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TEACHING MICRO/NANOSCALE HEAT TRANSFER

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ABSTRACT

In this paper, I will share some personal experience and views on teaching micro/nanoscale heat transfer. Due to the diverse science backgrounds underlying the micro/nanoscale heat transfer principles, a big question facing the instructors is what to teach. At the undergraduate level, I believe that micro/nanoscale concepts can be integrated into the current mainstream heat transfer curriculum through some discussion of the length scales of heat carriers and through examples of heat transfer problems in micro- and nanotechnologies. Experimental modules can also be developed for hands-on experience. At the graduate level, a systematic study of micro/nanoscale heat transfer should contain the following four parts: (1) energy states, (2) thermal energy storage, (3) energy transport in the forms of waves and particles, and (4) energy conversion. The principles behind these topics encompass quantum mechanics, condensed matter physics, statistical physics, kinetic theory, electronics and electromagnetic waves. Although integrating these diverse subjects into one course seems to be a daunting task, my experience of teaching such a course at MIT and UCLA convinced me that such an integrated course is feasible.

THE NEED FOR MICRO/NANO HEAT TRANSFER EDUCATION

Heat transfer as an engineering discipline emerged in the early half of the 20^{th} century. Prior to its emergence as an engineering discipline, basic heat transfer principles were laid down mainly by mathematicians and physicists, including such luminaries as Joseph Fourier and Max Planck. The emergence and development of heat transfer as an engineering discipline was mostly need-driven. Examples of the early needs are the power plant, petrochemical plants, and engines. In the 1960s, space and aerospace technologies played a central role in the heat transfer research while in the 1980s, the thermal management of microelectronics became a dominant driver.

What are the application drivers of micro/nanoscale heat transfer education? Micro/nanoscale heat transfer can be related to a wide range of contemporary technologies including information technology (IT), energy technology, micro/nano fabrication and nanomaterials, and biotechnology [1,2]. Examples of nanoscale heat transfer phenomena related to information technology are the reduced thermal conductivity of various thin films used to build integrated circuits and semiconductor lasers, and the higher temperature rise of nanoscale heat sources due to rarefied phonon heat conduction. These phenomena are part of the thermal management considerations of either individual devices or the whole computer chip. Another type of heat transfer applications in IT is the use of thermal energy for data storage, such as phase-change rewritable disks, the thermal writing of polymers, and the thermal-assisted switching of magnetic bits. In the energy conversion area, some nanoscale heat transfer phenomena can enable particular energy conversion technologies. For example, the reduced thermal conductivity of nanostructured materials can be utilized to improve the thermoelectric figure of merit for solid-state cooling and power generation. The enhanced radiation transfer in small gaps can be exploited to improve the thermophotovoltaic energy conversion efficiency and power density. The fabrication of nanostructures and the synthesis of nanostructured materials often also involve very interesting heat and mass transfer processes, such as the vapor and the liquid phase condensation in the synthesis of nanowires. Nanoscale heat and mass transfer is also seeing increasing applications in biology. Examples are the heating of nanoparticles to separate the DNA strands and mass transfer issues related to the detection of bio-agents.

Another question worth pondering is: what are the technological areas where we can place students educated in heat transfer into the driver's seats. The application examples of micro/nanoscale heat transfer are not necessarily all need-driven. In the last 10-15 years during which micro/nanoscale heat transfer has gone through rapid development, microelectronics was often used as the technological driver for understanding micro/nanoscale phenomena. Although heat transfer in microelectronics remains a crucial issue, it is not a driver for the product development. The intellectual pursuit to explore the difference between macro and nanoscale heat transfer actually was a much larger driving force for the rapid development of the field of micro/nanoscale heat transfer. The fundamental understanding gained from such intellectual pursuit is now seeing bigger rewards in technological areas other than microelectronics and photonics. Some of the applications put the heat transfer principles into the driver's seats. Examples are energy conversion based on nanostructured thermoelectric materials and based on nanoscale radiation heat transfer phenomena. The heat transfer community should capitalize on these new opportunities by equipping the students with the knowledge to place them into the driver's seats.

INCORPORATING MICRO/NANO HEAT TRANSFER INTO UNDERGRADUATE CURRICULUM

A typical heat transfer course at the undergraduate level already has very cramped contents and instructors often struggle to cover even the traditional syllabus. How can one include micro and nano topics? While having an advanced course in micro/nanoscale heat transfer is always an option, I believe that we also need to introduce some micro/nanoscale heat transfer concepts in the introductory level course. This can be done in the following three areas without much change to current course contents.

(1) **Introduction of fundamental concepts**. Some fundamental concepts can be incorporated into an undergraduate heat transfer course. For example, when discussing heat conduction, phonons and electrons as heat carriers can be explained in parallel to molecules for gases and liquids. Two important characteristic lengths of heat carriers should be discussed---the mean free path and the wavelength. Based on the mean free path, the validity of the Fourier law and the non-slip boundary condition can be discussed. The relaxation time can also be introduced together with the mean free path for explaining potential deviations in fast transport processes. The wavelength can be introduced when discussing the Wien displacement law for thermal radiation.

(2) **Examples and homework problems from micro and nanotechnology**. Many of the heat transfer problems in micro/nanotechnology can be solved based on macroscale constitutive equations. Examples from microelectronics, photonics, and microfluidics can be readily integrated into the teaching of heat conduction and convection. When solving these problems, one may discuss the justification of the classical laws based on the characteristic length and time scales.

(3) **Experiments.** Some experimental modules can be developed with different levels of investments, depending on the institutional resources. Taking thin-film thermal conductivity measurement as an example, different techniques can be employed for measuring the thermal conductivity of thin films. An AC calorimetry method can be used to measure the thermal diffusivity of thin membranes without the need of photolithography tools [3]. Several photothermal methods can also be adapted for thermal diffusivity measurements with little investment [4]. If photolithography tools are available, microfabrication-based experiments will provide students with an even richer experience [5,6]. One can also explore existing foundry services to obtain microfabricated samples. For fluidic experiments, soft lithography can be a good platform [7].

A GRADUATE LEVEL MICRO/NANO HEAT TRANSFER COURSE

At the graduate level, many universities have begun to offer courses related to micro/nanoscale heat transfer with large variations in the course contents, depending greatly on instructors and the targeted student bodies. The courses I developed at UCLA and MIT have targeted students in heat transfer and MEMS, mostly with typical mechanical engineering backgrounds. My philosophy is to start from fundamental physical principles to build microscopic pictures of the heat transfer processes, as shown in Fig. 1. The course contains the following three core parts (1) energy states, (2) thermal energy storage, and (3) thermal energy transport, and if time permitting, two additional topics (4) energy conversion and (5) liquids. I will briefly discuss the essential contents for each part.

The energy states in materials are determined by quantum mechanical principles. Mechanical engineering students normally have had some quantum concepts from their undergraduate physics but have seldom touched these topics in the rest of their engineering curriculum. In contrast, current electrical engineering, materials science, and chemical engineering curricula usually cover such topics in various courses. I believe that understanding the energy states is the starting point for gaining a microscopic picture of heat transfer I cover the Schrödinger equation, the energy states of quantum wells, harmonic oscillators, rigid rotors, hydrogen atoms, and electrons and phonons in crystals. These are usually the contents of quantum mechanics and solid-state physics; each of which is a year-long course in the physics department. The challenge for instructors is to shrink it within 3-4 weeks, preferably 3 weeks. I limit the detailed mathematical treatment using the Schrödinger equation to quantum wells, and for phonons to one-dimensional atomic chains. In addition to the energy states, some key concepts that I emphasize are quantum states, degeneracy, and density of states. Many examples of using the quantum energy states in nanotechnology can be given through these discussions, including semiconductor quantum well, quantum wire, and quantum dots lasers, superlattices, and photonic crystals.

My introduction to heat starts with the thermal energy storage that can be treated based on statistical thermodynamics. Although I favor a rigorous treatment based on ensembles, (microcannonical, canonical, and grand canonical ensembles), a direct introduction of the Boltzmann, the Fermi-Dirac, and the Bose-Einstein distributions are an acceptable alternative. From the distribution functions and the density of states concept, one can derive the Planck law, and the specific heat of ideal gases and of solids. Ideally, the essential statistics should be covered in one week, although my lecture often runs into the secondweek.

The coverage of the energy states and the thermal energy storage is preparatory for a discussion on the thermal energy transport. My treatment of the energy transport is divided into three themes, which will be discussed below.

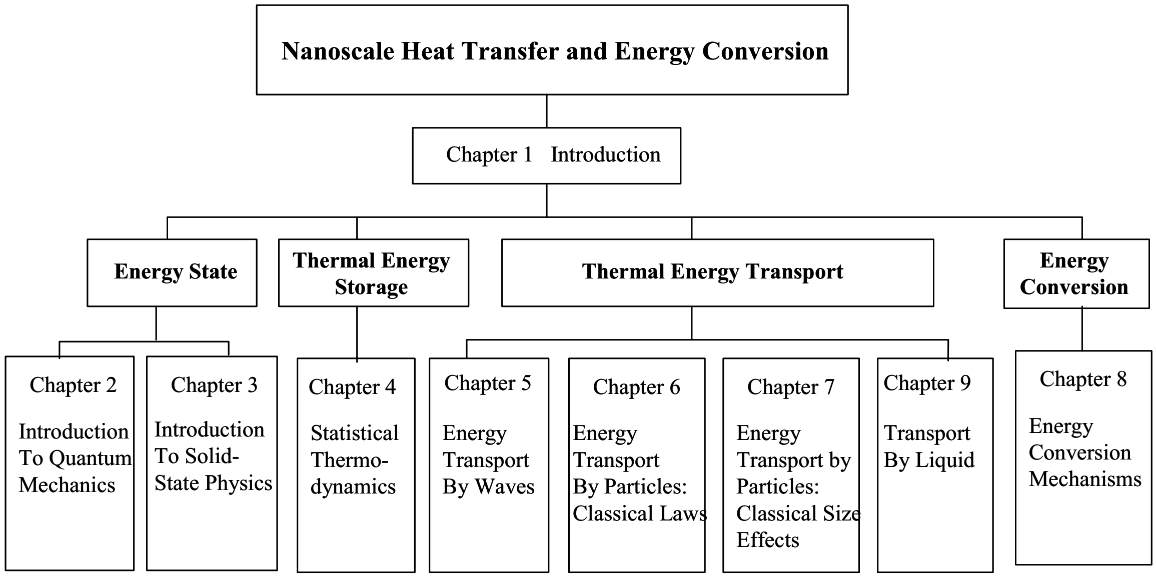

Figure 1 Contents of a graduate level nanoscale heat transfer course, which are also the major components of a textbook to be published by Oxford Press.

My treatment of transport starts with the heat transfer in the form of waves carried by electrons, phonons and photons. The wave treatment can begin with the quantum mechanics discussion of electron waves. I emphasize a parallel treatment of photons and phonons (throughout the whole course) and thus introduce electromagnetic waves here, with some discussion about acoustic waves. The key concepts emphasized in the wave treatments are the single-interface reflection of waves and related to this, the thermal boundary resistance phenomena, the interference and tunneling phenomena and their impacts on radiation heat transfer. In addition to these important heat transfer phenomena, another advantage of including a wave treatment is that it becomes easy for students to understand the recent development in science and technology. Examples include scanning tunneling microscopes, superlattices, and photonic crystals. The treatment of wave transport will end with a discussion of the criteria for neglecting the phases of the waves so that heat carriers can be treated as particles. Concepts such as wave packets and group velocity will be explained through such a discussion.

My teaching of heat transfer in the form of particles starts with the derivation of the Boltzmann equation, followed by a simplified discussion of scattering mechanisms and the relaxation time approximation. From the Boltzmann equation, classical constitutive laws such as the Fourier law, the Newton shear stress law, the Ohm law will be derived, together with a derivation of thermoelectric effects and a discussion of the Onsager relations. Here, students will see that the laws that they had taken for granted can be derived under various approximations, some of which are not valid in nanostructures. In addition to the constitutive equations, I also briefly discuss the derivation of the Navier-Stokes equation for gas molecules and its counterpart, the electrohydrodynamic equations for electrons, and the phonon hydrodynamic equations.

The final topic of transport is classical size effects. This is an area that has had the most development in the micro/nanoscale heat transfer research. My treatment is again based on the Boltzmann equation and treats electrons, phonons, and gas molecules in a parallel fashion. Phenomena discussed are the reduced thermal conductivity of thin films, the velocity slippage in rarefied gas flow and their applications in disk drives, the rarefied phonon gas heat conduction near nanoscale heat sources, and approximate treatments that allow quick estimation of size and interface effects. Some students commented that I should start the course here, although I do not agree.

My past teaching, both on the quarter system UCLA (four lecture-hours per week) or the semester system at MIT (three lecture-hours per week), essentially stops here. There are two additional topics, needing another three weeks, which I would like to cover. These are the microscopic picture of energy conversion and the liquid-based transport.

Regarding energy conversion, the relaxation-time based Boltzmann equation does not include the nonequilibrium between different carriers, such as hot electrons and hot phonons, and the photon-phonon interactions. My treatment of the microscopic energy conversion will deal with the nonequilibrium between different heat carriers, how energy is converted from one-type of carrier to another, and how transport affects such energy conversion processes. Applications include nonequilibrium between electrons and phonons during laser-materials interaction, the hot and cold electron effects in semiconductor devices and thermoelectric devices, and heat generation and heat source distributions. This chapter is also a place to summarize how nanotechnology can be used to improve the efficiency of energy conversion devices.

I have treated all the above-discussed topics in a parallel fashion for electrons, photons, phonons, and gas molecules. Liquids, however, defy such a parallel treatment. Luckily, at least for simple liquid, classical transport equations are still valid except a few atomic layers near the wall region. My treatment of liquid includes surface energy and surface force, and liquid-vapor phase change processes.

The last time I taught the course (Fall 2002), I left the last 10 minutes of each lecture for a student to give a in-class presentation. The topics are chosen from suggested papers for each chapter—ranging,for example, from the original papers of Einstein on photons, to some recent papers on micro/nanoscale heat transfer. Both students and I enjoyed these presentations.

Table 1 shows the weekly coverage of my course at MIT for the Fall of 2002. In retrospect and also in my future agenda, I think at a semester system like MIT, I will further shorten the time I spend on the energy states (currently 4 weeks) and thermal energy storage (currently 2 weeks) to a total of 4 weeks. This will leave time to cover the topics on energy conversion and liquid. Ideally, if a statistical thermodynamics course is offered, it should cover the energy states and the thermal energy storage, which would leave more time to cover the transport and energy conversion.

Clearly, the above-discussed contents include many diverse topics. My experience is that these diverse contents are still manageable and serious students benefit tremendously from such a wide exposure. It was quite gratifying when a student told me that after this course, he suddenly found that he could follow the topics of many papers in current journals (not necessarily just heat transfer journals). For students in my own group, some will continue to take more specialized courses from quantum mechanics and condensed matter physics, to electronics and materials, in addition to mechanical engineering courses and I encourage them to do so.

I would also like to comment that I have attempted to put minimum prerequisites on this course. The expected students background include general physics, introductory thermodynamics and heat transfer. Some junior and senior undergraduate students have taken the course and had excellent performance. There are also students who had not taking heat transfer before and who were still able to survive. One message I do want to deliver to students is that the barriers between different disciplines are actually not high. But it takes students courage and determination to go through the diverse topics and the large amount of new terminologies.

Finally, regarding the textbook. there are currently no published textbooks exist that I can use for the above-discussed contents in my course. I have been working on a textbook [8], which will be published by the Oxford Press as part of the MIT-Papallardo Series in Mechanical Engineering, with anticipated the publication of the book in late 2003 or early 2004. Currently, 10 chapters are planned, nine of which are shown in Fig.1. An additional chapter on numerical simulation techniques, including molecular dynamics and Monte Carlo simulation, will also be included.

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Table 1 An example of Course Coverage.

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MIT 2.57: Nano-to-Macro Transport Processes
Fall, 2002 Schedule

Week 1. 9/4 Introduction to nanotechnology and nanoscale transport phenomena. (Ch.1).
Week 2. 9/9 Microscopic picture of heat carriers (Ch.1).
9/11 Mean free path and simple kinetic theory. Basic wave characteristics (Ch.1&2).
Week 3 9/16 Material waves and Schrödinger equation, quantum well (Ch.2).
9/18 Quantum wells, 1D and 2D quantum structures (Ch.2).
Week 4 9/23 Student holiday, no class.
9/25 Harmonic oscillators, rigid rotors, and hydrogen atoms (Ch.2).
Week 5 9/30 Crystal structures (Ch.3).
10/2 Electronic energy levels in crystals, Kronig-Penney model (Ch.3).
Week 6 10/7 Electronic energy levels in 3D crystals (Chap3).
10/9 Phonons and density of states (Ch.3).
Week 7 10/14 Columbus day, no class
10/16 Density-of-states, Microcanonical ensembles (Ch.3&4).
Week 8 **10/21** Midterm No. 1**.**
10/23 Ensembles, molecular partition functions, specific heat of gases (Ch.4).
Week 9 10/28 Fermi-Dirac and Bose-Einstein distributions, specific heat (Ch.4).
10/30 Specific heat of phonons and electrons (Ch.4), Introduction to heat transfer by waves (Ch. 5).
Week 10 11/4 Energy transfer by waves, plane electron waves and reflection of waves, Introduction to electromagnetic waves (Ch.5).
11/6 Electromagnetic wave reflection at a single interface (Ch.5).
Week 11 11/11 Veteran's day, no class.
11/13 Interference and tunneling, acoustic waves (Ch.5).
Week 12 11/18 Landauer formalism, wave to particle transition (Ch.5).
11/20 Coherence, Energy transfer by particles, Boltzmann equation (Chap 6).
Week 13 11/25 Scattering and relaxation time (Ch. 6)
11/27 Fourier law, Newton's shear stress law, Ohm's law (Ch. 6).
Week 14 12/2 Electron transport, thermoelectric effects (Ch.6). Take home exam out.
12/4 Constitutive equations (Ch. 6), Classical size effects in thin films (Ch. 7), Take home exam due.
Week 15 12/9 Size effects parallel to films Size effects perpendicular to interfaces (Ch. 7).
12/11 Rarefied gas flow (Ch. 7).

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