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Development and validation of a 5 stroke engine for range extenders application

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ABSTRACT

A 5-stroke turbo-charged port-injection spark-ignition engine has been developed in the present study for use as a range extender or series-hybrid main power source. The development and the design of the engine are based on 0D/1D model and experimental results have been compared with the engine model. The 5-stroke engine is a three-cylinder in which two cylinders perform a four-stroke cycle and alternatively a second expansion of the burnt gases is performed in the third cylinder. The boost pressure delivered by the turbocharger is controlled by a particular innovative system called “smart wastegate”, different from a conventional wastegate, consisting in a variable valve timing of the two exhaust valves of the low pressure cylinder. The engine develops up to 40 kW for a speed range of 3500–4500 rpm. BSFC is 226 g/kW.h which corresponds to a fuel conversion efficiency of 36.1%. This efficiency can be achieved for an engine speed of 4000 rpm and a brake power of 32.5 kW, which are notable scores for an MPI two-valve per cylinder engine. Expected optimum should be below 217 g/kW.h BSFC and over 90 N.m torque. The engine has been tested over a wide range of conditions; model predictions and experimental results are compared and combustion efficiency increase discussed.

1. Introduction

Current trends in engine development [1,2] are governed by more and more stringent emission regulations and aim at lowering consumption and emissions in order to obtain ever cleaner engines. The emergence of hybrid powertrains is a way to reduce engine emissions [3–6] thanks to the development of dedicated internal combustion engines which would be used as range extenders [7,8] allowing the appearance of non-traditional concepts [9,10] such as Wankel engine, which provide a good compromise thanks to an attractive power-to-weight ratio. However, the Wankel engine does not present a high efficiency, compared to conventional internal combustion engine [10,7]. The efficiency of a reciprocating internal combustion engine is strongly linked to its expansion ratio [11,12] since increasing the expansion ratio allows an increase of the fuel conversion efficiency. In a recent study, Caton [12] showed that the major improvement in net indicated efficiency is due to an increase of the engine compression ratio. However, in traditional internal combustion engines, the compression ratio is limited due to mechanical stress and combustion issues (knock) [13,14]. Non-symmetric cycles are a way to avoid this geometric limit. The five-stroke engine, developed in the present study and based on the concept initially proposed by Schmitz [15], tends to answer this fundamental problem of internal combustion engines thanks a dual-expansion cycle. Using this innovative concept, the present study aims at developing a high-efficiency range-extender engine. Downsizing an internal combustion engine is also a way to increase engine efficiency [5,16,17] by using a turbocharger to increase engine performance and specific power. The five-stroke engine developed in this study uses a turbocharger and a wastegate with a particular design which allows a more efficient turbocharging strategy thanks to reduced heat losses and back pressure. The present paper first reviews the different concepts allowing an efficiency increase and presents different concepts for range-extender application. The design of the five-stroke engine is then discussed followed by the experimental results and the comparison with the 0D/1D modeling.

2. Thermodynamic analysis

Different theoretical solutions exist in order to improve the fuel conversion efficiency, η_f, of an internal combustion engine. This efficiency compares the mechanical power delivered by the engine

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Nomenclature

BDC	bottom dead center
BMEP	brake mean effective pressure (bar)
BSFC	brake specific fuel consumption (g.kW^{-1}.h^{-1})
CA	crank angle
FMEP	friction mean effective pressure (bar)
HP	high pressure
LHV	lower heating value of the fuel (J.kg^{-1})
LP	low pressure
MPI	multiple port injection
$\dot{m}_f$	mass fuel rate (kg.s^{-1})
NVH	noise vibration and harshness
OEM	original equipment manufacturer
rpm	rotation per minute
T	engine torque (N.m)
TDC	top dead center
γ	specific heat ratio
δ	pressure ratio
ϵ, ϵ_c	compression ratio
ϵ_e	expansion ratio
η_f	fuel conversion efficiency
η_T	thermodynamic efficiency
ω	engine speed (rad.s^{-1})

(calculated from the torque, T and rotation speed, ω) with the chemical power contained in the fuel (calculated from the mass flow rate of fuel, $\dot{m}_f$, and the lower heating value, LHV) (Eq. (1)).

$$\eta_f = \frac{T \cdot \omega}{\dot{m}_f \cdot LHV} \tag{1}$$

Overall, the maximum fuel conversion efficiency of an internal spark ignited combustion engine is around 30–33% [12,18,19]. Power losses from the engine are mainly due to thermal losses. For most engines, either spark ignition engines or compressed ignition engines, around one third of the energy available in the fuel is lost inside the cylinder due to heat losses through the wall. Another third of the energy is lost in the exhaust gases [20,21]. However, reducing heat losses to the wall thanks to insulation of the cylinder leads to a higher temperature of the exhaust gases. This results in increased energy losses in the exhaust gases [18,22,23]. Therefore, it is difficult to improve the fuel conversion efficiency of the internal combustion engine by reducing the heat losses. Other ways to improve the efficiency are either to recover exhaust heat [24] or to extract a large amount of energy during the expansion process thanks to a large expansion ratio. Saidur et al. [24] recently performed an important review of the different technologies which would allow an increase in fuel conversion efficiency by recovering heat from the exhaust gases. These technologies include thermoelectricity, turbocharger and alternative thermodynamic cycles. This study mainly focuses on alternative thermodynamic cycles.

2.1. Impact of the compression ratio

The thermal efficiency, η_T, therefore the global efficiency of an internal combustion engine is highly dependant on the geometry of the engine and the compression ratio [11,12]. For an ideal cycle of a spark ignition engine, the thermal efficiency only depends on the compression ratio, ϵ, and the specific ratio of the gas constants, γ (Eq. (2)) [25,26]:

$$\eta_T = 1 - \frac{1}{\epsilon^{\gamma-1}} \tag{2}$$

Thus, it can be clearly seen that increasing the compression ratio would lead to a better engine efficiency. Edson [33] studied analytically the efficiency of the Otto cycle, modeling the effects of chemical dissociation, working fluid thermodynamic properties, and chemical species concentration. He found that even at compression ratio of 300:1, the thermal efficiency increases with compression ratio for all of the fuels investigated. More recently, Caton [12] defined the characteristics of a high efficiency internal combustion engine and showed that, among the different possibilities, increasing the compression ratio is the best way to increase the engine efficiency. Su et al. [26] performed an experimental study of the impact of the compression increase on the thermal efficiency improvement over a wide range of conditions (engine speeds and loads). They found an improvement for low load operating points. However, in traditional internal combustion engines, the compression ratio for both the compression process and expansion process is the same due to the kinematic of the piston. In spark-ignition engines, the compression ratio is limited by mechanical stress and the combustion process which could lead to knock phenomenon [14,26,34]. Thus, these issues limit the expansion ratio and the thermal efficiency. Possible solutions would consist in higher expansion ratio during expansion than during compression in order to promote the thermal efficiency. Therefore, a possible solution to increase the efficiency is the use of an alternative thermodynamic cycle.

2.2. Alternative thermodynamic cycles

Different solutions have been developped as alternative thermodynamic cycle in order to optimize the fuel conversion efficiency. One solution is to increasing the expansion ratio with a compression ratio at the knocking limit. Such technologies include the Miller/Atkinson cycle [35–38], the Exlink engine developed by Honda [39], the Split cycle developed by Scuderi [40], and the 5-stroke engine [15]. Another possible solution is to extract the maximum energy from the burnt gases thanks to in-cylinder heat recovery by using water injection [21].

2.2.1. Miller/Atkinson

The Miller/Atkinson cycle (Fig. 1), firstly invented by Atkinson [36], is based on an over-expanded four-stroke cycle and has been modified by Miller [38] thanks to the addition of a turbocharger in order to increase the intake pressure. The Miller/Atkinson cycle can be obtained from a traditional four-stroke engine by shifting the closing of the intake valve during the compression process. In this case, part of the fresh gases is expelled from the cylinder. The thermal efficiency of the Miller/Atkinson cycle depends on the compression ratio, ϵ_c, the expansion ratio, ϵ_e and the pressure ratio between the beginning and the end of the isochoric combustion process (Fig. 1), $\delta = p_3/p_2$, (Eq. (3)) [25].

$$\eta_T = 1 - \frac{1}{\epsilon_c^{\gamma-1}} \frac{(\gamma-1)\frac{\epsilon_e}{\epsilon_c} + \delta\left(\frac{\epsilon_c}{\epsilon_e}\right)^{(\gamma-1)} - \gamma}{\delta - 1} \tag{3}$$

Based on this equation, for a pressure ratio of 4, a compression ratio of 9 and a expansion ratio of 18, the Miller/Atkinson cycle thermal efficiency would be 66.3%, compared to the Otto cycle thermal efficiency of 58.5% for a compression ratio of 9. Thus, using