Preface

Heat transport has been an essential topic in the foundations of thermodynamics since the beginnings of the nineteenth century. Fourier's mathematical description of heat transport served as a stimulus for mathematics (Fourier transforms arose because of the need to solve the classical heat equation following from the Fourier law), for physics (it provided a model and source of inspiration for the mathematical description of other transport phenomena, such as Fick's diffusion law and Ohm's electric transport law), and for natural philosophy (it provided a mathematical framework for an irreversible phenomenon, in contrast to Newton's mathematical framework for reversible mechanics). A century and a half before Fourier, Newton had formulated his heat transfer law for the cooling of bodies, or for heat exchange, but without providing a sufficiently wide mathematical framework. Half a century after Fourier, the Stefan-Boltzmann law provided a mathematical basis for radiative heat exchange. Since then, heat transport analysis in its different forms (conduction, convection and radiation) has been a classical topic in physics, engineering, and natural sciences of life and Earth.

Since the closing decades of the twentieth century, heat transport has been experiencing a true revolution, enlarging its domain of applicability and finding new regimes and phenomenologies where Fourier's theory is no longer applicable. This new epoch in heat transfer has been stimulated by miniaturization, but it was preceded, in some ways, by the earlier technological frontier of aerospace engineering due to the need of studying heat transfer and cooling of bodies in rarefied gases.

In both cases, the new aspects have arisen in association with the relation between the heat carriers' mean-free path ℓ and a relevant characteristic size of the system L, expressed by the Knudsen number $\mathrm{Kn} = \ell/L$. Fourier law (as well as classical hydrodynamics and continuous theory in general) are valid in the limit of a very small Knudsen number, i.e., when $\ell/L \ll 1$. Indeed, Kn may increase both because of an increase in ℓ (as in rarefied gases and aerospace engineering), and because of a reduction in L (as in miniaturization technologies).

The recent progress in nanotechnology and its huge economic impact have brought Kn for heat and electric transport to values at which neither Fourier law, nor classical continuum thermodynamics are strictly applicable. Ways to extend the domain of application of thermodynamics to nanosystems are being sought from the perspective of heat transport, in the same way as Carnot researches on thermodynamics were stimulated by the industrial revolution brought up by heat engines. Currently, research is being stimulated by three industrial revolutions: miniaturization (the need to refrigerate supercomputers, where much heat is dissipated in a tiny space), energy management (the need to develop sustainable energy sources such as photovoltaic and thermoelectric ones, which may be more efficient at the nanoscale than in bulk systems), and material sciences (where nanostructures such as, for instance, superlattices, carbon nanotubes, graphene, silicon nanowires, and porous materials may be decisive for the control of heat transport for insulation or refrigeration, or for delicate phonon control in heat rectification and thermal transistors).

Thus, these are exciting and challenging times for heat transfer and thermodynamics. Much of this impetus is coming from microscopic approaches, either from several versions of kinetic theory or fluctuation–dissipation theorems, or from detailed computer simulations. These approaches allow for detailed understanding and description. However, this should not make us forget the practical usefulness and the conceptual challenge of mesoscopic approaches starting from the macroscopic perspective and deepening into more detailed and accurate descriptions of physical systems.

This is the principal aim of the present book: how to formulate, from a mesoscopic perspective, generalized transport laws able to keep pace with current microscopic research, and to cope efficiently with new applications. The equations presented here are compatible with generalized formulations of nonequilibrium thermodynamics beyond local equilibrium. However, we try to emphasize the transport equations by themselves. When the mean-free path and relaxation times are negligible with respect to the characteristic size of the system and the rates of phenomena, respectively, these equations reduce to Fourier law, but in other situations they describe other physical features beyond it: heat waves, ballistic transport, and phonon hydrodynamics, for instance. We have tried to connect, as far as is possible our results with the results of microscopic theories. This is the reason, for instance, why we use the concept of phonon hydrodynamics as a denomination for a given regime of heat flow where the equations for the heat flux have a form analogous to the hydrodynamic equations for the velocity field. In fact, this form is derived here from the mesoscopic equations in some regimes, but without making explicit reference to the physical nature of heat carriers (they could be phonons, or electrons, or holes), but since the phenomenology known to date has been explored microscopically, we have retained the name "phonon hydrodynamics" to enhance the connection between the mesoscopic and the microscopic approach.

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