A Prelude to the Fundamentals and Applications of Radiation Transfer

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Abstract

Radiation transfer is one of the three pillars of heat transfer processes, along with conduction and convection. It is essential for any high-temperature industrial process taking place in combustion chambers, flames and fires, manufacturing processes, energy harvesting systems, atmospheric processes, large-scale and local thermal management problems, as well as in high-resolution thermal sensing and control applications. This chapter provides an introduction to the fundamental principles of radiation transfer, including the Planck law, Wien law, radiative intensity, solid angle, and radiative transfer equation. It is a prelude to the eight related chapters in this handbook, and provides an overview that leads to detailed discussion of the radiative transfer equation and its solution, the radiative properties of particles and gases, applications in combustion chambers, inverse

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problems, near-field radiation transfer, and advances in surface optical and radiative properties.

1 Introduction

The origin of radiation transfer can be traced back to the beginning of the universe. Our sun has been shining on Earth and providing light and heat for more than 4.5 billion years. During all these years, all kinds of plants, reptiles, birds, mammals and fish have adapted to the sun and its energy. This adaptation goes down to the level of cells and sub-cellular structures, and all governed with the fundamentals of radiative transfer in its most general form. Of course, the light-matter interactions are even more fundamental in nature and include all atomic and sub-atomic level physics. And the humans have been playing with fire, and with its light and heat, for over 200,000 years since they have started controlling it in Olduvai Gorge, in Tanzania. All kinds of technological developments since then have benefitted from the understanding of radiation transfer from flames and fires, within combustion systems and industrial processes at high temperatures.

The subject of radiation transfer has been discussed by many researchers over the years. Theory and applications were considered from the classical point of view by Planck (1906), Chandrasekhar (1960), Sparrow and Cess (1966), Hottel and Sarofim (1967), Brewster (1992), Viskanta and Mengüç (1987), Viskanta (2005), Modest (2013), and Howell et al. (2016). In addition, Chen (2005) and Zhang (2007) outlined the principles of near-field radiation transfer (NFRT) and nanoscale conduction heat transfer. A rigorous analysis of radiative transfer is based on Maxwell's equations for electromagnetic (EM) wave propagation and scattering. The interaction of EM waves with particles and surfaces is an important aspect of the physics behind such an analysis. Detailed discussion of EM waves and particle–surface interactions are found in the texts by Van de Hulst (1981), Bohren and Huffman (1983), and Mishchenko (2014). EM-wave-based analysis is also required for NFRT, as discussed by Chen (2005), Zhang (2007), and more recently by Basu (2016).

This chapter outlines the fundamental principles of radiation transfer. Different but related concepts are discussed in subsequent chapters to help the reader put them in perspective. References are listed at the end of the chapter for specific cases.

2 Fundamental Concepts and Equations

All objects radiate EM wave energy to their surroundings. At the same time, all objects receive energy emitted by other objects around them. A fraction of the incident energy on an object is absorbed and the rest is either transmitted through the object's boundaries or reflected back. The balance between the absorbed and emitted radiation, along with the other modes of energy transfer mechanisms, determines the thermal equilibrium state of an object, specifically by considering conduction, convection, and radiation transfer through the system boundaries and taking into account the heat source and mass and work flow distributions. Temperature is the measure of the internal energy of an object. This energy balance and the correlation between internal energy and temperature are manifested by the zeroth and the first law of thermodynamics; the latter is also known as the law of conservation of energy. If the net energy received is more than the energy lost, the internal energy of a body increases; otherwise, it decreases. Once energy is emitted, the object loses part of its energy; in other words, it cools off. However, it gets warmer by absorbing electromagnetic energy emitted by other objects. When EM radiation travels from one object to another, it can be scattered by all molecules, particles, cracks, or any inhomogeneity between them, which makes the problem quite complex as the absorption, emission, and scattering mechanisms should be evaluated at each wavelength (or frequency) of the EM wave spectrum. The polarization of EM waves may also be important because it affects the underlying physics, depending on the length scale of the system under consideration.

Radiation transfer enters into the conservation of energy equation as a source term. This equation, as written in terms of the temperature, T, of a control volume is expressed as follows:

$$\rho c \frac{\partial T}{\partial t} dV + \nabla(k \nabla T) dV = \dot{q} dV \tag{1}$$

Detailed discussion of the equations for the conservation of mass, momentum, and energy are provided in other sections of this handbook. The radiation source term in Eq. 1 is denoted as $\dot{q}$. Note that there may be more than one type of volumetric source, because they can be the result of different physical or chemical phenomena; thermal radiation transfer is only one of the sources. The radiation source term $\dot{q}$ is equivalent to divergence of the radiative flux in a volume element dV. This means that for the calculations we first have to determine the radiative flux profile in the medium of interest. In its most general sense, this profile is calculated in three-dimensional space and in transient fashion by solving the integro-differential and spectral radiative transfer equation (RTE). Note that such directional and spectral behavior is unique to radiation transfer, which makes it more complicated than conduction or convection heat transfer modes.

Obtaining the radiative flux profile in a medium starts with predicting all underlying physical phenomena within the medium and at its boundaries, in directional, spectral, and transient manners. The distribution of radiative flux depends on the temperature profile in the medium and on the boundaries. This makes the problem even more complex, because the temperature profile can be determined from Eq. 1 only if the radiative source term is available. Therefore, the problem requires an iterative solution of the energy and radiative transfer equations until the temperature profile converges. Beyond this obvious numerical complication, additional complexity arises because of the information required for the spectral and directional properties of surfaces (plus data on their composition and structural variation), of gases and their interactions, and of particles (plus data on their size, shape, structure, and complex indices of refraction).

A discussion of fundamental equations for radiative emission and absorption should start with the definition of a perfect emitter or absorber. The key point to be emphasized here is the spectral variation in thermal emission. Because of the dependency on wavelength (or frequency), the physics of radiation transfer is rich and complex, and allows intriguing design and process ideas. In other words, one can control the amount of radiation heat transfer to an object by modifying the geometry of the object and its surroundings, as well as its spectral radiative properties and those of its boundaries. To tackle these ideas, the fundamental expressions for blackbody emission should be introduced, including solid angle, radiation intensity, and the RTE. Here, we summarize these fundamental expressions. ► Chap. 23, "Radiative Transfer Equation and Solutions" by Zhao and Liu details the most important expressions required for prediction of thermal radiation heat transfer.

2.1 The Planck and Wien Laws

A perfect (ideal) blackbody emits the maximum radiative energy at all wavelengths. This emission from a surface to all directions is expressed by the Planck law, as given by Eq. 2:

$$E_{\lambda b}(T) = \frac{2\pi h c_0^2}{n^2 \lambda^5 \left[\exp\left(\frac{h c_0}{n k_B \lambda T} \right) - 1 \right]} \tag{2}$$

where $E_{\lambda\mathrm{b}}$ is the radiative energy emitted by a surface (of an object) to all directions, per area, at a given wavelength λ; h is the Planck constant ($h = 6.626070 \times 10^{-34}$ m^{2}kg/s); k_B is the Boltzmann constant ($k_B = 1.380648 \times 10^{-23}$ J/K); and T is temperature in Kelvin. There are two additional constants in this expression: c_0, the speed of light in a vacuum ($c_0 = 2.99792458 \times 10^8$ m/s) and n, the index of refraction of the medium in which the wave is propagating. For a vacuum, $n = 1$; for air it is very close to 1 and varies with the wavelength λ, which is omitted for the sake of clarity. The subscript "b" refers to "blackbody" to identify the ideal and maximum possible emission.

The spectral behavior of the Planck law for different temperatures is depicted in Fig. 1. With increasing temperature, the peak wavelength of emission shifts to lower wavelengths, and the corresponding emissive power increases. If the blackbody emissive power from an object is integrated at all angles within the entire spectrum, one can obtain a relatively simple expression proportional to the fourth power of temperature, T^4 (T being in Kelvin), which is known as the Stefan–Boltzmann Law, where σ is the Stefan–Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4):

$$\int_{\text{all } \lambda} E_{\lambda b} d\lambda = \sigma T^4 \tag{3}$$

The Planck blackbody equation given by Eq. 2 can be normalized with T^5 and plotted against λT to consolidate all the T-dependent curves shown in Fig. 1 to a single curve. The peak of this normalized curve, as shown in Fig. 2, is important and known as the Wien law:

$$(\lambda T)_{max} = 2893.6\ \mu\text{m-K} \tag{4}$$

This equation helps to determine the spectral behavior of radiation emission in an intuitive way in heat transfer analyses at any given T. For example, an object at room temperature, roughly at 20°C (293 K), has maximum emission at a wavelength of about λ=10 μm. On the other hand, the sun, at T=5867 K, has a peak emission at about λ=550 nm. The peak emission of solar light corresponds to the median of the visible radiation spectrum (at green), suggesting that the eyes of many organisms may have evolved to sense the maximum amount of sunlight. Note that the wavelength obtained from the Wien law is also referred to as the characteristic wavelength of emission. This value represents the demarcation between far- and near-field radiation transfers, as discussed in Sect. 6.

In many heat transfer calculations, the Stefan–Boltzmann law, as given in Eq. 3, is used to account for radiation transfer. Yet, by doing so, the spectral richness of radiation transfer phenomenon is neglected. In addition to the spectral nature of radiation transfer, we wish to emphasize once again its directional variation, which

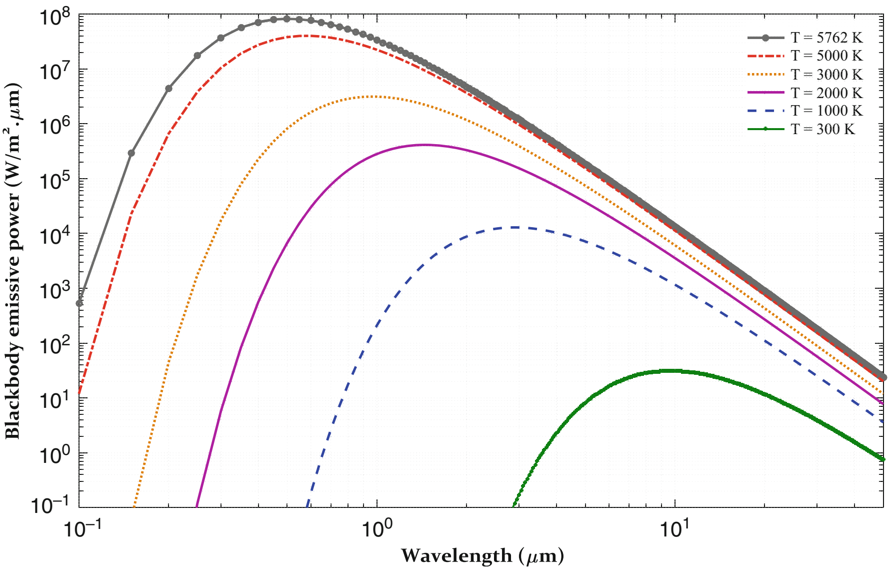

Fig. 1 Planck blackbody emission as a function of wavelength at different temperatures

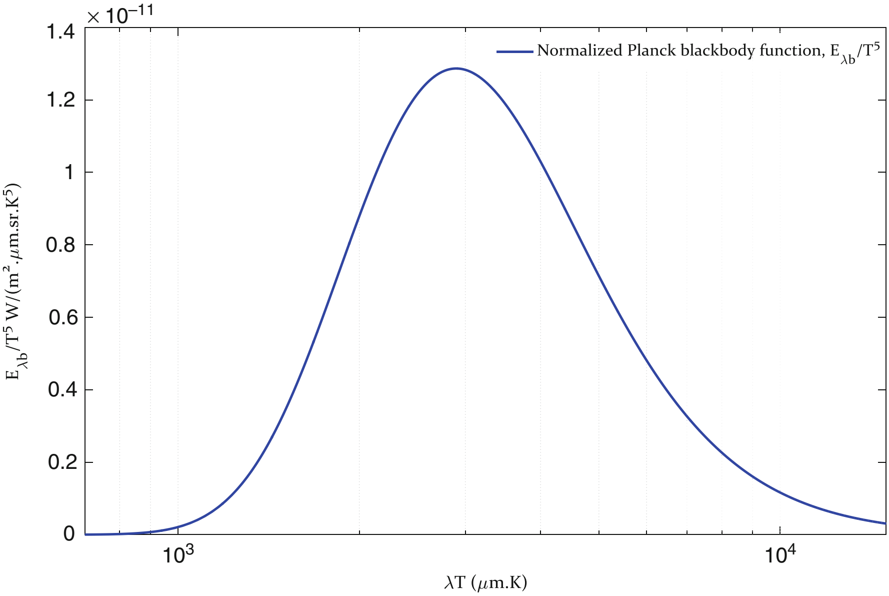

Fig. 2 Normalized Planck blackbody function $E_{\lambda b}/T^5$. The peak value is determined from the Wien law, as given in Eq. 4

is unparalleled compared with conduction and convection heat transfer. The spectral and directional behaviors of radiation transfer are discussed in the following sections.

2.2 Solid Angle

We all know that a beam of sunlight streaming off a dense cloud line is more noticeable than the background. Under these conditions, the directional variation of light is obvious just as the directional radiative heat coming from a fireplace. In an enclosure, the radiation from a hot surface is naturally more intense than from the rest of the enclosure. To account for that disparity, it is necessary to formulate the problem of directional variation with clear understanding. To do that, instead of using hemispherical emissive power, it is preferable to define the so-called radiation intensity (Howell et al. 2016). To understand this fundamental quantity, consider radiative energy emanating from a surface, per unit area and per unit time, and propagating in a given direction within a small directional "pencil." For mathematical derivation, it is preferable to define the pencil of light or the "solid angle," based on the geometry given in Fig. 3. Here, a small area on the sphere with radius r around the emitting surface is defined in terms of incremental azimuthal (ϕ) and zenith (θ) angles and related to the solid angle:

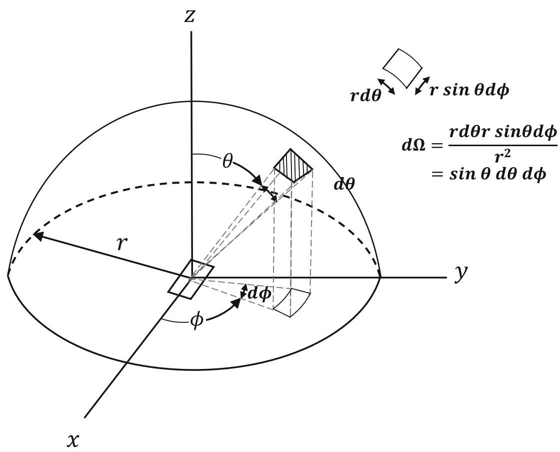

Fig. 3 Geometry for definition of the solid angle

$$d\Omega = \frac{rd\theta r\ \sin\theta d\phi}{r^2} \tag{5a}$$

The integration of this solid angle in all directions over the hemisphere gives the total angle, 2π. Integration of all angles would yield 4π:

$$\int_{4\pi} d\Omega = \int_{\theta=0}^{\pi/2}\int_{\phi=0}^{2\pi} \sin\theta d\theta d\phi = 2\pi \tag{5b}$$

The radiation intensity is defined as the energy leaving a surface at location S, per unit area dA, in the direction of Ω within an incremental solid angle $d\Omega$, within a small wavelength interval $d\lambda$ at the wavelength λ, per unit time interval dt, as:

$$I_\lambda(S,\Omega,t) = \lim \frac{dE_\lambda(S,\Omega,t)}{dAd\lambda d\Omega dt} \tag{6}$$

If the surface is a blackbody, then I_λ is replaced with $I_{\lambda b}$, and E_λ with $E_{\lambda b}$.

Using this formulation, the problem of radiative exchange between different volume and surface elements in an enclosure can be tackled. As an example, imagine the radiative energy leaving the surface element A_1 and reaching A_2, as seen in Fig. 4. To determine the net energy going from A_1 to A_2, a small area element dA_1 and an incremental solid angle between dA_1 and A_2 are considered. After that, dA_1 can be scanned over the entire area of A_1. Note that this is purely a geometric problem. This geometric analysis is known as the shape factor or configuration factor analysis, which is explained in text books by Sparrow and Cess (1966), Hottel and Sarofim (1967), Modest (2013), and Howell et al. (2016). A compendium of most exchange factors is provided by Howell and Mengüç (2011); the factors are also listed on the website www.thermalradiation.net by the same authors (Mengüç and Howell 2016).

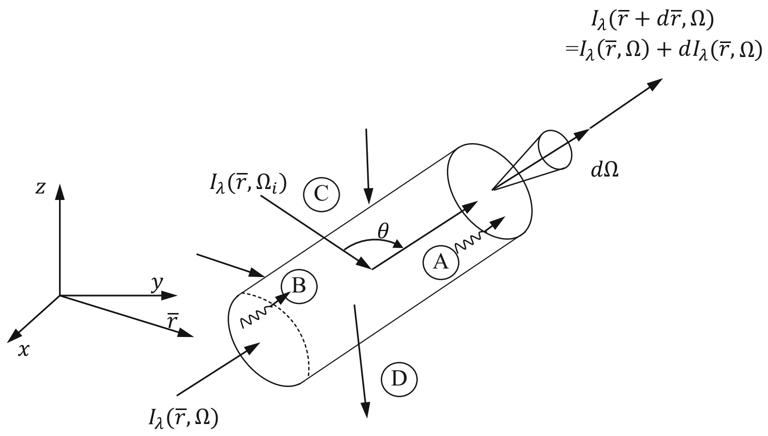

Fig. 4 Geometry for the derivation of the radiative transfer equation: *A* gain of energy resulting from emission, *B* loss of energy along the line-of-sight via absorption, *C* gain of energy resulting from scattering from other directions into the direction of the beam, *D* loss of energy resulting from scattering to other directions

Note that the shape factor analysis can be carried out if the properties of the radiating surfaces are available. If the problem requires a wavelength-dependent analysis, then the calculations should be carried out at each wavelength interval. The results for flux and the divergence of radiative flux are then integrated over the entire wavelength spectrum. It is also important to realize that the shape factor analysis is used if a medium is non-participating (i.e., completely transparent). If a medium is absorbing, emitting, and scattering, then it is called participating. Any type of medium, including foams, paints, combustion gases, and particles, that is non-transparent within a spectral window of importance falls into this category. The exchange of energy in a participating medium is more complex because of the change in direction of EM waves as a result of any inhomogeneity along their path. This change of direction is called scattering and encompasses reflection, refraction, and diffraction of beams. Under these conditions, we need to solve the RTE, which is derived phenomenologically in Sect. 3. ▶ Chap. 23, "Radiative Transfer Equation and Solutions" gives details.

3 Radiative Transfer Equation

The conservation of radiative energy for a beam of light along a given direction in a participating medium can be written using the nomenclature and geometry shown in Fig. 4. The resulting expression, in terms of spectral radiative intensity, is called the radiative transfer equation (RTE). As the beam propagates, it loses some of its energy along the line-of-sight via absorption (B in Fig. 4) and scattering to other directions (D). Furthermore, as the beam propagates through the medium, it gains energy as a result of emission (A) and scattering from all other directions into the direction of the beam (C).

These radiative gains and losses can be added, giving the time-dependent RTE:

$$\begin{aligned}\frac{\partial I_\lambda(r,\Omega,t)}{c\partial t}+\frac{\partial I_\lambda(r,\Omega,t)}{\partial S} &= \kappa_\lambda I_{\lambda b}(r,t)-\kappa_\lambda I_\lambda(r,\Omega,t)-\sigma_{S\lambda}I_\lambda(r,\Omega,t)\\ &+\frac{1}{4\pi}\int\limits_{\Omega_i=4\pi}\sigma_{S,\lambda}I_\lambda(r,\Omega_i,t)\Phi_\lambda(\Omega_i,\Omega)d\Omega_i\end{aligned} \tag{7}$$

Here, κ_λ is the spectral absorption coefficient and σ_λ is the spectral scattering coefficient (in units of m^{-1}). The sum of these two gives the spectral extinction coefficient, β_λ:

$$\beta_\lambda = \kappa_\lambda + \sigma_{s,\lambda} \tag{8}$$

In Eq. (7), $\Phi_\lambda(\Omega_i, \Omega)$ is the scattering phase function, which gives the probability of the radiative energy being redirected from any given direction Ω_i to the direction of propagation Ω. Therefore, all possible directions must be accounted for in the analysis, which is the reason for the integral term in the RTE.

The radiative properties coefficients and the scattering phase function can be determined starting from the Maxwell equations, which describe the propagation of EM waves in a given medium. For particulate matter, the methodologies for determining these properties have been discussed by Van de Hulst (1981), Bohren and Huffman (1983), Mishchenko (2014), and Howell et al. (2016). These calculations for particle radiative properties require information on the shape, size, and structural details as well as the spectral complex index of refraction data. The details and requirements for different techniques are outlined by Vaillon in ► Chap. 27, "Radiative Properties of Particles."

For radiative heat transfer calculations, scattering in gaseous media is not important and only the absorption coefficient is required. There are different types of gases that need to be considered for these calculations, the most important of them being water vapor (H_2O), carbon dioxide (CO_2), and carbon monoxide (CO). Their presence in the atmosphere, along with nitride oxides (NO, NO_2) and methane (CH_4), determines for the radiative balance of the Earth and climate change concerns. On the other hand, in combustion chambers, the spectral properties of H_2O, CO_2, and CO are needed at high temperatures and pressures. The spectral absorption coefficients of these gases show quite complex behavior and their calculation is by no means trivial. Details of the spectral radiative properties of different gases and the corresponding methodologies are available in Modest (2013) and Howell et al. (2016), as well as in ► Chap. 26, "Radiative Properties of Gases" by Solovjov et al.

4 Solution of the Radiative Transfer Equation

The RTE given in Eq. 7 forms the backbone of radiative transfer calculations. Because of the in-scattering term, the RTE is an integro-differential equation and its solution must first be obtained for every direction, before being integrated over all directions (i.e., over 4π). As one can imagine, this integration and the solution of the RTE is not a trivial task. Depending on the application, the problem can be simplified by considering the radiative intensity to be uniform over a given solid angle interval; however, the applicability of any approximation should be carefully evaluated. Over the years, several different publications have been devoted to this subject, as outlined by Chandrasekhar (1960), Hottel and Sarofim (1967), Viskanta and Mengüç (1987), Modest (2013), and Howell et al. (2016).

Discussion of the RTE and many solutions developed for different cases are given in ► Chap. 23, "Radiative Transfer Equation and Solutions" by Zhao and Liu. Among all these techniques, the most versatile, without question, is the Monte Carlo technique. A detailed analysis is available for fundamentals and applications in ► Chap. 29, "Monte Carlo Methods for Radiative Transfer" by Ertürk and Howell.

5 Applications of Radiative Transfer

Radiative transfer is important in both atmospheric and thermal sciences as well as in industrial systems. Atmospheric radiation transfer is not covered in this handbook, but its analysis can be found in texts such as Thomas and Stamnes (2002) and Coakley and Yang (2016). A detailed discussion of radiative transfer for thermal sciences is given by Howell et al. (2016).

For fires, flames and combustion systems radiation is the most dominant mode of heat transfer, as outlined by Coelho in ► Chap. 28, "Radiative Transfer in Combustion Systems." The applications to combustion and industrial systems require the solution of the RTE coupled with the energy equation in complex geometries and with significant variations in temporal and spatial distribution of the properties within the medium and on the surfaces. The properties of combustion gases and particles need to be accounted for spectrally, and they may change as a result of interaction of chemical species–turbulence–radiation within the medium. It is impossible to cover all these complexities here; however, this chapter, coupled with ► Chap. 23, "Radiative Transfer Equation and Solutions" by Zhao and Liu, provides fundamental ideas and detailed references for further discussion.

Understanding the details of radiation transfer mechanism is required to tailor a furnace or combustion chamber to perform under optimum conditions. For this, an inverse solution of the RTE can be employed to design an enclosure. The problem is not straightforward, but *ill-conditioned* (i.e., it may have more than one optimum solution), given that the problem is mathematically very challenging and very important. In ► Chap. 30, "Inverse Problems in Radiative Transfer," Daun outlines inverse problems in depth. He first discusses the inverse design criteria and then follows up with inverse parameter estimation problems for the determination of radiative properties in carefully conducted experiments.

6 Near-Field Radiative Transfer

Radiative transfer takes place between any two objects at different temperatures, regardless of the distance and the medium between them. As discussed above, the Planck law can predict the spectral emission from a surface at a given temperature. The solution of the RTE can be obtained following many available approaches. Examples are given in ▶ Chap. 23, "Radiative Transfer Equation and Solutions" by Zhao and Liu and ▶ 29, "Monte Carlo Methods for Radiative Transfer" by Erturk and Howell, as well as in texts by Modest (2013) and Howell et al. (2016).

If the objects are very close to each other, with distances below the characteristic wavelength (as determined from the Wien law given by Eq. 4), then an additional energy transfer mechanism takes place as a result of the coupled lattice and electron vibrations from two adjacent objects. This stems from the electromagnetic modes caused by evanescent waves generated by total internal reflection and surface polaritons, in addition to the emission by any heat source and manifested as propagating modes (Polder and Van Hove 1971; Chen 2005; Zhang 2007; Basu 2016). The thermal aspect of excitation of optical resonances, or polaritons, and the evanescent wave coupling is what we call Near-Field Radiative Transfer (NFRT). NFRT can be explained within the framework of fluctuational electrodynamics, starting with analysis of Maxwell's equations and the fluctuating current sources representing thermal emission (Rytov 1953; Rytov et al. 1989). Under these conditions, radiative heat transfer may exceed the blackbody limit between two bulk materials. Emission and tunneling of evanescent modes, volumetric thermal emission, and coherence effects of the NFRT based on fluctuational electrodynamics were outlined first by Rytov (Rytov 1953), (Rytov et al. 1989). In ▶ Chap. 24, "Near-Field Thermal Radiation," Francoeur discusses these concepts and the theories for predicting NFRT between close bodies.

Understanding the NRFT between close structures has matured in parallel with advances in nanoscale measurement and manufacturing techniques. These developments contributed to the materials revolution of the twenty-first century. With these advances, engineering design of tools and processes can now be enhanced with the design of materials used for these purposes. In that sense, the design of radiative and optical properties of surfaces has also become a reality. Zhao and Zhang outline these studies as related to radiation transfer in ▶ Chap. 25, "Design of Optical and Radiative Properties of Surfaces." The chapter summarizes how micro/nanostructured surfaces can interact with EM waves by excitation of optical resonances (polaritons) that can modify the polarization-dependent directional and spectral radiative properties. In addition, recent computational advances allow the consideration of different shapes and structures of nano-particles and nano-inclusions on or within the medium, and provide a predictive capability for the spectral optical properties of advanced functional surfaces (Didari and Mengüç 2017). These developments are crucial for the future design of energy harvesting systems, advanced photodetectors, large-scale and local thermal management solutions, and high-resolution thermal sensing.

7 Remarks

The radiative transfer section of this handbook describes state-of-the art developments in radiative transfer in thermal systems. The present chapter is an introduction to the concepts discussed in subsequent chapters, providing a coherent framework for the reader. Specific discussions to guide the reader to new ideas and applications are available in ► Chaps. 23, "Radiative Transfer Equation and Solutions" by Zhao and Liu, ► 27, "Radiative Properties of Particles" by Vaillon, ► 26, "Radiative Properties of Gases" by Solovjov et al., ► 29, "Monte Carlo Methods for Radiative Transfer" by Erturk and Howell, ► 28, "Radiative Transfer in Combustion Systems" by Coelho, ► 30, "Inverse Problems in Radiative Transfer" by Daun, ► 24, "Near-Field Thermal Radiation" by Francoeur, and ► 25, "Design of Optical and Radiative Properties of Surfaces" by Zhao and Zhang. These developments are crucial for the future design of combustion systems; manufacturing processes for glass, steel, and aluminum; solar energy harvesting systems; advanced heating and cooling devices; large-scale and local thermal management solutions; and high-resolution thermal diagnostic and sensing applications, among others. The discussion of these concepts is obviously extensive and cannot be exhausted in finite number of pages. The coverage here and the following chapters simply provide a starting point for any research or application related to radiative heat transfer.

8 Cross-References

► Design of Optical and Radiative Properties of Surfaces
► Inverse Problems in Radiative Transfer
► Monte Carlo Methods for Radiative Transfer
► Near-Field Thermal Radiation
► Radiative Properties of Gases
► Radiative Properties of Particles
► Radiative Transfer Equation and Solutions
► Radiative Transfer in Combustion Systems

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