CHAPTER

II.1

CHANG-LIN TIEN'S CONTRIBUTIONS TO MICRO- AND NANOSCALE HEAT TRANSFER

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Professor Tien pioneered and nurtured the field of micro- and nanoscale heat transfer. With his method of pushing to extremes in research and his keen physical insights, he started research on microscale radiation and heat conduction phenomena early on in his career. His work in the late 1960s and early 1970s on small gap effects on radiation heat transfer is still widely referenced in current research literature. In the 1980s, microelectronics cooling became a hot topic in the heat transfer community. Professor Tien, with his deep physical insights, saw a wide range of fundamental problems beyond the heat removal from computer chips, and started a systematic push in understanding micro- and nanoscale heat transfer phenomena. His rise, first to the post of executive vice chancellor at UC Irvine, and later to chancellor at UC Berkeley, did not slow down his research agenda for this field. On the contrary, he led the charge and pioneered a wide range of research topics in micro- and nanoscale heat transfer that continue to be among the most important topics today. He also used his great visibility to push the field of micro- and nanoscale heat transfer. He founded the journal of Microscale Thermophysical Engineering, and was the founding father of a U.S.-Japan seminar series on molecular to microscale heat transfer phenomena that has been held every three years, starting in 1993. He also organized two workshops in microscale heat transfer in U.S. and one in China. He, together with Majumdar and Gerner, edited the first book in this field, Microscale Energy Transport [1]. His direct leadership in micro-/nanoscale heat transfer research and in the heat transfer community not only greatly influenced the course of this field, but also had great impact far beyond the field of heat transfer. As a member of the U.S. National Science Board, he played an active role in the birth of the National Nanotechnology Initiative.

Although a formal push to the field of micro- and nanoscale heat transfer started in the late 1980s, much of Tien's research before then had micro- and nanoscale heat

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transfer content. Here, we will focus on a few micro- and nanoscale heat transfer areas that Professor Tien pioneered.

1 MICROSCALE RADIATION HEAT TRANSFER

Tien and his co-authors published a series of papers on radiation heat transfer across small gaps [2–5], motivated by applications in multilayer cryogenic thermal insulation. At low temperatures, the wavelengths of photons are long. They predicted [2] that photon tunneling increases the radiation heat transfer and conducted the first experiments to demonstrate the phenomenon [3]. This fundamental problem studied by Tien in the 1960s and early 1970s was pursued by several groups in various contexts of applications and physical situations, such as those in thermal insulation, scanning probe microscopes, data storage, and thermophotovoltaics.

Tien's keen interest in fundamentals and his deep insights naturally led him to consider other microscale radiation heat transfer problems that occur when the wavelength is comparable to the characteristic size. One example is the radiative properties of particulate systems. He started with single particle properties based on Mie theory [6] and moved on to consider the influence of dependent scattering [7–9]. His work in this area is reviewed in Chapter 1. These fundamental studies had significant impact on radiation heat transfer in flames, fluidized beds, and thermal insulation.

In the late 1980s and early 1990s, Tien had the foresight to see the importance of micro- and nanotechnology and started a systematic push in microscale heat transfer. The first few problems that he examined were heat transfer problems in thin films. Radiative properties of high-temperature thin films were investigated [10] for potential applications in detectors [11]. The fundamental question of thin-film formulation versus thick-film formulation was studied using the coherence theory of light [12, 13].

Tien never stopped to look for important and exciting research topics-they came to him naturally. He started to examine the laser-materials interactions in the 1990s and studied a wide range of fundamental microscale heat transfer problems from nonlinear optical phenomena in solids and liquids to nonequilbrium behavior between electrons and phonons in solids. His contributions in this area are reviewed by Longtin et al.

2 MICROSCALE HEAT CONDUCTION

Tien realized early on that heat conduction in small structures is different from that in macrostructures. His first paper on this topic investigated the thermal conductivity of metallic films and wires at low temperatures, when the electron mean free path is longer than the characteristic size of an object [14]. An extensive effort started with his examination of high-temperature superconductors. Flik and Tien [15] examined the thermal conductivity of high-temperature superconducting thin films. Before this study, the most well-established theoretical work was on the models established by

Fuchs and Sondheimer. Flik and Tien developed an alternative model, leading to simpler approximate expressions for the thermal conductivity of thin films. This study was important in the emergence of the field of micro- and nanoscale heat transfer. At that time, the topic of reduced thermal conductivity in thin films was just beginning to gain more attention as it became more important for applications in optical coatings and microelectronics. The heat transfer community was also paying increasing attention to heat transfer issues in microelectronics. The next studies of size effects on thermal conductivity were carried out by Chen and Tien [16] for quantum well structures, and Qiu and Tien [17] on metallic thin films. This was the first treatment of the thermal conductivity of thin films in the direction perpendicular to the film plane, which raised the interests of researchers to quantum structures. Chen and Tien suggested that superlattices can be made into superthermal insulators [18] and provided experimental evidence on quantum well semiconductor lasers containing superlattices [19]. Although the original motivations of these studies were for semiconductor lasers [20, 21], these studies turned out to have significant implications for the development of thermoelectric cooling and power generation materials. In recent years, extensive work has been conducted on the thermal conductivity of superlattices for potential applications in thermoelectrics, microelectronics, and photonic devices.

Tien did not stop at simple thin-film structures. He also investigated microscale effects on heat conduction in porous silicon [22, 23] and thermoelectric properties of thin films [24].

3 APPLICATION OF FRACTAL CONCEPT TO HEAT TRANSFER

Nature is replete with structures that are disordered. Examples related to heat transfer include the disordered nature of soot agglomerates, the roughness of solid surfaces, transport through a porous medium, and the multiple length scales and disorder in turbulent-flow structures. Tien was fascinated by the implications of structural disorder on heat transfer, starting first with radiative properties of soot agglomerates and then heat transfer across rough surfaces. The problem was: How does one quantify disorder? Tien proposed the use of fractal geometry, which characterized disordered objects by using fractional dimensions based on the generalization of Euclidean geometry that describes ordered objects through integer dimensions. Disorder generally spans multiple length scales, whereas heat transfer phenomena usually have a characteristic length scale. The interplay between these length scales was first studied by Tien, which led to intellectually provocative ideas and several new insights in heat transfer. Noteworthy was a deeper understanding of the scaling relations in thermal contact conductance [25], scattering of radiation by rough surfaces [26], and a new approach to studying the mechanics of contact between two surfaces [27] that have major implications in friction and tribology. Characteristic of Tien, his contributions were marked with boldness of new thought, the ability to identify important problems and new areas of research, and deep physical insight. In many ways, his investigations of the interplay between structural and thermal length scales naturally led to microscale heat transfer, since most of the thermal length scales in conduction and radiation occur at microscales.

4 MOLECULAR DYNAMICS SIMULATIONS

Established by Fermi, Pasta, and Ulam in the 1950s, molecular dynamics has been widely used to simulate physical properties and processes for a broad range of materials. The insights provided by molecular dynamics into fundamental phenomena in liquids have proven to be particularly valuable, since the combination of intermolecular interaction and disordered structure makes liquids difficult to treat by simple extension of theories of the solid or gaseous states. Tien realized the power of molecular dynamics to study not only disordered liquid systems, but also solid systems with deviations from perfect regularity including thin films, porous materials, superlattices, and other nanostructures. Additionally, he recognized the need for an improved, microscopically based understanding of surface tension and the bubble and droplet nucleation processes. Building on previous molecular dynamics heat transfer research performed in Japan, Europe, and the U.S., Tien began a research program focusing on molecular dynamics in microscale thermophysical engineering [28]. In this program, he and his coworkers used molecular dynamics simulations to study liquid-vapor interfacial phenomena [29–33] and heat conduction in thin films and superlattices [34, 35]. Tien's key contributions in these areas include determining the size and temperature effects on thin-film thermal conductivity [34], performing pioneering vapor bubble simulation studies [31], discovering the overlapping interface effect that leads to nonzero local stress across the liquid-vapor interface [32], and establishing the critical influence of strain on interfacial thermal conductance in heterostructures [35].

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