VOL. 10, NO. 1, JANUARY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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MULTISTAGE TURBOCHARGING SYSTEMS FOR HIGH ALTITUDE FLIGHT WITH COMMON RAIL DIESEL ENGINES

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ABSTRACT

A Fiat 1.9jtd diesel engine has been extensively reviewed to output 300HP. This paper introduces a multiple stage turbocharging system that uses commercial turbocharger, taken from the catalogue of a popular manufacturer. The calculation method and the problem connected are widely discussed. Along with the problem that may arise in using these off the shelf unit. The quite heavy result advice the user to adopt ad-designed turbochargers for this task.

Keywords:

INTRODUCTION

The research in the field of engines is aimed to the design and implementation of engines with increasing power to weight ratio, with reduced costs and with the restore altitude higher possible. In this context the project of the conversion of the Direct Injection Diesel (DID) FIAT 1.9 Jtd 8V (8 Valves) is a very interesting. Thanks to the innovations made in recent years in the compression-ignition engines, the power to weight ratio of these engines has been greatly increased. This fact, together with their very good efficiency has led to a great interest for aerospace applications. For all the above factors, but particularly to enable a higher restoring altitude, it was decided to study a multistage turbocharging system.

This solution has the drawback of a greater complication and higher total mass.

In this paper we intend to proceed with the design of a supercharging system that can guarantee full power restoration even at very high altitude for HALE (High Altitude Long Endurance) UAVs (Unmanned Aerial Vehicles).

It 'should be noted that the commercial offer in this field, it is very scarce and it is largely non-compliant with fuel economy requirements for a long duration of flights.

For this reason, the system proposed in this paper, once designed and developed, may prove to be satisfactory in a field where the concurrency is nearly absent.

Evolution of the project

In this section we briefly summarize the various stages of evolution of the project to develop a DID, based on the 1900 FIAT JTD engine, capable of a power output of 300 HP.

Clearly, this development had to comply with certain constraints imposed by the type of engine choice. The engine displacement (1910 cc) and the in-line arrangement of the cylinders should be kept as well as the same cast iron crankcase of the original engine, for obvious economic reasons. This choice imposes to keep similar dimensions of the main crankshaft journal bearings and consequently a certain difficulty is to obtain consistent lightening of this organ. Fortunately maximum power output is required at high rpm so journal bearing loads due to combustion are partially reduced by inertia load.

However the use as many original components, in particular pistons and connecting rods. may lead to important economic advantages, but reduces the maximum allowed pressure the combustion chamber since the original piston resist up to a maximum 180 bar.

Initially the aim of the project was only a new design of a special steel crankshaft 300 M, able to reach the required power of 300HP at 3800 rpm. This result an be achieved by using the new bimetallic pistons can withstand a peak pressure in the combustion chamber of 240 bar (see Figure-1).

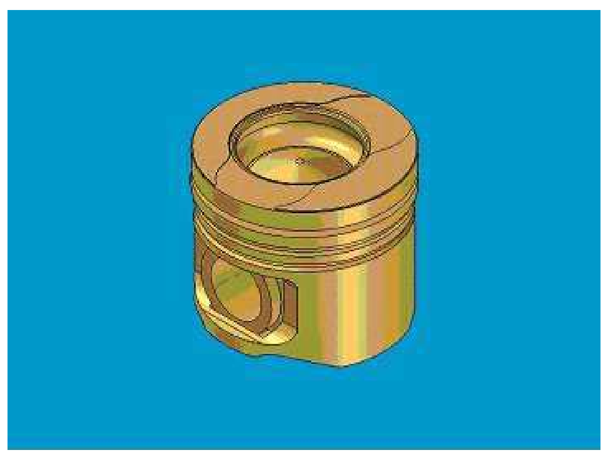

Figure-1. New bimetallic piston.

Also the connecting rods have been redesigned. The H-beam design is substantially stronger and lighter than the T-shaped OEM equipment, allowing the engine to rev quicker and hold up to the demands of high boost applications. The new titanium alloy rods have a mass of 0.457 kg instead of the original 0.653 kg (Figure-2).

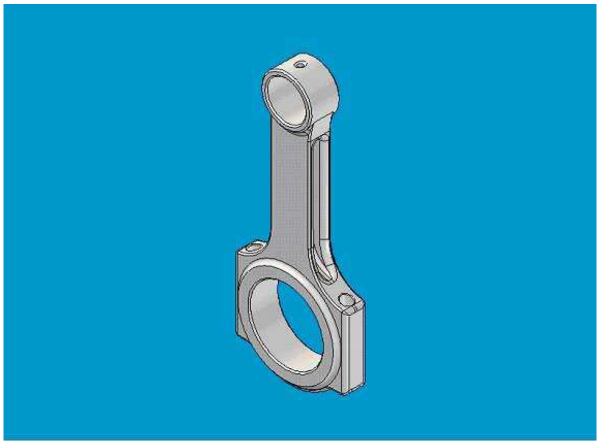

Figure-2. New titanium alloy connecting rod.

The original cranckshaft was replaced by a new one with increased journal bearing diameters and increased fillet radii (see Figure-3).

Common rail injection

New up-to-date injection system, with a maximum pressure of 2000 bar and an increased dynamic behaviour has been installed. This new arrangement makes it possible to improve the max rev from 4400 to 5000 rpm, in order to improve output the output power

The power of 300HP that can be obtained with higher pressures (240 bar) in the combustion chamber with the use of bimetallic pistons at 3800rpm, can be nearly reached with the original pistons at 5000rpm with slight improvements on pistons. Mono dimensional simulation of the 1900 jtd engine showed that an output power of 293 HP can be reached with and inlet manifold pressure of 293.5 HP at 5000 rpm.

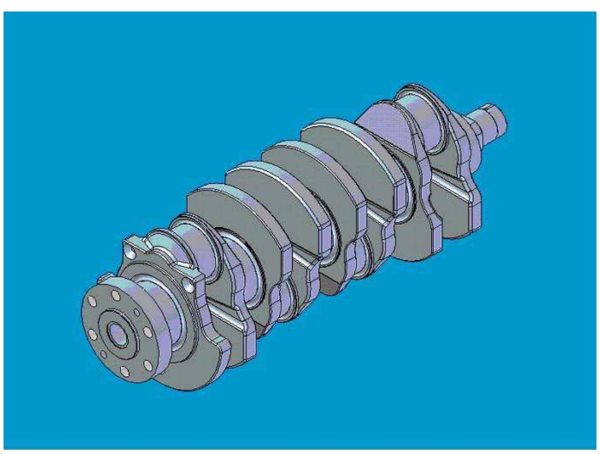

Figure-3. New crankshaft.

The actual flow calculated with this simulation of 920 kg/h, can be calculated with the Garrett formula of the theoretical (uncorrected) flow rate with a VE (Volumetric Efficiency) of 0.75 (1).

$$FR = \frac{(EngineCC/16.39) * (RPM/2) * VE}{1728} * 0.069*PR=33.84 \text{ [lb/min]} \quad (1)$$

Choice of the turbochargers

The original supercharging systems of 1.9 Jtd FIAT is a system designed for use at limited altitude and it is not suitable for the aeronautical use.

The compressors, at high compression ratios, may discharge air at temperatures of 250 or even 300 °C.

An increase in temperature in the air intake of 6-10°C decreases the power of the engine 1%, depending on the engine cooling system. This means that a tubocharged DID at an altitude of 7600m, if not aftercooled, would output a power equal to 80% of that at sea level.

However, in our case, if an increase in restoration altitude is needed, the supercharger system should be strengthened, in order to compensate the thinning of air and feed the engine with the same pressure and the same air density of sea level.

In our case, since the required manifold pressure is 3.93 bar, and then estimating the loss of pressure due to an aftercooler in about Pi=0.3 bar, the discharge pressure from the last compressor of the group must be at least 4.23 bar. This should happen at the restoration altitude require (20, 000m ISA+0). No filter is to be used at this altitude (Pf=0). The ram air intake effect is neglected.

Design preliminaries

We proceed now to the evaluation of the thermodynamic system at 20000m. This is an example on how to design a complex turbocharging system for a very high altitude engine using the standard US compressor maps. As usual the turbocharging system is taken as a whole, coupled with its own turbine, as supplied by the manufacturer.

At 20 km the pressure in the atmosphere is AP=5475 Pa (0.79 psi), then the pressure ratio is:

$$R = \frac{Ps}{Pa} = 18.5 \quad (2)$$

The overall compression ratio required is then

$$PR = R*Pi = 18.5*4.23 = 78.25 \quad (3)$$

The Actual Flow, as calculated above (1), is FR=33.84 lb/min. Ambient Air Temperature AAT at 20000m is -56.5°C (-69.7°F). Starting from this data we calculate the Corrected Flow Rate CFR at 20, 000 m is:

$$CFR = FR*\frac{\sqrt{(AAT/545)}}{AP / 13.95} -= 503.14 \quad (4)$$

At this point is inevitable to choose the largest compressor available from the Garrett catalogue, ie the GT60, which elaborates 150 lb/min with acceptable efficiency (see Figure-4). For the first compression stage It

VOL. 10, NO. 1, JANUARY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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then necessary to use at least three GT60. These turbochargers work in parallel and will elaborate an equal CFR (5):
flow rate equal to:

CFRs=CFR/3=167.71 (5)

With this flow rate value the compression ratio obtainable from the first stage with three GT60 is (Figure-4):

$$beta1 = \frac{P1}{Pa} = 3.6 \quad (6)$$

In these conditions the GT60 has an efficiency nc=0.7, the compressed air output temperature will be 80°C, and the output pressure equal to 19706 Pa.

We will proceed in a similar way for the next compression stages up to the final manifold pressure Pm=4.23 bar.

For the second compression stage, we then calculate the new flow rate, with the reduced compression ratio, with AAT=80°C=176°F= (176+460)°F absolute and AP=Pa/beta1=2.85 psi:

$$CFR=FR*\frac{\sqrt{(AAT/545)}}{AP / 13.95}=178.34 \quad (7)$$

Again we have to use a single GT60 for the second stage. Since the flow rate is practically the same, we have

$$beta2 = \frac{P2}{P1} = 3.6 \quad (8)$$

and an efficiency of nc = 0.7.

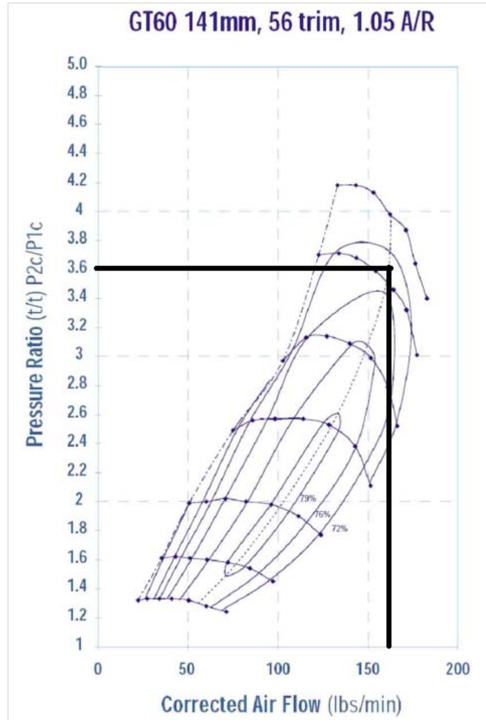

Figure-4. Garrett GT60 Compressor Map (low pressure stage).

The outlet temperature from the second stage is 287.4°C. This temperature is too high for an aluminum alloy compressor, so a titanium alloy wheel is needed. It is also necessary to use an intercooler to lower this temperature. Assuming that the intercooler has a minimum uses a ΔT=25°C to exchange heat to the outside, the inlet temperature to the third stage is:

T2=Ta+ ΔT=-56.5+25=-31.5°C=-24.7°F (9)

To take into account of the pressure drop of this intercooler Beta2 is then reduced from 3.6 to 3.5. The output pressure of the second stage becomes (9)

P2=P1*3.5=68983 (10)

the new CFR is then 50 lb/min.

In this condition the GT40 can with a beta3=4 (see Figure-5).

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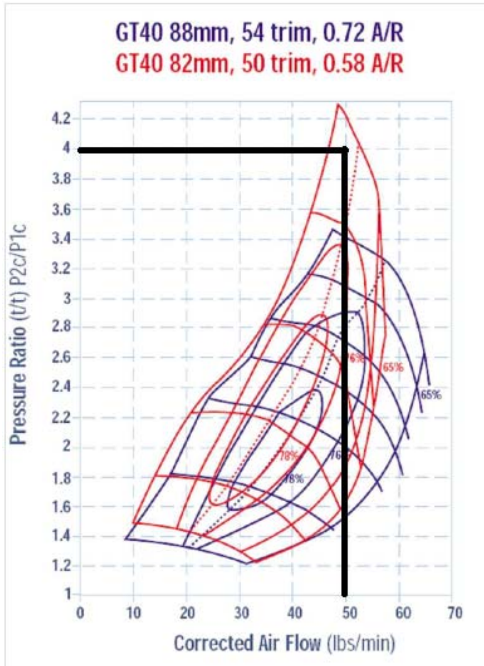

Figure-5. Garrett GT40 compressor map.

The outlet temperature from the third stage is then T3=299°C. Again we need a titanium alloy compressor wheel and an intercooler. Outlet temperature from the intercooler is again T2 and again we reduce beta3 to 3.9.

The output pressure from the third stage is then 269036 Pa with CFR=13 lb/min (AAT=435.4°Fabsolute, AP=39psi).

At this point the necessary beta4 can be calculated. The wastegate will keep this value constant through the flight;

beta4=PR/P3=1.6

A GT15 will be sufficient in this case (see Figure-6).

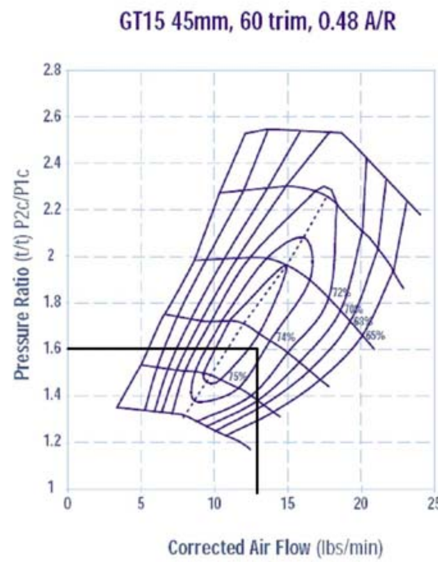

Figure-6. GT 15 compressor map.

For the whole system see Figure-7. The intercooler between the first and the second stage in necessary for intermediate flight levels and power settings between 10, 000m and 20, 000m.

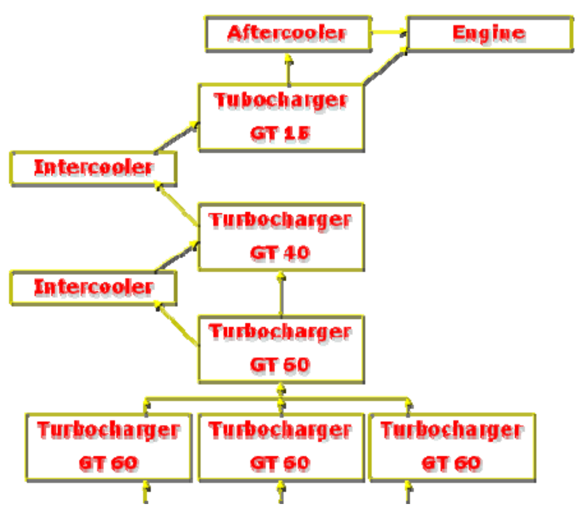

Figure-7. Turbocharging system from 17500m to 2000m.

CONCLUSIONS

In order to keep the output power constant up to 20000m, even small engines require large turbochargers. For a 1.9L 300HP common rail DID, it is necessary to use a 4 stage turbocharging system. The first stage should use 3, very large turbochargers. To avoid excessive weights, it will be necessary to use lightweight inconel alloy casings instead of the original cast-iron ones. In this case it is better to design ad-hoc high-compressor-ratio turbochargers. It will then possible to reduce the number of stages to 3. In any case, intercoolers should be adopted from stage to stage, with the possibility of a bypass also for the aftercooler, like in this case.

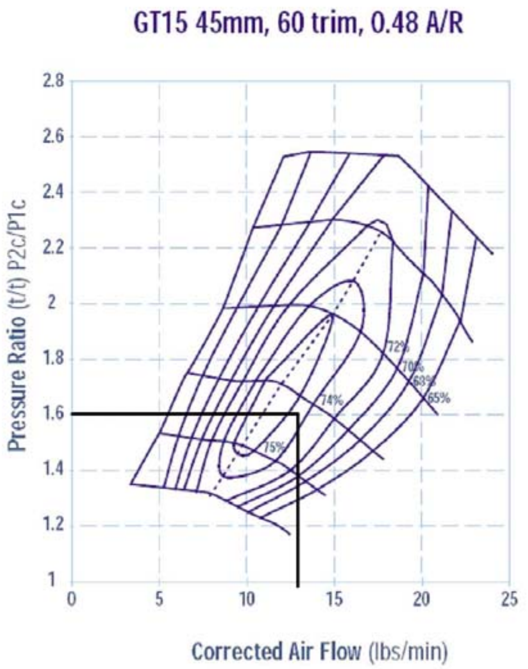

Figure-8. GT15 compressor map.

The final temperature is 21.4°C and the aftercooler should be bypassed. It is chosen a value of 10 bars, assuming a high backpressure drain. This fact, by the way, will reduce the volumetric efficiency of the engine. In fact, no valve overlap is allowed. This will affect the Specific Fuel Consumption of the engine. If it is necessary to keep the same efficiency it is necessary to keep the exhaust backpressure equal or better lower than intake pressure.

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Symbols

Symbol	Description	Unit	Value
Pm	Manifold pressure	bar	4.23
P1	Pressure outlet first compression stage	Pa	
P2	Pressure outlet second compression stage	Pa	
T2	Temperature oulet from the intercooler (second stage)	K	
nc	Compressor adiabatic efficiency	-	
R	Pressure ratio	-	
PR	Total compressor pressure ratio	-	
Pa	Ambient pressure (20,000m)	Pa	5475
Ta	Ambient temperature (20,000m)	°C	56.5
P0	Sea level pressure	Pa	101325
Pi	Aftercooler+intake-duct pressure loss	Pa	30000
Pf	Filter pressure loss	Pa	0
CFR	Corrected Flow Rate (Garrett)	lb/m	
CFRs	Corrected Flow Rate single turbocharger (Garrett)	lb/m	
EngineCC	Engine Displacement	cc	1910
VE	Engine Volumetric Efficiency	-	0.75
AAT	Absolute Air Temperature	°F+460	
AP	Ambient Pressure	psi	
RPM	Revolutions x minute	1/min	5000