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Combustion phasing for maximum efficiency for conventional and high efficiency engines

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ABSTRACT

The importance of the phasing of the combustion event for internal-combustion engines is well appreciated, but quantitative details are sparse. The objective of the current work was to examine the optimum combustion phasing (based on maximum *bmep*) as functions of engine design and operating variables. A thermodynamic, engine cycle simulation was used to complete this assessment. As metrics for the combustion phasing, both the crank angle for 50% fuel mass burned (CA_{50}) and the crank angle for peak pressure (CA_{pp}) are reported as functions of the engine variables. In contrast to common statements in the literature, the optimum CA_{50} and CA_{pp} vary depending on the design and operating variables. Optimum, as used in this paper, refers to the combustion timing that provides the maximum *bmep* and brake thermal efficiency (MBT timing). For this work, the variables with the greatest influence on the optimum CA_{50} and CA_{pp} were the heat transfer level, the burn duration and the compression ratio. Other variables such as equivalence ratio, EGR level, engine speed and engine load had a much smaller impact on the optimum CA_{50} and CA_{pp}. For the conventional engine, for the conditions examined, the optimum CA_{50} varied between about 5 and 11°aTDC, and the optimum CA_{pp} varied between about 9 and 16°aTDC. For a high efficiency engine (high dilution, high compression ratio), the optimum CA_{50} was 2.5°aTDC, and the optimum CA_{pp} was 7.8°aTDC. These more advanced values for the optimum CA_{50} and CA_{pp} for the high efficiency engine were largely due to lower heat losses.

1. Introduction

The phasing of the combustion event (and the related heat release) is known to have a direct impact on the thermal efficiency of internal combustion engines. The combustion event results in increases of cylinder pressure which is the source of the engine's work output. Advanced (early) combustion increases the compression work and heat losses, and retarded (late) combustion decreases the expansion work. By adjusting the start of combustion for the maximum brake work, an optimum (MBT) timing may be determined. This MBT timing then results in a specific crank angle for the consumption of 50% of the fuel mass (CA_{50}), and a specific crank angle for the peak cylinder pressure (CA_{pp}). Unless noted otherwise, the CA_{50} and CA_{pp} cited in this paper refer to those values obtained for MBT timing (for maximum *bmep* and brake thermal efficiency).

As described below, many authors cite ~10°aTDC as the optimum CA_{50} for highest efficiency with the implication that this value is invariant. Although the current work will show that this approximation may be correct for some of the combinations of variables, from a thermodynamic view, it is not a universal value. Further, understanding the ways that CA_{50} and CA_{pp} are influenced by various engine variables are important insights for effective engine designs.

A thermodynamic, engine cycle simulation was used in this work. One of the advantages of the use of a simulation as opposed to an experiment is that the effects of individual variables may be determined in a clear and unambiguous fashion. For this work, combustion was assumed to be successful and knock was not considered. Due to these assumptions, the results reflect only the governing thermodynamics.

The implications of this research include a more precise understanding of the trade-offs associated with combustion phasing. This could lead to higher efficiency engines with the obvious benefits of fuel use reductions, lower carbon dioxide emissions, and more economical operation.

The following parts of this paper include a brief discussion of previous work, a description of the engine cycle simulation, a presentation of the results, and a set of conclusions.

2. Background and literature review

A number of previous studies have examined combustion phasing using engine simulations and experiments. Some of the more recent of these studies are reviewed in this section in chronological

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order. Although other papers exist on this topic, the following are representative.

Zhu et al. [1] reported on the development of a simplified scheme to pursue on-board engine control based on measures of MBT timing. In the course of this work, they stated that the literature often noted that peak cylinder pressure usually occurs around 15°aTDC, and CA_{50} generally occurs from 8 to 10°aTDC at MBT timing. They made the point that these general observations were not universal, and their goal was to obtain a better understanding of the dependence of these parameters on engine operation. They proposed the use of the maximum acceleration location of mass fraction burned for the MBT timing criterion which appeared valid over a range of conditions.

Ayala et al. [2] reported a wide range of data from a spark-ignited engine concerning the effects of combustion phasing on efficiency. They used combustion modeling to interpret the experimental data, and reported a combustion phasing parameter which appeared to correlate the majority of the results. They stated that the fundamental factor causing the deterioration of efficiency for high air–fuel ratios is the longer burn durations.

Ma et al. [3] described a study of combustion phasing for a spark-ignited engine. They used a thermodynamic engine cycle simulation with some supplemental experimental data. The supplemental experimental data was mainly needed so that they could have combustion rates for different engine conditions. The experimental combustion rates were varied by adding varying amounts of hydrogen to natural gas (the main fuel). For conditions they examined, they claimed that highest efficiency was obtained for the peak combustion rate at 9°aTDC.

Ponti et al. [4] proposed to obtain information on CA_{50} from the engine speed fluctuation measurement rather than from a cylinder pressure measurement. Such a technique would be a cost-effective approach to on-board optimization of the combustion process. They recommended further improvements in the accuracy of the technique. In 2011, Ravaglioli et al. [5] reported on a continuation of their earlier work [4] on developing on-board evaluations of CA_{50} so that combustion could be controlled for optimum efficiency. They described an approach that used injection parameters and a zero-dimensional thermodynamic model to provide CA_{50}.

Lavoie et al. [6] presented the results of a study that explored operating conditions that would lead to optimum engine and vehicle performance. They based their work on engine cycle and engine-vehicle simulations. For their conditions, they reported that CA_{50} was ~10°aTDC. They stated that for shorter burn durations CA_{50} advanced a few degrees, and for adiabatic conditions the CA_{50} was at TDC.

Carvalho et al. [7] completed an investigation on which variables have an influence on the optimum CA_{50}. Their results indicated that the CA_{50} was sensitive to the cylinder heat transfer and slightly sensitive to the burn duration. They stated that the optimal CA_{50} is between about 8 and 10°aTDC, and this is due to a compromise between work output, heat transfer, and exhaust gas energy.

The results reported in the above literature illustrate the importance of a more complete understanding of combustion phasing for internal combustion engines. Although these studies have provided some valuable information, no study has provided a comprehensive evaluation of combustion phasing as functions of a more complete set of engine operating and design parameters. This need has motivated the current work.

3. Engine cycle simulation description

The cycle simulation used in this work has been described in detail elsewhere [8–13]. This simulation is largely based on thermodynamic formulations, and is a complete representation of the four-stroke cycle including the intake, compression, combustion, expansion and exhaust processes. The simulation uses detailed thermodynamic gas properties including equilibrium composition for the burned gases. The combustion process is based on a mass fraction burn relation from Wiebe [14].

The cylinder heat transfer correlation used in this work is selected from three representative correlations. For the convention engine, two correlations which are commonly used in the literature will be used here. One is from Hohenberg [15] and one is from Woschni [16]. For the high efficiency engine (highly diluted engine), a correlation from Chang et al. [17] will be used. This correlation [17] was based on experiments using a highly diluted engine, and may be representative of high efficiency engines.

The major assumptions and approximations used in the development of the engine cycle simulation include the following:

(1) The thermodynamic system is the cylinder contents (see Fig. 1).
(2) The engine is in steady-state such that the thermodynamic state at the beginning of each cycle (two crankshaft revolutions) is equivalent to the state at the end of the cycle.
(3) For the compression, expansion and exhaust processes, the cylinder contents are spatially homogeneous and occupy one zone.
(4) For the intake process, two zones (each spatially homogeneous) are used. One zone consists of the fresh charge and the other zone consists of the residual gases.
(5) For the combustion processes, three zones (each spatially homogeneous) are used. The three zones are: the unburned zone, the adiabatic core burned zone, and the boundary layer burned zone. The adiabatic core and boundary layer zones together comprise the burned zone. The total heat transfer is divided in an appropriate fashion between the unburned and burned zone. The heat transfer from the burned zone is assigned in total to the boundary zone [8,9].
(6) The thermodynamic properties (including pressure and temperature) vary only with time (crank angle) and are spatially uniform in each zone.
(7) The instantaneous composition is obtained from generally accepted algorithms [18] and the species obey the ideal gas equation of state.

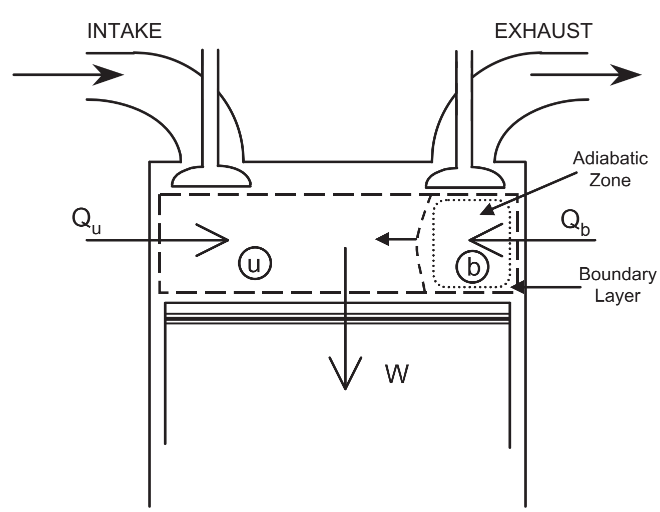

Fig. 1. A schematic of the engine cylinder depicting the three zones during combustion.