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Research Status and Development Trend of Printed Circuit Plate Heat Exchangers

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Abstract: This paper mainly conducts a comprehensive review of the research status and development trend of printed circuit plate heat exchangers. Firstly, the basic structure and working principle of the printed circuit plate heat exchanger were introduced. Then, its research status at home and abroad was elaborated in detail, including the research results in aspects such as heat transfer performance, flow characteristics, and manufacturing processes, aiming to provide a theoretical basis and research direction for the design of PCHE.

Keywords: FLNG; Printed circuit plate heat exchanger; Bad sea conditions; Heat transfer deterioration.

1. Introduction

After China proposed the strategic goals of "carbon peak" and "carbon neutrality", it has become an inevitable trend to reduce environmental pollution caused by the combustion of coal and other fuels, vigorously develop new clean energy sources such as hydrogen energy and natural gas, and gradually reduce coal consumption. Compared with other fuels, natural gas contains extremely low levels of sulfur, mercury and other harmful substances, has a high calorific value and emits less carbon dioxide during combustion. It is recognized as a high-quality and environmentally friendly energy source [1]. Data shows that it is expected that the proportion of natural gas consumption in China's energy consumption structure will increase by 9.4% by 2030. However, at present, China's recoverable natural gas is about 22 trillion cubic meters, and the per capita possession is only 17,000 cubic meters per person, which is 4% of the world average. Obviously, there is a very large gap in the supply of natural gas resources in our country, and it is impossible to completely rely on imports to solve the problem. Therefore, our country must further develop the development and exploration technologies of natural gas resources and expand the energy self-sufficiency.

With the increasing proportion of natural gas in China's energy consumption structure and the gradual intensification of offshore natural gas development efforts. FLNG and FSRU, as the basic facilities for offshore natural gas development, are widely used in the development of offshore natural gas due to their advantages such as low cost and good flexibility. The Floating Storage Regasification Unit (FSRU for short) has a series of functions such as offshore storage, transportation and regasification. It has the advantages of low cost and short construction time. Meanwhile, with the mobility of the platform itself, It can realize the transfer of gas field exploitation sites and the transportation of LNG during the exploitation process, facilitating the efficient and economic development of offshore oil and gas fields, and has broad development prospects [3]. PCHE has gradually become the core heat exchange equipment in offshore oil and gas processing units such as FSRU, and is also widely used in high-temperature reactor heat exchange, chemical processes, aerospace and other fields [4]. As the core equipment of this device, the heat exchanger must first meet the requirement of extremely high compactness. Traditional heat exchangers, such as wound tube heat exchangers [5] and plate heat exchangers [6], all have disadvantages such as easy leakage and large floor space, and cannot meet the requirements of compactance and high efficiency for offshore natural gas vaporizers. The Printed circuit heat exchanger (PCHE) is a new type of plate heat exchanger and is also a plate heat exchanger.

This paper reviews the research status of PCHE and the development status of PCHE in the field of FLNG. Aiming at the influence of FLNG sway conditions on the performance of PCHE, it analyzes the research points of the application of PCHE in the field of FLNG, including the structural selection of PCHE in FLNG, and the research progress of flow and heat transfer characteristics within PCHE. The influence of channel shape and structural form on the performance of PCHE.

2. The Research Status of PCHE and Its Application Progress in the Field of FLNG

2.1. Current Status of Basic Research on PCHE

PCHE holds an important position in the energy and chemical industries due to its compact, efficient, high-temperature and high-pressure resistant characteristics. The processing and manufacturing method of PCHE is different from that of traditional heat exchangers. PCHE is a compact plate heat exchanger that etches microchannels on the heat exchange plate through chemical etching. The flow channel structure classification of PCHE is shown in Figure 1, and it achieves diffusion connection by utilizing the interatomic binding force, making the heat transfer area density of PCHE as high as 2500 m2/m3. The heat transfer area densities of the commonly used large-scale wound tube heat exchangers and tubular heat exchangers are only 120 m2/m3 and 160 m2/3 respectively. The heat transfer area density of PCHE is much higher than the standard of compact heat exchangers, meeting the requirements of high efficiency and compactness. Connecting the heat exchange plates into the core of the heat exchanger by diffusion connection can greatly enhance the reliability of the welds. The mechanical strength of the welds is almost the same as that of the base metal, and they have high reliability under conditions such as high pressure, sway, and alternating stress, meeting the requirements of safety and reliability.

Studies show that the volumetric heat transfer coefficient of PCHE can reach 5 to 10 times that of conventional shell and tube heat exchangers, demonstrating strong adaptability in scenarios such as LNG liquefaction and hydrogen storage and transportation. In recent years, scholars have conducted in-depth research on the material properties, welding processes and flow channel optimization of PCHE, such as using nickel-based alloys to enhance corrosion resistance and improving diffusion welding parameters to reduce contact thermal resistance, promoting the continuous improvement of its technical maturity.

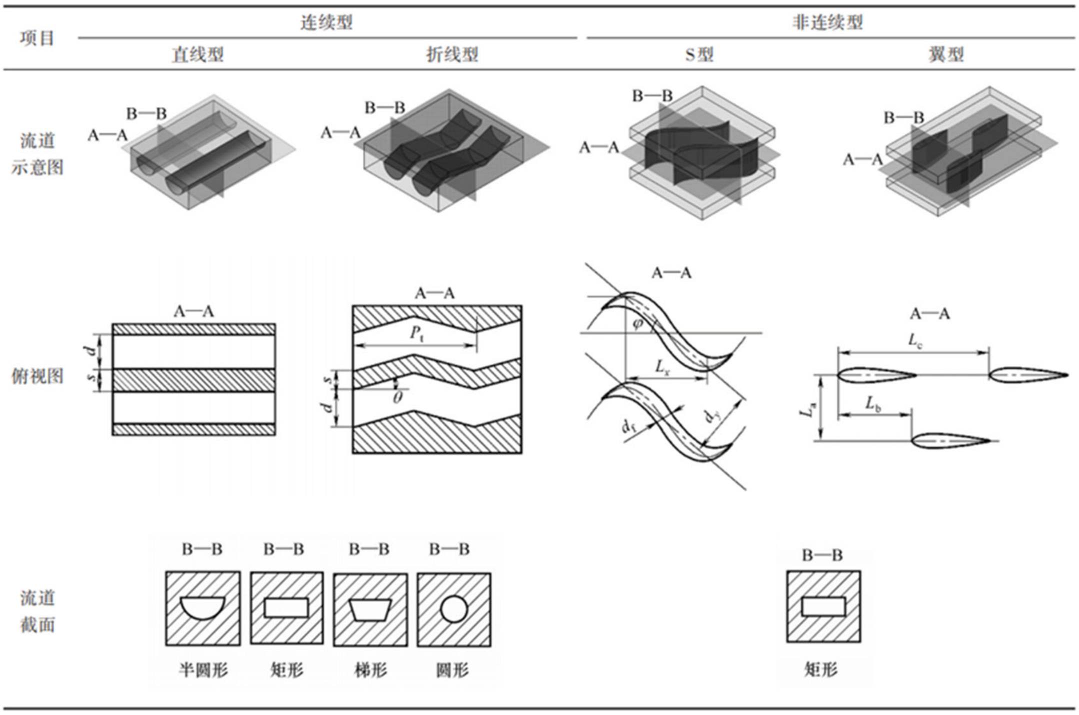

Figure 1. Classification of PCHE flow channel structure

2.2. The current development status of PCHE in the FLNG field

Floating liquefied natural gas (FLNG) plants need to achieve efficient heat exchange within a limited space, which poses strict requirements for the compactness and reliability of the equipment. Due to its small size and strong heat exchange capacity, PCHE has become the ideal choice for FLNG heat exchangers. For example, Shell Company adopted PCHE instead of traditional equipment in a certain FLNG project, reducing the space occupation of the natural gas liquefaction unit by 40%. In addition, the modular design of PCHE facilitates installation and maintenance at sea, and its fully welded structure effectively avoids leakage risks, meeting the safety requirements of FLNG. At present, PCHE has gradually moved from proof of concept to commercial application in the field of FLNG, but the adaptability research for complex working conditions at sea still needs to be deepened. At present, there are no cases of applying PCHE to FLNG in China.

3. Performance Response of PCHE under Swinging Conditions

3.1. Changes in fluid dynamic performance

The swinging condition causes the gas-liquid two-phase flow inside the PCHE to present a strong unsteady state characteristic. When FLNG oscillates, the fluid inside the heat exchanger moves relatively to the equipment due to inertia, intensifying the separation of gas and liquid phases. The originally uniform fluid distribution is disrupted, resulting in local stagnant flow areas. Experimental studies show that under the roll condition, the heat exchange efficiency of PCHE decreases by approximately 12% compared to the static condition, while the pressure drop increases by 8%. This is because gas-liquid separation reduces the effective heat exchange area, while the emergence of local stagnant flow areas increases the fluid flow resistance. By observing the swinging process through high-speed photography technology, it can be clearly seen that the fluctuation amplitude of the gas-liquid interface has significantly increased, reaching 2 to 3 times that under static working conditions. This intense interface fluctuation further deteriorates the flow state of the fluid and reduces the heat and mass transfer efficiency.

3.2. Changes in structural mechanical properties

The vibration caused by swinging will subject the PCHE to complex alternating stress. During the swinging process, the structure of the PCHE will vibrate along with the movement of the FLNG. Especially at the geometric shape change areas such as the corners of the flow channel and the welded joints, stress concentration is prone to occur. The numerical simulation results show that under the typical swinging condition, the stress concentration coefficient at the corner of the flow channel can reach 2.3 times that of the static condition. Being exposed to this alternating stress environment for a long time, fatigue cracks are very likely to occur at the welded parts. With the passage of time, the cracks may gradually expand, eventually leading to the failure of the PCHE structure. To evaluate the structural reliability of PCHE under the swinging condition, the finite element analysis (FEA) method is usually adopted, combined with the fatigue life prediction model, to calculate and analyze the stress state and fatigue life of its key parts, providing a basis for the structural optimization design.

4. Research on Flow and Heat Transfer Characteristics in Printed Circuit Plate Heat Exchangers (PCHE)

4.1. Research on Multiphase Flow Characteristics

In the FLNG process flow, the printed circuit plate heat exchanger (PCHE), relying on the micron-sized flow channels formed by the chemical etching process and the multi-layer plate bundle structure formed by diffusion welding, undertakes the heat exchange tasks of complex processes such as natural gas liquefaction and heavy hydrocarbon separation. This process involves the interaction of gas, liquid and solid multi-phase flows, and the study of its characteristics is the key to optimizing the performance of the equipment.

In terms of experimental research, particle image velocimetry (PIV) technology, taking advantage of its non-invasive measurement, has shown its prowess in the narrow microchannels of PCHE. By adding tracer particles to the fluid and combining them with high-speed cameras to capture the movement trajectories of the particles in the etched flow channels, the velocity vector distribution of the gas-liquid two-phase flow in the PCHE under the swinging condition can be accurately obtained, and the complex flow patterns such as vortices and circulations caused by the swinging can be visually presented. Laser-induced fluorescence (LIF) technology can visually analyze the fluid concentration field within the PCHE microchannel, clearly presenting the fluctuation and mixing process of the gas-liquid interface between the plate and beam structures.

In the field of numerical simulation, the Computational Fluid Dynamics (CFD) - Discrete Element Method (DEM) coupled model has become a powerful tool for studying the multiphase flow behavior of PCHE. This model fully considers the special channel geometry of PCHE and can effectively simulate the movement, deposition and agglomeration phenomena of particles in the microchannels, as well as the coalescence and fragmentation processes of bubbles in the plate bundle gaps. Taking the natural gas dehydration process in FLNG as an example, the movement trajectory of water droplets in the gas phase flow channel of PCHE is simulated through the coupling model, and its influence on flow resistance and heat transfer efficiency is analyzed to provide a basis for the design of the separation device. The research finds that under the swinging condition, the gas-liquid stratification phenomenon in the PCHE intensifies, forming a high-concentration liquid phase area locally in the microchannel, resulting in a reduction of the effective heat transfer area and an increase of 10%-15% in fluid flow resistance at the same time. In addition, the Lattice Boltzmann method (LBM) has gradually been applied to the study of PCHE multiphase flow. It has unique advantages in dealing with the complex boundaries and multiphase interfaces of microchannels and can more accurately simulate the flow characteristics at the microscopic scale of PCHE.

4.2. Strengthen heat exchange technology

In view of the microchannel structure characteristics of the printed circuit plate heat exchanger (PCHE), the microstructure treatment of the fin surface and porous coating technology have become the core means to improve its heat exchange performance. In microstructure design, in addition to conventional structures such as grooves, sawteeth and ripples, the bionics concept has been innovatively introduced. By imitating the micro-nano structure on the surface of lotus leaves, a special morphology was designed on the fin surface of the PCHE etched flow channel. This bionic microstructure not only enhances the turbulence degree of the fluid in the microchannel but also promotes the spread and evaporation of the droplet on the surface of the plate bundle by reducing the contact Angle between the droplet and the surface, thereby increasing the heat transfer coefficient by 20% - 25% compared with the traditional structure.

Porous coating technology significantly increases the inner surface roughness of microchannels by coating high-porosity materials such as metal foam and nano-porous ceramics on the surface of PCHE fins, promoting the mixing and mass transfer of gas and liquid phases in a narrow flow channel space. Experiments show that during the condensation process of PCHE, after adopting the porous coating, the shedding frequency of condensed droplets on the microchannel wall is accelerated, effectively suppressing the hindrance of the liquid film to heat transfer, and the heat transfer efficiency is increased by approximately 18%. In addition, the research on the application of new nano-fluid working media in PCHE has been continuously heating up. Adding nanoparticles such as alumina and copper oxide to traditional working media to form nano-fluids can increase the thermal conductivity of the working media in the PCHE microchannels by 15% to 30%. However, the long-term stability of nanoparticles in microchannels, as well as the risk of PCHE flow channel blockage caused by particle deposition and its long-term impact on flow resistance, remain the key research directions at present.

5. Summary

Under the impetus of the "carbon peak" and "carbon neutrality" strategies, natural gas, as a clean and efficient energy source, has become increasingly important in China's energy structure. However, there is a large gap between supply and demand of natural gas resources in China, and offshore natural gas development technology has become a key breakthrough point. Floating liquefied natural gas (FLNG) and floating storage and regasification units (FSRU) have become the core equipment for offshore natural gas development due to their low cost and strong flexibility. Printed circuit plate heat exchangers (PCHE) have gradually become the key heat exchange equipment for them thanks to their compact, efficient and corrosion-resistance characteristics. This study systematically reviews the current technical status of PCHE and its application progress in the field of FLNG, focusing on the influence of FLNG oscillation conditions on the performance of PCHE. Through theoretical analysis, experimental verification and numerical simulation, three major research directions, namely structural selection optimization, research on flow and heat exchange characteristics, and innovation of flow channels and structures, have been clarified. That is, 9% Ni steel and austenitic stainless steel were selected and a modular counter-flow structure was adopted to enhance the anti-sway and heat transfer performance of PCHE. It was found that sway would reduce the heat transfer efficiency of PCHE by 10%-15%, while technologies such as bionic microstructures could increase the heat transfer coefficient by 20%-25%. Moreover, the stepped flow channel and flexible connection structure can enhance the dynamic stability of the equipment. At the same time, it is also pointed out that the current PCHE in FLNG applications is facing challenges such as insufficient coupling simulation accuracy of multiple physical fields, lagging on-site monitoring technology, and the absence of industry design specifications. This research outcome provides a systematic technical solution for the engineering application of PCHE in the FLNG field, which has significant engineering practical value and strategic significance for promoting the efficient development of offshore natural gas in China and facilitating the realization of the "dual carbon" goals.

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