coatings

Editorial

Micro/Nanomaterials for Heat Transfer, Energy Storage and Conversion

Ming-Jian He [1,2,*], Ya-Song Sun [3], Zhao-Long Wang [4] and Bo-Xiang Wang [5]

1 School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China
2 Key Laboratory of Aerospace Thermophysics, Ministry of Industry and Information Technology, Harbin 150001, China
3 School of Power and Energy, Northwestern Polytechnical University, Xi'an 710072, China
4 Interdisciplinary Research Center of Low-Carbon Technology and Equipment, College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China
5 Institute of Engineering Thermophysics, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
* Correspondence: hemingjian@hit.edu.cn

It is well known that micro/nanomaterials exhibit many physical properties in the fields of heat transfer, energy conversion and storage, and also have great prospects in nanoelectronics, sensors, photonic devices and biomedical applications. As carbon dioxide emissions continue to rise and fossil energy supplies shrink, there is a great demand for clean and renewable energy technologies.

The purpose of this Special Issue is to provide a platform for publishing and sharing the latest advances in micro/nanomaterials for heat transfer, energy storage and conversion, and to promote further research on energy storage, heat transfer enhancement, solar energy harvesting, radiative cooling, two-dimensional materials, etc., so as to reflect the latest developments and advances in all aspects.

Solar energy is the main type of renewable energy and the efficient use of solar energy is considered an effective way to solve the problems caused by the burning of fossil fuels, by creating nanoparticles, metamaterials for perfect absorbers and, finally, achieve efficient absorption. Energy storage and conversion can be achieved by directly converting heat energy into electricity using thermal photovoltaic technology. At the same time, waste heat can be recovered using thermoelectric generators (TEGs) to directly convert heat into electricity, and the latest high-performance thermoelectric (TE) materials improve the efficiency of TEG conversion. It has also been proved that near-field radiative heat transfer (NFRHT) can exceed the blackbody limit, which greatly promotes the development of energy harvesting and conversion. This Special Issue focuses on the application of micro- and nanomaterials in different aspects to achieve heat transfer, energy storage and energy conversion applications and improve the utilization of solar energy.

Wang et al. carried out extensive work related to a perfect solar absorber [1], which was based on both nanoparticles [2] and metamaterials [3]. First, the surrounding medium, material, geometry and morphology of those nanostructures made a significant difference in their solar-absorption efficiencies [1,2,4]. In addition, multiple materials working with special structures could arouse both electric and magnetic polaritons [5,6], which also contributed to the perfect broadband absorption for solar energy harvesting. Furthermore, compound materials with absorptive nanoparticles, such as carbon nanoparticles [7], achieved broadband absorption.

Furthermore, the applications of perfect solar absorbers strongly depend on the fabricated devices [8]. Typically, the specially designed metamaterial absorber with nanostructures can be fabricated by ion-beam sputtering, atomic-layer deposition, electron-beam lithography, thermal evaporation/electron-beam evaporation, and lift-off [9,10]. However, such a kind of manufacturing process costs too much, no matter the time or money, which

Citation: He, M.-J.; Sun, Y.-S.; Wang, Z.-L.; Wang, B.-X. Micro/Nanomaterials for Heat Transfer, Energy Storage and Conversion. *Coatings* **2023**, *13*, 11. https://doi.org/10.3390/coatings13010011

Received: 17 November 2022
Accepted: 18 November 2022
Published: 21 December 2022

is only suitable for laboratory exploration. With the fast development of the 3D-printing technique [11], various new solar evaporators are being proposed, which are cheap but with integrated functions [12–14] for high-efficiency solar vapor generation, promising applications of desalination, sterilization, wastewater treatment and so on [15].

Wang et al. carried out extensive work related to micro-nanomaterials in the field of hybrid PV/T systems [16,17]. They designed nanofluid and TiO_2/SiO_2 nanofilms as spectral-beam splitting (SBS) devices, which could split sunlight into specific wavelength bands: sunlight with photon energy at and close to the band-gap of PV cells was allocated to PV for producing electricity, while the remaining sunlight was allocated to thermal absorbers for producing thermal energy [18]. Recently, they designed and fabricated a novel thin-film solar cell with a serrated groove structure at the bottom, which could convert 400~800 nm sunlight to electricity and focus 800~2500 nm sunlight to produce high-temperature thermal energy [19].

Another application for micro-nanomaterials is radiative cooling (RC) [20]. Wang et al. [21] prepared high-transmittance RC-coating-embedded SiO_2 microparticles with optimized volumetric fractions and diameters. The coating achieved a transmittance of 91.3% in the visible-light band and emissivity of 93.7% in the "atmospheric window" band. In addition, inspired by the human skin wrinkle structure, they proposed and prepared a biomimetic radiative cooling (Bio-RC) coating with a biomimetic skin natural wrinkle structure, containing BaSO4 and SiO2 micro-nanoparticles [22]. The naturally wrinkled surface enhanced the control of the dual-band radiative properties of the Bio-RC coating in the solar band and the "atmospheric window" band. Overall, the method of combining micro-nanomaterials with the surface microstructure established by Wang's group could provide guidance for designing radiative cooling coatings.

With regard to the theme of this Special Issue, we note a variety of novel micro/nanomaterials is currently studied for the use of TPV technology. Since it was initially proposed in the 1950–1960s [23], thermophotovoltaics (TPVs), which converts heat into electricity via the photovoltaic (PV) effect, has been a long-lasting topic of research in the fields of thermal radiation, thermal energy conversion, solar energy, etc. [24]. A thermophotovoltaic (TPV) system is an efficient technology that converts thermal energy into electricity directly. It has wide applications due to the fact that various heat sources, e.g., solar energy, chemical energy, nuclear energy and industrial waste heat, can be utilized.

The emitter, a key component in the TPV system, absorbs energy from the heat source and emits radiative energy into the TPV cell for thermoelectric conversion. To improve the TPV system efficiency, the emitter should be spectrally selective, i.e., achieving high emittances in the convertible waveband of the TPV cell while exhibiting low emittances in the non-convertible waveband. To promote the development of the TPV system, Cai et al. focused on the problems of the mechanism and practical application of the system, especially in the aspects of metamaterial-emitter-based near-field TPV systems and thermal degradation of the TPV emitter [25–31].

Photonic crystals, metamaterials and meta-surfaces, which are artificial materials composed of micro/nanoscale building blocks, can be designed to demonstrate spectrally selective emissivity, that is, to enhance the emissivity at super bandgap wavelengths of the PV cell and suppress the sub-bandgap emissivity [32,33]. In addition, there is a trade-off between the output power density and conversion efficiency with respect to the high-emissivity bandwidth [34]. In the last few decades, there has been a continuing burst in the study of such selective thermal emitters for TPV, both theoretically and experimentally [33]. Nevertheless, we should be aware of the fact that, despite all the claimed high performance of many selective emitters, for practical applications, the long-time thermal stability at elevated temperatures (~1200K or even higher) and resistance against thermal shocks are of the most importance. Considerable attention has been paid to this subject in recent years [35–37]. Another promising area is the development of high-efficiency TPV cells using two-dimensional (2D) materials, for instance, van der Waals (vdW) bilayer antimonene [38] and Sb/InSe vdW heterostructure [39], while experimental works in this subject matter are yet to be conducted.

In the last few decades, there have been up and downs for the research and development of TPV [40,41]. Recently, there has been a resurgence of interest in this technology. There are several possible reasons. Firstly, the rapid development of nanofabrication leads to the invention of high-performance selective emitters, filters and back-surface reflectors, which enables a delicate control of the thermal emission spectrum, resulting in excellent spectral efficiency [42,43]. Secondly, low-bandgap TPV cells, especially III-V semiconductor cells, have also witnessed significant progress, which, nowadays, can achieve near-ideal quantum efficiencies and effective carrier-management capability [42,44]. Thirdly, there is a growing demand for developing high-efficiency, solid-state thermal-to-electrical energy conversion technologies in the current world towards the goal of carbon neutrality [45], which show important applications in wearable electronic devices [46], solar energy harvest [47] and so on. We can note that, currently, it seems to be quite demanding for thermoelectrics to further improve its conversion efficiency in a significant manner [48], while TPV is promising with potential high efficiency approaching the Carnot limit and a recent experimentally demonstrated world record, over 40% [49].

Thermoelectric generators (TEGs) can recover waste heat and directly convert heat to electricity. The recent development of high-performance thermoelectric (TE) material improves the converting efficiency of TEGs and greatly promotes the applications of thermoelectric devices. The ZT value achieved 2.8 in n-type SnSe crystals and bulk Cu1.94Al0.02Se materials were prepared, whose ZT value of 2.62 was obtained [50,51]. TEGs are applied for recovering heat from automotive, ships, industrial, geothermal well and solar radiation [52–54]. In addition, TEGs have been applied in space to provide power to satellites for decades [55].

To enhance the efficiency of TE devices, not only the development of high-performance TE materials, but also geometry optimization and system configuration design need to be analyzed. Geometry analysis concerning the TE module and TE system optimizes the module height, module number, heat exchanger to maximize power output and their economic feasibility [56–58]. A proper design of a converging configuration or an annular shape improves the efficiency of the TE system [59,60]. In addition to output performance analysis, the aging effects in TEGs are worth analyzing in the future. Large thermal stress results from thermal expansion mismatch at the junction, severely damaging the lifespan of TEGs [61]. Performance degradation also occurs during working cycles due to increased internal resistance at the joint of different materials in TEGs [62]. The selection of stable heat source, thermal management and better welding techniques is also vital in achieving better TEG performance.

Due to the coupling effect of evanescent waves, the near-field radiative heat transfer (NFRHT) between two objects can exceed the blackbody limit, which has attracted widespread attention and driven the development of fields, such as energy harvesting and conversion [63,64]. Hyperbolic materials (HMs) [65,66], whose components of the dielectric constant tensor have opposite signs, can excite hyperbolic phonon polaritons (HPPs) in a wide frequency range to further enhance the NFRHT [67]. However, most HMs studied previously are artificial structures constructed with periodically stacked subwavelength metallic and dielectric layers, whose hyperbolic properties are limited by the tangential wavevector component [68]. In comparison, the lattice constants of natural HMs are subnanometer in size and there is no need to consider this limitation. Therefore, it is of great significance to investigate the NFRHT between natural HMs. In recent years, Professor Wu investigated the NFRHT between natural HMs, including hBN and α-MoO3 [69–71].

Research on these topics has predicted theoretically and demonstrated experimentally a huge enhancement in NFRHT associated with excited surface polaritons, such as surface plasmon polaritons [72–75], volume-hyperbolic polaritons (v-HPs) and surface-hyperbolic polaritons (s-HPs) [76–78]. In general, these related surface polaritons are supported by 2D materials, hyperbolic metamaterials and natural hyperbolic materials.

These materials are deeply investigated and demonstrated by excited polaritons in the angular frequency region within a negative real component of the permittivity (Re[ε] < 0) in many studies [79]. It has greatly promoted the application of near-field thermal radiation in thermal rectifications [80], thermal transistors [81], thermal modulators [82,83] and near-field thermophotovoltaics [84–87].

The previous paragraphs in this paper introduced the application of micro- and nanomaterials in different technologies. Energy storage, heat transfer and energy conversion can be realized by using different technologies, which greatly improve the reuse rate of energy. The use of fossil fuels has aroused global concern about the security of energy supply and the increase in energy demand. Therefore, people are turning their attention to non-fossil fuels and the efficient use of fossil fuels. Near-field-radiation heat transfer can efficiently and rapidly transmit thermal radiation energy, which can be used to improve the energy utilization efficiency of micro-energy systems and implement flexible, accurate and efficient thermal management for micro-electronic devices. The thermal photovoltaic system, which directly converts thermal energy into electricity, has been tested in all major energy sectors, such as solar and biofuels, as well as the efficient use of fossil fuels.

Funding: This work was supported by the National Natural Science Foundation of China (No. 52206082), China Postdoctoral Science Foundation (No. 2021TQ0086), the Natural Science Foundation of Heilongjiang Province (No. LH2022E063) and the Postdoctoral Science Foundation of Heilongjiang Province (No. LBH-Z21013), all of which are gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, Z.; Cheng, P. Enhancements of absorption and photothermal conversion of solar energy enabled by surface plasmon resonances in nanoparticles and metamaterials. *Int. J. Heat Mass Transf.* **2019**, *140*, 453–482. [CrossRef]
2. Wang, Z.; Zhang, Z.M.; Quan, X.; Cheng, P. A numerical study on effects of surrounding medium, material, and geometry of nanoparticles on solar absorption efficiencies. *Int. J. Heat Mass Transf.* **2018**, *116*, 825–832. [CrossRef]
3. Wang, Z.; Zhang, Z.M.; Quan, X.; Cheng, P. A perfect absorber design using a natural hyperbolic material for harvesting solar energy. *Sol. Energy* **2018**, *159*, 329–336. [CrossRef]
4. Liang, Q.; Yin, Q.; Chen, L.; Wang, Z.; Chen, X. Perfect spectrally selective solar absorber with dielectric filled fishnet tungsten grating for solar energy harvesting. *Sol. Energy Mater. Sol. Cells* **2020**, *215*, 110664. [CrossRef]
5. Wang, Z.; Liu, Z.; Duan, G.; Fang, L.; Duan, H. Ultrahigh broadband absorption in metamaterials with electric and magnetic polaritons enabled by multiple materials. *Int. J. Heat Mass Transf.* **2022**, *185*, 122355. [CrossRef]
6. Liu, Z.; Duan, G.; Duan, H.; Wang, Z. Nearly perfect absorption of solar energy by coherent of electric and magnetic polaritons. *Sol. Energy Mater. Sol. Cells* **2022**, *240*, 111688. [CrossRef]
7. Wang, Z.; Quan, X.; Zhang, Z.; Cheng, P. Optical absorption of carbon-gold core-shell nanoparticles. *J. Quant. Spectrosc. Radiat. Transf.* **2018**, *205*, 291–298. [CrossRef]
8. Wang, Z.; Yang, P.; Qi, G.; Zhang, Z.M.; Cheng, P. An experimental study of a nearly perfect absorber made from a natural hyperbolic material for harvesting solar energy. *J. Appl. Phys.* **2020**, *127*, 233102. [CrossRef]
9. Chen, Y.; Hu, Y.; Zhao, J.; Deng, Y.; Wang, Z.; Cheng, X.; Lei, D.; Deng, Y.; Duan, H. Topology Optimization-Based Inverse Design of Plasmonic Nanodimer with Maximum Near-Field Enhancement. *Adv. Funct. Mater.* **2020**, *30*, 2000642. [CrossRef]
10. Chen, Z.; Zhang, S.; Chen, Y.; Liu, Y.; Li, P.; Wang, Z.; Zhu, X.; Bi, K.; Duan, H. Double Fano resonances in hybrid disk/rod artificial plasmonic molecules based on dipole-quadrupole coupling. *Nanoscale* **2020**, *12*, 9776–9785. [CrossRef]
11. Ge, Q.; Li, Z.; Wang, Z.; Kowsari, K.; Zhang, W.; He, X.; Zhou, J.; Fang, N.X. Projection micro stereolithography based 3D printing and its applications. *Int. J. Extrem. Manuf.* **2020**, *2*, 022004. [CrossRef]
12. Chen, L.; Zhang, Y.; Ye, H.; Duan, G.; Duan, H.; Ge, Q.; Wang, Z. Color-Changeable Four-Dimensional Printing Enabled with Ultraviolet-Curable and Thermochromic Shape Memory Polymers. *ACS Appl. Mater. Interfaces* **2021**, *13*, 18120–18127. [CrossRef] [PubMed]
13. Chen, L.; Duan, G.; Zhang, C.; Cheng, P.; Wang, Z. 3D printed hydrogel for soft thermo-responsive smart window. *Int. J. Extrem. Manuf.* **2022**, *4*, 025302. [CrossRef]
14. Xie, M.; Duan, H.; Cheng, P.; Chen, Y.; Dong, Z.; Wang, Z. Underwater Unidirectional Cellular Fluidics. *ACS Appl. Mater. Interfaces* **2022**, *14*, 9891–9898. [CrossRef] [PubMed]
15. Wang, Z.; Li, Y.; Gong, S.; Li, W.; Duan, H.; Cheng, P.; Chen, Y.; Dong, Z. Three-Dimensional Open Water Microchannel Transpiration Mimetics. *ACS Appl. Mater. Interfaces* **2022**, *14*, 30435–30442. [CrossRef] [PubMed]
16. Liang, H.X.; Wang, F.Q.; Yang, L.W.; Cheng, Z.M.; Shuai, Y.; Tan, H.P. Progress in full spectrum solar energy utilization by spectral beam splitting hybrid PV/T system. *Renew. Sust. Energy Rev.* **2021**, *141*, 110785. [CrossRef]

17. Liang, H.X.; Wang, F.Q.; Zhang, D.; Cheng, Z.M.; Zhang, C.X.; Lin, B.; Xu, H.J. Experimental investigation of cost-effective ZnO nanofluid based spectral splitting CPV/T system. *Energy* **2020**, *194*, 116913.
18. Liang, H.X.; Han, H.; Wang, F.Q.; Cheng, Z.M.; Lin, B.; Pan, Y.Z.; Tan, J.Y. Experimental investigation on spectral splitting of photovoltaic/thermal hybrid system with two-axis sun tracking based on SiO_2/TiO_2 interference thin film. *Energy Convers. Manag.* **2019**, *188*, 230–240. [CrossRef]
19. Liang, H.X.; Su, R.H.; Huang, W.M.; Cheng, Z.M.; Wang, F.Q.; Huang, G.; Yang, D.L. A novel spectral beam splitting photovoltaic/thermal hybrid system based on semi-transparent solar cell with serrated groove structure for co-generation of electricity and high-grade thermal energy. *Energy Convers. Manag.* **2022**, *252*, 115049. [CrossRef]
20. Liang, H.X.; Wang, F.Q.; Li, D.; Zhu, J.; Tan, J.Y. Optical properties and transmittances of ZnO-containing nanofluids in spectral splitting photovoltaic/thermal systems. *Int. J. Heat Mass Transf.* **2019**, *128*, 668–678.
21. Cheng, Z.M.; Wang, F.Q.; Gong, D.Y.; Liang, H.X.; Shuai, Y. Low-cost radiative cooling blade coating with ultrahigh visible light transmittance and emission within an "atmospheric window". *Solar Energy Mater. Solar Cells* **2020**, *213*, 110563.
22. Cheng, Z.M.; Han, H.; Wang, F.Q.; Yan, Y.Y.; Shi, X.H.; Liang, H.X.; Zhang, X.P.; Shuai, Y. Efficient radiative cooling coating with biomimetic human skin wrinkle structure. *Nano Energy* **2021**, *89*, 106377. [CrossRef]
23. Nelson, R.E. A brief history of thermophotovoltaic development. *Semicond. Sci. Technol.* **2003**, *18*, S141–S143. [CrossRef]
24. Burger, T.; Sempere, C.; Roy-Layinde, B.; Lenert, A. Present Efficiencies and Future Opportunities in Thermophotovoltaics. *Joule* **2020**, *4*, 1660–1680. [CrossRef]
25. Cai, Q.; Chen, P.; Cao, S.; Ye, Q.; Wu, X. Performance analysis of GaSb cell and thermophotovoltaic system under near-field thermal radiation. *Int. J. Thermophys.* **2020**, *41*, 1–15. [CrossRef]
26. Chen, P.; Xu, Q.; Zhang, X.; Wu, X.; Cai, Q. Effectiveness of surface polaritons in performance improvement of the near-field thermophotovoltaic system with a metamaterial radiator. *Heat Transf. Res.* **2019**, *50*, 321–334. [CrossRef]
27. Li, K.; Wu, S.; Cao, S.; Cai, Q.; Ye, Q.; Liu, X.; Wu, X. Transient performance of a nanowire-based near-field thermophotovoltaic system. *Appl. Therm. Eng.* **2021**, *192*, 116918. [CrossRef]
28. Xu, Q.; Chen, P.; Wu, X.; Cai, Q. Performance analysis of a metamaterial-based near-field thermophotovoltaic system considering cooling system energy consumption. *Int. J. Thermophys.* **2019**, *40*, 1–18. [CrossRef]
29. Zhang, Y.; Cai, Q.; Cao, S.; Zhang, Q.; Yang, X.; Ye, Q.; Wu, X. Design and spectral performance of HfO_2-based multilayer spectrally selective emitters embedded with VO_2 nanoparticles. *ACS Appl. Energy Mater.* **2022**, *5*, 8769–8780. [CrossRef]
30. Zhang, Y.; Zhang, Q.; Cai, Q.; Ye, Q.; Wu, X. Thermal degradation of the multilayer Mo/HfO_2 emitter induced by the oxygen diffusion at high temperature in vacuum. *Int. J. Heat Mass Transf.* **2022**, *185*, 122425. [CrossRef]
31. Zhu, K.; Zhang, Y.; Cai, Q.; Ye, Q.; Liu, X.; Wu, X. Performance analysis of the solar thermophotovoltaic system based on the flat absorber-emitter with nonuniform temperature distribution. *Heat Transf. Res.* **2021**, *52*, 59–74. [CrossRef]
32. Wang, B.; Liu, M.; Huang, T.; Zhao, C. Micro/Nanostructures for Far-Field Thermal Emission Control: An Overview. *ES Energy Environ.* **2019**, *6*, 18–38. [CrossRef]
33. Sakakibara, R.; Stelmakh, V.; Chan, W.R.; Ghebrebrhan, M.; Joannopoulos, J.D.; Soljacic, M.; Čelanović, I. Practical emitters for thermophotovoltaics: A review. *J. Photonics Energy* **2019**, *9*, 1–20. [CrossRef]
34. Zhang, W.; Wang, B.; Zhao, C. Selective Thermophotovoltaic Emitter with Aperiodic Multilayer Structures Designed by Machine Learning. *ACS Appl. Energy Mater.* **2021**, *4*, 2004–2013. [CrossRef]
35. Zhang, Y.; Li, K.; Yang, X.; Cao, S.; Pang, H.; Cai, Q.; Ye, Q.; Wu, X. Thermal Degradation of Tungsten Nanowire-Based Hyperbolic Metamaterial Emitters for Near-Field Thermophotovoltaic Applications. *Int. J. Thermophys.* **2022**, *43*, 16. [CrossRef]
36. Chang, C.-C.; Kort-Kamp, W.J.M.; Nogan, J.; Luk, T.S.; Azad, A.K.; Taylor, A.J.; Dalvit, D.A.R.; Sykora, M.; Chen, H.-T. High-Temperature Refractory Metasurfaces for Solar Thermophotovoltaic Energy Harvesting. *Nano Lett.* **2018**, *18*, 7665–7673. [CrossRef]
37. Chirumamilla, M.; Krishnamurthy, G.V.; Rout, S.S.; Ritter, M.; Störmer, M.; Petrov, A.Y.; Eich, M. Thermal stability of tungsten based metamaterial emitter under medium vacuum and inert gas conditions. *Sci. Rep.* **2020**, *10*, 3605. [CrossRef]
38. Xie, M.; Zhang, S.; Cai, B.; Gu, Y.; Liu, X.; Kan, E.; Zeng, H. Van der Waals bilayer antimonene: A promising thermophotovoltaic cell material with 31% energy conversion efficiency. *Nano Energy* **2017**, *38*, 561–568. [CrossRef]
39. Zhang, Z.; Zhang, Y.; Xie, Z.; Wei, X.; Guo, T.; Fan, J.; Ni, L.; Tian, Y.; Liu, J.; Duan, L. Tunable electronic properties of an Sb/InSe van der Waals heterostructure by electric field effects. *Phys. Chem. Chem. Phys.* **2019**, *21*, 5627–5633. [CrossRef]
40. Chubb, D. *Fundamentals of Thermophotovoltaic Energy Conversion*; Elsevier: Amsterdam, The Netherlands, 2007.
41. Datas, A.; Vaillon, R. Chapter 11—Thermophotovoltaic energy conversion. In *Ultra-High Temperature Thermal Energy Storage, Transfer and Conversion*; Datas, A., Ed.; Woodhead Publishing: Cambridge, UK, 2021; pp. 285–308.
42. Fan, D.; Burger, T.; McSherry, S.; Lee, B.; Lenert, A.; Forrest, S.R. Near-perfect photon utilization in an air-bridge thermophotovoltaic cell. *Nature* **2020**, *586*, 237–241. [CrossRef]
43. Omair, Z.; Scranton, G.; Pazos-Outón, L.M.; Xiao, T.P.; Steiner, M.A.; Ganapati, V.; Peterson, P.F.; Holzrichter, J.; Atwater, H.; Yablonovitch, E. Ultraefficient thermophotovoltaic power conversion by band-edge spectral filtering. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 15356. [CrossRef] [PubMed]
44. Gamel, M.M.; Lee, H.J.; Rashid, W.E.; Ker, P.J.; Yau, L.K.; Hannan, M.A.; Jamaludin, M.Z. A Review on Thermophotovoltaic Cell and Its Applications in Energy Conversion: Issues and Recommendations. *Materials* **2021**, *14*, 4944. [CrossRef] [PubMed]
45. Kishita, Y.; Kashima, S.; Kawajiri, K.; Isoda, Y.; Shinohara, Y. Designing Technology Diffusion Roadmaps of Thermoelectric Generators Toward a Carbon-Neutral Society. *IEEE Trans. Eng. Manag.* **2021**, 1–8. [CrossRef]

46. Chia, L.C.; Feng, B. The development of a micropower (micro-thermophotovoltaic) device. *J. Power Sources* **2007**, *165*, 455–480. [CrossRef]
47. Bierman, D.M.; Lenert, A.; Chan, W.R.; Bhatia, B.; Celanović, I.; Soljačić, M.; Wang, E.N. Enhanced photovoltaic energy conversion using thermally based spectral shaping. *Nat. Energy* **2016**, *1*, 16068. [CrossRef]
48. Beretta, D.; Neophytou, N.; Hodges, J.M.; Kanatzidis, M.G.; Narducci, D.; Martin- Gonzalez, M.; Beekman, M.; Balke, B.; Cerretti, G.; Tremel, W.; et al. Thermoelectrics: From history, a window to the future. *Mater. Sci. Eng. R Rep.* **2019**, *138*, 100501. [CrossRef]
49. LaPotin, A.; Schulte, K.L.; Steiner, M.A.; Buznitsky, K.; Kelsall, C.C.; Friedman, D.J.; Tervo, E.J.; France, R.M.; Young, M.R.; Rohskopf, A.; et al. Thermophotovoltaic efficiency of 40%. *Nature* **2022**, *604*, 287–291. [CrossRef]
50. Wei, J.; Yang, L.; Ma, Z.; Song, P.; Zhang, M.; Ma, J.; Yang, F.; Wang, X. Review of current high-ZT thermoelectric materials. *J. Mater. Sci.* **2020**, *55*, 12642–12704. [CrossRef]
51. Elsheikh, M.H.; Shnawah, D.A.; Sabri, M.F.M.; Said, S.B.M.; Hassan, M.H.; Bashir, M.B.A.; Mohamad, M. A review on thermoelectric renewable energy: Principle parameters that affect their performance. *Renew. Sustain. Energy Rev.* **2014**, *30*, 337–355. [CrossRef]
52. Zoghi, M.; Habibi, H.; Chitsaz, A.; Holagh, S.G. Multi-criteria analysis of a novel biomass-driven multi-generation system including combined cycle power plant integrated with a modified Kalina-LNG subsystem employing thermoelectric generator and PEM electrolyzer. *Therm. Sci. Eng. Prog.* **2021**, *26*, 101092. [CrossRef]
53. Saleh, U.A.; Johar, M.A.; Jumaat, S.A.B.; Rejab, M.N.; Jamaludin, W.A.W. Evaluation of a PV-TEG Hybrid System Configuration for an Improved Energy Output: A Review. *Int. J. Renew. Energy Dev.* **2021**, *10*, 385–400. [CrossRef]
54. Gholamian, E.; Habibollahzade, A.; Zare, V. Development and multi-objective optimization of geothermal-based organic Rankine cycle integrated with thermoelectric generator and proton exchange membrane electrolyzer for power and hydrogen production. *Energy Convers. Manag.* **2018**, *174*, 112–125. [CrossRef]
55. Suraparaju, S.K.; Kartheek, G.; Sunil Reddy, G.V.; Natarajan, S.K. A short review on recent trends and applications of thermoelectric generators. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *312*, 012013. [CrossRef]
56. Dongxu, J.; Zhongbao, W.; Pou, J.; Mazzoni, S.; Rajoo, S.; Romagnoli, A. Geometry optimization of thermoelectric modules: Simulation and experimental study. *Energy Convers. Manag.* **2019**, *195*, 236–243. [CrossRef]
57. Ji, D.; Wei, Z.; Mazzoni, S.; Mengarelli, M.; Rajoo, S.; Zhao, J.; Pou, J.; Romagnoli, A. Thermoelectric generation for waste heat recovery: Application of a system level design optimization approach via Taguchi method. *Energy Convers. Manag.* **2018**, *172*, 507–516. [CrossRef]
58. Ji, D.; Hu, S.; Feng, Y.; Qin, J.; Yin, Z.; Romagnoli, A.; Zhao, J.; Qian, H. Geometry optimization of solar thermoelectric generator under different operating conditions via Taguchi method. *Energy Convers. Manag.* **2021**, *238*, 114158. [CrossRef]
59. Luo, D.; Wang, R.; Yu, W.; Zhou, W. A numerical study on the performance of a converging thermoelectric generator system used for waste heat recovery. *Appl. Energy* **2020**, *270*, 115181. [CrossRef]
60. Shittu, S.; Li, G.; Zhao, X.; Ma, X.; Akhlaghi, Y.G.; Ayodele, E. High performance and thermal stress analysis of a segmented annular thermoelectric generator. *Energy Convers. Manag.* **2019**, *184*, 180–193. [CrossRef]
61. Yu, J.; Kong, L.; Zhu, Q.; Zhu, H.; Wang, H.; Guan, J.; Yan, Q. Thermal Stress Analysis of a Segmented Thermoelectric Generator under a Pulsed Heat Source. *J. Electron. Mater.* **2020**, *49*, 4392–4402. [CrossRef]
62. Harish, S.; Sivaprahasam, D.; Jayachandran, B.; Gopalan, R.; Sundararajan, G. Performance of bismuth telluride modules under thermal cycling in an automotive exhaust thermoelectric generator. *Energy Convers. Manag.* **2021**, *232*, 113900. [CrossRef]
63. Zhang, Z.M. *Nano/Microscale Heat Transfer*; Springer: Berlin/Heidelberg, Germany, 2007; Volume 410.
64. Liu, X.; Wang, L.; Zhang, Z.M. Near-field thermal radiation: Recent progress and outlook. *Nanoscale Microscale Thermophys. Eng.* **2015**, *19*, 98–126. [CrossRef]
65. Wu, X.; Fu, C.; Zhang, Z.M. Effect of orientation on the directional and hemispherical emissivity of hyperbolic metamaterials. *Int. J. Heat Mass Transf.* **2019**, *135*, 1207–1217. [CrossRef]
66. Wu, X.; McEleney, C.A.; González-Jiménez, M.; Macêdo, R. Emergent asymmetries and enhancement in the absorption of natural hyperbolic crystals. *Optica* **2019**, *6*, 1478–1483. [CrossRef]
67. Biehs, S.-A.; Tschikin, M.; Ben-Abdallah, P. Hyperbolic metamaterials as an analog of a blackbody in the near field. *Phys. Rev. Lett.* **2012**, *109*, 104301. [CrossRef] [PubMed]
68. Liu, R.; Zhou, C.; Zhang, Y.; Cui, Z.; Wu, X.; Yi, H. Near-field radiative heat transfer in hyperbolic materials. *Int. J. Extrem. Manuf.* **2022**, *4*, 032002. [CrossRef]
69. Wu, X.; Fu, C.; Zhang, Z.M. Near-field radiative heat transfer between two α-MoO3 biaxial crystals. *J. Heat Transf.* **2020**, *142*, 072802. [CrossRef]
70. Wu, X.; Fu, C. Near-field radiative heat transfer between uniaxial hyperbolic media: Role of volume and surface phonon polaritons. *J. Quant. Spectrosc. Radiat. Transf.* **2021**, *258*, 107337. [CrossRef]
71. Wu, X.; Liu, R. Near-field radiative heat transfer between graphene covered biaxial hyperbolic materials. *ES Energy Environ.* **2020**, *10*, 66–72. [CrossRef]
72. Shi, K.Z.; Sun, Y.C.; Chen, Z.Y.; He, N.; Bao, F.L.; Evans, J.; He, S.L. Colossal Enhancement of Near-Field Thermal Radiation Across Hundreds of Nanometers between Millimeter-Scale Plates through Surface Plasmon and Phonon Polaritons Coupling. *Nano Lett.* **2019**, *19*, 8082–8088. [CrossRef]

73. Song, J.L.; Cheng, Q. Near-field radiative heat transfer between graphene and anisotropic magneto-dielectric hyperbolic metamaterials. *Phys. Rev. B* **2016**, *94*, 125419. [CrossRef]
74. Wu, H.H.; Huang, Y.; Cui, L.J.; Zhu, K.Y. Active Magneto-Optical Control of Near-Field Radiative Heat Transfer between Graphene Sheets. *Phys. Rev. Appl.* **2019**, *11*, 054020. [CrossRef]
75. Zhang, Y.; Yi, H.L.; Tan, H.P. Near-Field Radiative Heat Transfer between Black Phosphorus Sheets via Anisotropic Surface Plasmon Polaritons. *ACS Photonics* **2018**, *5*, 3739–3747. [CrossRef]
76. Shi, K.Z.; Bao, F.L.; He, S.L. Enhanced Near-Field Thermal Radiation Based on Multilayer Graphene-hBN Heterostructures. *ACS Photonics* **2017**, *4*, 971–978. [CrossRef]
77. Shi, K.Z.; Liao, R.; Cao, G.J.; Bao, F.L.; He, S.L. Enhancing thermal radiation by graphene-assisted hBN/SiO2 hybrid structures at the nanoscale. *Opt. Express* **2018**, *26*, A591–A601. [CrossRef] [PubMed]
78. Wu, X.H.; Fu, C.J.; Zhang, Z.M. Influence of hBN orientation on the near-field radiative heat transfer between graphene/hBN heterostructures. *J. Photonics Energy* **2019**, *9*, 032702. [CrossRef]
79. Hu, Y.; Sun, Y.S.; Zheng, Z.H.; Song, J.L.; Shi, K.Z.; Wu, X.H. Rotation-induced significant modulation of near-field radiative heat transfer between hyperbolic nanoparticles. *Int. J. Heat Mass Transf.* **2022**, *189*, 122666. [CrossRef]
80. Zhu, L.X.; Otey, C.R.; Fan, S.H. Ultrahigh contrast and large-bandwidth thermal rectification in near-field electromagnetic thermal transfer between nanoparticles. *Phys. Rev. B* **2013**, *88*, 184301. [CrossRef]
81. Ben-Abdallah, P.; Biehs, S.A. Near-Field Thermal Transistor. *Phys. Rev. Lett.* **2014**, *112*, 044301. [CrossRef]
82. Biehs, S.A.; Rosa, F.S.S.; Ben-Abdallah, P. Modulation of near-field heat transfer between two gratings. *Appl. Phys. Lett.* **2011**, *98*, 243102. [CrossRef]
83. Liu, X.L.; Shen, J.D.; Xuan, Y.M. Pattern-free thermal modulator via thermal radiation between Van der Waals materials. *J. Quant. Spectrosc. Radiat. Transf.* **2017**, *200*, 100–107. [CrossRef]
84. Fiorino, A.; Zhu, L.X.; Thompson, D.; Mittapally, R.; Reddy, P.; Meyhofer, E. Nanogap near-field thermophotovoltaics. *Nat. Nanotechnol.* **2018**, *13*, 806. [CrossRef] [PubMed]
85. Inoue, T.; Ikeda, K.; Song, B.S.; Suzuki, T.; Ishino, K.; Asano, T.; Noda, S. Integrated Near-Field Thermophotovoltaic Device Overcoming Blackbody Limit. *ACS Photonics* **2021**, *8*, 2466–2472. [CrossRef]
86. Inoue, T.; Koyama, T.; Kang, D.D.; Ikeda, K.; Asano, T.; Noda, S. One-Chip Near-Field Thermophotovoltaic Device Integrating a Thin-Film Thermal Emitter and Photovoltaic Cell. *Nano Lett.* **2019**, *19*, 3948–3952. [CrossRef] [PubMed]
87. Lucchesi, C.; Cakiroglu, D.; Perez, J.-P.; Taliercio, T.; Tournié, E.; Chapuis, P.-O.; Vaillon, R. Near-Field Thermophotovoltaic Conversion with High Electrical Power Density and Cell Efficiency above 14%. *Nano Lett.* **2021**, *21*, 4524–4529. [CrossRef] [PubMed]