REVIEWS

Combustion Processes, edited by B. LEWIS, R. N. PEASE and H. S. TAYLOR (Volume II of High Speed Aerodynamics and Jet Propulsion). Princeton University Press, 1956. 662 pp. $12.50 or 84*s*.

Almost every major advance in civilization has involved an increased understanding by man of the use of fire. The use of the camp fire for preparation of food was probably one of man's first steps away from animal ways. Fire was used as an aid in fashioning stone tools, and in the smelting of ores in the making of metal tools. The discovery of gunpowder made untenable the types of civilization existent at the time of its introduction. Although the industrial revolution was made possible by the steam engine which used fire only in a rather simple furnace, modern society has developed as the industrial furnace developed. The automobile and airplane are practical devices only because of the compact internal combustion engines.

It might be supposed that the scientific, quantitative knowledge of combustion processes would have reached an advanced stage in view of the great importance of fire. Much indeed is known, and great effort is being expended to increase this knowledge, but in spite of all effort the available information is in large part empirical.

The empirical nature of much of our knowledge and the amount of effort that has been put into the study of combustion processes is illustrated by the volume under review. This book would have been impossible 50 years ago. We have 662 pages devoted to a brief account of the state of knowledge of combustion processes in gases, liquids, and solids for premixed fuel and oxidizer and in non-premixed systems. And yet in spite of the great progress made since the last century, this book makes amply clear, in nearly every chapter, the unsatisfactory state of our present knowledge and frequently points the way to the obviously needed further research.

During the nineteenth century, while one group of physical chemists were struggling with the study of the kinetics of chemical reactions, another group were laying the foundations of thermodynamics and its application to chemical equilibrium. The present volume very appropriately opens with a discussion of the essential relations from thermodynamics that permit the calculation of the equilibrium composition of reaction products, the heat release and the flame temperature. Only the briefest treatment is given since the entire first volume of this series is entitled *Thermodynamics and Physics of Matter*.

In spite of the logical completeness of the understanding of chemical equilibrium afforded by thermodynamics, its practical usefulness is limited, as is made clear in the next two sections. From section C it is clear that, between the specification of a problem, involving a fuel and oxidizer composition, and the desired values of pressure, temperature, entropy and other properties of the combustion gases, lies a long path of computation. This path, even for simple systems for which all thermal and equilibrium constants are available, is so involved that it is seldom

pursued unless large scale automatic computers are available. The immediate future should see great progress in this area since the computing machines make practical many calculations which to date have been merely possible.

It would seem that section B on " Expansion Processes " was placed between A on " High Temperature Equilibrium " and C on " Computation Methods " so that the reader would see immediately the limitations as well as the importance of the thermodynamic methods. Section B, in a sense, is the real meat of jet propulsion ; it is the analysis of the production of the jet from high temperature combustion gases. Besides the usual compressible flow discussion of the flow of a gas through a nozzle, there is treated the appropriate modifications required by the fact that chemical equilibrium may or may not be preserved during the expansion. The additional problems presented by the fact that sometimes a condensed phase forms during the expansion are also considered.

The enormous progress that has been made during the past century in the understanding of the kinetic rate mechanism for various chemical processes is attested by the 60 pages devoted to the fundamentals of this subject. A short text on chemical kinetics would be a good name for these chapters. They start with an empirical introduction to reaction rate theory, introducing order, half life, temperature, rate constants, activation energy. This is followed by the theoretical understanding of the empirical facts through kinetic collision theory and absolute rate theory. By considering a series of specific cases, the ideas of free radicals, chain mechanisms, explosions, wall reactions, solid and gas reactions and experimental techniques are presented. Finally the bearing of all these effects on non-equilibrium in systems involving rapid changes is explained.

With the above as introduction, several reactions of importance in propulsion are studied in detail. The reader is brought up to date in our understanding of the hydrogen–oxygen, carbon monoxide–oxygen and hydrocarbon–oxygen systems. The uninitiated reader learns of the great complexity of even the simplest of these reactions and is thus brought to appreciate the present-day potentialities and limitations in the analysis of combustion systems. A brief treatment of several systems of interest in modern propulsion is included: boron hydrides, hydrogen–fluorine and nitromethane decomposition.

One more section on fundamental ideas is included, namely, " The Mechanics of Reacting Continua ". In this 11 page section the reader is taken through the ideas and derivations of the continuity, momentum and energy equations for flowing, reacting, viscous, heat conducting compressible fluids in general vector form. Only 7 pages are required for this, the last 4 pages of the chapter being devoted to a discussion of irreversible processes, including entropy transport, forces, currents, and the kinetic coefficients, and the introduction of the Onsager reciprocal relations. This section is an excellent very concise review of fundamentals from a general viewpoint for readers already well prepared in advanced theoretical fluid mechanics. As a text it's next to useless.

In present day combustion, a careful observer notes a discontinuity between the discussions of fundamentals and of applications. The fundamentals are rather precisely known physical principles, worked out in large part in precise mathematical form by carefully reasoned mathematical arguments. The applications on the other hand consist of many empirical facts ' explained ' by a series of *ad hoc* assumptions assisted by the fundamentals as by a crutch. This discontinuity was very sharp half a century ago. Today—as if by a diffusion process—the discontinuity has become dulled. The detailed nature of the blurred discontinuity in ideas and methods occupies the last two thirds of this volume.

Almost all of the middle third of the book is devoted to the combustion of gases. First the phenomena encountered in non-turbulent gases are discussed. A rather brief account of ' the flame ' is given which indicates the qualitative ideas of flame thickness, ignition temperature, etc. Only the simplest and least adequate relation for the flame speed, that of Mallard and LeChatelier, is derived, although a very adequate bibliography of the literature on more adequate flame speed relations is included. There follows a discussion of ideas and assumptions and corresponding derivations on a host of important topics; quenching distance, flame stabilization, blowoff and flashback, flame shape and fluid velocity field, propagation in channels, ignition, limits of inflammability, minimum ignition energy, etc. For those readers who approach combustion from the more exact field of aerodynamics, this chapter will leave them reeling. However, in most cases combustion is complicated, our understanding is not complete, and those who desire a more exact understanding should regard these phenomena as challenging and the *ad hoc* assumptions as the best treatment yet possible, a zeroth order approximation, so to speak. Some 20 pages devoted to quantitative experimental results on laminar flames serve to make these available for use and to show the need for more analytical studies.

The problems associated with the turbulent flame are, as would be expected, more complex and less well established than for laminar flames. In the turbulent case, even the simplest ideas, such as the flame ' speed ', are hard to define and measure. The fact that a conflict rages between the proponents of the wrinkled laminar flame sheet and the proponents of the extended reaction zone is not surprising. The author of this section (H) is a wrinkled flame sheet man, and most of the 50 pages of the section is devoted to an examination of available data in the light of the most modern form of this theory. It should be stated that so far the flame sheet wrinklers have succeeded in deriving quantitative consequences of their ideas in a reasonably basic way, while the extended reaction zone proponents have not. In the reviewer's opinion, the turbulent flame contains significant proportions of both wrinkled flame sheets and extended reaction zones. The success of one group in deriving formulas should not be interpreted as showing that turbulent flames do not involve extended reaction zones.

The diffusion flame, i.e. the combustion of a jet of fuel in air (say), is controlled more by the aerodynamic mixing processes than by the chemical rates. Hence there is a clear separation into laminar, transition

and turbulent diffusion flames. The experimental results are compared with present theoretical ideas of the parts played by molecular and turbulent diffusion. Again the understanding, as for example of flame height, is adequate to zero order but leaves much to be learned in the future.

Liquid fuels are usually burned by first atomizing and evaporating them. The study of such processes has yielded more precise knowledge than some other areas of combustion. However the added complexity still leaves much for future study. The same is true of solid fuels both in lumps and as dust. The treatment given both of these subjects is such as to bring the uninitiated reader a long way toward the understanding he will need for further work in these areas.

The application of the fundamental and empirical knowledge of combustion processes to jet propulsion is discussed in two long sections, one on liquid propellants and one on solid propellants. As is so often the case, the knowledge of fundamental processes serves more as a guide than as a quantitative calculation procedure on complete engineering systems. The complexity is of too high an order. Monopropellants, bipropellants and common solid propellants are considered. Equipment, ignition and ignition delay problems, chemical and physical mechanisms, pressure dependence, thermal decomposition, and performance characteristics are all treated. The performance attainable and the problems remaining are clearly presented.

The chemical part of this book on combustion closes with a qualitative discussion of detonation processes. Because of the small thickness of the detonation front, the overall gas dynamics of the detonation process is perhaps simpler than the more extended combustion zones of ordinary fires but the chemical and physical processes are at least as complex. Often the chemical and physical nature of explosives is complex and the processes confined to narrow zones are hard to study experimentally. The parts played by composition, reaction time, lateral expansion, detonation characteristics, including initiation and decay, are presented from a physical chemist's (rather than aerodynamicist's) point of view.

The last section gets into a book on combustion as a most modern touch, " Energy Production by Nuclear Reactions ". This section in a book on combustion processes in a series on high speed flight and jet propulsion suggests the inference that the future development of rocket vehicles both for terrestrial and space flight could be influenced in a major way by nuclear developments. There are some close relationships between combustion and nuclear energy production from both the hydrodynamic and transport mechanism points of view. The present chapter of 40 pages can, however, do no more than review the elementary physical principles, and this it does in a simple and clear manner.

This book is the best presentation of the whole of the knowledge of combustion currently available. The general excellence of the selection of material and its presentation will leave this book in first place until the growth of the field makes the present understanding inadequate.

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