COMBUSTION AERODYNAMICS

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COMBUSTION AERODYNAMICS

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Preface

This book is intended as material for undergraduate and postgraduate courses on combustion, and also as a work of reference for practising engineers. Combustion is one of the oldest branches of science and, as in other areas of science and technology, rapidly rising interest in a wide range of applications has added a wealth of new knowledge, first during the period between the two world wars, and, in particular, in the last two decades. The large increase in the number of books, periodicals and conference proceedings has led to a high degree of specialisation within the broad spectrum of combustion technology, embracing branches of many sciences such as physics, chemistry, spectroscopy, thermodynamics, and also the engineering science of transport processes.

Our purpose is to discuss aerodynamic processes, which play important roles in turbulent diffusion flames, the type most generally used in industrial practice. A large proportion of the material in the book has been selected from the area of fully separated flows; turbulent jets and wakes with and without combustion. Whilst attempting to give a general picture, the limitations of a short monograph for presenting a comprehensive treatment had to be recognised. There is a preponderance of topics and discussion of results originating from our research work carried out at the Research Station of the International Flame Research Foundation at Ijmuiden, and later at the University of Sheffield. The convenience of following a line of thought familiar to us, rather than any other consideration, has led to this choice of material.

An attempt has been made to balance descriptive and analytical treatment in the monograph, and analysis, whenever possible, has been associated with a physical model of the process. Where a detailed mathematical analysis leading to a generalisation of results has been available it has been included, while in other cases a simpler, quantitative treatment based upon relationships between appropriate non-dimensional groups has been recommended as the most reliable tool for use by the designer. In this respect the treatment of the material reflects the authors' views of the 'state of the art'. The ideal is surely that the designer should be able to solve his problem by computation only, *i.e.* without need for resorting to experimentation. Prediction methods have made encouraging progress, and they will provide the guidelines for research in the years to come. But the designer will have to rely for some time ahead on semi-empirical relationships and on physical modelling. It is therefore equally important that this well-known approach to design should be further developed. Discussions have been included on both the analytical and critical modelling of combustion aerodynamics.

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CHAPTER 1

Introduction

The phenomenon of flame is the result of complex interactions of physical and chemical processes whose study involves numerous disciplines such as thermodynamics, chemical kinetics, fluid dynamics, etc. Although combustion is in general terms an exothermic oxidation reaction, physical processes, in particular transfer of energy of mass and of momentum, play significant roles in a combustion system and are the most important rate determining steps in the overall reaction of most industrial flames.

For the sake of discussion it is convenient to distinguish between premixed and diffusion flames. In premixed flames the reactants are mixed completely before entering the flame, while in diffusion flames fuel and air are not fully mixed or are not mixed at all before combustion starts. As a result, mixing of the reactants and combustion are concurrent in the latter type of flame.

In both premixed and diffusion flames the flow can be laminar or turbulent. The combustion technologist is primarily interested in

(a) the rate of propagation of the burning zone into the unburned mixture,

(b) the volumetric combustion rate in the flame, and

(c) the energy transfer, mostly by radiation, but also by convection from the flame to the surroundings.

Information on the mechanism and the rate of flame propagation will give flame stability limits. Data on the rate of combustion in the flame are necessary for determining the physical dimensions of the flame. The rate of energy transfer is important because it is the objective of some combustion systems to transfer as much heat as possible to a heat sink while it is important in others (gas turbine combustors) to avoid excessive heat transfer from the flame to the bounding surfaces. In either case details of the heat transfer process need to be known for efficient design and operation.

In both the processes of propagation of the burning zone and the burnout of fuel in the flame, transfer of heat, mass and momentum play important roles. The transfer will be molecular in laminar flames and will be by turbulent diffusion in turbulent flames. In all cases, however, the rate of molecular or turbulent transfer will be dependent on the flow pattern in the flame or the combustor. The connection between mixing, *i.e.* concentration distribution on the one hand and flow pattern on the other, gives combustion aerodynamics its significance in flame studies.

Burners are devices for the injection of fuel and oxidant and their mixing in combustion chambers. Gaseous fuels can be pumped directly to burners for mixing with the oxidant, but liquid and solid fuels require preparation. Liquid fuels are normally heated in order to reduce their viscosity for efficient atomisation in the burner. The atomised fuel is then injected in the form of a cloud of finely dispersed droplets. Solid fuel can be burned on grates, in fluid beds or as pulverised fuel. Our discussion of burner flames will, however, be relevant only to the latter form in which fuel ground in mills is pneumatically transported to burners and injected into the combustion chamber as a cloud of finely dispersed particles. The oxidant most generally used is air which is pumped through the burner into the combustion chamber by means of a fan, blower or compressor. Fuel and oxidant are rarely completely premixed in the burner; they are either injected separately or more often the fuel is mixed with a small proportion of the combustion air only (primary air) on its path through the burner. The splitting of the combustion air into primary and secondary streams is made for reasons of flame stability and safety, such as prevention of flash back and explosion in the fuel supply lines. It also enables higher preheat temperatures to be used in the secondary air which in turn may favourably affect the thermodynamic efficiency of the system.

With the exception of those cases where the air stream fills the total cross section of the combustion chamber (*e.g.* cement kilns), the streams of fuel and air issuing from the burner are both in the form of a jet, *i.e.* flows fully separated from walls. The jet momentum of the fuel flow and the air stream are utilised for directing the flame and for controlling mixing in the combustor. The flow and mixing patterns in the flame are dependent upon the pressure energy that is converted into kinetic energy at the burner exit and also upon the burner geometry (Chapter 2).

Round jets are formed by fluid issuing from pipes or nozzles of circular cross section. Because of their symmetry about the jet axis, round jets may be considered 'two dimensional' for purposes of analysis, in a cylindrical co-ordinate system. For very low flow rates and small burner diameters the jets may be laminar at exit and subsequently break down into turbulent flow, but in general the size of industrial burners and the exit velocities are sufficiently large for the flow to be turbulent at nozzle exit.

Annular jets frequently serve for the introduction of secondary air around the primary jet that carries the fuel or surrounding an oil gun situated on the burner axis. Non-streamlined, so-called 'bluff bodies' are often placed in the centre of round nozzles. The flow is then issuing from an annular nozzle and a region of reverse flow forms in the wake of the bluff body which is instrumental to flame stabilisation.

Double concentric jets are compound jets consisting of a central and a coaxial annular jet. At a distance of several nozzle diameters downstream from the burner, the two jets combine and the behaviour of the compound jet in this region can be predicted with good approximation from the combined mass flow rates and jet momenta. Near the burner, however, size and geometry of the interface separating the central and annular nozzles has an important influence on the mixing. Because of its effect on flame stability, this region is of special interest to combustion technologists.

Jets penetrating into a main stream at some angle—*transverse jets*—have a frequent application as secondary air or dilution air injection into the flame (*e.g.* gas turbine combustors). For design purposes, knowledge of the path of the transverse jet, its penetration into and mixing with the main stream is necessary. While a complete analytical treatment of transverse jets is not possible, a semi-empirical approach to the prediction of significant parameters of the flow is shown to yield results with good approximation.

When jets are *confined* there is a limited supply of fluid available for entrainment. As a result, an adverse pressure gradient is set up along the jet associated with a recirculating flow outside the jet stream. Two methods of predicting characteristics of enclosed jets are presented. One of these is based on the simplifying assumption that the development of an enclosed jet, such as that of a free jet, is determined by its momentum and that the entrainment and spread of the jet is unaffected by the enclosure. The more comprehensive method is based on the detailed treatment of the equations of motion. It is shown that, while this second method gives more generally applicable results, the simple method can be used for most practical cases to predict the rate of recirculation and the position of the core of the recirculation eddy from input parameters of the enclosed jet system.

As a result of combustion, density gradients arise in combustion chambers. The rate of entrainment of gases from the surroundings into a jet or flame is dependent upon the density differences between the jet and its surroundings. When jet densities are higher than those of the surrounding gases, entrainment is reduced and, conversely, a low density or high temperature jet penetrating into cold environment has a higher entrainment rate than a jet in a constant density system. These effects are taken into account when the combustion length and the concentration distribution in diffusion flames are being discussed.

Some basic concepts of flame theory are discussed in Chapter 3. In premixed fuel–oxidant mixtures the flame propagation can be described in terms of transfer of heat and chemically active species from the reaction zone upstream into the fresh mixture where, again, combustion reaction is initiated. The new layer then becomes the new source of heat and of chemically active species. In laminar flames the transport is by molecular diffusion, while under turbulent conditions the transfer of heat and mass is considerably augmented resulting in an increased rate of flame propagation. This can be further increased by convective flows such as occur in recirculation zones.

Recirculation zones are formed in flows when an adverse axial pressure gradient exceeds the kinetic energy of fluid particles and a stagnation point is formed. This can be brought about by (a) throttling entrainment to a turbulent jet by confinement in a chamber, (b) introducing a bluff body into the main stream, and (c) imparting strong swirl to jets.

Significant relationships exist between the size and strength of the recirculation vortex and the stability characteristics of the flame. On the other hand, the size and strength of the vortex will depend upon input conditions such as blockage ratio and forebody geometry. Some of the information is in a semi-empirical form where the relationship between relevant groups of parameters is determined experimentally.

An analysis of burning, swirling jet flows without recirculation is presented in Chapter 4. Prediction of time–mean average velocity, pressure, concentration and temperature in turbulent flames can be made provided the turbulent momentum flux tensor $\boldsymbol{\tau}$, the turbulent enthalpy flux vector $\mathbf{J}_h$ and the turbulent chemical species' flux vector $\mathbf{J}_j$ (one for each chemical species) are specified. Turbulent exchange coefficients μ, Γ_h and Γ_j (defined by analogy with Newton's, Fourier's and Fick's laws for laminar flows) are generally used and assumed to be isotropic, the latter two bearing fixed ratios (Prandtl and Schmidt numbers) to the former. A method is presented which allows the distributions of μ_{rz}, $\mu_{r\theta}$, $(\Gamma_h)_r$ and $(\Gamma_j)_r$ (the significant flux components in non-recirculating, swirling flames) to be determined from experimental time–mean distributions of v_z, v_θ, T and m_j. Calculations show that previous assumptions are not generally valid and that for swirling flows the turbulent stress distribution is non-isotropic. The exchange coefficients are shown to be functions of the degree of swirl and position in the flow field.

In swirling flows (Chapter 5) the fluid emerging from the orifice has a tangential or swirl velocity component in addition to the axial and radial components of velocity encountered in free, axial, non-swirling jets. Because of their wider spread and their faster mixing with the surrounding fluid, swirling jets are frequently applied to flames as an effective means of controlling mixing of reactants and of recirculating flow. Recirculating flow, which arises in the central region of strongly swirling jets, may be used to stabilise flames on burners. Practical methods of swirl generation are discussed together with the quantitative characterisation of swirl intensity. The non-dimensional ratio of two invariants, that of the angular and linear momenta of the jet, can be used as a measure of the degree of swirl. The stability of swirling flow in divergent nozzles—conditions of separation of fluid flow from the divergent nozzle walls—is considered for varying swirl intensities and for different nozzle geometries.

Because of the effective control of the proportion of nozzle fluid mass recirculated in swirling jets, the residence time distribution of fluid particles in a combustion chamber with such a jet can be varied over a wide range by the burner geometry and the swirl intensity of the flow. If the dependence of the overall rate of a combustion reaction upon the concentration of the reactants and temperature, together with the residence time distribution of the reactants in a combustion chamber, is known, good approximate calculations of combustion performance can be made. The ability to vary residence time distributions is shown to be valuable for optimising combustion performance.

When rotating flow is coupled with a strong positive density gradient in the radial direction, this can result in a damping of the turbulent exchange of mass and momentum in the radial direction and a corresponding increase in the combustion length of a turbulent jet flame burning along the axis of a rotating environment. A dimensionless criterion is given for the laminarisation of the boundary layer.

Heterogeneous combustion, the burning of droplet sprays, is discussed in Chapter 6. The kinetics of combustion of single droplets, of monosize drop arrays and of polydispersed sprays are considered. For purposes of qualitative statements on the mechanism of droplet combustion, single droplets may be regarded as a microcosm of a spray. Theoretical studies have shown that the combustion rate of a droplet is determined by the rate of vaporisation, which in turn is controlled by the rate of heat transfer from the flame to the drop. Experimental studies have enabled the combustion rate to be given as a function of input parameters such as the droplet diameter, partial pressure of oxygen and temperature of the ambient gas. When fuel droplets burn in a turbulent jet diffusion flame, the aerodynamic parameters such as the momentum flux of the jet, entrainment into the jet and nozzle geometry become significant. Twin fluid or blast atomised oil flames and pressure jet oil flames are shown as aerodynamically contrasting types. In blast atomised oil flames the combined momentum flux of the oil and atomising agent flow is high and is therefore the factor determining the development of the flame. By contrast, in pressure jet oil flames the energy for mixing of fuel, oxidant and hot combustion products is mainly imparted to the airstream, and the momentum flux of the oil spray is relatively low. In these latter flames the oil spray characteristics such as drop size, spray angle and the spatial overlap of fuel spray and air flow pattern have significant effects upon the stability and combustion characteristics of the flame.

In Chapter 7, the merits and laws of physical modelling of combustion systems are discussed. While there is a good prospect that analytical prediction procedures will in the near future be developed to the stage where they can be used for purposes of design, physical modelling is at present a powerful tool of the engineer. It will most likely still be needed in the future for predicting the highly complex geometries usual in industrial combustors and furnaces.

Modelling laws are, at best, based on the same system of differential equations which constitute the starting point for analytical prediction procedures. For purposes of modelling, however, these equations need not be solved; it is sufficient that they be reduced to form relationships between dimensionless ratios of forces, energies or masses. The judicious choice of the dimensionless groups required as the basis of modelling criteria for a particular system has to be made with engineering insight. The combination of physical modelling with analytical procedures will in many practical cases lead to the fastest and least expensive method of predicting combustor and furnace performance.

The final chapter is concerned with measurements in flames. The objective of measurement may be to explore flames, to test theoretical predictions of flame properties or to monitor certain flame parameters for purposes of control. Also, flames are sometimes used as steady-state systems, convenient for determining material properties at high temperatures.

Several of the methods discussed in Chapter 8 were developed in conjunction with research on industrial size flames by the International