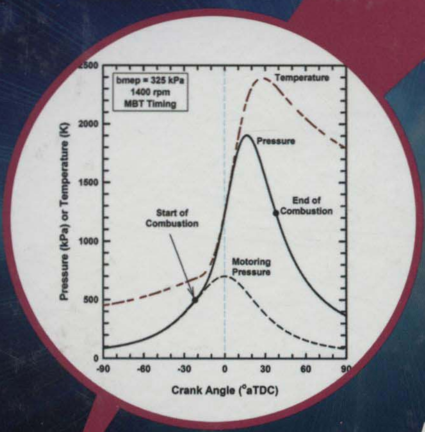

JERALD A. CATON

An Introduction to Thermodynamic Cycle Simulations for Internal Combustion Engines

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AN INTRODUCTION TO THERMODYNAMIC CYCLE SIMULATIONS FOR INTERNAL COMBUSTION ENGINES

To my wife, Roberta,
our children, Jacob, Lewis and Kassandra, and
our grandchildren

Preface

The use of engine cycle simulations is an important aspect of engine development, and yet there is limited comprehensive documentation available on the formulations, solution procedures, and detailed results. Since beginning in the 1960s, engine cycle simulations have evolved to their current highly sophisticated status. With the concurrent development of fast and readily available computers, these simulations are used in routine engine development activities throughout the world. This book provides an introduction to basic thermodynamic engine cycle simulations and provides a substantial set of results.

This book is unique and provides a number of features not found elsewhere, including:

- comprehensive and detailed documentation of the mathematical formulations and solutions required for thermodynamic engine cycle simulations;
- complete results for instantaneous thermodynamic properties for typical engine cycles;
- self-consistent engine performance results for one engine platform;
- a thorough presentation of results based on the second law of thermodynamics;
- the use of the engine cycle simulation to explore a large number of engine design and operating parameters via parametric studies;
- results for advanced, high efficiency engines;
- descriptions of the thermodynamic features that relate to engine efficiency and performance;
- a set of case studies that illustrate the use of engine cycle simulations—these case studies consider engine performance as functions of engine operating and design parameters;
- a detailed evaluation of nitric oxide emissions as functions of engine operating parameters and design features.

Although this book focuses on the spark-ignition engine, the majority of the development and many of the results are applicable (with modest adjustments) to compression-ignition (diesel) engines. In fact, the major difference between the two engines relates to the combustion process, and these differences are mostly related to the details and not the overall process. But to be consistent, extrapolations to compression-ignition engines are largely avoided.

The examples and case studies are based on an automotive engine, but the procedures and many of the results are valid for other engine classifications. In addition, the thermodynamic simulation could be used for these other applications. Many of the results are fairly general and would be applicable to most engines. For example, results highlighting the difficulty of converting thermal energy into work (a consequence of the fundamental thermodynamics) applies to all engines.

Although the main purpose of the writing of this book was to document the development and use of thermodynamic engine cycle simulations, a secondary purpose was to stimulate the interest and excitement of using fundamental thermodynamic principles to understand a complex device. As the following pages will demonstrate, many phenomena related to engine operation and design may be understood in a more complete fashion by focusing on the fundamental thermodynamics.

The work of Professor John B. Heywood needs to be acknowledged as a major part of the foundations of the material in this book. These foundations are recognized in the book by numerous citations to the work of Professor Heywood, his colleagues, and his students.

The author has enjoyed his work on this topic and writing this book. He hopes that the reader will gain insight into engine design and operation, and be stimulated to use engine cycle simulations to answer his/her own questions. Although this presentation and these results have been examined by many reviewers, any mistakes remaining are the sole responsibility of the author. Notification of the author of these mistakes and suggestions for improvements would be greatly appreciated.

Contents

1

Introduction

The internal combustion (IC) engine is a spectacular, complex device that has been an unqualified success. The IC engine is probably best known as the power plant for vehicles, but, of course, is also successfully used in a variety of other applications. These other applications include, for example, simple garden equipment, stationary electrical power generation, locomotives, and ships. A powerful approach to aid in the design and understanding of these engines is through the use of mathematical simulations.

Engine cycle simulations have been developed and used to study a variety of features and issues relative to IC engines since the 1960s. In the beginning, engine cycle simulations were fairly elementary, and were limited by both computing capabilities and a lack of knowledge concerning key sub-models. In time, these simulations have become more complete and more useful.

Today, engine cycle simulations are sophisticated, complex computer programs that provide both global engine performance parameters as well as detailed, time-resolved information. Many of these simulations contain advanced and detailed sub-models for the fluid mechanics, heat transfer, friction, combustion, and chemical kinetics. The most advanced simulations include calculations in three dimensions. Some of these simulations are grouped in the general category of computational fluid dynamics (CFD). Some comments on the early history (pre-1990) of the development of engine simulations may be found in References 1–3.

1.1 Reasons for Studying Engines

As mentioned above, IC engines have been an unqualified success in several major economic markets. Certainly, as the propulsion unit for light duty vehicles, the IC engine has been a significant accomplishment. The number of such vehicles and their engines is estimated at one billion throughout the world, and is expected to be about two billion by 2020. For a rather complex, major device, these are exceptional numbers. Other applications of IC engines include stationary power generation, marine propulsion, small utility, off-road, and agriculture.

The reasons for the success of the IC engine have been well documented (e.g., References 2, 4, and 5). These reasons include relatively low initial cost, high power density, reasonable

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driving range (say, more than 200 miles for a standard fuel tank size), able to refuel on the order of minutes at many locations, robust and versatile, reasonably efficient, able to meet regulated emission limits, and well matched to available fuels. This last item is particularly important and results in some of the other favorable features.

Liquid hydrocarbon fuels (such as gasoline and diesel) possess relatively high energy densities, are relatively safe and stable, and (currently) are widely available. In addition, these fuels possess excellent characteristics for combustion processes utilized by spark-ignited and compression-ignited engines.

Current (2015) engine technology spans a wide range from fairly basic to relatively advanced. Some engines are still based on the use of carburetors, mechanical valve trains, and large displacements. More advanced engine designs include direct fuel injection, variable valve timings, turbocharging, and the capability to deactivate some cylinders for part load operation. Most spark-ignition engines are designed for operation at or near stoichiometric with compression ratios less than about 11 (to avoid spark knock).

The demise of the IC engine is often a popular topic in the lay press due to the perception that it is based on "old" technology. Despite this perception, the IC engine remains a successful device. Alternative power plants for light-duty vehicles include electric motors operated with batteries or fuel cells. Some advances have been accomplished regarding these technologies, but these alternatives are still many years away from displacing the IC engine. Especially considering the long time frame for replacement of existing vehicles in the current fleet, IC engines are expected to be the dominant power plant for many decades into the future.

1.2 Engine Types and Operation

Several versions of the IC engine exist. The two major categories are spark-ignition engines and compression-ignition (diesel) engines. The spark-ignition engine is based largely on a (nearly) homogeneous mixture of fuel and air, and on a more-or-less organized flame propagation. To satisfy this type of ignition and combustion process, the fuel must vaporize relatively easily and resist autoignition. Fuels with these characteristics include gasoline, natural gas, propane, and alcohols. The spark-ignition engine is often restricted to moderate compression ratios to avoid spark knock. Almost all spark-ignition engines for today's light-duty vehicles operate with stoichiometric mixtures and utilize three-way catalyst systems to meet emission regulations.

The compression-ignition engine, on the other hand, is based on the injection of the fuel into a cylinder with air, and on the self-ignition of the fuel due to the temperature of the compressed air. For the compression-ignition engine, combustion occurs in various locations throughout the cylinder with no organized flame propagation. To satisfy this type of ignition and combustion process, the compression ignition engine must utilize a fuel that can readily self-ignite. This fuel is typically a diesel fuel, but jet fuel and other oils can be used. The compression-ignition engine generally requires a relatively high compression ratio to generate sufficiently high temperature air for the auto-ignition process. These engines typically must operate with excess air (fuel lean) to ensure all the fuel is burned. In many applications, the compression-ignition engine uses intake air compression (turbochargers and superchargers) to increase its power density.