Energy Conversion and Management 122 (2016) 279–289

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance optimization of a Two-Stroke supercharged diesel engine for aircraft propulsion

Antonio Paolo Carlucci *, Antonio Ficarella, Gianluca Trullo

University of Salento, Department of Engineering for Innovation, via per Monteroni, 73100 Lecce, Italy

A R T I C L E I N F O

Article history:
Received 8 April 2016
Received in revised form 24 May 2016
Accepted 27 May 2016

Keywords:
Two-Stroke diesel engine
Aircraft propulsion
Breathing system
Multiobjective optimization
Engine supercharging
Uniflow scavenging

A B S T R A C T

In Two-Stroke engines, the cylinder filling efficiency is antithetical to the cylinder scavenging efficiency; moreover, both of them are influenced by geometric and thermodynamic parameters characterizing the design and operation of both the engine and the related supercharging system. Aim of this work is to provide several guidelines about the definition of design and operation parameters for a Two-Stroke two banks Uniflow diesel engine, supercharged with two sequential turbochargers and an aftercooler per bank, with the goal of either increasing the engine brake power at take-off or decreasing the engine fuel consumption in cruise conditions. The engine has been modeled with a 0D/1D modeling approach. Then, the model capability in describing the effect of several parameters on engine performance has been assessed comparing the results of 3D simulations with those of 0D/1D model. The validated 0D/1D model has been used to simulate the engine behavior varying several design and operation engine parameters (exhaust valves opening and closing angles and maximum valve lift, scavenging ports opening angle, distance between bottom edge of the scavenging ports and bottom dead center, area of the single scavenging port and number of ports, engine volumetric compression ratio, low and high pressure compressor pressure ratios, air/fuel ratio) on a wide range of possible values. The parameters most influencing the engine performance are then recognized and their effect on engine thermodynamic behavior is discussed. Finally, the system configurations leading to best engine power at sea level and lowest fuel consumption in cruise conditions – respectively +42% and −7% with respect to baseline – have been determined implementing a multicriteria optimization procedure.

1. Introduction

Due to increasingly stringent request for higher performance and lower fuel consumption, the definition of supercharging system in reciprocating engines for aircraft propulsion is a crucial task [1–3]. In Two-Stroke engines, particular care must be addressed in designing the breathing system in order to obtain a good scavenging process, whose effectiveness is quantified by both the Scavenging Efficiency (SE) and Trapping Efficiency (TE).

Many parameters affect the scavenging process. Ravi and Marathe in [4] conducted a numerical analysis on the effect of size, opening and closing timings of both scavenging ports and exhaust valves on the flow field established in the cylinder of an Uniflow Two-Stroke engine. The analysis, conducted in transitory conditions, revealed that: (1) a larger size, an earlier opening and a delayed closure of the inlet ports lead to better gas exchange process; (2) the earlier the exhaust valve closes, higher is TE but lower is SE; moreover, properly choosing the exhaust valve closing angle, it is possible to obtain best scavenging process or minimal fresh charge loss.

The effects of inlet duct length, geometric port swirl angle, and number of ports on swirl generating capability in the cylinder of an Uniflow Two-Stroke engine have been explored by Ravi and Marathe in [5]. It was proven that the pressure value at the inlet and

---

Abbreviations: A, area of the single scavenging port; AFR, air/fuel ratio; ATDC, after top dead center; BDC, bottom dead center; BSFC, brake specific fuel consumption; CAD, crank angle degree; CC, cruise condition; CR, engine volumetric compression ratio; DoE, design of experiment; DR, delivery ratio; ES, effect size; EVC, exhaust valves closing; EVO, exhaust valves opening; HBI, distance between bottom edge of the scavenging ports and bottom dead center; HEV, exhaust maximum valve lift; HP, high pressure; IPO, inlet/scavenging ports opening angle; LP, low pressure; n, number of inlet/scavenging ports; P_b, engine brake power; PR_{HP}, high pressure compressor pressure ratios; PR_{LP}, low pressure compressor pressure ratios; S, Significance; SE, scavenging efficiency; SL, sea level; TE, trapping efficiency.

* Corresponding author at: Systems for Energy and Environment (CREA), University of Salento, Dept. Engineering for Innovation, via per Monteroni, 73100 Lecce, Italy.

E-mail address: paolo.carlucci@unisalento.it (A.P. Carlucci).

http://dx.doi.org/10.1016/j.enconman.2016.05.077
0196-8904/

exhaust have a global effect on the scavenging process; in particular, the higher the pressure drop between inlet and exhaust, the better is SE, but, at the same time, TE deteriorates.

Fleck and Cartwright in [6] measured the coefficients of discharge in high performance Two-Stroke engines varying different engine architectures. Modifying the inlet and exhaust ports section, it was found that the discharge coefficient variation is caused by duct geometry only in the case of inlet ports, while it is function of the pressure ratio as well in the case of the exhaust system.

Laser Doppler Velocimetry measurements allowed, as reported for example in [7,8], to characterize the velocity field at the exit of intake ports of a Two-Stroke engine. This helped assessing the goodness of different intake geometries in improving SE.

More recently, Kinoshita and Motoyama in [9] proposed a model for the scavenging process of a Loop scavenged Two-Stroke engine, function of shape, section and tangential angle of inlet ports, based on the experimental observations using a three-dimensional anemometric-tester. As a result, with the goal of optimizing the engine performance, it is necessary: (1) to direct the airflow coming from the main transfer port toward the center of the bore and (2) the inner vent radius of the main transfer duct to assume a relatively large value.

The optimization of the scavenging system has been also pursued using CFD approach. Mattarelli et al. in [10] reports 3D models of several architectures and different scavenging configurations including different bowl shapes for Two-Stroke compression ignition engines. According to the different proposed layouts, SE, TE, air purity, fresh air concentration, velocity vector magnitude and mean effective pressure have been calculated at different engine speed for both Loop and Uniflow scavenging systems. Furthermore, a comparison between the two different scavenging models has been run using KIVA software analyzing several engine output parameters. The attained output parameters revealed that the well-known performance gap between Loop and Uniflow scavenged engine could be slightly reduced by a 3D CFD design support; furthermore, considering the same Two-Stroke engine (either for automotive or aircraft propulsion), scavenged with one of the previous systems, presents better performance than the related 4 S engine and, at the same time, lower emissions.

Leep et al. in [11] report the simulation results of the scavenging process, taking place in a three-cylinder engine, obtained coupling a 3D CFD and a 0D/1D models. Simulations were run over the whole engine characteristic map; investigating the outputs obtained in different operating conditions, it was revealed that the scavenging process becomes hard to manage and then detrimental when the engine speed increases. Furthermore, the 3D study demonstrated that the flow field vectors inversion weakly influence the process, but the orientation of inlet ports is able to modify the flow velocity field changing the phenomena associated to fuel injection and combustion. Considering the interactions taking place in a multi-cylinder engine, it has been determined that, at high engine speed, the final combustion pressure reaches a higher value but the scavenging process is further penalized.

In [12] the effect of several design parameters of a Two-Stroke Uniflow engine on the swirl generated into the combustion chamber, and then the quality of the scavenging process, was studied using ARIS 3D code. The Authors highlighted that the swirl level increases if the length of the inlet duct increases as long as it reach a maximum; from that point on, pressure losses become relevant. Equally, increasing the swirl angle as well as the number of ports generates high swirl level producing, though, high pressure losses.

In order to obtain the best engine performance, all the parameters affecting its behavior must be carefully tuned [13–15]. Multi-objective optimization based on genetic algorithms are often used to support the tuning process of a multivariable system drastically reducing the required time [16].

Aim of this work is to provide several guidelines about the definition of design and operation parameters for a Two-Stroke two banks Uniflow diesel engine, supercharged with two sequential turbochargers and an aftercooler per bank, with the goal of either increasing the engine output power at take-off or decreasing the engine fuel consumption in cruise conditions. The engine has been modeled with a 0D/1D modeling approach. Then, the model capability in describing the effect of several parameters on engine performance has been assessed comparing the results of 3D simulations with those provided by 0D/1D model. The validated 0D/1D model has been used to simulate the engine behavior varying many design and thermodynamic parameters. Then, the effect of most influential parameters on engine brake power (P_b) at Sea Level (SL) and specific fuel consumption (BSFC) in cruise condition (CC, corresponding to an altitude equal to 10,680 m) has been analyzed. Finally, the configurations optimizing the aforementioned engine performance have been determined.

2. Engine model

The engine analyzed in the present work is a Two-Stroke diesel engine for aircraft propulsion, composed by six cylinders arranged in two independent banks. The scavenging system is Uniflow, with 14 inlet ports and 2 exhaust valves per cylinder. The supercharging system consists of two turbochargers and one aftercooler per bank. This configuration has been selected since it proved to be the only one, among the configurations analyzed in [1], able to guarantee the target engine brake power at different altitudes with the minimum fuel consumption. The engine main specifications are reported in Table 1, while a general scheme of the engine layout is shown in Fig. 1.

The software used for modeling the engine is AVL Boost v2011.2, characterized by a 0D/1D approach. This approach has been preferred since it is functional for obtaining meaningful results about the behavior of the whole engine with a not excessive computational time. More details about the software can be found in [17], while the model description and calibration are illustrated in [1]. Regarding the scavenging model, the one used in this paper is the model suggested by Blair [18] representing an intermediate approach between the *perfect mixing* and the *perfect displacement* models:

$$SE = 1 - \exp(4.35 + 1.36DR - 0.22DR^2) \qquad (1)$$

where DR is the Delivery Ratio, defined as the ratio between the mass of fresh charge entering the cylinder during the scavenging process and the air mass at ambient conditions necessary to fill the cylinder.

3. Optimization procedure of the engine breathing system

The architecture with two turbochargers and one aftercooler per bank was further investigated, seeking for the design trends for the breathing system optimizing the engine performance. A multiobjective optimization procedure was chosen, finalized to the determination of the engine parameters maximizing P_b at SL

Table 1
Engine main specifications.

Cycle	Two-Stroke diesel uniflow
Bore/stroke	1
Compression ratio	17.2:1
Injection system	Common rail
Engine speed	2000 rpm
Inlet ports opening/closing angles	115 CAD ATDC/245 CAD ATDC
Exhaust valves opening/closing angles	80 CAD ATDC/250 CAD ATDC