Lecture 40: Introduction, absorbtion techniques

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Introduction

This module briefly introduces a few optical methods that are based on the scattering phenomenon. In optical techniques related to interferometry, schlieren, and shadowgraph, the medium under question was taken to be transparent. In contrast, scattering is concerned with the interaction of light (in general, radiation) with matter. Methods such as infrared thermography rely on thermally stimulated emissions from the surface and do not need a separate radiation source. Methods of interest to the present discussion employ an external light source such as a laser and track changes in the optical properties of light after scattering; for a review see Tropea (2011) (included in this module as review article on light scattering, 2011).

Consider a light beam of wavelength λ falling on a particle of size dp, its characteristic dimension. The scattered energy will show changes with respect to intensity, directionality, wavelength, phase, and other properties of the wave. The property that shows the most pronounced change depends on the ratio of the wavelength λ and the particle diameter dp. Broadly speaking, we have the following limits:

Ray optics :

$$\frac{\lambda}{d_p} \ll 1$$

Wave optics:

$$\frac{\lambda}{d_p} \sim 1$$

Quantum optics:

$$\frac{\lambda}{d_p} \gg 1$$

Ray optics (also called geometric optics) is the applicable limit when the particle size is much greater than the wavelength of the incident radiation. The particle may be opaque and simply block the passage of light, casting a dark shadow. An example already studied in the context of velocity measurement (module 3) is particle image velocimetry where the particle is transparent and glows when illuminated by a sheet of light. The wave nature of light is revealed when the particle size matches that of wavelength. An example would be laser Doppler velocimetry where the frequency of light is altered by the speed of the particle. A second example is liquid crystal thermography where the color of radiation is selectively enhanced depending on the spacing between atomic layers in a liquid crystal material (module 6). Quantum optics refers to wave-particle interactions that alter the electronic states in the material, thus inducing emissions of its own. Such trends are obtained when the wavelength of light is large when compared to the particle size. It is to be understood that all three effects are jointly present in any application. For example, very small particles in PIV may show light intensity variations as a function of angle with respect to the incident, mainly because of interference effects. The phenomenon that is highlighted in a given measurement, thus, depends of the wavelength-particle size ratio. A second aspect of scattering techniques is the reduction in signal strength as one progresses from geometric to wave and finally to quantum optics. Accordingly, one can expect a considerable increase in the cost of the instrumentation in this sequence that demands extremely high laser power for quantum measurements to capture mild emission signals. The present chapter is intended to give a short introduction to wave and quantum optics from a measurement perspective.

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Classification

Optical techniques can be classified as linear or nonlinear, depending on the relationship between an attribute of the optical signal generated and the flow property to be measured. For example, LDV is a linear device since the Doppler shift in frequency scales linearly with the fluid velocity. Interferometry is a linear instrument since the fringe shift scales with temperature difference. In the presence of refraction errors, linearity is lost since nonlinear effects related to light refraction should be accounted for. As shown in module 4, these nonlinearities, to a first approximation, are quadratic with respect to temperature. Similarly, schlieren and shadowgraph are linear devices since, under some approximations, the change in intensity scales with temperature or its derivatives (modules 4 and 5). This reasoning holds even when temperature derivatives or its Laplacian is involved. Spatial derivatives can be resolved by integration with respect to the spatial coordinate and the linearity in the relationship between temperature and change in intensity is recovered. PIV can be considered a linear measurement technique for fluid velocity if it viewed as tool for measurement of the particle displacement. Methods such as tomography for three dimensional reconstruction of the temperature field can also be viewed as linear devices since the extraction of data is in space and mathematical operations are temperature independent.

Nonlinear measurements were encountered in liquid crystal thermography where the temperature-color (equivalently, temperature-hue) information had to be generated from a calibration experiment. As discussed in the following sections, scattering techniques are invariably nonlinear and the relationship can be established, generally, from first principles.

Scattering techniques are classified as elastic or inelastic depending on the changes taking place in the wavelength of the photon leaving the particle with respect to that incident. Mie and Rayleigh are examples of elastic scattering. Invariably, inelastic scattering is the norm and the majority of techniques such as Raman, Bragg, Compton, and Brillouin are inelastic. Fluorescence is inelastic since the emitted wavelength is material-specific. Methods that rely on absorption in a material medium can be seen as special cases of scattering techniques. Since the absorption coefficient is wavelength-dependent, the outgoing radiation is spectrally distorted with respect to the incoming and the method classifies as inelastic.

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Classification (contd...)

The variation of the radiation intensity after scattering as a function of the particle diameter-to-wavelength ratio is shown schematically in Figure 7.1. The regimes of geometric, wave, and quantum optics are highlighted. It is intrinsically true that signal strengths in the quantum domain are weaker than in wave domain, that in turn are smaller than in geometric optics. This expectation is borne out in Figure 7.1. Geometric optics has been discussed at length in the module on particle image velocimetry. The present module is focused on wave and quantum domain measurements of flow properties using the scattering phenomenon.

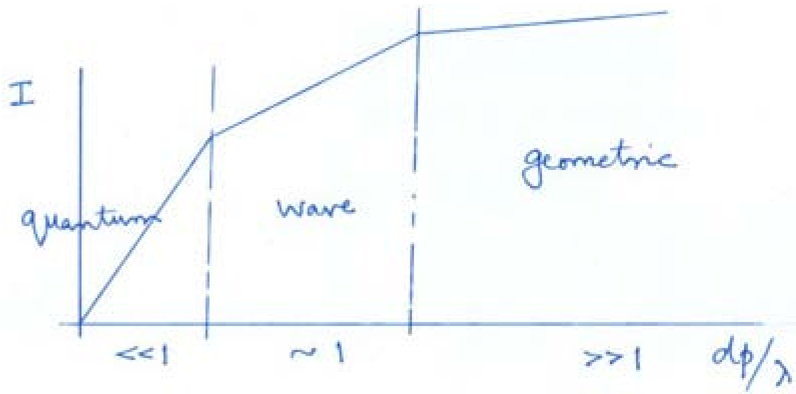

Figure 7.1: Intensity I of the scattered radiation plotted as a function of the particle diameter-to-wavelength dp/λ.. Rayleigh scattering is at the interface between wave and quantum optics at $dp/\lambda = 0.3$. Geometric optics is predominant for the ratio greater than around 25.

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Absorption technique

The special case of absorption, interpreted as a scattering technique is discussed in the present section. Several gases and liquids are practically transparent to visible radiation. The transmittivity is close to unity, the associated absorptivity being close to zero. In the presence of suspended particles, light is scattered and transmittivity is no longer unity. Scattering is generally uniform in all directions, unless the particle is transparent or unsymmetric in shape. In the former, considerable anisotropy is generated by refraction, internal and external, in radiation leaving the particle surface. Scattering redirects energy from a given direction to others. Consequently, energy transmitted in a particular direction is reduced. One can then think of scattering as being equivalent to absorption of energy.

Even in the absence of particles, molecules of a medium – solid, liquid or gas, can scatter radiation at specific wavelengths. Thus, when radiation passes through the physical medium, it is possible that the material shows non-zero absorptivity for certain wavelengths, while being purely transparent to others.

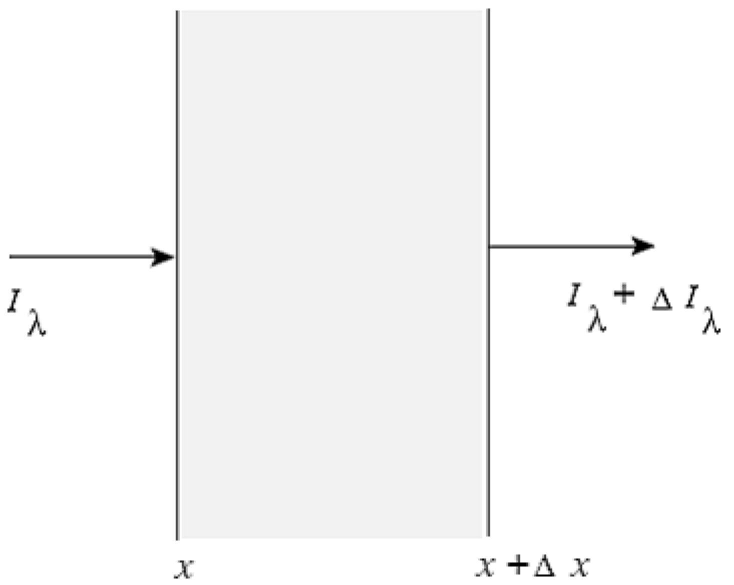

Figure 7.2 Absorption of radiation in a gaseous medium. The incoming energy is denoted as I_λ while changes are calculated over a gas layer thickness of Δx.

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Absorption technique

The process of absorption of energy in a gaseous medium is well-modeled by the expression

$$\frac{I_\lambda}{I_{\lambda,0}} = \exp\{(-K_\lambda x)\} \qquad (7.1)$$

Equation 7.1 is presented in the context of one dimensional radiative heat transfer. Here, I_λ is the intensity of radiation in the direction along the *x*-coordinate and suffix λ indicates dependence on wavelength. Suffix *0* refers to the value of intensity at $x = 0$, namely the initial intensity before radiation enters the region filled with the medium being studied. The parameter K_λ is called *absorption coefficient*; it is dependent on the chemical composition of the material being studied as well as wavelength. Equation 7.1 is called Beer's law. Equation 7.1 shows that the gas has a transmittivity equal to

$$\tau_\lambda = \exp\{(-K_\lambda x)\}$$

Hence, it has an absorptivity that can be calculated as

$$\alpha_\lambda = 1 - \exp\{(-K_\lambda x)\}$$

Total material properties can be determined from the spectral values by suitable integration over the entire range of wavelength $0 - \infty$.

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Absorption technique (contd...)

The basis of absorptivity measurement is the fact that α_λ and τ_λ are unique functions of the material density. In an experiment, quantities I_λ and $I_{\lambda 0}$ are measured and yield the absorption coefficient and hence, the transmittivity and absorptivity of the material of thickness *L* . If the composition of the specimen changes with position, Equation 7.1 shows that a *path integral* of attenuation of the incident radiation is obtained. A linear form of Equation 7.1 useful in measurements is

$$In \frac{I_\lambda(L)}{I_{0,\lambda}} = -\int_0^L K_\lambda(x)dx \qquad (7.2)$$

The integral is resolved by working with an average value over the thickness of the material used as sample. Spectral values of absorption coefficient are converted into total values if the dependence on wavelength is weak or the property is averaged over the spectrum of the incident radiation. Hence, a greatly simplified form of Equation 7.2 for an average absorption coefficient is

$$In \frac{I(L)}{I_0} = \bar{K} \times L \qquad (7.3)$$

If the chemical composition of the medium is known in advance, the absorption properties can be determined from the density of the constituent species and their mass fractions. Thus, differences in the measured values with respect to the estimation will shed light on the microstructural defects in the medium, for example, the presence of voids.

See article 1 and article 2 for an application involving x-ray absorption, tomography, beam hardening, and methods of alleviating inversion errors.

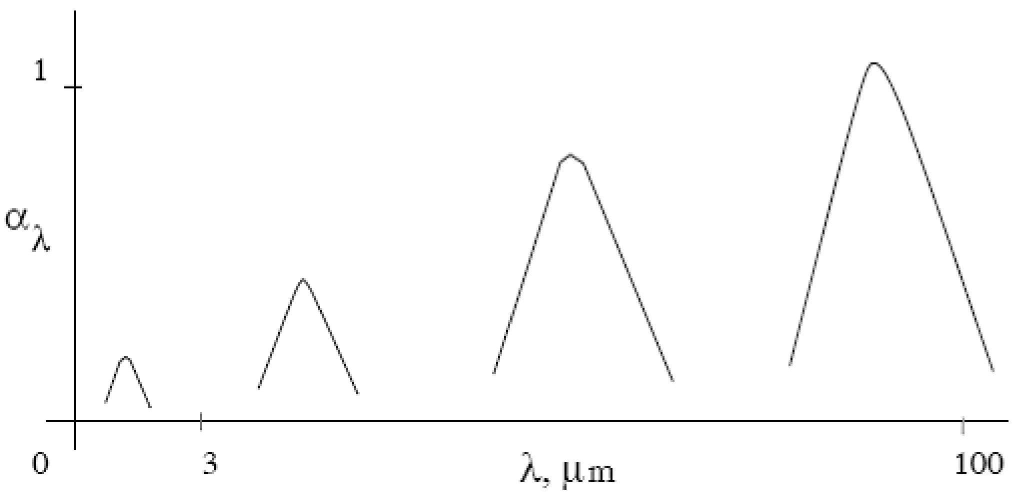

Figure 7.3: Variation of absorptivity of CO_2 in the earth's atmosphere as a function of wavelength.

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Remarks

1. Beer's law (Equation 7.1) can be applied to solid, liquid and gaseous media.
2. Equation 7.1 is equivalent to stating that

$$dI_\lambda = -K_\lambda I_\lambda dx$$

3. In other words, the reduction in radiation intensity is proportional to the intensity at that location and the thickness over which the change is being determined.
4. The process of absorption shows that the equivalent transmittivity decreases with increasing x, Equation 7.2, and hence the thickness of the material. For transmittivities much less than unity $\tau \ll 1$, the layer is said to be *optically thick* . When τ is close to unity, the layer is said to be *optically thin* .
5. A material layer can be optically thick at one wavelength but optically thin at another. For an example, see Figure 7.3.
6. When a material is optically thick, all the radiation leaving a surface is fully absorbed in a region of small thickness.
7. The absorption coefficient K_λ depends on the nature of scattering elements in the gas, chemical composition and concentration of species. In addition, it can depend on pressure and temperature. Beer's law brings out the dependence of light attenuation on distance, but all other contributing factors are lumped into the absorption coefficient.
8. Extensive tabulation of absorption coefficient is available in the literature.
9. In semi-transparent media, the material will exhibit refraction effects (namely, changes in the speed of propagation of light) as well as absorption (attenuation in the energy transmitted). Refractive index jointly with absorption coefficient is then viewed as the real and imaginary parts of a complex property (*complex refractive index*) of wave propagation. The composite property, as expected, scales with material density. While this interpretation of a complex property is required in radiation analysis of energy transfer, it has not been exploited in measurements and is not discussed here.

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