Review Article

Experiments on near-field radiative heat transfer: A review
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Abstract: Near-field radiative heat transfer (NFRHT) has been demonstrated to exceed the blackbody limit due to the coupling effect of evanescent waves in the near-field regime, opening the door to application in active thermal control, thermophotovoltaics, and nanoscale imaging. Although the theoretical studies on NFRHT have been investigated exhaustively, the experimental measurement of NFRHT has been stagnant due to the challenges in controlling gap distance at the nanoscale. Remarkable progress has been greatly boosted until the 21st century to overcome the nanoscale controlling and measurement of NFRHT, benefiting from the advances of micro-nanofabrication techniques and materials science. This review examines an in-depth discussion of the experimental development of NFRHT. According to the structure of the emitter and receiver, the experimental devices are divided into three different categories: plate-to-plate structure, tip-to-plate structure, and sphere-to-plate structure. Existing experimental setups and methodology of NFRHT between metals, semiconductors, two-dimensional materials, and hyperbolic metamaterials are thoroughly explored and analyzed in detail. Finally, the remarks on outstanding challenges at the nanoscale and promising advances in applications are briefly concluded in the measurements of NFRHT.

Keywords: near-field radiative heat transfer; experiment; plate-to-plate; tip-to-plate; sphere-to-plate

1. Introduction

Global energy shortage is a long-term and persistent crisis. The traditional use of fossil energy performs inefficiency and causes global warming. It is crucial to develop clean energy to reduce greenhouse gas emissions. All clean electricity (renewables and nuclear) reportedly accounts for 39% of global electricity[1]. As a result, electricity is still mainly derived from fossil fuels, leading to substantial greenhouse gas emissions. Researchers have dedicated their efforts to exploring clean energy transitions to develop fast and efficient clean technologies as well as infrastructure. The solar photovoltaic system directly converts solar energy into electricity, reducing pollution and protecting the environment. Recently, the thermal photovoltaic system in the near-field conditions can greatly improve the efficiency of the photovoltaic system[2–5]. Moreover, the practical implementation of a near-field thermal photovoltaic system relies on the development of experiments.
focused on near-field radiative heat transfer (NFRHT). Therefore, the study of NFRHT experiments is crucial for the future development of clean energy transitions.

The NFRHT primarily involves the study of thermal radiation in the near-field regime. An object with a finite temperature radiates energy, in the form of electromagnetic waves, which are created by the random thermal motion of electric charges within the material. Traditional theory has evolved from the Planck law of blackbody radiation to the fluctuation-dissipation theorem\cite{6}, which makes it possible to relate thermal radiation to its origin in random fluctuations of electric charge in direct and detailed mathematical descriptions. However, the application of the fluctuation-dissipation theorem is limited in the extreme near-field regime (sub-10-nm gap), since not only electromagnetic waves contribute to thermal fluctuations but also phonons and electrons give rise to heat transport in the extreme near-field regime\cite{7–10}. This limitation presents a significant milestone for researchers, prompting them to investigate and discuss the thermal radiation from various sources in the near-field regime.

With the advancements in micro-/nano-technology, it is essential to understand the thermal radiation in a system at the micro-/nano-scale. Under the circumstances, two effects have garnered significant attention\cite{11}. First, electromagnetic interference causes a noticeable difference in radiative heat transfer. Secondly, the dominant contribution to heat transfer comes from evanescent waves, which encompass total frustrated modes and surface modes like plasmonic and phonon polaritons (Figure 1(a) and (b)). It has become crucial to understanding the role of evanescent waves in the near-field energy transfer. Although the amplitude of the evanescent wave decays exponentially with increasing distance from the interface, the energy density and energy flow experience a significant increase due to the contribution of evanescent waves. Therefore, the study of near-field radiation becomes intriguing yet intricate. Near-field radiative heat transfer (NFRHT) is expected to be the key to developing new technologies, such as high-efficiency near-field thermophotovoltaics (NFTPV)\cite{12–14}, radiative cooling technology\cite{15–17} and thermal devices\cite{18,19}. Owing to the near-field effect, the photon tunneling probability between the emitter and the TPV cell could be significantly enhanced, thereby aiding in the improvement of thermoelectric conversion power. In addition, NFRHT can also find application in enhanced near-field optical microscope\cite{20,21}.

**Figure 1.** Basic principles of heat transfer by far- and near-field radiation. (a) Schematic diagram of far-field radiation between two parallel semi-infinite bodies; (b) Radiative heat transfer through a vacuum gap smaller than the thermal wavelength.

The physical mechanism of radiative heat transfer at the nanoscale differs significantly from that at the macroscopic scale. When two objects are separated at a distance smaller than the characteristic wavelength of thermal radiation, the classical thermal radiation theory fails to accurately describe the radiative heat transfer\cite{22–26}. The short distance range is known as the near-field region, while the far-field region follows Planck’s law,
which can be simplified as Wien’s formula for small values of $\lambda_T$ and as Rayleigh-Jeans formula for large values of $\lambda_T$, where $\lambda$ represents the thermal wavelength and $T$ denotes the temperature. In the near-field region, the radiative heat flux can be calculated based on the fluctuation-dissipation theorem and fluctuational electrodynamics as well as Kirchhoff’s law. Theoretical calculations and experimental findings increasingly demonstrate the emergence of a new thermal radiation path known as photon tunneling in the near field, which is attributed to the presence of evanescent waves\cite{27,28}. Experimental evidence confirms that near-field effects can significantly increase the heat power exchanged between two objects in the near field by several orders of magnitude, compared to the far field or the blackbody limit\cite{29-84}.

Theoretically, for two infinite parallel plates separated by a gap distance in the near-field regime, the radiative heat flux can be obtained by the following equation\cite{85}:

$$Q = \frac{1}{8\pi} \int_{0}^{2\pi} \left[ \Theta(\omega,T_1) - \Theta(\omega,T_2) \right] d\omega \int_{0}^{2\pi} \xi(\omega,\beta,\phi) d\beta d\phi$$

where $\Theta(\omega,T) = \hbar \omega / \left( e^{\hbar\omega/k_B T} - 1 \right)$ is the mean energy of a Planck oscillator. Subsequently, $\beta$ denotes the wave vector in the x-y plane; $k_B$ the Boltzmann’s constant; $\hbar$ the reduced Planck’s constant; $\Phi$ the azimuthal angle; $T_1$ and $T_2$ are thermal equilibrium temperature of the emitter and receiver ($T_1 > T_2$), respectively. $\xi(\omega,\beta,\Phi)$ is called the energy transmission coefficient, which is expressed as\cite{85}:

$$\xi(\omega,\beta,\Phi) = \begin{cases} \text{Tr} \left[ (1-R_1^R;R_2^T - T_1^T;T_2^T) D(R_1^R;R_2^T) D^* \right], & \beta < k_B \\ \text{Tr} \left[ (R_1^T;R_2^T) D(R_1^R;R_2^T) D^* \right] e^{-\Phi^2}, & \beta > k_B \end{cases}$$

where $R$ and $T$ indicate Fresnel’s reflection/transmission coefficients for $p$ or $s$ polarization, which is given by:

$$R_{1,2} = \begin{bmatrix} r_{ss}^{1,2} & r_{sp}^{1,2} \\ p_{sp}^{1,2} & p_{pp}^{1,2} \end{bmatrix}, \quad T_{1,2} = \begin{bmatrix} t_{ss}^{1,2} & t_{sp}^{1,2} \\ t_{pp}^{1,2} & t_{pp}^{1,2} \end{bmatrix}$$

where $D$ denotes a Fabry-Perot-like denominator matrix and can be obtained by $D=(I-R_1^R;R_2^T e^{2\beta B})^{-1}$. The process and method of calculation are in detailed in the study by Wu et al.\cite{86}. Recent advances in experiments of NFRHT supply reliable verification of theoretical studies in the near-field regime.

Here, we review the experimental techniques currently used in NFRHT research and elaborate on their advantages and limitations. It is worth noting that most theoretical calculations of NFRHT focus on parallel-plate structures, and that in almost all cases significant effects only occur at nanoscale gaps. However, achieving this geometry experimentally is challenging, as it is difficult to achieve and maintain good parallelism between macroscopic plates at the nanoscale separation. Therefore, in many previous studies, all experimental measurements between parallel plates were limited to microscale gaps. With the development of science and technology, researchers have now successfully achieved NFRHT measurements of parallel plate-to-plate structures in the nanometer scale. Furthermore, to address the challenges encountered in near-field measurements, researchers have also employed tip-to-plate or sphere-to-plate structures. These alternative geometries have been widely used in various quantitative NFRHT studies. Below, we provide detailed discussions on NFRHT with different geometric structures, including plate-to-plate structure, tip-to-plate structure and sphere-to-plate structure.

2. Experiments
In this section, we discuss the experiments on NFRHT. As shown in Figure 2, we first introduce the experimental setups of plate-to-plate structure, followed by the presentation of experimental results for NFRHT in section 2.1. The plate-to-plate structure setup primarily comprises closely spaced parallel plates, which can be made of various materials, such as copper[22], glass[29], tungsten[31,32], silicon[42,43], and graphene[52–58]. With the development of micro and nano experiments, the achievable gap distance in NFRHT experiments has progressively decreased, thanks to the utilization of microelectromechanical systems[33–35] and nanopillars[44,53–56]. The emergence of new materials has also contributed to the development of NFRHT experiments. Therefore, in section 2.1, we describe the evolution of NFRHT experiments in terms of changes in gap distance, materials and asymmetric structures.

In Sections 2.2. and 2.3., we focus on the results of NFRHT for tip-to-plate structure and sphere-to-plate structure, respectively. Based on the development of scanning probes, the tip-to-plate structure primarily involves NFRHT between nanotips and plates[66–75], which can be categorized into three different types: scanning thermal profile, scanning thermal microscope, and scanning probe-microdevice nanostructures. Moreover, the sphere-to-plate structure commonly consists of a microsphere and a flat plate[76–84]. Different approaches have distinguished these setups, as shown in Figure 2.

Figure 2. Three different structures used in the experiments on NFRHT.

In total, we have compiled detailed experiments on NFRHT from fifty-eight reported works, classified into three categories: plate-to-plate structure, tip-to-plate structure, and sphere-to-plate structure. The three structures are not only distinguished by their physical configuration but also exhibit complex plasmon excitation and various applications. Specifically, the conduction of plate-to-plate structure can be further exploited the energy harvesting and thermophotovoltaics[51]. The investigation of tip-to-plate structure opens up possibilities for the near-field thermal imaging[70] in the crossover regime, where both radiative and conductive effects come into play[74]. The development of the microsphere-to-plate structure promotes near-field-based lithography[84]. Consequently, the experiments conducted on these three structures contribute to advancements in thermal management devices across various domains. Table 1 provides a detailed summary of the information extracted from these fifty-eight reported works.
Table 1. Summary of the experimental information from the literature.

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<tbody>
<tr>
<td>Plate-to-plate</td>
<td>Cravalho et al., in 1968[22]</td>
<td>Two parallel copper disks of diameter 8.5 centimeters</td>
<td></td>
<td>0.001 inches to 1.000 inches</td>
<td>11 K</td>
<td>4.6 K</td>
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<tr>
<td>Plate-to-plate</td>
<td>Reprinted from Hargreaves, in 1969[25]. Copyright (1969), with permission from Elsevier.</td>
<td>Two optically-flat surfaces A, B, coated with chromium about 1000 Å thick</td>
<td>Both the emitter and receiver plates (25 mm in diameter) were supported by three separate piezo-electric ceramic pillars, allowing precise adjustment of the gap size and parallelism between the plates</td>
<td>1 μm–5.8 μm</td>
<td>323 K–380 K</td>
<td>297 K</td>
</tr>
<tr>
<td>Plate-to-plate</td>
<td>Chen et al., in 2008[29]. Copyright 2008, AIP Publishing.</td>
<td>Two parallel glass optical plates (1 × 1 in²)</td>
<td></td>
<td>1 μm</td>
<td>327.0K–308.0K</td>
<td>312.0K–305.2K</td>
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<tr>
<td>Plate-to-plate</td>
<td>Ottens et al., in 2011[30]. Copyright 2011, American Physical Society.</td>
<td>Two sapphires with an area of 50 × 50mm²</td>
<td></td>
<td>2–100 μm</td>
<td>322.0K–307.0K</td>
<td>317.0K–305.8K</td>
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<td>Plate-to-plate</td>
<td>Kralik et al., in 2012[31]. Copyright 2012, American Physical Society.</td>
<td>Two parallel tungsten plates</td>
<td></td>
<td>1–300 μm</td>
<td>8.7 K–60K</td>
<td>5 K</td>
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<tr>
<td>Plate-to-plate</td>
<td>Kralik et al., in 2011[32]. Copyright 2011, AIP Publishing.</td>
<td>Two parallel tungsten plates</td>
<td></td>
<td>1–500 μm</td>
<td>313 K–396 K</td>
<td>293 K</td>
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<td>Plate-to-plate</td>
<td>Feng et al., in 2013[34]. CC BY 3.0.</td>
<td>Two freestanding membranes</td>
<td></td>
<td>1 μm</td>
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<tr>
<td>Plate-to-plate</td>
<td>Reprinted with permission from Fan et al., in 2014[35], Copyright (2014) American Chemical Society.</td>
<td>Two parallel nanobeams</td>
<td>Far-field</td>
<td>250 nm–740 nm</td>
<td>134 K + 273 K</td>
<td>∆T = 3 K − 14.7 K</td>
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<td>Plate-to-plate</td>
<td>Lim et al., in 2015[36]. Copyright 2015, American Physical Society.</td>
<td>Doped silicon plates</td>
<td></td>
<td>400 nm–1030 nm</td>
<td>371 K</td>
<td>294 K–303 K</td>
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<tr>
<td>Plate-to-plate</td>
<td>Reproduced from Song et al., in 2016[37], with permission from Springer Nature.</td>
<td>Prototypical materials (SiO₂-SiO₂, Au-Au, SiO₂-Au and Au-Si)</td>
<td></td>
<td>&lt;100 nm–10 μm</td>
<td>305 K</td>
<td>295 K</td>
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<tr>
<td>Plate-to-plate</td>
<td>Reproduced from Bernardi et al., in 2016[38]. CC BY 4.0.</td>
<td>Intrinsic silicon planes</td>
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<td>150 nm–3500 nm</td>
<td>420 K</td>
<td>300 K–420 K</td>
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<tr>
<td>Plate-to-plate</td>
<td>Ito et al., in 2015[40]. Copyright 2015, AIP Publishing.</td>
<td>Fused quartz substrates</td>
<td></td>
<td>0.5 μm, 0.93 μm, 1.92 μm</td>
<td>298 K</td>
<td>303 K</td>
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<td></td>
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<td>SiO₂ and Vanadium dioxide</td>
<td></td>
<td>308 K</td>
<td>313 K</td>
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<tr>
<td>Plate-to-plate</td>
<td>Reprinted with permission from Ito et al., in 2017[41]. Copyright (2017) American Chemical Society.</td>
<td>SiO₂ and Vanadium dioxide</td>
<td></td>
<td>370 nm</td>
<td>355 K</td>
<td>295 K</td>
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<td></td>
<td>385 K</td>
<td>325 K</td>
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<td>Plate-to-plate</td>
<td>Zhang et al., in 2016[42]. Copyright 2016, AIP Publishing.</td>
<td>Two 1 cm by 1 cm doped-Si parallel plates</td>
<td></td>
<td>200 nm–780 nm</td>
<td>318.5 K</td>
<td>302.3 K</td>
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<td>Plate-to-plate</td>
<td>Reproduced from DeSutter et al., in 2019[43], with permission from Springer Nature.</td>
<td>5.2 × 5.2mm² silicon plates</td>
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<td>110mm–1000nm</td>
<td>305 ± 0.5 K-400 ± 0.5 K</td>
<td>300 ± 0.5</td>
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<td>Plate-to-plate</td>
<td>Reprinted with permission from Ying et al., in 2020[44], Copyright (2020) American Chemical Society.</td>
<td>Highly doped silicon chips with 1 × 1 cm² size</td>
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<td>507 ± 47 nm–190 ± 20 nm</td>
<td>400 K</td>
<td>300 K</td>
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<td>Plate-to-plate</td>
<td>Reproduced from St-Gelais et al., in 2016[45], with permission from Springer Nature.</td>
<td>Parallel SiC nanobeams</td>
<td></td>
<td>42 nm–1500 nm</td>
<td>293 K–720 K</td>
<td>293 K</td>
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<td>Plate-to-plate</td>
<td>Reprinted with permission from Fiorino et al., in 2018[46], Copyright (2018) American Chemical Society.</td>
<td>Parallel planar surfaces</td>
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<td>25 nm–10 μm</td>
<td>ΔT = 13 K</td>
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<td>Plate-to-plate</td>
<td>Reprinted with permission from Salihoglu et al., in 2020[47], Copyright (2020) American Chemical Society.</td>
<td>Two quartz plates</td>
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<td>7 nm</td>
<td>ΔT = 7.1 K</td>
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<td>Plate-to-plate</td>
<td>Reproduced from Zhu et al., in 2019[48], with permission from Springer Nature.</td>
<td>An unbiased photodiode and a planar surface</td>
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<td>8.2 μm, 1.3 μm, 378 nm, 285 nm, 181 nm, 78 nm</td>
<td>ΔTcal &lt; 0, cooling can be observed in some conditions</td>
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<td>Plate-to-plate</td>
<td>Reprinted with permission from Fiorino et al., in 2018[49], Copyright (2018) American Chemical Society.</td>
<td>Doped Si and VO₂ surfaces</td>
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<td>155 nm, 250 nm, 500 nm</td>
<td>ΔT = −70 K–70 K</td>
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<td>Plate-to-plate</td>
<td>Reproduced from Thompson et al., in 2020[49], with permission from Springer Nature.</td>
<td>Two coplanar SiN membranes</td>
<td>1 μm–35 μm</td>
<td>ΔT = 7–9 K</td>
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<td>Plate-to-plate</td>
<td>Ghosh et al., in 2008[52]. Copyright 2008, AIP Publishing.</td>
<td>Suspended graphene flakes and silicon substrate</td>
<td>775 nm</td>
<td>ΔT = 70 K–100 K</td>
<td>Thermal conductivity in the range of 3080–5150 W/m K</td>
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<td>Plate-to-plate</td>
<td>Reproduced from Yang et al., in 2018[53], CC BY 4.0.</td>
<td>Two macroscopic graphene sheets</td>
<td>430 nm ± 25 nm</td>
<td>303 K–348 K</td>
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<td>Plate-to-plate</td>
<td>Reprinted with permission from Shi et al., in 2019[54], American Chemical Society.</td>
<td>Two identical graphene-covered nano silica heterostructures</td>
<td>170 nm–1200 nm</td>
<td>323.2 ± 0.5 K</td>
<td>301.5 ± 0.5 K</td>
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<td>Plate-to-plate</td>
<td>Reproduced from Shi et al., in 2021[55], CC BY 4.0.</td>
<td>Graphene/SU8 five-layered heterostructures</td>
<td>52.4 nm–57 nm</td>
<td>303.15 K–328.15 K</td>
<td>303.15 K</td>
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<td>Plate-to-plate</td>
<td>Reprined with permission from Shi et al., in 2022[56], American Chemical Society.</td>
<td>Graphene-covered SU8 single-layered heterostructures</td>
<td>~81.3 nm</td>
<td>308.15 K</td>
<td>303.15 K</td>
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<td>269 K</td>
<td>90 K</td>
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<td>Plate-to-plate</td>
<td>Shi et al., in 2015[59]</td>
<td>Metal nanowire arrays</td>
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<td>~100 nm</td>
<td>ΔT = 29 K</td>
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<td>Plate-to-plate</td>
<td>Reprinted from Du et al., in 2020[60]. Copyright (2020), with permission from Elsevier.</td>
<td>Silicon nanorod arrays</td>
<td>50 nm,500 nm, 1 mm</td>
<td>322 K</td>
<td>300 K</td>
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<td>Plate-to-plate</td>
<td>Reproduced from Lim et al., in 2018[61]. CC BY 4.0.</td>
<td>Metal-dielectric multilayer structure</td>
<td>160 nm–1000 nm</td>
<td>400 K</td>
<td>300 K</td>
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<td>Plate-to-plate</td>
<td>Lim et al., in 2020[63]. Copyright 2020, American Physical Society.</td>
<td>Doped Si and SiO$_2$</td>
<td>380 nm–2200 nm</td>
<td>430 K</td>
<td>300 K</td>
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<td>Plate-to-plate</td>
<td>Tang et al., in 2020[64]. Copyright (2020) American Chemical Society.</td>
<td>6H-SiC and doped Si surfaces</td>
<td>150 nm</td>
<td>300 K–380 K</td>
<td>300 K</td>
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<td>Plate-to-plate</td>
<td>Reproduced from Iqbal et al., in 2022[65], CC BY 4.0.</td>
<td>Graphene-SiC heterostructures</td>
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<td>Reprinted from Williams et al., in 1986[66], Copyright (1986), with permission from Elsevier.</td>
<td>Scanning thermal profile</td>
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<td>Tip-to-plate</td>
<td>Müller-Hirsch et al., in 1999[68]</td>
<td>Scanning thermal microscope</td>
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<td>&lt;100 nm</td>
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<td>100 K</td>
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<td>Tip-to-plate</td>
<td>Kittel et al., in 2005[69]</td>
<td>Scanning thermal microscope</td>
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<td>&lt;10 nm</td>
<td>300 K</td>
<td>100 K</td>
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<tr>
<td>Tip-to-plate</td>
<td>Kittel et al., in 2008[70]</td>
<td>Scanning thermal microscope</td>
<td></td>
<td>9 nm</td>
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<td>110 K</td>
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<td>Scanning tunneling microscope</td>
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<td>Reproduced from Kim et al., in 2015[73], with permission from Springer Nature.</td>
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<td>2 nm–400 nm</td>
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<td>310 K</td>
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<td>Reproduced from Kloppstech et al., in 2017[74], CC BY 4.0.</td>
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<td>Scanning thermal microscopy probe</td>
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<td>Few Å to 5 nm</td>
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<td>Sphere-to-plate</td>
<td>Chen et al., in 2008[76]</td>
<td>A microsphere and a substrate using a biomaterial cantilever</td>
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<td>100 nm–10 μm</td>
<td>∆T = 46.5 K</td>
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<td>A microsphere and a flat surface</td>
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2.1. Plate-to-plate structure

2.1.1. Early experiments

To the best of our knowledge, the first realization of plate-to-plate measurements was reported by Cravalho et al. at the AIAA conference and in a subsequent paper[22,23]. The initial measurements of the NFRHT between plates are conducted between two copper disks with a diameter of 85 mm at liquid helium temperatures. The phenomena of near-field effect have been observed when the two plates were separated by 200 μm. The overall enhancement of the measured heat flow was an order of magnitude larger than that they predicted by computational wave interference and tunneling effect[24]. In 1969, Hargreaves[25] became the first researcher to successfully measure plate-to-plate NFRHT at room temperature, varying the gap size from 1 μm to 5.8 μm. The results showed that at room temperature (emitter temperature 323 K and receiver temperature 306 K), the radiative heat transfer strongly depended on the distance between the plates, with a significant increase when the gap size turns smaller than 2.5 μm. These results of calculations allowing comparison were obtained by Polder and Hove two years later[26]. The early experimental attempts[22,25] conducted at liquid helium temperature and room temperature serve as valuable references for subsequent NFRHT experiments.

2.1.2. NFRHT without graphene

Following these pioneering measurements, the need for a better understanding of heat transfer between closely spaced objects has led to new experimental results on heat flow between parallel planes until 21st
century. In 2008, Hu et al.\cite{29} further measured NFRHT between two parallel glass optical plates. The observed enhancement in radiative heat flux was much larger compared to the metallic plates. The two samples used in this experiment were glass plates with dimensions of $1 \times 1$ in$^2$. The experimental setup is shown in Figure 3(a). The spacing between the sample pieces was maintained using 1 μm diameter polystyrene particles. The heat transfer coefficient through the micrometer gap was approximately twice as large as the value recorded in the far-field data and 50% larger than the blackbody limit. The experimental data exhibited reasonable agreement with the calculated results.

Subsequently, NFRHT with tunable gap sizes was investigated in two studies\cite{30,31}. Ottens et al. reported the measurement of NFRHT heat flux between two sapphires with an area of $50 \times 50$ mm$^2$ under various temperature differences and intervals at room temperature. The experimental setup is shown in Figure 3(b). The measured heat transfer coefficients (Figure 3(c)) demonstrated a reasonably close agreement with the theoretically predicted heat transfer coefficients, despite a slight deviation due to the surface curvature of the samples.
Kralik et al.\textsuperscript{[31,32]} conducted the NFRHT experiment between two parallel tungsten plates at liquid helium temperature, and the gap between the two plates varied from 1 μm to 500 μm, as shown in Figure 3(d).\textsuperscript{[32]} The temperature difference between the heater and the surface of the hot sample was less than 0.1 K, and the heat flux was measured using a thermal resistance-type heat flux meter positioned at the bottom of the device. The results are shown in Figure 3(e). Similar to the previous report on sapphire plates\textsuperscript{[30]}, the difference observed can be attributed to the concavity of the tungsten plate. It was worth noting that, despite the concavity, the measured heat flux at a 2 μm gap was still two orders of magnitude higher than the blackbody heat flux.

In addition to the experimental apparatus with independent macroscopic emitter and receiver plates, there have been studies that explore approaches based on microelectromechanical systems (MEMS)\textsuperscript{[33–35]} to study NFRHT between suspended microstructures within partially monolithic devices. Feng et al.\textsuperscript{[33,34]} employed MEMS techniques to measure near-field heat flow and observed values approximately 10 times higher than the blackbody limit at a gap of 1 μm in the temperature range of 300 K to 400 K. All of the aforementioned experiments\textsuperscript{[22,25,29–34]} achieved a gap distance exceeding 1 μm between the emitter and the receiver.

In 2014, St-Gelais et al.\textsuperscript{[35]} conducted MEMS to measure NFRHT of a 250 nm gap between parallel nanobeams (1.1 μm × 500 nm thick, 200 μm length) coated with a 100 nm layer of SiO\textsubscript{2}. Results showed that the near-field heat transfer at a 250 nm gap was 7 times stronger than the limit imposed by far-field radiation. This effect was observed when the temperature of the mobile sensing beam was 14.7 K higher than the ambient room temperature. The approach used in this study involved integrating the nanobeam with MEMS actuation. This technique shows promise in facilitating the development of new near-field thermal control devices, such as thermal rectifiers and thermal transistors.

Subsequently, Lim et al.\textsuperscript{[36]} utilized a novel MEMS-based platform to quantitatively measure the NFRHT between doped silicon plates. The maximum radiative heat transfer coefficient of 25.0 W/m\textsuperscript{2}K was obtained and approximately 2.91 times greater than the blackbody limit at a 400-nm vacuum gap. Experiments conducted by Lim et al.\textsuperscript{[36]} were limited by difficulties in angular alignment, surface curvature and particle contamination. To address these limitations and achieve a direct and systematic measurement of the radiative heat flow between two parallel planes separated by a nanoscale vacuum gap, Song et al.\textsuperscript{[37]} measured NFRHT between prototype materials (SiO\textsubscript{2}-SiO\textsubscript{2}, Au-Au, SiO\textsubscript{2}-Au and Au-Si) under the vacuum gap from <100 nm to 10 μm. Figure 4(a) and Figure 4(b) show scanning electron microscope (SEM) images of the novel receiver and emitter, respectively. The height of the Si mesa was carefully designed so that only its top surface formed a nanoscale gap with the receiver, while the remainder of the device remained in the far field. For accurate alignment of the emitter and receiver in parallel and laterally, a custom nanopositioning platform was employed. The outcomes of their experiments revealed a significant increase in near-field radiative conduction, surpassing the far-field limit by a factor of 100 to 1000 at room temperatures. Their experimental approach of using the MEMS-based platform\textsuperscript{[35–37]} allowed for contactless modulation of thermal conduction and radiative cooling, thus paving the way for novel thermal management strategies in the future.
Maintaining nanoscale vacuum gaps between macroscopic surfaces in NFHRT experiments poses a significant challenge. Bernardi et al.\cite{38} addressed this issue by measuring the NFRHT between intrinsic silicon planes under large temperature differences using a customized platform. Figure 5(a) shows the near-field radiation heat exchange device with a fixed minimum separation gap of 150 nm. They measured the radiative heat transfer under a substantial temperature difference of 120 K. Remarkably, they achieved an enhancement over the blackbody limit by a factor of 8.4 when the gap size was reduced to 150 nm. This breakthrough paved the way for the development of novel evanescent wave-based systems. In a similar vein, Ghashami et al.\cite{39} conducted NFRHT experiments between crystalline quartz with an area of $5 \times 5$ mm$^2$. They observed a remarkable thermal radiation enhancement of over 40 times compared to the blackbody limit when employing thermal gradients of approximately 156 K. Using micromachined low-density pillars, Ito et al.\cite{40} obtained heat transfer coefficients in submicron gaps. Building upon this work, Ito et al.\cite{41} subsequently reported experimental findings on NFRHT controlled by the phase transition of vanadium dioxide. Overall, the comprehensive experimental protocols established by these studies\cite{38–41} facilitate the measurement of NFRHT for various materials and structures. By achieving narrower gap distances of 150 nm and larger temperature differences of up to 156 K, researchers can now investigate NFRHT more effectively.

Figure 4. Microdevices for probing NFRHT between parallel-planar surfaces. Reproduced from Song et al.\cite{37}, with permission from Springer Nature.
Figure 5. The experimental setup for near-field radiation measurement in a large area. (a) the NFRHT device in a vacuum chamber (Reproduced from Bernardi et al.’s study[38], CC BY 4.0); (b) the variation of radiative heat flow with temperature and gap (Reproduced from Bernardi et al.’s study[38], CC BY 4.0); (c) schematic diagram of the experimental setup for measuring the NFRHT between two plates[42] (Copyright 2016, AIP Publishing); (d) the radiative heat transfer coefficients of different gaps for 14 measurements[42] (Copyright 2016, AIP Publishing); (e) NFRHT measuring device. Reproduced from DeSutter et al.’s study[43], with permission from Springer Nature; (f) variation of radiative heat transfer coefficient with gap. Reproduced from DeSutter et al.’s study[43], with permission from Springer Nature.

Later, Watjen et al.[42] used two $1 \times 1$ cm$^2$ doped silicon plates to conduct NFRHT experiments with a vacuum gap ranging from 200 nm to 780 nm. The experimental device is shown in Figure 5(c). The spring pressing device was positioned atop the entire apparatus to compress the two sample pieces. As shown in Figure 5(d), the largest measured radiative heat transfer coefficient reached 11 times the blackbody limit for a gap distance of 200 nm when the temperature of the emitter and receiver were 318.5 K and 302.3 K, respectively.

Afterwards, DeSutter et al.[43] proposed an NFRHT device with a fixed gap distance and a large sample area. As shown in Figure 5(e), the emitter and receiver, each with a surface area of $5.2 \times 5.2$ mm$^2$, are separated by SU-8 micropillars. The results showed that the maximum enhancement of NFRHT was approximately 28.5 times greater than the blackbody limit when maintaining a gap distance of 110 nm (Figure 5(f)). Micropillars were utilized to minimize parasitic heat conduction while preserving structural integrity. These devices have opened up possibilities for potential NFRHT applications in energy conversion and thermal management. Due
to the heat stability of SU-8, the NFRHT device described in this study cannot operate at temperatures exceeding 450 K. However, by maintaining the same design and adjusting the fabrication process (for example, using hybrid SU-8/SiO₂ micropillars), the researchers expect the proposed device to withstand temperature differences exceeding 1000 K.

Most of the previously reported near-field experiments for larger area flat plates either involve additional fabrication processes, which increase the complexity of the sample preparation process or utilize SEM and optical interferometry to characterize the gap between samples, limited to optical or infrared transparent mediums. In near-field experiments, it is crucial to achieve accurate gap determination with fewer or simpler manufacturing processes for large centimeter-scale samples, thus reducing the chance of sample contamination and ensuring more accurate experimental results. Ying et al.⁴⁴ measured the NFRHT between two highly doped silicon with 1 × 1 cm² size. The experimental setup is shown in Figure 6(a). The sample intervals were adjusted by carefully crafted SU-8 nanopillars, allowing for vacuum gaps ranging from 507 ± 47 nm to 190 ± 20 nm, as precisely determined by capacitance measurements. As shown in Figure 6(b), the near-field effect between the heavily doped silicon plates resulted in an enhancement of radiative heat transfer exceeding the blackbody limit by 11 times when the vacuum gap was 190 nm and the temperature difference between the emitter and the receiver was 74.7 K. The prepared SU-8 nanopillars offered a straightforward method to generate nano-vacuum gaps without necessitating additional electrode microfabrication or etching on the actual sample surface. This approach significantly reduced conductive heat transfer and minimized the probability of sample contamination in near-field experiments. Notably, successful NFRHT experiments have been conducted between large silicon plates measuring 1 × 1 cm²⁴²,⁴⁴.

![Figure 6](image)

**Figure 6.** (a) Schematic diagram of near-field thermal experiment setup. Reprinted with permission from the study by Ying et al.⁴⁴ (Copyright 2020, American Chemical Society). (b) Relation between near-field radiant heat flow Q and temperature difference between emitter and receiver at three different vacuum gaps. Reprinted with permission from the study by Ying et al.⁴⁴ (Copyright 2020, American Chemical Society).

St-Gelais et al.⁴⁵ investigated the NFRHT of parallel SiC nanobeams in the deep subwavelength range. They employed parallel nanobeams integrated with an electrostatically driven actuator (Figure 7(a)) to facilitate heat transfer between the two parallel nanobeams at the deep subwavelength level. The researchers successfully demonstrated the enhanced NFRHT of these parallel beams in the deep subwavelength region (~100 nm) under high temperature gradients of 260 K. This nanoscale approach holds promise for NFRHT applications, especially in near-field thermophotovoltaic energy conversion. The method employed by St-Gelais et al.⁴⁵ yielded a significant net energy flux between the beams (Figure 7(b)). This net energy flux is of greater importance in energy conversion applications than the relative enhancement of far-field radiation.
Thus, their findings provide valuable insights for the advancement of energy conversion technologies in the field of NFRHT.

Figure 7. The device for near-field radiation measurement at ultra-close range. (a) diagram of MEMS. Reproduced from the study by St-Gelais et al.\cite{45}, with permission from Springer Nature. (b) Near-field heat transfer intensity varies with heating beam temperature. Reproduced from the study by St-Gelais et al.\cite{45}, with permission from Springer Nature. (c) Schematic diagram of the NFRHT measurement configuration. Reprinted with permission from the study by Fiorino et al.\cite{46} (Copyright 2018, American Chemical Society). (d) The relationship between the heat flow and the gap size. Reprinted with permission from the study by Fiorino et al.\cite{46} (Copyright 2018, American Chemical Society). (e) schematic diagram of the experimental setup. Reprinted with permission from Salihoglu et al.\cite{47}, (Copyright 2020, American Chemical Society). (f) The variation of the radiative heat flow with the gap. Reprinted with permission from Salihoglu et al.\cite{47} (Copyright 2020, American Chemical Society).

When the gap between parallel surfaces narrows to the nanometer scale, the radiative heat transfer rate is expected to exceed the blackbody limit by several orders of magnitude. However, prior to 2018, researchers had only achieved a 100-fold enhancement in experiments due to limitations imposed by device curvature and particle contamination, which restricted the smallest achievable gap size to 50 nm. In a notable advancement, Fiorino et al.\cite{46} demonstrated a significant improvement by achieving a 1200-fold enhancement relative to the
far-field in their investigation of near-field radiation between parallel planar surfaces. To accomplish this, they employed a novel method utilizing a microscopic emitter and a macroscopic slab (Figure 7(c)). The emitter microdevice was fabricated from Si and featured a square mesa, measuring 20 μm in height and 50 μm × 50 μm in size. The upper surface of the mesa, which was the part that entered the near field of the receiver, was coated with a 2 μm thick layer. The experimental results (Figure 7(d)) revealed a pronounced enhancement of NFRHT at a remarkably small gap size of 25 nm, surpassing the blackbody limit by over 700 times.

Subsequently, Salihoglu et al. [47] conducted a study on NFRHT at a closer distance (7 nm) by measuring the near-field radiation between two quartz plates. Figure 7(e) shows schematic diagrams of the experimental setup including manual and piezoelectric manipulation stages for the substrate and mask, an ISPI (interference spatial phase imaging) system for measuring the gap between the substrate and mask, an optical interferometry system for coarse tilt measurements, and a microfabricated sensor for measuring temperature changes induced by near-field radiation. All components shown in Figure 7(e) were housed in a vacuum chamber, except for the ISPI camera, laser and optical interferometry components. The entire instrument underwent sampling and calibration under an ultralow-particulate-air (ULPA) filter. The results showed that the near-field radiation was enhanced by 4 orders of magnitude compared to the blackbody radiation. Additionally, the experimental findings verified the theoretical prediction of separation below 10 nm. The employed experimental techniques exhibited promise for studying near-field radiation among different materials and potentially for expanding investigations into radiation at even closer distances.

It is evident that the remarkable enhancement of thermal radiation between general metals and media has been thoroughly tested, and the associated formula has also been experimentally verified. The development of NFRHT promotes its wide application in thermal rectification, photonic cooling and thermal diodes. In terms of experimental evidence, Fiorino et al. [48] have demonstrated thermal rectification at the nanoscale between doped Si and VO₂ surfaces. In another study, Zhu et al. [16] have applied NFRHT to achieve near-field photonic cooling and introduced the optical-refrigeration technique in 2019. They utilized a nanopositioning platform, along with calorimetry and thermometry, to systematically investigate the cooling effect of the calorimeter. Results showed that cooling effects could be observed under different conditions, depending on the size of gap distance and the bias voltage applied to the photodiode. Furthermore, Thompson et al. [49] have conducted experiments on radiative heat transfer between two coplanar SiN membranes in the far-field, aiming to modulate the heat current between two nanostructures. These experiments on NFRHT demonstrated gap distances ranging from less than 100 nm [16,45,46] to as small as 7 nm [47]. These findings pave the way for the development of advanced radiative thermal management systems in various applications.

2.1.3. NFRHT with graphene

In recent years, graphene (Gr), consisting of a single layer of carbon atoms packed in a honeycomb structure, has emerged as a material with a unique plasmonic response in the infrared band. This property makes it a promising choice for controlling the excitation and emission of thermal photons. In comparison to highly doped plasmonic semiconductors, graphene offers significant advantages in terms of transferability and integration with different substrates, along with good thermal stability. Theoretical investigations have explored the potential applications of graphene in TPVs [50,51], thermal circuits [52], and other thermal management devices. However, obtaining high-quality, large-scale graphene samples, particularly for near-field applications that require precise surface topography and substrate alignment, is challenging. In a study by Yang et al. [53], a custom-made setup was used to directly measure plasmon-mediated thermal radiation between two macroscopic graphene sheets. The experimental setup is shown in Figure 8(a). The gap distance was 430 nm ± 25 nm in experiments. Results showed that the heat flux was 4.5 times larger than the blackbody
limit (Figure 8(b)). Moreover, the positive impact of graphene plasmons on intrinsic silicon substrates, characterized by low infrared losses and thermal emissivity, was further confirmed.

Figure 8. Graphene-based near-field radiative heat exchange device. (a) Schematic diagram of the home-made measurement device. Reproduced from Yang et al.’s study[53], CC BY 4.0. (b) The variation of radiative heat flow with temperature and gap. Reproduced from Yang et al.’s study[53], CC BY 4.0. (c) Schematic illustration of structure for the active area. A symmetric cross graphene sheet with \(L_1 = 5\, \text{mm}, \, L_2 = 3.5\, \text{mm}\) was covered onto the surface of ~2.06-μm-thick SiO\(_2\) film deposited on the intrinsic Si substrate. Inset is the photo of the well-prepared sample. Reprinted with permission from Shi et al.’s study[54]. Copyright (2019) American Chemical Society. (d) Comparison of the NFRHT power (normalized with the corresponding BB limit) for Gr/SiO\(_2\), SiO\(_2\), and ideal Gr/intrinsic-Si with a gap distance varying from 170 to 400 nm. Reprinted with permission from Shi et al.’s study[54]. Copyright
However, despite the broadband properties of SPPs of graphene, near-unity energy transmission only occurs within a narrow wave-vector range where the SPPs are supported, which limits the enhancement. In view of this, Shi et al.\textsuperscript{[54]} investigated the NFRHT between two identical graphene-covered silica heterostructures. In their study, the authors used a pair of graphene-covered SiO\textsubscript{2} heterostructures (Gr/SiO\textsubscript{2}) (Figure 8(c)) to further improve NFRHT via stable coupling mode of surface plasmon and phonon polaritons (SPP-SPhPs). The SPP-SPhPs supported by Gr/ SiO\textsubscript{2} heterostructure can operate in a larger k-space range and a wider frequency band compared to those supported by plain SiO\textsubscript{2} or Gr/Si heterostructures, leading to a greater improvement of the NFRHT. Through the SPP-SPhPs coupling in the Gr/SiO\textsubscript{2} heterostructure, the researchers achieved a remarkable 64-fold enhancement compared to the blackbody limit at a gap of 170 nm (Figure 8(d)), which gives the strongest experimental demonstration of NFRHT for a gap distance in the regime of hundreds of nanometers.

Previous experiments have shown that surface phonon polaritons allow emission two orders of magnitude higher than the limit at a gap distance of 50 nm. To improve the enhancement (like up to three orders of magnitude) at such nanogap, Shi, Chen et al.\textsuperscript{[55]} further studied the roles of coupled multiple graphene plasmons in NFRHT enhancement and proposed a gap-bridging suspended crystal of multiple graphene sheets. The authors fabricated a Gr/SU8/5L heterostructure on a 300 nm-thick SiO\textsubscript{2} layer. The measured results achieved ~1129-fold enhancement compared to the blackbody limit at a gap of 55 nm, which improves the state of the art by around one order of magnitude. The experimental setup is shown in Figure 8(e), in which SU8 spacers and graphene sheets were stacked layer by layer. Graphene was in contact with Au/Ti electrodes to control the Fermi level. The experimental setup consisted of an emitter and a receiver with a fixed gap separated by SU8 nanopillars. The results (Figure 8(f)) showed that the Gr/SU8/5L heterostructures behaved the strongest experimental NFRHT at the gap distance of tens of nanometers.

Later, to improve the modulation of the near-field radiative heat flux, Shi et al. reported an ultrahigh modulation depth of ~32.2% by a pair of graphene-covered SU8 heterostructures at a gap distance of ~80 nm (Figure 8(g))\textsuperscript{[56]}. Dissimilar Fermi levels tuned by bias voltages allow the mismatched surface plasmon polaritons, which improves the modulation. The modulation depth when switching from a matched mode to a mismatched mode is ≈ 4.4-fold compared to that when switching between matched modes, and is the largest modulation depth to date in a two-body system with a fixed gap distance and operating temperature.

Meanwhile, Lu et al.\textsuperscript{[57]} have conducted experimental investigations on NFRHT between graphene-covered hexagonal boron nitride (hBN) heterostructures with a gap distance of 400 nm, demonstrating the coupling of SPPs and HPPs can experimentally enhance the NFRHT for the first time. Results showed that the NFRHT between graphene/hBN heterostructures was three times higher than the blackbody limit, and the sandwich structure of graphene/hBN/graphene multilayers was measured to be six times higher than the blackbody limit. Additionally, Thomas et al.\textsuperscript{[58]} have reported the heat flux modulation as high as 4 ± 3% when the gap size increases from 1 μm to 3 μm. These intriguing results regarding NFRHT with graphene\textsuperscript{[52–58]} are expected to inspire further exploration in the development of graphene-based NFRHT devices, advancements in technology, and innovative materials and structural designs.
2.1.4. NFRHT between metamaterials

In the near-field regime, the construction of high local density of states (LDOS) of photons for designing emitting surfaces has emerged as a fascinating field of study. This field aims to control thermal photons and explore new applications. Generally, there are two material approaches to improve LDOS far beyond non-polar media. One approach involves the utilization of natural materials with surface plasmons (such as graphene) or surface phonon polaritons (such as SiO$_2$). Another approach focuses on the use of infrared metamaterials, which can essentially generate the properties of bounded surface modes. Examples of such metamaterials include hyperbolic metamaterials and resonant meta surfaces. Compared to natural materials, artificial structures offer greater degrees of freedom to optimize electromagnetic performance for specific applications.

Shi et al.$^{[59]}$ conducted the first experimental study on the role of metamaterials in near-field thermal extraction using metal nanowire arrays. Their measurement scheme utilizing metal wire arrays demonstrated the guided wave behavior of hyperbolic media in the transfer of thermal photons. However, it was unable to provide a quantitative explanation. Consequently, it was necessary to conduct measurements on high-quality, large-scale samples with controllable loss to fully unveil the light-matter interactions in spontaneous emission from artificial structures. In this context, Du et al.$^{[60]}$ performed the first quantitative measurements of NFRHT between two hyperbolic metamaterials made of doped silicon nanorod arrays (SNA). These nanorod arrays were assumed to have the capability to transmit photons with large momentum, which is ultimately limited by the lattice constant, along with a high surface LDOS. To carry out their experiment, a custom-made setup was utilized. The measured near-field heat flux between SNAs reached up to 830 W/m$^2$ at a gap of 500 nm and a temperature deviation of 32 K, surpassing the blackbody limit by 4.7 times. The authors found that the local model built from the retrieved parameters was sufficiently accurate to explain the measurements of the nanorod medium, which validated the classical effective medium theory in hyperbolic metamaterials.

To examine the role of SPPs in metal materials in the infrared regime near room temperature, Lim et al.$^{[61]}$ conducted measurements on the radiative heat flux of the metal-dielectric multilayer structures at a gap of 160 nm, and the net radiative heat flux was 100 times larger than the value in far-field and approximately 7 times larger than the blackbody limit due to coupled SPP at the metal-dielectric interface. In a similar vein, Sabbaghi et al.$^{[62]}$ demonstrated that the radiative heat transfer between metallic planar surfaces could exceed the blackbody limit through the influence of thin-film effects. Results showed that the near-field radiative heat flux was 6.4 times higher than the blackbody limit and 420 times higher than the far-field radiative heat transfer at the vacuum gap of 215 nm when utilizing an aluminum film with a thickness of 13 nm. These experimental results were further validated by calculation, affirming the capability of the aluminum thin film to enhance the near-field radiative heat flux. It is important to emphasize that these NFRHT experiments$^{[59–62]}$, conducted between metamaterials, play a crucial role in guiding the design and application of near-field thermophonics based on metamaterials.

2.1.5. NFRHT between asymmetric structures

It is evident that in the majority of the previous experiments, the sample were composed of metal, glass, graphene, and hyperbolic metamaterials. However, in these experiments, both the emitter and receiver were typically made of the same material, constituting what is commonly referred to as a symmetrical structure. Nevertheless, for application in TPV devices, it is imperative that materials on both sides of the system differ. This necessitates an asymmetric configuration. Lim and Son$^{[63]}$ demonstrated a substantial enhancement of the near-field radiative heat flow between an asymmetric emitter and receiver by introducing a metal thin film as a plasmonic coupler. As shown in Figure 9(a), doped Si and SiO$_2$ served as emitter and receiver, respectively.
When Ti films were deposited on the SiO$_2$ side (Figure 9(b)), the SPP generated at the vacuum-Ti-SiO$_2$ interface can be effectively coupled with the SPP at the vacuum-doped Si interface in a wider frequency range, thereby enhancing the net radiant heat transfer. The results showed that the film can enhance heat transfer through both p- and s-polarization. Given that thin metal films are compatible with engineering applications of NFRHT, such as near-field TPV systems, the results obtained in this study will guide the future development of high-flux near-field devices.

Tang et al.$^{[64]}$ discovered spectral enhancement between 6H-SiC and doped Si surfaces through the excitation of SPP-SPhP coupling modes. Although enhancement resulting from the SPP-SPhP coupling mode was slightly weaker than that caused by the SPP-SPP mode, it exhibited a more pronounced monochromatic behavior with larger flux resonances. This coupled mode demonstrated the capability to control NFRHT, which was critical for numerous applications, including photonic thermal rectification and near-field TPVs.

Figure 9. Schematic diagram of (a) doped Si emitter and bare SiO$_2$ receiver (without plasma coupler) and (b) doped Si emitter and 10nm Ti film coated SiO$_2$ receiver (with plasma coupler). (c) Near-field radiation between doped Si emitter and bare SiO$_2$ receiver, (d) near-field radiation between doped Si emitter and Ti film-covered SiO$_2$ receiver$^{[63]}$. Copyright 2020, American Physical Society. (e) Schematic of the NFRHT measurement setup. Reproduced from the study by Iqbal et al.$^{[65]}$, CC BY 4.0. (f) measured and simulated results. Reproduced from the study by Iqbal et al., CC BY 4.0.

Recently, Iqbal et al.$^{[65]}$ introduced an all-optical method for characterizing heat transfer in a plasmonic-phonon hybrid polarized system between graphene-SiC heterostructures. Figure 9(e) shows the schematic diagram of the NFRHT measurement device. The emitter and receiver were separated by a fixed gap distance of 150 nm using a photoresist. The results were shown in Figure 9(f), the samples both with and without graphene exhibited pronounced super-Planckian thermal radiation effects. These works$^{[63–65]}$ provide an efficient approach to harnessing thermophotonic properties and applications facilitated by natural and artificial materials in the infrared spectral range.
To sum up, experimental research on parallel-plane NFRHT spans nearly half a century, and the instrument’s efforts and accomplishments have been extensive. Initially constrained to measuring gaps in the micron range, it has now advanced to measure gaps below 10 nm, rivaling the capabilities of tip-to-plate structures. As the most suitable structure for investigating NFRHT enhancement, parallel plates are poised to become a cornerstone technology in future applications related to energy conversion and thermal management.

2.2. Tip-to-plate structure

In the early 1980s, Binnig and Rohrer made groundbreaking inventions in the field of nanoscience and nanotechnology with the creation of the scanning tunneling microscope (STM) and atomic force microscope (AFM), which revolutionized the fields of nanoscience and nanotechnology. Shortly after the initial demonstration of these scanning probe microscopy techniques, Williams et al.\[^{66}\] introduced the concept of the scanning thermal profile (STP) in 1986. Similar to STM and AFM probes, the scanning probe used in STP featured a sharply tapered tip equipped with tiny thermocouples formed by connecting two dissimilar metals. Unlike STM, the STP probe operates in ambient air and can achieve high-resolution surface profiles (100 nm lateral and 3 nm vertical) based on the heat flow between the heated tip and the cold sample, thus eliminating the need for a conduction layer. An increase in the signal-to-noise ratio can be observed as the tip approaches the sample.

Dransfeld and Xu\[^{67}\] observed that the high vertical resolution of STP necessitates extreme sensitivity in detecting heat flow concerning the tip-sample distance. Consequently, they proposed an alternative explanation, suggesting that there was a greater heat flow between the tip and the sample through near-field radiation compared to that through air conduction/convection. Following this insight, Xu et al.\[^{67}\] devised a platform akin to the one employed by Williams et al.\[^{66}\] for measuring NFRHT between the scanning probe and the sample within a high vacuum chamber. Despite conducting creative and meticulous experiments, their results proved inconclusive. This was primarily due to the thermocouple’s lack of sensitivity, rendering it incapable of detecting any temperature changes until the tip physically made contact with the sample plate. It is noteworthy that their research has been instrumental in shaping early-stage NFRHT studies by introducing a new direction. The unique design of the sharply tapered scanning tip and the planar sample allowed for a minimal tip-sample gap of just 1 nm without the need for technically challenging alignment procedures. This innovation facilitated a more profound exploration of NFRHT compared to plate-to-plate structures. However, it is important to note that the limited heat transfer area associated with the tip also results in a reduced heat flow. Consequently, high-resolution calorimetric techniques become imperative for accurately measuring NFRHT in this configuration.

In subsequent research, Müller-Hirsch et al.\[^{68}\] conducted experiments involving the interaction between a scanning tip and a plate within an ultra-high vacuum environment. The first method, referred to as the STM device, shared key principles with the approach used by Xu et al.\[^{67}\], utilizing metal probes and planar thermocouples. Conversely, the second experiment, known as the SThM setup, featured a scanning thermal microscope probe in conjunction with a flat metal surface. Notably, both of these setups employed sharp tips, which marked a departure from the flat tips employed in prior studies. When the gap distance is below 10 nm, the temperature of the thermocouple increases significantly, indicating enhanced net heat transfer from room temperature to low temperature samples. However, within the experimental configurations of both the STM and SThM devices, uncertainty concerning the thermal resistance of various components posed a challenge, preventing researchers from precisely quantifying heat flow for direct comparison with theoretical predictions\[^{68}\].
Kittel et al.\cite{Kittel2023} performed NFRHT measurements between the tip of a scanning thermal microscope and a gold (or gallium nitride) surface. The experimental setup of this work was functionally similar to that employed by Müller-Hirsch et al.\cite{Muller-Hirsch2023}, albeit with a distinct approach to detector design. Kittel et al. redesigned the probe, as shown in Figure 10(a)\cite{Kittel2023}, by inserting a Pt/Ir (iridium) wire into a glass microtubule and subsequently pulling the microtubule until it fractured. NFRHT was studied by positioning the room-temperature tip near a cold substrate (100 K) and measuring the thermal voltage generated through a thermocouple. Remarkably, the authors observed that the heat flow experienced an enhancement of three orders of magnitude as the gap between the gold tip and the gold surface varied from 200 nm to 1 nm. Additionally, they noted that the measurements of heat flow in gallium nitride (GaN) substrates exhibited similar characteristics\cite{Kittel2023}. As a result of their findings, the authors proposed that non-local effects assumed significant importance at extremely small gap sizes within the geometries explored. By simulating the spatial dispersion of the dielectric function of the material, they reported a better agreement of trends between experiments and dipole calculations (solid lines in Figure 10(b)).

Furthermore, researchers employed SThM probes to conduct non-contact thermal microscopy at ultra-high voltage\cite{Kittel2023}. Specifically, in the galvanostatic STM mode, Kittel et al.\cite{Kittel2023} scanned SThM probe (50 nm probe radius, Figure 10(c)) on a cooled (100 K) Au substrate at room temperature while recording the thermovoltage of the probe. Comparing the STM topography (Figure 10(d)) and thermovoltage (Figure 10(e)) images of the STM, it becomes evident that this thermal microscopy technique indeed offers valuable insights into surface topography. Additionally, the authors employed a model that considered the tip as a spherical dipole. Using the perturbation method, they calculated the electromagnetic LDOS above the Au sample. Remarkably, these calculations yielded results that qualitatively matched the thermovoltage map (Figure 10(d)). However, it is worth noting that the authors expressed concerns regarding the application of the dipole approximation for calculations in gaps smaller than the tip size.

Later, experiments were conducted by the same group to study NFRHT between the tip (Figure 10(c)) and a dielectric monolayer of salt (NaCl) deposited on a flat substrate\cite{Kittel2023}. A significant enhancement of near-field heat transfer can be observed only when the gap size is smaller than 6 nm. Probe resistance was not explicitly reported, hence heat flow was not quantified.

Subsequent investigation of NFRHT in tip structures was the measurement of the heat flow from the planar heating island to the detector\cite{Kim2015}. The experimental setup of this work (Figure 10(f)) was quite different from previous studies. In the experiment, micropores with a diameter of 30 μm were coated with 2 μm thick SiO$_2$ and stored at room temperature. The measured data of membrane temperature (Figure 10(g)) exhibited good agreement with theoretical expectations. A horizontal offset of 160 nm in the data allowed for an even better agreement between experimental results and theory (Figure 10(g), inset). Due to the large radius of curvature of the probe, the minimum gap size in the experiment was limited to 300 nm, and the range below 100 nm was not detected.

It is evident from the above description that the tip-to-plate experimental setup has significant potential for studying and harnessing NFRHT in comparison to the plate-to-plate structure, especially in the extreme near-field with gap sizes around and below 10 nm. In 2015, Kim et al.\cite{Kim2015} deposited metal or dielectric layers on scanning probes and microdevices, promoting the investigation of extreme near-field radiation heat transfer (eNFRHT) between silicon dioxide, silicon nitride and gold surfaces, revealing a significant and gap size-dependent enhancement of radiative heat transfer. One of the key points in this work to overcome the technical challenges was the use of highly sensitive custom probes embedded with Au-Cr thermocouples, called scanning thermal microscopy probes. The probes were optimized for high thermal resistance and stiffness, and coated with the desired media, resulting in probe diameters ranging from 350 nm to 900 nm. The results showed
Figure 10. Measurement of NFRHT between the tip and flat specimens. 
(a) Schematic diagram of the SThm probe used by Worbes et al.\textsuperscript{[72]} Copyright 2013, American Physical Society. (b) Thermal current of gold tip and sample versus gap size\textsuperscript{[69]}. Copyright 2005, American Physical Society. (c) SEM image of the tip\textsuperscript{[70]}. Copyright 2008, AIP Publishing. (d) Au surface image obtained by STM\textsuperscript{[70]}. Copyright 2008, AIP Publishing. (e) Thermal image of the same gold surface\textsuperscript{[70]}. Copyright 2008, AIP Publishing. (f) SEM image of the suspended silica membrane and silica-coated probe used by Guha et al.\textsuperscript{[17]}. (g) Decrease of membrane temperature with tip-to-plane gap for both initial temperatures\textsuperscript{[17]}.

That near-field radiation was significantly enhanced at gaps of just a few nanometers, providing the initial experimental evidence for the well-established eNFRHT phenomenon between dielectrics and metallic surfaces, thus establishing the fundamental validity of wave electrodynamics in modeling eNFRHT (down to gaps as small as two nanometers) and NFRHT. However, it is worth noting that despite the tip-to-plate structure in these NFRHT experiments achieving smaller gap distances than those attainable with the plate-to-plate structure, the gap distances in these tip-to-plane experiments\textsuperscript{[17,67–73]} still exceeded 1 nm.

After a 10-year study of NFRHT at the tip plate by Kittel et al.\textsuperscript{[69–72]}, they have performed near-field radiative measurements with a gap distance smaller than 1 nm between a near-field scanning thermal microscope (NSThm) probe and a gold flat sample\textsuperscript{[74]}. The experiments were performed in a custom-made NSThm, which was based on a commercial scanning tunneling microscope (STM), in an ultra-high vacuum.
chamber. As shown in Figure 11 (a, b), the homemade STM probe consisted of a platinum wire, melted into a glass capillary, pulled out with a pipette, and then coated with 100 nm Au by electron beam in-situ evaporation. The protruding of the probe was usually about 1–2 μm in length, 300–700 nm in diameter, and the radius of the tip was about 30 nm. The results showed that in the gap of 0.2–7 nm, the measured heat flow was four orders of magnitude higher than the predicted value of fluctuating electrodynamics, and five orders of magnitude higher than the blackbody limit. This paper mentioned that there was currently a lack of suitable theoretical models under this distance and the range of geometries, whether the measured heat flow can be explained by phonon or photon tunneling, or another unknown mechanism, remained to be explored further. Subsequently, Tokunaga et al.\textsuperscript{[7]} investigated the physical mechanism of eNFRHT between gold surfaces in the sub-10nm-gap. They demonstrated the distinct dominant roles of radiation, acoustic phonon, and electron transport in the extreme near-field regime.

Figure 11. NSThM probe. (a) Schematic diagram of the probe in the Omicron-type tip holder. (b) Sectional diagram of the sensing end of the probe. (c) SEM image of a typical NSThM probe. (d) Transmission electron microscope image. Reproduced from the study by Kloppstech et al.\textsuperscript{[74]}, CC BY 4.0. (e) Experimental set-up of the SThM probes. Reproduced from the study by Cui et al.\textsuperscript{[75]}, CC BY 4.0. (f) SEM images of the SThM probes. Reproduced from the study by Cui et al.\textsuperscript{[75]}, CC BY 4.0.
NFRHT in Angstrom- and nanometer-sized gaps have been conducted by Cui et al.\cite{75}, who utilized SThM probes (Figure 11 (e,f)) with a diameter of 300 nm to measure the radiative conductance for solvent-cleaned probes. Results showed that the radiative conductance increased when the gap size was smaller than 2.5 nm, and reached the maximum value at the smallest gap size as small as a few Å. The radiative conductance observed in this work was ~30 nW/K, that was three to four orders magnitude higher than the calculated prediction by theory of fluctuational electrodynamics. Authors have explained this phenomenon by the possible presence of contaminants on the sample. Subsequently, they employed cleaning probes by oxygen plasma-based techniques to obtain thermal conductance reduced by a factor of 2. The approaches and insights presented in these studies\cite{74,75} will be valuable in the development of measurements in the field of NFRHT in sub-1 nm gaps.

Thanks to recent technological advances, NFRHT has successfully minimized the spatial gap between the tip and the plate to just a few Å. Furthermore, both experimental evidence and theoretical support have significantly propelled the advancement of NFRHT.

2.3. Sphere-to-plate structure

Studying the NFRHT between spheres and plates represents a compromise between plate-to-plate geometry and tip-to-plate geometry. The sphere-to-plate geometry allows for relatively greater heat flow than the tip-to-plate geometry due to the increased heat transfer area. Furthermore, macroscopic material properties (such as dielectric functions) can be employed even with moderately sized spheres when predicting NFRHT. Unlike plate-to-plate geometry, measurements using sphere-to-plate geometry do not require the technically challenging alignment and parallelism of the heat transfer surfaces, therefore small gaps (like 10 nm) can be achieved relatively easily.

In 2008, Narayanaswamy et al.\cite{76} developed an experimental technique of a cantilever-based bi-material approach to measure the NFRHT between a microsphere and a plate. The experimental setup is shown in Figure 12(a). The diameter of the silica sphere selected in the experiment was 50 μm, and the substrate was a glass microscope slide, which was rigidly attached to the motion console. In these experiments, the gap size was reduced by moving the substrate stepwise toward the sphere, with a minimum step size of 100 nm, representing the limit of the minimum gap size and gap size uncertainty.

Shen et al.\cite{77} employed a similar method to systematically explore the role of SPhPs in enhancing heat transfer. In these experiments, they reported a high-resolution (5 nm) piezoelectrically controlled sample position and presented near-field thermal transfer data for sphere-plate structures with a gap size of 30 nm. It was finally demonstrated that the polar medium surface exhibited extremely high radiative heat transfer at the nanogap (Figure 12(b)), which was 3 orders of magnitude higher than that predicted by Planck’s law of blackbody radiation. Subsequently, Shen et al.\cite{78} investigated the NFRHT between the gold-coated sphere and the substrate, with the measurement results shown in Figure 12(c)). Furthermore, Shi et al.\cite{79} demonstrated that the near-field conductance between SiO$_2$ spheres and doped Si substrates with different doping types (boron and arsenic) and concentrations can vary from 2 nW/K to 60 nW/K at a gap of 60 nm (Figure 12(d)).
Figure 12. Measurement of NFRHT between a sphere and a plate using a cantilever-based bimaterial approach. (a) Schematic diagram of the experimental setup[76]. Copyright (2009) American Chemical Society. (b) Near-field vacuum gap thermal conductivity versus gap size between silica spheres and glass slides (blue circles), doped Si surfaces (green squares), and Au surfaces (red triangles)[77]. Copyright (2009) American Chemical Society. (c) Experimental results of measuring the near-field conductance between an Au-coated 50 μm diameter silica sphere and an Au substrate[78]. Copyright 2012, AIP Publishing. (d) Experimental results of measuring the near-field conductance between 100 nm glass spheres and Si substrates with different doping types and concentrations[79]. Copyright 2013, AIP Publishing.

To conduct a detailed quantitative comparison between NFRHT theory and experiments in the nanometre regime, Rousseau et al.[80] conducted an experiment between silica microspheres and a heated silica (borosilicate) substrate. Their technique, shown in Figure 13(a), differed from that of Shen et al. in two significant ways. First, they measured the cantilever deflection using interferometry instead of the laser beam deflection. Second, they used the heated substrate as an emitter instead of employing heated spheres. Their results[70] for a 40-micron sphere are shown in Figure 13(b), which precisely demonstrate the validity of proximity approximation in the near-field heat transfer with microspheres. These results differ from the predictions in the studies by Narayanaswamy et al. and Shen et al.[76,78].

Two consecutive papers by Chevrier’s group[81,82] have demonstrated the tunability of NFRHT. The former publication[81] reported an investigation of NFRHT between a soda-acid glass sphere with a diameter of 40 μm and a heated VO₂ substrate. In the low-temperature insulating stage, the VO₂ substrate supported SPhPs and was expected to enhance the heat transfer to the SiO₂ spheres. In fact, the experimental data confirmed the predictions for gap sizes smaller than 150 nm (Figure 13(c)). Furthermore, they investigated another tuning mechanism by measuring the NFRHT between SiO₂ spheres and SiC substrates with and without a top-layer graphene[82]. They observed an increase in NFRHT in the presence of graphene (Figure
13(d)) and attributed this enhancement to thermally excited SPPs on graphene. In both works, it is critical to properly characterize and subtract the gap-related force effects from the total cantilever deflection.

![Figure 13. Sphere-to-plate NFRHT interferometric deflection based on a bimaterial cantilever beam. (a) Schematic diagram of the device. Reproduced from the study by Rousseau et al.[80], with permission from Springer Nature. (b) The vacuum-gap thermal conductance as a function of gap size obtained by experimental data and the theoretical mode. Reproduced from the study by Rousseau et al.[80], with permission from Springer Nature. (c) The cantilever deflection versus gap size measured on 40 μm diameter sodium salt glass spheres and VO₂ substrates[81]. Copyright 2012, American Physical Society. (d) Beam deflection measurements between SiC and SiO₂ spheres on SiC as well as 2 or 6 layers of graphene[82]. Copyright 2012, American Physical Society.](image)

The cantilever-based bimaterial approach described above represents a significant experimental breakthrough in NFRHT research. However, it may have two disadvantages: 1) the detection of the contact between the sphere and the plate relies on the deflection of the cantilever beam, which also monitors temperature changes through its deflection; 2) the cantilever, due to the electrostatic force between the sphere and the plate bending, also experiences deflections that can potentially interfere with the signals generated by temperature changes. Cahill et al.[83] identified these challenges and called for experimental solutions. The recent work by Song et al.[84] aims to develop a new experimental platform to address these challenges, which are described below.

Song et al.[84] utilized optical deflection scheme to conduct near-field radiation measurements between silicon nitride and suspended silicon spheres. The experimental setup is shown in Figure 14(a) and Figure (b), the emitter (Figure 14(c)) comprised a suspended silicon region to which a silicon dioxide sphere with a diameter of 53 μm was attached. The emitter was integrated with a platinum resistor heating thermometer, which modulated the temperature of the suspension region and sphere. The receiver (Figure 14(d)) was
constructed with silicon dioxide layers of varying thicknesses on a 100-nm-thick Au film deposited on a silicon nitride substrate. Using these devices, Song et al. systematically investigated NFRHT between silicon spheres and a set of SiO$_2$ films to demonstrate the effect of film thickness on NFRHT.

In their study, a receiver device covered with SiO$_2$ layers of varying thickness on a 100 nm-thick gold film was utilized (Figure 14(b)). The spheres and films underwent examination for roughness and cleanliness through various microscopy techniques including AFM and SEM. Contact between the emitter and receiver was detected using an optical deflection scheme for monitoring receiver displacement (Figure 14(e)). This stands in strong contrast to the cantilever-based bimaterial approach of NFRHT measurement technique described earlier, as in the technique described here, mechanical motion was optically detected, while temperature changes were registered by resistance thermometers. Therefore, mechanical and thermal effects were effectively decoupled in the calorimeter scheme based on suspended resistance.

![Figure 14. Experimental setup and equipment. Reproduced from the study by Song et al.\cite{84}, with permission from Springer Nature. (a) Schematic diagram of the experimental apparatus. (b) Schematic cross-section of the planar receiving area and spherical silica emitter. (c) SEM image of the suspended platform and optical image of the spherical emitter (inset). (d) SEM image of the receiver showing ribbed beams and overhanging areas. (e) Optical image of the emitter and receiver during alignment.](image)

According to the previous experimental results\cite{76-82} in sphere-to-plate structures, the gap distance between the microsphere and plate can be as small as 20 nm\cite{84}. Narrower gap distances can be achieved in the future with the development of nanoscale devices and near-field-based lithography.

3. Conclusion and prospect

The surge of interest in nanoscale heat transfer over the past 20 years has yielded important insights enabling nanostructured thermoelectric materials and interface engineering for the thermal management of electronic and photonic devices. Despite offering a wide array of unique opportunities for intricately
controlling heat flow and developing innovative energy conversion and information storage devices, the study of NFRHT has garnered considerably less attention. This is mainly due to the lack of appropriate experimental tools for systematically detecting NFRHT.

Since the first measurement of NFRHT using parallel copper disks, there have been significant improvements in NFRHT measurements. For applications of NFRHT in thermal management and radiative cooling technology, maintaining parallelism in plate-to-plate structures over large areas at the nanoscale gap distance is crucial. Simultaneously, it is important to maintain a temperature difference between the emitter plate and the receiver plate. To date, the minimum gap distance between parallel plates achieved is 7 nm, with a temperature difference of 7.1 K and an 18,000-fold enhancement of heat flux in thermal radiation[47]. To address measurement errors resulting from the inability to maintain complete parallelism in parallel plate measurements, researchers have explored the tip-to-plate structure for extreme NFRHT measurements. The tip-to-plate structure can achieve even closer distances, just a few Å, compared to parallel plates. The results of measured thermal conductance demonstrate that the fluctuation-dissipation theorem fails to describe NFRHT in the extreme near-field regime[75]. With the advancement of micro-nano technology, researchers have also investigated sphere-to-plate structures. Recent experimental techniques with sphere-to-plate structures have successfully decoupled mechanical motion from temperature measurements, allowing for precise measurements without the influence of electrostatic, Casimir, and Van der Waals forces[84]. Gap sizes can be controlled to as small as 20 nm, with NFRHT measurements achieving a resolution of approximately 100 pW.

As the most widely used structure to achieve near-field radiation, the plate-to-plate structure has been continuously undergone improvements by researchers. Currently, the plate-to-plate structure has demonstrated its capability to achieve near-field radiation measurements below 10 nm, thus significantly expanding the application range of near-field radiation. The advancement of technology in sensitive mechanical motion within nanogaps and the fabrication of functional thermometers will profoundly impact the measurement of NFRHT. Recent advances in experimental setups and progress in nanoscale techniques are expected to facilitate in-depth NFRHT measurements. In the future, a pressing challenge will be the development of experimental setups based on plate-to-plate structures, enabling measurements in smaller nanoscale gaps with larger surface areas and greater temperature differences. Additionally, a growing trend in NFRHT measurements involves tip-to-plate and sphere-to-plate structures, with a focus on achieving measurements at smaller tip and sphere sizes in the years to come.

In current NFRHT experiments, researchers primarily focus on two-body systems, while experiments involving more than two bodies have not yet been conducted. Many-body experiments in the field of NFRHT are anticipated in the future, promising significant advancements in radiative heat transfer technologies. To facilitate the development of appropriate experimental tools and enable in-depth measurements of extreme NFRHT, the fundamental theory and underlying mechanisms must be experimentally validated. Further research is necessary to investigate the spectral distribution of NFRHT, in order to explore the physical mechanisms related to thermal fluctuations, acoustic phonons, and electron transport. We firmly believe that the development of NFRHT experiments will not only contribute to the advancement of fundamental theory but also accelerate practical applications in the field of energy. A long-term challenge lies in the difficulty of integrating new materials into established NFRHT experimental platforms. The development of a flexible experimental platform capable of accommodating multiple materials holds the potential to enable NFRHT measurements between various materials, providing further evidence for theoretical studies and their translation into practical applications in energy harvesting and thermal management. In conclusion, we anticipate that NFRHT experiments will thrive in the near future, driving innovation and progress in the field.
Author contributions

Conceptualization, JZ, KS, LL and DF; methodology, JZ and KS; software, JZ and KS; validation, JZ and KS; formal analysis, LL, DF and HL; investigation, JZ and KS; resources, XW; data curation, JZ and KS; writing—original draft preparation, JZ and KS; writing—review and editing, JZ, KS and HL; visualization, JZ and KS; supervision, XW; project administration, XW; funding acquisition, XW. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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