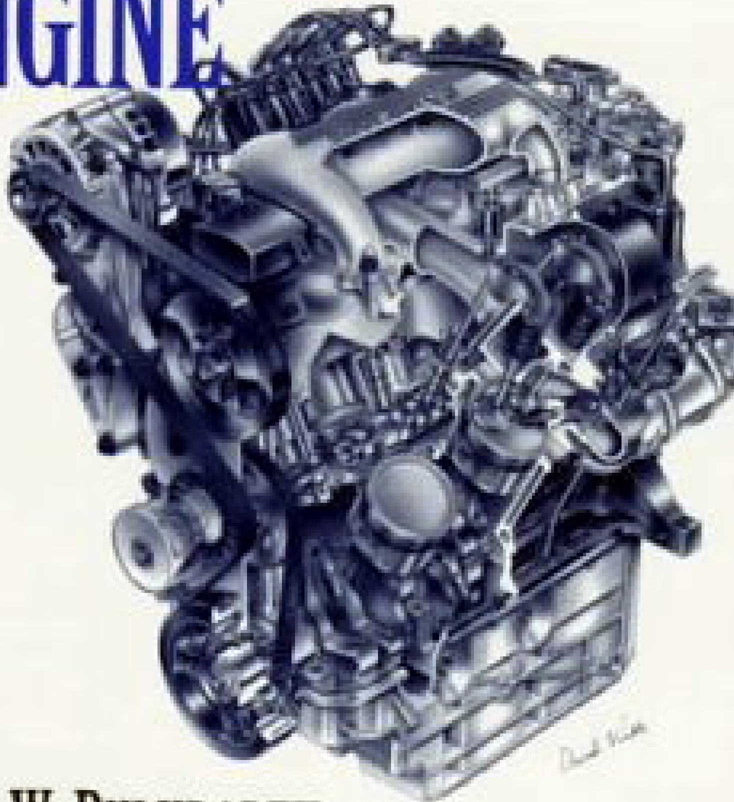
ENGINEERING FUNDAMENTALS OF THE INTERNAL COMBUSTION ENGINE



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Engineering Fundamentals of the Internal Combustion Engine

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Contents

Preface

This book was written to be used as an applied thermoscience textbook in a one-semester, college-level, undergraduate engineering course on internal combustion engines. It provides the material needed for a basic understanding of the operation of internal combustion engines. Students are assumed to have knowledge of fundamental thermodynamics, heat transfer, and fluid mechanics as a prerequisite to get maximum benefit from the text. This book can also be used for self-study and/or as a reference book in the field of engines.

Contents include the fundamentals of most types of internal combustion engines, with a major emphasis on reciprocating engines. Both spark ignition and compression ignition engines are covered, as are those operating on four-stroke and two-stroke cycles, and ranging in size from small model airplane engines to the largest stationary engines. Rocket engines and jet engines are not included. Because of the large number of engines that are used in automobiles and other vehicles, a major emphasis is placed on these.

The book is divided into eleven chapters. Chapters 1 and 2 give an introduction, terminology, definitions, and basic operating characteristics. This is followed in Chapter 3 with a detailed analysis of basic engine cycles. Chapter 4 reviews fundamental thermochemistry as applied to engine operation and engine fuels. Chapters 5 through 9 follow the air-fuel charge as it passes sequentially through an engine, including intake, motion within a cylinder, combustion, exhaust, and emissions. Engine heat transfer, friction, and lubrication are covered in Chapters 10 and 11. Each chapter includes solved example problems and historical notes followed by a set of unsolved review problems. Also included at the end of each chapter are open-ended problems that require limited design application. This is in keeping with the modern engineering education trend of emphasizing design. These design problems can be used as a minor weekly exercise or as a major group project. Included in the Appendix is a table of solutions to selected review problems.

Fueled by intensive commercial competition and stricter government regulations on emissions and safety, the field of engine technology is forever changing. It is difficult to stay knowledgeable of all advancements in engine design, materials, controls, and fuel development that are experienced at an ever-increasing rate. As the outline for this text evolved over the past few years, continuous changes were required as new developments occurred. Those advancements, which are covered in this book, include Miller cycle, lean burn engines, two-stroke cycle automobile engines, variable valve timing, and thermal storage. Advancements and technological changes will continue to occur, and periodic updating of this text will be required.

Information in this book represents an accumulation of general material collected by the author over a period of years while teaching courses and working in research and development in the field of internal combustion engines at the Mechanical Engineering Department of the University of Wisconsin-Platteville. During this time, information has been collected from many sources: conferences, newspapers, personal communication, books, technical periodicals, research, product literature, television, etc. This information became the basis for the outline and notes used in the teaching of a class about internal combustion engines. These class notes, in turn, have evolved into the general outline for this textbook. A list of references from the technical literature from which specific information for this book was taken is included in the Appendix in the back of the book. This list will be referred to at various points throughout the text. A reference number in brackets will refer to that numbered reference in the Appendix list.

Several references were of special importance in the development of these notes and are suggested for additional reading and more in-depth study. For keeping up with information about the latest research and development in automobile and internal combustion engine technology at about the right technical level, publications by SAE (Society of Automotive Engineers) are highly recommended; Reference [11] is particularly appropriate for this. For general information about most engine subjects, [40,58,100,116] are recommended. On certain subjects, some of these go into much greater depth than what is manageable in a one-semester course. Some of the information is slightly out of date but, overall, these are very informative references. For historical information about engines and automobiles in general, [29, 45, 97, 102] are suggested. General data, formulas, and principles of engineering thermodynamics and heat transfer are used at various places throughout this text. Most undergraduate textbooks on these subjects would supply the needed information. References [63] and [90] were used by the author.

Keeping with the trend of the world, SI units are used throughout the book, often supplemented with English units. Most research and development of engines is done using SI units, and this is found in the technical literature. However, in the non-technical consumer market, English units are still common, especially with automobiles. Horsepower, miles per gallon, and cubic inch displacement are some of the English terminology still used. Some example problems and some review problems are done with English units. A conversion table of SI and English units of common parameters used in engine work is included in the Appendix at the back of the book.

I would like to express my gratitude to the many people who have influenced me and helped in the writing of this book. First I thank Dorothy with love for always being there, along with John, Tim, and Becky. I thank my Mechanical Engineering Department colleagues Ross Fiedler and Jerry Lolwing for their assistance on many occasions. I thank engineering students Pat Horihan and Jason Marcott for many of the computer drawings that appear in the book. I thank the people who reviewed the original book manuscript and offered helpful suggestions for additions and improvements. Although I have never met them, I am indebted to authors J. B. Heywood, C. R. Ferguson, E. F. Obert, and R. Stone. The books these men have written about internal combustion engines have certainly influenced the content of this textbook. I thank my father, who many years ago introduced me to the field of automobiles and generated a lifelong interest. I thank Earl of Capital City Auto Electric for carrying on the tradition.

ACKNOWLEDGMENTS

The author wishes to thank and acknowledge the following organizations for permission to reproduce photographs, drawings, and tables from their publications in this text: Carnot Press, Fairbanks Morse Engine Division of Coltec Industries, Ford Motor Company, General Motors, Harley Davidson, Prentice-Hall Inc., SAE International, The Combustion Institute, and Tuescher Photography.

Notation

Notation, symbols, and abbreviations used in this text. Common units are given in brackets, both SI and English.

A	Cross-section area of flow [cm^2] [in.^{2}]
A_c	Flow area of fuel capillary tube [mm^2] [in.^{2}]
A_{cc}	Surface area of combustion chamber [cm^2] [in.^{2}]
A_{ch}	Cylinder head surface area [cm^2] [in.^{2}]
A_{ex}	Area of exhaust valve [cm^2] [in.^{2}]
A_i	Area of intake valve [cm^2] [in.^{2}]
A_p	Piston face area of flat-faced piston, and/or cross-section area of cylinder [cm^2] [in.^{2}]
A_t	Throat area of carburetor [cm^2] [in.^{2}]
AF	Air–fuel ratio [kg$_a$/kg$_f$] [lbm$_a$/lbm$_f$]
AKI	Anti-knock index
AON	Aviation octane number
B	Cylinder bore [cm] [in.]
C	Constant
C_{D}	Discharge coefficient
C_{Dc}	Discharge coefficient of capillary tube

C_{Dt}	Discharge coefficient of carburetor throat	
CI	Cetane index	
CN	Cetane number	
EGR	Exhaust gas recycle	[%]
F	Force	[N] [lbf]
F_f	Friction force	[N] [lbf]
F_r	Force of connecting rod	[N] [lbf]
F_x	Forces in the X direction	[N] [lbf]
F_y	Forces in the Y direction	[N] [lbf]
F_{l-2}	View factor	
FA	Fuel-air ratio	[kgf/kga] [lbmf/lbma]
FS	Fuel sensitivity	
I	Moment of inertia	[kg-m^2] [lbm-ft^2]
ID	Ignition delay	[sec]
K_e	Chemical equilibrium constant	
M	Molecular weight (molar mass)	[kg/kgmole] [lbm/lbmmole]
MON	Motor octane number	
N	Engine speed	[RPM]
N	Number of moles	
N_c	Number of cylinders	
N_v	Moles of vapor	
Nu	Nusselt number	
ON	Octane number	
P	Pressure	[kPa] [atm] [psi]
P_a	Air pressure	[kPa] [atm] [psi]
P_{ex}	Exhaust pressure	[kPa] [atm] [psi]
P_{EVO}	Pressure when the exhaust valve opens	[kPa] [psi]
P_f	Fuel pressure	[kPa] [atm] [psi]
P_i	Intake pressure	[kPa] [atm] [psi]
P_{inj}	Injection pressure	[kPa] [atm] [psi]
P_o	Standard pressure	[kPa] [atm] [psi]
P_l	Pressure in carburetor throat	[kPa] [atm] [psi]
P_v	Vapor pressure	[kPa] [atm] [psi]
Q	Heat transfer	[kJ] [BTU]
Q	Heat transfer rate	[kW] [hp] [BTU/sec]
Q_{HHV}	Higher heating value	[kJ/kg] [BTU/lbm]
Q_{HV}	Heating value of fuel	[kJ/kg] [BTU/lbm]
Q_{LHV}	Lower heating value	[kJ/kg] [BTU/lbm]
R	Ratio of connecting rod length to crank offset	
R	Gas constant	[kJ/kg-K] [ft-Ibf/lbm-OR] [BTU/lbm-OR]
Re	Reynolds number	
RON	Research octane number	
S	Stroke length	[cm] [in.]
S_g	Specific gravity	

SOF	Soluble organic fraction
SR	Swirl ratio
T	Temperature [°C] [K] [°F] [°R]
T_a	Temperature of air [°C] [K] [°F] [°R]
T_c	Temperature of coolant [°C] [K] [°F] [°R]
T_{EVO}	Temperature when the exhaust valve opens [°C] [K] [°F] [°R]
T_{ex}	Temperature of exhaust [°C] [K] [°F] [°R]
T_g	Temperature of gas [°C] [K] [°F] [°R]
T_i	Intake temperature [°C] [K] [°F] [°R]
T_m	Temperature of mixture [°C] [K] [°F] [°R]
T_{mp}	Midpoint boiling temperature in °F [°F]
T_o	Standard temperature [°C] [°F]
T_w	Wall temperature [°C] [K] [°F] [°R]
U_p	Piston speed [m/sec] [ft/sec]
$\overline{U}_p$	Average piston speed [m/sec] [ft/sec]
V	Cylinder volume [L] [cm^3] [in.^{3}]
V_{BDC}	Cylinder volume at bottom-dead-center [L] [cm^3] [in.^{3}]
V_c	Clearance volume [L] [cm^3] [in.^{3}]
V_d	Displacement volume [L] [cm^3] [in.^{3}]
V_{TDC}	Cylinder volume at top-dead-center [L] [cm^3] [in.^{3}]
W	Work [kJ] [ft-lbf] [BTU]
W_b	Brake work [kJ] [ft-lbf] [BTU]
W_f	Friction work [kJ] [ft-lbf] [BTU]
W_i	Indicated work [kJ] [ft-lbf] [BTU]
$\dot{W}$	Power [kW] [hp]
$\dot{W}_b$	Brake power [kW] [hp]
$\dot{W}_c$	Power to drive compressor [kW] [hp]
$\dot{W}_f$	Friction power [kW] [hp]
$\dot{W}_i$	Indicated power [kW] [hp]
$\dot{W}_m$	Power to motor engine [kW] [hp]
$\dot{W}_{sc}$	Power to drive supercharger [kW] [hp]
$\dot{W}_t$	Turbine power [kW] [hp]
a	Crank offset (crank radius) [cm] [in.]
c	Speed of sound [m/sec] [ft/sec]
c_{ex}	Speed of sound at exhaust conditions [m/sec] [ft/sec]
c_i	Speed of sound at inlet conditions [m/sec] [ft/sec]
c_o	Speed of sound at ambient conditions [m/sec] [ft/sec]
c_p	Specific heat at constant pressure [kJ/kg-K] [BTU/lbm-°R]
c_v	Specific heat at constant volume [kJ/kg-K] [BTU/lbm-°R]
d_v	Valve diameter [cm] [in.]
g	Acceleration of gravity [m/sec^2] [ft/sec^2]
h	Height differential in fuel capillary tube [cm] [in.]
h	Convection heat transfer coefficient [kW/m^2-K] [BTU/hr-ft^2-°R]
h	Specific enthalpy [kJ/kg] [BTU/lbm]

h_a	Specific enthalpy of air [kJ/kg] [BTU/lbm]
h_c	Convection heat transfer coefficient on the coolant side [kW/m^2-K] [BTU/hr-ft^2-°R]
h_{ex}	Specific enthalpy of exhaust [kJ/kg] [BTU/lbm]
h_g	Convection heat transfer coefficient on the gas side [kW/m^2-K] [BTU/hr-ft^2-°R]
h_m	Specific enthalpy of mixture [kJ/kg] [BTU/lbm]
h_f°	Enthalpy of formation [kJ/kgmole] [BTU/lbmmole]
Δh	Change in enthalpy from standard conditions [kJ/kgmole]
k	Ratio of specific heats
k	Thermal conductivity [kW/m-K] [BTU/hr-ft-°R]
k_g	Thermal conductivity of gas [kW/m-K] [BTU/hr-ft-°R]
l	Valve lift [cm] [in.]
m	Mass [kg] [lbm]
m_a	Mass of air [kg] [lbm]
m_{ex}	Mass of exhaust [kg] [lbm]
m_f	Mass of fuel [kg] [lbm]
m_m	Mass of gas mixture [kg] [lbm]
m_{mi}	Mass of mixture ingested [kg] [lbm]
m_{mt}	Mass of mixture trapped [kg] [lbm]
m_{tc}	Mass of total charge trapped [kg] [lbm]
$\dot{m}$	Mass flow rate [kg/sec] [lbm/sec]
$\dot{m}_a$	Mass flow rate of air [kg/sec] [lbm/sec]
$\dot{m}_{\text{EGR}}$	Mass flow rate of exhaust gas recycle [kg/sec] [lbm/sec]
$\dot{m}_f$	Mass flow rate of fuel [kg/sec] [lbm/sec]
$\dot{m}_i$	Mass flow into the cylinder [kg/sec] [lbm/sec]
mep	Mean effective pressure [kPa] [atm] [psi]
n	Number of revolutions per cycle
q	Heat transfer per unit mass [kJ/kg] [BTU/lbm]
q	Heat transfer per unit area [kJ/m^2] [BTU/ft^2]
$\dot{q}$	Heat transfer rate per unit mass [kW/kg] [BTU/hr-lbm]
$\dot{q}$	Heat transfer rate per unit area [kW/m^2] [BTU/hr-ft^2]
r	Connecting rod length [cm] [in.]
r_c	Compression ratio
r_e	Expansion ratio
rh	Relative humidity [%]
s	Distance between wrist pin and crankshaft axis [cm] [in.]
t	Time [sec]
u	Specific internal energy [kJ/kg] [BTU/lbm]
u_t	Swirl tangential speed [m/sec] [ft/sec]
v	Specific volume [m^3/kg] [ft^3/lbm]
v_{BDC}	Specific volume at bottom-dead-center [m^3/kg] [ft^3/lbm]
v_{ex}	Specific volume of exhaust [m^3/kg] [ft^3/lbm]
v_{TDC}	Specific volume at top-dead-center [m^3/kg] [ft^3/lbm]

w	Specific work	[kJ/kg] [ft-Ibf/lbm] [BTU/lbm]
w_b	Brake-specific work	[kJ/kg] [ft-Ibf/lbm] [BTU/lbm]
w_f	Friction-specific work	[kJ/kg] [ft-Ibf/lbm] [BTU/lbm]
w_i	Indicated-specific work	[kJ/kg] [ft-Ibf/lbm] [BTU/lbm]
x	Distance	[em] [m] [in.] [ft]
x_{ex}	Fraction of exhaust	
x_r	Exhaust residual	
x_v	Mole fraction of water vapor	
a	Pressure ratio	
a	Ratio of valve areas	
13	Cutoff ratio	
r	Angular momentum	[kg-m^2/sec] [lbm-ft^2/sec]
e_g	Emissivity of gas	
e_w	Emissivity of wall	
T]c	Combustion efficiency	[%]
T]f	Fuel conversion efficiency	[%]
T]m	Mechanical efficiency	[%]
T]s	Isentropic efficiency	[%]
T]t	Thermal efficiency	[%]
T]v	Volumetric efficiency of the engine	[%]
9	Crank angle measured from TDC	[0]
Ace	Charging efficiency	
Adr	Delivery ratio	
Arc	Relative charge	
Ase	Scavenging efficiency	
Ate	Trapping efficiency	
/.L	Dynamic viscosity	[kg/m-sec] [lbm/ft-sec]
/.Lg	Dynamic viscosity of gas	[kg/m-sec] [lbm/ft-see]
v	Stoichiometric coefficients	
P	Density	[kg/m^3] [lbm/ft^3]
Pa	Density of air	[kg/m^3] [lbm/ft^3]
Po	Density of air at standard conditions	[kg/m^3] [lbm/ft^3]
Pf	Density of fuel	[kg/m^3] [lbm/ft^3]
CJ'	Stefan-Boltzmann constant	[W/m^2-K4] [BTU/hr-ft^2-OR4]
T	Torque	[N-m] [lbf-ft]
Ts	Shear force per unit area	[N/m^2] [lbf/ft^2]
<|>	Equivalence ratio	
<|>	Angle between connecting rod and centerline of the cylinder	
W	Angular velocity of swirl	[rev/see]
W_v	Specific humidity	*[kgv/kga]* [grainsv/lbm$_a$]

1

Introduction

This chapter introduces and defines the internal combustion engine. It lists ways of classifying engines and terminology used in engine technology. Descriptions are given of many common engine components and of basic four-stroke and two-stroke cycles for both spark ignition and compression ignition engines.

1-1 INTRODUCTION

The **internal combustion engine** (Ie) is a heat engine that converts chemical energy in a fuel into mechanical energy, usually made available on a rotating output shaft. Chemical energy of the fuel is first converted to thermal energy by means of combustion or oxidation with air inside the engine. This thermal energy raises the temperature and pressure of the gases within the engine, and the high-pressure gas then expands against the mechanical mechanisms of the engine. This expansion is converted by the mechanical linkages of the engine to a rotating crankshaft, which is the output of the engine. The crankshaft, in turn, is connected to a transmission and/or power train to transmit the rotating mechanical energy to the desired final use. For engines this will often be the propulsion of a vehicle (i.e., automobile, truck, locomotive, marine vessel, or airplane). Other applications include stationary engines to drive generators or pumps, and portable engines for things like chain saws and lawn mowers.

Most internal combustion engines are **reciprocating engines** having pistons that reciprocate back and forth in cylinders internally within the engine. This book concentrates on the thermodynamic study of this type of engine. Other types of IC engines also exist in much fewer numbers, one important one being the rotary engine [104]. These engines will be given brief coverage. Engine types not covered by this book include steam engines and gas turbine engines, which are better classified as **external combustion engines** (i.e., combustion takes place outside the mechanical engine system). Also not included in this book, but which could be classified as internal combustion engines, are rocket engines, jet engines, and firearms.

Reciprocating engines can have one cylinder or many, up to 20 or more. The cylinders can be arranged in many different geometric configurations. Sizes range from small model airplane engines with power output on the order of 100 watts to large multicylinder stationary engines that produce thousands of kilowatts per cylinder.

There are so many different engine manufacturers, past, present, and future, that produce and have produced engines which differ in size, geometry, style, and operating characteristics that no absolute limit can be stated for any range of engine characteristics (i.e., size, number of cylinders, strokes in a cycle, etc.). This book will work within normal characteristic ranges of engine geometries and operating parameters, but there can always be exceptions to these.

Early development of modern internal combustion engines occurred in the latter half of the 1800s and coincided with the development of the automobile. History records earlier examples of crude internal combustion engines and self-propelled road vehicles dating back as far as the 1600s [29]. Most of these early vehicles were steam-driven prototypes which never became practical operating vehicles. Technology, roads, materials, and fuels were not yet developed enough. Very early examples of heat engines, including both internal combustion and external combustion, used gun powder and other solid, liquid, and gaseous fuels. Major development of the modern steam engine and, consequently, the railroad locomotive occurred in the latter half of the 1700s and early 1800s. By the 1820s and 1830s, railroads were present in several countries around the world.

HISTORIC-ATMOSPHERIC ENGINES

Most of the very earliest internal combustion engines of the 17th and 18th centuries can be classified as **atmospheric engines.** These were large engines with a single piston and cylinder, the cylinder being open on the end. Combustion was initiated in the open cylinder using any of the various fuels which were available. Gunpowder was often used as the fuel. Immediately after combustion, the cylinder would be full of hot exhaust gas at atmospheric pressure. At this time, the cylinder end was closed and the trapped gas was allowed to cool. As the gas cooled, it cre-

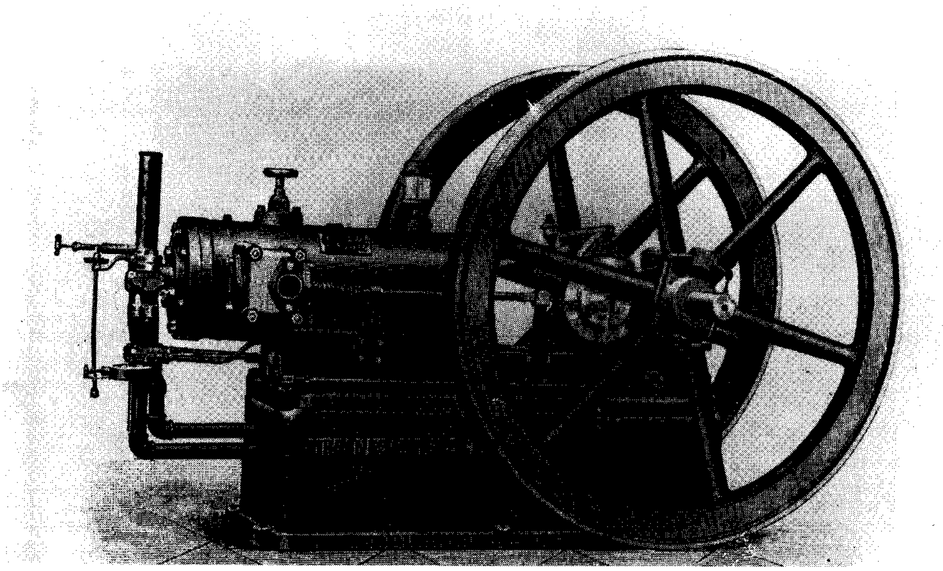

Figure 1-1 The Charter Engine made in 1893 at the Beloit works of Fairbanks, Morse & Company was one of the first successful gasoline engine offered for sale in the United States. Printed with permission, Fairbanks Morse Engine Division, Coltec Industries.

> ated a vacuum within the cylinder. This caused a pressure differential across the piston, atmospheric pressure on one side and a vacuum on the other. As the piston moved because of this pressure differential, it would do work by being connected to an external system, such as raising a weight [29].
>
> Some early steam engines also were atmospheric engines. Instead of combustion, the open cylinder was filled with hot steam. The end was then closed and the steam was allowed to cool and condense. This created the necessary vacuum.

In addition to a great amount of experimentation and development in Europe and the United States during the middle and latter half of the 1800s, two other technological occurrences during this time stimulated the emergence of the internal combustion engine. In 1859, the discovery of crude oil in Pennsylvania finally made available the development of reliable fuels which could be used in these newly developed engines. Up to this time, the lack of good, consistent fuels was a major drawback in engine development. Fuels like whale oil, coal gas, mineral oils, coal, and gun powder which were available before this time were less than ideal for engine use and development. It still took many years before products of the petroleum industry evolved from the first crude oil to gasoline, the automobile fuel of the 20th century. However, improved hydrocarbon products began to appear as early

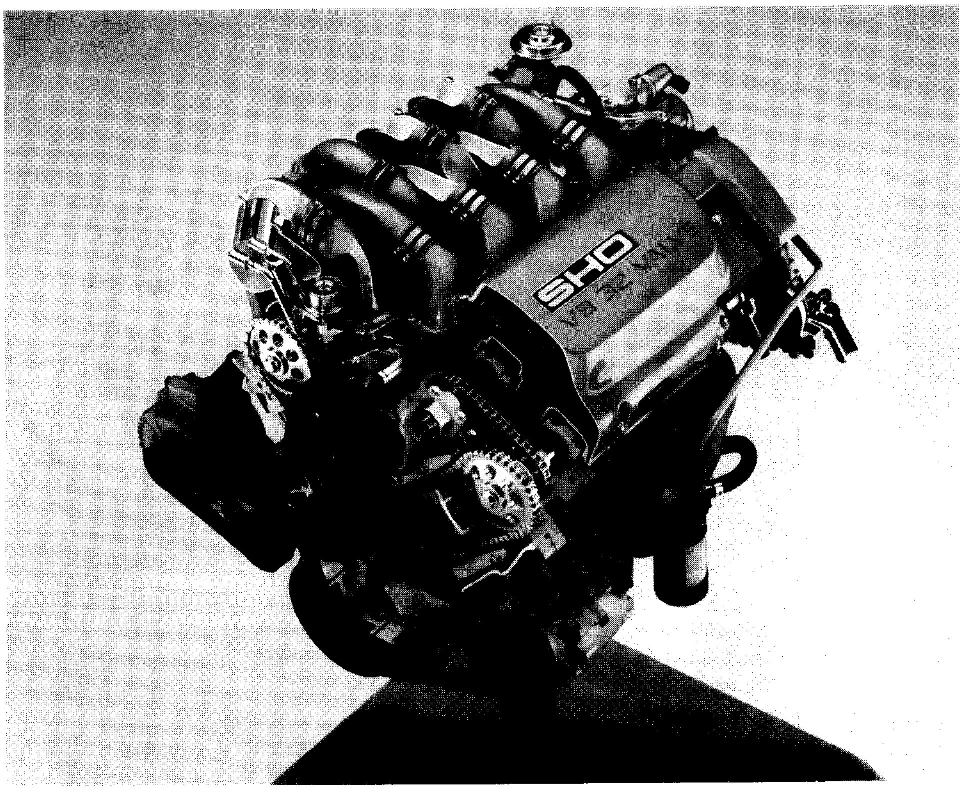

Figure 1·2 Ford Taurus SHO 3.4 liter (208 in.^{3}), spark ignition, four-stroke cycle engine. The engine is rated at 179 kW at 6500 RPM (240 hp) and develops 305 N-m of torque at 4800 RPM (225 lbf-ft). It is a 60° V8 with 8.20 cm bore (3.23 in.), 7.95 cm stroke (3.13 in.), and a compression ratio of 10: 1. The engine has four chain driven camshafts mounted in aluminum heads with four valves per cylinder and coil-on-plug ignition. Each spark plug has a separate high-voltage coil and is fired by Ford's Electronic Distributorless Ignition System (ED IS). Courtesy of Ford Motor Company.

as the 1860s and gasoline, lubricating oils, and the internal combustion engine evolved together.

The second technological invention that stimulated the development of the internal combustion engine was the pneumatic rubber tire, which was first marketed by John B. Dunlop in 1888 [141]. This invention made the automobile much more practical and desirable and thus generated a large market for propulsion systems, including the internal combustion engine.

During the early years of the automobile, the internal combustion engine competed with electricity and steam engines as the basic means of propulsion. Early in the 20th century, electricity and steam faded from the automobile picture-electricity because of the limited range it provided, and steam because of the long start-up time needed. Thus, the 20th century is the period of the internal combustion engine and the automobile powered by the internal combustion engine. Now, at the end of the century, the internal combustion engine is again being challenged by electricity and other forms of propulsion systems for automobiles and other applications. What goes around comes around.

1-2 EARLY HISTORY

During the second half of the 19th century, many different styles of internal combustion engines were built and tested. Reference [29] is suggested as a good history of this period. These engines operated with variable success and dependability using many different mechanical systems and engine cycles.

The first fairly practical engine was invented by J.J.E. Lenoir (1822-1900) and appeared on the scene about 1860 (Fig. 3-19). During the next decade, several hundred of these engines were built with power up to about 4.5 kW (6 hp) and mechanical efficiency up to 5%. The Lenoir engine cycle is described in Section 3-13. In 1867 the Otto-Langen engine, with efficiency improved to about 11%, was first introduced, and several thousand of these were produced during the next decade. This was a type of atmospheric engine with the power stroke propelled by atmospheric pressure acting against a vacuum. Nicolaus A. Otto (1832-1891) and Eugen Langen (1833-1895) were two of many engine inventors of this period.

During this time, engines operating on the same basic four-stroke cycle as the modern automobile engine began to evolve as the best design. Although many people were working on four-stroke cycle design, Otto was given credit when his prototype engine was built in 1876.

In the 1880s the internal combustion engine first appeared in automobiles [45]. Also in this decade the two-stroke cycle engine became practical and was manufactured in large numbers.

By 1892, Rudolf Diesel (1858-1913) had perfected his compression ignition engine into basically the same diesel engine known today. This was after years of development work which included the use of solid fuel in his early experimental engines. Early compression ignition engines were noisy, large, slow, single-cylinder engines. They were, however, generally more efficient than spark ignition engines. It wasn't until the 1920s that multicylinder compression ignition engines were made small enough to be used with automobiles and trucks.

1-3 ENGINE CLASSIFICATIONS

Internal combustion engines can be classified in a number of different ways:

1. Types of Ignition
   (a) Spark Ignition (SI). An SI engine starts the combustion process in each cycle by use of a spark plug. The spark plug gives a high-voltage electrical