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1

Introduction and Preliminaries

> After countless metamorphoses (i.e., conversions) all energy, unless it is stored (i.e., converted to other than thermal energy), eventually turns into heat and adds its share to the thermal budget.
>
> – H.C. von Baeyer

In this introductory chapter, we discuss some of the reasons for the study of heat transfer (applications and history), introduce the units used in heat transfer analysis, and give definitions for the thermal systems. Then we discuss the heat flux vector $\mathbf{q}$, the heat transfer medium, the equation of conservation of energy (with a reformulation that places $\mathbf{q}$ as the central focus), and the equations for conservation of mass, species, and other conserved quantities. Finally we discuss the scope of the book, i.e., an outline of the principles of heat transfer, and give a description of the following chapters and their relations. Chart 1.1 gives the outline for this chapter. This introductory chapter is partly descriptive (as compared to quantitative) in order to depict the broad scope of heat transfer applications and analyses.

1.1 Applications and History

Heat transfer is the transport of thermal energy driven by thermal nonequilibrium within a medium or among neighboring media. As an academic discipline, it is part of the more general area of thermal science and engineering. In a broad sense, thermal science and engineering deals with a combination of thermal science, mechanics, and thermal engineering analysis and design. This is depicted in Chart 1.2. In turn, thermal science includes thermal physics, thermal chemistry, and thermal biology. Thermal physics encompasses the thermodynamics (interplay between energy and work) and the physics of thermal energy transport and thermal energy conversion mechanisms and properties (i.e., physics of heat transfer). The thermal energy transport mechanism is by fluid particles, solid crystal quantized lattice vibration (referred to as phonon transport), mobile electrons (and ions), and emission and absorption of photons. The physics of thermal energy conversion covers a large number of phenomena. In an electromagnetic thermal energy conversion, such as microwave heating, the molecules absorb the electromagnetic energy and convert it into internal

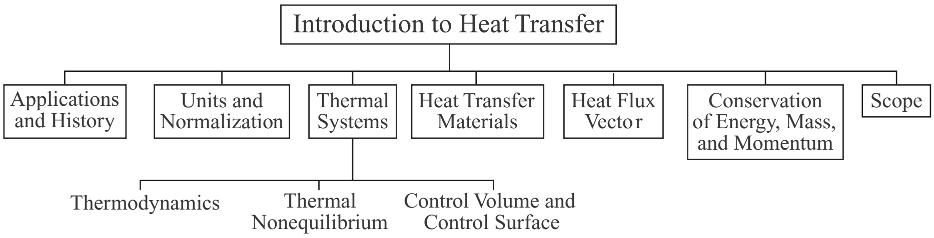

Chart 1.1. A summary of the topics presented in Chapter 1.

energy storage. The storage of thermal energy is by molecular translation, vibration, and rotation, and by change in the electronic or intermolecular bond energy. Thermal chemistry addresses the changes in the chemical and physical bonds caused by, or affecting, a change in the temperature (such as the exothermic, self-sustained chemical reaction of combustion). Thermal biology deals with the temperature control and thermal behavior of biological systems (e.g., plants, animals, or their organs) and subsystems (e.g., cells). In a broad coverage, nearly all aspects of thermal science and engineering are encountered in the heat transfer analyses.

The mechanics addresses force-displacement-motion and includes thermal strain and stress in solids and thermobuoyant motion in fluids.

The thermal engineering analysis and design includes representation of heat transfer on the energy conservation by use of thermal circuit models, use of analytical and numerical methods in solving the energy conservation equation, and optimization.

In this section, a further description of this field, along with its applications and history, is given.

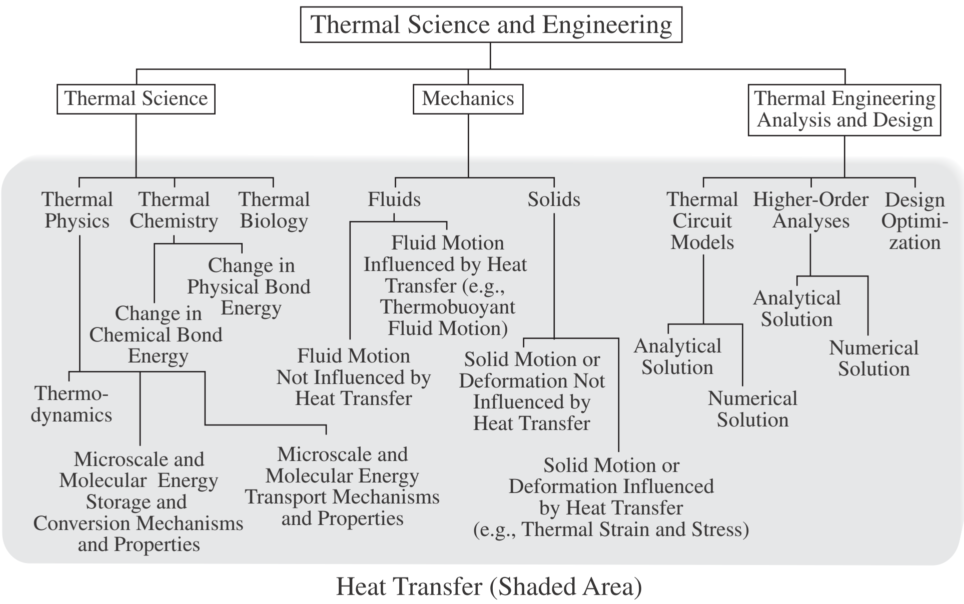

Chart 1.2. A general definition of thermal science and engineering and the disciplines encountered in the heat transfer analyses.

1.1.1 Heat Transfer

(A) Thermal Energy Transport, Storage, and Conversion

Heat transfer is the study of thermal energy transport within a medium or among neighboring media by molecular interaction (conduction), fluid motion (convection), and electromagnetic waves (radiation), resulting from a spatial variation in temperature. This variation in temperature is governed by the principle of energy conservation, which when applied to a control volume or a control mass (i.e., a control system), states that the sum of the flow of energy and heat across the system, the work done on the system, and the energy stored and converted within the system, is zero.

(B) Heat Transfer Medium: Single- and Multiphase Systems

A heat transfer medium may be a single-phase medium such as gas, liquid, or solid. The medium may be multiphase, such as a brick which has about 20 percent volume void space which is filled by air. So the brick is a solid-gas, two-phase medium.

Another two-phase medium is the water-crushed ice mixture where under gravity, the suspended-ice particles (i.e., the solid phase) move until they reach a mechanical equilibrium. Note that in this water-ice system, a pure-substance, liquid-solid phase change (a change in the physical bond) can occur.

When heat flows into a medium, it may cause (at elevated temperatures) a chemical reaction, such as when a polymeric (e.g., polyurethane) foam, used for insulation, is heated to above 200°C. At this temperature, this heat transfer medium is not chemically inert and in this case a thermochemical degradation (manifested by charring) occurs.

Another example of a multiphase system is the heat exchanger, in which heat transfer within and across the boundaries of two or more media occurs simultaneously (i.e., thermal nonequilibrium exists among them).

(C) Thermal Equilibrium Versus Nonequilibrium

In the water-ice example, consider that before adding the ice to water, the water is in a cup and in thermal equilibrium with the ambient air (room temperature, generally assumed 20°C). Then after mixing, heat transfer occurs between the water and ice because of the difference in their temperature. After some elapsed time, exchange of heat, and some melting, the heat transfer between the water and ice becomes less significant than that between the combined cup-water-ice system and the ambient air. Here we may assume that after the first regime, where the water-ice thermal nonequilibrium was dominant, a second regime arrives, where we may assume a thermal equilibrium within the cup-water-ice system and a thermal nonequilibrium between these and the ambient air.

The length scale over which the thermal nonequilibrium is considered can be as small as that between electrons and their lattice nucleus, as is the case in very rapid laser heating of surfaces. Such small-scale thermal nonequilibria are generally transient and short lived. The length scale can also be large, such as in radiation heating of the earth by the sun. These large-scale thermal nonequilibria are generally considered steady state.

As part of the engineering analysis, depending on the regime of interest, justifiable assumptions and approximations need to be made in order to reduce the problem to a level which can be solved with a reasonable effort. In heat transfer analysis, establishment of the dominant thermal nonequilibria is the primary step.

(D) Theory, Empiricism, Semi-Empiricism, and Modeling

The analysis of heat transfer is based on the principles of thermodynamics (for describing the physical and chemical states and the conservation of energy), the physics of heat conduction, fluid motion (for convection), and electromagnetic fields (for radiation), and the physics of thermal energy conversion. The mathematical analyses of such phenomena are established and continue to be developed. However, for simplicity and ease of use, semi-empirical or empirical relations are also used. This blend of fundamentals and semi-empiricism allows for the engineering analysis of some very complex and yet often encountered systems. Thermal circuit models allow for the reduction of problems involving multiple media and multiple heat transfer mechanisms to readily interpretable and solvable relations.

1.1.2 Applications

Heat transfer occurs in natural and engineered systems and over a very large range of temperature T, length L, time t, and mass m, scales. These scales and systems are briefly discussed below.

(A) Temperature, Length, Time, and Mass Scales

In order to allow for a broad introduction to the range of phenomena and scales involved in heat transfer applications, Figure 1.1 gives examples of the temperature T [Figure 1.1(a)], length L [Figure 1.1(a)], time t [Figure 1.1(b)], and mass M [Figure 1.1(b)] scales that are encountered.

At the temperature of absolute zero, the entropy may become zero (as in a perfect crystalline structure), i.e., the highest structural order. The lowest temperature possible is $T = 0$ K (or $T = -273.15°$C), the absolute zero in Kelvin scale. Helium has the lowest boiling temperature ($T = 4.216$ K) among the elements and compounds. The absolute zero is not expected to be reached, but very low temperatures, of the order of $T = 10^{-3}$ K, are achieved by the dilution refrigeration technique [1,25]. Yet lower temperatures, of the order $T = 10^{-5}$ K, are achieved by the adiabatic demagnetization technique. In this method, a paramagnetic salt is first exposed to a magnetic field, thus causing a molecular order. When the magnetic field is removed, this causes a disorder and heat is absorbed (while the paramagnetic salt is at a very low temperature).

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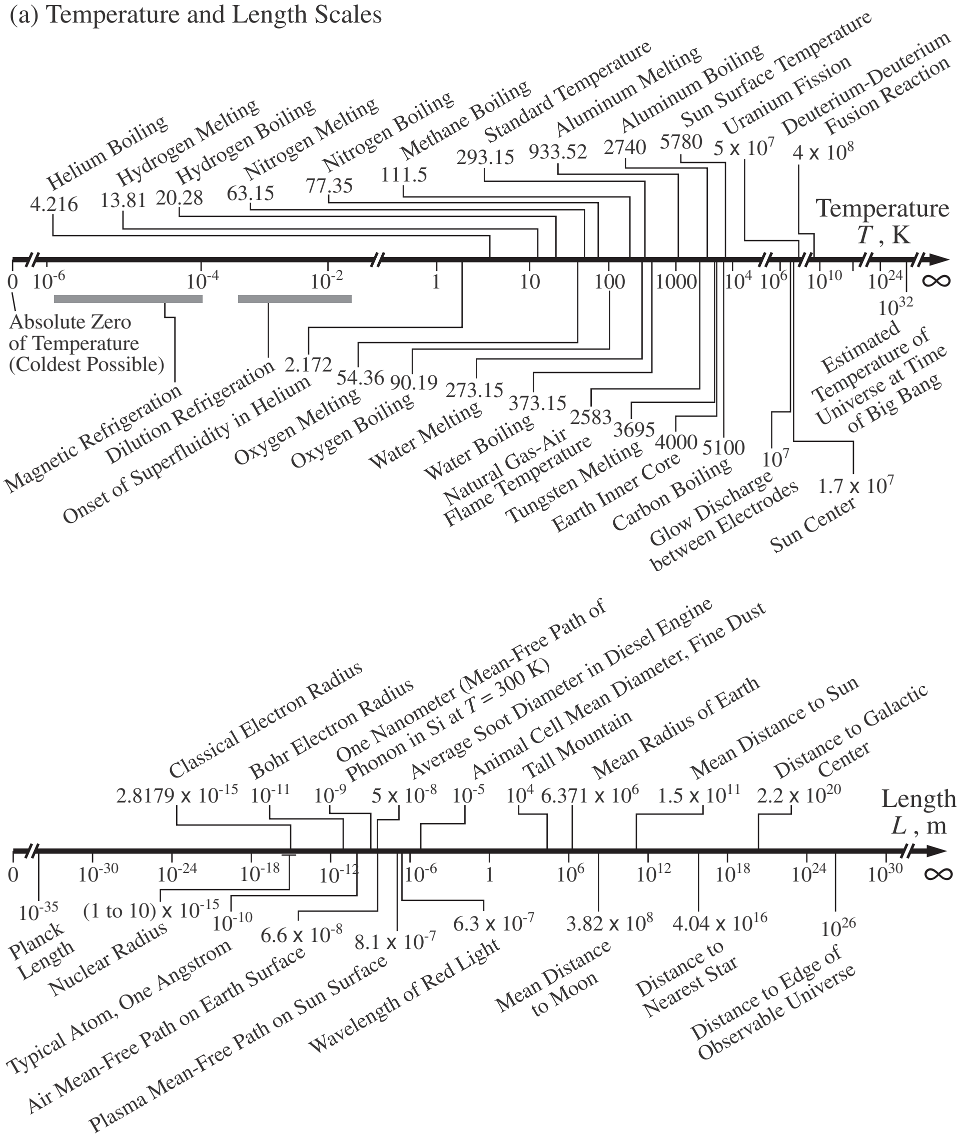

Figure 1.1. (a) Range of temperature and length scales encountered in heat transfer analysis.

For detection of very small temperature differences, the semiconductors are used. The electrical resistivity ρ_e of semiconductors has a rather unusually large dependence on temperature, especially at low temperatures. Then temperature variations as small as one-millionth of one °C can be measured.

The upper bound for temperature is not known. One of the highest temperatures predicted is that based on a theory of formation of the universe. This will be discussed shortly, but the theory predicts a temperature of nearly $T = 10^{32}$ K, at the very beginning of the creation of the universe [8]. In a fusion reactor, temperatures of the order of $T = 10^8$ K are required for a continuous reaction. Thermal plasmas with

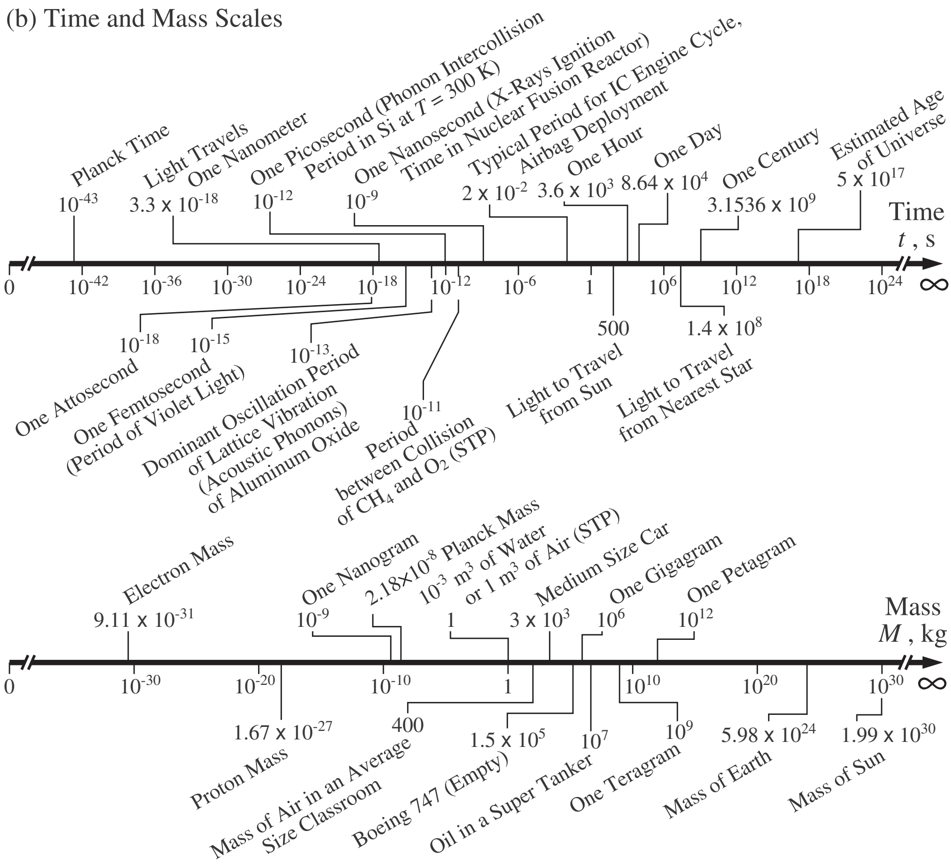

Figure 1.1. (b) Range of time and mass scales encountered in heat transfer analysis.

temperatures in the range of $T = 10^4$ to 10^6 K are used for materials processing. The prefix cryo- is used in reference to very cold and pyro- in reference to very hot (as in cryogenics and pyrogenics referring to physical phenomena at very low and very high temperatures).

The smallest length with a physical significance is the Planck length, $L_P = 1.616 \times 10^{-35}$ m (obtained by combining the Newton constant of gravity G_N, Planck constant h_P, and speed of light in vacuum c_o), while the radius of the earth is $R = 6.371 \times 10^6$ m, and the mean distance between the earth and the sun is $L = 1.5 \times 10^{11}$ m. The mean-free path of the air (mostly nitrogen and oxygen) at standard temperature ($T = 20°$C) and pressure ($p = 1.013 \times 10^5$ Pa), i.e., atmospheric STP conditions, is about $\lambda_m = 66$ nm. The heat transfer medium may be as small or smaller than the components of a transistor in an integrated circuit (i.e., submicron) or as large as an airplane, if not larger.

The shortest elapsed time for a significant physical change is the Planck time, $t_P = 5.391 \times 10^{-44}$ s (obtained in a similar manner to the Planck length). The shortest time used in the analysis of low-energy interactions is the duration of collision time τ_c, which is the average duration of intramolecular or intermolecular collision (this is of the order of femtoseconds). The next, and larger time scale, is the average time between collisions τ_m (or mean-free time). The establishment of molecular-level equilibrium requires a yet larger time scale τ_e, called molecular relaxation time. The next larger time required for establishing equilibrium over large length scale is called the hydrodynamic time τ_h. Then $\tau_c < \tau_m < \tau_e < \tau_h$. Pulsed lasers with the duration of pulse being of the order of 10^{-15} s (i.e., one femtosecond 1 fs) are used for surface thermal modification of solids. The average period for the cyclic motion of the internal-combustion, gasoline engine is about $t = 2 \times 10^{-3}$ s (20 ms).

The smallest mass (not considering sub-electron particles) is the mass of an electron and is $m_e = 9.109 \times 10^{-31}$ kg. The average classroom contains $M = 400$ kg of air. The mass of the earth is estimated as about $M = 10^{24}$ kg.

The particular application defines the range of the temperature, the length, the time, and the mass (system) of interest. Knowing these ranges would allow for the proper inclusion of the relevant thermal phenomena and the imposition of the various simplifications and approximations needed to make the analysis practical. Generally, scale filtration is used, where, depending on the relative scale of interest, the finer scales and the associated phenomena are averaged and represented at the largest scale of the filter. In many engineering applications, this filter scale is rather large. However, there are also some very short and very small scale thermal problems, such as the picosecond pulsed lasers used in the nanometer-structure manufacturing of integrated circuits and devices. There, the thermal nonequilibrium between the electrons and the inert and/or ionized molecules is important and influences the transient heat transfer and phase change.

The various natural occurrences and engineering applications of heat transfer are summarized in Chart 1.3(a). The major division is natural versus engineered systems.

(B) Natural Systems

Chart 1.3(a) lists some examples of geological and biological heat transfer. In biological application, in addition to the normal mammalian temperatures, higher and lower temperatures occur or are imposed. Examples are heat therapy, cryo-preservation, and cryo-surgery [17]. Examples of the thermal aspects of natural systems are the universe, the earth, and the human body.

(C) Engineered Systems

Examples of engineered thermal systems occur in applications ranging across electronics, energy, environment, manufacturing, processing, transportation, sensing, and others. These are listed in Chart 1.3(a).

As an example, Chart 1.3(b) shows the thermal aspects of manufacturing. Manufacturing is making materials into products suitable for use [20]. As expected, this processing of materials would involve heat transfer. In shaping of materials, reduction of mass is achieved by, for example, sintering materials by heating, or the volume is reduced by sintering-compacting while heating. Joining of similar or dissimilar materials, such as welding, soldering, brazing, or thermal fusing, involves

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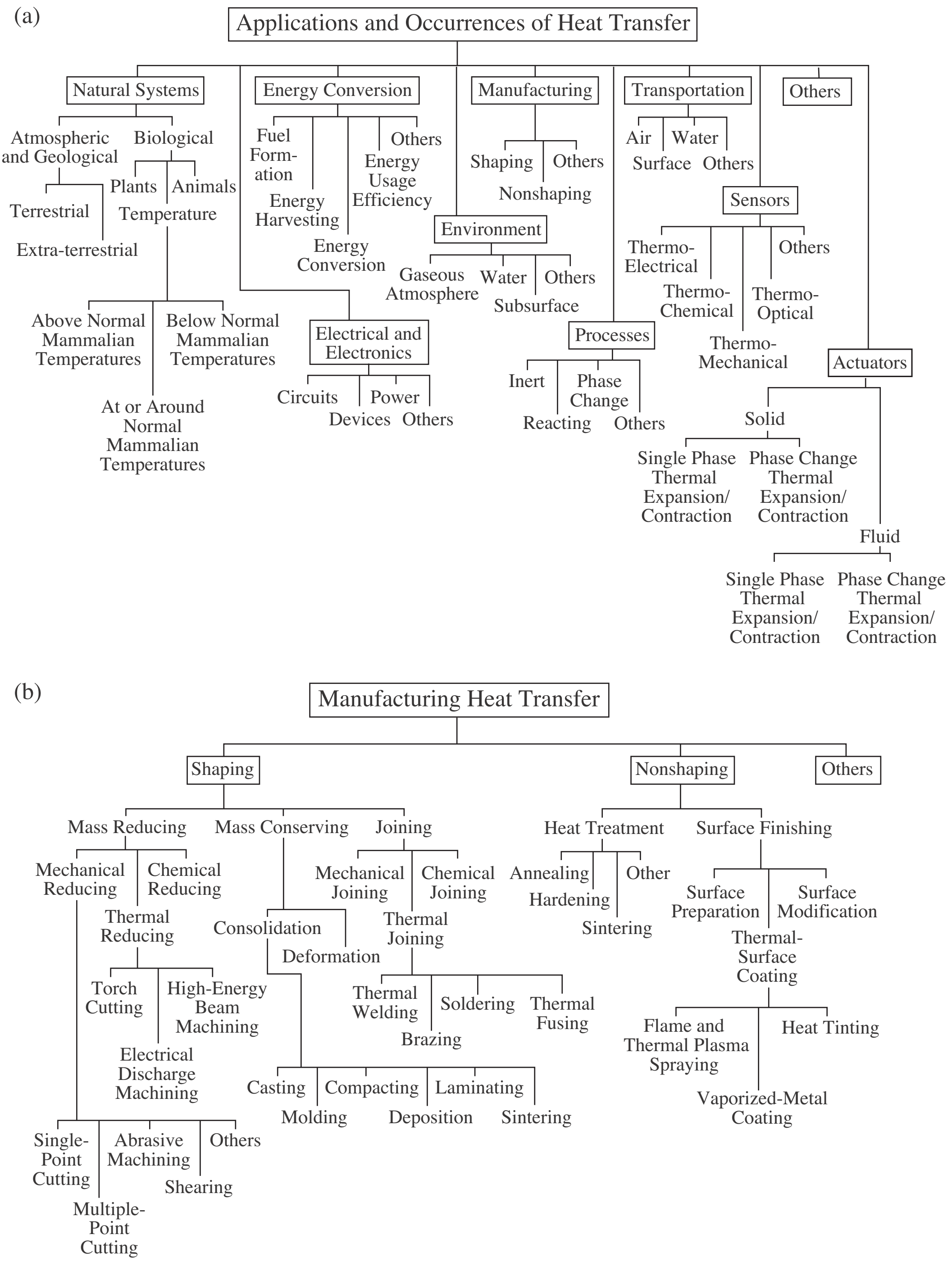

Chart 1.3. (a) Various applications of heat transfer in natural and engineered systems. (b) Various aspects of manufacturing heat transfer.

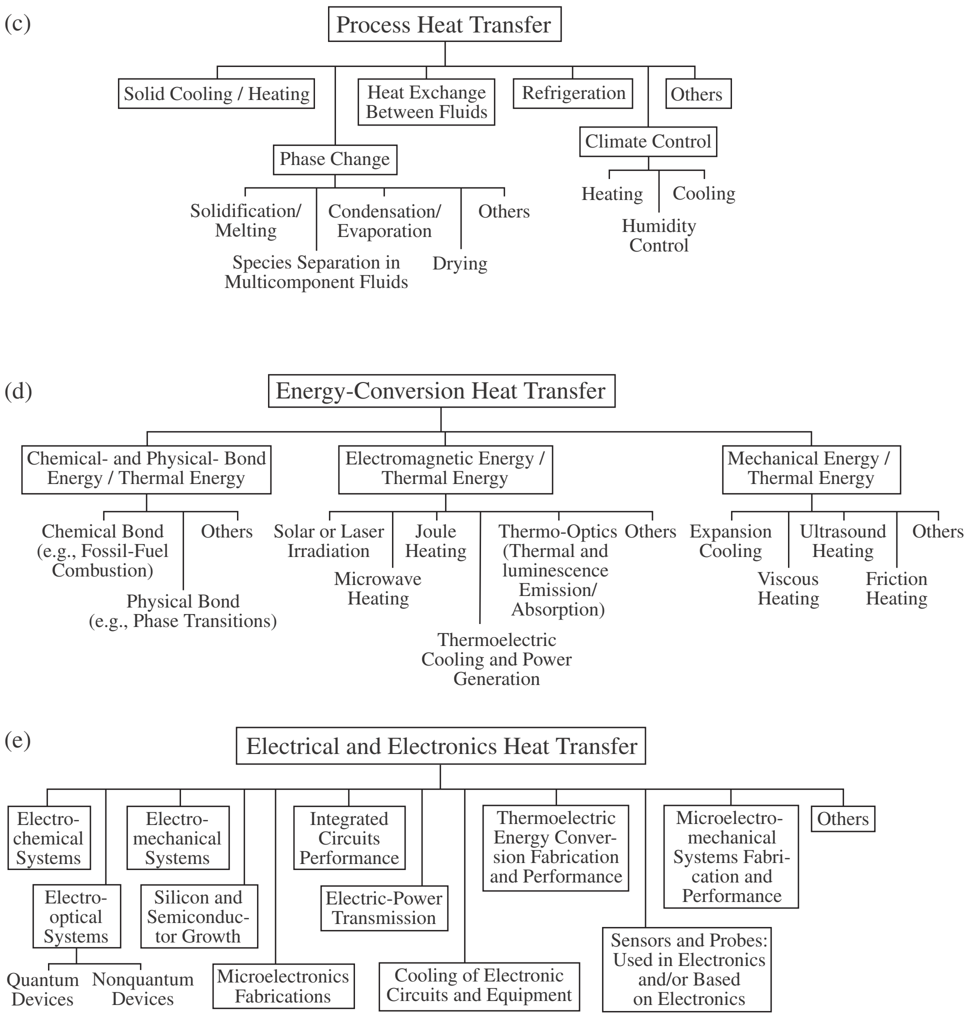

Chart 1.3. (c) Various aspects of process heat transfer. (d) Various aspects of energy-conversion heat transfer. (e) Various aspects of electrical and electronic heat transfer.

heat transfer. In nonshaping manufacturing processes, heat treatment of the metals and ceramics (e.g., glass) and surface coating by deposition of semi-molten particles, can be mentioned. Mechanical energy is converted to thermal energy in machining and grinding (both are among shaping of materials by mass reduction).

As another example of engineering applications, consider the process heat transfer. Chart 1.3(c) gives some aspects of process heat transfer [11]. Process heat transfer is the controlled addition/removal of the heat as a step in a process. In some processes a heat transfer device performs this task (as in heat exchangers, dryers, distillators, molds, etc.). In others, heat transfer is a supplement to another process (as in heat applied for melting in crystal growth, heating of organic-liquid transfer lines for reduction of the liquid viscosity, or in electrical preheating of the automobile catalytic converters for enhancement in performance during the engine start up). It can also be the heating/cooling of solids as in food processing. The heat transfer processes requiring phase change, including the drying of wet porous solids (such as clothes), consume a significant portion of the energy used in the process heat transfer. Another example is the distillation of organic and nonorganic liquid mixtures for purification purposes. Climate control (mobile or immobile indoor climates) is another example of process heat transfer.

Currently, 40% of all energy consumed is from oil, 20% from natural gas, 26% from coal, 6% from nuclear reactions, and 8% from renewable sources. The major areas of consumption of energy are 18% in space heating, 16% in process steam, 14% in automotive, 11% in direct heating, 8% in electric motors, 6% in other transportation, 5% in lighting, 5% in traveling, 4% in water heating, 4% in feedstock, 3% in air conditioning, 2% in refrigeration, 1% in cooking, and 3% others. Energy conversions may involve heat transfer with the thermal energy as the final (or initial) form of energy or as an intermediate form of energy. Direct-energy conversion heat transfer is where energy from chemical- and physical-bond energy (such as fossil-fuel and phase-transition energy), electromagnetic energy (such as solar and laser irradiation and microwave), and mechanical work (such as solid-surface friction work or gaseous expansion/compression pressure work) are converted to (or from) thermal energy [10].

Chart 1.3(d) gives examples of energy-conversion heat transfer. (This topic will be discussed in detail in Section 2.3). In the case of electromagnetic/thermal with indirect energy conversion, electrical power is generated when heat is added to a junction of a semiconductor and a metal (a direct energy conversion). Some of these examples are irreversible (e.g., Joule, microwave, and ultrasound heating) and some are reversible (e.g., phase-change heat storage, and thermoelectric energy conversion). An example of indirect energy conversion would be conversion of kinetic energy of a moving automobile into heat by the intermediate step of brake contact friction. Another example is the electrical power generation involving shaftwork (turbines) as the intermediate form of energy.

Yet another application is electrical and electronics heat transfer. This is shown in Chart 1.3(e). The applications include removal of Joule heating (energy conversion) or heat transfer used in the microelectronic fabrication processes. In some miniaturized, integrated sensors and devices, heat transfer controls the sensor performance or the device actuation. In automobile electrical generators, heat generated by Joule heating must be removed from the induction coils for improved performance (the electrical resistance of the electrically conducting copper wires increases with temperature). In thermal sensor applications, thermal sensing may be used to detect chemicals, determine radiation intensity, etc. [14]. As an example in hot-wire anemometry (discussed in Section 6.8), the rate of heat transfer from a heated wire submerged in a moving fluid is used to measure the velocity of the fluid near the wire.

Throughout the text, in discussions, examples, and end of chapter problems, we will consider various applications of heat transfer in natural and engineered systems. As is expected, in these applications the energy conversion (from and to thermal energy) is an important part of the problems. Therefore, we will address quantitative analysis of the energy conversion, to and from thermal energy, by chemical- and physical-bond electromagnetic, and mechanical energy.