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

www.arpnjournals.com

SUPERCHARGING SYSTEMS IN SMALL AIRCRAFT DIESEL COMMON RAIL ENGINES DERIVED FROM THE AUTOMOTIVE FIELD

Luca Piancastelli and Leonardo Frizziero
Department of Industrial Engineering, Alma Mater Studiorum University of Bologna, viale Risorgimento, Bologna, Italy
E-Mail: Leonardo.frizziero@unibo.it

ABSTRACT

Common rail automotive diesels are always turbocharged. This engine works at limited altitude and should output torque at low rotational speeds. Not so for engines that work coupled to propeller and fans. This is the case of aircraft and helicopter engines. In this case it is important to have high output power at high rpm and to keep throttle authority and power as high as possible. Some basic concepts to achieve this result are introduced in this paper. Single turbocharging systems are introduced and an option to improve the altitude performance is discussed. Far from being exhaustive, this paper is an initial step in the long and awkward technology of aircraft common rail diesels. The basic combustion principles and the basic concepts for efficiency are also discussed.

Keywords: aircraft, DIDs, rail automotive diesels, turbocharging systems.

INTRODUCTION

Density of air decreases with gain in altitude. At an altitude of about 20, 000ft (6, 100m) in the International Standard Atmosphere (ISA) the density of air is reduced to half of what it is at sea level. An aircraft in climb would experience a lower mass of air entering the cylinders; the result is a decrease in the efficiency of a naturally aspirated aircraft engine. A naturally aspirated aircraft engine loses more than 50% of its sea level power when at 20, 000ft. For Direct Injection Diesel (DID) this problem may render ignition impossible with a total loss of output power.

This paper introduces some concepts behind turbocharging the modern common rail DIDs, and the advantages it gives us in performance at high altitude. Modern common rail DIDs are already turbocharged since automotive manufacturers are looking for is good power output. The air flows through the cylinder head, from the induction system to the exhaust system and then out into the ambient again. This is best accomplished by inlet pressure increase, because air naturally flows from areas of higher concentration (pressure) to lower concentration (pressure). In supercharged engines only the intake system is running under pressure above atmospheric, everything in the engine will be working at pressure above atmospheric and the pressure differences will be greatest in the induction system, so all air will exit out the tail pipe quickly. A supercharger is any device that pressurizes the intake to above atmospheric pressure, and turbochargers do these exactly like superchargers do. The only difference is that superchargers take energy from the crankshaft, while turbochargers recover the wasted energy of the exhaust. The exhaust has kinetic energy and temperature that can be recovered. Backpressure is a negative side effect to control. As altitude reduces air density it is possible to recover it by increasing boost pressure. The altitude at which the nominal boost pressure can be maintained is called recovery altitude. From this altitude up the DID engine will not only loose power. It will also lose the possibility of starting (not only cold starting, but also hot restarting) and the possibility of full throttle authority. So for modern turbocharged common rail DIDs five altitudes are significant. Recovery altitude (1) this is the altitude at which the engine maintains nominal full power and full throttle authority. Starting altitude (2) this is the altitude at which the engine can be started-up (hot starting). Full throttle authority altitude (3) this is the altitude at which the throttle can be freely used. From this altitude up the throttle must be kept to "continuous full". The engine will continue to run with an output power that usually decreases with altitude. Maximum altitude (4), that is the altitude at which the engine will continue to run (ignite). These four altitudes are meant for ISA (ISA+0°C) conditions. Offsets from this condition define different altitudes. A common temperature envelope is (ISA-50°C)-(ISA+20°C). This means (-35°C)-(+35°C) at sea level. So an engine will have 3 sets of 4 altitudes, a set for the minimum temperature (for example ISA-50°C), a set for nominal conditions (ISA+0°C) and a set for maximum temperature (ISA+20°C).

THE EVIL OF TURBOCHARGING

Since intake pressures will always be higher than in any other part of the system (except of course during the engine power stroke, but the combustion chamber is always sealed off from the rest of the system); it is very easy to make this combination a powerful one.

Turbocharging runs off what is largely wasted energy; exhaust energy is given by Temperature and Speed. By keeping the speed constant it is possible to write:

$$TPR = pt5 / pt4 <= 1.0 \quad (1)$$

$$Tt5 / Tt4 = (pt5 / pt4) \wedge ((gam -1) / gam) \quad (2)$$

$$TW = ht4 - ht5 \quad (3)$$

$$TW = cp * (Tt4 - Tt5) \quad (4)$$

TW = nt * cp * Tt4 * [1 - TPR ^ ((gam -1) / gam)] (5)

So the wasted exhaust temperature Tt5 can be converted to energy (5). In this way a turbocharger is a device that harnesses the wasted energy dumped out through the exhaust system to actually force more air into the engine. This has one major drawback: it increases the pressure within a portion of the exhaust system (the backpressure). While turbocharging a motor increases the amount of air that can be flowed into it, it has a negative effect on how easily we can flow it back out again during valve overlap. This weakens the pressure difference between these two fundamental sides of the engine, and causes both cam timing and exhaust system design to again become extremely important to making good power. Fortunately common rails DIDs from the automotive market are always turbocharged and the cam timing is already optimized for the application. Exhaust and intake, at least for the aircraft/helicopter application, can be improved for a better altitude performance. An unavoidable side-effect of forced induction is that compressing air, as stated in the first law of thermodynamics, raises the inlet temperature. As a result, the charge density is reduced and the cylinders receive a reduced mass of air. The hot air introduced in the engine also increases the engine temperature ant the thermal stresses. These drawbacks are countered by charge-air cooling, which passes the air leaving the turbocharger or supercharger through a heat exchanger called aftercooler. This is done by cooling the charge air with an ambient flow of either air (air-air intercooler) or liquid (liquid-to-air intercooler). In multi stage compression systems intercooling between compressions stages is also used. The drawback of inter/aftercooling is its mass and volume of the cooler along with the associated plumbing and piping. This also reduces reliability and increases turbo-lag. The "turbo lag" drawback is that engine response suffers greatly because it takes time for the turbocharger to come up to speed (spool up). However, this delay in power delivery is negligible in aircraft/helicopter applications since fan/propeller inertia is the main "lag factor".

Compressor design and choices

The compressor field is dominated by centrifugal compressors. Multistage inter and aftercooled compression systems can be used to arrive at recovery altitudes up to 20,000m. Mixed axial centrifugal system has been also used to overcome the "natural" compression ratio limit of centrifugal compressors that is around 6 (8 with adiabatic efficiency reduction). The problem of mixed compression system has been always poor off-design performance. The advantages of centrifugal compressor are: good off-design performance, wide volumetric-flow range (from the surge to the choke lines) and low manufacturing costs. The main drawback is adiabatic efficiency that is typically below 80%, while axial compressors may reach 88%. Rotational speeds may be as high as 350, 000 rpm. Centrifugal compressor isn’t a positive displacement compressor design. It doesn’t have a reliable airflow amount based on any RPM, because it’s very design only flows air efficiently at high RPM. So although these compressors are very efficient at high RPM, they are ineffective at creating meaningful boost at lower RPM. This concept is called surge limit, or the point in the airflow vs. pressure map where the compressor can no longer flow air into the system.

Materials

In aircrafts and helicopters, high pressure single-stage turbocharging usually requires expensive materials as titanium alloys on the compressor side. When using proven aluminum alloy compressors, this requires additional cooling of the compressor wheels. Also the other turbocharger components too, such as the turbine, bearings, shaft seals, the casings and their connections, are exposed to higher thermal and mechanical stresses as a result of the pressure ratios being far higher than those of common automotive turbochargers currently on the market. Fortunately, the continuous research for downsizing and performance brought high pressure, high performance turbochargers. By using the available Finite Element Analysis (FEA) and Computational Fluid Dynamic (CFD), it is now possible to find compressors with pressure ratios of up to 6 in continuous operation with single-stage turbocharging. The advantage of using titanium compressors is without doubt the fact that no additional structural measures for cooling are needed. This slightly improves the compressor efficiency, since cooling air is spilled out of the compressor output. However, the big disadvantage is the substantially more difficult material from the fatigue point of view. It is also possible the use of optionally coated parts, multiple gas inlet turbine housings or different housing materials for applications with higher temperature ranges. Today centrifugal turbocharger use both ball bearing and plain bearings, supported by a squeeze oil damper in the bearing flanges. This later remains the most reasonable option in terms of costs and operational reliability [8] also for the new high-pressure turbochargers. To ensure the new high-pressure turbochargers are of compact design, these also feature an axial thrust bearing positioned between the two plain bearings. In these turbochargers also overspeed and containment should be considered. High-pressure compressor stages with cooling, not only allows high pressure compressor stages one-piece aluminum alloy compressor. In addition, due to blow-by mass flow, whereby part of the air at the impeller outlet during operation enters the oil charge near the impeller-shaft attachment area, a source of heat exists between the bearing cover and impeller. The temperature of this air increases with increasing pressure ratio. The air injection cooling can also limit this flow of hot fluid into the area between the impeller and bearing cover as well as reduce the heat transfer into the impeller [9]. The air injection can also reduce bearing temperatures at high speeds. In larger high altitude multi stage turbine it is advisable to use Inconel welded casings instead of the automotive cast iron ones.

Water injection

Water injection is another effective means of cooling the charge air. Water injection, unlike nitrous oxide or forced induction, doesn't add much power to the engine by itself, but allows more power to be safely added. It works by being sprayed into the compressed air charge. The water "absorbs heat as it evaporates" to cool the charge down to the wet bulb temperature. Due to the lower intake temperatures and denser air charge, more boost pressure and fuel can be safely added. It has been successfully used at take off or for emergency.

Exhaust design

The optimization of the most effective exhaust configurations of turbocharging system is of paramount importance. In fact turbochargers and engine performances are greatly affected by the gas flow unsteadiness. Four different systems are used: the Constant Pressure turbocharging system (CP), the Pulse Turbocharging system (PT), the Pulse Converter (PC) turbocharging system and the Modular Pulse Converter (MPC) turbocharging system [2]. In the PC turbocharging system the exhaust gases coming from all cylinders flow into a common exhaust manifold, whose volume is calculated to damp down the unsteady flow, and then feed the single-entry turbine. The CP system [3, 4] is designed to keep the pressure at the turbine entry are essentially steady with time, providing a nearly constant pressure turbocharging. As the mass flow is relatively constant, high efficiency of the turbine is achieved. The disadvantage of this kind of turbocharging system is that a large part of the high kinetic energy of the exhaust gases is lost. The turbulence losses, due to the mixing process between exhaust flows, coming from different cylinders, decrease the available energy. The larger advantage of this system is that the turbocharger is used at its best. In fact both the turbine and the compressor are basically quasi steady flow machines, with surge and choke line that is drawn in the steady state condition. Maximum pressure, maximum efficiency and reliability of the turbocharger can be obtained. A better utilization of the exhaust kinetic energy can be obtained by adopting the PT system [5, 6], in which the converted energy at the turbine is greater than the CP turbocharging system architecture. However, the turbine efficiency and flux stability are lower because the gas flow into the turbine is highly unsteady and the turbine operates under variable conditions. The flow unsteadiness in the pulse turbocharging system can be partially reduced by grouping together several cylinders in a common exhaust pipe, which is then connected to a pulse converter PC. The disadvantage of PC is that the structure of the exhaust manifolds is complicated [2]. The MPC turbocharging system became popular because of its simpler structure and convenience of production. However in MPC turbocharging system the scavenging interference often occurs at any two of the first four cylinders near the closed end of the exhaust manifold. Thus, the amount of the scavenging air of each cylinder is discrepant. This discrepancy will cause a large difference of the exhaust gas temperatures at each cylinder outlet. MIXed Pulse converter (MIXPC) turbocharging system [7] has been proposed to solve the problem without much success. CP is then the best solution in aircraft applications where high altitude performance and high reliability are always required.

An example: the adaptation of the FIAT 1300 Multijet engine for aircraft use

The FIAT 1300 Multijet was chosen for the avionization. The original intake and exhaust were removed in order to improve the "steady state" behaviour of the engine. Besides, the Euro 4 specifications are not to be met for aircraft applications.

The new CP exhaust (see Figure 1 and 2)

The exhaust is the most critical part of the turbocharging system. In this particular engine temperature as high as 1050 K are reached and kept during medium altitude fly. In this PC turbocharging system the exhaust gases coming from all cylinders flow into a common exhaust manifold, the piping of each cylinder being slightly divergent to recover pressure. The exhausts has a revolving common divergent chamber that brings to the main damping hose whose volume was calculated to damp down the unsteady flow, and then feed the single-entry VGT (Variable Geometry turbine). This CP system is designed to keep the pressure at the turbine entry as steady as possible with time, providing a nearly constant pressure "ideal" turbocharging. A welded Inconel alloy structure was used to reduce weight. Thermal insulation is provided on the outside to keep temperature as high as possible since this improves engine performance. The gas recirculation system is kept active to reduce warm up time and to improve maximum operating altitude by mixing exhaust to incoming air. In fact diesel ignition depends both on temperature and pressure. In this condition however, maximum power output is reduced. Hot hyping makes it possible to improve maximum operational speed of the turbocharger of 15% allowing better performance. However to avoid overspeed a wastegate should be used.

Figure-1. The original exhaust.

Figure-2. The new CP exhaust.

Another advantage of PC is that temperatures at the exhaust of the single cylinder are almost equal (±5%). In this way it is possible to monitor anomalies in single cylinder performance and behave accordingly. FEA was performed (Figure-6) with standard maximum pressure (10bar), maximum acceleration (6g in every direction) a proper safety coefficient (3.5). The material is Inconel 625.

The new CP intake (see Figure 3, 4 and 5)

A similar operation has been made for the intake. In this case the possibility to have an air reservoir reduces the pulsations at compressor output. This has the practical effect to move the true chocking line to the left. FEA uses the same coefficients as exhaust. The material is 5059 aluminum alloy.

Figure-3. Original intake.

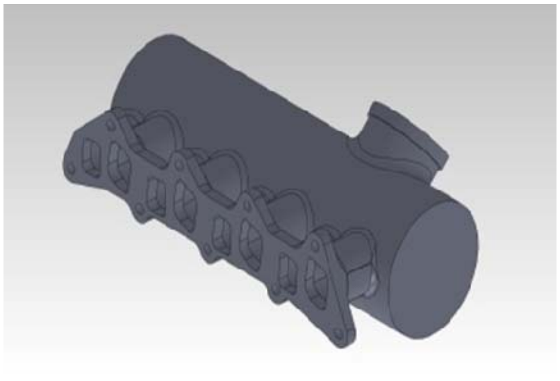

Figure-4. New intake manifold.

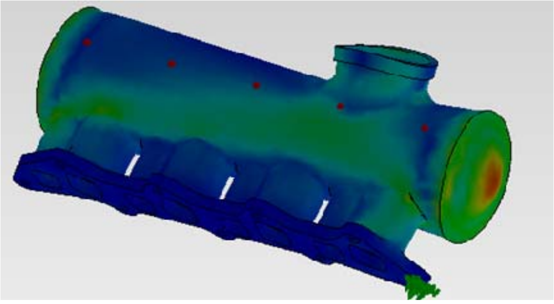

Figure-5. Intake FEA simulation.

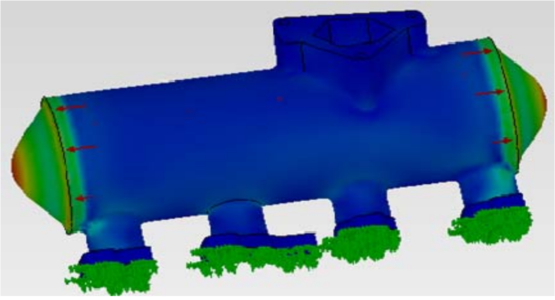

Figure-6. Exhaust FEA simulation.

High altitude operation: diesel fuel combustion

DID combustion is temperature induced and depends to a major extent on successful vaporization and mixing over an extremely short time. In DIDs air alone is initially supplied to the cylinders. It is then compressed so that its temperature exceeds than that necessary for spontaneous combustion of the fuel. The fuel is then injected into the cylinder as very fine spray. Consequently, combustion is initiated at a number of points throughout the charge. The auto-ignition point of diesel fuel is around 493 K, which is lower than the compression temperature of more than 900 K attained almost throughout the charge. Due to heat losses, temperatures of charge adjacent to the cylinder walls are significantly lower than the latter Figure.

The droplets of fuel in the spray mix thoroughly with the air, evaporate, and then burn completely in a very short time during the engine cycle. This process is more critical for starting in very cold conditions, when the temperature on Top Dead Center (TDP) can be as low as 673 K and the auto-ignition temperature of the cold fuel is generally approximately between 773 to 873 K. For this reason DIDs incorporate glow plugs to facilitate starting. Once auto-ignition starts, a (few) small flame(s) may be alternately initiated and quenched. Altitude operation is similar to the starting condition. During starting a very low timing advance and a low injection pressure are used. The low timing advance makes it possible to increase the air temperature inside the combustion chamber and the low pressure increases the travel time of droplets from injectors to piston walls. In this condition a very low power output is available. In automotive engines Starting takes place at about 300 rpm. On the contrary, high altitude operations usually require high rpm (3000-6000) in order to move the propeller at a suitable speed. In this case speeds worsen the problem since travel time of droplet from injector to piston wall is reduced. In this time the fuel spray should mix, evaporate and burn.

High altitude operation: ignition delay

Ignition delay is the time interval between the evaporation and mixing of the fuel in the air and the initiation of combustion. It is generally of the ms, however varies according to the size of droplets, their rate of mixing with the air, the pressure and the temperature. As a first approximation, the diesel fuel ignition delay can be calculated in terms of the relationship between the delay time, pressure, and temperature. Regression analysis was used to develop a diesel fuel ignition delay correlation. The "historical" from Wolfer (1938) [11] correlation is as follows:

$$\tau_{ign} = 0.44 P_o^{-1.19} \exp\left[\frac{4650}{T_o}\right] \qquad (6)$$

A more modern approach [12] differs slightly:

$$\text{Tau}_{ign} = 9.00\ P_o^{-1.0218} \exp\,[2100/To] \qquad (7)$$

(6) and (7) show that the delay in exponentially proportional to the temperature. The dependency from pressure is less important. The higher the temperature the better. The pressure influence is less important.

So to contain the delay and increase injection pressure, charge and power output it is necessary to increase the manifold temperature.

As altitude increases the air becomes thinner and colder. Since the turbocharger is a turbomachine that elaborate a volume, the air mass that arrives in the inlet manifold is reduced. The turbocharger rotational speed can be then increased to the maximum possible to recover pressure and density (mass). This is the recovery altitude. From this point on power output is reduced. The temperature in the pressure chamber at the TDC will be lower and lower. FADEC will reduce fuel charge to the point that the engine will stop. This situation can be partially corrected by increasing intake air temperature. In Figure-7 a possible solution is proposed. At altitudes below the recovery one, the fresh air is elaborated by the compressor, sent to the aftercooler (1) and then to the inlet manifold. In this condition the DID is running very hot and air charge should be cooled down to 323.15 K that is the usual value for automotive DIDs. As altitude increases beyond the recovery value, pressure in the intake manifold drops. To keep the engine running the aftercooler is bypassed and compressed air is send to a heat-exchanger (5) with the exhaust (4). A bypass (3) sends the air to the air intake that is thermally insulated. FADEC controlled butterfly valves operate the bypass. In this way it is possible to keep the engine running at higher altitudes and to retain (partial) throttle control. The bypass is useful also for hot starting. In this arrangement the cooling air enters in the bellow-mouth under the propeller spinner, passes through the aftercooler (1) and the radiator (2). The air duct that connects the aftercooler and the radiator is not shown in Figure-7.

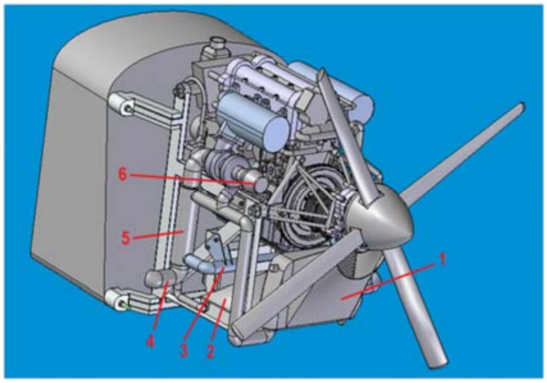

Figure-7. A partial assembly of the engine with the new intake and exhaust.

CONCLUSIONS

An important factor in the conversion of automotive common rail DIDs to aircraft/helicopter application is the optimization of the turbocharging system. In this paper constant pressure exhaust and intake were suggested. This modifications optimizes turbocharger overall performance and efficiency. Turbolag is not important in aircraft applications, since propeller or fan inertia delay significantly the response time of the engine. For this reason a larger diameter, higher pressure turbocharger can be adopted. This turbocharger may use an air cooled aluminum alloy or a titanium alloy compressor. Turbocharger overspeed should be also controlled by a wastegate or through a VGT. A well dimensioned or overdimensioned aftercooler should be used to keep air charge as cool as possible. As altitude increases the air becomes thinner and colder. The increase of turbocharger speed may compensate this fact up to the recovery altitude. In order to operate with full or partial throttle control at higher altitudes, it becomes necessary to increase air intake temperature. In this paper a solution to bypass the aftercooler and to transfer thermal energy from the exhaust to the intake is proposed. This solution does not improve power output, but it is conceived to operate the engine at higher altitudes with full or partial throttle authority. It is also beneficial to hot restarting.

REFERENCES

[1] Meherwan P. 1992. Principles of operation and performance estimation of centrifugal compressors. Boyce Chairman and CEO Boyce Engineering International, Inc. Houston, Texas Proceedings of the Twenty-first Turbomachinery Symposium, Texas A and M University. Turbomachinery Laboratory Editor the Laboratory.

[2] Watson N. 1982. Turbocharging the Internal Combustion Engine. Macmillan Press Ltd, London, UK.

[3] Capobianco M., Gambarotta A. and Cipolla G. 1989. Influence of the Pulsating Flow Operation on the Turbine Characteristics of a Small Internal Combustion Engine Turbocharger. I. Mech. E., Paper No. C372/019.

[4] Capobianco M., Gambarotta A. and Cipolla G. 1990. Effect of Inlet Pulsating Pressure Characteristics on Turbine Performance of an Automotive Wastegated Turbocharger. SAE Paper No. 900359.

[5] Capobianco M. and Gambarotta A. 1993. Performance of a Twin-Entry Automotive Turbocharger Turbine. ASME Paper No. 93-ICE-2.

[6] Yeo J. H. and Baines N.C. 1990. Pulsating Flow Behavior in a Twin-Entry Vaneless Radial-Inflow Turbine. I. Mech. E., Paper No. C405/004.

[7] 2010. Study on Mixed Pulse Converter (MIXPC) Turbocharging System and Its Application in Marine Diesel Engines. Cui, Yi; Gu, Hongzhong; Deng, Kangyao; Yang, Shiyou Source. Journal of Ship Research. 54(1): 68-77(10). Publisher: Society of Naval Architects and Marine Engineers (SNAME).

[8] Born H.R. 1987. Analytical and experimental investigation of the stability of the rotor bearing system of a new small turbocharger. ASME Conference 1987, Reference No. 87-GT-110.

[9] Senn S., Seiler M. and Schaefer O. 2009. Fluid-structure interactions in turbocharger mixed-flow turbines: three dimensional comp. modeling and experimental validation, ASME Turbo Expo, GT2009-59142.

[10] http://what-when-how.com/automobile/diesel-fuel-combustion-automobile/.

[11] Wolfer H. Ignition Lag in DieseI E gines VDI-Forchungsheft 392, 1938, (English Translation, RAE Farnborough, Lib. No. 359, UDC 621-436 - 047, Ig5g).

[12] 2013. A Correlation for Estimation of lgnition Delay of Dual Fuel Combustion Based on Constant Volume Combustion Vessel Experiments *M. Mbarawa R and D Journal, 19(3) incorporated into The SA Mechanical \ Engineer.

[13] L. Piancastelli, G. Caligiana, Frizziero Leonardo and S. Marcoppido. 2012. Piston engine cooling: an evergreen problem. 3rd CEAS Air and Space Conference - 21st AIDAA Congress - Venice (Italy), 24th-28th October.

[14] L. Piancastelli, L. Frizziero, E. Morganti and A. Canaparo. 2012. Fuzzy control system for aircraft diesel engines” edizioni ETS. International journal of heat and technology. ISSN 0392-8764. 30(1): 131-135.

[15] L. Piancastelli, L. Frizziero, S. Marcoppido and E. Pezzuti. 2012. Methodology to evaluate aircraft piston engine durability” edizioni ETS. International journal of heat and technology. ISSN 0392-8764. 30(1): 89-92.

[16] L. Piancastelli, L. Frizziero, G. Zanuccoli and N.E. Daidzic, I. Rocchi. 2013. A comparison between CFRP and 2195-FSW for aircraft structural designs. International Journal of Heat and Technology. 31(1): 17-24.

[17] L. Piancastelli, L. Frizziero, N.E. Daidzic and I. Rocchi. 2013. Analysis of automotive diesel conversions with KERS for future aerospace applications. International Journal of Heat and Technology. 31(1): 143-154.

[18] L. Piancastelli, L. Frizziero and I. Rocchi. 2012. An innovative method to speed up the finite element analysis of critical engine components. International Journal of Heat and Technology. 30(2): 127-132.

[19] L. Piancastelli, L. Frizziero and I. Rocchi. 2012. Feasible optimum design of a turbocompound Diesel Brayton cycle for diesel-turbo-fan aircraft propulsion. International Journal of Heat and Technology. 30(2): 121-126.

[20] L. Piancastelli, L. Frizziero, S. Marcoppido, A. Donnarumma and E. Pezzuti. 2011. Fuzzy control system for recovering direction after spinning. International Journal of Heat and Technology. 29(2): 87-93.

[21] L. Piancastelli, L. Frizziero, S. Marcoppido, A. Donnarumma, E. Pezzuti. 2011. Active antiskid system for handling improvement in motorbikes controlled by fuzzy logic. International Journal of Heat and Technology. 29(2): 95-101.

[22] L. Piancastelli, L. Frizziero, E. Morganti and E. Pezzuti. 2012. Method for evaluating the durability of aircraft piston engines. Published by Walailak Journal of Science and Technology. The Walailak Journal of Science and Technology, Institute of Research and Development, Walailak University, ISSN: 1686-3933, Thasala, Nakhon Si Thammarat 80161. 9(4): 425-431, Thailand.

[23] L. Piancastelli, L. Frizziero, E. Morganti and A. Canaparo. 2012. Embodiment of an innovative system design in a sportscar factory. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006. 9(2): 69-98, Allahabad, India.

[24] L. Piancastelli, L. Frizziero, E. Morganti and A. Canaparo. 2012. The Electronic Stability Program controlled by a Fuzzy Algorithm tuned for tyre burst issues. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 9(1): 49-68, Allahabad, India.

[25] L. Piancastelli, L. Frizziero, I. Rocchi, G. Zanuccoli and N.E. Daidzic. 2013. The "C-triplex" approach to design of CFRP transport-category airplane structures. International Journal of Heat and Technology. ISSN 0392-8764, 1(2): 51-59.

[26] L. Frizziero and I. Rocchi. 2013. New finite element analysis approach. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006. 11(2): 85-100, Allahabad, India.

[27] L. Piancastelli, L. Frizziero and E. Pezzuti. 2014. Aircraft diesel engines controlled by fuzzy logic. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608. 9(1): 30-34, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[28] L. Piancastelli, L. Frizziero and E. Pezzuti. 2014. Kers applications to aerospace diesel propulsion. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(5): 807-818, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[29] L. Piancastelli, L. Frizziero and G. Donnici. 2014. A highly constrained geometric problem: The inside-outhuman-based approach for the automotive vehicles design. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608. 9(6): 901-906, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[30] L. Frizziero and F. R. Curbastro. 2014. Innovative methodologies in mechanical design: QFD vs TRIZ to develop an innovative pressure control system. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608. 9(6): 966-970, 2014, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[31] L. Piancastelli and L. Frizziero. 2014. How to adopt innovative design in a sportscar factory. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608. 9(6): 859-870, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[32] L. Piancastelli, L. Frizziero and I. Rocchi. 2014. A low-cost, mass-producible, wheeled wind turbine for easy production of renewableenergy. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 12(1): 19-37, Allahabad, India.

Symbols

Symbol	Description	Unit
TPR	Total pressure ratio	-
Pt4	Turbine inlet pressure	Pa
Pt5	Turbine outlet pressure	Pa
Tt4	Turbine inlet temperature	K
Tt5	Turbine outlet temperature	K
ht4	Turbine inlet specific stagnation enthalpy	J/kg
ht5	Turbine outlet specific stagnation enthalpy	J/kg
TW	Specific turbine work	J/kg
cp	Specific Heat	J/kgxK
nt	Turbine adiabatic efficiency	-
gam	Specific heat ratio	-
τ_{ign}	Ignition delay	ms
p_o	Combustion chamber pressure	MPa
T_o	Combustion chamber temperature	K