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Review on the Integration of Printed Circuit Heat Exchanger (PCHE) and Thermoelectric Generation (TEG) Technology

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Abstract

This paper systematically reviews the latest progress in the research on the integration of Printed Circuit Heat Exchanger (PCHE) and Thermoelectric Generation (TEG) technology. With the increasingly prominent issue of energy shortage, the efficient utilization of the large amount of cold energy released during the gasification process of Liquefied Natural Gas (LNG) has become a research hotspot in the energy field. As a new type of compact heat exchanger, the Printed Circuit Heat Exchanger shows great application potential in the field of LNG gasification due to its advantages of compact structure, high heat transfer efficiency, and high pressure resistance. The thermoelectric generation technology based on the Seebeck effect can directly convert thermal energy into electrical energy, providing an innovative solution for LNG cold energy recovery. This paper comprehensively analyzes the integrated innovation of PCHE and TEG technologies from the aspects of technical principles, structural design, performance optimization, and application fields, focuses on key issues such as composite structure design, heat transfer enhancement methods, and thermoelectric conversion characteristics, and looks forward to the challenges and future development trends of this technology. Research shows that the organic combination of PCHE and TEG can simultaneously achieve efficient gasification of LNG and cold energy power generation, providing a new idea for efficient energy utilization.

Keywords

Printed Circuit Heat Exchanger; LNG Cold Energy Recovery; Thermoelectric Conversion; Composite Structure.

1. Introduction

Energy is the material basis for the development of modern society. With the continuous development of the global economy and the continuous growth of population, the demand for energy is expanding day by day. How to improve energy utilization efficiency has become a major issue of common concern to all countries in the world. As a clean energy source, Liquefied Natural Gas (LNG) occupies an increasingly important position in the global energy structure. During the LNG gasification process, each ton of LNG releases approximately 830-860 MJ of cold energy[1].In traditional gasification methods, this part of cold energy is usually directly released into the environment,resulting in a great waste of energy.Therefore, the efficient recovery and utilization of LNG cold energy has important economic value and environmental significance.

In recent years, the Printed Circuit Heat Exchanger (PCHE),as a new type of compact heat exchanger, has attracted widespread attention in the field of LNG gasification.The concept of PCHE was first proposed by Heatric Company in the United Kingdom. It has the advantages of compact structure and flexible flow channel design, and is one of the ideal heat exchangers for low-temperature systems. Compared with traditional heat exchangers, PCHE has the advantages of small volume, light weight, high heat transfer efficiency, safety, and reliability, and is especially suitable for occasions with limited space such as Floating Storage and Regasification Units (FSRU)[2]. At the same time, the thermoelectric generation technology based on the Seebeck effect can directly convert thermal energy into electrical energy, which has the advantages of simple structure, no moving parts, no noise, no pollution, and long service life, and is one of the most promising LNG cold energy utilization methods at present.

This paper will deeply discuss the research status of the combination of Printed Circuit Gasifier and thermoelectric generation technology, analyze the design principles and optimization methods of composite structures, summarize key technical challenges, and look forward to future development trends, so as to provide a reference for the research and application of this technology.

2. Printed Circuit Gasifier Technology

2.1. Structural Characteristics of PCHE

The Printed Circuit Heat Exchanger is a micro-channel heat exchanger manufactured using chemical etching and diffusion welding technologies. Its core manufacturing processes include: forming micro-channel flow channels on a metal plate through chemical etching, then stacking multiple metal plates together, and forming an integral structure through high-temperature diffusion welding[3]. This manufacturing process gives PCHE the characteristics of highly customized flow channel design, high pressure resistance, and high compactness.

The channel structure of PCHE can be optimally designed according to fluid characteristics and heat transfer requirements. Common channel forms include straight channels, Z-shaped channels, S-shaped channels, etc. Studies have shown that airfoil rib channels can effectively suppress flow separation, eliminate backflow and vortices, improve the uniformity of fluid flow distribution, and significantly reduce flow resistance loss[4]. This design is particularly suitable for the change characteristics of gas-liquid two-phase flow during the LNG gasification process.

2.2. Application of PCHE in LNG Gasification

Table 1. Performance Comparison between Traditional Gasifiers and PCHE

Performance Indicator	Traditional Shell-and-Tube Gasifier	Printed Circuit Gasifier	Improvement Range
Heat Transfer Coefficient (W/m^2K)	500-800	1000-3000	Increased by 100%-275%
Pressure Resistance (MPa)	5-10	30-60	Increased by 400%-500%
Compactness (m^2/m^3)	100-500	1000-2500	Increased by 400%-900%
Anti-Sloshing Performance	Poor	Excellent	Significantly ImprovedSignificantly Improved
Floor Space	Large	Small	Reduced by 60%-70%

In LNG gasification applications, PCHE usually adopts alternately stacked hot fluid channels and cold fluid channels. The hot fluid channels usually circulate propane or other low-boiling organic working fluids, while the cold fluid channels circulate LNG. This arrangement can maximize the heat transfer temperature difference and heat transfer efficiency[5].

Compared with traditional gasifiers, PCHE, as an LNG gasifier, has significant advantages. Studies have shown that the heat transfer efficiency of PCHE is more than 30% higher than that of traditional shell-and-tube heat exchangers, and it can still maintain stable heat transfer performance under the condition of hull sloshing. This feature is particularly suitable for the application environment of offshore FSRU. In addition, the small volume and light weight of PCHE can significantly reduce the floor space of the gasification device and the requirements for supporting structures[6].

3. Principle and Application of Thermoelectric Generation Technology

3.1. Seebeck Effect and Thermoelectric Materials

Thermoelectric generation technology is based on the Seebeck effect, which means that when two different conductors or semiconductors form a closed loop and there is a temperature difference between the two ends, an electromotive force will be generated in the loop[7]. The Seebeck coefficient (S) is a key parameter to measure the performance of thermoelectric materials, defined as the potential difference generated per unit temperature difference, and its unit is usually μV/K.

The performance of thermoelectric materials is mainly determined by the dimensionless figure of merit ZT. High-performance thermoelectric materials need to have a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity at the same time. Currently commonly used thermoelectric materials include: bismuth telluride (Bi_2Te_3) and its alloys (used near room temperature), lead telluride (PbTe)-based materials (used in the medium-temperature range), and silicon-germanium (SiGe) alloys (used in high-temperature environments), etc.

In recent years, significant progress has been made in the research of thermoelectric materials. For example, the aerospace-grade thermoelectric materials developed by Saifun Energy Technology Co., Ltd. have increased the conversion efficiency to 15%, and it is planned to increase it to 20% through material innovation and system optimization[7]. Once this breakthrough is achieved, static thermoelectric technology is expected to replace traditional turbine power generation and become a new generation of main power generation technology.

3.2. Structure of Thermoelectric Generation Devices

A Thermoelectric Generator (TEG) is usually composed of multiple thermocouples connected in series or parallel. Each thermocouple includes a p-type thermoelectric arm and an n-type thermoelectric arm[2]. The thermoelectric arms are connected by a conductive material (such as a copper sheet), and the whole is located between the hot end and the cold end. In order to improve the thermoelectric conversion efficiency and reliability, modern TEG adopts a variety of innovative structures:

Table 2. Performance Characteristics of Different Types of Thermoelectric Generation Devices

Device Type	Conversion Efficiency	Power Density	Applicable Temperature Range	Typical Application
Conventional Bulk TEG	5%-8%	0.1-0.5 W/cm^2	Room Temperature - 600°C	Industrial Waste Heat Recovery
Lateral TEG	3%-5%	0.05-0.2 W/cm^2	Room Temperature - 300°C	Surface Waste Heat Collection
Flexible TEG	2%-4%	0.01-0.1 W/cm^2	Room Temperature - 200°C	
Wearable Devices Miniature TEG	1%-3%	0.1-0.8 W/cm^2	Room Temperature - 400°C	Microelectronic Devices

Lateral structure: Suitable for in-plane heat flow applications, especially for collecting surface waste heat.

Flexible structure: Uses a flexible substrate and packaging materials, can adapt to curved surfaces, and is suitable for wearable devices.

Miniaturized structure: Uses micro-manufacturing technology to prepare micron-scale thermoelectric arms, suitable for powering microelectronic devices.

4. Composite Structure Design and Optimization

4.1. Integrated Design of PCHE and TEG

The integrated design of PCHE and TEG is the key to realizing efficient LNG cold energy recovery. An advanced design scheme is the "composite structure printed circuit type LNG gasifier core with thermoelectric generator", which includes flat rib channels (hot fluid channels) and airfoil rib channels (cold fluid channels) arranged alternately up and down[2].

The flat rib channel includes a first partition plate, a flat rib plate, and a first thermoelectric generation module from top to bottom. Guide strips are arranged on both sides of the top of the flat rib plate, a number of continuous flat ribs are arranged at equal intervals between the guide strips on both sides, and a number of tapered longitudinal vortex generators are arranged at equal intervals between two adjacent continuous flat ribs[8]. These designs aim to enhance the heat transfer effect and improve the thermoelectric conversion efficiency.

The airfoil rib channel includes a second partition plate, an airfoil rib plate, and a second thermoelectric generation module from top to bottom. Guide strips are arranged on both sides of the top of the airfoil rib plate, a number of rows of discontinuous airfoil ribs are arranged at equal intervals between the guide strips on both sides, the discontinuous airfoil ribs in adjacent rows are arranged in a staggered manner, and dimpled structures are symmetrically arranged in the wake area of the discontinuous airfoil ribs. This design can generate boundary layer disturbance, further improving the heat transfer efficiency of the core.

The thermoelectric generation module includes sealing strips on both sides. A thermoelectric generator is arranged between the sealing strips on both sides, and the top and bottom surfaces of the thermoelectric generator are covered with insulating ceramics. The thermoelectric generator is composed of a number of p-n junctions connected in series. The p-n junctions include p-type thermoelectric arms and n-type thermoelectric arms arranged in parallel at intervals, and the top and bottom surfaces of the p-type thermoelectric arms and n-type thermoelectric arms are respectively connected with conductive copper sheets in a staggered manner.

4.2. Heat Transfer Enhancement Technologies

In the PCHE-TEG composite structure, heat transfer enhancement is the key to improving the overall performance. At present, the following technologies are mainly used:

Tapered longitudinal vortex generators: Installed in the hot fluid channel (flat rib channel), with an attack angle of 40°-50° to the central axis[6]. These vortex generators can generate longitudinal vortices, destroy the flow boundary layer, enhance fluid mixing, and thus strengthen the convective heat transfer process.

Dimpled structures: Arranged in the wake area of the airfoil ribs in the cold fluid channel (airfoil rib channel), with a height-to-diameter ratio ranging from 0.2 to 0.25. Studies have shown that within this parameter range, vortex dead zones are less likely to be generated in the wake area of the airfoil ribs, and the comprehensive performance of the heat exchanger is optimal. The dimpled structure can promote fluid disturbance, enhance the renewal of the thermal boundary layer, and improve the heat transfer efficiency.

Staggered arrangement of discontinuous airfoil ribs: This arrangement can increase the heat transfer area and density, and at the same time effectively suppress flow separation, eliminate backflow and vortices, improve the uniformity of fluid flow distribution, and significantly reduce flow resistance loss.

4.3. Thermodynamic Optimization and Field Synergy Optimization

The optimization of the PCHE-TEG system needs to comprehensively consider the thermodynamic performance and thermoelectric conversion efficiency. The optimization principles include:

Temperature field uniformity optimization: Ensure the uniform temperature distribution at the hot and cold ends of the TEG, avoid excessive local thermal stress and reduce the thermoelectric conversion efficiency[6].

Flow resistance minimization: Under the premise of ensuring the heat transfer effect, reduce the flow channel resistance as much as possible to reduce the pump power consumption.

Field synergy optimization: Achieve the optimal synergy state of the velocity field, temperature field, and pressure field to realize the optimal overall performance of the system.

Studies have shown that the optimal operating parameters and structural parameters of the PCHE-TEG system can be obtained through multi-objective optimization algorithms, so that the system can achieve the optimal performance under specific working conditions. For example, the geometric parameters such as the length, width, and height of the insulating ceramics, conductive copper sheets, and p-n junction thermoelectric arms can be adjusted to meet the requirements of different design parameters.

5. Application Fields and Market Prospects

5.1. Offshore LNG Transportation and Regasification

The PCHE-TEG composite system has broad application prospects in offshore LNG Floating Storage and Regasification Units (FSRU). The heat transfer efficiency of traditional heat exchangers is significantly reduced under the condition of hull sloshing. However, due to its micro-channel structure, PCHE has excellent anti-sloshing performance and can maintain stable heat transfer performance in the marine environment. At the same time, the integrated TEG technology can recover the large amount of cold energy released during the LNG gasification process, provide electricity for monitoring equipment and control systems on the FSRU, and realize energy self-sufficiency[8].

5.2. Industrial Waste Heat Recovery

The PCHE-TEG technology also has great potential in the field of industrial waste heat recovery. For example, in high-energy-consuming industries such as electrolytic aluminum, iron and steel, and chemical industry, a large amount of medium and low-temperature waste heat is not effectively utilized at present. The PCHE-TEG system can recover both waste heat and cold energy, realizing the cascade utilization of energy. The high-power static thermoelectric power supply developed by Saifun Energy Technology Co., Ltd. is designed for industrial waste heat, with a conversion efficiency of 15%, which can replace the traditional boiler system, and the first set has been put into use in the electrolytic aluminum field[9].

5.3. Wearable Devices and Internet of Things

With the rapid development of flexible electronics and intelligent wearable devices, their demand for power supplies with long battery life and high energy density is increasing day by day. Flexible thermoelectric generators can collect human body waste heat to continuously provide electricity for intelligent wearable devices. The research team of Zhejiang University has developed a new type of wearable flexible thermoelectric generator, which uses bismuth telluride-based thermoelectric materials to manufacture bulk semiconductor thermoelectric arms, and forms a structure with thermal circuits in series and electrical circuits in series through electrode connection, successfully realizing human body wearable drive.

5.4. Market Prospects and Economy

The thermoelectric generation market has broad prospects. It is predicted that the global thermoelectric generation market size will grow from hundreds of millions of US dollars in 2020 to billions of US dollars in 2030. As an innovative energy solution, the PCHE-TEG technology will play an important role in the following fields:

Nuclear energy field: PCHE can withstand high-temperature and high-pressure environments and has high compactness. It can meet the heat transfer and safety requirements of liquid metal/molten salt-supercritical carbon dioxide heat exchangers, regenerators, and coolers in liquid metal reactors/molten salt reactors, and is currently the most recommended heat exchanger type for liquid metal reactors/molten salt reactors coupled with Brayton cycle systems, and also the preferred type for intermediate heat exchangers of high-temperature gas-cooled reactors[10].

Marine engineering field: With the characteristics of compactness, high efficiency, and reliability, PCHE has been applied to oil and gas platforms, LNG floating storage and regasification systems, floating LNG liquefaction devices, etc., and is one of the key equipment in the entire LNG industry chain.

Thermal power generation field: Supercritical carbon dioxide power generation technology is an important innovative technology in the field of thermal power generation. Different from traditional mainstream thermal power generation technologies, this technology uses carbon dioxide as the cycle working fluid and has significant advantages such as high thermoelectric conversion efficiency, small volume of power equipment and systems, good flexibility, and low pollution. PCHE is a key equipment in the supercritical carbon dioxide cycle, and its thermal-hydraulic characteristics have a direct impact on the efficiency and volume of the entire power generation system.

In terms of economy, although the initial investment of the PCHE-TEG system is relatively high, its operation and maintenance costs are low, and its service life is long. The investment payback period is generally between 3 and 8 years, depending on the application scenario and energy price.

6. Challenges and Future Development Trends

6.1. Technical Challenges

Although the PCHE-TEG technology has many advantages, it still faces some technical challenges:

Limitations of thermoelectric material performance: The ZT value of current commercial thermoelectric materials is generally not high, resulting in low thermoelectric conversion efficiency. The ZT value of most thermoelectric materials is between 1 and 2, and the corresponding thermoelectric conversion efficiency is only 5%-15%[7].

Thermal stress matching problem: The thermal expansion coefficients of PCHE metal materials (usually nickel-based alloys) and thermoelectric materials do not match, and thermal stress is generated when the temperature changes, which affects the reliability and service life of the equipment.

Contact thermal resistance problem: The contact thermal resistance between the TEG and the heat source/cold source will reduce the effective temperature difference, thereby affecting the power generation. Reducing the contact thermal resistance requires optimized interface materials and assembly processes.

Complexity of system integration: The efficient integration of PCHE and TEG requires comprehensive knowledge of fluid dynamics, thermodynamics, materials science, and electrical engineering, making system design and optimization difficult[2].

6.2. Future Development Trends

The future development of PCHE-TEG technology will mainly focus on the following directions:

New material development: Research on new thermoelectric materials, such as nanostructured thermoelectric materials, topological insulators, and hybrid perovskite materials, is expected to significantly improve the ZT value. Saifun Energy Technology Co., Ltd. plans to "increase the thermoelectric conversion efficiency from 15% to 20% through material innovation and system optimization" [6].

Multi-stage structure design: For wide temperature range applications, develop multi-stage TEG structures, using different thermoelectric materials for different temperature ranges to achieve optimal matching of the entire temperature range and improve overall conversion efficiency.

System-level optimization and intelligent control: Combine artificial intelligence and big data technology to conduct real-time monitoring and intelligent control of the PCHE-TEG system, so that the system always works in the optimal state.

Multi-energy complementary systems: Combine PCHE-TEG with other energy technologies (such as photovoltaics, energy storage, etc.) to form multi-energy complementary systems, improving the reliability and utilization rate of energy supply.

Innovation in manufacturing processes: Develop low-cost and high-efficiency manufacturing processes, such as additive manufacturing technology, for rapid prototyping of complex flow channel structures and thermoelectric modules[8].

7. Conclusion

This paper systematically reviews the latest progress in the research on the integration of Printed Circuit Gasifier and thermoelectric generation technology. As a compact and efficient heat exchange equipment, PCHE, combined with TEG technology based on the Seebeck effect, can simultaneously achieve efficient gasification of LNG and cold energy power generation, with the advantages of simple and compact structure, high heat transfer efficiency, energy saving, environmental protection, and strong applicability, and its development is imperative.

Studies have shown that through heat transfer enhancement technologies such as tapered longitudinal vortex generators and dimpled structures, as well as optimized flow channel design and thermoelectric module arrangement, the comprehensive performance of the PCHE-TEG system can be significantly improved. This technology has broad application prospects in offshore LNG transportation and regasification, industrial waste heat recovery, wearable devices, and the Internet of Things.

However, the PCHE-TEG technology still faces technical challenges such as limitations of thermoelectric material performance, thermal stress matching, and contact thermal resistance. Future research should focus on the development of new thermoelectric materials, multi-stage structure design, system-level optimization and intelligent control, and innovation in manufacturing processes. PCHE is increasingly used in fields such as liquefied natural gas, but understanding the heat transfer characteristics of flow condensation in channels is a necessary prerequisite for the optimal design of PCHE. Therefore, more efforts should be made to study the phase change heat transfer mechanism of working fluids in channels.

With the increasingly serious problems of energy shortage and environmental pollution, the PCHE-TEG technology, as an efficient energy recovery and utilization solution, will make important contributions to sustainable development. Through continuous research and innovation, this technology is expected to play a more important role in the future energy system.

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