

DIESEL ENGINES FOR AEROSPACE USE

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ABSTRACT

The paper describes new developments in aircraft diesel engines. Light aircraft flying today use gasoline spark ignition engines for propulsion. This trend is starting to change.

Modern diesel engines are starting to be used in light aircraft. The main drivers for these phenomena are reduced availability of Avgas (aviation gasoline) coupled with newly developed automotive diesel engines. The new diesel engines provide higher reliability with lower maintenance and lower operating costs, with reduced fire hazard and lower EMI.

The reduced availability of Avgas has created a need for engines working on other types of fuel. Engine manufacturers have identified this need and have started to develop aviation diesel engines from scratch or as automotive engine conversions. NASA has also identified this area and has initiated the development of a diesel engine by Teledyne Continental motors under the GAP (General aviation propulsion) initiative.

The diesel engine has lower specific fuel consumption than a gasoline engine. This has a beneficial influence on the aircraft:

- Increasing range and endurance.
- Required fuel tank size is reduced (Density & SFC)
- Operation at high / low temperatures, and at high altitudes is facilitated.

It seems that diesel engines are here to stay and will gradually replace many gasoline engines.

INTRODUCTION

Light aircraft propulsion during the last half century is identified with gasoline spark ignition engines. This trend is starting to change.

Modern diesel engines are starting to be used in light aircraft. The main drivers for these phenomena are:

- The decline of leaded automotive fuels has reduced the availability of leaded Avgas.
- The availability of Jet A and diesel fuel.
- Availability of lighter modern diesel engines.
- Better reliability of diesel engines.
- Less maintenance
- Lower operating costs.
- Better specific fuel consumption.
- Reduced fire hazard
- Lower EMI – spark ignition eliminated

The transition to unleaded automotive fuel has caused a rise in Avgas (aviation gasoline) prices and in some places Avgas has become difficult to procure. This is caused by the transition of refineries to production of unleaded fuels. Automotive gasoline is not a good replacement for Avgas mainly due to its higher vapor pressure and relatively lower Octane Number.

Various engine manufacturers have identified the need for engines running on fuels, which are easier to procure, and have started to develop aviation diesel engines from scratch or as automotive engine

conversions. NASA has also identified this area and has initiated the development of a diesel engine by Teledyne Continental motors under the GAP (General Aviation Propulsion) initiative.

The list of aviation diesel engine manufacturers is quite varied, Teledyne Continental, Delta Hawk, Sietec, SMA, Thielert, A-Tech, Diesel-Air, Wilksch, Zoche, and other small companies. The engines are of various designs: two stroke with or without valves, various four strokes, air or water cooled and use of various starting methods.

The diesel engine has a lower specific fuel consumption than a gasoline engine. The higher density fuel requires less storage volume. Diesel engines run on diesel fuel and on jet fuel. Jet fuel is easier to operate in a harsh environment.

Modern diesel engines are of comparable weight to spark ignition engines installed in light aircraft (generally of older design). A diesel engine burns less fuel for the same mission.

The following paragraphs describe the history of the diesel engine and new developments in diesel engines.

THE DIESEL ENGINE HISTORY

The diesel engine was invented by Dr. Rudolf Diesel. The first patent was issued to Dr. Diesel on the 28th February 1892 for a compression ignition engine using coal dust as fuel. His first successful petroleum fueled engine delivered 25 hp at 170 rpm.

In 1901 licenses were granted to: Krupp M.A.N. Duetz (Germany) Sulzer (Switzerland), Nobel (Russia) and started to be used successfully in submarines and ships. At the beginning of the 20th century the use of diesel engines spread over the whole world. Various companies developed many diesel engines. Diesels were used for railways, ships and heavy equipment.

All over the world, various companies built aircraft diesels. In Germany: BMW Flugmotorenbau, Mercedes-Benz, and Daimler. In the USA Godfrey corp., Packard, and Gulberson. In Britain: Bristol diesel, Beardmore, Napier & Sons, Rolls Royce, and Sunbeam motorcar Co. In France: Clerget, Compagnie Lilloise de Moteur, Ateliers et Chantiers de la Loire, and Lorraine Delafontaine, in Italy Fiat, in Japan Mitsubishi, and in Czechoslovakia: Walter.

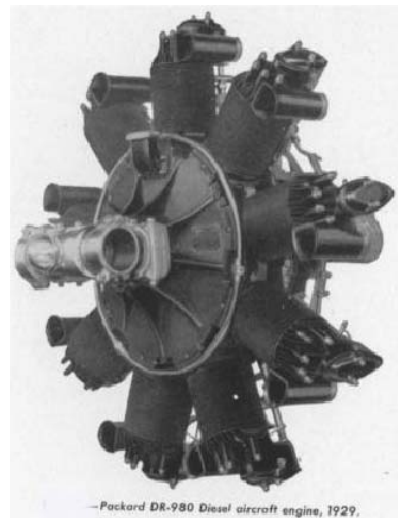


Figure 1: Packard DR-980 diesel aircraft engine 1929

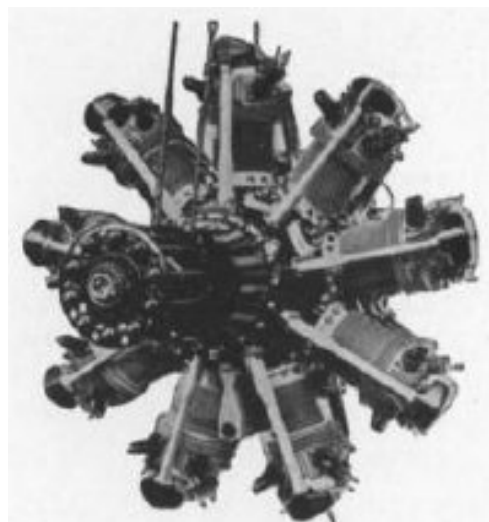


Figure 2: Bristol Phoenix Diesel Aircraft engine 1933



Figure 3: Mercedes diesel airship engine, 1936

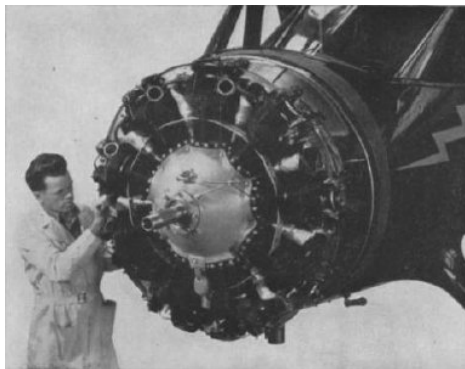


Figure 4: Gulderson A-1020 310 hp diesel engine, 1940

In 1913 Dr. Hugo Junkers built one of the first diesel engines for aviation, the MO-3. Diesel aircraft engines ranging from 200 to 2000 + hp were designed and flown until the forties. In 1931 the Junkers' 720 hp, Jumo 4 diesel engine was flown in regular service on Lufthansa.

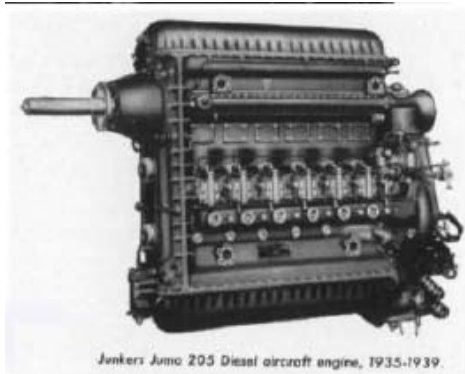


Figure 5: Junkers Jumo 205 Diesel aircraft engine 1935-1939

One of the largest diesel aircraft engines of that era was the Clerget 16-H 2000 hp water cooled, turbocharged to 20,000 feet weighing 3800 lb, 1.9 lb/hp. Diesels were flown un-turbocharged to 21,000 feet and turbocharged to 27,000 feet. After the Second World War the use of diesel engines in aircraft declined, possibly due to their relatively high weight. Diesel engines continued to be used on land based systems (Trucks, ships, railways, large generators, etc.) due to their higher reliability and lower operating costs.

All diesel engines require an injection system. Until lately, injection systems were mechanical. During the last decade electronically controlled injection systems have been designed. Electronically controlled injection systems like the common rail system have improved the fuel proportioning ability; multiple fuel injections per cycle are possible.

WHY DIESEL

Diesel engines are more robust, durable and more reliable. Diesel engines have a higher thermal efficiency; their specific fuel consumption is lower, the fuel they use is cheaper and has a higher volumetric energy content. Diesel engines have lower operating costs compared to spark ignition engines. Kerosene based fuels present a lower fire hazard. Diesel engines cause less electromagnetic noise. The diesel combustion products are more environmentally friendly than gasoline engine products. The advent of modern computer aided design has reduced the amount of experimentation and assembly errors thus facilitating new engine design. The move to unleaded fuels, as explained in the next paragraph, requires adaptation or replacement of current gasoline engines, thus creating a demand for different engines.

THE AVGAS FUEL SHORTAGE

Aviation gasoline (Avgas) is based on automotive leaded fuel with special additives. Produced by refineries as “a by-product”, Avgas is a low volume product compared to automotive fuel. With the advent of unleaded fuels most refineries are reluctant to produce Avgas for economic reasons. Shortage of Avgas supply has caused a rise in prices. In some places Avgas is no longer available. One of the main additives to boost Avgas (100LL) octane number is TEL. It is made in the UK by a plant which is planned to be shut down in 2005.

Some general aviation organizations and manufacturers have foreseen the problem and gained STCs for use of automotive unleaded fuel with aviation engines that were originally designed for low octane fuel. Although many light aircraft use automotive fuel it has its drawbacks. Automotive fuel has a lower octane number. It has higher vapor pressure than Avgas and tends to boil off the more volatile ingredients at low pressure. Some engines require the lead for valve seat lubrication. High performance spark ignition engines still require Avgas.

Diesel fuel and jet fuel Jet A are both readily available. Larger airports carry jet fuel. Diesel fuel is available at any civil or military gas station. The production of jet fuel is in larger volumes for commercial aviation. Its price is relatively low, and there is no shortage foreseen.

Some military operators prefer diesel fuel since it is used for their ground vehicles.

DIESEL ENGINE CLASSIFICATION

The diesels engines referred to in this paper are all direct injection, compression ignition engines. High-pressure fuel is injected into the cylinder head at the point when ignition is scheduled.

Diesel engines divide into two main classes: two stroke, and four stroke. Four stroke diesels are similar to four-stroke spark ignition engines, one power stroke per cylinder for every second revolution. Four stroke engines have at least two valves per cylinder head. Two stroke diesels have a power stroke per cylinder on every engine revolution. Two stroke diesels are classified according to their scavenging method - Piston ported, valve ported or uniflow scavenging.

There are other types of diesel or heavy fuel engines such as:-

- Converted spark plug engine using a pre-ignition chamber.
- Two-cylinder compression
- Two opposing piston engine
- Wankel type
- and others

Diesel engines come with or without supercharging or turbo charging.

Injection systems are generally mechanical for older engines or for very large engines. Modern passenger car diesel engines use electronically controlled fuel injection. The most widespread electronic injection system today, is the common rail system, invented by Fiat. The common rail injection is in use by all major car manufacturers for engines in the range of 30 to 300 hp.

The mechanical injection system limits the maximum engine rpm since the plunger cannot follow the cam, and starts floating at high rpm (about 2700 rpm) thus reducing the amount of fuel metered into the cylinder. The common rail injection system is not limited by inertial phenomena. Engines using the common rail system can easily reach 4500 rpm and more.

Many pre-world-war-two diesel engines were two stroke engines. Two stroke engines are simpler and produce approximately 80% more power for the same displacement compared to four stroke diesels

TURBO CHARGING

All modern diesel engines are turbocharged to increase the volumetric efficiency. The same turbo charger is used to keep power at altitude with existing automotive turbochargers a critical altitude of 5000 to 11000 feet is reached depending on turbocharger and engine combination. The turbo charging is used to get more air mass into the engine. This enables the engine manufacturer to reduce the compression ratio and decrease the stress. The compression ratio of normally aspirated diesel engines is in the range of 20 to 24. With turbo charging the compression ratio range drops to 16 to 20. Turbo charging is performed with exhaust driven turbo chargers, two stroke diesels require some kind of pressurizing device for starting, generally a supercharger directly driven by the engine is used. Other devices are also used; Zoche uses pressurized air for starting.

DIESEL RELIABILITY

The diesel engine has fewer systems therefore making it more reliable. A diesel has no ignition system, removing the least reliable system in spark ignition engines. State of the art injection systems whether electric or mechanical are relatively high reliability items. When an injection system fails the failure is gradual and can be easily detected and corrected without undue loss of power. Exact mixture control is not required, unlike gasoline engines where incorrect mixture can cause engine shutdown.

MODERN DIESEL ENGINE COME BACK

For the reasons previously mentioned, some engine manufacturers have decided to design new or converted automotive engines. These manufacturers hope to capture a large portion of the aircraft diesel

engine market. There are at least three engine manufacturers in the USA. Delta Hawk with a two-stroke piston ported liquid cooled V Diesel. Teledyne Continental funded by DARPA to develop a two-stroke diesel in the GAP (General Aviation Propulsion Program). DARPA has given SBIR (small business contracts) to Sietec and to the Global Aircraft Corporation to develop a new diesel engine. Sonnex Research has also been awarded a contract by DARPA to modify a gasoline automotive engine to burn jet fuel by use of stratified charge ignition.



Figure 6: Delta Hawk USA



Figure 7: The GAP engine –TCM

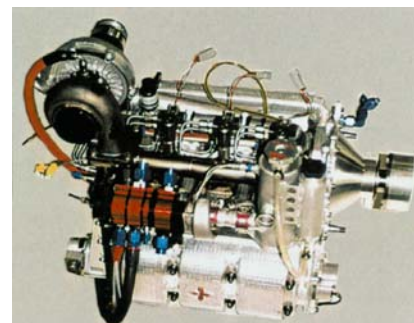


Figure 8: General Atomics USA

In Britain various small companies have started to develop diesel engines. The

Wilksch WAM 120 diesel is already flying on experimental aircraft (home built).

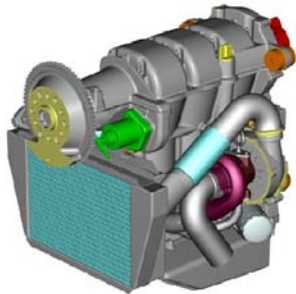


Figure 9: Wilksch WAM-120 UK

In France SMA, a consortium of Renault Sport, Snecma, and EADS has succeeded in developing a 230 hp four stroke, horizontally opposed, air cooled, mechanically injected, turbocharged to 10,000 feet, diesel engine.



Figure 10: SMA SR 305 France



Figure 11: SMA SR 305 France

In Germany Thielert Aircraft Engines has succeeded in converting a modern 1.7 liter Mercedes automotive turbocharged diesel to aircraft use, providing 135 hp with a critical altitude of 8,000 feet. The engine is liquid cooled, has four cylinders in line, and has a common rail electronically controlled injection system. Zoche is also developing a

four cylinder diesel since 1985 but it has not yet reached the market.



Figure 12: Thielert TAE-125 Germany



Figure 13: Thielert TAE-125

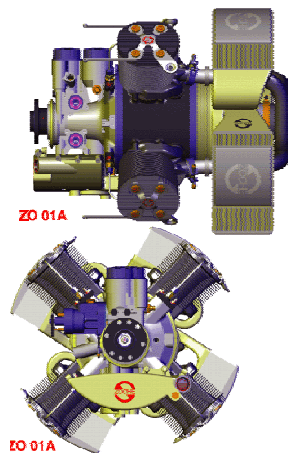


Figure 14: ZOCHE ZO 01A

Both the SMA and Thielert engines are already flying, and have JAR-VLA certification. The wilksch engine is also flying on an experimental air vehicle. Its certification is not anticipated. The following table displays the main engine characteristics of a few modern diesels. One must bear in mind that the data is based on manufacturer data sheets and that only three

of the eight engines shown have flown. As shown the diesel engine weight is approximately 2 lb/hp (engine without build up). Both certified engines SMA and TAE are four stroke diesels. The TAE is the fastest turning engine. This is possible due

to the electronic injection control. The TAE has the highest power to displacement ratio. The General Atomics engine project is the one with the least data available.

Table 1- Modern diesel development engines characteristics.

Manufacturer	SMA SR-305	Thielert TAE -125	Delta Hawk	General Atomics	ZOCHE ZO-01A	GAP Teledyne Continental	Airship UK A-Tech 100	Wilksch UK WAM -120
Power [Hp]	230	135	150	150	150	200	100	120
RPM	2500	3900	2700	3000	2500	2200		2200
Volume [Liter]	5	1.7	3.3	1.9	2.66	3.9	1.81	1.8
S.F.C [lb/hp×hr]	0.37	0.38	0.38	0.42-0.36	0.37	0.36	0.36	0.46
Fuel Injection	mechanic	electronic	mechanic		mechanic	mechanic		mechanic
Turbocharged	Y	Y	Y	Y	Y	Y	Y	Y
Cylinders	4	4	4	3 (x2)	4	4	2	3
T.B.O [hr]	3000	2400	2000		2000	3000		1000
Dry Weight [lb]	400	300	270	260	185	300	220	220
Type	4 st HO	4 st InLine	2 stroke V	2st uniflow	2st Radial	2 st uniflow HO	2 st uniflow HO	2st uniflow - inverted
Critical Altitude	12,000	8,000	15,000		9,000		25,000	
Cooling	Air/oil	Liquid	Liquid		Air	Liquid	Liquid	Liquid
Compression ratio	16:1	19:01	19:1		17:1	18:1		
W/P [lb/hp]	1.7	2.2	1.8	1.7	1.2	1.5	2.2	1.8
Status	Certified	Certified	Development	?	Development	Development	Development	For sale
HxWxL (cm)	75*90*75	58x78x80	48*58*68	46*58*70	56*56*81	60*85*89	35*70*57	66x53x77

AUTOMOTIVE ENGINE CONVERSION

Conversion of a new modern four-stroke diesel engine with common rail for use in general aviation is very attractive.

The basic engine already has a relatively high power to displacement ratio. More than 80 HP per liter has already been achieved.

In conversions of automotive engines to aviation use the power can be increased by up to 50 percent (more than 100 hp per liter) with very small increase in engine stress, by the following modifications:

- Reduction in engine compression ratio and compensating with higher turbocharger boost to maintain same pressures. This provides a larger combustion chamber, hence more charge and power

The only drawback is engine start capability. While the car manufacturer's target is that the engine will start immediately, an aviation engine may start after a few seconds of motoring.

- The diesel engine operates with excess of air. The common rail system enables maintaining longer combustion, and maintains the peak torque for a prolonged time by a precise metering of fuel. In each cycle fuel is introduced in sequential multiple injections to maintain the above. In the aviation engine more fuel is introduced since pollution laws are less restricting (The only rule in UAVs, for example, is no visible smoke)
- Short power boost for the takeoff phase is feasible.

A weight reduction program is also possible. A cast iron crankcase may be

designed from aluminum and certain other parts have a good potential for weight reduction.

In an effort to improve the power to weight ratio, the weight reduction programs are less cost effective. It is better to increase engine power instead, as is the case with automotive engine design.

With the above modification the four-stroke diesel Compression Ignition (CI) engine is comparable to the four-stroke Spark Ignition (SI) engine.

AIR VEHICLE IMPLICATIONS

Modern diesel engines can favorably compete with existing spark ignition engines, most of which have been designed more than 30 years ago.

The main advantages in going from gasoline spark ignition engines to kerosene compression ignition engines are:

Lower SFC

Due to the improved efficiency of the diesel cycle, the required fuel for a specific mission is generally reduced. The use of electronic ignition, enables exact proportioning of fuel.

Diesel engine SFC is .32 to .39 lb/hp/hr compared to .40 to .50 for spark ignition. Older gasoline engines SFCs run between .45 to .5 lb/hp/hr. Gasoline engines, designed from 1960 and on, run between .41 to .44 lb/hp/hr. On average we get 20% reduction in fuel consumption.

Insensitivity to fuel proportioning

Diesel engines use excess air, and a lean mixture is not a problem. The change of fuel flow with altitude is easier to handle with an engine that can tolerate errors in both directions. In gasoline engines the mixture has to be on the rich side of the EGT (exhaust gas temperature) curve, otherwise the engine runs hot. A very rich mixture will cause irregular running and loss of power.

Higher fuel density

The increase in density from .7 for gasoline to .8 for jet fuel reduces the size of the fuel tank or increases the range for fixed volume. The reduction in fuel tank size has a beneficial effect on new aircraft designed for diesel engines reducing the required fuel tank size and reducing the overall empty weight for a fixed mission.

Reduction in rejected heat

Due to the higher efficiency, the heat produced by the engine is reduced by 10% to 15% for the same power. This reduces the cooling requirements, reducing the size of heat exchangers (less weight, and volume-weight again) and reducing the cooling drag.

Change of fuel system

Most aero diesel engines are designed or converted to operate on jet fuels (jet A1)

Jet A1 true vapor pressure is an order of magnitude smaller than Avgas hence operation at higher altitudes is enabled.

Reliability increase

Increased engine reliability tends to decrease the in flight engine shutdown incidents. Thus increasing flight safety.

- Reduction in maintenance

Diesel engines are of more robust design than gasoline engines and tend to have less unscheduled maintenance. Modern diesel engines are designed for long intervals between scheduled maintenance. This is a carry over of automotive technology. The mileage between scheduled periodical maintenance has risen in the last decades by a factor of ten. The class of light diesels has inherited this property since it had to compete with other automotive engines.

Reduction in operating cost

Diesel engines use less fuel and the fuel is cheaper. Reduction in maintenance and reduction in fuel cost, reduce the direct operating cost of diesel-powered aircraft.

Improved range and loiter performance

With respect to the Breguet range formula, an inverse relationship of range with SFC is evident. Diesel engine SFC is reduced by 10% to 30% compared to spark ignition engines, giving the same increase in range, for the same aircraft and fuel weight. In some cases the empty aircraft weight would increase due to increased engine weight.

For a new design, the increase in engine weight and the reduction in fuel tank size tend to balance each other out, resulting in increased range or reduced fuel weight.

DIESEL ENGINE DRAWBACKS

Diesel engines are still relatively heavy. The use of turbochargers is good for high altitude performance but sacrifices low altitude performance (e.g. takeoff).

Diesel fuel tends to become viscous at low temperatures and at a certain point it becomes more like jelly.

Development of commercial modern diesel engines for aircraft has just begun. The number of diesel engine suppliers is low, and the prices are high. Maintenance support is non-existent for diesel engines. Most FBOs don't know how to fix a modern "automotive" gasoline engine, let alone a diesel. If every thing works out well these teething problems will pass. SMA is using its partners to provide a sales and support network throughout the world, and others will follow.

CONCLUSION

The automotive field influences the aeronautical piston engine technology. Ecological reasons have forced the automotive engine technology to adapt to reduced emissions. Automotive engine emissions have become friendlier to the ecology. The gradual disappearance of leaded fuel has sent the aerospace piston engine developers looking for solutions.

Today the most promising solution is the diesel engine. New manufacturers have entered the aerospace diesel engine market, due to the slow reaction of the traditional aeronautical piston engine manufacturers.

Two certified diesel engines have started to be marketed. At least one uncertified diesel is also selling, and many more are in development.

As explained before due to the lower SFC and smaller fuel tank, range and loiter performance are increased. This is especially true for long range and long endurance air vehicles.

It is common belief of the diesel engine manufacturer that diesel engines are here to stay. This idea is reinforced by the decline of leaded fuel.

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