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A Review of Heat Flow Control and Enhancement Techniques

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Abstract

Most nanoelectronic systems have serious problems with heat dissipation and thermal management, which are important hurdles in many scientific and technological fields. Experimental improvements in thermal characterisation and phonon engineering have greatly improved our knowledge of heat transport and shown us effective techniques to regulate its propagation in nanomaterials; these are the topics we discuss in this review. We provide a comprehensive overview of the most recent phonon engineering techniques for 2D materials and semiconductor nanostructures, such as graphene and transition metal dichalcogenides, and their potential device applications. Then, we explore the fundamental difficulties and limits of thermal characterization approaches while reviewing the most recent developments in this field.

Keywords: Heat transfer, Thermal management, Thermal transport.

Introduction

For our purposes, heat transfer is defined as the movement of heat from one place to another as a result of a temperature gradient. Exchanging mass, momentum and energy via radiation, convection and conduction are all aspects of transport processes that scientists research. If you want a faster pace at which heat is dissipated, you may use a method called HT enhancement. As can be seen in Figure 1, we may further categorise these methods into two groups: active and passive. Adding extended surfaces,

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increasing thermal conductivity, and altering the surface or geometry of the flow channel through the use of inserts or other devices are all examples of passive enhancement methods, while ultrasonic enhancement and electrohydrodynamic are examples of active enhancement methods, as shown in Figure 1. In this article, we will be looking at passive methods of improving heat transport. Using expanded surfaces in manufacturing requires more room for the thermal setup and also increases the amount of surface area being heated or cooled. When compared to more traditional methods, increasing thermal conductivity via boiling heat transfer stands out as one of the most effective solutions. When water boils, it undergoes a phase transition from the liquid to the gaseous state through convection and radiation rather than pure conduction. Boiling occurs when a surface's saturation temperature is higher than that of the liquid it's in contact with. Figure 2 depicts the boiling curve, which explains this phenomenon. The production of steam, distillation, refining, dehydrating, cooling of nuclear reactors, fluid handling, metallurgical processing, air conditioning, refrigeration and cryogenics, and control, electronics cooling, power systems, on-orbit storage, microchip cooling, space systems, chemical process industries, thermal management, food processing, health care processes, etc. are all examples of industrial applications of boiling. In order to determine the rate of heat transfer or heat flux during boiling:

$$\dot{q} = \frac{\dot{Q}}{A} = h \cdot \Delta T_e \ \left[\mathrm{W \cdot m^{-2}}\right]$$

where h = HT Coefficient (W/(m^2·K), A = Area (m^2), ΔT_e = Excess Temperature = $T_{surface} - T_{saturation}$, T_S = Surface Temperature, and T_{sat} = Saturation Temperature of Liquid.

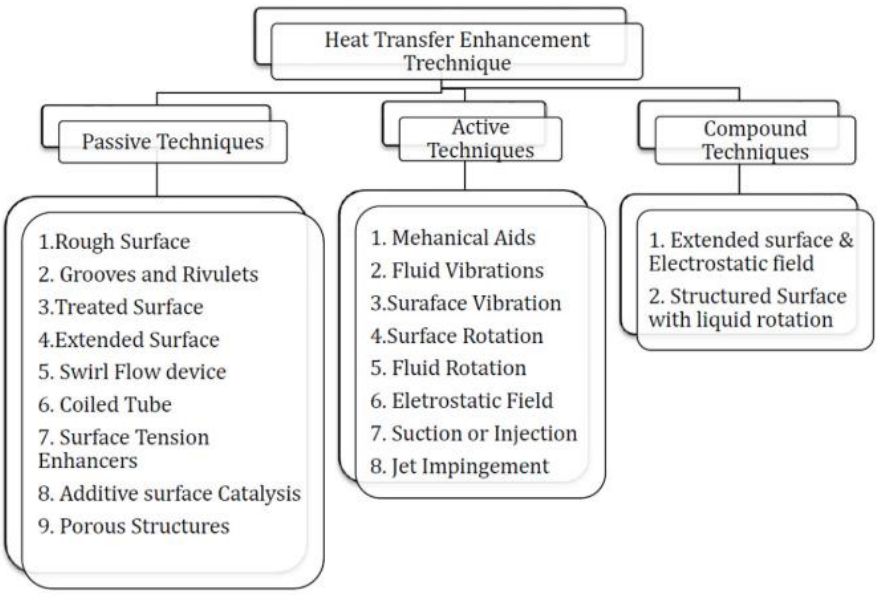

Figure 1. Heat transfer enhancement techniques.

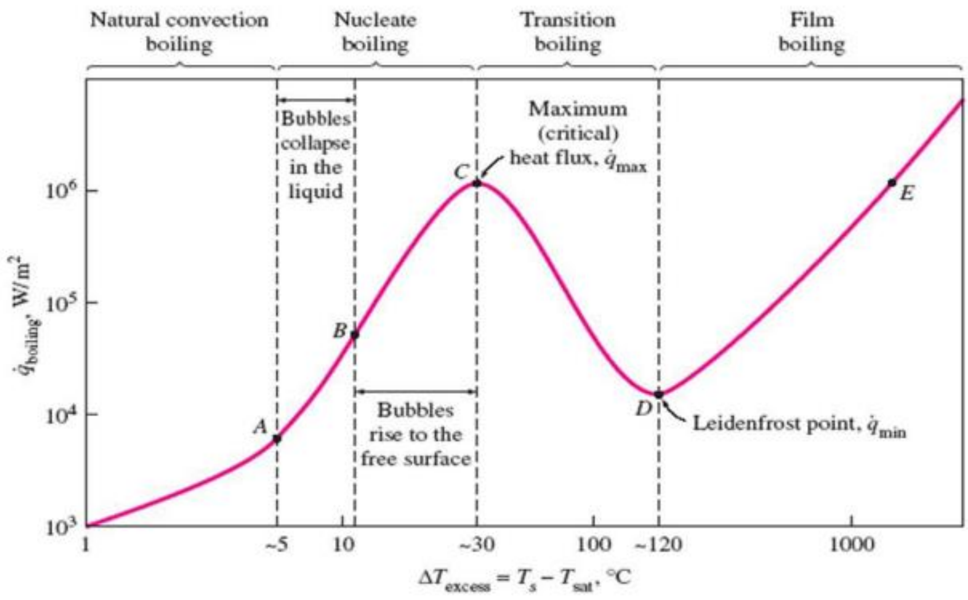

Figure 2. Boiling regimes

All the different phases and boiling regimes are shown in Figure 2. Natural convection boiling, seen as the first zone in Figure 2, occurs when liquid close to the surface is somewhat superheated. Boiling happens in a very shallow layer just below the liquid's surface. Evaporation takes place at the liquid-vapor interface, where the superheated liquid rises. The free convection effect is the primary factor in fluid motion. Heat transfer improves with rising excess temperature.

Background, enhancement strategies, and prior research are discussed with a description of HT enhancement methods for both flat and curved surfaces. In addition, we provide a qualitative evaluation of the present literature by outlining our quantitative knowledge of boiling heat transfer and referencing many other numerical concepts on the topic.

Nucleate boiling, seen by the area on the curve from A to C in Figure 2, occurs when the liquid is heated beyond its saturation temperature, producing bubbles of vapour at specific locations known as active sites. Rather from reaching the liquid-vapor barrier, these bubbles instead condense into liquid. Eventually, the pressure, temperature and surface tension all combine to cause the bubbles to swell. The rate at which bubbles develop and ascend to the surface of the liquid, resulting in fast evaporation, increases as Te increases. Due to the production of bubbles, the liquid undergoes agitation, which in turn leads to mixing and an increase in heat flow as well as the boiling heat transfer coefficient.

The boiling in the third zone of Figure 2 occurs between the partial nucleate boiling and the unstable film boiling. A bubble blanket is used to prevent any new liquid from entering the area where it will be heated. The surface is covered in a layer of vapour as bubbles develop (active sites). When the thermal conductivity of a substance drops, the rate at which heat is transferred to its surroundings falls, and the value of Kliquid exceeds that of Kvapour.

Film boiling, the fourth zone in Figure 2, is when the vapour film is stabilised, active sites are covered by vapour blankets and heat flow is at its minimum. Then, radiation kicks in, and the heat flow increases dramatically.

Experimentally, we want to investigate nucleate boiling, a phenomenon in which heat flow increases with increasing excess temperature and to apply additional enhancing methods, such as surface and geometrical alterations, to the same boiling regime.

- **Influence of Ultrasound on Heat Transfer**

The first investigations on the use of ultrasonic vibrations to increase heat transfer date back to the 1960s. The findings of these early investigations were often intriguing but ultimately unpromising, preventing them from inspiring further investigation. During that period, a plethora of new methods have likely been invented (e.g., channel size reduction). Thus, it was mostly ignored until the 1990s, when the trend toward creating ever-more-efficient technologies for energy management revived interest in the field. Figure 4's suggested graph displays the total number of articles that discuss the use of ultrasound to improve heat transmission.

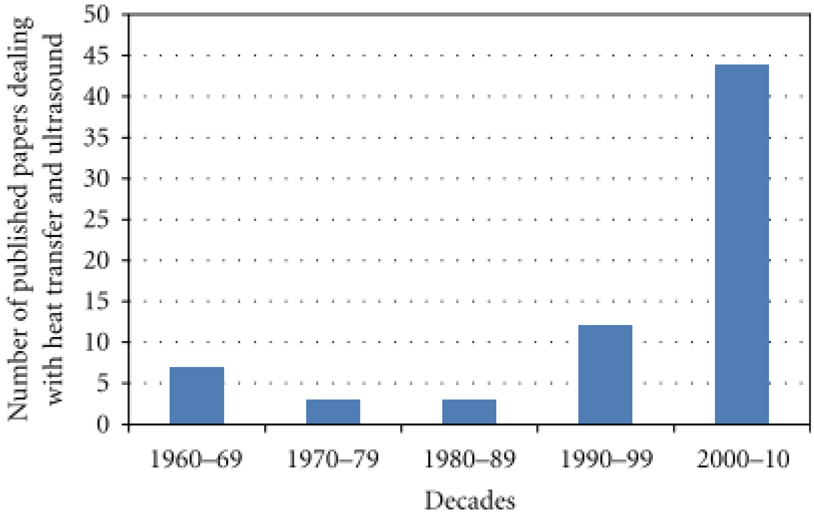

Figure 4: Evolution of the number of published papers per decade dealing with heat transfer enhancement by ultrasound.

- **Thermal Conduction in Semiconductor Nanostructures and 2D Materials**

Lattice waves, also known as phonons, are the primary heat conductors in semiconductors and insulators. For atoms or molecules in a lattice, vibrational energy is quantized into modes known as phonons. Taking into account that phonons are pseudo-particles, we may assign them the energy (where is the reduced Planck's constant = h/(2) and is the angular frequency) and the pseudo-momentum p = q (where q is the wavevector), both of which follow Bose-Einstein statistics. A dispersion relation, or the connection between the phonon frequency and its wavevector, may be used to describe the wavelength dependence of the phonon energy. A curve in the dispersion relation, the slope of which gives us the phonon group velocity, is a useful tool for this purpose.

Thermal conductivity is a measure of a material's heat-transfer capabilities. It's crucial to the development and functionality of modern technological gadgets. Three primary frequency-dependent parameters—specific heat (CV), phonon group velocity (vg), and phonon mean free path (Λ)—are needed for the calculation of thermal conductivity (k) in semiconductor material. Last but not least, the kinetic theory of gases provides an equation for thermal conductivity: k = CVvg.

Knowing the mean free path = vg/, where is the effective or total phonon lifespan, is crucial for calculating k. When all scattering mechanisms are treated as independent, Matthiessen's rule may be used to estimate. Phonon-phonon scattering (ppS), impurity scattering (I), and border scattering (B) are the primary factors that restrict the phonon lifespan. Due to dimensionality constriction, low-dimensional materials have different heat transport characteristics, and the latter effect is more prominent. Phonon engineering's potential to fine-tune low-dimensional materials' thermal conductivity is exciting and might lead to a number of significant advances (e.g., high figure of merit, improved energy efficiency).

- **Semiconductor Nanostructures**

The phonon group velocity, polarisation, and density of states, among other acoustic phonon parameters, are all directly affected by changes to the dispersion relation in nanostructures. These are often produced by periodic boundary conditions and may be created in free-standing nanowires (NWs) and thin films (PnCs). Both conventional size effects and phonon confinement effects may be thought to contribute to the theoretical reduction of heat transfer in such nanostructures. When the typical dimensions of the nanostructures are on par with the phonon MFP, a first effect manifests itself strongly; this effect is associated with enhanced phonon-boundary scattering. Group velocity, phonon density of states and phonon lifespan are all affected by the nanostructure's dimensions, which must be on the same order as or lower than the phonon wavelength for phonon confinement or coherence effects to become apparent and influence dispersion branches. Phonon confinement has an almost indiscernible effect on heat transport at ambient temperature. On the other hand, it is the diffuse dispersion of phonons at the borders that is primarily responsible for the reduction in thermal conductivity. The phonon confinement effect has been proposed in various publications as a means to regulate heat transfer, despite the fact that this process has already been extensively investigated and used.

Only with the help of superlattices has it been possible to study the effect of phonon confinement on heat transport at room temperature. However, the discovery of confinement effects is often constrained by the fact that nanofabrication procedures yield nanostructures with length scales longer than the phonon wavelength of the major heat carriers (at room temperature 5 nm). The issue may be solved by cooling to cryogenic temperatures (T 10 K). Here, we discuss recent experimental experiments that have shown how to effectively regulate heat transfer in semiconductor nanostructures.

Literature Review

(Dede et al., 2018)This article provides a concise overview of thermal metamaterials and how they are used in electronics. Anisotropic thermal conductivity is a key feature of the thermal metamaterial systems that have recently undergone extensive study and development for the purpose of controlling heat flow in ultra-thin composites. Following is a description of some of the basic experimental research conducted on the regulation of heat flow with conventional printed circuit board technology. This leads to a discussion of the fundamentals of heat flux cloaking, focussing, and reversing, with an emphasis on their generalisation to a range of electronics-related contexts.

(Javvadi et al., 2020)Despite much theoretical and experimental study, scientists still don't fully understand its complicated operating mechanism, which involves a coupling effect between hydrodynamics and thermodynamics. The report provides a high-level overview of the thermo-hydro dynamic features of this apparatus. This article will provide a quick overview of tube cross-section, working fluid volume, and internal diameter.

(Meena et al., 2022)When compared to alternative convection or conduction mechanisms of HT augmentation, boiling offers the ability to reduce energy losses from HT devices. The goal of this review paper was to examine the literature on methods for improving boiling heat transfer during the last several decades.

(Medapati & Gundra, 2021)A well-designed heat exchanger and supporting heat transfer network can have a significant impact on an organization's bottom line by lowering operating expenses and making more efficient use of resources. This paper compares the efficiency of double-pipe heat exchangers with and without inner pipes that are triangular, hexagonal, or octagonal in shape.

(Sahu, 2015)While saving money is its major function, it also safeguards workers by allowing for more precise regulation of process temperatures. Condensation and the resultant corrosion are avoided on cool surfaces. The critical radius of insulation, which we determined to be the point at which heat loss is greatest, was also investigated.

(Banerjee, 2021)Accurately determining structural member temperatures when the members are subjected to an actual fire is crucial for carrying out a performance-based approach to structural design for fire. Accurately determining the temporal and geographical change of temperatures is necessary for assessing the fire resistance of structural elements such as structural steels and concrete.

(El Sachat et al., 2021)Experimental improvements in thermal characterisation and phonon engineering have greatly improved our knowledge of heat transport and shown us effective techniques to regulate its propagation in nanomaterials; these are the topics we discuss in this review.

(Legay et al., 2011)A literature study is conducted, with a focus on cases where ultrasonic technology was employed in conjunction with a traditional heat transfer procedure to improve its effectiveness. Ultrasound is used in multiple industrial applications not just to improve process efficiency but also to capitalise on a number of secondary phenomena.

(Naje & Hasan, 2022)The vertical face up was discussed as well, along with the process of locating the heat source in the vertical channel. Devices that employ convective heat flow transfer with the inner body in a vertical channel include heat exchangers, nuclear reactors, fuel elements, heat dissipation in electronic circuits, and cooling towers.

(Nikose et al., 2021)Heat exchangers should be made smaller and lighter while also having their transfer rates increased. Work on the warm display is accomplished using blade and cylinder heat exchangers facing in a variety of directions. We hope that this poll will help us understand the impact of all of the above constraints on the development of thermal performance.

Conclusion

Several research have looked at the possibility of using passive approaches to improve heat transfer rates for structured surfaces. Discrete and continuous nucleation sites have both been tested experimentally, but more work is required to fully understand the nucleation site interactions. Studies of boiling over a cylinder have been limited since the majority of structured surfaces are flat. More research on bubble formation, growth, and ejection is required for cylinders with radii less than the departure radius and for cylinders of huge sizes.

Important thermal metamaterial building block architectures for hiding, concentrating, and reversing heat flow were emphasised. Anisotropic thermal-composite metamaterials were discussed from the standpoint of their potential applications in heat shielding, thermal energy harvesting, and the construction of electro-thermal power conversion circuits. With these three uses, the printed circuit board was considered the macro level. Aside from that, several ideas were presented on how thermal steering structures may be used at the micro-to-nano size of devices, as they have been described in the literature. The concept of thermal metamaterials provides the basis for these thermal guiding structures, and it is anticipated that the principles of heat flow control will become pervasive in next-generation power converters, computers, and sensors, where electrical, optical and thermal function will be tightly integrated.

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