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# Combustion of Two-Phase Reactive Media

With 249 Figures

Springer

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# Preface

The subject of the book is combustion of two-phase reactive media. The study of this problem is of utmost importance for the understanding of complex phenomena characteristic of burning of solid and liquid fuels. Improvements in industrial furnaces, internal combustion and jet engines, as well as in high temperature combustion reactors, directly depend on progress in the field of combustion of two-phase media.

Combustion of two-phase media is accompanied by a number of physico-chemical processes, such as decomposition of fossil fuels, melting and swelling of solid particles, droplet evaporation, intensive heat release by chemical reactions, etc. The interphase and particle-to-particle interactions affect significantly the hydrodynamical flow structure, the intensity of heat and mass transfer and, as a result, the general characteristics of combustion of two-phase media. Two-phase combustion of porous matrixes when gaseous oxidizer filters through them adds extra features to the combustion process.

A multiplicity of phenomena characteristic of the combustion of two-phase media determine the contents of the book. We consider only a number of principal problems related to the processes developing under conditions of phase changes, intensive heat release and strong interaction of dispersed and continuous phases. These include the problems of heating, ignition and combustion of a single particle, droplet and bubble, combustion wave propagation in two-phase media, as well as the thermal regimes of combustion reactors.

To a certain degree, the choice of the problems considered is subjective. It was determined by the problems which, in our opinion, are of significant scientific interest, as well as illustrate the specific approaches characteristic of the theory of combustion of two-phase media. In the book we also used the results of our own investigations of a number of problems of two-phase flows, as well as the materials of graduated courses given by the authors at the Technion – Israel Institute of Technology.

The book consists of three parts. They deal with the dynamics of a single particle (Chaps. 1.1 – 1.5), combustion wave propagation in two-phase reactive media (Chaps. 2.6 – 2.9) and thermal regimes of high temperature combustion reactors (Chaps. 3.10 – 3.11).

A number of comprehensive monographs dealing with mechanics of two-phase flows have been published in the last decades. Numerous articles concerning various aspects of this problem are also published in the current literature.

However, as far as we know, there are practically no special monographs devoted to combustion of two-phase media. We have attempted to fill this gap.

The book is not an undergraduate text, although it could be used for a graduate-level course. It is intended for professional scientists and engineers interested in the combustion of two-phase reactive media.

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# Introduction

## 0.1 General overview

The usage of fire became one of the most remarkable events in the history of humanity. It determined the face of modern civilization. The development of heat-power stations, automobile and railway transportations, central heating systems, aviation and astronautics, etc. would not have been possible without traditional sources of energy that are based on fossil fuels.

Despite the fact that the combustion process has been used for thousand years, the true mechanism of this process became clear only in the first half of the 20th century when a number of fundamental researches concerning kinetics of chemical reactions, theory of thermal explosion and flame propagation, combustion of non-premixed gases, turbulent combustion and stability of flame were performed. These researches laid the foundation of the modern theory of combustion which involves a wide class of problems associated with combustion of various types of fuels, as well as their application in energetics and chemical technology.

Over a long period of time the attention of investigators was concentrated on the studies of combustion of homogeneous media. Starting in the 1950s combustion of heterogeneous media, in particular the combustion of two-phase systems, became the subject of systematic theoretical and experimental investigations. The growing interest in this problem was related to the elaboration of gas turbines, jet engines, as well as to the improvement of industrial furnaces working on solid and liquid fuels. It was also related to the problems associated with environmental protection. At that time the important features of combustion of two-phase systems were revealed and the simplest models of this process were suggested. It was shown that the combustion of two-phase media possesses certain peculiarities related to the interplay of the strong dependence of chemical reaction rate on temperature with dynamic and thermal phase interaction. This process essentially depends not only on physico-chemical properties of reactants and the thermodynamic state of the system, but also on its structural characteristics. In order to describe such complex phenomena, an approach which combines the methods of the classical theory of combustion with the methods of the theory of multiphase flows is called for. The application of such an approach to combustion of two-phase media is the main topic of the present book. It contains eleven chapters which deal with burning of isolated particles, combustion wave propagation in two-phase reactive systems, as well as with the thermal regimes of high temperature combustion reactions.

## 0.2 Scope and Contents of Part 1

The first part of the book deals with the behavior of a single particle in a fluid flow. It is concerned with the basics of dynamics of a reactive particle in two-phase flows. The reason that a separate part of the book is devoted to the dynamics of a single particle stems from the following: (i) it is important for understanding the mechanism of a number of microprocesses determining the particle heating, ignition and burning, (ii) it is the basis of the theory of combustion of two-phase media, and (iii) it is directly applicable to many cases in engineering and technology.

Part 1 includes five chapters related to particle drag, its heating, ignition and burning, as well as to particle/particle and particle/turbulence interaction.

Chapter 1.1 deals with the drag of a solid particle, a droplet and a bubble. The classical results of the theory of hydrodynamic resistance and a number of specific problems related to the particle drag under conditions of intensive heat and mass transfer are discussed. Effects of flame in the vicinity of particle on its drag are also considered.

In Chapt. 1.2 the problems of particle heating, devolatilization and vaporization are considered. The basic correlations used to calculate the heat transfer coefficient are presented in this chapter. The focus is on the thermal regime of a particle of a fossil fuel under the conditions of decomposition of solid material and filtration of volatiles through the solid matrix. Some results related to vaporization of one- and multicomponent droplets are also discussed.

The concepts of particle ignition and combustion are considered in Chapt. 1.3. The mechanisms of homogeneous and heterogeneous ignition, the peculiarities of ignition and combustion of coal and metallic particles, as well as the models of combustion of one- and multicomponent droplets are treated in this chapter.

Some problems concerning collective effects in dense particle clouds are briefly considered in Chapt. 1.4.

Chapter 1.5 deals with turbulence intensity in dilute two-phase flows. The effect of particle size distribution and of the concentration of a heavy admixture on turbulence intensity is considered. Turbulence modulation in two-phase flows loaded with fine or coarse particles, as well as temperature fluctuations in two-phase flows are studied in detail in this chapter. The theoretical analysis of these phenomena is based on the mixing-length theory, modified to account for the peculiarities of viscous interaction of particles with carrier fluid and for the effect the admixture inertia. A brief discussion of the effect of temperature fluctuations on the average rate of chemical reaction is also presented in Chapt. 1.5.

## 0.3 Contents of Part 2

In the second part of the book a number of problems arising in relation to wave propagation in two-phase media are considered. In this part the attention is focused on the study of the mechanism of flame propagation in media loaded with reactive particles, droplets of liquid fuel, or bubbles filled with a gaseous oxidizer.

Chapter 2.6 deals with the combustion wave propagation in gas–particle systems. The characteristics of flame propagation under the conditions of conductive or radiant heat transfer are considered.

Combustion wave propagation in bubble media with low and high volumetric content of gaseous oxidizer are discussed in Chapt. 2.7.

Chapter 2.8 is devoted to the flame propagation under the conditions of filtration combustion of porous media.

Chapter 2.9 describes in brief some questions of the theory of turbulent heterogeneous flames.

## 0.4 Contents of Part 3

The third part of the book treats some specific, technologically important problems characteristic of high temperature combustion reactors. It contains two chapters, in which the results of the study of the ideally stirred and displacement reactors are presented.

The model of an ideally stirred gas–liquid reactor is considered in Chapt. 3.10. This model takes into account the principal features of the gas–liquid reactive systems, e.g. the multistage character of the process, as well as its dependence on the physico-chemical and structural properties of the two-phase media. The theoretical description of the process is based on the thermal theory of combustion and on a model of two-phase media as an interpenetrating continuum. In this approximation the heat and mass balance equations for the actual and space-averaged parameters are obtained. The dimensional analysis of the system of the governing equations is used to reduce the number of the dimensionless groups describing the processes in the gas–liquid ideally stirred combustion reactors. The general characteristics of the gas–droplet, bubble and jet gas–liquid ideally stirred combustion reactors are discussed. The features of the ideally stirred combustion reactors are considered in relation to the change of their regimes, as well as to the variation of the physico-chemical and structural characteristics of the gas–liquid media. The thermal regimes of the gas–solid particle ideally stirred combustion reactor are also considered in Chapt. 3.10.

Chapter 3.11 is devoted to the displacement combustion reactors. Two characteristic types of such reactors (bubble and filtration) are considered in this chapter. The kinematic balance method is used for the analysis of the thermal regimes of both types of the displacement reactors discussed. Special attention is paid to

the states of the filtration reactor: its stationary regimes, stability of the stationary states, hysteresis phenomena, and regimes with self-sustained oscillations.