Experimental Fluid Mechanics

Tommaso Astarita
Giovanni Maria Carlomagno

Infrared Thermography for Thermo-Fluid-Dynamics

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To our children
Enrico
Francesca
Giuseppe
Marina

Preface

The Earth's natural energy resources (i.e. essentially the sun and the fossil fuel reserves: oil, coal and natural gas) are limited, which is of concern especially for future generations, as the demand for energy is continuously increasing. Most probably, even if much cheaper and/or safer energy forms (such as for example, nuclear fusion or a significant increase in the use of renewable energy) will become available in the near future, a significant rationalization of the production and use of energy will be unavoidable. This process has—or should have—already started with the Kyoto protocol, which came into force on February 16 2005, with the ambition of not overloading our planet with chemical and thermal pollution.

Energy conversion as well as energy use and energy saving are focussing more and more attention on heat transfer questions and, since heat transfer often involves fluids, thermo-fluid-dynamics represents a fundamental engineering issue to be faced. How can energy be efficiently transferred, in the form of heat, between a body and a fluid?

Computational Thermo-Fluid-Dynamics is of course helpful in answering such a question, even if the acronym CTFD is not frequently seen in the literature. However, in spite of recent advances in numerical techniques, partly due to the enormous increase in the efficiency of computers, the need to perform experiments, especially in complex fluid flows, still exists. In addition, although computer models have been increasingly successful in simulating and solving a wide range of rather intricate thermo-fluid-dynamic problems, it is nevertheless indispensable that their results are experimentally validated.

Naturally, experimental techniques have also undergone enormous development and, amongst these techniques, InfraRed Thermography (IRT) has proved to be a very effective investigative tool for thermo-fluid-dynamic experimental research. One major drawback experienced by the authors over the last two decades, while using this technique (this is particularly true for Astarita but Carlomagno has been working in this field for longer than he cares to admit), was the fact that they had to continuously update their research instrumentation because of the uninterrupted development of infrared cameras. Fortunately, the involved costs decreased almost accordingly.

Infrared thermography is a methodology that allows remote detection of thermal energy that is radiated from objects in one of the InfraRed (IR) bands of the electromagnetic spectrum, conversion of such energy into a video signal, and representation of the surface temperature map (distribution) of an object. In simpler terms, IRT allows one to obtain a temperature map over a body surface.

The method has great potential to be exploited in many application fields and for many different purposes, as long as temperature variations are involved. For example, IRT may be used in various types of diagnosis (in medicine, architecture, maintenance), or for material characterization and assessment of procedures, which can help in improving the design and manufacture of products, as well certain modes of their testing. As technology evolves, infrared systems offer new opportunities for innovative applications. Undoubtedly, any process which is temperature dependent may benefit from the use of an infrared device.

The aim of this monograph is to present an analysis of how to exploit thermographic measurements in complex fluid flows, either to evaluate wall convective heat fluxes, or to investigate flow field behaviour over complicated body shapes in order to better comprehend some peculiar fluid dynamics phenomena, such as flow instability, flow separation and reattachment.

The monograph covers the following important points, which may be of benefit both to newcomers and those already using infrared thermography in convective heat transfer:

1. What is infrared thermography and how did it develop in thermo-fluid-dynamics?
2. What are the very basic principles of radiation heat transfer that make the IR scanner (camera) a temperature transducer?
3. What is the current technology of modern IR cameras?
4. Once a camera has to be acquired, how can one evaluate its performance?
5. How is the calibration of this temperature transducer performed?
6. Since an IR camera is nothing more than a temperature transducer, we provide detail on the heat flux sensors that must accompany it, including their limits in space and time and paying particular attention to their use in infrared thermography.
7. The degradation (modulation) of the thermal image (introduced by the IR imaging system, the heat flux sensor and the environment) is considered and we provide a general analysis of its restoration.
8. We discuss a number of selected applications in several different areas with the principal aim of indicating either how this experimental method progressed or how to apply it correctly.

Of course, some of the points tackled herein are of little use to those who are already involved with infrared thermography. However, these elementary points are included to provide researchers with little experience of IRT enough knowledge to begin using it, and also for the sake of completeness.

The development of ideas and the final achievement of the volume and the thoughts contained therein are due not only to the authors' knowledge but also to helpful insights provided by many others. The observations, criticisms and findings of our Master and PhD students over the past several years contributed to broadening and refining this work; further, they carried out the majority of the experimental work. In addition, the authors are truly grateful to several colleagues for offering data, their valuable comments and intense support. Amongst others, we would especially like to mention Gennaro Cardone, Luigi de Luca and Carosena Meola, whose information, contributions and resources were essential to accomplish the final goal of writing this monograph and to George Powell for copy editing the final version. Finally, the authors are grateful to Wolfgang Merzkirch for the suggestions he made after reading the initial manuscript.

Napoli, February 2012 The authors

Editorial

With the present volume, the monograph series Experimental Fluid Mechanics now comprises 11 volumes. These monographs describe either progress with the application of experimental methods for research in fluid mechanics and convective heat transfer, or they discuss the measurement principles, scientific background and applicability of a particular class of experimental methods. The contributions to this series are authored by scientists that lead in their respective fields, and the volumes of this series have become helpful and practical guides for researchers in the laboratory. Although the series already covers a broad range of topics, we expect new volumes as the field of experimental fluid mechanics continues to develop and expand in scope.

The appearance of the present monograph, the 11th of the series, is motivation for the editors to express their thanks to all authors who contributed to the series and in this way to its success. As the authors of this volume point out, "Infrared thermography for thermo-fluid-dynamics" is of major interest both for fundamental research as well as for applied studies of problems in energy management and environmental research, and the volume addresses technical and social challenges that demand such approaches. The content of the book summarises the many contributions of the life-long research of Professor Giovanni Maria Carlomagno in this field. Over the years, he has established a "school" of graduates, one member being his former student, Professor Tommaso Astarita, who has joined him in writing this monograph. We are convinced that the users of thermography will appreciate the guidance provided by this book and will join us in thanking the authors for their conscientious and comprehensive efforts in compiling the monograph.

February 2012

W. Merzkirch
D. Rockwell
C. Tropea

Contents

Symbols

Acronyms

2D	Two-dimensional
3D	Three-dimensional
AEDC	Arnold Engineering Development Center
AR	Aspect ratio
BO	Bolometric
BR	Blowing ratio
CIRA	Centro Italiano Ricerche Aerospaziali
CMT	Cadmium mercury telluride
DB	Dual-band
DLT	Direct linear transformation
FOV	Field of view
FPA	Focal plane array
HITRAN	HIgh-resolution TRANsmission database
HTF	Heated thin foil
IFOV	Instantaneous field of view
IR	Infrared
IRT	Infrared thermography
LW	Long wave
LWIR	Long wavelength infrared spectral band
MCT	Mercury cadmium telluride
MDTD	Minimum detectable temperature difference
MRTD	Minimum resolvable temperature difference
MS	Mechanical scanning
MTF	Modulation transfer function
MW	Middle wave
MWIR	Middle wavelength infrared spectral band
NASA	National Aeronautics and Space Administration
NEP	Noise equivalent power

NETD	Noise equivalent temperature difference
NIHT	Numerical inverse heat transfer
NUC	Non-uniformity correction
ONERA	Office National d'Etudes et de Recherches Aérospatiales
OTF	Optical transfer function
PC	Photoconductive
PIV	Particle image velocimetry
PSF	Point spread function
PTF	Phase transfer function
PV	Photovoltaic
QWIP	Quantum well infrared photodetector
RTD	Resistance temperature detector
SWBLI	Shock wave/boundary-layer interaction
SWIR	Short wavelength infrared band
TE	Temperature
TF	Thin film
TS	Thin skin
VNIR	Very near infrared band

Roman Letters

a	Constant, Eq. (7.5), Speed of sound
A	Amplitude
b	Coefficients, Eq. (4.40), Linear distortion coefficient
B	Calibration constant of the IR scanner, Eq. (3.12)
c	Sensor specific heat capacity, Speed of propagation of electromagnetic wave
C	Heat capacity
c_o	Speed of propagation of electromagnetic wave in vacuum
C_1	First radiation constant, Eq. (2.4)
C_2	Second radiation constant, Eq. (2.4)
c_p	Fluid specific heat capacity at constant pressure
C_T	Thermal contrast
d	Degraded thermal image, Distance from the leading edge
D	Fourier transform of the degraded thermal image, Hydraulic diameter, Nozzle diameter
D^*	Normalized detectivity
D_a	Lens aperture
D_{Airy}	Diffraction diameter
e	Photon energy, Rib height
E	Emissive power
E_g	Energy gap

f	Fractional emissive power function, Eq. (2.9), Function used in Eq. (5.16), Lens focal length
F	Calibration constant of the IR scanner, Eq. (3.12), Temperature modulation transfer function
$f_\#$	Focal ratio (also normally called f number)
F_c	Mapping function for the optical calibration
F_D	Non-linear distortion function
g	Joule energy rate per unit volume
G	Thermal conductance
h	Convective heat transfer coefficient
H	DLT matrix, Height
$\hbar$	Planck's constant
h_r	Radiative heat transfer coefficient
I	Integral
k	Radial distortion coefficient, Sensor thermal conductivity coefficient
$\not{k}$	Boltzmann's constant
$\underline{\underline{K}}$	Thermal conductivity tensor
k_f	Fluid thermal conductivity coefficient
L	Length
M	Mach number, Optical magnification
n	Noise function, Refractive index (or index of refraction), Total number of measurement points
N	Fourier transform of the noise function
o	Original thermal image
O	Fourier transform of the original thermal image
p	Constant in Eq. (4.18) to determine the maximum measurement time, Tangential distortion coefficient
P	Pitch
q	Heat flux
Q_T	Quality factor
r	Radial coordinate
R	Calibration constant of the IR scanner, Eq. (3.12), Fourier transform of the restoration function
$\underline{\underline{R}}$	Rotation matrix
r_e	Electrical resistivity
s	Sensor thickness
S	Detector surface area
$(sk)_e$	Equivalent thermal conductance per unit length
S_x	Pixel width
S_y	Pixel height
t	Time
t_m	Measurement time interval for the thin film sensor
T	Temperature
$\underline{T}$	Translation vector
U	Output signal from the IR scanner

V	Fluid velocity
w	Homogenous coordinate, Width
x	Spatial coordinate
X	Image coordinate
y	Spatial coordinate
Y	Image coordinate
z	Nozzle-to-plate-distance, Spatial coordinate

Greek Letters

α	Sensor thermal diffusivity coefficient, Angle of attack
α_f	Fluid thermal diffusivity coefficient
α_r	Absorptivity coefficient
β	$h\sqrt{t/\rho ck}$, Fluid thermal expansion coefficient
γ	Parameter in Eq. (4.20)
γ^*	Width parameter
δ	Angle, Rib Angle
Δf	Equivalent noise bandwidth
Δt	Time interval
ε	Emissivity coefficient
ζ	Local variable, Eq. (2.10)
η	$\sqrt{\omega/2\alpha}$
ϑ	Angle between normal to surface and emitted radiation
θ	$(T_w\text{-}T_{wi})/(T_r\text{-}T_{wi})$
Θ	Temperature ratio, Eq. (4.29)
κ	Extinction coefficient
λ	Wavelength of the electromagnetic wave
λ_o	Wavelength above which no transition occurs
λ_{max}	Wavelength of maximum spectral emissive power
ν	Fluid kinematic viscosity coefficient, Frequency of the electromagnetic wave
ξ	$x/\sqrt{4\alpha t}$
Ξ	Equivalent conductance ratio, Eq. (5.14), Temperature ratio, Eq. (4.21)
Π	Temperature derivative ratio, Eq. (4.30), Thermal conductance ratio $(sk)_c/(sk)_f$
ρ	Sensor mass density
ρ_f	Fluid mass density
ρ_r	Reflectivity coefficient
ς	Spectral absorption coefficient
σ	Stefan-Boltzmann constant
τ	Response time, Shear stress at the wall
τ_r	Transmissivity coefficient
Φ	Parameter defined in Eq. (7.7)

φ	T_w-T_{wi}
χ	Phase angle
ω	Angular frequency, Angular speed
ϖ	Spatial frequency, Wave number

Subscripts

∞	Infinite
1	Back surface
a	Ambient environment
atm	Atmospheric
b	Black body
c	Convective, Copper, Referred to lens reference system
d	Distorted
de	Thermal detector
el	Electronics
f	Fibreglass, Fluid
hs	Heat flux sensor
i	Initial
is	Infrared scanner
j	Jet, Joule heating
k	Conductive
m	Main, Mean, Measured, Measurement
n	Normal
o	Disk centre
obj	Object
op	Optics
q	Relative to the heat flux
r	Radiative, Reference
s	Secondary, Slab
t	Total
T	Temperature
tf	Thin film
ts	Thin skin
u	Undistorted
w	Front surface, Wall
x	Along the x-direction
y	Along the y-direction
ϑ	Directional
λ	Spectral

Dimensionless groups

Bi	Biot number, hs/k
C_f	Wall friction coefficient, $2\tau\ /\rho\ V^2$
Fo	Fourier number, $\alpha\ t/s^2$
M	Mach number, V/a
Nu	Nusselt number, hD/k_f
Pr	Prandtl number, $c_p\mu\ /k_f$
Ra	Rayleigh number, $g\beta L^4 q_c/\nu\alpha_f\ k_f$
Re	Reynolds number, VL/ν
r_f	Recovery factor, Eq. (7.3)
Ro	Rotational number, $\omega\ D/V$
St	Stanton number, $h/(\rho_f\ c_pV)$
η	Adiabatic film cooling effectiveness, Eq. (7.1)

1 Introduction and historical grounding

1.1 Introduction

The main purpose of this book is to examine ways of taking advantage of InfraRed Thermography (IRT) either for measuring wall convective heat fluxes, or for investigating flow field behaviour over complex body shapes. This is to better and quickly recognize as well as understand particular fluid dynamic behaviours, such as flow instabilities, flow separations and reattachments.

Naturally, between the two above-mentioned goals the most difficult to achieve is the first one since it requires a quantitative evaluation of the heat fluxes, while flow field characterization (even if connected to heat flux measurements) has a more qualitative nature.

Measuring heat fluxes in thermo-fluid-dynamics requires both a *thermal sensor* (which is herein called a *heat flux sensor*), with its related physical model, and one or more *temperature transducers*.

In more conventional techniques where the temperature is measured with standard transducers (e.g. thermocouples, resistance temperature detectors (RTDs), pyrometers, etc.), each transducer yields either the temperature at a single point or, better, a space-averaged one; hence, in terms of spatial resolution, the sensor itself has to be considered as *zero-dimensional*. This constraint makes measurements essentially meaningless whenever the temperature and/or the heat flux fields exhibit high spatial variations.

Instead, the *infrared* (IR) *camera*, also called *infrared scanner*, constitutes a truly *two-dimensional* temperature transducer since it allows accurate measurements of surface temperature maps even in the presence of relatively high spatial gradients. Accordingly, also the heat flux sensor becomes two-dimensional, as long as one performs the likely necessary corrections.

When compared to standard techniques, the use of an infrared camera as a temperature transducer in convective heat transfer measurements appears advantageous from several points of view.

In fact, since the IR camera is fully two-dimensional (today up to more than 1M pixels per frame), besides producing a whole temperature map, it allows for an easier evaluation of errors due to radiation and tangential conduction (see section 5.2). Furthermore, the camera is non-intrusive (i.e. it does not disturb the measuring process and, e.g. allows one to get rid of conduction errors due to thermocouple or RTD wires), it has *high sensitivity* (down to $10mK$) and *low response time* (down to $20\mu s$). As such, IR thermography can be effectively

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exploited to measure convective heat fluxes, with either steady or transient techniques, and/or to perform detailed thermal surface flow visualizations.

1.2 Historical grounding

The origin of infrared thermography dates back to the year 1800 when the English physicist William Herschel (1800) discovered the so-called *thermal radiation*, outside the deep red in the visible spectrum, the invisible light later called *infrared*. In the succeeding years, many physicists, amongst them Macedonio Melloni, Gustav Kirchhoff, Clark Maxwell, Joseph Stefan, Ludwig Boltzmann and Max Planck, addressed the problem of fully understanding the properties and energy distribution of the wide spectrum of radiation.

The first infrared cameras were developed in the 1960s as offshoots of military programs but without significant accuracy features, not mandatory for the perceived existing needs.

The energy crisis of the 1970s brought government support in Sweden and so AGA and Bofors, both Swedish companies, developed the first radiometric thermal imagers. These cameras used a single detector, the two-dimensionality of the image being achieved by rotating, or oscillating, mirrors and/or refractive elements (such as prisms) which optomechanically scanned the whole *field of view* (FOV) in both the vertical and horizontal directions (see sub-section 3.1.2). In fact, they were also called *infrared scanning radiometers*.

The infrared detector employed in these radiometers was the photon type (see sub-section 3.2.2), where the release of electrons is directly associated with photon absorption, its main features being a quite short response time and a limited spectral response. However, such a detector required cooling, well below ambient environment temperature, to allow for rapid scanning, high sensitivity and low noise. In fact, the sensor was often located in the wall of a Dewar vessel filled with liquid nitrogen (at $77K$, see Fig. 3.6). Subsequent scanning radiometers used various types of cooled photon detectors, with lower time constants, allowing frame rates of $15 \div 30Hz$ and improved sensitivity.

All real-time commercial cameras used single cooled photon detectors with optomechanical scanning well into the 1980s, at which point infrared (*staring*) *Focal Plane Array* (FPA) detectors, having time constants enabling $30 \div 60Hz$ frame rates, were introduced. By using these staring arrays, the infrared camera, long restricted to a point-sensing detector, became an effective two-dimensional transducer.

Infrared cameras based on non-cooled FPA thermal detectors (such as microbolometers, see sub-section 3.2.1) emerged in the mid-1990s and led to the development and diffusion of thermal imagers requiring no cooling.

The earliest attempts to measure convective heat transfer coefficients originated in the hypersonic regime and were performed by using scanners operating in the middle IR band ($3 \div 6\mu m$) of the infrared spectrum, at that time called the *short* *wave* IR band and now named the *middle wavelength infrared* band (MWIR). In particular, the AGA Thermovision 680SWB camera was employed by Thomann and Frisk (1967) to measure temperature distributions over the surface of an elastomeric paraboloid in a hypersonic wind tunnel at Mach number $M = 7$. The unsteady thin film sensor (see section 4.2) was used to determine convective heat transfer coefficients, which showed a good agreement with data already obtained with different techniques and was encouraging in view of using infrared systems for heat flux measurements.

Once the method had been shown to work effectively, efforts were mainly oriented towards the comprehension of potential error sources, which could affect measurement accuracy, and especially towards the development of devices that could facilitate the use of the IR camera.

Compton (1972), at NASA Ames, realized that the bottleneck of IR thermography was data acquisition, storage and processing. In fact, each heat flux map had to be computed on a pixel-by-pixel basis from temperature readings, which, at the time, were generated at rates of about 88,000 data points per second. The solution was devised in the automation of data processing and the development of this concept finally brought to the systems currently in use.

In 1976, the Arnold Engineering Development Center (AEDC) was embarked on a large-scale research program to develop IR cameras with capability to perform extensive heat transfer testing in the hypersonic regime (Bynum et al., 1976). In particular, the von Karman facility was dedicated to hosting an infrared imaging system for test series that extended over a long period. To assess the usefulness of the method, calibration procedures and a measurement error model were developed, while in addition further automated data processing was implemented (Noble and Boylan, 1978). The camera displayed a blur effect at high temperature gradients, not completely understood at the time, which presently is ascribed to the concurrent low scanner spatial resolution.

Meanwhile, the infrastructure and expertise developed at AEDC were used to measure convective heating rates on a Space Shuttle model, under flow conditions prevailing in the re-entry phase, to aid in the design of the orbiter's thermal protection system (Stalling and Carver, 1978).

All the previously mentioned experiments were generally carried out by applying the infrared camera to the thin film sensor, but this was not feasible at very high Mach number values, under rarefied flow conditions, because of resultant low heat flux values. Some years later, Allegre et al. (1988) used the thin skin sensor (see section 4.3) to overcome this drawback.

Apart from heat flux evaluation, the characterization of flow field behaviour, with location of boundary layer transition to turbulence, as well as of separation and reattachment zones, constituted a subject of great interest to aerodynamicists and efforts were devoted to acquiring information on the infrared camera capability required to deal with these phenomena.

In fact, IR thermography allows evaluation of the laminarity of the airflow over a wing profile both in laboratory tests (see section 7.4) as well as during flight (Brandon et al., 1990).

To look for transition to turbulence, the boundary layer over a flat plate was examined by Peake et al. (1977) who carried out measurements on a stainless steel plate with a Bakelite (low thermal inertia material) insert. In the thermograms, they observed a hot front to be attributed to the different adiabatic wall temperatures (see chapter 4), which occur among laminar and turbulent flows, and were able to detect the location of the transition.

Solicited by the late professor Wen-Jei Yang of Ann Arbour, Carlomagno and de Luca (1989) developed a first comprehensive analysis of convective heat transfer measurements with IR thermography and reviewed a circumscribed number of applications. Three years later, Gartenberg and Roberts (1992a) reported an extensive retrospective on aerodynamic research with infrared cameras. In 2001, Carlomagno and de Luca produced an updated version of their 1989 paper.

More recently, Carlomagno and Cardone (2010) presented a detailed review on infrared thermography for convective heat transfer measurements, in which they considered some of the topics examined in greater detail, along with other relevant subjects, in this monograph.

2 Physical background

In this chapter, first the basic radiation heat transfer theory of a black body is analysed from the user point of view (readers interested in a more rigorous analysis may refer to more specialized books, e.g. Siegel and Howell, 1992). Then, some specific information on the behaviour of real bodies is given including a differentiation between dielectric and electrically conducting materials. Finally, a brief description of the atmospheric absorption of radiation is presented.

2.1 Basic radiation heat transfer theory

Heat transfer by *radiation* (or *radiative heat transfer*) is an energy transport mechanism that occurs by means of electromagnetic waves. Atoms and molecules constituting a body contain charged particles (protons and electrons) and their movement results in the emission of electromagnetic radiation, which carries energy away from the body surface.

Contrary to the case of heat conduction (and consequently convection), energy can be transmitted by thermal radiation also in the absence of a medium and, therefore, radiation is the only mechanism that enables the exchange of energy between two unconnected bodies placed in a vacuum.

If a medium is present in between the two exchanging bodies, the transferred energy may be partially or completely absorbed and/or reflected, or may even pass through the medium without downgrading. In the latter case, the medium is called *fully transparent* and this practically enables an IR scanner to *view* the temperature of a body without touching it. A medium can also be *partially transparent*, i.e. if it allows only a fraction of the transmitted energy to pass through.

Thermal radiation can originate from a solid, a liquid or even a gas since all materials at a temperature above absolute zero emit energy by means of electromagnetic waves. At the same time, all materials also absorb electromagnetic waves; both emission and absorption behaviours are possible because materials change their internal energy state at a molecular level.

The amount of thermal radiation which is absorbed or emitted, as well as its propagation, depend not only on the nature of the material and surface finish but also on its thermodynamic state and on the specific wavelength of the considered electromagnetic wave.

The wavelength λ $[m]$ is linked to the frequency of the wave ν $[s^{-1}]$ by the wave speed of propagation (speed of light) c $[m/s]$ in the material (medium):

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$$\lambda = \frac{c}{\nu} \tag{2.1}$$

The speed of propagation in a generic medium is related to the propagation speed in vacuum c_o ($2.998 \times 10^8 m/s$, independent of λ) by the relationship:

$$c = \frac{c_o}{n} \tag{2.2}$$

where n is the dimensionless *index of refraction* (or *refractive index*) of the medium, which generally depends also on the wavelength.

While both c and λ depend on the nature of the medium through which the wave travels and its thermodynamic state, ν is a constant dependent only on the source of the electromagnetic wave.

A different approach based on quantum theory, where the radiation is seen as a collection of discrete particles termed *photons* or *quanta*, is quite useful. In this approach, each photon is considered to have an energy e $[J]$ given by:

$$e = \hbar\nu = \frac{\hbar c}{\lambda} \tag{2.3}$$

where $\hbar = 6.626 \times 10^{-34} Js$ is named *Planck's constant.*

From the previous equation, it is clear that, while both c and λ depend on the medium through which the wave travels, ν is constant because the energy of the photon must be conserved.

The entire electromagnetic spectrum is quite roughly divided into a number of wavelength intervals, called *spectral bands* or more simply *bands*, and extends from very small wavelength values ($\lambda \to 0$) to extremely large ones ($\lambda \to \infty$).

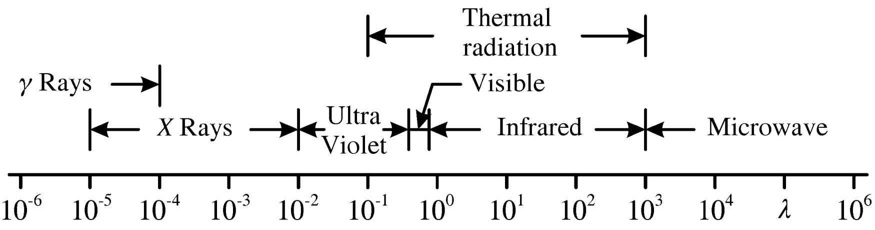

Fig. 2.1 - Electromagnetic spectrum (wavelength λ in micrometres).

On inspection of the relevant portion of the electromagnetic spectrum shown in Fig. 2.1, the *thermal radiation* band is conventionally defined as a relatively small fraction of the complete spectrum, positioned between $0.1\mu m$ and $1000\mu m$, which includes part of the ultraviolet and all of the visible and IR bands.

In particular, when a body is at ambient temperature most of the energy is radiated in the infrared spectral band. This band is generally sub-divided into four