Energy Conversion and Management 101 (2015) 470–480

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Supercharging system behavior for high altitude operation of an aircraft 2-stroke Diesel engine

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ARTICLE INFO

Article history:
Received 19 March 2015
Accepted 3 June 2015

Keywords:
Engine supercharging
Supercharging architecture
2-stroke Diesel engine
Trapping efficiency
Scavenging efficiency
General aviation
UAV

ABSTRACT

Different studies on both 2- and 4-stroke engines have shown how the choice of different supercharging architectures can influence engine performance. Among them, architectures coupling one turbocharger with a mechanical compressor or two turbochargers are found to be the most performing in terms of engine output power and efficiency. However, defining the best supercharging architecture for aircraft 2-stroke engines is a quite complex task because the supercharging system as well as the ambient conditions influence the engine performance/efficiency. This is due to the close interaction between supercharging, trapping, scavenging and combustion processes. The aim of the present work is the comparison between different architectures (single turbocharger, double turbocharger, single turbocharger combined with a mechanical compressor, single turbocharger with an electrically-assisted turbocharger, with intercooler or aftercooler) designed to supercharge an aircraft 2-stroke Diesel engine for general aviation and unmanned aerial vehicles characterized by a very high altitude operation and long fuel distance. A 1D model of the engine purposely designed has been used to compare the performance of the different supercharging systems in terms of power, fuel consumption, and their effect on trapping and scavenging efficiency at different altitudes.

The analysis shows that the engine target power is reached by a 2 turbochargers architecture; in this way, in fact, the cylinder filling, and consequently the engine performance, are maximized. Moreover, it is shown that the performance of a 2 turbochargers architecture performance can be further improved connecting electrically and not mechanically the low pressure compressor and turbine (electrically-assisted turbocharger). From an energetic point of view, this system has also proved to be particularly convenient at high engine speed and load, because it is possible to extract power from the electric turbocharger without a penalty on specific fuel consumption.

1. Introduction

One of the crucial points of the use of a reciprocating internal combustion engine for aircraft propulsion is the performance decline with the increase in altitude. This is due to the negative effect of air density reduction on cylinder filling process. The solution to this problem is the engine supercharging [1]. To supercharge a 2- and 4-stroke engines a turbocharger (TC), and/or a mechanical compressor, can be used: the first involves an air compressor fed by a turbine driven by exhaust gases; the second one consists of a compressor mechanically coupled to the engine crankshaft [1].

In 2-stroke engines, the cylinder filling and emptying phases are driven by the difference between inlet and outlet pressure. Therefore, the supercharging system of a 2-stroke engine is responsible for the air density increase and cylinder scavenging. Due to the strict interaction among supercharging, scavenging and combustion, 2-stroke engines are very sensitive to the variation of engine working parameters and ambient conditions with altitude [2,3].

Several studies on both 2- and 4-stroke engines have shown how the supercharging architecture can influence the engine performance. Pohorelsky et al. [4] simulated numerically different supercharging systems, characterized by positive displacement or dynamic compressors mechanically coupled to the engine before or after a TC with Waste-Gate (WG) or variable nozzle turbine to ensure power and scavenging targets of 2-stroke Diesel engines. They proved that the best configuration is to place the positive displacement compressor upstream the TC with WG. Systems with

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http://dx.doi.org/10.1016/j.enconman.2015.06.009
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Nomenclature

AFR_{cmb}	trapped air/fuel ratio
AP	air purity
ATDC	after top dead center
BSFC	brake specific fuel consumption
c_{pC}	mean specific heat at constant pressure during compression phase
c_{pT}	mean specific heat at constant pressure during expansion phase
C_P	propeller power coefficient
CAD	crank angle degree
DR	delivery ratio
EAT	electrically assisted turbocharger
eCOM	electrical compressor
eTURB	electrical turbine
HP	high pressure
LP	low pressure
m_{as}	mass of fresh charge entering the cylinder during the scavenging phase
m_{sc}	mass of fresh charge short-circuiting the cylinder during the scavenging phase (fraction of m_{as})
m_{cp}	mass of combustion products exiting the cylinder during the scavenging phase
m_{tr}	total mass trapped into the cylinder after the scavenging phase (with valves and ports closed)
m_{tas}	mass of intake fresh charge trapped into the cylinder
m_{ex}	mass of exhaust gases not discharged from the cylinder (fraction of m_{cp})
m_{ar}	mass of residual air from the previous cycle not having participated to the combustion
$\dot{m}_C$	compressor mass flow
$\dot{m}_T$	turbine mass flow
n	engine speed
p_amb	International Standard Atmospheric pressure
p_2/p_1	compressor pressure ratio
p_4/p_3	turbine expansion ratio
P_b	engine brake power
R	propeller radius
SE	scavenging efficiency
T_amb	International Standard Atmospheric temperature
T_1	compressor inlet temperature
T_3	turbine inlet temperature
tcPLUS	difference between the power produced by the turbine and the power required by the compressor
TC	Turbocharger
TE	trapping efficiency
UAV	unmanned aerial vehicle
V	aftercooler volume
VGT	variable geometry turbocharger
WG	waste gate valve
Δp	aftercooler pressure drop
ε	aftercooler efficiency
ρ_a	ambient air density
η_{sC}	compressor isentropic efficiency
η_{sT}	turbine isentropic efficiency
η_m	turbocharger mechanical efficiency

electric compressor and Electrically Assisted Turbocharger (EAT) required excessive electric power.

Knoll [5] modeled numerically and compared different supercharging architectures for a 2-stroke engine prototype: a mechanical compressor, a TC coupled with a crankcase scavenging pump, and a TC combined with an external mechanical compressor. The last one proved to be the best option, thanks to the compression power reduction, and beneficial effect of the exhaust backpressure on trapping efficiency.

Mattarelli [6] analyzed two different architectures for a 4-stroke Diesel engine. The first one comprises two TCs; the second one comprises a TC and a mechanical positive displacement compressor. The analysis revealed that, using a mechanical compressor and a Variable Geometry Turbocharger (VGT), the engine performance at full-load are improved together with the fuel consumption and pollutants control [7].

Chen et al. [8] studied the influence of two-stage turbocharging system parameters on the engine performance. It was found that engine efficiency and performance are strongly influenced by high pressure (HP) and Low Pressure (LP) compressors efficiency, by intercooler efficiency and cooling water temperature. In off-design operation, the turbocharging system shall be designed to ensure the two compressors to operate with a similar value of the compressor efficiency. A similar analysis with similar results has been presented by Liu et al. [9], in which a matching method for two-stage turbocharging system has been proposed. Shan et al. [10] proposed a simulation method for the design and analysis of an aerial turbocharging system, composed by two TCs, two intercoolers, and two turbine by-pass valves. It was concluded that, operating the two by-pass valves correctly, it is possible to meet the design objectives at different altitudes, and to operate the compressors to minimize the compression work.

Divekar et al. [11] simulated the performance of a supercharging scheme decoupling the intake-boost system from the exhaust recovery system using electric supercharging and turbo-generation with two separate electric machines and a dedicated energy storage buffer. In this way, the system transient response is faster if compared to a conventional turbocharged system, and a reduction in fuel consumption over driving cycles characterized by frequent transient operation is obtained. These conclusions are confirmed by Katrasnik et al. [12].

Terdich et al. [13] showed that the hybridization of the TC is the most effective way to recover the transient response of a TC; VGT, moreover, decreases the fuel consumption. Mamalis et al. [14] showed that the system with two TCs leads to the best extension of the operational range of a 4-stroke Homogeneous Combustion Compression Ignition engine, i.e. an engine in which well-mixed fuel and oxidizer are compressed to the point of auto-ignition.

The aim of the present work is to compare different architectures – single turbocharger, double turbocharger, single turbocharger combined with a mechanical compressor, single turbocharger with an EAT, with intercooler or aftercooler – to supercharge an aircraft 2-stroke Diesel engine for general aviation and Unmanned Aerial Vehicles (UAV). This engine is characterized by a very high altitude operation and long fuel endurance. To carry out tests, a 1D model of the engine has been realized with AVL BOOST software. The performance of the different supercharging systems were compared to determine the most performing system in terms of power and specific fuel consumption. Moreover, the results have been validated analyzing the cylinder scavenging and filling processes. Lastly, the effect of the EAT compression ratio on the power produced or required by the EAT at part load has been also analyzed to define the best control strategies of fuel consumption.