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Diesel engines for light-to-medium helicopters and airplanes (Editorial)

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About 16 years after Nikolaus August Otto invented gasoline (petrol) engine (1876), another German engineer Rudolf Diesel patented his Internal-Combustion (IC) engine which later became known as "diesel" engine (Molenhauer & Tschoeke, 2010). Rudolf Diesel (1858-1913) was mainly interested in improving the efficiency of Otto's IC engine which in itself was motivated by the engine made by Belgian Jean Joseph Etienne Lenoir in 1860s. Diesel died under mysterious circumstances in 1913 (Molenhauer and Tschoeke, 2010). Not long after invention, diesel engines were manufactured in almost every industrially developed country in the world of that time (Challen and Baranescu, 2006; Molenhauer and Tschoeke, 2010; & Woodyard, 2010).

Many still associate diesel engines to stinky plumes of black exhaust released by noisy heavy-duty trucks. These days are long gone. Modern turbo-charged (TC) common-rail (CMR) Full Authority Digital Engine (Electronic) Control (FADEC) equipped, liquid-cooled, and low-emission diesel engines are clean, neat, mature, and advanced IC engines. For example, the Italian manufacturers from the FIAT group (FIAT, Alfa Romeo, Lancia) are the industry leaders in CMR and Direct Injection (DI) diesels for passenger cars. Other notable diesel engine manufacturers are French "Peugeot" and German's "Daimler-Benz".

Current turbo-charged railroad diesels (4,000-6,000 hp) are the prime movers on the contemporary Alternating Current (AC) traction diesel-electric locomotives (from GE and EMD), for example, providing the backbone of the fuel-efficient railroad freight transportation system in USA. Many new diesel-electric locomotives also employ hybrid solutions. The biggest and the most powerful IC engines today are the 2-stroke marine diesels, such as the Finnish Wärtsilä-Sulzer 14RT-flex96-C that can deliver 115,000 hp (86 MW) per shaft with immense torque at about 100 RPM.

Modern diesel engines are environmentally friendly, reliable, and robust with relatively high Power Densities (PDs) and lowest existing Brake Specific Fuel Consumption (BSFC) of any practical man-made heat engine. Another often forgotten fact about diesels is that its Power-to-Volume (P/V) ratio is often higher compared to gasoline engines. Ultimately, in aeronautics, this leads to less aerodynamic drag and higher speeds. Modern aero-diesels incorporate DI CMR fuel delivery system, liquid cooling, turbochargers for altitude compensation, FADEC for efficient throttle-by-wire engine control and protection, and many other advanced features. One of the main advantages of diesel engines is the absence of the Spark Ignition (SI) gear that makes gasoline aero-engines so vulnerable in aeronautical applications. A good summary of existing gasoline aero-engines with cost, maintenance and failure history is given in Bertorelli (2012).

Unlike Otto engines, diesels are not throttable and so their efficiency does not decrease appreciably at lower power settings. Often a diesel engine can be left idling for hours and even days. Additionally, diesel fuel(s) are quite denser (0.832 kg/L or 6.95 lb/gal) than regular aviation gasoline or Avgas (0.715 kg/L or 6 lb/gal). Although they are practically of equal heat value (Hill & Peterson, 1992) per mass (kJ/kg), for most gasoline-powered airplanes and helicopters retrofitted with diesel engines this would translate into longer range as the fixed volume of fuel tanks basically carries more energy (kJ/m^3 or kWh/m^3).

German-made Centurion/Thielert's 2-Liter 135 hp, 134 kg (295 lb) and 75% cruise-power BSFC of about 0.35 lb/hp-hr aero-diesels mounted on an Austrian-made DA-40 and -42 Diamond light-airplane models essentially constitutes the entire market of certified aero-diesels today. Thielert's aero-diesels are based on Daimler-Benz's automotive diesel engines. Some Cessna's C172 and Piper's PA28 are retrofitted with similar aero-diesels.

In their 7th book edition, almost 20 years ago, Kroes & Wild (1995) made a visionary statement: "*Because of new technology in diesel-engine operating principles, the future use of diesel engines in aircraft is not only feasible but also probable*". Many may be surprised to learn that designs and the use of diesel engines in aeronautics/aviation is not of recent history. Junkers Motorenwerke in Germany started production of the Jumo aero-diesel engines in mid 1930s. The most famous of these was the Jumo 205 and almost 1000 engines were produced by the outbreak of WW2.

The need to increase the efficiency of existing light-to-medium aero-propulsion systems, i.e., lower BSFC and simultaneously increase PD, naturally leads to aero-diesels. In our opinion, aero-diesels have now matured for widespread use in Aviation/Aerospace industry. As a matter of fact some Unmanned Aerial Vehicles (UAVs) use and will be using more frequently aerodiesel engines to achieve longer range and endurance. Centurion/Thielert, SMA, and few other aero-diesels have paved the way, but many problems still plague these engines and especially the problem with reliability, low Time Between Overhaul (TBO) or Time Between Replacement (TBR), maintenance availability and cost, etc. Often the problem was that automotive diesels were not sufficiently well modified for aerospace use.

A group of scientists, and students at the University of Bologna (UniBo) in Bologna, Italy with test facilities at the Forli airport in Forli, Italy have introduced new aero-diesel concepts and resolved some of the outstanding problems associated with the existing aero-diesel engines. All redesigned aero-diesel engines today were ultimately developed from the automotive versions. However, all original reciprocating gasoline aircraft engine designs, whether for airplanes or helicopters, ultimately came from their automotive counterparts then. Unfortunately, expensive and tortuous testing and certification by appropriate regulatory agencies (FAA, 2014e) is required before wider use of aero-diesels is possible. Since introduction of every new engine design is followed by many problems and setbacks before technology matures, few established engine manufacturers are willing to risk. Certification of new types of engines under FAR Part 33 (USA) is expensive, time-consuming, and tedious process. Certification of airplanes in USA is regulated by FARs 23 and 25 (FAA, 2014a, 2014b) for normal, utility, aerobatic, commuter - and transport-category respectively. Similarly, certification of helicopters is regulated by FARs 27 and 29 (FAA, 2014c, 2014d) for normal- and transport-category rotorcraft/helicopter respectively.

Human society is on a constant search for more efficient, dependable, and environmentally friendlier aerospace propulsion concepts. The trend today in addition to more efficient low-altitude propulsion is also toward supersonic/hypersonic propulsion, suborbital and orbital flights, and space tourism. Some new propulsion concepts for space/aeronautics/aviation applications were discussed recently in, for example, Daidzic (2011), Gohardani and Gohardani (2012) and Piancastelli et al. (2013).

Methods and Materials

In this section, a basic theory of operation of diesel engines will be introduced. Also the comparison with the gasoline (Otto) engines will be stressed. An interested reader is directed to references to learn more about design and operational details of various reciprocating and turbine engines discussed here.

Basic Theory of Diesel Engine Operation and Performance

Diesel engines utilize lean-combustion unlike mostly rich- or stoichiometric-combustion in gasoline engines. The internal combustion process in diesels generates high gas pressures and temperatures translating into rotary motion of crankshaft (Braess & Seifert, 2005; Challen & Baranescu, 2006; Molenhauer & Tschoeke, 2010; & Woodyard, 2010) and delivering net torque and horsepower on the crankshaft. An illustration of generic diesel engine torque-power curve is shown in Figure 1. Older diesels featured long- and slow-strokes also due to slower burning diesel fuel producing massive torques at low RPMs. However, torque and horsepower steeply declined as the shaft RPM increased beyond 2,000-2,500. This is no longer the case with the modern turbocharged high-speed aero-diesels (3,000-5,000 RPM) where piston stroke is sometimes shorter than bore and little torque at low RPM is sacrificed to get more horsepower and torque at high RPM.

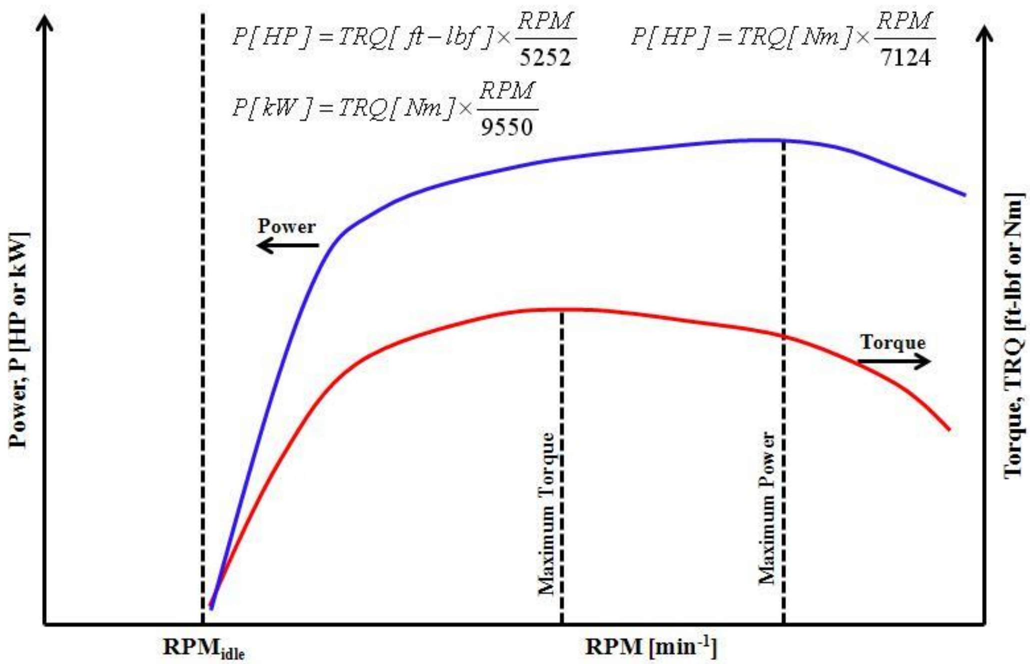

Figure 1. Net torque and power curves of a typical diesel engine. Not to scale.

An ideal Otto and Diesel thermodynamic cycles are shown in Figure 2. For the same compression ratio ($CR=V_{BDC}/V_{TDC}$), the gasoline (Otto) cycle is thermodynamically more efficient than diesel because of the diesel's finite fuel cut-off (injection) ratio. However, gasoline aero-engines are limited to relatively low compression ratios of 8:1 to 10:1 due to detonation characteristics of light and highly volatile aviation gasoline fuels. Modern diesel engines operate with CRs of up to 25:1, ultimately resulting in 20%-40% higher thermodynamic efficiency over gasoline engines. Typical modern CMR diesels run with CRs of 14:1 to 18:1 which is almost twofold of the equivalent petrol engines. An ideal thermodynamic efficiency of gasoline (Otto cycle) engine is:

$$\eta_O = 1 - CR^{1-\gamma} \qquad CR = \frac{v_1}{v_2} \tag{1}$$

An ideal thermodynamic efficiency of diesel (Diesel cycle) engine is:

$$\eta_D = 1 - CR^{1-\gamma} \cdot f(\alpha) \qquad CR = \frac{v_1}{v_2} \qquad f(\alpha) = \frac{\alpha^{\gamma} - 1}{\gamma \cdot (\alpha - 1)} \qquad \alpha = \frac{v_3}{v_2} \tag{2}$$

An ideal thermodynamic efficiency of gas-turbine (Brayton or Joule cycle) engine is (Davies, 2003: Hill & Peterson, 1992):

$$\eta_B = 1 - PR^{\left(\frac{1-\gamma}{\gamma}\right)} \qquad PR = \frac{p_2}{p_1} \tag{3}$$

Modern turbofan engines may reach Pressure Ratios (PRs) of 40+ in many stages of axial multi-compressors. For a theoretical Brayton cycle efficiency of 65% would be achieved at PR = 40. Of course, the final efficiencies are much lower. A comparison of calculated ideal gasoline and diesel cycle efficiencies (Braess & Seifert, 2005; Challen & Baranescu, 2006; Hill & Peterson, 1992) is shown in Figure 3. Compression ratios higher than 10:1 are not practical for typical gasoline aero-engines. Excel™ 2007 (Microsoft Corporation, Seattle, WA) was used for spreadsheet calculations and graphic presentations of results.

All heat-engine cycles can, at best, "dream" to reach the theoretical maximum of the Carnot-cycle as limited by the 2nd Law of Thermodynamics. For example, Otto engine with CR of 9:1 will have an ideal thermodynamic efficiency of 53.7% while diesel engine with CR of 18:1 and cut-off ratio of 1.5 will have ideal theoretical efficiency of 60.7%. The air temperature and pressure in diesel engine will be about 520^{0}C and 50 bar (727 psi) respectively after polytropic compression of environmental air at Sea Level (SL) International Standard Atmosphere (ISA). Cycles shown in Figure 2 are idealized and do not include other losses. A real diesel cycle replicates more a dual or mixed (Sabathe) cycle in which part of the combustion is under constant volume (Otto-like) and part under constant pressure (Brayton-like) further increasing overall efficiency (Woodyard, 2010). An actual gasoline engine has practical total efficiency of 30-33% at best, while diesel engine may have efficiencies in the range 40-50%. Turbine engines generally do not fair better than Otto engines. That 50% to 70% of energy contained in fuel is "wasted" to environment is just the consequence of the thermodynamics of heat-conversion engines. IC engines itself are marvels of engineering and testimony of creative human capabilities.

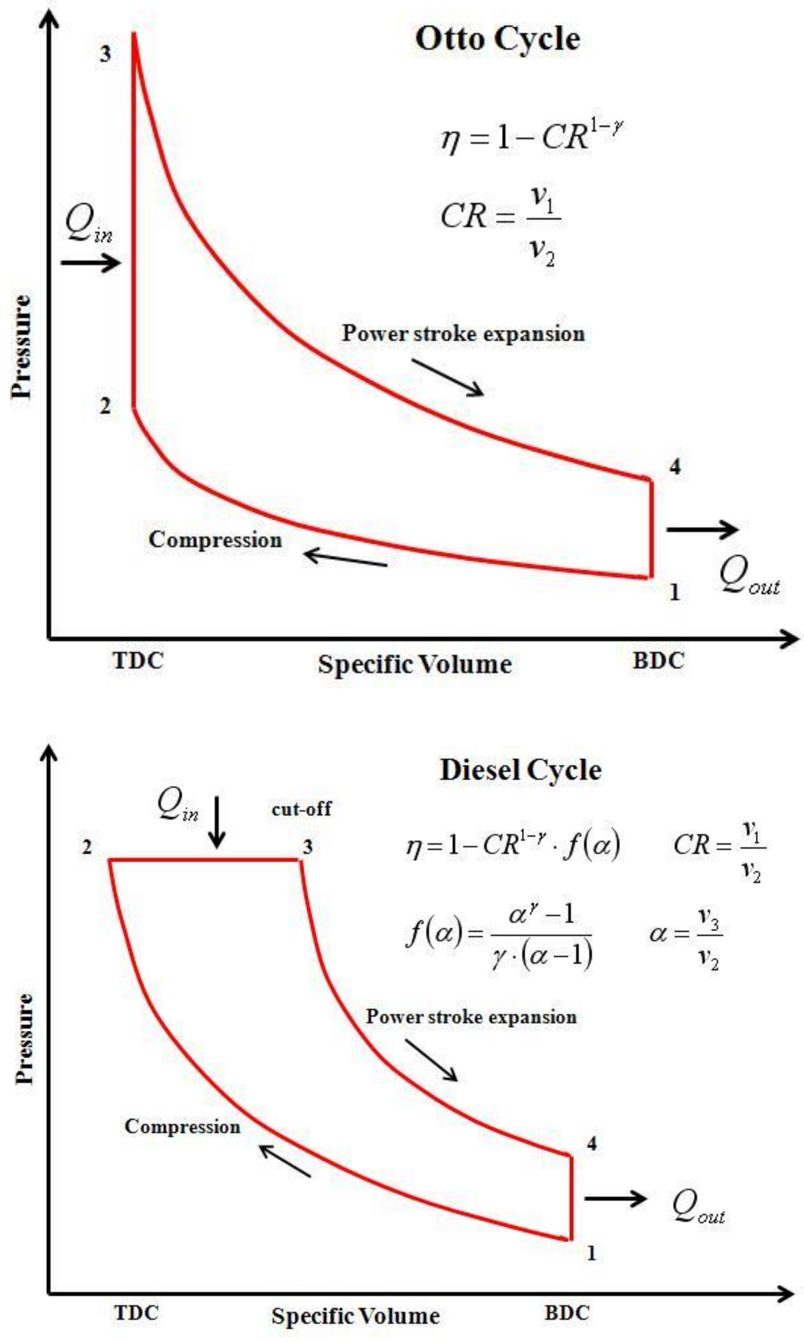

Figure 2. Ideal Otto and Diesel thermodynamic cycles. Not to scale.

Unlike gasoline engines there is no danger of detonation and/or pre-ignition in diesels since it is only air that is being compressed. Typically, air temperatures at the end of compression will reach 550^0 to 600^0C. When diesel fuel is injected in such hot compressed air it will burn spontaneously due to Combustion Ignition (CI) increasing pressure and temperature further. Diesels do not need SI as Otto engines do. Gasoline engines have to compress pre-mixed fuel-air mixture and the CRs are limited by the detonation/knocking characteristics of the engine-fuel combination.

Modern diesels have BSFCs on the order of 0.23-0.35 lb/hp-hr (0.14-0.21 kg/kW-hr). Compare that with the best average of 0.45-0.50 lb/hp-hr for gasoline aero-engines (0.290 kg/kW-hr). Some advanced helicopter turboshaft engines (e.g., GE's CT7-8) may reach at an optimum operational set-point equivalent BSFC of 0.451 lb/HP-hr (0.274 kg/kW-hr) at maximum continuous power of 1,608 kW (2155 hp) with dry weight of 246 kg.

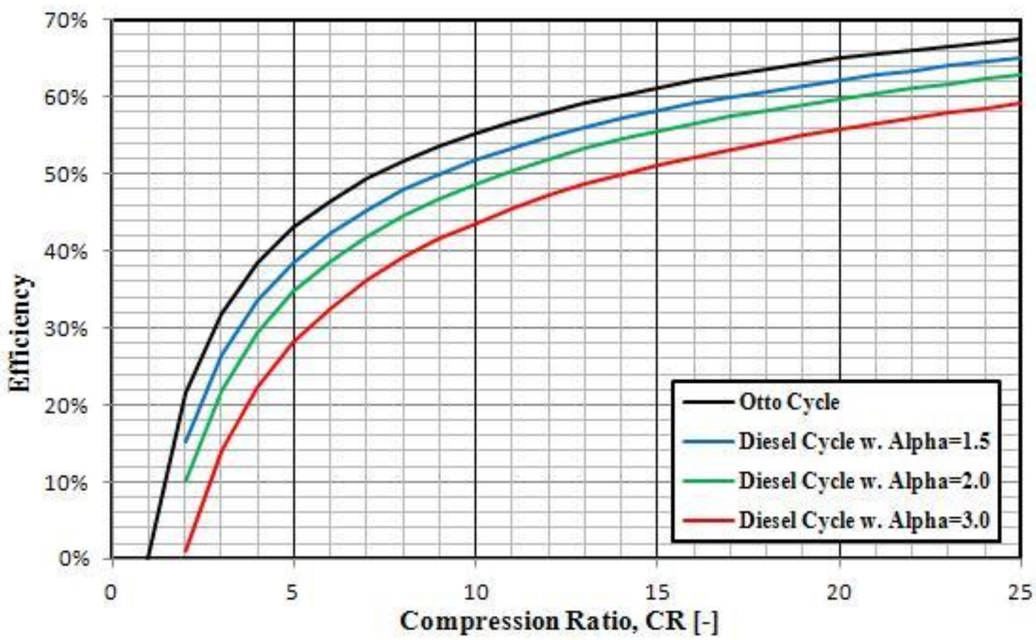

Figure 3. Comparison of ideal Otto and Diesel thermodynamic cycles for various CRs and cut-off ratios (Diesel only).

A contemporary diesel-powered passenger car gets 50-60 mpg (4-5 L/100 km) while non-hybrid gasoline at best 30 mpg in mixed driving. Gasoline engines are typically lighter in construction, but the new diesels can be all made of advanced lightweight aluminum alloys and there is additional space to up horsepower (performance tuning) without major modifications – something that would be impossible in an Otto engine. Existing enabling technologies when employed would make aero-diesel superior to gasoline engine and a tough competitor to light-to-medium turboshafts and turboprops. A color illustration of a modern aero-diesel with propeller attached is shown in Figure 4. Diesel engines are typically, 4-stroke or 2-stroke (cycle) with the number of cylinders varying from 1 to 20 depending on the application: marine diesels, railroad diesel-electric, trucks, personal cars, tanks, aero-engines, heavy-duty equipment, etc. (Woodyard, 2010).

Common Rail Direct Fuel Injection Aero-Diesels

In the older diesel engines fuel was injected and atomized at a proper moment by using individual high-pressure pumps. A CMR high-pressure (HP) fuel delivery and DI for automotive use was developed in 1980's although diesels for submarine and marine applications had sort of CMR delivery systems developed in early 1920's.

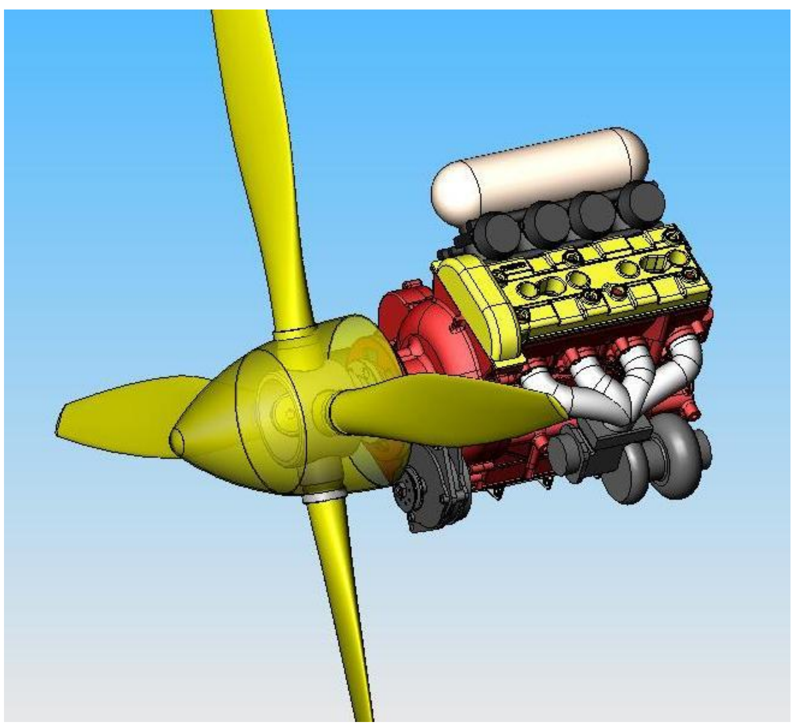

Figure 4. Aero-diesels offer increased reliability, safety, performance, and lowest BSFC of all existing heat-engines.

A CMR system utilizes common HP tube/pipe that delivers fuel under extremely high pressures of 2,000+ bar (30,000+ psi) to individual solenoid or piezoelectric injectors. There are sometimes multiple fuel injectors with one or more combustion "chambers" per cylinder controlled individually to increase combustion efficiency. A HP-pump stores fuel at high pressure in a common tube (HP accumulator or rail). Fuel pump works continuously with variable displacement maintaining high-pressure within operational limits with safety valves "leaking" excessive fuel back to fuel tank.

In the older fuel injection systems the HP pump was directly geared to the engine and low engine RPM would result in low fuel pressure directly affecting the atomization process and the combustion efficiency. The modern CMR always uses the same Compression-Direct-Ignition (CDI) high pressures. Diesel's FADEC meters the calculated fuel amount and timing by the duration of the individual solenoid or piezoelectric injectors open position. Accordingly, the atomization process always delivers finely dispersed tiny fuel droplets that mix with hot air completely and burn spontaneously and efficiently throughout the entire working envelope – from idling to maximum speed.

Utilizing modern diesel FADEC systems it is also possible to control "pilot" pre-injection before the main injection event. This lowers the characteristic "knocking" sound of diesel engines caused by sudden combustion onset and cylinder pressure spikes following the main injection event. It also simplifies otherwise problematic cold starts, lowers engine vibrations, etc. Some advanced CMR CDI diesels deliver up to five discrete injections per stroke/per cylinder. Clearly, the CMR system with associated HP pump and engine digital control is a critical component requiring independent power source and redundancy.

In the case of the 4-stroke 4-cylinder high-speed diesel only one stroke is combustion (power) stroke. Thus, it will take two full crankshaft revolutions for one power stroke in a particular cylinder. A 3,600 RPM aero-diesel will need fuel injection in a particular cylinder once every 33.3 milliseconds (30 Hz). Power stroke in this case lasts only about 8.3 milliseconds. Therefore, main and eventual pilot injections have all to fit within a fraction of this short interval. This is evidence why modern redundant digital electronic controls are superior to mechanical control with associated tear and wear.

Discussion of Results

UniBo has developed and tested a family of CDI CMR Variable-Geometry-Turbocharger (VGT) and FADEC–equipped aero-diesels (Figure 5). UniBo's aero-diesel rebuilds range in power from air-cooled 100 hp for Light Sport Airplane (LSA) to liquid-cooled Leviathan's 1,600 hp with design peak cylinder pressures up to 180 bar (2,644 psi). These aero-diesels could be used in light-to-medium airplanes and helicopters while directly competing with smaller turboprops and turboshafts. Most of the UniBo aero-engines are based on the automotive diesels from Peugeot, Daimler-Benz, FIAT, etc. However, each engine was completely disassembled and many parts were changed and modified for improved performance and to comply with certification standards by aviation authorities. In particular, the newest FADEC technology has been borrowed from the racing cars (Formula 1) industry. Such electronic engine controls, actuators, and sensors are of highest quality and designed to operate under high-"g" and in a very harsh environment.

Most of the UniBo high-speed, 4-stroke, CMR CDI aero-diesels, are liquid cooled with 70% Ethylene-Glycol and 30% water in weight. The cooling system is contained within the engine casing and only an air cooler is external to it. Motive fuel is, of course, petrodiesel, compliant with the European standard EN 590:2009 and Cetane index of minimum 50 (ASTM D976 and D4737). Engine cylinders (4, 6, or 8) are in-line or V-90^0 arrangement. Custom made VGTs with no turbo-lag are used to flatten the torque-curve, widen naturally narrow power band of diesels, and deliver high power at high RPMs. Turbocharging is far less critical in diesel engines compared to gasoline engines. Most of the UniBo high-speed aero-diesels have Propeller Reducing Speed Unit (PRSU). Basically, this is a very reliable gearbox consisting of quiet quadruple helical gear train, contained entirely within the engine and lubricated by the engine oil. Fuel injection is via CMR using one injector per cylinder and fully controlled electronically. Direct Current (DC) power for FADEC is provided by standby DC battery and backed up by airframe AC/DC generator(s). Fuzzy logic and other controlled strategies are used to optimize FADEC performance, monitor engine health, contain failed sensor(s), and implement recovery strategies after partial engine failures. Accelerometer sensors are used to electronically control engine vibrations (less stress on engine mounts) and noise through "pilot" fuel injections. FADEC relieves pilots from much of the workload (Daidzic, 2012a). One lever per engine controls torque (power), fuel conditioning, and propeller speed/pitch in diesel-props. In helicopter aero-diesels, the main rotor and the engine RPM remain constant in normal operations while torque/power is changed manually by throttle or automatically by collective governor to address blade pitch changes.

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Excellent hybrid-power solutions are also possible when marrying aero-diesel with Kinetic Energy Recovery System (KERS) and Li-Ion electrical storage batteries (Daidzic, 2013; & Piancastelli et al. 2013). Hybrid power is today very common in automotive vehicle designs (Ehsani et al, 2010; & Miller, 2005). Specifically, Daidzic (2013) describes future Helicopter Energy Recovery System (HERS). A super-power assist capabilities are based on the high-density packing of multiple counter-rotating aramid-epoxy flywheels (mechanical ultra-capacitor) in vacuum with magnetic bearings to minimize energy leakage, gyroscopic precession, and provide for flywheel failure containment. Flywheel's shaft is connected via clutch to a highly efficient and powerful Brushless DC motor (BLDC) which is actually a permanent-magnet variable-frequency brushless inverted-DC self-synchronous AC motor. All-mechanical flywheel utilizing Continuously Variable Transmission (CVT) is a viable alternative. Charge and discharge of electro-mechanical flywheel system is controlled by BLDC motor. Angular speeds up to 65 kRPM are possible and with 0.1 kg m^2 flywheel's rotary inertia one can store about 587 Wh of kinetic energy. Discharging this entire energy in 10 seconds for emergency super-power assist can generate about 210 kW (281 hp) of power. Using Li-Ion battery for energy storage a mild-hybrid helicopter can be designed with the power-assist of 40-50 kW over a period of several minutes. The conventional powerplant starter/generator and Ni-Cd battery would be eliminated then.

Comparative Analysis

Modern helicopter gasoline reciprocating engines (e.g., Lycoming engines for Robinson, Enstrom and Sikorsky/Schweizer light helicopters) normally have PD of about 1 kW/kg (0.6 hp/lb) with BSFC on the order of 0.5 lb/hp-hr. Helicopter aero-diesel engines achieve 10-20% better PDs with half of the BSFC. The PD of modern helicopter turboshafts is about quadruple, while the BSFC is on the same order of the gasoline engines. Accordingly, for higher horsepower applications (> 300 hp), turboshafts are clearly technically superior to gasoline engines. However, the total purchasing, operational, maintenance costs and more complex turbine operations need to be considered as well.

On the other hand, aero-diesels have low purchase and maintenance cost (as gasoline or lower) while delivering superior BSFC compared to turboshafts. While the gasoline engines can only use Avgas and turboshaft mostly only JP fuels, aero-diesels can use cheaper diesel as well as widely available jet fuels (JP-4, JP-5, etc.). Some basic properties of the engine fuels is given in Table 1. A summary of essential comparative analysis of gasoline, diesel, and turboshaft engines for small airplanes and helicopters is given in Table 2.

For example, a Rolls-Royce Allison 250-C20J turboshaft powering Bell 206B (JetRanger III) helicopter is compared against a compact 2-Liter UniBo D004MAF aerodiesel and a Lycoming's gargantuan 8.8-Liter TIO-540 (or improved 541). Various manufacturer's information and references were used to design and verify data in Tables 1 and 2 including Davies (Eds) (2003), Kroes & Wild (2002), and Treager (2001). One also has to keep in mind different power ratings used for 250-C20J and both IC engines. A 420 hp 5-minutes takeoff power (MTP) with 317 hp Maximum Continuous Power (MCP) RR-turboshaft was used. Bell 206B has actually de-rated 250-C20J with 317 hp MTP and 270 hp MCP. Both power ratings for reciprocating engines are maximum takeoff or short-term overload ratings (D004MAF). Various versions of each engine exist and to discuss them all would be an incredible effort. Additionally, while the Lycoming has maximum RPM of about 2,600, the UniBo's D004MAF delivers about 3,000 RPM (after internal gearbox), and the RR turboshaft delivers 6,016 RPM (100% N_2) after internal gearbox reduces it from power-turbine's 33,290 RPM. Thus, a bigger and heavier main transmission (two stages) is required for turboshaft engine turning the Bell's 206B main rotor mast at about 395 RPM (100% NR). An aero-diesel engine can be overloaded shortly without damage while in turbo-charged gasoline powerplant that would be very difficult and possibly lead to engine and turbocharger damage. Aerodiesel's turbocharging works without much trouble while the same cannot be said for the delicate gasoline turbocharged engine. A turboshaft engine is essentially normally-aspirated engine losing power with altitude. For example, at 10,000 feet pressure altitude a RR turboshaft would deliver only about 74% of its rated SL power, while both turbocharged IC engines would still deliver 100% of its rated power, being well below its critical altitudes.

Smaller (and lighter) transmissions are required to power helicopter's main and anti-torque rotors with reciprocating engines. Proposed aero-diesel prime movers are reaching 1.5 kW/kg (0.9 hp/lb) PDs, at half of BSFC, higher service ceilings, and with added robustness and reliability compared to gasoline engines. New helicopter turboshafts have SL PDs about 5.0 kW/kg (not all subsystems included). With takeoff, 30 seconds, 2 min or continuous One Engine Inoperative (OEI) ratings, modern turboshaft PD can increase another 20% for limited time only (Daidzic, 2012b). However, helicopter turboshafts must have massive internal and external transmissions (safety critical and expensive to maintain) due to much higher RPMs of free power-turbines. Turboshaft's or turboprop's BSFC is typically 70-120% higher than that of aero-diesels. If we consider the entire helicopter power-train, which also includes fuel storages turboshafts show small advantage and then only at lower DAs. At higher DAs turbocharged aero-diesels may actually have higher PD than turboshafts resulting in higher cruise and Hover Out of Ground Effect (HOGE) service ceilings. For reference, power-assist flywheels have spectacular PDs exceeding 12 kW/kg. In combination with more limiting BLDC that would be about 6 kW/kg fully rechargeable super-power assist independent of Density Altitude (DA).

Table 1

Some basic fuel properties

Fuel	Density at 15^0C [kg/m^3]	Typical Energy Content	
		Specific [MJ/kg]	Volumetric [MJ/L]
Avgas 100LL	715	43.71	31.25
Diesel	832	43.10	35.86
JP-4	751	43.46	32.64
JP-5	818	43.00	35.17
Jet A-1	710	43.23	30.69

Table 2

Selected Engine Data

Engine	Power [hp]/[kW]	Weight/ Mass [lb]/[kg]	Displacement Volume [in^3]/[L]	BSFC [lb/hp-hr]/ [kg/kW-hr]	P/W (PD) [hp/lb]/ [kW/kg]
Ly TIO-540	310/231	450/205	540/8.8	0.495/0.302	0.69/1.13
D004MAF	300/224	392/178	122/2.0	0.468/0.285	0.77/1.26
250-C20J	317/237	174/79	NA	0.768/0.468	1.83/3.0

Weight and volume are of essential importance in aeronautical applications. We believe that hybrid and power-assist aero-diesel with HERS and possibly Li-Ion batteries for intermediate regenerative energy storage could be a viable propulsion option on light-to-medium helicopters and airplanes.

Advantages of Aero-Diesels

Diesel engines are overall more efficient, reliable, and durable engines than gasoline engines and in several points they excel over smaller turboshafts and turboprops. It would be impossible to list here all the advantages aero-diesels have over gasoline and/or smaller turbine engines, but we will highlight some more important ones:

- Fire safety
    - Diesel fuels are far safer than volatile and explosive light gasoline fuels.
- Fuel economy
    - Diesel engines can use a wide variety of cheaper heavy kerosene/paraffin fuel oils (also biodiesels).
    - The practical efficiency of modern diesels is, at least, 20% higher than gasoline engines.
- Engine life and efficiency
    - Diesel engines are more robust and last on average twice as long as gasoline engines of similar power.
    - Efficiency of Diesel engines is uniform throughout the entire operating envelope.
    - The P/W ratio of diesel aero-engines is potentially better than gasoline engines.
    - Range and endurance can increase by 20% to 40% using aero-diesel over gasoline aero-engine.
- Flight safety
    - Practically every aero-diesel is turbocharged making high DA operations much safer.
    - Absence of high-voltage spark-ignition makes aero-diesels more reliable.
    - There is far less danger of carbon monoxide poisoning.

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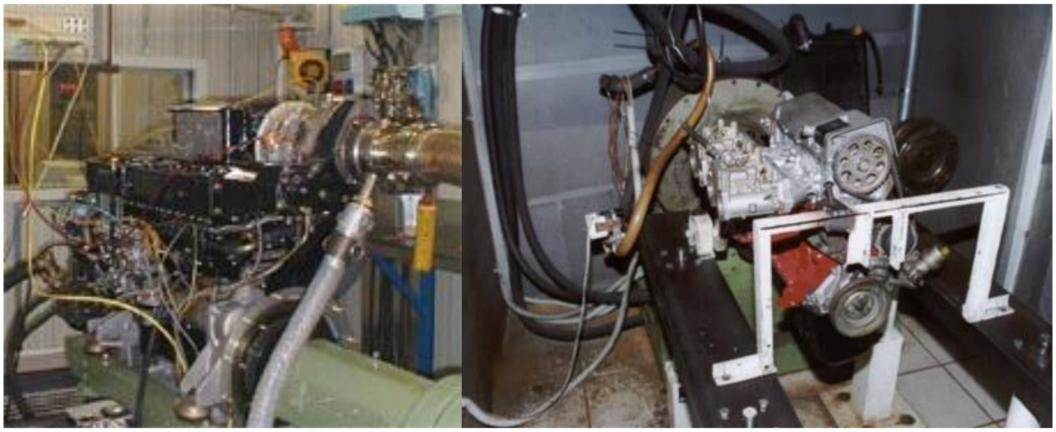

Figure 5. Engine test facilities of University of Bologna are located at the Forli "Luigi Ridolfi" airport (ICAO: LIPK; IATA: FRL).

Conclusion

Aero-diesels are "the new kid on the block" in the world of aviation propulsion and have, in our opinion, bright future. Diesels deliver highest efficiency of all existing practical heat-conversion engines. They are reliable, robust, and safe and have some clear advantages over gasoline engines in terms of higher efficiencies, higher performance figures, flight safety, and fire safety due to combustion of heavier low-flammability fuels. The use of environmentally friendlier biodiesels and cheaper jet fuels is easily accommodated. Combined with the custom-designed FADEC's, single-unit aero-diesels can be produced today in the range of 50 to 2,000 hp to cover the operating range of light-to-medium airplanes and helicopters. Aero-diesels are also becoming engines of choice for UAVs. Particularly, a combination of aero-diesel with the HERS power-assist system could offer attractive advantages to helicopters all but eliminating "no-man's land" in Height-Velocity (H/V) curve and increasing service altitudes. We believe that in the low-to-medium power range aero-diesels could provide many advantages over other aero-engines in General and Business/Commercial aviation. It is not difficult to imagine that within the next 30 years half of the IC reciprocating aero-engines worldwide will be diesel.

Author Bios

Dr. Nihad E. Daidzic is president of AAR Aerospace Consulting, L.L.C. He is also a full Professor of Aviation, adjunct professor of Mechanical Engineering, and research graduate faculty at Minnesota State University, Mankato. He was formerly a staff scientist at the National Microgravity Research Center and the National Center for Space Exploration and Research at NASA Glenn Research Center in Cleveland, OH. He also held various faculty appointments at Vanderbilt University, University of Kansas, and Kent State University. His current research interest is in theoretical, experimental, and computational fluid dynamics, aircraft stability, control, and performance, mechanics of flight, piloting techniques, and aerospace propulsion. Dr. Daidzic is CFII and ATP with flight experience in airplanes, helicopters, and gliders.

Dr. Luca Piancastelli is a full Professor (Professore Ordinario) of Mechanical and Industrial Engineering at the University of Bologna in Bologna, Italy. His previous technical experience includes work on design and optimization of engines for formula 1 (F1) racing cars (Ferrari), racing motorbikes (Ducati) and passenger cars (FIAT group). Dr. Piancastelli has pioneered new concepts and designs for modern common-rail turbocharged aerodiesels and FADEC's. His current expertise and interest is in computational Finite Element Methods (FEM), fuzzy-logic and optimal control, structural aerospace/aeronautics design, composite materials and metal alloys, and manufacturing methods and industrial engineering.

Mr. Andrea Cattini lives in region Emilia Romagna close to the Ferrari factory in Maranello and is chiefly responsible for commercialization and marketing of aerodiesel engines as well as organization of industrial production and technology transfer. Mr. Cattini still drives his 1997 Alfa Romeo 156 2.4 JTD, a first passenger car with the common-rail diesel, and has "logged" more than 350,000 miles in it. Mr. Cattini has keen interest in WW2 airplanes and has original drawings of the Italian WW2-airplane Caproni Reggiane and hopes to build one.

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