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A computational analysis of the impact of bore-to-stroke ratio on emissions and efficiency of a HSDI engine

J. Benajes[a], R. Novella[a], J.M. Pastor[a,*], A. Hernández-López[a], T. Duverger[b]

[a] CMT – Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
[b] Combustion and Fuel Supply Functions, PSA Groupe, 18 rue des Fauvelles BP16, 92256 La Garenne Colombes Cedex, France

HIGHLIGHTS

- A CFD study of the impact of bore-to-stroke on engine performance has been done.
- Efficiency increases with smaller B/S ratio due to lower heat losses.
- Higher NOx emissions for lower B/S ratio mainly due to faster mixing and combustion.
- Lower B/S ratio decreases fuel rich pockets in squish region and then soot formation.

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ABSTRACT

Research on combustion systems for Internal Combustion Engines (ICE) is guided by the necessity of improving engine efficiency while achieving the pollutant regulations. In this framework, this study identifies and describes the effect of the bore-to-stroke ratio (B/S) on the combustion system performance and emissions by means of computational fluid dynamics (CFD).

The study is applied to a 4-cylinder 4-stroke High Speed Direct Injection (HSDI) CI engine. It is divided in two parts, the first part is focused on one operating point and presents a detailed description of the main effects of different B/S ratios configurations, and the second part compares the results with different engine operating conditions. For both parts the air management, injection settings and compression ratio were kept constant in order to isolate the impact of the B/S ratio.

The results confirmed that the indicated thermal efficiency was increased for lower B/S ratio because of the combustion chamber surface area decrease and faster combustion. Regarding the emissions, NOx and soot presented a strong and opposed dependence on B/S ratio generated mostly due to enhanced air–fuel mixing for lower B/S ratio. Finally, those trends were proven to be independent from the operating condition, giving the study a more general value.

1. Introduction

Optimizing the Internal Combustion Engines (ICE) for transport applications is a major research topic due to the needs of fulfilling the current and future pollutant emission regulations. For that reason, the investigation in this field has been driven by the need of decreasing pollutants and overcome mechanical limitations. Nowadays, especially for Compression Ignition (CI) engines, keeping their fuel consumption levels competitive compared to the Spark Ignition (SI) engines to control CO_2 emissions have gained importance and some aspects, such as heat transfer, have become even more relevant in the current framework of ICE research.

Historically, the optimization strategies in compression ignition (CI) engines have been focused on improving air management [1], injection settings [2], nozzle definition or piston bowl geometry [3–5]. This trend continues due to the increasingly stringent emission standards and further CI engine investigation focuses on including dual fuel strategies [6] or fuel blends coupled with injection settings optimization [7]. However, the basic geometric architecture, such as bore-to-stroke, tend to be kept unchanged or modified within a quite limited range for small and some medium sized diesel engines. This fact has generated a recent interest since a fine tuning of B/S ratio has potential to improve heat transfer, mixing time or friction [8], resulting in an overall improvement in engine efficiency or power density. It is interesting, therefore,

* Corresponding author.
E-mail address: jopasen@mot.upv.es (J.M. Pastor).

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Nomenclature

aTDC	After Top Dead Center
BDC	Bottom Dead Center
B/S	bore-to-stroke
CA90	crank angle for 90% of fuel burnt
CI	Compression Ignition
CFD	computational fluid dynamics
DI	Direct Injection
EGR	Exhaust Gas Recirculation
EVO	Exhaust Valve Opening (angle)
EXP	experimental
HRR	heat release rate
HRL	accumulated heat release law
ICE	Internal Combustion Engines
IMEP	indicated mean effective pressure
IVC	Intake Valve Closing (angle)
m_{IVC}	in-cylinder mass at IVC
P_{IVC}	pressure at IVC
TDC	Top Dead Centre
T_{IVC}	temperature at IVC
Y_{O2}	in-cylinder oxygen concentration
Y_{N2}	in-cylinder nitrogen concentration
Y_{RES}	in-cylinder residuals concentration

to re-examine those scaling relationships traditionally used to describe engine performance, and assess their impact on 4-cylinder 4-stroke High Speed Direct Injection (HSDI) CI engine.

Experimental optimization is a well-known method due to the simplicity of adjusting air management, injection setting or fuel composition aiming for an improved combustion process. Therefore, in the past years a lot of the research works focused on combustion system optimization, have been performed experimentally [9–11]. However, when engine hardware, such as the combustion chamber or the injector nozzle definition, is involved in the optimization tasks, the process is costly in terms of time and resources since it involves manufacturing and assembling parts, together with weeks or even months of intensive testing. For that reason, limited experimental research has been reported in the literature discussing the optimum bore-to-stroke (B/S) ratio for engines equipped with state-of-the-art air management and injection systems, and also restricted to the current emissions constraints. Kermani et al. [12] performed an experimental study of the influence of the B/S ratio on fuel consumption, performance and emissions on a light-duty Diesel engine. Experiments proved how higher B/S ratios increase heat transfer losses, due to the higher combustion chamber area-to-volume ratio at TDC, resulting in a decrease of the indicated mean effective pressure (IMEP). Additionally, it was also shown that decreasing B/S ratios increase the piston swept surface resulting in an increase of friction losses. The study converges to an optimum B/S ratio range of 0.9–0.95, being 0.85 the smallest B/S ratio evaluated. Also from an experimental study, Lavoisier et al. [13] pointed out that higher B/S ratio will allow wider bowls that improve combustion process at high speed and load. This could be counteracted by the less favorable *k*-factor (ratio of bowl volume to total volume of the combustion chamber at TDC), which limits the air utilization. In this study was found an optimal B/S ratio close to 0.93, taking into account maximum rated power, fuel consumption and pollutants.

In terms of engine efficiency, the B/S ratio has an impact on both heat losses to the walls and friction losses [14], so a balance has to be found between those two counteracting effects. Several studies have been performed investigating the mechanical losses, Payri et al. [15] showed that the mechanical losses represents around 4–10% of the total fuel energy injected. Subsequently, those authors [16] further developed their research, proving that the friction between the piston and the liner is responsible for 50% of the total mechanical losses, so that the piston friction results in 2–5% of the total energy.

Recently, computational modeling is gaining reliability in predicting combustion and pollutants by using properly calibrated and validated models, not only because the predicted results have a high accuracy but also because it offers an in depth analysis that cannot be performed experimentally with the current measurement techniques. Then, computational modeling has been used to further study the effect of B/S ratio in CI engines, mostly for predesign purposes. During this stage of the engine design, 1D models are dominant since they offer a quick and robust prediction of the whole engine behavior. However, these models tend to excessively simplify the combustion process or even use correlations to simulate its behavior. Vassallo et al. [17] carried out an investigation of the impact of B/S ratio also on a light-duty engine. The results were obtained by employing a 1D approach based on Design of Experiments (DOE) methodology. They show that B/S ratio close to 1, enables a good equilibrium between specific power rating and low-end torque thanks to the volumetric efficiency profile and the lower heat transfer by convection in the pipes. The higher volumetric efficiency for this ‘square design’ and lower convection is proven to compensate its unfavorable surface-to-volume ratio. In addition, the longer stroke length of low B/S ratio generates higher friction losses leading to better thermal efficiencies for higher B/S ratios. The next step in the computational modeling approach, which is the use of 3D CFD simulations, have also been performed [18]. As proven, even operating with advanced combustion concepts they offer a more detailed insight on the effect of B/S ratios and its interaction with the combustion process, in-cylinder pollutants distributions and heat transfer, allowing a better understanding of the complete problem.

From the previous discussion, due to the recent interest on the potential benefits in terms of engine efficiency attainable by redefining the optimum B/S ratio and the high computational cost of integrating CFD modeling activities in the engine predesign stage, it is evident how the key effects of B/S ratio and how they interact are still not well understood. In this framework, the research work reported in the present paper focuses on the identification and description of the impact of the B/S ratio on the trade-off between thermal efficiency and emissions by means of CFD modeling, this is, taking into account the detailed interaction between B/S ratio and the combustion process. The process carried out in this paper has two main blocks, the first one focuses on one operating point and presents all the important effects of different B/S ratios configurations. On the second block, the previous results are compared against other operating points of the same engine.

2. Experimental tools

2.1. Engine characteristics

The experimental data required for the calibration and validation of the CFD model was obtained from a 4-cylinder 4-stroke High Speed Direct Injection (HSDI) CI engine, equipped with a common-rail injection system. Table 1 contains the main engine characteristic and Table 2 contains the main fuel characteristics.

All the experimental results used in this paper, and additional

Table 1
Engine main characteristics.

Engine data	
Bore × stroke [mm]	85 × 88
Unitary Displacement [cm^3]	499.36
Connecting rod length [mm]	145
Geometric compression ratio [–]	16.7
Nozzle hole number	7