Preface

A number of technological processes and natural phenomena are accompanied by heat transfer concerned with media thermal radiation. Generally, thermal radiation is thought to be relevant only at high temperatures. This widespread error is easily overcome if we recall, for example, that the weather and climate on our planet are mainly determined by thermal radiation of cloudy atmosphere and the Earth surface. Few people are aware that the quality of an ordinary sleeping-bag is connected with changing of radiation transfer conditions in a fibrous material.

In the examples mentioned, as well as in many other cases, thermal radiation emission, absorption, and scattering take place in a medium containing numerous particles of size comparable with the radiation wavelength. Such media are customary called the disperse systems. One has to solve radiation heat transfer problems for disperse systems in highly different applications such as heat transfer in solid propellant rocket engines and solar chemical reactors, characterization of advanced composite coatings and highly porous thermal insulations, microwave remote sensing of the ocean surface with breaking waves, and spacecraft thermal control by use of a liquid droplet radiator. The geometrical scales of particles, bubbles, and pores in the above mentioned thermal radiation problems and in many other problems may vary in a very wide range — from nanometers in some advanced materials to several millimeters or even greater in the microwave applications. As a result, both the experimental technique and theoretical modeling should be based on a general physical analysis of electromagnetic waves interaction with single particles and adequate description of the radiation propagation in complex disperse systems. It goes without saying that direct simulation of the radiation emission, absorption, and scattering based on the first principles is impractical at the moment and one should find alternative engineering approaches by using the known solutions to some simplified problems. Of course, a correct choice or elaboration of an approximate model which is appropriate to the problem to be solved depends on personal skill and experience of a researcher in this field. In our book, we were trying to do our best to help our young colleagues in improving their knowledge and qualification in thermal radiation problems specific for various disperse systems.

One should remember the usual error of some people who are starting to work in heat transfer modeling. They think that all the problems can be solved by more and more computational skill in combination with great possibilities of the present-day supercomputers. We have several arguments which show that this ambitious point of view is not correct:

- In many problems, radiative heat transfer is not a sole transfer mode and it should be considered simultaneously with the conduction and convective heat transfer. The complex hydrodynamic processes and phase change in the medium components makes a rigorous mathematical statement of such transient combined problems too complicated for the direct numerical simulation.
- The spectral radiative properties of substances are not well-known especially at very low or high temperatures as well as in the regions of extreme values of other physical parameters. The uncertainties in these properties limit the resulting accuracy of the radiation field calculations and make the use of detailed numerical simulation to be not so important.

To our mind, the understanding of physics and the use of relatively simple theoretical models are very important components of the engineering approach to experimental and computational study of thermal radiation in disperse systems.

The known textbooks on thermal radiation are not focused on detailed analysis of radiative properties of various disperse systems and do not give practical examples of solving the radiative and combined heat transfer problems. In this book, we were trying to bridge a gap between the ordinary university education and the research and engineering work. The contents of the book is determined by research and teaching experience by the authors in this field. To make reading easier, we avoid detailed derivations and give the minimal mathematical transformations. All these details can be found in the referenced archive papers.

Of course, the analysis of some problems considered in the book is not so detailed. A reader could find these sections as a kind of starting points which still await his or her further research contributions. But we hope that our efforts were sufficient to pave the way for engineers and researchers in the field of thermal radiation and combined heat transfer in disperse systems. By including a large number of references for further reading, the book may also be used as a reference book by the practicing engineer.

The authors are grateful to the colleagues Wojciech Lipiński, Jaona Randrianalisoa, Remi Coquard, Herve Kamdem Tagne, Sylvain Lallich, Mathilde Loretz, Aurélie Kaemmerlen, Ségoléne Gauthier, Luis Moura, and Mikhail Davydov for their contribution to the studies presented in Sections 1.5.3.1, 1.7.2, 3.3–3.9, and 4.11 of the book. The interest to our joint project and support by professors Jean-Francois Sacadura, Dany Escudie, Truc-Nam Dinh, Leonid Zaichik, Yuri Zeigarnik, and Alexander Leontiev is much acknowledged.


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Introduction

The physical basis of the majority of solutions considered in this book is the notion of radiation transfer in an absorbing and scattering medium as some macroscopic process, which can be described by a phenomenological transfer theory and radiative transfer equation for spectral radiation intensity. It is of great importance that the problems, to which the radiation transfer theory can be applied, are quite numerous and contain thermal radiation of various disperse systems. In the book, we use the following main assumptions concerning disperse system properties and radiative transfer:

- Radiation propagation is more rapid than any change of physical parameters, therefore the radiation intensity field is quasi-steady;
- Radiative properties of the medium do not depend directly on the radiation intensity, but they vary only with temperature;
- Wave polarization can be ignored in radiative transfer calculations;
- Radiation scattering is not accompanied by any frequency variation.

In many (but not all) cases, we assume also that characteristics of absorption and scattering of radiation by a small (elementary) volume of the disperse system can be determined from the properties of single particles regardless of any collective effects. The last assumption simplifies the problem, and gives also a chance for direct investigation of the medium composition influence on thermal radiation transfer. The restrictions occurring from this assumption are usually not as significant, as might seem, since the assumption about small collective (dependent scattering) effects remains valid up to a high enough particle concentration.

The radiation transfer theory has been developed by a number of famous scientists working in the physical optics, astrophysics, nuclear reactor theory, and heat transfer theory. The mathematical theory was created containing up-to-date analytical and numerical methods. Numerous particular publications dealt with computational methods applied to radiative transfer problems. Together with the development of the radiation transfer theory, significant achievements took place in theoretical investigations of particle radiative properties for various disperse systems. Properties of particles comparable with the wavelength turned out to be diverse and complex. Many applied investigations and well-known monographs were published on this subject. In order to solve the practical problems of thermal radiation in disperse systems, one needs to combine achievements of both the scattering theory and radiation transfer theory. A reasonable choice of the method for solving the radiative transfer equation depends upon the medium properties. On the other hand, the requirements for completeness and accuracy of single particle properties are determined by essential precision of radiation flux calculations. This was also reflected in the book.

While solving many practical heat transfer problems, one should take into account not only the thermal radiation but also heat transfer by conduction and convection in the medium. Most general problems of combined radiative-convective heat transfer are very complicated and their solution is possible only by employing approximate computational models for radiative transfer. Therefore, more attention was given to errors resulting from these approximate models.

As the measurements of radiative characteristics of diverse dispersed materials are very important to develop and validate appropriate theoretical models, a special emphasis is put on recent overviews of experimental characterization of spectral radiative properties of disperse systems and comparison between experimental and theoretical results. The examples of the simultaneous use of both theoretical analysis and experimental identification to understand unusual radiative properties of quite different porous materials of complex morphology are expected to be interesting for potential readers to know the complete set of tools employed in this field.

It is natural that the choice of material for this book corresponds to the field of practical work by the authors. The book is divided into four chapters. Chapter 1 deals with computational models for radiative transfer in disperse systems. The main attention is given to simple approximate models, both traditional and modified, which have a clear physical sense and enable one to derive some useful analytical solutions to classic problems. Computer codes based on these approximate models for radiative transfer are widely used in engineering practice especially in combined heat transfer calculations. The error of various approximations is analyzed in some details by comparison with exact analytical and numerical solutions. Approximate models presented in Chapter 1 form a basis of solutions obtained for applied problems considered in the book. A detailed numerical simulation of radiative transfer using the discrete ordinate method and the Monte Carlo procedure as applied to disperse systems is also discussed in this chapter.

Spectral radiative properties of single particles and fibers are considered in some detail in Chapter 2. The theoretical part of this chapter includes the Mie solution for homogeneous spherical particles and more general solutions for hollow and core-mantled spheres. We give also the known solution for arbitrary illumination of long cylinders. This solution is widely employed in modeling the radiative properties of single fibers and highly porous fibrous materials. A complete set of equations is presented for homogeneous, hollow, and two-layered cylinders. The main limiting cases of the general theory (the Rayleigh and Rayleigh–Gans scattering, the geometrical optics, and the anomalous diffraction approximation) are considered in Section 2.2. Absorption and scattering of the visible, infrared, and microwave radiation by single particles and fibers of various substances are analyzed in Section 2.3. Thermal radiation from nonisothermal particles and the radiation from a particle to ambient medium through narrow concentric gap are considered in Sections 2.4 and 2.5. The radiative properties of polydisperse systems and applicability of monodisperse approximation are discussed in the last section of Chapter 2.

Chapter 3 presents an engineering approach for both theoretical prediction and experimental determination of spectral radiative properties of quite different dispersed materials containing the morphology elements of arbitrary shape. A general theoretical basis of radiative properties determination and present-day principles of experimental characterization with identification procedure are recalled. Physical limitations of independent scattering theory are also discussed in this chapter. Experimental and computational results, approximate theoretical models and engineering estimates important for potential applications are presented for porous materials such as cellular foams, fibrous materials, ceramics, polymer coatings containing microspheres, and nanoporous aerogel superinsulations. The materials under investigation can be applied in advanced energy and combustion systems, such as low-NO_x combustion burners, solar thermal energy systems or specific applications requiring lightness and high insulating efficiencies. Thus the characterization of radiative properties of such dispersed materials plays an important role in many engineering systems.

Some radiative and combined heat transfer problems in various disperse systems are considered in Chapter 4. These problems include the main results for radiation heat transfer in solid-propellant rocket engines (Section 4.1), the problems of radiative cooling of particle flow in vacuum (Section 4.2), the combined heat transfer in boundary-layer flows (Section 4.3), the thermal microwave radiation of foam and water sprays produced by breaking ocean waves (Section 4.4), the radiative-conductive heat transfer in composite coatings, fibrous materials, and foam insulations (Sections 4.5, 4.6), the radiative effects in a semi-transparent liquid containing gas bubbles (Section 4.7), the effects of nonuniform absorption and heating of semi-transparent particles by an external radiation (Section 4.8, 4.9), and the thermal radiation modeling in multiphase flows with high-temperature nonisothermal particles (Sections 4.10 and 4.11).

Chapters 1, 2, and 4 are only partially based on the revised material of the previous book by Leonid Dombrovsky "Radiation Heat Transfer in Disperse Systems" (Begell House, New York, 1996). These chapters include some new results obtained in the period from 1994 to 2010. Sections 1.7 and 4.6.2, which are written by Dominique Baillis, are also presented in Chapters 1 and 4. As to Chapter 3, it involves mainly a systematic presentation of the research by a group of Dominique Baillis. Sections 3.6–3.9 of this chapter are written by Leonid Dombrovsky on the basis of the research work, which has been done in cooperation with Dominique Baillis and her students.

For a topic which is broad as the one considered in this book, it is very difficult to be comprehensive. However, we hope that enough key references are cited in the book to enable an interested reader to undertake a more detailed study of specific thermal radiation problems in disperse systems.