Feasible optimum design of a turbocompound Diesel Brayton cycle for diesel-turbo-fan aircraft propulsion

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ABSTRACT

This paper is conceived to optimize the design of the thermodynamic cycle of a turbine (Brayton cycle) that uses a modern common rail diesel engine as an "active" combustion chamber.
In this case the "active" combustion chamber produces the mechanical energy that drives the fan. The incoming air is compressed by the compressor, then is cooled (aftercooler) and inputted in the diesel engine. A high pressure common rail system optimizes the combustion in the diesel combustion chamber and the expansion begins inside the diesel engine. At the exhaust of the combustion chamber a turbine completes the expansion of the hot gases. A nozzle accelerates the exhaust from the turbine to increase the overall thrust. The mechanical energy from the diesel and from the turbine engizes the compressor and the fan. The system can be seen as a turbocharged diesel engine with the turbocharger that outputs energy to the turbofan, increasing the output power and or the efficiency. A diesel-turbine compound can be realized in this way.
The coupling of the two system may be obtained in several different ways. The simplest is to put on the same shaft the compressor, the diesel crankshaft and the turbine. In front of the compressor a speed reducer drives the fan.
A second example is to connect the turbine and the diesel on to electric generators. Electric engines are connected to the compressor and to the fan. The traditional turbo-diesel has the compressor coupled to the turbine, and the diesel engine that moves the fan. In this latter case, however, the turbine does not energize the fan.
Many other hybrid and non hybrid solution are possible. The problem is to optimize temperatures, pressures and rpm to the different machines that form the compound. The availability of many experimental data for diesel and turbines makes it possible to obtain a design of a "true" feasible optimum Diesel-Brayton cycle. The high efficiency justifies the huge manufacturing and development costs of these turbocompound engines.

1. INTRODUCTION

The increasing speculation on combustion prices has revived technical solutions that where abandoned due to costs and reliability.
The advantage of combined cycles is the increase in thermodynamic efficiency. This solution was abandoned in the aircraft market with the supremacy of turbofan, turboshaft and turbojet engines.
The price of combined cycles is the increase of weight and cost and reduced reliability.
Also the overall dimension of the system may make the turbocompound installation impractical.
The best and more efficient piston engine available is the diesel common rail engine. This engine has huge efficiency (more than 50%), very high combustion temperature and pressure (up to 2800 K and 30 MPa) and the high specific power (due to high combustion speed). It is now possible to run diesel engines up to 10,000 rpm.
The modern diesel engine has already a turbocharger that also improves high altitude performances.
However this turbocharger usually does not output mechanical energy. Some cases of electric generators coupled to turbocharger are available (Cartepillar, Octo…), but they are conceived more to increase diesel performance than to obtain a true hybrid solution.
On the other side the off-the-shelf reliable diesel engine has several temperature limitation. The intake air should be cooled down to 323 K (50°C) to improve volumetric efficiency and the exhaust should not exceed 1323 K (1050°C) due to head design and cooling.
Turbines have also limitations. The maximum turbine temperature is about 1950 K (1677°C) with a more common value of 1700 K (1427°C). Intake pressure and velocity fields should be very constant and close to the optimum since turbines are essentially steady state machines.
Compressor may reach very high value (up to 65:1 or more), however a practical limit is about 46:1 in order to avoid an enormous increase in dimension and weight.
This paper is organized with these following steps:

- A brief introduction to Brayton cycle limitations and choices.
- A description of a state of the art turbofan.
- A description of a state of the art common rail diesel engine.
- A paragraph about the combination of the diesel and the turbine and the individuation of the optimization parameters.
- An optimum diesel-brayton cycle and its efficiency.

2. A BRIEF INTRODUCTION TO BRAYTON CYCLE LIMITATIONS AND CHOICES

The turbofan engine cycle can be easily split into main parts:

1. The core or primary cycle done by the primary flux which begins at the intake (outside air conditions) and ends at the exhaust nozzle (after the low pressure turbine). This cycle is the energizer, since it outputs all the power needed for the fan. This cycle also outputs a limited thrust.
2. The secondary cycle that compresses the bypass flux that generates the remaining thrust.

With this simplification various variables to enhance the performances of the engine cycle can be considered.
The simplest model of the gas turbine is the parametric study of the cycle using constant gas properties.
So the possibility to increase the burner exit temperature can be considered, with the option of constant and variable pressure ratio. Anyway, as an example, by limiting the pressure ratio at 40, the potential increment regarding the thermal efficiency is not so good with a EGT (Exhaust Gas Temperature) over 2000 K [1][2].

Exhaust gas from fossil fuels, like kerosene (Jp4, Jp8, jet A1..) or Diesel, that use air as oxidizer, has approximately the same gas constant of dry air. Therefore it may be acceptable to consider compressor and turbine gas constants equal to the one of dry air, but their isotropic exponents are not constant and change significantly with the temperature.

Normally the thermal efficiency is defined as

$$\eta_{\text{th}} = \frac{H_T - H_C}{H_B}$$

where H_T is the specific turbine shaft power
H_C is the specific compressor shaft power-level
H_B is the amount of energy given by the burner to the cycle

It is possible to use another definition:

$$\eta_{\text{th}} = \frac{H_T - H_C}{W_F \cdot \text{FHV}}$$

where W_F means the fuel flow
FHV the lower calorific value (LCV)

the result is that there is an optimum of thermal efficiency at temperatures below the stoichiometric limit.

So the maximum thermal efficiency is found with fuel-air ratios about the 50% of the stoichiometric value [2].

To make the calculation more accurate it must be considered the quantity of cooling air needed by the turbine and the losses related to it. So, once this quantity is found, the cycle shows that the equivalence ratio at the optimum thermal efficiency is 60%, 10% higher than the un-cooled cycle [2].

3. THE THERMODYNAMIC CYCLE OF A STATE OF THE ART LOW-BYPASS TURBOFAN @ 15360 M ISA+0

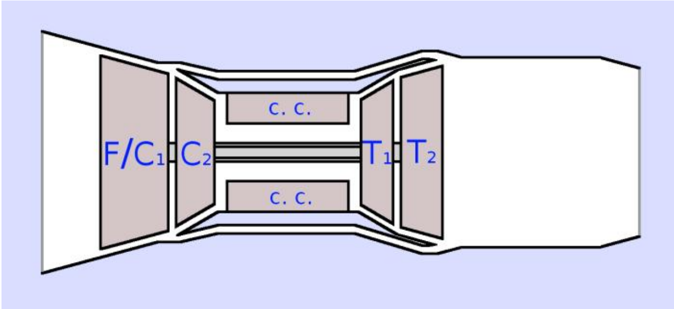

Figure 1 - Scheme of a typical turbofan engine

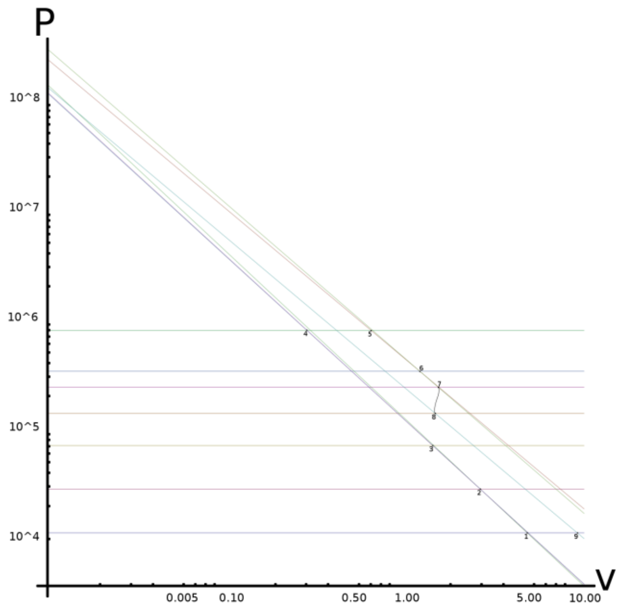

Figure 2 – pressure (**p**) [Pa], specific volume (**V**)[m^3/kg] log-log diagram of a very high performance military turbofan engine

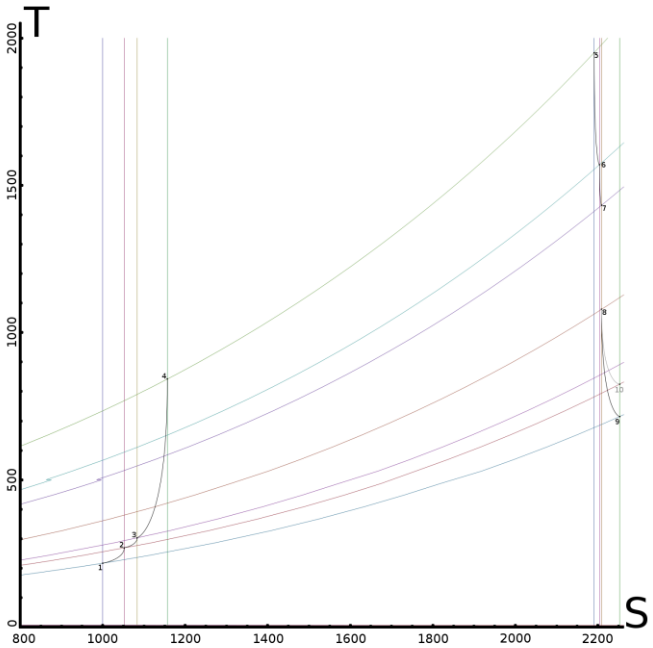

Figure 3 Temperature **T** [K], Entrophy **S** diagram of a very high performance military turbofan engine

pressure at intake (ISA +0)@ 15360 m	[Pa]	p1	11380
temperature at intake (ISA+0)@ 15360 m	[K]	T1	216.65
pressure after the intake duct	[Pa]	p2	28449.7
temperature after the intake duct	[K]	T2	293.1
pressure after low pressure compressor	[Pa]	p3	71124.2
temperature after low pressure compressor	[K]	T3	391.3
efficiency of low pressure compressor	[-]	etacompbp	0.88
work of low pressure compressor x kg of dry air	[J]	Lcompbp	99194.2
pressure after high pressure compressor	[Pa]	p4	796591
temperature after high pressure compressor	[K]	T4	842
efficiency of high pressure compressor	[-]	etacompap	0.88
work of high pressure compressor x kg of dry air	[J]	Lcompap	490182
temperature after the burner (EGT) [K]	[K]	T5	1950
efficiency of high pressure turbine	[-]	etaturbap	0.96
temperature after high pressure turbine	[K]	T6	1569.91
pressure after high pressure turbine	[Pa]	p6	337780
work of high pressure compressor x kg of dry air	[J]	Lturbap	490180
efficiency of low pressure turbine	[-]	etaturbbp	0.96
pressure after low pressure turbine	[Pa]	T7	1431.9
pressure after low pressure turbine	[Pa]	p7	242114
work of high low compressor x kg of dry air	[J]	Lturbbp	99204.3
efficiency of nozzle	[-]	etaugello	0.95
Temperature of mix bypass air and low press turbine exhaust	[K]	T8	793.7
Temperature of mix bypass air and low press turbine exhaust	[Pa]	p8	139.2
Temperature exit nozzle	[K]	T9	418.5
Overall cycle efficiency	[-]	etathr	0.42

Table 1: data of military low-bypass turbofan engine @ 15360 m ISA+0

The thermodynamic cycle and the data of a state-of-art military low-bypass turbofan without aftercooler are summarized in table 1 and fig. 1, 2 and 3.

3.1 A description of the state of the art common rail diesel engine cycle

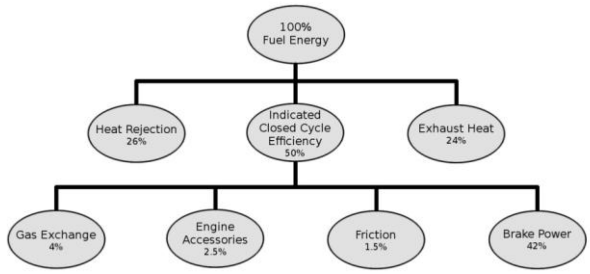

Figure 4: Energy audit for a typical diesel engine
[Source: Adapted from Vinod, Duggal, Cummins, Inc., " Industrial Perspectives of the 21st Century Truck Partnership" presentation to the Committee, Dearborn, Mich., 6 April 2009, Slide 14 (and TIAX 2009, p 4-3, Table 4-1)]

Contemporary piston aircraft engines

The German experience

In Germany, the Anglo German DAIR (Diesel Air GMBH), has proposed a new four-cylinder two-stroke diesel derived from the construction scheme of the Junkers Jumo 207 pre WWII engine. This turbocharged engine has two counter rotating crankshafts connected by a gearbox that it is the weak part of the engine It has a dry weight of 90 kg and it outputs of 100 HP@2500 rpm; the fuel injection runs with by diesel (d2) or jp4 @600bar.

Another WWII Jumo derived German engine is the 2 stroke-direct-injection radial ZOCHE aero-diesel. Charge air pressure is obtained by a combination of a highly efficient mechanical blower and a turbocharger, reducing power loss at altitude. The quadruple flow compressor is integral to the monoblock intercooler, resulting in a very high efficiency of the turbocharger and intercooler installation. The intake manifold is an integral part of the crankcase casting. The fuel injection pump together with its feed pump, the fuel filter and all connecting plumbing are integrated into the crankcase assembly, further reducing the parts count and improving reliability. This WWII engine had crack problems in the basement that seems to have been solved in the modern Zoche.

The Thielert Company has developed a certified aeronautical diesel engine derived from the four-cylinder Common Rail Mercedes, 1689 cc, which equipped the Mercedes A 170 CDI (W168) until 2005. From this modern common rail turbo-diesel 4-stroke engine, Thielert has extrapolated two aircraft engines: the 110TAE 110HP@3675rpm and the most powerful TAE125, with125HP @3,800rpm.

Another Mercedes derivative is manufactured by the AustroEngine company. The A300 with 168HP@3, 880 rpm is a direct derivation of the Mercedes A 200CDI (W169) in production until 2012.

Both Thielert and AustroEngine use a PSRU (Propeller Speed Reducer Unit) with integrated damper.

The french production: the SR 305

In April 2001 the SMA (from RenaultSport and Socata), finally obtained the European type certification (JAA), for the SR 305, boxer 4-cylinder 4-stroke direct-injection turbocharged, engine that outputs 230 horsepower at 2,200 rpm, with direct coupling of the propeller to the crankshaft.

The Nasa GAP project

In April 1997 NMA and Teledyne Continental Motors (TCM) signed a cooperation agreement for the development of a next generation two-stroke turbocharged diesel engine that can facilitate a relaunch of the American General Aviation thanks its advanced (and ambitious) features: fuel consumption reduced by 25 percent compared to a conventional engine, a reduction to half of the purchase price, an increase in revision times of 75 percent and a very low level of the exhaust emissions.

The program, called GAP (General Aviation Propulsion), received special funding from government agencies and membership of major aviation companies such as Cirrus and Lancair, for the study of new cells of aircraft specifically designed for the engine, and Hartzell, for the realization of a special three-bladed propeller with high efficiency and extremely silent.

The engine, which has a displacement of 3.9 liters and develops 200 HP at 2,200 rpm with a 18:1compression ratio , is provided with a brand new monoblock which includes heads, cylinders and main bearings of the crankshaft, and is liquid cooled.

The Italian production - Dieseljet

The CRF (Centro Ricerche Fiat) has developed a common rail diesel engines for aeronautical use. It is a derivative of the Fiat 1.9 JTD-8V that outputs 165HP@3800 rpm.

A PSRU (Propeller Speed Reducer Unit) with integrated damper is used.

Table 2 summarizes the current state of the research on aeronautical Diesel:

Typology	No. of cylinders and configuration	Displacement and type of cycle	Power @ crankshaft speed [HP @ rpm]	Weight [kg]	Weight / Power ratio [kg / HP]	Cooling system
Continental CSD 283	4 Boxer	4,700 2S	200@2,200	136	0.68	liquid
Delta Hawke	4 V (90°)	3,300 2S	200@2,700	123	0.61	liquid
Lycoming TDIO - 360	4 Boxer	5,900 4S	205@2,700	136	0.67	air
Morane Renault MR 200	4 Boxer	5,000 4S	200@2,000	144	0.72	air
Zoche ZO 01A	4 Radial	2,660 4S	150@2,500	84	0.56	air
DAIR 100	4 Opposite	1,800 4S	100@2,500	90	0.8	liquid
Thielert TAE 125	4 in line	1,680 4S	125@3,800	118	0.7	liquid
Austro Engine A300	4 in line	2,000 4S	168hp@3,880	185	0.9	liquid
Dieseljet 1,9 JTD	4 in line	1,900 4S	165@3,800	175	0.9	liquid

Table 2: a few available aero-diesels

3.2 The combination of the diesel and the turbine and the individuation of the optimization parameters

Traditional supercharged diesel engines

The supercharged diesel engine usually use a compressor, driven mechanically by a turbine, who compress the air that is supplied to the piston engine. This configuration improves the power output because the compressor uses the energy available from exhaust gases.

The overall efficiency of this cycle is determined by the inlet turbine temperature and the compressor pressure ratio. The results are depicted in fig. 5 and 6. However the increase of the turbine inlet temperature increases the overall efficiency.

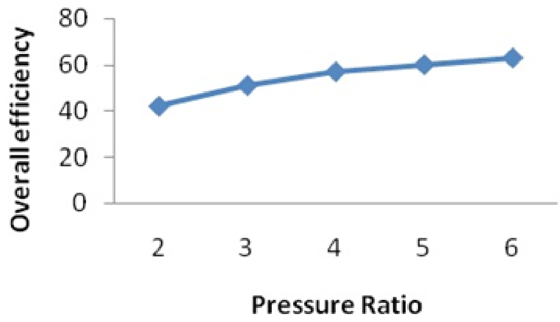

Figure 5: turbodiesel efficiency with compressor pressure ratio

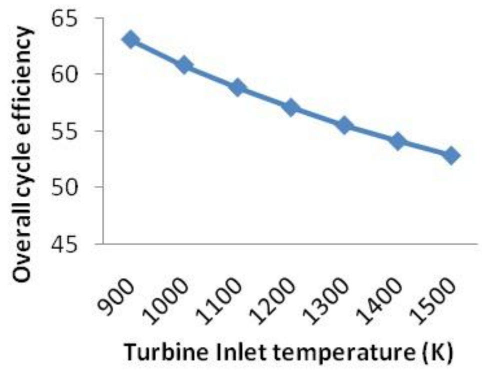

Figure 6: turbodiesel efficienc with exhaust temperature

3.3 The optimum Diesel-Brayton turbocompound fan cycle and its efficiency (figure 7)

It is possible to calculate the optimum turbocompound fan cycle efficiency by assuming very few basic data summarized in table 7.

These are:

maximum allowable diesel chamber pressure	280	[bar]
maximum allowable diesel chamber temperature	2800	[K]
compressor efficiency	0.88	[-]
piston compressor efficency	0. 8	[-]
piston expansion efficiency	0.9	[-]
turbine efficiency	0.96	[-]

Table 7: basic assumptions of turbocompound cycle

The method of [4][5][6] can be adopted for the diesel cycle. The only variable is then the compressor compression ratio.

The optimum was found to be 18.4:1, that requires a multi-stage axial compressor.

The results are summarized in table 8.

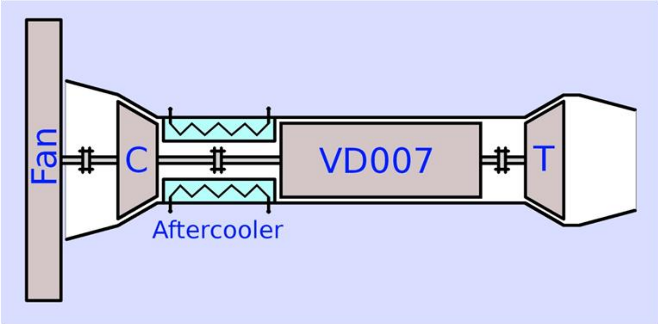

Figure 7 - Scheme of the Diesel-Brayton turbocompound engine

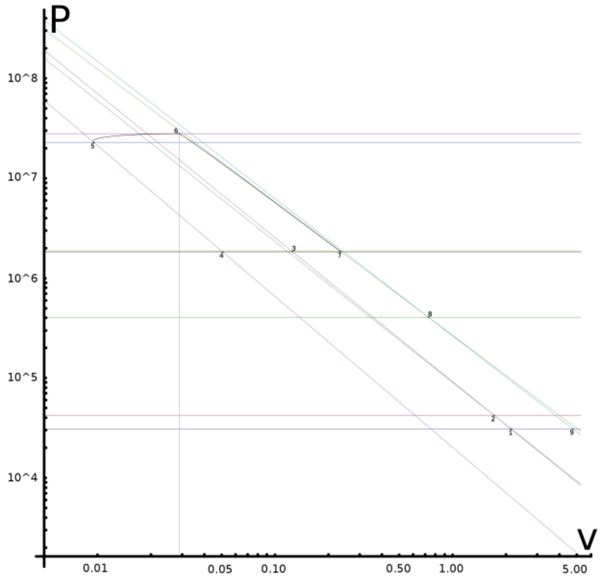

Figure8: pressure (**p**) [Pa], specific volume (**V**)[m^3/kg] log-log diagram of the turbocompound engine

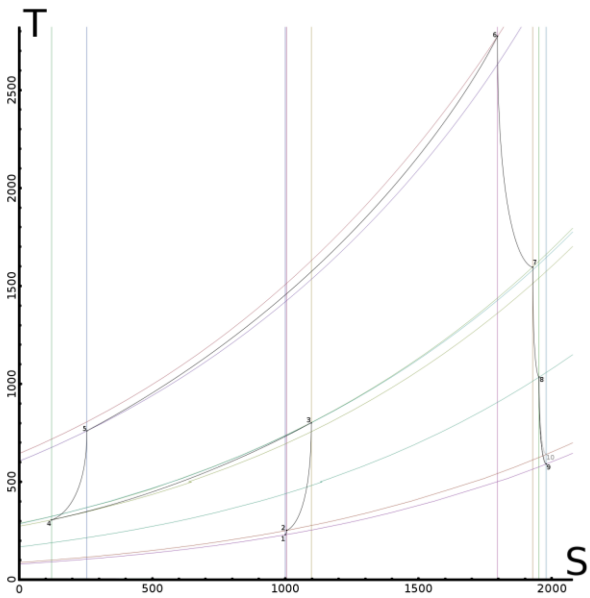

Figure 9 Temperature/Entropy diagram of the turbocompound engine

pressure at intake (ISA+0)	[Pa]	p1	30742.5
temperature at intake (ISA +0)	[K]	T1	229.65
pressure after intake duct	[Pa]	p2	42253.6
temperature after intake duct	[K]	T2	251.944
pressure after compressor	[Pa]	p3	1.84211*10^6
temperature after compressor	[K]	T3	802.6
efficiency compressor	[-]	etacomp	0.88
work compressor x kg dry air	[J]	Lcomp	585964
pressure after aftercooler	[Pa]	p4	1.83211*10^6
temperature after aftercooler	[K]	T4	323.15
pressure after piston compression (combustion begins)	[Pa]	p5	2.29013*10^7
temperature after piston compression (combustion begins)	[K]	T5	759.8
piston compression efficiency	[-]	etapist	0.80
work piston compression x kg dry air	[J]	Lpist	467203
peak combustion pressure	[Pa]	p6	28000000
peak combustion temperature	[K]	T6	2773.15
pressure at turbine inlet	[Pa]	p7	1.85211*10^6
piston expansion efficiency	[-]	etacil	0.90
work piston expansion x kg dry air	[J]	Lcil	1.64819*10^6
temperature at turbine inlet	[Pa]	T7	1511.67
efficiency turbine	[-]	etaturb	0.96
pressure after turbine	[Pa]	p8	405900
work turbine x kg dry air	[J]	Lturb	585914
efficiency nozzle	[-]	etaugello	0.95
temperature at nozzle exit	[K]	T9	511.5
diesel cycle efficiency		[-]etadiesel	0.47
compound cycle efficiency	[-]	etacomp	0.70

Table 8: the optimum turbocompound results

4 CONCLUSIONS

A diesel turbocompound fan engine was compared with a state-of-the-art turbofan.

The turbocompund diesel engine may be the best option with the actual fuel costs since theoretical efficiency up to 70% may be obtained.

Further increase in efficiency may be obtained by a “Meredith effect” cooling system both for engine and aftercooler [7].

However the turbocompound engine is quite complicated and it may require large investments in order to obtain reliability figure comparable with modern turbofans.

5. REFERENCES

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