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COMBUSTION AND MASS TRANSFER

A Textbook with Multiple-Choice Exercises for Engineering Students

BY

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PREFACE

The following series of twenty lectures represents the outcome of several years of teaching the subjects of combustion and mass transfer to final-year undergraduate students of mechanical engineering at Imperial College.

The subject of combustion is a large and important one. Because of its size, a twenty-lecture course can include only a small fraction of the available useful information; and it is hard to make the selection. I have here selected the topics which I have personally found interesting and helpful, in the course of an academic and consulting career in which combustion has been an abiding theme. Naturally, the knowledge possessed by the students entering the course, and their need to integrate combustion studies with other parts of the curriculum, have exerted limiting influences.

Although the advent of the digital computer has recently transformed the extent to which combustion theory can be applied to engineering, I have confined attention in the present lectures to analyses which can be made without the computer's aid. The reason for this restriction is that I regard it as important for students of combustion to gain the clear understanding of phenomena which formulae and graphs can provide, before they become immersed in the welter of information (and misinformation) which the computer can generate.

Each of the twenty chapters is provided with a set of exercises, designed to assist the student to digest the material of the lectures. Most of these are of the multiple-choice variety; and many are of the "P is Q because R is S" kind, in which the student has to ask himself: "Is P Q?"; "Is R S?"; and "If so, is R S because P is Q?". I have found these to be valuable in stimulating and refining thought about "why" as well as "what".

It is a pleasure to thank Colleen King and Christine MacKenzie for the assistance which they have given me with the preparation of the book. That the numerous and overlapping hand-written versions have finally taken a legible and orderly form is largely due to their efforts.

I must also thank Drs F C Lockwood, A S C Ma and W M Pun, who have assisted me, at various times, with the delivery of the course; and the students whose critical comments have also had a constructive influence.

D BRIAN SPALDING
London
September 1978

CHAPTER 1

INTRODUCTION TO COMBUSTION

1.1 THE IMPORTANCE OF THE SUBJECT

A) THE PLACE OF COMBUSTION IN ENGINEERING

(i) Power production

There are only a few means by which man produces the power with which he dominates his environment; and almost all of them involve the combustion of a fuel, either solid, liquid or gas.

Coal is burned in central power stations to raise the steam for the turbines.

Oil is used for the same purpose, and also as the source of energy for vehicles of all sorts - automobiles, aircraft and ships.

Natural gas may be used as the fuel for gas turbines or for reciprocating engines, as well as for steam-raising.

Although nuclear power will certainly become increasingly significant as an energy source in industrial societies, and although solar energy, and wind and wave power, are being actively developed, combustion will remain the predominant source of power for many generations.

(ii) Process industry

Much fuel is also burned as an essential ingredient of the production of engineering materials, for example:-

- iron, steel, and many non-ferrous metals;
- glass and ceramics;

- cement;
- refined fuels, carbon black, and other hydrocarbon derivatives.

Sometimes the fuel must be specially processed before it is employed, as when coke is produced from coal, by a carefully-controlled heating process, in order that it can be later burned in an iron-ore-reducing "blast furnace".

(iii) Domestic and industrial heating

Residences, factories, offices, hospitals and other buildings require to be heated, in many parts of the world. In the majority of cases, the preferred source of heat is a fuel. The camp fire radiates heat within the tent; while the basement furnace distributes its heat through the agency of ducted air or piped water; but combustion is the foundation of both means of heat transfer.

(iv) The "energy crisis"

The "energy crisis" is first and foremost a "fuel crisis", and still more a "combustion crisis". The world's supplies of fuel are being rapidly diminished; and those fuels which are easiest to burn are being used up most rapidly.

If engineers were able to burn heavy fuel oil in domestic heating appliances, or to use coal dust as the fuel for automobile engines, mankind's difficulties would be greatly alleviated. Thus it is in part a deficiency in combustion technology which gives the "energy crisis" its urgency.

(v) Unwanted combustion

Forests, buildings, and even clothing, can act as fuels; and fire-prevention engineers have to ensure that they do not, or that means are to hand for extinguishing such conflagrations as do inadvertently arise. The damage caused by fires can be so great that much attention must be given by specialist engineers to the techniques of prevention and extinguishment.

B) SOME FACTS ABOUT EXPECTED ENERGY USAGE

The following table gives an indication of the magnitudes of the annual energy usages expected in Europe and the U.S.A. Evidently, combustion-derived energy is likely to dominate.

	OECD EUROPE		U S A	
YEAR	1980	1985	1980	1985
Coal	94.0	90.0	178.1	237.3
Oil	477.8	603.5	470.1	547.0
Gas	92.6	127.1	265.7	282.0
Nuclear	41.5	114.6	58.5	123.4
Hydro & Geothermal	118.2	20.5	14.7	16.5
Units are 10^{18} joules				

C) REASONS FOR THE ENGINEER'S CONCERN WITH COMBUSTION

(i) Procurement of combustion efficiency

Combustion appliances do not necessarily burn all the fuel which is supplied to them; and that which is not burned completely is often discharged into the atmosphere.

Fuel is too expensive to waste in this way; and the products of incomplete combustion are often noxious. Appliance designers therefore have a double reason for ensuring that combustion efficiency is very close to 100%.

(ii) <u>The reduction of costs</u>

Fuel is expensive; and so is the equipment for preparing it for combustion and for burning it. This equipment must therefore be designed from the point of view of cost reduction as well as from that of efficiency.

Costs are of two kinds: capital, and running. To reduce the former, the combustion engineer may well try to bring the chemical reaction to completion in a small space; to reduce the former, he may try to reduce the pressure drop experienced by the gases in passing through the device. Often the two aims are incompatible; an enlightened compromise must be sought.

(iii) <u>Temperature and composition control</u>

Sometimes it is not sufficient that the fuel should burn: there may be an additional requirement that the products of combustion should have a particular temperature or a specified composition. This can occur when the combustion products are to engender some physical or chemical transformation in another material, as when metals are being "heat-treated"; or it may be that the combustion products must not exceed a certain temperature, lest damage ensue to nearby structural elements.

The engineer who designs combustion equipment must therefore be able to predict what the temperature and composition of the combustion products will be, and to bring them under his control.

D) SOME SPECIAL FEATURES OF COMBUSTION AS AN ENGINEERING SPECIALISATION

(i) Multiplicity of constituent disciplines

The engineer who specialises in compressors, pumps and turbines needs to understand the laws of thermodynamics and fluid mechanics, but little more.

The heat-transfer specialist must understand thermodynamics and fluid mechanics; but, in addition, he must be fully conversant with the laws of conduction and radiation, with the thermal properties of materials, and with mass transfer.

The combustion engineer is concerned with fluid flow, because his fuel may be a fluid, as is certainly the air in which it burns. He must understand heat transfer because combustion both produces and is influenced by variations in temperature. In addition, however, he must understand the laws governing chemical transformations, both in respect of their speeds (chemical kinetics) and their effects (chemical thermodynamics).

It follows that, if he is to perform his function efficiently, a specialist in combustion must have a rather extensive grounding in science. Understandably, the proportion of engineers who can afford the time for these studies is rather small; so well-trained combustion engineers are in much demand. At a time when many branches of the engineering profession are over-staffed, this consideration is worthy of attention.

(ii) The role of the computer

The combustion engineer needs to make quantitative predictions of what will occur in the equipment which he is designing; and this, because of the multiplicity of processes which he must master, is a formidable task.

Until recently, it has been an impossible one. However, the development of the digital computer, and of methods of using it to solve complex mathematical problems, has transformed the situation. Now it is possible, to an increasing extent, to make realistic and useful predictions of combustion phenomena, with the aid of computers of modest size.

(iii) The role of the "mathematical model"

Whether the prediction is made by way of a computer or of more primitive devices, the focus of study is always a "mathematical model" of the process, i.e. of an idealisation possessing some of the features of reality, but not all.

Such "mathematical models" are, of course, an essential feature of all engineering analyses; but the concept of "modelling" must be given special attention when there are numerous constituent processes, as is true of combustion; for care is needed to select for scrutiny only those which play the major roles.

The publications cited at the end of this chapter (see Section 4) contain many references to mathematical models of combustion; and the present book is, indeed, an account of those models which are necessary to an understanding of the majority of combustion processes.

1.2 THE STRUCTURE OF THE SUBJECT OF COMBUSTION

A) CLASSIFICATION INTO LEVELS

(i) Engineering practice

The subject matter of concern in the present book appears at three levels, those of:-

- engineering practice;
- mathematical models; and
- fundamental science.

The first level involves the description of items of engineering equipment, discussion of their modes of operation, and delineation of their desired and undesired features of performance.

This might be regarded as the user's and designer's level. The user of the equipment is concerned with how well it performs; the designer's attention is concentrated on how the shape, size, configuration, materials, etc., can influence its performance.

(ii) Mathematical models

The human mind, being limited, must select for attention only those parts of reality which are immediately relevant to its purpose; the rest must be excluded, or at least subordinated. So it comes about that all engineering analyses are concerned with models of reality, rather than reality itself; and, when quantitative predictions are in question, the models are necessarily mathematical in character.

These mathematical models take the form of sets of differential and algebraic equations, the solutions of which agree, in important respects, with the behaviour of the pieces of equipment, or the processes, which are being modelled. The models can be regarded as "idealisations", or "essences", of the interactions which actually exist between the design and operating characteristics of the equipment on the one hand, and the fundamental laws of physics and chemistry on the other.

The mathematical-model level of study is therefore intermediate between the level of engineering practice and the level of fundamental science.

Mathematical models often have names, e.g. "the burning droplet", "the well-stirred reactor", "the laminar-propagating flame". Many will be encountered in the present book.

(iii) Fundamental science

As already mentioned, combustion processes are affected by the laws of nature which appear, in the usual classification of scientific knowledge, under the headings of:-

- thermodynamics;
- fluid mechanics;
- heat and mass transfer;
- and chemical kinetics.

Differently classified, the knowledge may be organised under the headings of:-

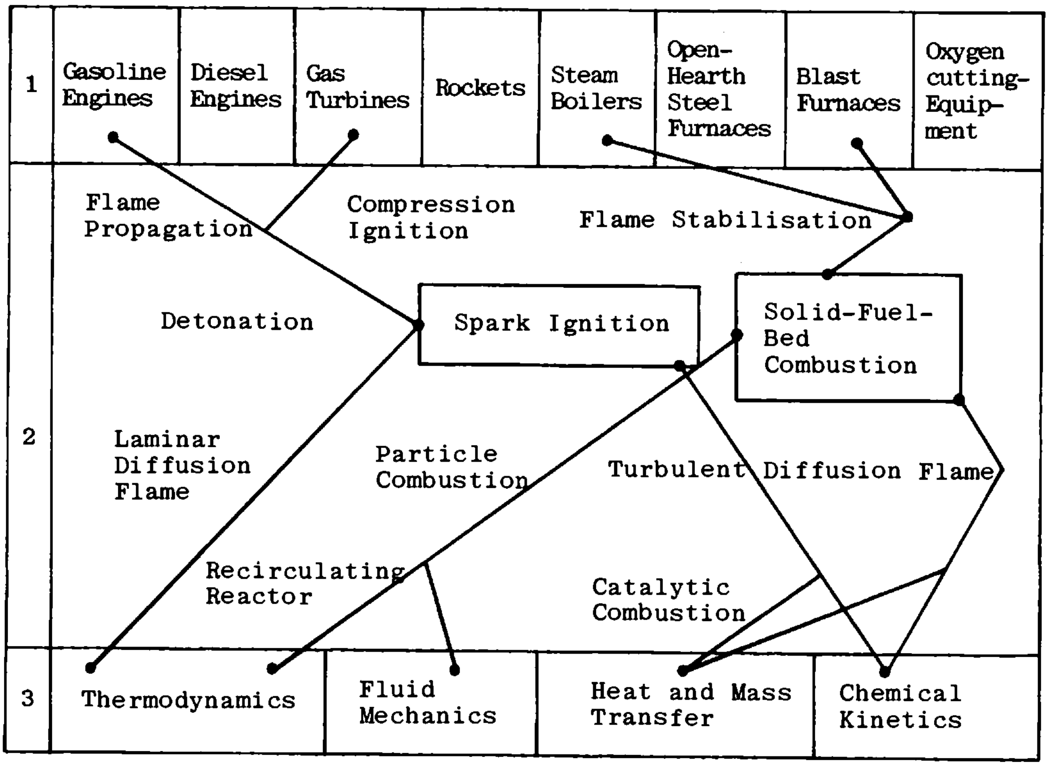
- conservation laws (of mass, energy, etc.);
- transport laws (of momentum, mass, chemical

species, energy, etc.); and

source laws (of the same entities).

(iv) Linkages

The following table contains entries at each of the above three levels; and two of the mathematical models appearing at level 2 are linked, by way of illustration, with the relevant fundamental disciplines at the lower level and the fields of engineering application at the upper one.



It may prove to be interesting to the reader to return to this table, after he has concluded his study of the book, so as to draw on the table the link lines for all the other models.

B) SOME FEATURES OF CURRENT ENGINEERING PRACTICE

(LEVEL 1)

There is no space to provide here more than a few notes on what are the common components of engineering combustion practice. The following tables provide these notes, first for steady-flow equipment and secondly for that in which the processes vary significantly with time.

The connexions of combustion theory with items of engineering equipment are discussed in the remainder of this book as opportunity offers, usually at the beginnings and ends of the individual chapters.

(i) Steady-flow equipment

FUEL	FORM & MEANS OF SUPPLY TO EQUIPMENT	APPLICATION
Coal	Lumps on grate	Domestic Small industrial boilers Cupola and blast furnaces
	Powder, suspended in air stream	Large industrial boilers Cement kilns
Kerosine	Vapour, from heated tube or pot	"Primus" stove Some aircraft gas turbines Small domestic boilers
	Spray of droplets from rotating cup	Domestic boilers
	Spray from swirl atomiser	Aircraft gas turbines
Gas Oil	Spray from swirl atomiser	Industrial gas turbines Larger domestic boilers
Residual Oil	Jet of droplets impelled by steam	Open-hearth furnaces
	Swirl atomisers	Large industrial boilers
Liquid Rocket Propellants	Spray formed by impingement of liquid jets	Large rocket engines, especially for re-use
Solid Rocket Propellants	As perforated blocks, the burning occurring at the free surface	Small rocket engines, and those (e.g. Polaris) requiring instant readiness

(ii) Unsteady-flow equipment

Gasoline	Vaporised by contact with air and hot surfaces	Spark-ignition engines
Gas Oil	Spray formed by injection through small orifice into compressed air	Compression-ignition (Diesel) engines

c) SOME MATHEMATICAL MODELS (LEVEL 2)

The following notes are provided as a further introduction to some of the mathematical models which will be described elsewhere in this book.

(i) The single carbon particle, burning in still air

This concerns the interactions of diffusion of oxygen, of heat conduction and radiation, and of chemical kinetics, so as to determine the rate and time of burning.

Ordinary differential equations are involved.

The model is discussed in Chapter 20.

(ii) The single-liquid fuel droplet, burning in still air

This mathematical model is discussed in Chapter 7 because, although it might appear more complex than that for carbon-particle combustion, it is actually simpler; for chemical-kinetic aspects are of little significance.

A model of a droplet which vaporises without burning is presented in Chapter 3.

(iii) The one-dimensional liquid-propellant rocket

Droplets interacting with a gas stream comprising their combustion products feature in the mathematical model of a liquid-propellant rocket which is discussed in Chapter 8.

This model, provided that certain simplifying assumptions are made, is described by ordinary differential equations which are capable of analytical solution. Algebraic formulae are therefore derivable for the length of rocket which is needed for complete combustion.

The processes concerned are those of droplet combustion, together with that of droplet drag.

The model is a composite one; it embodies that of Section (ii), and combines it with one for one-dimensional gas flow in ducts.

(iv) <u>The turbulent diffusion flame</u>

A mathematical model of relevance to many industrial processes is that of the turbulent diffusion flame, or "gas torch". It can be represented mathematically by partial differential equations, expressing the interplay of the processes of transport of mass, momentum and energy; and these equations may be solved analytically if simplifying assumptions are made.

The model is presented in Chapter 12, after the simpler cases of laminar and non-burning jets have been discussed in Chapters 9, 10 and 11.

(v) <u>The well-stirred reactor</u>

Chemical kinetics is subordinate, in diffusion flames, to heat, mass and momentum transfer. The reverse is true of the mathematical model known as the "well-stirred reactor": here conditions are governed by the interaction of the supply rate of gas with the rate of the chemical reaction; the laws of thermodynamics also play a part.

This model is described at length in Chapter 16, after preliminary studies of chemical kinetics have been presented in Chapters 13, 14 and 15.

Because of the simplicity of the flow system, from which all non-uniformities are supposed absent, the model involves only algebraic equations. However, they require graphical or numerical solution.

(vi) The baffle-stabilised flame

Although well-stirred reactors never occur in practice, the flame which exists behind a "baffle" in a high-velocity stream of pre-mixed gas and air has some similarities of behaviour. "Baffles", also called "flame-holders" or "flame-stabilisers", are widely used in combustion equipment: they are obstacles which, because of their "bluff" shape, create regions of recirculating gas in their immediate wake.

The relevant mathematical model is described in Chapter 17.

(vii) Spark ignition

Flames require to be ignited; and frequently this ignition is effected by way of a spark, i.e. of a brief and localised discharge of electrical energy.

In order that this important process can be properly understood, a mathematical model of spark ignition is presented in Chapter 19. The differential equations are partial ones, requiring a computer for their exact solution. However, approximate solution procedures have been employed which permit the most important features to be revealed by simple hand calculations.

The model involves the full interaction of physical and chemical processes, albeit in laminar flow only. It is perhaps the most advanced model discussed in the present book.

D) THE FUNDAMENTAL SCIENCES (LEVEL 3)

In this section, some introductory notes will be provided to the fundamental scientific disciplines which will be touched on in the remainder of the book.

(i) <u>Thermodynamics</u>

Only few concepts from thermodynamics will be employed; and they will appear in their simplest forms. Thus, specific heats will be taken as independent of temperature, and it will be presumed that equilibrium exists only when one of the two participants in a reaction has been completely consumed.

This practice is adopted so as to permit the student to concentrate his mind on aspects of combustion which are (for present purposes) more interesting than the fact that specific heats actually vary with temperature.

The main use of thermodynamics in the present book is to link the rise of temperature resulting from combustion quantitatively with the amount of fuel which is consumed. Knowledge of the First Law of Thermodynamics, usually in its steady-flow form, is all that is demanded.

(ii) <u>Fluid mechanics</u>

A few of the mathematical models draw upon knowledge of the laws of fluid mechanics, particularly as expressed by the so-called "boundary-layer" equations. In these, the effects of inertia and of viscosity are of similar orders of magnitude; and their interplay governs the flow pattern. These equations first make their appearance, in the present book, in Chapter 9.

Despite the fact that the viscosities of gases are strongly temperature-dependent, the analyses presented in the present book neglect the variation. Once again, the motive is to procure clarity at the expense of quantitative exactitude; for the latter can always be obtained from computer studies, once the sought-for understanding has been achieved.

Some elementary ideas about turbulence will be presented in Chapter 11. They suffice for present purposes.

(iii) Heat transfer

Chemical reactions proceed so slowly at low temperatures, that, if it were not for the transfer of heat from hot reacted to cold unreacted gases, flames would seldom exist. This is sufficient reason for combustion theory to make extensive use of the science of heat transfer

All three main modes are important, namely conduction, convection and radiation; but the first has especial significance because its rate is proportional to the gradient of temperature, which is often large in a flame. The relevant law, that of Fourier, will be introduced in Chapter 2; but it will be frequently returned to thereafter.

In some processes, conduction heat transfer is the dominant mechanism. Droplet vaporisation is one of these.

(iv) Mass Transfer

Whereas heat transfer is a subject which is studied by engineers of nearly all disciplines, mass transfer features regularly in the undergraduate courses only of chemical engineers. It is however of great importance to combustion specialists; so it is allotted a rather extended treatment in the present book. The main concepts are introduced in Chapters 2 and 4; and they are used in many places.

Mass transfer is similar in many ways to heat transfer: the place of conduction in the latter