

2-Stroke High Speed Diesel Engines for Light Aircraft

2011-24-0089

Published
09/11/2011

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doi:10.4271/2011-24-0089

ABSTRACT

The paper describes a numerical study, supported by experiments, on light aircraft 2-Stroke Direct Injected Diesel engines, typically rated up to 110 kW (corresponding to about 150 imperial HP). The engines must be as light as possible and they are to be directly coupled to the propeller, without reduction drive. The ensuing main design constraints are: i) in-cylinder peak pressure as low as possible (typically, no more than 120 bar); ii) maximum rotational speed limited to 2600 rpm. As far as exhaust emissions are concerned, piston aircraft engines remain unregulated but lack of visible smoke is a customer requirement, so that a value of 1 is assumed as maximum Smoke number.

For the reasons clarified in the paper, only three cylinder in line engines are investigated. Reference is made to two types of scavenging and combustion systems, designed by the authors with the assistance of state-of-the-art CFD tools and described in detail in a parallel paper. The former is a uniflow system, featuring two exhaust valves per cylinder in the engine head, piston controlled inlet ports and a combustion bowl in the piston; the latter is a loop scavenged design, with both inlet and exhaust ports controlled by the piston, and a non conventional combustion chamber in the engine head (no bowl in the piston).

All the calculations presented in the paper are performed by using GT-Power models calibrated by means of CFD-3D calculations (by KIVA-3V) and experiments. The experimental support is provided by two engines: the former is a modern commercial aircraft 2-Stroke Diesel engine, indirect injected, uniflow scavenged; the latter is a research

engine based on an old marine unit, featuring loop scavenging and direct injection. The calibration of the GT-Power models is reviewed in the paper.

INTRODUCTION

The application of the 2-Stroke Diesel concept to aircraft engines is everything but a novelty: as just one example, Junkers built a very successful series of these engines in the late 19-'30's, named "JUMO". The main advantage offered by such an engine is fuel efficiency; even in 1938, the JUMO engine was capable of a Brake Specific Fuel Consumption of 213 g/kWh [1], an impressive figure even by modern standards. It should be noticed that fuel consumption is very important for aircraft performance, since a relevant portion of the aircraft total weight (sometimes up to 50%) is due to fuel storage. The main reason of the outstanding fuel economy of 2-Stroke Diesel engines is the high mechanical efficiency ensuing from the 2-Stroke cycle; besides the possibility of having no poppet valves and the associated driving system, mechanical friction losses over the cycle are about halved, in comparison to a four-stroke engine having the same crank and piston and crankcase design, thanks to the double cycle frequency. Furthermore, the two-stroke cycle is a good match for aircraft engines, since it is possible to achieve high power density at low crankshaft speed, allowing direct coupling to a propeller without the need for a reduction drive (which is heavy and expensive, besides adsorbing energy).

Supercharging further improves power density and fuel efficiency, as well as enhancing altitude performance. Diesel combustion allows a higher boosting level, in comparison to Spark Ignited engines, limited by knocking. In addition, high octane aviation gasoline is expected to be subject to strong

limitations, due to its polluting emissions of lead, while a Diesel engine can burn a variety of fuels: besides automotive Diesel, also turbine fuels such as JP4 and JP5, and Jet A. Further advantages in comparison to gasoline power-plants are: reduced fire and explosion hazard, better in-flight reliability (no mixture control problems), no carburetor icing problems and safe cabin heating from exhaust stacks (less danger of Carbon Monoxide intoxication).

The recent development of Diesel technology, along with the above mentioned series of advantages, has made the 2-stroke, compression ignition engine an interesting option for light aircraft manufacturers, seeking power unit of 100-300 HP, preferably not heavier than existing SI powerplants. Conversion of automotive four stroke units is generally not attractive, since they are relatively heavy. Thus, design must be carried out from scratch, in order to achieve an acceptable power to weight target. The mission is not impossible: as an example, already in the second half of the '90's, AVL developed a 1-liter 2-Stroke turbocharged Diesel engine, with uni-flow scavenging, achieving a brake power of 50 kW, and a weight less than 80 kg [2], and Wilksch Airmotive brought to the experimental aircraft market a 90kW three cylinder two-stroke unit using IDI combustion and weighing only 100kg [3].

The aircraft Diesel engine market is in its infancy: several two-stroke prototypes have been built but none have achieved type certification at the time of writing [3,4,5,6,7]. Selected cylinder configurations have included loop and uni-flow scavenging as well as opposed piston uni-flow. For the sake of brevity, this paper will consider only the two most widespread scavenging designs: uniflow with exhaust poppet valves, and loop scavenging with piston controlled ports.

The goal of the paper is to assess the potential of 2-Stroke High Speed Diesel engines on light aircraft. In order to limit the field of investigation, 110 kW is assumed as the power rating at 2600 rpm (the typical top speed of a propeller suitable for this type of aircraft), along with a maximum weight of 120 kg; such an engine should be attractive for several light aircraft manufacturers. For the choice of the fundamental engine parameters (bore, stroke, number of cylinders, etc.), a number of valid options are possible, but it is not feasible in a technical paper to explore all of them in detail. Therefore, reference is made to the most successful design at the time of writing the paper, that is 3 cylinder in-line engine, with turbocharger, positive displacement compressor and intercooler. Furthermore, in order to be as close as possible to a real project, bore, stroke, connecting rod length and compression ratio correspond to a commercial engine developed by Wilksch Airmotive [3].

This report is focused on the main thermo-fluid-dynamic issues involved in engine design: separate studies are planned to assess the mechanical and thermal robustness of the

proposed engines, as well as to address durability issues. Since the maximum power/weight ratio is paramount for aircraft engines, the power density is high and it is expected that further challenges will arise. Both engine proposals will feature liquid cooled cylinders and "cocktail shaker" style oil cooling of the pistons. However, the proposed power density and expected component thermal loading are within the bounds of the current technology, as demonstrated by previously successful two-stroke liquid cooled CI aircraft engines. It is considered unlikely that air cooled variants of either engine would be viable.

All the calculations presented in the paper are performed by using GT-Power models calibrated by means of CFD-3D calculations (by KIVA-3V) and experiments. The experimental support is provided by two engines: the former is a modern commercial aircraft 2-Stroke Diesel engine, indirect injected, uniflow scavenged; the latter is a research engine based on an old marine unit, featuring loop scavenging and direct injection. The experimental calibration of the GT-Power models is reviewed in the following section.

EXPERIMENTAL CALIBRATION OF THE ENGINE MODELS

For the configuration combining loop scavenging and direct injection, reference is made to the prototype engine, installed at the dynamometer bed of the Engineering Faculty in Modena. This prototype is derived from an old marine engine, manufactured by Detroit Diesel in the '50s and named "Model 51" after its cylinder capacity in cubic inches, fully restored for research purposes. The main features of the engine are listed in [table 1](#).

The choice fell on this engine because of the striking similarities between this old technology and the small bore virtual engine developed at the University of Modena and Reggio Emilia, for automotive applications [8, 9, 10, 11]. Despite the different dimensions, both combustion and scavenging systems are designed following the same concepts. Furthermore, bore and stroke are very close to the range the authors believe to be optimum for aircraft engines, which is 90-100 mm (this assumption will be explained in the following). Having found a sample in reasonable working condition, the authors decided to build a demonstrator engine basing on it, instead of starting from scratch. Obviously, the purpose of this demonstrator is not to be a typical of modern aircraft engine concepts, but a cost effective "mule", where measures on scavenging and combustion processes can be taken, in order to calibrate the computational models. Finally, a further reason to select the Detroit Diesel engine is the comprehensive experimental information already available in a technical paper, published by SAE in 1953 [12].

A GT-Power model, for 1-D engine cycle simulation, was built on the basis of available data, including all the

geometrical details, measured fuel flow rates and calculation of some burn rates (from measure of in-cylinder pressure traces). Empirical assumptions were required in order to bridge information over a few grey areas. In particular, the blower performance map was estimated, considering a commercial machine of the same type and displacement; mechanical friction losses were calculated using a simple correlation proposed by Blair for this type of engines [13]; for the sake of simplicity, ports discharge coefficients were assumed to be independent of piston position and pressure ratio across the cylinder; scavenging patterns (i.e. the correlation between the composition of the flow leaving the cylinder and the average composition of the cylinder) were assumed to be the same as a similar engine, analyzed in [11]; wall temperatures for the cylinder block, pistons, head were estimated on the basis of the authors' experience.

Table 1. Main features of the Model 51 engine, by Detroit Diesel, used as a “mule” in this study

Engine type	2-Stroke, 4-cylinder in-line
Combustion	Diesel, Direct Injection
Scavenging type	Loop
Number of Ports	10 inlet + 3 exhaust
Air Metering	Roots-type blower
Fuel Metering	Mechanical Unit Injectors
Injector nozzle type	Multi-hole (10)
Displaced volume	3548 cc
Stroke	104.1 mm
Bore	104.1 mm
Connecting Rod	213 mm
Compression ratio	26:1
Exhaust Ports Open	83° BBDC
Exhaust Ports Close	83° ABDC
Inlet Port Open	67° BBDC
Inlet Port Close	67° ABDC
Maximum Brake Power	102 HP @ 3000 rpm

The main parameters used for calibrating the model are: a multiplier for the blower efficiency, as a function of engine speed; the average discharge coefficient of inlet ports; the average discharge coefficient of exhaust ports; the combustion efficiency; a multiplier for in-cylinder heat transfer rate.

Running the calibrated model at full load, the agreement between experiments and CFD-1D simulation is good, as visible in [figures 1](#) and [2](#). Plotted as a function of engine speed, [figure 1](#) shows the parameters on which calibration was focused: volumetric efficiency, scavenging pressure (i.e. blower delivery pressure), delivered air-to-fuel ratio, indicated mean effective pressure and total friction mean effective pressure (i.e. the sum of mechanical losses and blower energy absorption), heat rejected by the engine (through water and oil). [Figure 2](#) presents a comparison in

terms of conventional brake performance parameters, that is: torque, power and specific fuel consumption. To further demonstrate the physical soundness of the GT-Power model, it is remarked that calibrated value of average discharge coefficient found for both inlet and exhaust port is 0.8, a figure quite coherent with literature data (for instance, in [13]) and with the authors' CFD multidimensional calculations on a very similar configuration, reported in a parallel paper [15].

For modeling uniflow scavenged engines, reference is made to a modern aircraft 2-Stroke turbocharged Diesel power plant, named WAM 100/120, produced by Wilksch Airmotive, with a top brake power of 100-120 HP, from a notably light design. The engine features are listed in [Table 2](#), while the lay-out can be deduced by [figure 3](#). This engine was the object of a previous study [15], carried out by the same authors and focused on the development of a direct injection combustion system. To achieve that purpose, a GT-Power model of the IDI engine was built and calibrated against experiments. For the sake of brevity, the model calibration will not be discussed again, being already reviewed in the previous paper [15]. [Figure 4](#) just shows the comparison between simulation and experiments, considering a typical propeller power curve.

Table 2. Main features of the WAM 100 engine, assumed as a reference for uniflow scavenging

Engine type	2-Stroke, 3-cylinder in-line
Combustion	Diesel, Indirect Injection
Scavenging type	Uniflow
Number of Valves/Ports	2 Exh. valves/20 inlet ports
Air Metering	Turbocharger + Roots
Fuel Metering	In-line mechanical pump
Injector nozzle type	Single-hole (Pintle)
Displaced volume	1832 cc
Stroke	90.5 mm
Bore	95.0 mm
Connecting Rod	167.0 mm
Compression ratio	17:1
Exhaust Valves Open	83° BBDC
Exhaust Valves Close	80° ABDC
Inlet Port Open	53° BBDC
Inlet Port Close	53° ABDC
Maximum Brake Power	102 HP @ 2750 rpm

SIMULATION AND DESIGN

To achieve a power target of 112 kW - 150 HP at 2600 rpm within the weight constraints, the engines are turbocharged. Turbocharging also results in good altitude performance, highly desirable with an aircraft engine. Therefore, as visible in [figure 3](#), the air metering system is made up of a dynamic turbocharger, an air-to-air intercooler and a positive

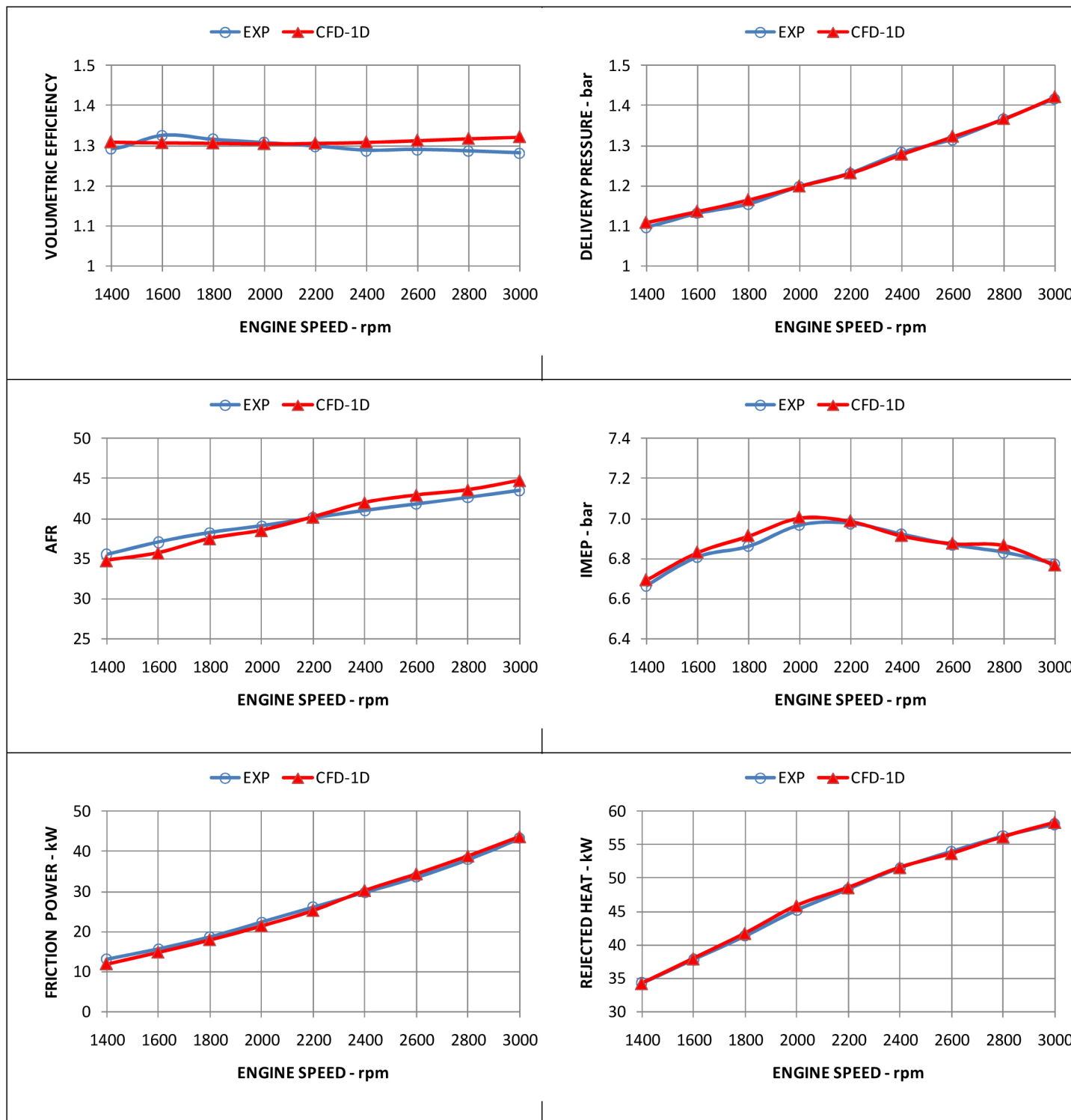


Figure 1. Comparison between experimental and simulation results on the Model 51 engine, by Detroit Diesel. The figure shows the main parameters on which calibration was focused.

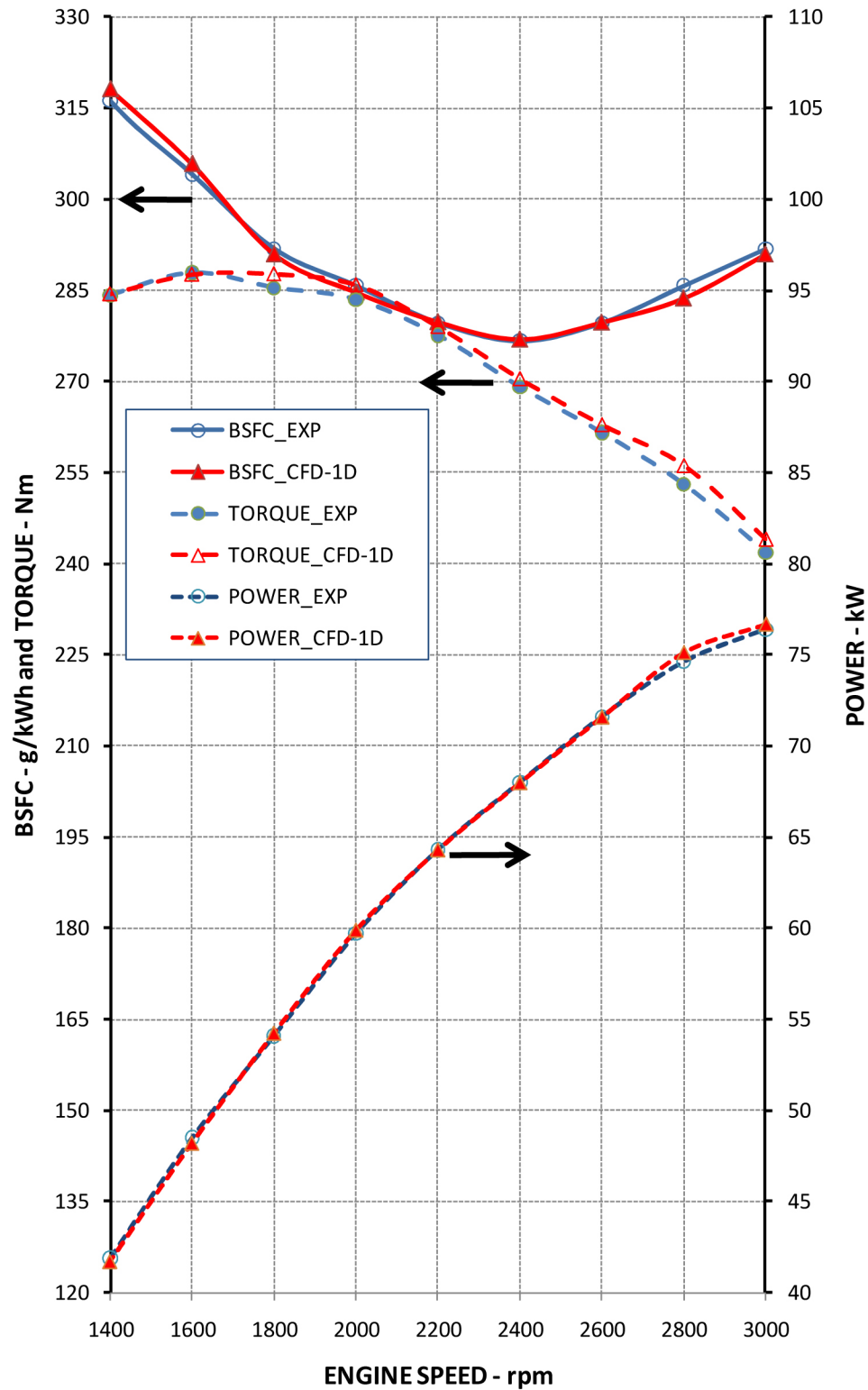


Figure 2. Comparison between experimental and simulation results on the Model 51 engine, by Detroit Diesel: brake performance parameters

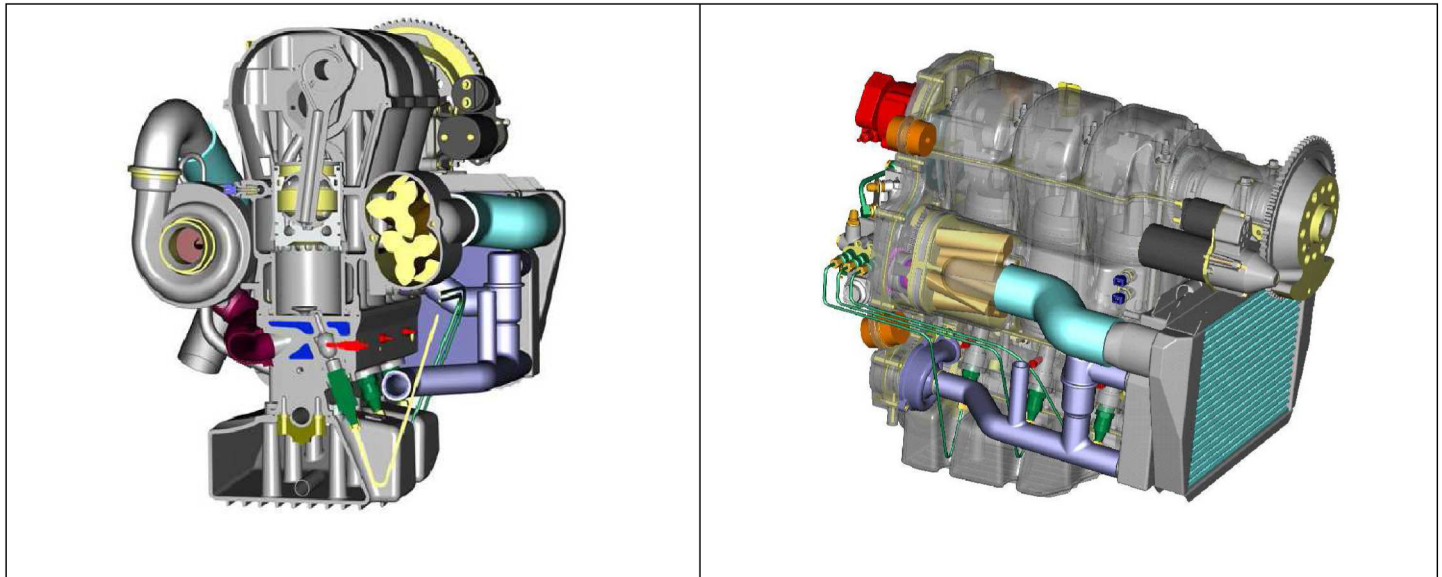


Figure 3. CAD drawings representing the lay-out of the WAM 100/120 engine

displacement compressor of the Roots type. The latter could be by-passed at most operating conditions, being essential only to crank up the engine and sustain it at low load and “over-run” conditions. However, the use of a by-pass system has been discarded, since it introduces more complication and cost, and yields only a very small reduction of fuel consumption. The same conclusion was reached regarding the adoption of a waste-gate: the benefits in terms of back-up torque and performance over sea level seemed to be not balanced by the worsening of fuel consumption and the complication of the control system. As far as the intercooler is concerned, it is observed that this component places a heavy burden on the aircraft installation, since the radiator heat exchange area increases drag, so penalizing aircraft speed. Therefore, this component must be as small as possible: in this analysis, a temperature drop of about -80°C and a charge-side pressure loss of 0.15 bar across the component were assumed as typical installation values at rating conditions. As a result, the “effectiveness” of the heat exchanger (defined as the ratio of the charge actual temperature drop to the ideal temperature drop) is slightly higher than 50%. An important constraint on the air metering system is the temperature of the charge entering the cylinder: a reasonable lower limit suggested by experience is 70°C .

As far as the combustion system is concerned, direct injection is essential, in order to achieve a power rate 25% higher than that of the correspondent IDI commercial engine.

Considering a uniflow scavenged cylinder, with exhaust poppet valves in the head, the combustion chamber featuring a bowl in the piston designed by the authors and presented in [15] can be directly adopted. The computational grid that was used in the multidimensional CFD calculations supporting the project is shown in [figure 5](#).

Considering a loop scavenged engine, some advantage can be obtained with a combustion chamber formed in the cylinder head, such as the one of the DD 4-51 engine, or the configuration shown in [9]. In fact, besides the possibility of lighter pistons without the bowl and a simpler cooling of the chamber, the latter can be more compact (lower surface to volume ratio), with less heat lost through the walls. The CFD simulation indicated that good performance may be achieved with the configuration visible in [figure 6](#).

CFD multidimensional simulation reported in [16] also provided the information necessary to represent the combustion and scavenging processes in the engine simulation models, built by means of GT-Power. The latter has been used in order to optimize the gas exchange processes and predict all the performance parameters. For this purpose, reference was made to the calibrated GT-Power model of the WAM engine. Several hypotheses had to be made, as reviewed in the following list.

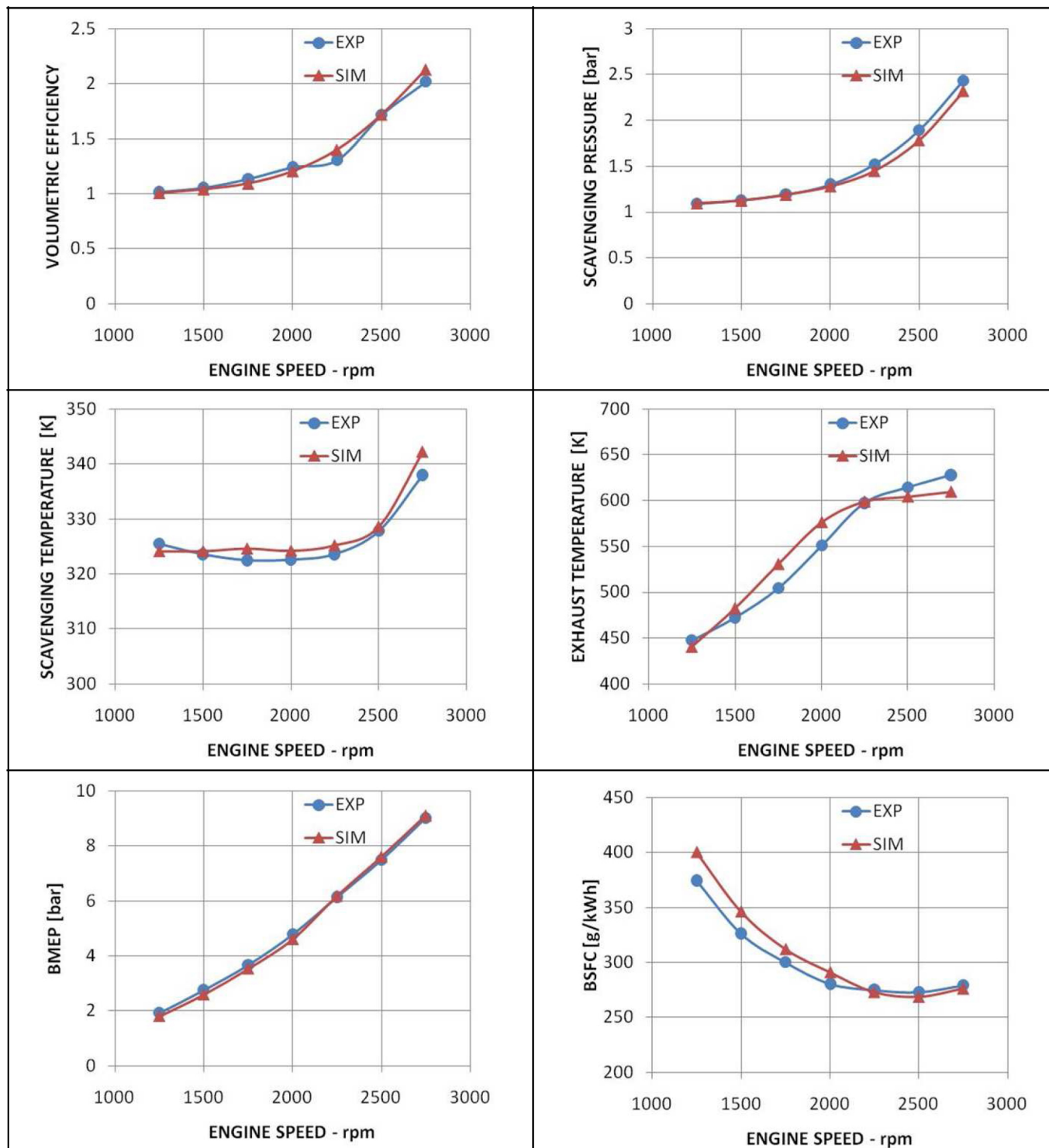


Figure 4. Calibration of the GT-Power model for the Uniflow Scavenged reference engine (propeller operating conditions, ambient pressure 1.013 bar, temperature 295 K)