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Computer-aided conversion of an engine from diesel to methane

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HIGHLIGHTS

- A computer aided procedure for automatic generation of the new piston profile.
- Manufacturability, feasibility and CFD analyses and a multi-objective optimization.
- Experimental validation for the combustion model and the optimization procedure.
- Application to a CNG dedicated engine to avoid detonation.
- Application to a dual fuel engine to minimize HC and NO_x emissions at part load.

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ABSTRACT

The paper proposes an analytical methodology that uses empirical based models and CFD simulations to efficiently evaluate design alternatives in the conversion of a diesel engine to either CNG dedicated or dual fuel engines. The procedure is performed in five steps. Firstly, a database of different combustion chambers that can be obtained from the original piston is obtained. The chambers in the database differ for the shape of the bowl, the value of the compression ratio, the offset of the bowl and the size of the squish region. The second step of the procedure is the selection, from the first database, of the combustion chambers able to resist to the mechanical stresses due to the pressure and temperature distribution at full load. For each combination of suitable combustion chamber shape and engine control parameters (ignition/injection crank angle, EGR, etc.), a CFD simulation is used to evaluate the combustion performance of the engine. Then, a post-processing procedure is used to evaluate the detonation tendency and intensity of each combination. All the tools developed for the application of the method have been linked in the ModeFrontier optimization environment in order to perform the final choice of the combustion chamber.

The overall process requires not more of a week of computation on the four processor servers considered for the optimization. Moreover, the selected chambers can be obtained from the original piston of the engine. Therefore, the conversion cost of the engine is quite small compared with the case of a completely new piston. The paper also describes the application of the procedure to two different engines.

1. Introduction

Gaseous fuels like natural gas have been extensively investigated in literature [1–4] as alternative to gasoline and diesel. Compressed Natural Gas (CNG) has higher octane number than gasoline, is more economical than traditional fossil fuels due to its low production cost, and reduces air pollution significantly. Moreover, CNG contains neither lead nor benzene and greenhouse gases emission from combustion of CNG is about 25% lower than that of gasoline. Another important advantage of CNG is the high stability against knocking and the possibility to use higher compression ratios than gasoline engines thus increasing brake thermal efficiency and power [2]. On the other hand, the higher compression ratio causes greater NO_x and HC emissions.

Two different methods have been developed to convert a direct injection diesel engine into a natural gas engine, *CNG dedicated* and *Dual Fuel*. In the first case, ignition is performed with the use of a spark plug like in a gasoline engine while the dual-fuel mode uses Compressed Natural Gas (CNG) as the primary fuel and small quantities of diesel pilot-fuel for ignition. Of course, the engine configuration has to be changed in order to allow the combustion of the new fuel. In the CNG-dedicated conversion, the diesel injector is no more used and it is usually replaced by a spark-plug after a proper redesign of the cylinder head [1]. Moreover, the intake manifold has to be modified to include the gas injector, the control valve and its control unit. The conversion from diesel to CNG causes a reduction of brake power up to 30% and an increasing of

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Nomenclature

CFDs	Computational Fluid Dynamics	KI	Knock Intensity
CNG	Compressed Natural Gas	KOCA	Knock Occurrence Crank Angle
CR	compression ratio	MCC	Manufacturable Combustion Chamber
D	cylinder bore	MT	minimal thickness
ER	equivalence ratio	SH	squish height
FMCC	Feasible and Manufacturable Combustion Chamber	Vs	cylinder displacement

CO and HC emissions [1]. Therefore, the conversion of the engine requires a multi-objective approach to find the combination of design and control parameters that gives the best compromise in terms of performance and emissions.

In the case of dual fuel conversion, the cylinder head is not modified since the spark plug is not required and the injection of the liquid fuel is still performed with an in-cylinder injection system. Dual-fuel engines deriving from the conversion of conventional diesel engines usually operate un-throttled, with the load regulated by the admission of natural gas in the intake manifold. This introduce a further challenge in the numerical simulation of this systems i.e. the lean fuel combustion mode. Dual fuel engines have lower emissions of smoke and nitrogen oxides than conventional CI engines while maintaining their high thermal efficiencies. However, an increase of emissions of unburned hydrocarbons (HC) and carbon monoxide (CO) is obtained due to poor ignitability of the mixture [4]. Once again the optimization of dual fuel combustion requires a multi-objective approach.

In the conversion of the diesel engine to either CNG dedicated or dual fuel, it is important to keep the original components of the engine in order to reduce the conversion costs. However, some alterations have to be made to optimize the behavior of the engine when CNG is used. For example, the choice of compression ratio is a key factor in the conversion as described before. The selection of the new compression ratio is usually performed with the help of simple combustion models or with experimental campaigns. However, detonation is well known to be dependent on the design of the combustion chamber.

Direct Injection diesel engines use re-entrant bowl with a central protrusion in order to improve the air–fuel mixing and accelerate the combustion process. Of course, this kind of combustion chamber is not optimized either for CNG dedicated or for dual fuel combustion. The aim of the present investigation is to study the effect of the combustion chamber in the diesel-CNG conversion and optimizing its design with the help of a computer aided procedure already applied to several diesel engine configurations [5]. The procedure is based on the coupling of a multi-objective genetic algorithm with a multi-dimension simulation code able to accurately predict the combustion process. The procedure has been applied to several direct injection diesel engine and its results have been experimentally verified by building and testing the optimized combustion chamber [5]. Compared with statistic methods based on a reduced number of experiments like Taguchi method [6], genetic algorithms require a large number of evaluations but allows the number of levels to be increased for each design variables thus increasing the accuracy in finding the optimum. Moreover, genetic algorithms can be applied to multi-objective optimizations because are implicitly parallel. If the evaluation of the proposed design is performed through time-consuming CFD simulations, like in the present investigation, the implicit parallelism also simplifies the distribution of computational load on multi-node servers by running a different design on each node. This is preferable to parallelize the computational code [10] because each run is independent of the others.

In order to apply the procedure to a CNG dedicated or a CNG dual fuel engine, it is mandatory to have an accurate model for the selected combustion mode. The simplest way to model the combustion of CNG is a simplified combustion model like the Wiebe [7]. The parameters of the Wiebe model for the CNG-dedicated or Dual-Fuel combustion model can be obtained on experimental or numerical basis, e.g. with the use of detailed reaction schemes [8]. This approach is not suitable for the present investigation since it does not take into account the effect of the flow-field generated by the particular shape of the combustion chamber.

In order to optimize the combustion chamber design for a CNG-dedicated engine, it is important to implement also a detonation model. Detailed models for detonation describe the complex chemical mechanisms that govern the oxidation process in the end-gas region during the auto-ignition delay. The chemical kinetic schemes involve thousands of elementary reaction steps that are believed to take place in this kind of engines [9]. Since the rate coefficients are determined on the basis of fundamental chemical processes, there should be no need to adjust any of the rate coefficients of the schemes. However, detailed chemical models may need some calibration because the actual kinetic mechanisms for each combustion process are unknown. Moreover, the required computational time is still prohibitive in the case under examination. In fact, the coupling of the CFD model with the multi-objective genetic algorithm require hundreds of runs to be performed with respect to different combustion chamber profiles [5].

For design purpose applications, simple empirically based models based on a global reaction for auto ignition delay can be sufficient. Recently, Soylu and Van Gerpen [11] developed a detonation model for CNG named *Knock Integral Method*. It can be applied to propane-methane mixture but in the present investigation it will be used only for CNG combustion.

Dual fuel combustion is extremely complex because it involves two fuels with different characteristics which are simultaneously burned inside the cylinder. The heat release rate of dual fuel combustion is the results [12,13] of three combustion stages: the combustion of the pilot injection of diesel fuel, the combustion of the gaseous fuel that is in the immediate vicinity of the ignition kernel and the pre-ignition activity and subsequent turbulent flame propagation. However, the relevance of the third stage depends on the amount of natural gas. In the case of very lean mixtures, no consistent flame propagation will take place from the ignition centers and combustion is mainly influenced by the pilot combustion. Only when the mixture becomes richer, a more regular propagation of the flame can be obtained.

Reitz et al. [14,15] developed a new combustion model for dual fuel engine where flame propagation is simulated with the level set method of Peters [16]. According to the analysis of Reitz et al. [14,15], ignition occurs in two different positions, namely in the vicinity of the nozzle injector and in the region of the combustion chamber where the spray impacts on the cylinder walls. Then, combustion extends through the remaining part of the chamber, but leaves unburned a large proportion of mixture next to the wall of the cylinder.