Heat Transfer at Intersects

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Abstract

Research over the past three decades in understanding micro/nanoscale heat transfer phenomena and mechanisms has significantly broadened our knowledge base and created larger intersections with other disciplines. This paper gives a high level reflection of the increased intersections of heat transfer with other disciplines through some examples of progress made in micro/nanoscale heat transfer research. At the fundamental level, we witnessed the blurring of the boundaries among heat transfer, physics and chemistry. New insights on heat transfer mechanisms led to opportunities in developing materials for heat transfer and energy applications such as high thermal conductivity plastics and improved thermoelectric energy conversion materials. Great opportunities exist in taking the fundamental understandings and advanced materials to develop innovative systems.

Key Words: *Heat transfer, Overview, Materials, Devices and Systems*

1. Introduction

I would like to thank the Heat Transfer Society of Japan for bestowing on me the Nukiyama Memorial Award. I truly appreciate the award committee selecting me among many strong candidates, as my own research has focused on nanoscale heat conduction and thermal radiation rather than phase change heat transfer. Although I learnt the Nukiyama boiling curve as an undergraduate student, this award motivated me to read Professor Nukiyama's pioneering paper in pool boiling (Nukiyama, 1966), from which I developed great appreciation for his milestone contribution. It is clear that Professor Nukiyama is an experimentalist with great physical insights. He reasoned through what the boiling curve should be, including the difficult-to-observe nucleate boiling to film boiling transition, and then went on to design experiments and prove his conjecture. He is clearly a very humble man and his attention to prior literature is a great example for us to follow (Nukiyma, 1984).

There is no doubt that the most influential person leading to my current career stage is the late Professor Chang-Lin Tien, who was my Ph.D. thesis advisor from 1989 to 1993, and the Chancellor of the University of California at Berkeley from 1990-1997. In the summer of 1988, he gave a one-week seminar at Huazhong University of Science and Technology (then Huazhong Institute of Technology), where I was a young assistant professor after completing my master degree in 1987 there. During that week, he gave half-day seminars for five consecutive days, each day talking on a different topic. On microelectronics cooling, he emphasized the difference of heat conduction at microscale from that in macroscale. That was the first time I was introduced to microscale heat transfer phenomena. I was lucky that Professor Tien also took me as a graduate student during that trip. This allowed me to enter into the emerging field of micro/nanoscale heat transfer at its early stages. In 1993, Professor Tien, working with his close friend Professor Hijikata at Tokyo Institute of Technology, kicked off the first US-Japan seminar that has been held every three years since, with the 8th seminar held the past July in Santa Cruz. These seminars helped build a strong community in micro/nanoscale heat transfer, and I have met many Japanese friends through such interactions. Although there exists not a single paper or event that can be identified as the starting point of micro/nanoscale heat transfer and some of the topics we

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study today can be traced back to pioneers such as Planck, Maxwell, Casimir, and Knudsen, it is fair to say that Professor Tien's vision and energetic leadership was instrumental in the emergence of this field.

Many progresses have been made in micro/nanoscale heat transfer over the last thirty years. In this article, I will give a high level view to argue that these progresses are made at the intersections of heat transfer with other fields. On a fundamental level, micro/nanoscale heat transfer interacts well with physics and chemistry through its emphasis of transport mechanisms distinct from continuum theories. The new understanding is exploited to improve materials for thermoelectric energy conversion and thermal management. I would like to especially emphasize the ample opportunities stemming from new materials and new understanding in devices and systems. My view can be summarized in Fig. 1, with heat transfer as the center of focus.

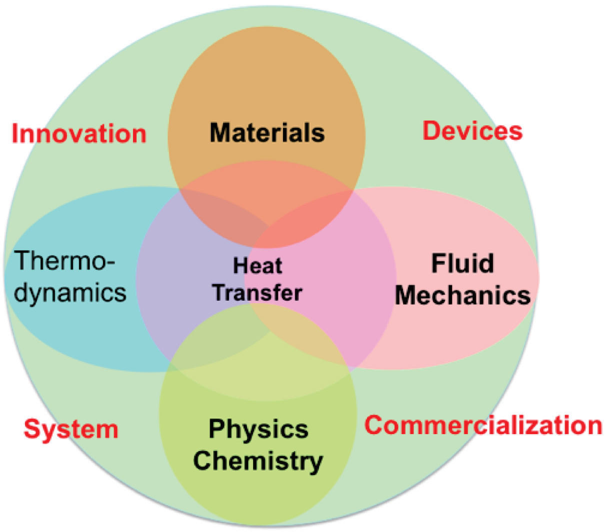

Fig. 1 Schematic diagram of experimental loop.

2. Heat Transfer with Basic Science

Heat transfer has always been interdisciplinary; it naturally intersects with thermodynamics and fluid mechanics. In fact, at MIT (and other institutions), we combine the three subjects into a two-semester long sequence in our undergraduate curriculum. Heat transfer derives its basic principles from fundamental physical laws such as the Fourier law of heat conduction and the Planck law of blackbody radiation that are applicable to macroscale objects. Most of the subsequent developments in the field are built on these basic principles to solve many engineering problems. Recent research focus on heat transfer at micro/nanoscales has shown that these basic laws that we are familiar with may not be applicable at such length scales (Cahill et al., 2003; Gang Chen, 2005). These research efforts advance fundamental understanding of phonon and photon thermal transport at nanoscale and expand the intersection of heat transfer to basic science community, especially physics but also increasingly chemistry and biology.

One example is the size effect on thermal conductivity in micro and nanostructures, which can be traced back to the work of Casimir (Casimir, 1938). He explained the thermal conductivity trend of crystalline solids at low temperatures as due to boundary scattering limiting the phonon mean free path (MFP). The phonon MFP increases with decreasing temperature to be larger than the sample (millimeters or centimeters) at cryogenic temperatures. In micro/nanostructures, the characteristic lengths of the structures are comparable or smaller than the phonon MFP even at room or above-room temperatures, leading often to decreased thermal conductivities of nanostructures compared to their bulk parent materials. However, surprisingly, the phonon MFPs of most materials are unknown, and thermal conductivity modeling had been mostly based on phenomenological models established in 1950s (Callaway, 1959; Klemens, 1951). This situation has now changed as first-principles or molecular dynamics based approaches enable thermal conductivity of single crystals and alloys simulation without any fitting parameters (Broido, Malorny, Birner, Mingo, & Stewart, 2007; Esfarjani, Chen, & Stokes, 2011; Kotake & Wakuri, 1994; Ladd & Moran, 1986; Volz & Chen, 2000). Such tools have led to new insights. For example, although standard kinetic theory gives a phonon MFP in silicon as short as 41 nm, molecular dynamics and first-principles simulations show that phonons with MFPs longer than 1 μm contribute more than 50% of the total heat conduction (Esfarjani et al., 2011; A. S. Henry & Chen, 2008). Although we usually do not think optical phonons are important for heat conduction, they too play a significant role in some materials by providing scattering channels to acoustic phonons (Lee et al., 2014; Tian et al., 2012). Meanwhile, experimental tools have also progressed;

inelastic neutron scattering can now be used to map out phonon modes and relaxation time across the whole Brillouin zone (Ma et al., 2013). Recent developments taking advantage of ballistic phonon transport provide hope that desktop systems can be developed to characterize phonon MFPs distributions (Johnson et al., 2013; Koh & Cahill, 2007; Minnich, 2012; Minnich et al., 2011; Regner et al., 2013; Siemens et al., 2010). Several of these experiments often rely on size effects surrounding nanostructures (G. Chen, 1996) rather than boundary scattering as in the Casimir classical size effect picture. In fact, much more can be learnt from examining extensive studies of rarefied gas heat conduction as pioneered by Knudsen and extending to phonon heat conduction in analogous configurations relevant to solid-state applications..

Although nanostructured materials usually have reduced thermal conductivities compared to their bulk materials, they can also be engineered to have higher thermal conductivities. One example is single-walled carbon nanotubes or graphene sheets, which can be thought of as 1D or 2D materials, respectively (Balandin, 2011; Kim, Shi, Majumdar, & McEuen, 2001). A single layer of suspended graphene has no boundaries in the through-plane direction, and thus no boundary scattering. Phonon wavevectors are always along the sheet plane and their energy levels are more discrete than that of 3D graphite, making it harder for phonons to scatter with each other due to difficulties in satisfying the momentum and energy conservation rules required for the Umklapp scattering process. This leads to longer phonon mean free paths and potentially higher thermal conductivities than that of their bulk parent materials. However, atomic scale defects, as well as adsorbed atoms or physical contact with substrate materials, can lead to degradation of the thermal conductivity by reducing phonon MFPs. Hence, clear experimental data on the thermal conductivities of carbon nanotubes or graphene beyond that of bulk graphite along the in-plane direction are rare. One could also imagine that by shrinking the thickness of a film, it will eventually become a 2D layer. The transition from the classical size effect that leads to a reduced thermal conductivity with decreasing thickness below their bulk values to increased thermal conductivity above that of the bulk materials in a 2D sheet is an interesting regime to study. In fact, a one-dimensional nonlinear atomic chain may have infinite thermal conductivity, as implied in the discovery made in 1950s by Fermi, Pasta, and Ulam (E. Fermi, J. Pasta, S. Ulam, 1955) that the energy input into one vibration mode will eventually come back fully despite scattering into the other modes. This problem, widely studied in statistical thermodynamics as an example of nonergodic systems, has implications on the thermal conductivity of polymers. Although polymers usually have low thermal conductivity values around 0.2 $Wm^{-1}K^{-1}$, molecular dynamics simulations reveal that a single polyethylene molecular chain can have infinite thermal conductivity (A. Henry & Chen, 2008). Experimentally, thermal conductivities as high as ~100 $Wm^{-1}K^{-1}$ have been achieved in polyethylene nanofibers with aligned molecular chains (Shen, Henry, Tong, Zheng, & Chen, 2010). Even fibers with aligned amorphous polymer chains have shown an order of magnitude improvement in their thermal conductivity (Singh et al., 2014).

The Casmir or Knudsen pictures for phonon heat conduction in nanostructures fall into the classical size effects regime where phonons can be treated as particles and their phase information is lost at the boundaries. The ability to engineer phonon heat conduction as waves will open up many possibilities. The above examples of high thermal conductivity nanostructures can be considered a result of the quantum size effect on phonon waves. Other wave phenomena such as interference, stop bands, tunneling, and localization similar to that of photon transport are of great interests, but are difficult to observe and validate because the phonons responsible for heat conduction have short wavelengths. Coherency in heat conduction was recently demonstrated in superlattice structures via combined experimental studies and numerical simulations (Luckyanova et al., 2012). This is a surprising observation considering the dominance of interface roughness for short wavelength phonons. Simulations show that although the short wavelength phonons are strongly scattered, leading to a significant reduction of thermal conductivity, the remaining heat conduction is due to long wavelength phonons that cannot be scattered effectively by interface roughness. These phonons propagate through the whole superlattice structure coherently, maintaining their phase information.

This observation suggests the possibility of phonon wave engineering to achieve lower thermal conductivities.

Another example of the fundamental departure from the established macroscale heat transfer picture is in near-field thermal radiation. Blackbody radiation as governed by Planck's law and Stefan-Boltzamnn law's is generally considered the maximum any object can emit. However, Planck himself already knew that his theory did not apply to objects with characteristic length comparable to the wavelength of emitted radiation (Planck, 1912). One well-known example is predicted by the Mie theory, where the emittance of a sphere can be larger than unity (Craig F. Bohren, 1998). Another example is thermal radiation between two surfaces at small separations significantly exceeding blackbody radiation due to tunneling of evanescent waves, especially surface waves (Domoto, Boehm, & Tien, 1970; Mulet, Joulain, Carminati, & Greffet, 2001; Polder & Van Hove, 1971). This was demonstrated experimentally by measuring the radiation heat transfer between a sphere and a flat plate (Narayanaswamy, Shen, & Chen, 2008; Shen, Narayanaswamy, & Chen, 2009). These experiments show that as the separation between two surfaces goes below 100 nm, radiation heat transfer can be 3-4 orders magnitude higher than that of Planck's law. In fact, in the limit of two surfaces touching each other, heat transfer is described by an interfacial thermal conductance, which has a value ~10^8 $Wm^{-2}K^{-1}$ (Cahill et al., 2003), while the effective radiation heat transfer coefficient between two black surfaces at room temperature is ~5 $Wm^{-2}K^{-1}$. Between 100 nm to physical contact, there is a transition from the thermal radiation picture to the heat conduction picture. How this transition happens is a fundamental and unanswered question.

3. Heat Transfer with Materials

New understandings of nanoscale heat transfer phenomena and microscopic heat transfer pictures are being exploited by people from different communities to develop better materials. One example is in thermoelectric energy conversion, which relies on the motion of electrons and holes for power generation and cooling. The efficiency of thermoelectric energy conversion relies on the figure-of-merit, ZT, of the materials used for the devices, where $Z=\sigma\square^2/k$ is proportional to the square of the Seebeck coefficient (S), the electrical conductivity (σ), and inversely proportional to the thermal conductivity (k), and T is the absolute temperature. The reduced thermal conductivity of materials due to classical size effects are now widely exploited to make nanostructured thermoelectric materials in the form of thin films, nanowires, and bulk nanostructures to improve their ZT above bulk parent materials, with most success from bulk nanostructures (Dresselhaus et al., 2007). Although the nanostructuring approach has been proven to be quite effective in many materials, our ability to predict the properties of such materials is still limited since these structures are very complex, including many interfaces and many other defects, in addition to heavy doping and strong coupling between electrons and phonons.

Another example is polymers that were mentioned before. Although bulk polymers have low thermal conductivity, by engineering polymer structures, for example, aligning the molecules into the same direction, significant increase in thermal conductivity has been demonstrated (Choy, 1977; Langer, Billaud, & Issi, 2003; Shen et al., 2010). However, currently, there are not high thermal conductivity polymers available for heat transfer applications. Process development is needed to produce such polymers at large quantity and low cost (Loomis et al., 2014).

A third example is the thermal conductivity of nanofluids---suspensions of liquids with nanoparticles. Some work has reported that such suspensions have thermal conductivity beyond what current theory can explain (Eastman, Choi, Li, Yu, & Thompson, 2001). However, the experimental data was difficult to repeat, and potential mechanisms were also debated (Keblinski, Phillpot, Choi, & Eastman, 2002). From our current understanding, the reason behind the poor reproducibility of experimental data is that the nanoparticles form clusters that are very much dependent on the surface chemistry of the nanoparticles, as well as the suspension liquid (Wang, Zheng, Gao, & Chen, 2012; Zheng et al., 2012). It is the heat conduction through such clusters that lead to increased thermal conductivity. We also observed interesting percolation behavior of heat conduction in graphite suspensions opposite to what are usually observed in electrical conductivity, and rheological properties. These observations suggest that for convective applications, one should work with nanofluids with concentration below that of the percolation threshold.

Based on our studies of heat conduction in polymers and suspensions, I believe there are good opportunities in exploring heat transfer in soft materials, because rich structures can be engineered to have desirable properties. For example, a single polymer chain is periodic and can be microns long, but they gyrate into clusters. Over bulk length scales, most polymers are amorphous. Between the amorphous bulk state and the single chain's periodicity lies a wide range of structures that can be engineered to achieve desirable thermal properties. Similarly, there are many studies of structures of various colloidal systems (Trappe, Prasad, Cipelletti, Segre, & Weitz, 2001). Their thermal transport properties have yet to be explored.

4. Heat Transfer with Devices and Systems

The accumulation of fundamental understanding of nanoscale heat transfer phenomena and accessible materials opens many new opportunities to innovate, and the heat transfer community should harness our interdisciplinary strength to translate scientific discoveries into applicable innovations that benefit society. For example, in thermoelectric materials, much attention has been paid to increasing material's ZT, but relatively little work has focused on developing devices, systems, and applications. In fact, there exists a large gap between materials research and applications research that needs to be filled (Tian, Lee, & Chen, 2013). Some challenges that must be carefully considered in making devices include developing good electrical contacts, mechanical stress, thermal expansion, and oxidation. Building devices and measuring their efficiencies are difficult tasks but must be done (Muto, Yang, Poudel, Ren, & Chen, 2013). Unlike photovoltaic cells and batteries that have only electrical contacts as inputs and outputs, thermoelectric devices require consideration of both heat and electrical inputs and outputs. Although heat is usually difficult to manipulate, we have shown that in solar thermal electric devices, the concept of thermal concentration can be exploited to reduce the cost associated with optical concentration (Kraemer et al., 2011).

Another example that combines materials and heat transfer knowledge is in our recent work to generate steam by concentrating solar irradiation near the surface of water using a double-layer carbon structures (Ghasemi et al., 2014). The top layer absorbs the sunlight, while the bottom layer serves as a thermal insulator between the hot sunlight-absorbing layer and cooler water supply. This thermal insulator allows the creation of a local hot region at the surface of the double-layer carbon structure, which leads to efficient vapor generation. Such a material structure can easily be incorporated in devices with potential applications in solar desalination and solar thermal power generation.

5. Concluding Remarks

I have given some examples, mostly from our own research, to illustrate my belief that exciting opportunities exist at the boundaries between heat transfer and basic science and materials, and the new understandings and materials will enable better thermal and energy conversion systems. I hope sharing these thoughts will stimulate continued growth of micro/nanoscale heat transfer and expansion of its intersections with other disciplines. I have benefitted tremendously from many collaborators from different disciplines. The research that qualified me for the Nukiyama Memorial Award is conducted by many graduate students and post-docs whom I had the fortune to work with. I would like to thank them and look forward to continuing our collaboration in exploring this exciting field.

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