3.35%. The external pressure loss was determined to be around 5.3% before mixing. The optimal intercooler bypass ratio Φ was established to be around 17.0.

The mission fuel burn for the intercooled engine was determined to 3522 kg corresponding to a reduction of 3.1% compared with the conventional engine. Since the aircraft is considered fixed the carousel effect will here be quite limited. As described in Ref. [1], repeated mission analysis may be undertaken to take into account that the reduced fuel will allow a reduced take-off weight, which, in turn, will save additional fuel. For the relatively short mission studied here, this effect will increase the saving to 3.4%, whereas for the aircraft design range mission, this will correspond to a reduction in fuel burn equal to 4.0%.

3.1.3 Gas Paths—Optimal Engines. The gas paths of the optimal intercooled engine and the optimal conventional engine are displayed in Fig. 1. Since the optimal IPC pressure ratio for the intercooled engine is quite low, an HPC pressure ratio of 13.0 is needed in top-of–climb (TOC). This would require a considerable aerodynamic load to be taken on a single stage turbine. In conjunction with having to simultaneously meet the HPC exit blade height constraint, a single stage HPT was not found feasible. A reduced OPR engine could have been designed with a single stage HPT, but this would have incurred a fuel burn penalty, even when taking the lower weight of the single stage core into account.

One of the key features of the intercooled engine design displayed in Fig. 1 is the gas path definition. Radially tilted combustors are typical for single stage HPT designs, allowing high turbine blade speeds and still limiting the rotational speed. Simplified turbine stress and aerodynamic analysis can be used to show (see, for instance, Ref. [6]), that

$$\sigma_{\text{blade root}} \propto N^2 \quad (2)$$

$$\Delta h \propto U^2 \quad (3)$$

where $\sigma_{\text{blade root}}$ is the centrifugal stress in the turbine blade root and Δh is the enthalpy drop over a turbine stage. From these relations, it is clear that a radially tilted combustor may allow an increase in turbine power without compromising centrifugal root stresses. The other element that has to be considered to establish the suggested engine gas path definition is to realize that it is necessary to locate the HPC entrance as close to the low pressure shaft as possible. This will maximize the blade height for a given area.

3.1.4 Weight Assessment. The weights of the key modules of the two engines described above are summarized in Table 5. The total weight of the two powerplants is quite similar but a considerable variation between the different modules can be noted. The top-of-climb pressure ratio distribution of the IPC and HPC of the conventional engine is 5.4 and 5.5, respectively, whereas for the intercooled engine, the corresponding numbers are 3.5 and 13.0. This leads to a relatively larger proportion of weight distributed on the HPC for the intercooled engine. The intercooler also reduces the power requirement of the HPC, which, in turn, reduces the weight penalty that normally would arise from the considerable pressure ratio of the HPC. The major weight benefits of the intercooled engine stem from the fact that the overall pressure ratio is much higher, making the turbines more compact. This is illustrated through the comparative cross-sectional drawing, i.e., Fig. 1. This has the effect that the two stage HPT of the intercooled engine is only slightly heavier than the one stage HPT of the conventional engine. The weight benefits of compression become less marked for the intermediate pressure turbine (IPT), and the effect is further reduced for the low pressure turbine (LPT).

3.2 Parametric Studies and Analysis of the Search Space. To analyze the optimal solution obtained, a number of parametric variations have been carried out. The FPR/BPR search space is illustrated in Fig. 2. The circular marker represent the optimal SFC point and the white curves represent iso curves for SFC. The SFC optimum is, as expected, located at higher BPR and lower FPR than the point of optimal fuel burn. The black lines represent the weight of a single engine, including both nacelle and thrust reverser. The somewhat noisy region running across the search space, indicated by the dashed line, originates from a jump in the number of stages in the LPT (eight stages above the line and seven stages below). The noise arises due to truncation error in the rapidly changing region of the stage jump. The colors and the color bar indicate mission fuel burn. The location of the optimum, which is the square marker, is thus the design point, where a seven stage LPT is sufficient and an optimal combination of FPR and BPR is selected.

4 Conclusions

A fuel burn benefit of 3.4% was observed from introducing an intercooler into a turbofan engine. A large part of the fuel saving had been lost by meeting the HPC exit blade height restriction if the engine gas path would not have been re-optimized. The CFD analysis has increased the confidence in the pressure loss and heat transfer models used to predict the intercooler performance, as well as in its aerodynamic design. Engine weight for the conventional and the intercooled engines were predicted to be quite similar, despite the considerable differences in OPR. Module weight breakdown support the idea that weight penalty added by the increased OPR and the added intercooler is to a large extent cancelled by the increased power density of the intercooler cycle. The intercooler concept stands out as one of the more promising ways of increasing the efficiency of the turbofan engine, and is expected

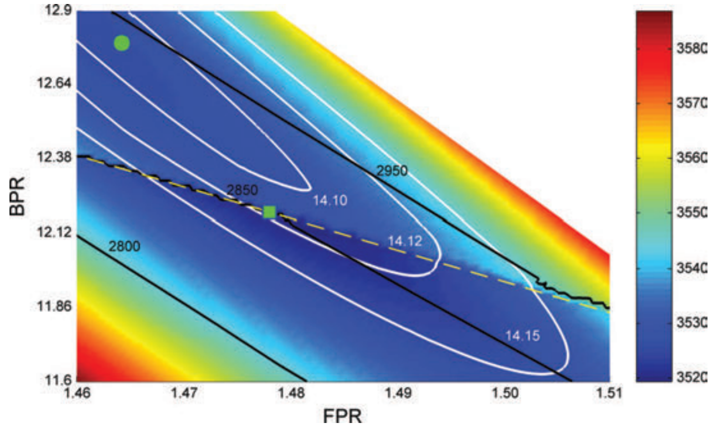

Fig. 2 Fuel burn variation in FPR/BPR search space for intercooled engine. OPR optimal. Black lines are iso curves for engine weight and white lines are for SFC.

to be a leading candidate among the more radical concepts being considered to provide a way forward toward greener air transport.

Acknowledgment

This study has been performed under the European Commission Contract No. AIP5-CT-2006-030876. The authors gratefully acknowledge this funding. The authors also acknowledge the valuable discussions provided by Anders Lundbladh at Volvo Aero. We also acknowledge the general discussions on intercooling provided by Andrew Rolt at Rolls-Royce.

References

[1] Xu, L., Gustafsson, B., and Grönstedt, T., 2007, "Mission Optimization of an Intercooled Engine," Paper No. ISABE-1157.

[2] Kays, W. M., and London, A. L., 1964, *Compact Heat Exchanger*, 2nd ed., McGraw-Hill, New York.

[3] Xu, L., 2008, "Innovative Core Concepts for Future Aero Engines,"Licentiate thesis, Chalmers University of Technology, Gothenburg, Sweden.

[4] Grönstedt, T., 2001, "Development of Methods for Analysis and Optimization of Complex Jet Engine Systems," Ph.D. thesis, Division of Thermo and Fluid Dynamics, Chalmers University of Technology, Gothenburg, Sweden.

[5] Avellan, R., and Grönstedt, T., 2007, "Preliminary Design of Subsonic Transport Aircraft/Engines," Paper No. ISABE-1195.

[6] Saravanamuttoo, H. I. H., Rogers, G. F. C., Cohen, G. F. C., and Straznicky, P. V., 2008, *Gas Turbine Theory*, Prentice-Hall, Englewood Cliffs, NJ.

UTC-2022.004