

Review of Recent Applications of Heat Pipe Heat Exchanger Use for Waste Heat Recovery

Yi Ding ¹, Qiang Guo ², Wenyuan Guo ², Wenxiao Chu ¹  and Qiuwang Wang ^{1,*} 

¹ Key Laboratory of Thermo-Fluid Science and Engineering, MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China; wxchu84@xjtu.edu.cn (W.C.)

² Ningbo Liantong Equipment Co., Ltd., Ningbo 315207, China

* Correspondence: wangqw@mail.xjtu.edu.cn

Abstract: With the reduction in fossil fuels and growing concerns about global warming, energy has become one of the most important issues facing humanity. It is crucial to improve energy utilization efficiency and promote a low-carbon transition. In comparison with traditional heat exchangers, heat pipe heat exchangers indicate high compactness, a flexible arrangement, complete separation of hot and cold fluids, good isothermal operations, etc. As a result, heat pipe heat exchangers have attracted wide attention and application in various fields in recent years. This paper provides an overview of the application of heat pipe heat exchangers, with a focus on the application in waste heat recovery, and analyzes the opportunities and challenges of heat pipe heat exchanger applications based on existing publications.

Keywords: heat pipe heat exchanger; applications; waste heat recovery; air conditioning and refrigeration systems; improve energy utilization efficiency; low-carbon transition



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1. Introduction

Since fossil fuel resources are continuing to diminish and the issue of global climate change is intensifying, energy has emerged as one of the most pressing challenges facing humanity. According to a report from the International Energy Agency (IEA) in 2022 [1], global carbon dioxide (CO₂) emissions resulting from energy combustion and industrial processes increased by 0.9%, reaching a historic high of 36.8 billion tons. Accelerating the transition to clean and low-carbon energy sources and actively addressing climate change remain global priorities today. The efficient utilization of energy and the innovation of heat exchange technologies are now more urgent than ever.

A heat exchanger is a device that can be used to transfer thermal energy between two or more fluids while keeping them isolated from each other. Heat exchangers can effectively recover heat from waste, thereby improving energy efficiency; heat exchangers are widely used in industry, construction, transportation, and other fields. A heat pipe (HP) is usually regarded as a very-high-conductivity device due to its evaporation and condensation phenomena, which can be used to construct heat exchangers. HPs are good at transferring substantial quantities of heat across relatively long distances while maintaining a minimal temperature gradient. Table 1 summarizes the commonly applied HPs, including the wick heat pipe, thermosyphon, flat heat pipe, concentric tube heat pipe, and micro-structure heat pipe. The corresponding working principles, merits, configurations, and industrial applications are tabulated. Note that the thermosyphon that is driven by gravity shows better economic when being used for constructing heat pipe heat exchangers (HPHXs).

Compared with traditional heat exchangers (plate-fin, tube-and-fin, shell-and-tube, etc.), HPHXs always display the following advantages:

1. Unidirectional heat transfer: In some applications, it is necessary to transfer heat from one medium to another in a unidirectional manner, and it is not desirable to have

unnecessary heat transfer. Traditional heat exchangers transfer heat in the presence of a temperature difference, whereas HPHXs possess thermal diode characteristics, ensuring unidirectional heat conduction from a primary medium to a secondary medium [2].

- 2. Complete separation of hot and cold media: In HPHXs, the hot and cold media are completely separated, with almost no cross-leakage for heat exchange. This means that no mixing of media occurs when the heat is transferred, ensuring the safety and reliability of the system. For instance, employing HPHXs in nuclear reactors can eliminate the need for secondary pumped heat exchange loops and reduce the possibility of tritium entering the process heat flow [3].
- 3. Isothermal operations: HPs within HPHXs can achieve isothermal operations, meaning that the working fluid inside the HP maintains a stable temperature during the heat transfer process. For example, during waste heat recovery, if the temperature of acid gases is below the dew point, the gases would condense, leading to severe corrosion. Due to the isothermal operation characteristics of HPHX, this situation can be effectively prevented, improving the stability and reliability of the system [4–6].
- 4. Modularization: Each HP in HPHX can be considered an independent entity, and the failure of a single HP will not lead to the entire system becoming inoperative. For example, applying HPHXs to heat sink systems can avoid the issue of single-point failure of the original radiators [7].

Table 1. Common types of HPs using for HPHXs.

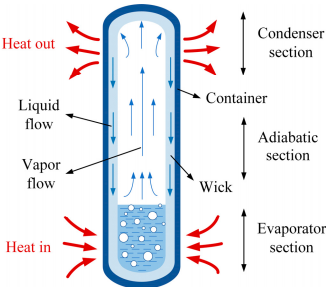
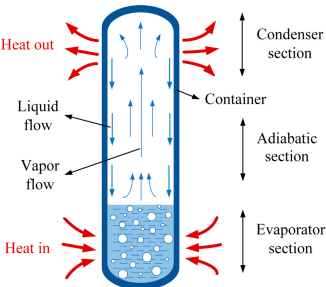
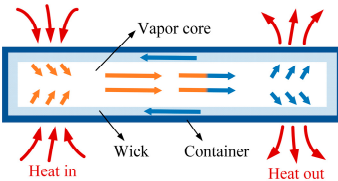
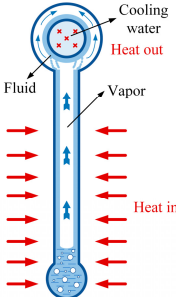
HP Types	Principles	Advantages	Applications in References	Configurations
Wick heat pipe	When the hot end is heated, the working fluid at the hot end evaporates, forming vapor. The vapor moves through the pipe to the cooling end, where it condenses into liquid and then returns to the hot end through wick structure, forming a closed heat cycle.	Simple, reliable, requiring no external power, and suitable for most heat conduction needs.	TOPAZ-II power system [7], nuclear power plant [8], withering of tea leaves [9], HVAC systems [10]	
Thermosyphon	The key distinction from wick heat pipes is that thermosyphons use natural convection and gravity to transfer heat, eliminating the need for a wick structure. Their dependence on gravity means that the condensing end must be positioned above the evaporating end.	They require no external power and are suitable for vertical heat transfer and microgravity environments.	nuclear reactor [3,11], the ceramic industry [4–6,12], solar collector [13,14], coal to liquid process [15,16], HVAC systems [17–22], heat recovery system [23–29], gas city gate station [30], steel industry [31,32], dyeing and printing industry [33], the pressure reduction stations [34], heat recovery of coal-fired flue gas [35], aluminum industry [36], combine harvester [37]	

Table 1. Cont.

HP Types	Principles	Advantages	Applications in References	Configurations
Flat-plate heat pipe	Flat-plate heat pipes typically have thinner cross-sections, making them suitable for heat conduction within limited spaces.	They are suitable for confined spaces and can achieve efficient heat conduction within thinner structures.	solar collector [38–40], photovoltaic panel [41], steel industry [42,43]	
Concentric tube heat pipe	Concentric tube heat pipes consist of two concentric pipes, where the inner pipe serves as the evaporator section, and the outer pipe serves as the condenser section. The working fluid circulates within the inner pipe, facilitating heat transfer.	They can handle larger heat conduction distances and exhibit high heat transfer efficiency.	electronic component system [44,45]	
Micro-structure heat pipe	Micro-heat pipes are similar to wick heat pipes but are smaller in size, making them suitable for efficient heat transfer in small-scale devices.	They are suitable for microdevices and can achieve efficient heat transfer within limited spaces.	HVAC systems [46,47], heat recovery in the cold regions [48], industrial equipment [49], oil fume heat recovery [50]	/

HPHXs are constructed based on HPs and typically consist of multiple HPs connected in parallel to achieve larger-scale heat exchange, as shown in Figure 1. In an HPHX, the evaporator end of the HP is placed in a high-temperature heat source, while the condenser end is located in a cooler environment. When the high-temperature fluid carrying heat passes through the HP’s evaporator end, the working fluid begins to boil and absorb large amounts of heat using only a small amount of working fluid. During this process, the phase change to vapor occurs with no change to the temperature inside the HP vessel. The vapor then travels at sonic speed from the evaporator end to the condenser end. When the vapor flow meets the cold at the condenser end of the pipe, it releases heat and condenses back to a liquid form. The condensed liquid then travels back to the origin end of the pipe by gravity or the wick structure. This process repeats continuously, effectively transferring heat from the heat source to the cold source.

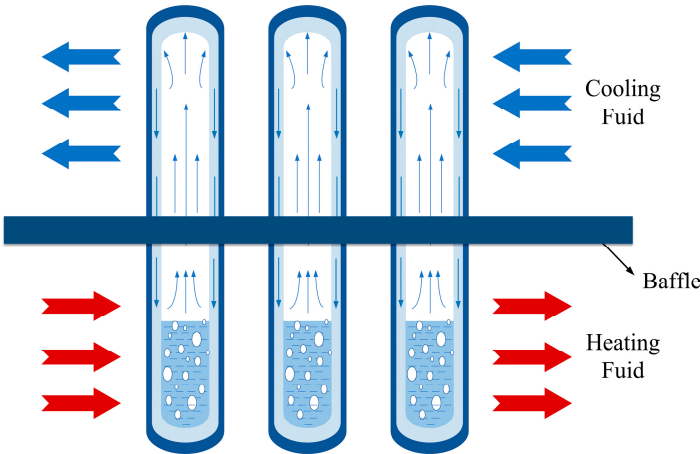


Figure 1. Schematic diagram of HPHX.

Table 2 summarizes the previous review literature on HPHXs [2,51–55]. Shabgard et al. [2] provided a review of HPHX applications, design methodologies, and analytical tools employing the thermal network approach. They investigated the fundamental thermal resistances associated with HPs and thermosyphons and constructed typical thermal resistance networks for HPHX systems. Tiwatane et al. [51] summarized experimental studies of waste heat recovery using HPHX with a hybrid nanofluid. The article indicated that heat transfer performance in a straight, circular tube is significantly enhanced by the suspension of hybrid nanoparticles compared to pure water. The Nusselt amount for the hybrid nanofluid increased by an average of 10.94% compared with the pure water. Ong [52] provided a review of HPHXs used in air conditioning systems to enhance dehumidification and cooling. HPHXs were shown to be highly effective in improving dehumidification and reducing air conditioning costs, particularly in hot and humid tropical regions. Zohuri et al. [53] reviewed the state of HP technology and its limitations, focusing on the use of HPHXs in preventing salt freezing and controlling tritium in salt-cooled fission and fusion reactors. Parab et al. [54] reviewed the application of HPHXs in air conditioning systems and summarized the factors affecting the performance of pulsating heat pipes. However, it can be seen that there is no literature that systematically summarizes the progress in the application of HPHXs. Nithin et al. [55] reviewed the research progress on flexible HP systems based on heat exchangers. As a kind of high-efficiency heat transfer device, HPHXs have garnered widespread attention and application in various fields in recent years, such as solar energy systems, nuclear energy systems, geothermal energy systems, HVAC (heating, ventilation, and air conditioning) systems, and waste heat recovery, with the most extensive application in waste heat recovery.

Table 2. Summary of review articles for HPHXs [2,51–55].

Reference	Main Contents	Major Contributions and Conclusions
Shabgard et al. in 2015 [2]	(1) Thermal network modeling (2) Classification and application of HPHXs and heat pipe heat sinks (HPHSs) (3) Three case studies	The applications, general design procedures, and analytical tools for HPHX, based on the thermal network approach, were summarized. It included three practical case studies where the predicted outcomes revealed the potential advantages of HPHXs. Various HPHX and HPHS systems, including a potential thermal energy storage solution utilizing a phase change material, were detailed accompanied by their corresponding thermal networks.
Tiwatane et al. in 2015 [51]	(1) A comprehensive investigation of heat transfer capacity limits of HPs (2) Applications of HPs in energy conservation and renewable energy-based systems (3) Energy savings in air conditioning system by heat recovering using HPHX (4) Nanoparticles application in enhancing thermal conductivity of fluids with nanoparticles (5) The impact of the filling ratio on the thermal characteristics of wire-mesh HPs utilizing copper oxide nanofluid	The theory, design and construction of waste heat recovery using HPHXs with nanofluids, especially their use in waste heat recovery for energy recovery in automobiles, were summarized. The characteristic design and heat transfer limitations of single HPs without wick and working with Hybrid Nanofluids were investigated.

Table 2. Cont.

Reference	Main Contents	Major Contributions and Conclusions
Ong in 2016 [52]	(1) HPHXs for enhanced dehumidification and cooling in air conditioning systems (2) HPs for cooling (3) HPs for cooling and dehumidification (4) Wrap-around HPHX (5) Testing of HPHXs	Several studies on the cooling and dehumidification aspects of different air conditioning systems were summarized. Examining the use of heat exchangers with multiple HPs for salt-cooled fission and fusion systems that serve four functions: (1) transfer heat from primary coolant to power cycle, secondary loop, or environment; (2) enhance the safety of the secondary circuit by ensuring the reactor's salt coolant is isolated from the high-pressure power cycle; (3) cease heat transfer if the reactor coolant nears its freezing point, averting primary loop obstruction; and (4) prevent tritium release into the environment while enabling tritium recovery. The status of HP technology and the limits of HP technology were summarized.
Zohuri et al. in 2020 [53]	(1) Reactor systems and HP design requirements (2) HP design and start-up temperatures (3) HP heat transfer analysis (4) Tritium control	The performance, components, and applications of the most current HP devices were analyzed. The study on HPs that has been performed in terms of design and analysis were summarized.
Parab et al. in 2023 [54]	(1) Application of HP (2) Literature review: HPs, HPHXs, pulsating heat pipe & factors affecting its performance	
Nithin in 2024 [55]	(1) Types of HPs (2) Heat pipe recuperative heat exchanger for air preheating (3) Heat pipe regenerative heat exchanger for air preheating	Research progress on flexible HP systems based on heat exchangers is summarized.

Since many types and structures of HPHXs are experimentally and numerically investigated in various fields, there is a lack of studies that summarize and categorize HPHXs considering the applicable environment and heat source quality. In the present paper, recent publications of HPHXs in solar energy systems, nuclear energy systems, geothermal energy systems, and HVAC systems are summarized. Then, we focus on the waste heat recovery background while the temperature threshold is regarded as the classification criterion to specify various HPHXs. Consequently, the applications of HPHXs in waste heat recovery from both low-temperature and medium-high-temperature perspectives are concluded, aiming to provide valuable guidance for future research and applications of HPHXs.

2. HPHX Industrial Application

Table 3 tabulates investigations of HPHXs in various backgrounds, including solar energy, nuclear energy, geothermal energy, and HVAC systems. In the realm of solar energy harnessing, the design of solar collectors frequently gravitates towards flat heat pipes, primarily due to their significant aspect ratios. The deployment of flat heat pipes in such systems maximizes the surface area exposed to solar radiation, enhancing the absorption and transfer of heat. Flat heat pipes are particularly effective in solar thermal systems where efficient heat capture and transfer are critical for the system's performance. In terms of working fluids, low-saturated temperature mediums such as ammonia and acetone are commonly used. This preference is due to the limitations imposed by the water saturation temperature at an ambient pressure. Water is always regarded as an excellent heat transfer fluid in many contexts. However, water has a saturation temperature that may not be suitable for all environmental conditions. Ammonia and acetone, on the other hand, can operate efficiently at lower temperatures, showing superiorities in solar applications, while

lower ambient temperatures might be encountered. In nuclear energy applications, the appeals and requirements are significantly different. Note that high saturated temperature working fluids such as sodium are preferred. Moreover, reliability is the first and most significant concern in nuclear applications. Thermosyphons are widely used due to their simple design and high reliability. The circulation of thermosyphons' working fluid is driven by gravity without the need for a wick structure. This simplicity reduces potential points of failure, making thermosyphons ideal for the demanding conditions of nuclear energy systems. In an HVAC system, the materials and designs of HPs are chosen to ensure compatibility with refrigerants and to enhance system efficiency. Copper is the primary material for HPs in these systems due to its excellent thermal conductivity and compatibility with common refrigerants. Additionally, the loop heat pipe design is becoming increasingly popular in HVAC applications. Loop heat pipes offer high vapor and liquid separation efficiency, which is crucial for maintaining optimal performance in HVAC systems. The loop design facilitates efficient heat transfer and reduces the risk of fluid backflow, enhancing the overall reliability and efficiency of the system.

Table 3. Applications of HPHXs in solar, nuclear, geothermal, and HVAC systems.

Reference	Application	External Fluid	HP Type	HP Material Wick Material	Working Fluid
Jouhara et al. in 2016 [38]	solar collector	radiation– water/glycol	flat heat pipe	N/A	N/A
Jouhara et al. in 2017 [39]	solar collector	radiation–water	flat heat pipe	aluminum	ammonia
Al-Mabsali et al. in 2021 [41]	photovoltaic panel	radiation–air	flat heat pipe	copper wick: fiber mesh	water
Sahu et al. in 2013 [13]	solar collector	radiation–water	thermosyphon	copper	pure water, water surfactant, CNT–water nanofluid
Sarafraz et al. in 2019 [40]	solar collector	radiation–water	flat heat pipe	N/A	graphene–methanol nanofluid
Sarafraz et al. in 2019 [14]	solar collector	radiation–water	thermosyphon	copper	acetone, nanofluids
Dobson et al. in 2013 [3]	nuclear reactor	gas–water	thermosyphon	steel	sodium
Dobson et al. in 2013 [11]	nuclear reactor	gas–water	thermosyphon	N/A	Dowtherm-A
Tshamala and Dobson in 2014 [15]	coal to liquid process	helium–water	thermosyphon	N/A	sodium
Tshamala and Dobson in 2016 [16]	coal to liquid process	helium–water	thermosyphon	N/A	sodium
Zhang et al. in 2016 [7]	TOPAZ-II power system	radiation–air	wick heat pipe	Inconel wick: stainless steel	potassium
Qiao et al. in 2022 [56]	cooling water tank	air–water	separated heat pipe	carbon steel	water
Xie et al. in 2019 [8]	nuclear power plant	water–water	wick heat pipe	N/A wick: N/A	water
Zorn et al. in 2014 [57]	de-Icing and snow melting system	geothermal energy–solid	N/A	copper	CO ₂
Gunawan et al. in 2021 [9]	withering of tea leaves	air–water	wick heat pipe	copper wick: copper	water
Diao et al. in 2017 [46]	HVAC systems	air–air	micro-heat pipe	aluminum alloy	N/A
Jing et al. in 2020 [47]	HVAC systems	air–water	micro-heat pipe	aluminum alloy	R141b
Zhang et al. in 2017 [17]	HVAC systems	air–air	thermosyphon	aluminum	R134a
Sukarno et al. in 2021 [10]	HVAC systems	air–air	wick heat pipe	copper wick: sintered copper	water
Sharma et al. in 2022 [18]	HVAC systems	air–air	thermosyphon	copper	R22, R407c
Abedalh et al. in 2021 [19]	HVAC systems	air–air	thermosyphon	copper	distilled water
Abdallah et al. in 2022 [20]	HVAC systems	air–air	thermosyphon	copper	copper oxide nanofluid
Monirimanesh et al. in 2016 [21]	HVAC systems	air–air	thermosyphon	copper	TiO ₂ /methanol nanofluids
Abdelaziz et al. in 2021 [22]	HVAC systems	air–air	thermosyphon	copper	R123
Hakim et al. in 2021 [58]	HVAC systems	air–air	loop heat pipe	copper wick: sintered copper	water
Longo et al. in 2014 [59]	HVAC systems	air–air	N/A	copper	HFC134a, HFO1234ze(E)
Jouhara et al. in 2018 [60]	HVAC systems	air–air	loop heat pipe	copper	water

'N/A' is short for 'Not Available'.

2.1. Solar Energy Systems

Due to the advantages of solar energy, such as its universality, environmental friendliness, capacity, accessibility, and cost-effectiveness, it is posited as a viable solution for solving long-term energy crises [61]. A solar collector is a device that utilizes solar energy to heat fluid (usually water or air), and its main function is to convert solar energy into thermal energy for heating, hot water, and other thermal applications. Solar collectors employing HP technology are widely studied due to their minimal hydraulic and thermal resistance, consistent heat transfer fluid flow, and nearly isothermal absorption surfaces [62]. Furthermore, photovoltaic components can convert solar energy into electrical energy. An important factor affecting photovoltaic cell efficiency is the cell temperature and an increase in cell temperature decreases the efficiency of solar electric energy conversion and causes thermal fatigue due to higher temperatures of the photovoltaic panel throughout the day. Cooling photovoltaic cells can improve power generation efficiency. Many scholars have studied PCM cooling, water cooling, and HP cooling. However, PCM cooling systems depend on the cooling effect stored during low-temperature periods to counteract the heating effect of photovoltaics under solar irradiation, which cannot utilize the waste heat generated during the solar energy collection process. Water cooling requires special arrangements and additional facilities to prevent freezing in cold climate conditions. HPs can significantly enhance the performance of photovoltaic/thermal (PV/T) solar collector systems by preventing freezing and corrosion through the selection of appropriate working fluids. By integrating HP-based solar PV collectors with water cooling systems, it is possible to recover waste heat generated during the cooling process. This integration enables the simultaneous production of thermal and electrical energy. The recovered waste heat and generated electrical energy can be utilized to power heat pumps, providing an efficient solution for meeting domestic hot water needs. This dual-functionality not only improves the overall efficiency of the solar energy system but also ensures a sustainable and continuous energy supply for household use [39].

Jouhara et al. [38] designed and developed a novel flat-plate heat pipe solar collector and tested it in the UK to analyze its performance. The performance of the solar/thermal, uncooled PV, and PV/T was compared, and the results showed that the solar/thermal energy conversion efficiency for a collector without PV was approximately 64%, while the system with a PV layer achieved about 50%. The impact of cooling on solar/electrical energy conversion efficiency was also examined, showing a 15% increase in efficiency for the cooled PV system due to the homogeneous cooling provided. In addition, the collector could effectively absorb thermal energy from the environment in the absence of solar radiation, which was expected to enhance the energy efficiency of the integrated heat pump system. To further improve the performance of heat pipe solar collectors, Jouhara et al. [39] combined photovoltaic–thermal solar collectors with a water-cooling system in order to increase the electrical efficiency of the collector and improve the total thermal efficiency of the building. Simulation and experimental studies showed that the solar-to-thermal energy conversion efficiency for the solar flat heat pipe collector ranged from 45.4% to 64.2%, while for the integrated heat pipe solar collector with PV panels, it ranged from 35% to 52%. The HP system effectively provided sufficient cooling, as evidenced by the temperature of the cooled PV panels being 18–48 °C lower than that of the uncooled PV panels. In addition, under different solar radiation conditions, this hybrid solar collector was able to cover about 60% of the hot water demand under low solar radiation conditions and 100% of the hot water demand under high solar radiation conditions, indicating that this HP-based hybrid solar PV/T collector could efficiently convert solar energy into electricity and heat to meet the hot water demands of a household.

The materials used for HPs in solar energy utilization are mainly aluminum and copper due to their excellent thermal conductivity and high corrosion resistance. The working fluid inside the HP is usually water, ammonia, methanol, and other fluids with a low boiling point so that the phase change from liquid to gas can be realized at relatively low temperatures, thus prompting the working fluid inside the HP to form a gas phase

under solar irradiation and move upward to transfer the heat to the heat exchanger part of the collector. In order to improve the thermal performance of the HPHX and the efficiency of the solar collector, materials such as surfactants and graphene nanoplates have been added to the working fluid for research.

Al-Mabsali et al. [41] used water as a sustainable refrigerant in HPs for cooling purposes, aiming to improve its operational performance under harsh climate conditions. They investigated the use of an inclined HPHX as a passive cooling mechanism on a photovoltaic panel and investigated its heat transfer coefficient. The experimental results showed that the inclined HPHX can significantly improve the efficiency of PV power generation by up to 29% gain. The study also established a thermal characteristic model and calculated the average heat transfer coefficient of $2.346 \text{ W/m}^2\cdot\text{K}$, which provided valuable experimental and simulation results for improving the efficiency of photovoltaic power generation under harsh climate conditions. Sahu et al. [13] experimentally investigated the effects of surfactant and nanofluid on enhancing the performance of heat pipe solar collectors. The thermal performance of three distinct wickless heat pipe solar collectors was investigated utilizing pure water, water surfactant, and CNT–water nanofluid at various coolant mass flow rates and tilt angles. The results showed that the solar collector using 2-ethyl-hexanol surfactant with water as the coolant outperformed those using pure water and CNT/water nanofluid. Sarafraz et al. [40] charged HPs with graphene–methanol nanofluid to enhance the efficiency of solar collectors. The study also examined the effect of various operating conditions, including the collector’s tilt angle, filling ratio, mass fraction of graphene nanoplatelets, and the flow rate of the collector’s loop, on the thermal efficiency. The results demonstrated that graphene nanoplatelets enhanced the thermal conductivity of methanol while the heat capacity of the nanofluid decreased with a reduction in the graphene mass fraction. When the mass fraction of nanofluid was 0.1%, and the flow rate was 3 lit/min, the thermal efficiency of the solar collector was up to 95%. When the mass fraction of graphene–methanol nanofluid is 0.1%, the temperature difference between the inlet and outlet of the collector is at its maximum, and the heat capacity is at its minimum. Additionally, the highest daily thermal energy absorption of the collector was achieved at a tilt angle of 35 degrees and a filling ratio of 60%. Sarafraz et al. [14] investigated the intelligent optimization of thermal efficiency for thermosyphons in evacuated tube solar collectors using a nano-suspension of carbon nanotubes dispersed in distilled water through response surface methodology (RSM). The effects of the HPs’ filling ratio, the collector’s tilt angle, and the dispersion mass fraction of the carbon nanotubes in distilled water on the thermal efficiency were experimentally investigated. A model based on RSM was developed in order to optimize the operating conditions and maximize the collector’s thermal efficiency. It was found that carbon nanotubes can promote the nucleate boiling mechanism to increase the thermal efficiency of the solar collector. The RSM-optimized model achieved high thermal efficiency under specific operating conditions, with an accuracy of 1.6%.

2.2. Nuclear Energy Systems

As the energy structure evolves, the importance of clean and efficient nuclear energy becomes increasingly paramount. Given the ongoing depletion of mineral fuel resources, the impact of global pollution, and the consequences of their use, the employment of nuclear energy for process heating is becoming increasingly attractive. In addition, in harsh space environments, solar energy is not always available, and energy sources are limited. In contrast, nuclear energy offers a compact and durable energy solution that can operate stably over long periods of time, providing a continuous power supply for space missions and planetary exploration.

However, in the high-temperature nuclear reactors, conventional heat exchangers may lead to tritium contamination into the secondary coolant. HPHXs have been proposed for use in nuclear reactors to avoid the need for a secondary pumping heat exchange loop and to reduce the potential for tritium to enter the process heat stream. Simultaneously, HPHXs are also applied to space reactor power systems for heat dissipation, where each

HP in the radiator functions as an independent entity, avoiding the issue of single-point failure inherent in the original pumped loop radiators. In addition, HPHXs are also used in emergency passive residual heat removal systems in pressurized water reactors to reduce evaporative losses of water caused by natural circulation, enhancing the passive cooling capability of pressurized water reactors.

When selecting the working fluid for HPs used in high-temperature nuclear reactors, the operating temperature should be within the effective working range of the fluid. At the same time, at the required operating temperature, the corresponding saturation pressure should be between 0.1 and 20 bars to avoid the risk of overpressure and rupture of high vacuum equipment [63]. The materials used for HPs in high-temperature nuclear reactors are usually high-temperature alloys that are resistant to high temperatures and corrosion, and the working fluid should be selected to avoid reaction with the material. The effective working range of sodium is 600 to 1200 °C, and the saturation vapor pressure of sodium at these temperatures is between 0.15 and 9.6 bars [3]. Moreover, sodium is also compatible with high-temperature steel, which is a commonly used material for HPs in high-temperature nuclear reactors. Therefore, sodium is used as the working fluid for HPs in high-temperature nuclear reactors. In existing research, Dowtherm-A (a eutectic mixture of 26.5% diphenyl and 73.5% diphenyl oxides) has also been used as the working fluid at high temperatures due to its thermal stability and high boiling point at relatively low pressures. When HPHXs are used in space reactor power systems or pressurized water reactors for heat dissipation, water and alkali metals (e.g., potassium, cesium, etc.) are usually used as the working fluid for HPs in consideration of the operating temperature range.

The research group at Stellenbosch University, led by Dobson, which proposed the use of HPHXs in nuclear reactors to avoid tritium diffusion and the addition of intermediate heat-transfer loops, has performed a lot of research on the subject. In 2013, Dobson et al. [3] proposed a design for a sodium-charged HPHX that did not require an intermediate coolant loop and used a theoretical model for the heat exchanger sizing preliminary design. This design physically separated the reactor coolant from the secondary coolant using two pipe walls, which can avoid the need for additional pumping and piping work as well as a high-pressure heat exchanger shell. It enhanced the tritium diffusion barrier while saving on the initial and operating costs of the power cycle. In another paper [11], Dobson et al. focused on the HPHX design for high-temperature nuclear reactors and developed a transient heat transfer theoretical model. They established an experimental model for an HPHX with a rated power of 2 kW using Dowtherm-A as the working fluid, thus validating the theoretical model and design. The feasibility of adopting this new concept was analyzed using both theoretical and experimental results. For the coal-to-liquid fuel (CTL) process, the use of high-temperature gas-cooled nuclear reactors instead of coal combustion for the heat supply can extend the life of coal reserves and reduce carbon emissions. Nevertheless, the diffusion of radioactive nuclides (specifically, tritium) into the product streams via the walls of the high-temperature heat exchanger presents a risk during the nuclear-to-liquid fuel conversion process. Consequently, the implementation of an intermediate heat exchanger is essential to mitigate this hazard. Tshamala and Dobson [15] replaced the intermediate heat exchanger with an HPHX that operates in the middle of the supply heat stream and the process heat stream, and in this context, a conceptual design and simulation of a high-temperature nuclear gas-cooled reactor was carried out to predict the dynamic control of the reactor. In another research study by Tshamala and Dobson [16], a high-temperature gas-cooled reactor was considered to provide heat for a 240 MWth CTL process, and a conceptual design of the HPHX was carried out in terms of the physical dimensions. The heat transfer process of the HPHX after passing through a steam generator was modeled and simulated to predict the transient and dynamic heat transfer behavior of the HPHX, and the simulation results were in good agreement with the design expectations.

In addition, the applications of HPHXs for heat dissipation systems in nuclear reactors have also been studied. Zhang et al. [7] proposed the use of alkali-metal HP radiators for the power system of the TOPAZ-II space nuclear reactor in Russia to enhance safety and

heat transfer performance and to avoid the single-point failure problem of the original pumped loop radiators. They used numerical simulations to perform a steady-state analysis of the designed HP radiators, predicted their heat dissipation characteristics, and compared the heat transfer performance of the HP radiators with the pump loop radiators. The results indicated that the designed HP radiators satisfied the waste heat rejection criteria for the TOPAZ-II power system during normal operating conditions. The HP radiator demonstrated superior isothermal characteristics and safety compared to the pumped loop radiator. In order to enhance the passive cooling capability of the emergency passive residual heat removal system (EPRHR), Qiao et al. [56] proposed the use of HPHXs to realize the long-term passive heat exchange of the EPRHR cooling water tank (CWT). Through experiments and numerical simulations, a scheme capable of taking away 9 MW of the heat load at an average water temperature not exceeding 90 °C was proposed. The location and layout of the HPs affected the heat removal capacity of the system, which was particularly enhanced when the dimensionless layout factor was 3/4. This passive cooling scheme improved the performance of the EPRHR and reduced heat loss, which was suitable for nuclear power plants. Xie et al. [8] applied wick HPHXs to nuclear reactor waste heat discharge systems and numerically simulated the heat transfer under steady state turbulence and thermal resistance networks and verified it experimentally. The study compared heat transfer and turbulence conditions for different pipe arrangements, HP diameters, and Reynolds numbers. In the case of a highly turbulent flow ($Re \approx 104$), each HP with a diameter of 16 mm achieved a heat transfer power exceeding 2.65 kW. For an HP with a diameter of 19 mm, the heat transfer performance improved by about 3~6% compared with that of an HP with a diameter of 16 mm. The results indicated that HPHXs not only offer safety advantages in preventing radioactive liquid leakage but also demonstrate excellent heat transfer performance when applied in waste heat dissipation systems.

2.3. Geothermal Energy Systems

Geothermal energy is a reliable, environmentally friendly, sustainable, and versatile clean energy source with the potential to play a significant role in future energy supplies, especially in the context of sustainable development and reducing carbon emissions. The direct utilization of geothermal energy is usually achieved by pumping geothermal fluid (especially by pumps) or by flow (based on differences in soil height). However, due to the high silicon content and corrosiveness of geothermal fluid, the use of pumps and pipelines for production is prone to scaling and corrosion [64,65]. Utilizing HPHXs to capture geothermal energy without pumping and discharging fluid is a method to solve this problem.

Zorn et al. [57] used a CO₂ HP in a de-icing and snow melting system, which utilized geothermal energy to heat the street through the HP's own circulation without using any external energy source. Due to the geothermal heat source, the evaporated warm CO₂ rose to the condensing end of the HP, where the CO₂ underwent heat release and condensed, returning to the evaporating end of the HP as a cold liquid. A theoretical model considering all the coupled processes was developed and used in a fire station in Germany. The results showed that there was a good agreement between the measured and simulated values, and by using this system, it was possible to de-ice and melt snow on the streets using geothermal resources at very low surface temperatures. Gunawan et al. [9] investigated a new concept to wither tea leaves by directly utilizing the geothermal energy through an HPHX as a solution for energy sources free from anthraquinone. The experimental results showed that the effectiveness of the HPHX varied from 66% to 79.59% and was able to wither 100 g of fresh tea leaves from 80% moisture content to 54%, reducing the time required from 11 h 56 min to only 49.6 min. The study also used a Page mathematical model to describe the behavior of the tea leaves, demonstrating that HPHXs utilizing low-temperature geothermal energy could be effective in achieving drying treatments for tea.

2.4. HVAC Systems

In recent years, the global climate has dramatically changed. Energy consumption in buildings has become a major issue, accounting for 40% of the global energy demand. Approximately 40–60% of each building's energy demand is used for HVAC systems [66]. Therefore, it is necessary to adopt energy-saving measures to reduce the energy consumption of HVAC systems.

Humidity control is essential to maintain the comfort and health of building occupants and the proper functioning of electronics [67]. Traditional HVAC systems dehumidify by cooling the air stream below its dew point temperature. Afterward, to reach a comfortable temperature for the occupants, the excessively cooled air is subsequently reheated to an appropriate temperature. This reheating process usually requires the use of reheating coils, consuming additional energy. The use of HPHXs in air conditioning systems allows for the pre-cooling or preheating of the air entering the unit, regulating the temperature and humidity of the air without adding additional energy, allowing the air conditioning system to operate more efficiently. HPHXs have been used in HVAC systems for residential ventilation [46], data centers [47], and communication base stations [17]. Diao et al. [46] designed a small flat-plate heat pipe heat recovery device as the core heat transfer component of a residential heat recovery system. Jing et al. [47] applied an air–water heat exchanger based on a micro-heat pipe array in data centers and investigated the performance of the heat exchanger under different operating conditions. Zhang et al. [17] proposed a thermosyphon heat exchanger for the cooling of communication base stations to replace the traditional air-conditioning systems during winter and transitional seasons. Furthermore, because hot and cold fluids are completely separated in HPHXs, there is almost no cross-leakage between the exhaust and supply air, making it suitable for systems where two airflows should not mix. For instance, since the intake and return air in hospitals should not be mixed, Sukarno et al. [10] coupled the HVAC system with HPHXs to meet the standards for Airborne Infection Isolation (AII) rooms.

Due to their lack of wick structure, simplicity of production, and low cost, thermosyphon heat exchangers are widely used in HVAC systems. In the literature [17–22], thermosyphon heat exchangers have been employed to transfer the heat from the discharged hot air to the fresh air entering the system, reducing the energy consumption of HVAC systems. To further reduce energy consumption, U-type HPHXs have been proposed for HVAC systems that require both cooling and reheating. The evaporator side of a U-type HPHX is positioned within the air inlet duct preceding the cooling coil, and the condenser side is located within the air inlet duct following the cooling coil, with the adiabatic section encircling the cooling coil, situated between the evaporator and condenser sides. The U-type HPHX has many advantages in pre-cooling and reheating fresh air compared to the inline HPHX, such as an easy installation in a single duct and a compact size [68]. Hakim et al. [58] explored the utilization of U-shaped HPHXs in a vertical configuration to reduce the cooling and reheating energy in HVAC systems. However, due to the limitations of the circular HP shape, which makes it difficult to integrate with fins, flat-plate micro-heat pipe arrays have been used in HVAC systems. Diao et al. [46] designed a small flat-plate heat pipe heat recovery unit based on flat-plate micro-array heat pipes. Jing et al. [47] used micro-heat pipe array-based heat exchangers for data centers.

The working fluid of HPs is crucial for the performance of HPHXs. Refrigerant is considered the ideal working fluid for HVAC systems operating at common temperatures. The original fluids included R12 and R22, which were later replaced by R134a. However, due to the high global warming potential (GWP) of hydrofluorocarbons, the Kyoto Protocol established the goal of gradually phasing out hydrofluorocarbons [69]. Since refrigerant R134a has been widely used in domestic and industrial applications, an alternative working fluid must be found.

Sharma et al. [18] conducted experimental studies on the thermal performance of air–air HPHXs using R22 and R407c as refrigerants under different evaporator inlet airflow rates and temperatures. The results showed that the heat transfer rate was proportional

to the evaporator inlet air temperature and flow rate. The efficiency of HPHXs increased with the increase in the evaporator inlet air temperature and the decrease in the airflow rate, reaching 33% and 20% for R22 and R407c, respectively, with R22 being the superior refrigerant of the two. Longo et al. [59] compared the performance of HPHXs using the well-known hydrofluorocarbon refrigerant HFC134a and the new low GWP hydrofluoro-olefin HFO1234ze(E) as the working fluid. The tests were conducted in a dual duct system, with air operating conditions typical of summer and winter conditions in European countries. The results showed that the HPHX performance was comparable under the same conditions using both refrigerants, indicating that HFO1234ze(E) could be considered a viable environmental solution as a two-phase fluid in HPHXs.

Though the GWP values of alternative refrigerants are extremely low, there is a possibility they will be legislated against in the near future. Research on zero GWP refrigerants has become critical [70]. In this regard, water has been investigated as a working fluid for HPs. Jouhara et al. [60] investigated the effectiveness and heat recovery values of a U-type HPHX with water as the working fluid in HVAC systems. The results showed a maximum reduction in the inlet temperature of 10.3 °C in a three-row configuration. The HPHX effectiveness values for this configuration also ranged from 47.9% to 54.4%. At an inlet wind speed of 1 m/s and an inlet temperature of 45 °C, the efficiency value was highest (54.4%). The highest heat recovery value of HPHX was 5368 W at an inlet air velocity of 2 m/s. Abedalh et al. [19] experimentally investigated the efficiency and evaporator thermal recovery rate of an HPHX using water as the working fluid under different speeds and a different number of HPHX rows. It was shown that the heat recovery and energy saving of HPHX increased with the increasing air velocity and number of rows.

3. HPHX for Low-Temperature Waste Heat Recovery

Waste heat recovery technology, as an energy-saving and environmentally friendly technical method, has become a hot spot for researchers in recent years. Conducting waste heat recovery not only helps save energy and reduce production costs but also contributes to environmental protection, reduces greenhouse gas emissions, and improves energy utilization efficiency. HPs can be categorized based on their operating temperatures into low-temperature HPs (<277 °C), medium-temperature HPs (277~427 °C), and high-temperature HPs (>427 °C) [71]. When HPHXs are used for waste heat recovery, the temperature of the waste heat determines the operating temperature of the HPs. Therefore, the waste heat temperature is crucial for HPHXs. Low-temperature waste heat refers to waste heat with lower temperatures and lower energy content, which is difficult to directly utilize. It often requires energy enhancement or conversion through equipment like heat pumps, heat exchangers, etc. According to research by Haddad et al. [72], 66% of waste heat occurs in low-temperature heating applications (100–400 °C), as shown in Figure 2, so it is important to carry out low-temperature waste heat recovery.

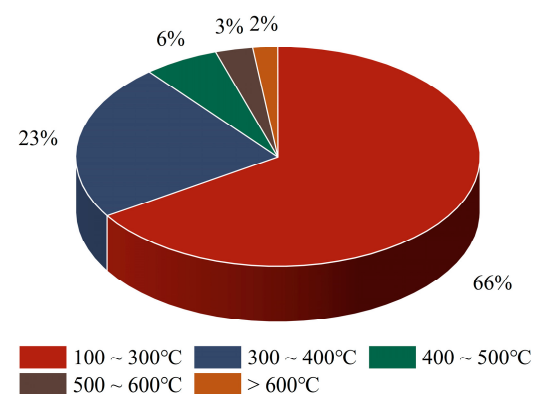


Figure 2. Waste heat energy by temperature range [72].

When recovering low-temperature waste heat, HPHX is used in fields such as the ceramic industry, city gate stations, and pressure reduction stations. Industrial exhaust gases often contain acid gases and particles. During low-temperature waste heat recovery, if the temperature of the acid gases falls below the dew point, they will condense, causing severe corrosion. The presence of particles can also lead to fouling, accumulating on the surface of heat transfer materials in the heat exchanger and causing performance degradation. To avoid this situation, Jouhara's team [4–6] applied HPHXs to the ceramic industry. Due to the isothermal operation of the HPs in the HPHX, condensation of acid gases due to temperature reductions can be effectively avoided. The smooth surface and low-pressure drop of the HPHX also help reduce the fouling rate. To prevent the natural gas at city gate stations from hydrating due to the temperature drop, water bath heaters are used to heat the natural gas before the pressure reduction stage. However, the efficiency of water bath heaters is low. In order to improve efficiency, Alizadeh et al. [30] used HPHXs to recover flue gas waste heat for preheating gas, thereby enhancing the energy performance of the system. Since the indirect water bath heater (IWBH) used for the pressure reduction station requires a large amount of distilled water and the efficiency of the solar still is low, to improve the efficiency of the solar still, Rastegar et al. [34] used HPHX in pressure reduction stations for waste heat recovery to heat the water and generate distilled water required by the IWBH.

Table 4 summarizes the literature on the use of HPHXs in low-temperature waste heat recovery. In industrial applications, economic factors play a crucial role in the selection and implementation of HPHXs. Cost-effectiveness is essential for ensuring the viability and widespread adoption of these systems. As a result, carbon steel is commonly used as the material for constructing heat pipes, while water is frequently chosen as the working fluid. This combination offers a balance of durability, thermal conductivity, and affordability, making it suitable for a wide range of industrial environments. One of the most popular types of heat pipes in industrial settings is thermosyphon. The wickless design simplifies the construction and reduces maintenance needs as it relies on gravity to return the condensed working fluid to the evaporator section. This simplicity makes thermosyphon an attractive option for recovering waste heat from flue gas, which is a common byproduct in many industrial processes. The recovered waste heat from flue gas can be effectively utilized in various applications, enhancing overall energy efficiency. One key application is in cold air preheaters, where the recovered heat is used to preheat the incoming combustion air. This improves the combustion efficiency and reduces fuel consumption. Another important application is in economizers, where the waste heat is used to preheat the boiler feedwater, thereby reducing the energy required to bring the water to steam-producing temperatures. Additionally, the recovered heat can be used for hot water supplies, providing a cost-effective means of generating hot water for industrial processes or domestic use. However, the quality of the waste heat recovered from flue gas is generally considered low, meaning it has a relatively low temperature and may not be suitable for all potential applications. Due to this limitation, the direct use of this waste heat for electric power generation is uncommon. The temperature is often insufficient to drive turbines or other power generation equipment efficiently. To overcome this challenge and make better use of low-quality waste heat, a temperature transformer can be designed and utilized. Temperature transformers, also known as heat pumps or thermoelectric devices, can increase the temperature of the waste heat, making it suitable for more demanding applications, including power generation. By upgrading the quality of the waste heat, these devices can significantly expand the potential uses of HPHEs in industrial settings, improving overall energy recovery and efficiency.

Table 4. Research on HPHXs in low-temperature waste heat recovery.

Reference	Waste Heat Temperature/°C	Application	External Fluid	HP Type	HP Material Wick Material	Working Fluid
Gedik et al. in 2016 [23]	75~175	heat recovery system	flue gas–water	thermosyphon	copper	R134a, R410a
Alizadeh et al. in 2022 [30]	~32	gas city gate station	flue gas–natural gas	thermosyphon	copper	R134a
Ozturk et al. in 2018 [24]	~90	heat recovery system	air–air	thermosyphon	copper	distilled water, Al ₂ O ₃ nanofluid
Ramos et al. in 2014 [25]	50~300	waste heat recovery	air–water	thermosyphon	carbon steel	distilled water
Ramos et al. in 2016 [26]	50~300	waste heat recovery	air–water	thermosyphon	carbon steel	distilled water
Mroue et al. in 2015 [27]	100~300	waste heat recovery	air–water	thermosyphon	carbon steel	distilled water
Mroue et al. in 2017 [28]	100~250	waste heat recovery	air–water	thermosyphon	carbon steel	water
Jouhara et al. in 2021 [73]	102 ± 1	N/A	air–water	thermosyphon	copper	distilled water
Brough et al. in 2020 [4]	135~270	ceramic kiln	exhaust gas–water	thermosyphon	N/A	distilled water
Geum et al. in 2024 [29]	200	waste heat recovery	air–water	thermosyphon	copper	water
Ma et al. in 2017 [31,32]	70~85	steel industry	waste liquid–water	thermosyphon	carbon steel	distilled water
Tian et al. in 2017 [33]	173~192	dyeing and printing industry	exhaust gas–air	thermosyphon	steel	water
Delpech et al. in 2018 [5]	204	the ceramic industry	air–air	thermosyphon	N/A	N/A
Jouhara et al. in 2021 [6]	204	the ceramics industry	flue gas–air	thermosyphon	carbon steel	water
Danielewicz et al. in 2014 [74]	120	N/A	air–air	thermosyphon	carbon steel	methanol
Rastegar et al. in 2020 [34]	100~105	the pressure reduction stations	exhaust gas–water	thermosyphon	copper	water
Zhang et al. in 2021 [35]	50~70	heat recovery of coal-fired flue gas	flue gas–water	thermosyphon	enamel	N/A
Wang et al. in 2015 [75]	40~80	N/A	electric heating units–water	concentric tube heat pipe	aluminum	acetone
Han et al. in 2018 [76]	N/A	N/A	electric heating units–water	concentric tube heat pipe	aluminum	acetone
Ramkumar et al. in 2021 [44]	55~70	electronic component system	water–water	concentric tube heat pipe	copper wick: stainless steel	methanol, acetone
Ramkumar et al. in 2022 [45]	50~70	electronic component system	water–water	concentric tube heat pipe	copper wick: stainless steel	methanol, acetone
Yang et al. in 2019 [48]	~36.6	heat recovery in the cold regions	flue gas–air	micro-heat pipe	aluminum	N/A
Yang et al. in 2022 [49]	50~210	Industrial equipment	flue gas–water	micro-heat pipe	aluminum	acetone
Yang et al. in 2024 [50]	~44 °C	oil fume heat recovery	air–air	micro-heat pipe	N/A	acetone
Zhang et al. in 2013 [77]	~40	N/A	air–air	micro-heat pipe	aluminum	δ-Al ₂ O ₃ -R141b nanofluids, R141b

3.1. HP Type and Dry-Out Analysis

As aforementioned, thermosyphons are widely used due to economic concerns. When the wickless thermosyphon is filled with little working fluid and the radial heat flux density in the evaporator section is relatively low, a dry-out heat transfer limit may occur at the bottom of the evaporation section. This means that the working fluid in the thermosyphon is completely exhausted, and it can no longer provide enough liquid to maintain normal

operations. Dry-out limits can cause an increase in the pipe wall temperature and lead to overheating, potentially resulting in the destruction of the HP. In order to prevent the dry-out limit, Wang et al. [75] developed a novel concentric condenser heat pipe array for low-temperature waste heat recovery, consisting of five vertically arranged evaporator tubes sharing a single horizontally placed condenser tube. This unique structure enhanced the condensation heat transfer coefficient and expanded the condensing surface area. Due to its special design, it could eliminate the negative effects of the dry-out phenomena and maintain the stability of the waste heat recovery system. Han et al. [76] designed a novel concentric tube HPHX based on previous work [75]. Ramkumar et al. [44] used a concentric tube HPHX to harness waste heat dissipation in electronic component systems.

Given that the heat exchanger's internal working medium is liquid, it is prone to freezing and cracking in severe winter conditions, which may lead to reduced efficiency. As a result, these devices are unsuitable for use in cold regions or confined working environments. Therefore, there is a need for a high-efficiency, compact, lightweight, corrosion-resistant heat exchanger to replace the cores of traditional heat exchanger devices. The micro-heat pipe represents a novel class of flat-plate heat pipes, usually with a very small diameter and complex structure, which has the advantages of a rapid thermal response, expansive specific surface area, superior heat transfer capabilities, and low cost. In order to solve the problem of freezing the internal working medium of the heat exchanger in cold regions, Yang et al. [48] investigated the structure and characteristics of micro-heat pipe arrays and applied them to low-temperature flue gas heat recovery in cold regions. Furthermore, Yang et al. [49] proposed a gas–water heat exchanger utilizing micro-heat pipe technology for waste heat recovery and experimentally analyzed the effects of different inlet temperatures and wind speeds on the heat exchanger. After that, Yang et al. [50] proposed a new micro-heat pipe heat exchanger for oil fume heat recovery in order to realize the non-polluting heat recovery of low-temperature oil fumes. The effects of different operating conditions on heat transfer and heat exchange efficiency of the heat exchanger were analyzed experimentally. It was found that when the temperature of the condensing section was the same, the heat transfer efficiency increased with the increase in the temperature of the evaporating section.

3.2. HP Materials and Working Medium Compatibility

When using HPHXs for low-temperature waste heat recovery, materials with good thermal conductivity and corrosion resistance are usually chosen for the HPs. Copper is commonly used in HP production due to its good thermal conductivity and compatibility with many working fluids. Copper has been widely used in manufacturing HP containers and wick structures, as indicated in the literature [23,24,30,34,44,45,73]. Aluminum, whose density is about 25% of the density of copper, is also widely used in manufacturing HP containers. Although the thermal conductivity of aluminum is about 50–60% of that of copper, it still has a good heat transfer performance in low-temperature HP applications, as seen in the literature [48,49,75–77]. Meanwhile, steel is also used as HP material for low-temperature waste heat recovery due to its relatively high mechanical strength and low cost, as shown in the literature [6,25–28,31–33,74].

For each working fluid, there is a specific range of operating temperatures, as shown in Figure 3. At different operating temperatures, common working fluids for HPs are listed in Table 5 [78]. Meanwhile, the choice of working fluid also takes into account pressure conditions and compatibility with HP container materials (wick materials). Chemical treatment of HPs is required to prevent corrosion if necessary. The HPs in the literature [25–28] used carbon steel materials and underwent chemical treatment before water injections to prevent chemical interactions between the carbon steel pipe wall and the water that is continuously boiling/condensing during operation, ensuring the extended service life of carbon steel thermosyphons.

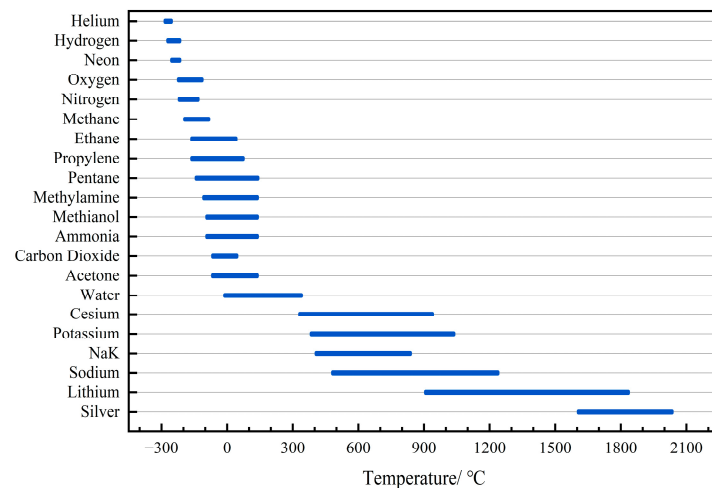


Figure 3. Operating temperature range of common working fluids [78].

Table 5. Applicable working fluids at different operating temperatures [78].

Temperature Type	Temperature Range	Working Fluid
Low temperature	<277 °C	Commonly used working fluids include methanol, ethanol, ammonia, acetone, and water.
Medium temperature	277~427 °C	Special organic fluids like naphthalene and biphenyl can be used for medium-temperature applications.
High temperature	>427 °C	Liquid metals, such as potassium, sodium, and silver, are used to achieve very high heat fluxes due to their large surface tensions and high latent heats of vaporization.

In the low-to-medium-temperature range, water is probably the most widely used working fluid due to its excellent thermophysical properties, including high latent heat of vaporization and significant surface tension, as well as its relative safety during handling [71]. Therefore, most of the literature uses water as the working fluid in low-temperature waste heat recovery [4,6,24–29,31–34,73]. Meanwhile, researchers have also studied the influence of other working fluids on the performance of HPHXs, such as ethanol [44,74], acetone [44,45,49,75,76], R134a, R410A [23], and R141b [77].

In addition, the injection of nanoparticles into the working fluid of HPs for low-temperature waste heat recovery has also been studied [24,77]. Since the thermal conductivity of solids is higher than that of liquids, adding a certain number of solids to liquids can enhance the thermal performance of the fluid. The addition of nanoparticles may increase the fluid capacity, fluid turbulence, and interaction and collision to channel walls [79].

Gedik et al. [23] conducted experiments to investigate the thermal performance of a thermosyphon filled with R134a and R410A in a heat recovery system. The results showed that the HP efficiency ranged from 35.7% to 57.7% when the working fluids were R134a and R410A. When the working fluid was R134a, the efficiency of the HP bundle was approximately 14% higher than when R410A was used as the working fluid. Alizadeh et al. [30] selected the real city gate station data as boundary conditions to design an HPHX with R134a as the working fluid. They evaluated and analyzed the thermal performance of the HPHX in a laboratory system. The results showed that utilizing the HPHX to recover waste energy from flue gas and preheat the natural gas before the heater can improve thermal efficiency, reduce energy consumption, and lower greenhouse gas emissions. Ramkumar et al. [44] investigated the performance of the concentric tube HPHX using methanol and acetone as working fluids for waste heat dissipation in electronic

component systems. Acetone showed a 29.75% increase in effectiveness, a 79.81% increase in the heat transfer coefficient, and a 39.53% increase in the heat transfer rate compared to methanol.

When operating systems at low waste heat temperatures, the working fluid inside the HP needs to evaporate at low temperatures. Since Al_2O_3 nanofluids can evaporate at lower temperatures than water, Ozturk et al. [24] improved the performance of the HP by adding a nanofluid of Al_2O_3 particles to water. They experimentally investigated the heat recovery performance of HPHXs using nanofluids and distilled water as the working fluid. Nanofluids were found to enhance the efficiency of the HP, with higher thermal and energy recovery performance observed for Al_2O_3 /water compared to distilled water. Zhang et al. [77] introduced nanoparticles into the HP working fluid. They compared the heat transfer performance of three different concentrations of $\delta\text{-Al}_2\text{O}_3\text{-R141b}$ nanofluids with pure R141b in a flat micro-heat pipe array heat exchanger. Experimental results showed that using a 0.01 vol% nanofluid as the working fluid significantly improved the heat transfer efficiency, with a maximum efficiency increase of approximately 110%. This indicated that employing nanofluids as working fluids could effectively conserve energy.

3.3. HPHX Performance Optimization

The heat transfer rate and pressure loss are usually regarded as the direct criteria for HPHX performance evaluation. The nanoparticles were proposed to further improve the features of working fluids. In addition, researchers also investigated the effects of the HP inclination angle, HP structures, HP evaporation section length, and operating conditions to further raise the heat recovery efficiency of the HPHX. It should be mentioned that fouling may lead to an increase in the flow resistance, reducing the heat transfer efficiency and increasing energy consumption. Therefore, measures to prevent and reduce the formation of fouling are necessary.

Gedik et al. [23], Ozturk et al. [24], Brough et al. [4], Zhang et al. [35], and Ma et al. [31,32] used thermosyphon heat exchangers for waste heat recovery, while Yang et al. [48,49] used micro-heat pipe heat exchangers for waste heat recovery. They investigated the effect of operating conditions (e.g., hot fluid inlet temperature and flow rate, cold fluid inlet flow rate, etc.) on the performance of the HPHX. Gedik et al. [23] investigated the thermal performance of a heat recovery system with R134a and R410A as the working fluids and conducted experiments to study the effects of the flue gas temperature, velocity, and cooling water flow rate. The results showed that the efficiency of both R134a and R410A increased with the increasing flue gas temperature and velocity. Ozturk et al. [24] experimentally investigated the heat recovery performance of HPHXs using nanofluids and distilled water as the working fluids under various cooling airflow rates and heating powers for the evaporation section. It was found that increasing the heat input decreases the efficiency of HPHXs, with the highest efficiency ($\eta = 59\%$) achieved in experiments using the Al_2O_3 nanofluid at 3 kW of the heating power and an airflow rate of 112 g/s. Brough et al. [4] studied the impact of the exhaust gas temperature, exhaust gas flow, and cooling water temperature on HPHX performance through experimentation. The results showed that the HPHX could achieve energy recovery rates of up to 63 kW from exhaust gas temperatures close to 270 °C, exhaust gas flows of 1298 kg/h, and water flows of 1320 kg/h. In addition, the conductance of the HPHX increased with increasing water and exhaust gas mass flow rates or temperatures. Zhang et al. [35] analyzed the performance of an HPHX in conjunction with an existing 135 t/h combined heat and power plant. The results demonstrated that within the exhaust gas temperature spectrum of 50 to 70 °C, implementing the HPHX significantly enhanced energy efficiency and slightly increased exergy efficiency. With the decrease in the exhaust temperature, the energy and exergy efficiencies gradually increased. Yang et al. [48] investigated the micro-heat pipe array for low-temperature flue gas heat recovery applied in cold regions by numerical simulation and experiment. It was found that the thermal efficiency of the heat exchanger was above 60% through several experiments and calculations. Sensible heat efficiency values varied

from 0.77 to 0.83. As the temperature differential between the fresh air inlet and outlet increased, the efficiency initially increased and then decreased, while resistance displayed a linear growth in response to escalating wind speeds. Furthermore, Yang et al. [49] proposed a gas–water heat exchanger based on micro-heat pipe technology for waste heat recovery. The effects of different inlet temperatures and air velocities on the heat exchange were analyzed experimentally. The analysis data revealed that the temperature differential between the inflow and outflow of flue gas across the heat exchanger amplified as the inlet temperature rose. It was determined that, at a flue gas inlet temperature of 190 °C, the heat transfer efficiency maintained stability above 0.7 during the peak heat transfer. Ma et al. [31,32] conducted a study on liquid-to-liquid HPHXs from both experimental and theoretical perspectives. They proposed a novel method for determining the optimal operating conditions by combining the first and second laws of thermodynamics. The analysis showed that the heat transfer ratio and heat transfer coefficient increased with the increase in the wastewater flow rate at a constant cold-water flow rate. When the wastewater flow varied within the range of 0.8–1.9 m³/h, the exergy destruction rate, exergy efficiency, and effectiveness of HPHX varied within the ranges of 0.277–0.510 kW, 66.1–42.9%, and 0.085–0.192, respectively.

Meanwhile, in the studies of Wang et al. [75], Han et al. [76], and Ramkumar et al. [44,45], a concentric tube heat pipe heat exchanger was used for waste heat recovery. In addition to investigating the effect of operating conditions on HPHX performance, they also explored the effects of the HP inclination angle and HP evaporation section length. Wang et al. [75] investigated the effects of the operating temperature, input power, inclination angle, and evaporator section length on the overall thermal performance of the heat pipe array. The results demonstrated that maximum heat transfer capacity escalated with higher operating temperatures, greater lengths of the evaporator section, and expanded condensation areas, while it diminished with an increase in the inclination angle. At an inclination angle of 60° and an evaporator section length of 270 mm, the novel waste heat recovery device delivered a better heat transfer performance. Han et al. [76] designed a novel concentric tube heat pipe heat exchanger based on the previous work [75]. They conducted experiments to investigate the optimal operating conditions of the heat exchanger. The optimal operating conditions of the heat exchanger were investigated, and the results showed that when the length of the evaporation section was 260 mm, the inclination angle was 60°, the cooling water flow rate was 0.5 m³/h, and at a cooling water temperature of 30 °C, the heat exchanger exhibited an improved heat transfer performance. The maximum heat transfer quantity was approximately 1600 W, with an average thermal resistance of 0.042 °C/W. Ramkumar et al. [44] used the concentric tube HPHX for the utilization of waste heat dissipation in an electronic component system. They investigated the impact of inclination angles, mass flow rates, and inlet temperatures of hot and cold fluids on the performance of the heat exchanger. In this study, the gravity effect showed a significant improvement in the performance, with a gradual increase in the observed results as the angle varied from 10° to 60°, obtaining a maximum at 60°, beyond which a decreasing trend in the observed results was observed until 80°. The optimal operating conditions for the heat exchanger are the mass flow rate of the hot fluid being 100 LPH, the mass flow rate of the cold fluid being 50 LPH, and the inlet temperature being 60 °C. In another study by Ramkumar et al. [45], the performance of HPHXs was investigated on various orientation angles (0° and 90°). The results showed that the maximum thermal performance was obtained at 0° rather than 90°.

It is well known that the greater the turbulence, the larger the forced convection heat transfer coefficient. To adjust the Reynolds number of the fluid while maintaining a consistent flow rate, one mechanical approach is to introduce baffles to alter the number of passes within the heat exchanger. This reduces the flow area, increases the Reynolds number, and enhances turbulence [73]. Ramos et al. [25] conducted experimental research on an HPHX with a single-pass evaporator and a condenser divided into two passes by baffles. They investigated the effect of different hot air mass flow rates (0.05–0.2 kg/s)

and inlet temperatures (50–300 °C). The heat transfer rate of the heat exchanger showed a constant upward trend as the hot air mass flow rate increased. However, the maximum heat transfer rate was limited due to the limited amount of heat absorbed by the cold water and the fact that the hot air did not have enough time to transfer the heat to the pipes, and at the same time, the efficiency of the heat exchanger showed a constant decreasing trend. Mroue et al. [27] designed the evaporator as a two-pass structure based on the work of Ramos et al. [25] and conducted experiments to investigate the impact of multiple air passes on heat transfer performance under different inlet air temperatures (100–250 °C) and air mass flow rates (0.05–0.14 kg/s). The results showed that, at a higher heat fluid inlet temperature and flow rate, the heat exchange rate of the HPHX was higher, and the efficiency of the HPHX was proportional to the heat fluid inlet temperature and inversely proportional to the inlet flow rate. At the lowest heat fluid inlet flow rate and highest inlet temperature, the efficiency of the HPHX reached 29%. Subsequently, Mroue et al. [28] designed the evaporator as a three-pass structure and compared the thermal performance of the HPHX with three different numbers of evaporator passes (single-pass, double-pass, and three-pass) at different inlet temperatures (100–250 °C) and mass flow rates (0.05–0.14 kg/s) through experiments and simulations. The results showed that the heat transfer rate and the overall efficiency of the multi-pass heat exchanger were higher compared to the single pass. When the inlet temperature was 250 °C, and the mass flow rate was 0.14 kg/s, the heat exchangers for single, double, and three passes were 4403, 6191, and 9375 W, respectively. Jouhara et al. [73] investigated the impact of the Reynolds number on the heat transfer rate by incorporating different baffles to alter the number of passes in the evaporator section and adjusting the water flow rate in the same system. The experimental results emphasized a pronounced correlation between the performance of the heat exchanger and the Reynolds number. An increase in the number of passes from one to five led to an enhancement in the HPHX's effectiveness by over 25%. It was shown that a higher count of passes elevated the Reynolds number of the flow, which, in turn, resulted in greater heat transfer coefficients and reduced thermal forced convection resistances. Geum et al. [29] proposed an optimized HPHX design using a full-size conjugate simulation, which improved the heat transfer rate and efficiency by changing the configuration of baffles and the height of the condenser and experimentally verified the proposed design. The results showed that the heat transfer rate and heat transfer efficiency increased by 36.3% and 36.0%, respectively, with the addition of baffles to the HPHX. The effect of hot-side baffles on the heat transfer rate was more significant than that of cold-side baffles. Conversely, increasing the condenser height by five times only improved the heat transfer rate by 3.5%. Brough et al. [4] applied a vertical multi-pass HPHX to the ceramics industry for heat transfer from kiln exhaust gases to water. Experimental and simulation studies were carried out, and the results showed that the heat exchanger could recover up to 63 kW of heat in the exhaust gas temperature range of 135 to 270 °C, proving the feasibility of multi-pass HPHXs for industrial applications.

In the literature on waste heat recovery from hot gases mentioned above, the gas-side heat transfer is usually treated as a clean medium. However, gas emitted from numerous industrial systems often contains particulate matter or contaminants, and the deposition of dirty substances increases the thermal resistance and restricts the fluid flow in the heat exchanger. The impact of fouling on the heat exchanger design and operation has been documented in the literature [80]. In order to improve the efficiency of HPHXs, it is necessary to take measures to minimize the effect of fouling on HPHXs. Ma et al. [31,32] designed an on-line cleaning device to clean the HPs to improve heat transfer efficiency. The effects of the on-line cleaning device on heat transfer and fouling cleaning were experimentally verified. The results showed a substantial enhancement in the heat transfer performance subsequent to the deployment of the on-line cleaning device. Tian et al. [33] designed a new air–gas HPHX to minimize the deposition of dirty substances and to strengthen the heat transfer. Its distinguishing characteristic involved clean air flowing through fin-enhanced vertical tubes, where the interior served as a condenser, while impure gas traversed the smooth inner surfaces of the horizontal tubes,

with the exterior functioning as an evaporator. The new HPHX had a large boiling chamber. The condensate descended into the vessel under the influence of gravity. Because the gas flow within the smooth tubes had a sufficiently high velocity, it was less prone to fouling, effectively addressing issues with internal blockages. The results show that after 3 months of continuous recovery of dirty exhaust gas waste heat, the new HPHX can save 15% of natural gas without blocking the gas-side channel.

3.4. HPHX Performance Prediction

Based on experimental and numerical results, theoretical analysis is essential when studying the performance of HPHXs. Theoretical analysis assists in predicting system performance and estimating the return on investment for specific installations, which is of interest to companies and engineers. However, before using theoretical analysis for predictions, it is necessary to validate it with experimental data.

Delpech et al. [5] applied an air-to-air HPHX to recover waste heat from the cooling stage in the ceramics industry. They developed a theoretical model based on the established and validated performance characteristics of HP technology. Subsequently, a comprehensive numerical model incorporating both lumped and distributed parameters of the kiln was developed and corroborated through experimental measurements, which could simulate the kiln's dynamic behavior under actual operating conditions. Jouhara et al. [6] similarly used an air-to-gas HPHX for waste heat recovery in the ceramics industry and theoretically predicted the thermal performance of the HPHX. The anticipated heat recovery rate stood at 100.5 kW, whereas the actual measured rate was 99.5 kW, demonstrating good agreement between the prediction and experimental results. Ramkumar et al. [45] developed an adaptive neuro-fuzzy inference system and created a prediction model based on the experimental data. This model considered three input factors: the angle, mass flow rate, and temperature, with the output response being thermal resistance. Comparative results demonstrated that the predictive model exhibited strong robustness and reliability. Yang et al. [49] analyzed the irreversibility in the heat transfer process through the introduction of the dimensionless equivalent thermal resistance (R^*) and thermal conductivity (N^*), both derived from the entransy dissipation number. The optimization theory and implementation strategy based on the microtube array heat exchanger were obtained, which laid the foundation for further optimization of the heat exchanger with minimum irreversibility.

When predicting the performance of heat exchangers, two techniques are commonly used: the Log Mean Temperature Difference (LMTD) method and the Effectiveness-Number of Transfer Units (ϵ -NTU) method [81]. These two methods serve different purposes but complement each other. The LMTD method is particularly effective when the inlet and outlet temperatures are known, providing a reliable means for evaluating and designing efficient heat exchange systems. By calculating the log mean temperature difference, engineers can determine the required heat transfer area to achieve the desired thermal performance. Unlike the LMTD method, which requires the inlet and outlet temperatures of both fluids, the ϵ -NTU method is particularly useful when the outlet temperatures are unknown or difficult to measure. The ϵ -NTU method is based on two key parameters: the effectiveness (ϵ) of the heat exchanger and the number of transfer units (NTU). This method focuses on the heat exchanger's effectiveness and its ability to transfer heat between the fluids. In brief, the LMTD method is more suitable for the dimensional design of heat exchangers when the inlet and outlet temperatures are known, and the focus is on evaluating the required heat transfer area. The ϵ -NTU method is more suitable for performance prediction and analysis, especially when the fluid outlet temperature is unknown, and it focuses on predicting the heat exchange efficiency and the final temperature.

Danielewicz et al. [74] proposed a method for predicting the performance of an air-to-air thermosyphon heat exchanger through the ϵ -NTU method, which was experimentally validated, demonstrating a strong correlation between theoretical forecasts and experimental outcomes. This method not only allows for the determination of the overall heat transfer coefficient and effectiveness but also enables the prediction of the airflow temperature

and flow between any two rows of thermosyphons. Ramos et al. [25] developed a design tool for predicting the performance of the HPHX based on an experimental study of an air-to-water thermosyphon heat exchanger using the ε -NTU method and treating the HP as a solid with constant thermal resistance. Similar to previous work [25], Ramos et al. [26] also treated the HP as a solid with known thermal conductivity and predicted the thermal performance of a cross-flow HPHX using a combination of CFD modeling and numerical calculations. The thermal network analogy was employed to project the thermal conductivity of the thermosyphon, which was then applied as a boundary condition in the HPHX's CFD model. Comparison between the computational and experimental outcomes revealed that the discrepancy in the model's predictions and the empirical data was less than 10%, indicating that the thermal resistance analogy inside the HP could be generalized to three-dimensional CFD simulations. Jouhara et al. [73] predicted the overall performance and the fluid exit temperatures in an air-to-water multi-pass thermosyphon heat exchanger using two theoretical models based on the LMTD and the ε -NTU method. These forecasts were compared with experimental outcomes to report the precision of the models. The validation demonstrated that the refined iterative LMTD model gauged the HPHX performance with a margin of error of $\pm 15.5\%$, while the ε -NTU model predicted the overall effectiveness with an utmost error of 19% and predicted the exit temperatures for both air and water flows, within an accuracy of $\pm 0.7^\circ\text{C}$.

4. HPHX for Medium- and High-Temperature Waste Heat Recovery

Medium- and high-temperature waste heat refers to waste heat with a relatively high temperature and energy density. This type of waste heat typically comes from high-temperature industrial processes, combustion processes, or other high-temperature waste heat sources. Compared to low-temperature waste heat, medium- and high-temperature waste heat is relatively easier to efficiently recover and reuse, and it can be utilized for power generation, heating, or other energy recovery applications.

Table 5 shows that when the operating temperature is medium, special organic fluids such as naphthalene and biphenyl are commonly used as working fluids, while liquid metals are commonly used as working fluids when the operating temperature is high. It can be seen that the cost of the working fluid filled inside the HP is higher when recovering medium- and high-temperature waste heat compared to recovering low-temperature waste heat. In addition, using liquid metal as the working fluid also suffers from freezing start-up and heat transfer limitations, which may cause the HP to fail. Therefore, unlike the widespread use in low-temperature waste heat recovery, HPHXs are less applied in medium- and high-temperature waste heat recovery. Table 6 illustrates research on HPHXs in medium- and high-temperature waste heat recovery.

Table 6. Research on HPHXs in medium- and high-temperature waste heat recovery.

Reference	Waste Heat Temperature/ $^\circ\text{C}$	Application	External Fluid	HP Type	HP Material Wick Material	Working Fluid
Xu et al. in 2019 [37]	434	combine harvester	exhaust gas–air	thermosyphon	carbon steel	water
Jouhara et al. in 2017 [42]	>500	steel industry	radiation–water	flat heat pipe	stainless steel	water
Almahmoud et al. in 2019 [43]	400~580	steel industry	radiation–water	flat heat pipe	stainless steel	water
Han et al. in 2015 [82]	450	N/A	air–air	thermosyphon	carbon steel	low temperature: water; transition temperature: naphthalene, water; medium temperature: naphthalene distilled water, Dowtherm
Jouhara et al. in 2023 [36]	400	aluminum industry	air–air	thermosyphon	N/A	
Delpech et al. in 2019 [12]	500~580	ceramics industry	radiation–water	thermosyphon	stainless steel	N/A

Studies on the use of HPHXs for medium- and high-temperature waste heat recovery mostly remain in the experimental stage and have not been applied in practice. Due to the economy and cleanliness of water, it is still used as the working fluid in HPs for medium- and high-temperature waste heat recovery, as documented in the literature [37,42,43]. However, water is usually not recommended as a working fluid for medium- and high-temperature waste heat recovery because of its relatively low boiling point, which may be exceeded under high-temperature conditions, leading to the vaporization of water into steam, resulting in vapor lock and reduced heat transfer. As the waste heat flows through the HPs, the temperature gradually decreases. In order to meet the need for waste heat recovery temperature and save costs, the option of using different working fluids in different regions was investigated to optimize the system performance and improve the recovery efficiency. Han et al. [82] selected water and naphthalene as working fluids for the HP, developed a mathematical model of the HPHX system and used numerical simulation to compute temperature and flow field distributions within the heat exchanger. They established a single HP inner temperature field model and conducted numerical simulations, focusing on the transition part and the temperature distribution both inside and outside each row of the HP for a medium-temperature HPHX. Based on the resulting temperature distribution, the distribution of working fluid within the HPHX was determined: water for the low-temperature section, naphthalene for the medium-temperature section, and a transition section where rows 23 and 24 used naphthalene as the working fluid, while row 25 used water as the working fluid. Jouhara et al. [36] used both water and Dowtherm as the working fluid in an HPHX for waste heat recovery from the aluminum industry, considering that the maximum operating temperature of Dowtherm is higher than that of water. Theoretical and experimental studies showed that this HPHX could recover up to 88.6 kW of power at 400 °C under steady-state conditions. After 35 months of experimental evaluation, 86 tons of CO₂ emissions could be reduced per year under the best engineering practices.

For medium- and high-temperature waste heat recovery, stainless steel and carbon steel are used as HP container materials in existing literature, with previous studies [37,82] using carbon steel and other studies [12,42,43] using stainless steel. However, attention needs to be paid to the high-temperature stability of the materials, which is usually in the range of 500~600 °C for carbon steel and 600~800 °C for stainless steel, beyond which oxidation, corrosion, or deformation may occur.

As in low-temperature waste heat recovery, thermosyphon heat exchangers are also used in medium- and high-temperature waste heat recovery. Xu et al. [37] proposed a thermosyphon heat exchanger for diesel engine exhaust waste heat recovery. The heat transfer performance parameters of each HP were obtained by assuming the HP as a definite heat source and substituting them into the CFD simulation model by using the constant heat flow density method. For the rated condition and maximum torque condition commonly used in this diesel engine, the effects of the air inlet temperature and inlet flow rate on the heat transfer process at the cold side of the heat exchanger were calculated and analyzed. The results showed that the inlet air velocity affected the heat transfer process much more than the inlet air temperature in both diesel engine operating conditions; the HPHX was able to recover more exhaust waste heat energy, and the total heat transfer efficiency was higher when the diesel engine was operating at rated conditions compared to the maximum torque condition. Jouhara et al. [36] designed, manufactured, and installed thermosyphon heat exchangers in the solution furnace exhaust stack to provide a waste heat recovery solution for an aluminum die-casting factory.

In high-temperature waste heat recovery, it is necessary to consider the effect of radiation, in which case maximizing the area of radiation absorption can help to improve the efficiency of heat recovery. The wick heat pipes, Thermosyphons, and concentric tube heat pipes mentioned above are typically designed with cylindrical shells. However, an HP can be designed not only with a cylindrical shell but also with a flat shape or a flat evaporator combined with a cylindrical condenser, referred to as a flat-plate heat pipe.

The advantages of the flat-plate heat pipe include its isothermal properties and the flat evaporator surface, which maximizes the radiation absorption area and meets the needs of high-temperature waste heat recovery.

Delpech et al. [12] designed a flat-plate radiative heat pipe for recovering waste heat during the cooling phase in the ceramic industry. The thermal performance of the radiative heat pipe was experimentally investigated on a laboratory-scale kiln, and a theoretical model was used to evaluate the contribution of radiant heat transfer and natural convective heat transfer to the total heat transfer of the HP. The results showed that the HPHX was capable of recovering heat using radiation and natural convection in a closed kiln and that the radiation heat transfer rate played a dominant role at higher temperatures. Jouhara et al. [42] used a flat-plate HPHX to recover radiative and convective heat from high-temperature sources, like hot steel in the steel industry, exceeding 500 °C. The flat-plate HPHX consisted of stainless-steel HPs connected via a bottom header and capped with a shell and tube top header. Unlike the study of Delpech et al. [12], this flat-plate HPHX could be operated at various inclination angles, ranging from vertical to nearly horizontal. The thermal performance of the heat exchanger was investigated in both laboratory and industrial settings, and a theoretical model was formulated to forecast its performance. The experimental results were in good agreement with the theoretical results. The results showed that flat heat pipe was an innovative and efficient waste heat recovery technology. Based on the study of Jouhara et al. [43], Almahmoud et al. [42] examined the influence of a back panel on heat recovery through comparative testing of the flat heat pipe, both with and without the back panel. They also investigated the impact of the flat heat pipe's surface emissivity and absorptivity on its thermal efficiency using pipes coated with high-temperature black paint in contrast to untreated pipes. The results showed that the black paint had a significant effect on heat recovery, with a 470% increase in the heat transfer rate. In addition, the back panel could increase the heat transfer rate by up to 330%. The combined effect of the black paint and the back panel increased the heat recovery by 570%, allowing the flat-plate HPHX to recover 8.5 kW of energy.

5. Conclusions

The HPHX holds great potential for a wide range of applications in the fields of energy, environment, and industrial production when considering its merits of high compactness, flexible arrangement, complete separation of hot and cold fluids, and good isothermal operation. The HPHXs usually show high-efficiency heat transfer performance and unique operating principles, providing effective solutions for various application scenarios. This paper provides a review of the recent progress in research on HPHXs in different fields. Major conclusions can be summarized as follows:

1. HPHXs have been applied in the fields of solar energy, nuclear energy, geothermal energy, HVAC systems, and waste heat recovery. However, they are more commonly applied in low-temperature fields because the operating temperatures of HPHXs fit the temperatures of most economic HPs. When HPHXs are applied in medium- and high-temperature fields, some special organic fluids or liquid metals are often used as working fluids, which are more costly. In addition, high-temperature HPs using liquid metals as the working fluid also have freezing start-up and heat transfer limitation problems, which may cause the HP to fail.
2. The HP feature is crucial for the construction of the HPHX. The HP type, material, and working fluid should be compatible. Meanwhile, the thermosyphon but not wick-structure HP is more commonly used due to less flow resistance for condensation. Thermosyphon-based HPHXs are widely used in nuclear reactors, HVAC systems, and low-temperature waste heat recovery due to their simple and low-cost production. In addition, in low-temperature waste heat recovery, a concentric tube heat pipe heat exchanger has been proposed and applied in order to prevent the drying-out limit in thermosyphons. In solar energy systems and high-temperature waste heat recovery,

flat-plate HPHXs are utilized more often to maximize the radiation absorption area in order to further improve the heat transfer efficiency.

3. Copper and aluminum are also commonly used materials for HPs in HVAC systems, and refrigerants are regarded as ideal fluids. Alternative low GWP and near-zero GWP working fluids are being investigated in HVACs. On the other hand, the materials of HPHXs used in nuclear reactors and medium- and high-temperature waste heat recovery are usually high-temperature alloys with high-temperature resistance and corrosion resistance. The choice of working fluid should consider the saturation temperature, working pressure, and material compatibility. Different working fluids are used in different temperature regions in order to meet the demand for waste heat recovery and save costs.
4. The addition of surfactants and nanoparticles to the working fluid shows a substantial impact on HPHX performance. In addition, the impact of the HP inclination angle, structure, length of HP evaporation sections, and operating conditions were also studied. Moreover, measures to prevent and reduce the formation of fouling are necessary. For low-temperature waste heat recovery, the impact of the number of passes and descaling devices on enhancing HPHX heat exchange has also been studied in the field of low-temperature waste heat recovery.

In conclusion, most existing studies have focused on the data report of HPHXs, but a rare fundamental analysis on the impact of HP parameters (diameters, filling ratios, insulation section area, etc.), HP layouts (parallel and staggered), air-side channel arrangements, and air-side surface areas has been conducted. In addition, numerical investigations considering the HPHX nonlinear temperature distribution and HP equivalent conductivity may indicate great contributions to the precise design of HPHXs.

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Nomenclature

IEA	International Energy Agency
HP	heat pipe
HPHX	heat pipe heat exchanger
CFD	computational fluid dynamics
VOF	volume of fluid
LMTD	log mean temperature difference
ϵ -NTU	effectiveness-number of transfer units
HVAC	heating, ventilation, and air conditioning
PV/T	photovoltaic/thermal
PV	photovoltaic
RSM	response surface methodology
PTC	parabolic trough collector
CTL	coal-to-liquid fuel
EPRHR	emergency passive residual heat removal system
CWT	cooling water tank
EGS	enhanced geothermal system
MHPA	micro-heat pipe array

LPH	liters per hour
HVAC	heating, ventilation, and air conditioning
AII	airborne infection isolation
COP	coefficient of performance
vol%	volume percent
IWBH	indirect water bath heater

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