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Review of Heat Transfer Performance and Application Research of Primary Surface Heat Exchangers

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Abstract

Compared to traditional heat exchangers, primary surface heat exchangers are characterized by their compact structure, light weight, small size, and high heat transfer efficiency, making them widely applicable in military, aerospace, transportation, and civilian sectors. This review first examines the structure of primary surface heat exchangers, summarizing the results of numerical simulations that compare the impact of different structural parameters on heat transfer performance, as well as the optimization design of primary surface heat exchangers. Subsequently, it reviews the research progress on primary surface heat exchangers, focusing primarily on the structure of corrugated plates. Different corrugated plate structures affect the heat transfer performance of primary surface heat exchangers in various ways. Finally, it reviews the specific application scenarios of primary surface heat exchangers and provides a summary and outlook on the development of primary surface heat exchangers.

Keywords: Primary surface heat exchanger; Research status; Structural parameters; Optimization Design; Research Progress; Application Scenarios

The structure of Primary Surface Heat Exchanger

Characteristics of the Structure

The primary surface heat exchanger is the current international advanced heat exchanger type, whose heat transfer surface is processed and shaped once, without secondary fins. It has the advantages of compact structure, small size, light weight, high efficiency, etc., and it can transfer heat from the hot side to the cold side through corrugated plate without the problem of fin efficiency, which is one of the best structures for the regenerator in micro gas turbine [1]. Taking a 10 MW gas turbine recuperator as an example, a highly compact primary surface heat exchanger occupies only 1/10 of the volume and 1/9 of the weight compared to conventional heat exchangers. Moreover, the assembly flexibility of highly compact primary surface heat exchangers significantly surpasses that of traditional plate-fin and shell-and-tube heat exchangers. In terms of compactness, highly compact primary surface heat exchangers achieve a compactness level exceeding 1300 m^2/m^3, whereas plate-fin and shell-and-tube heat exchangers generally offer compactness levels of approximately 700 m^2/m^3 and 100 m^2/m^3, respectively, which are far lower. Therefore, under conditions requiring small size, light weight, and highly integrated high-temperature heat exchange, primary surface heat exchangers are better suited to meet these demands.

The primary surface heat exchanger has corrugated plate structure for the heat transfer primary, which is divided into CC type (Cross Corrugated), CU type (Corrugated Undulated) and CW type (Cross Wave) according to the surface shape. The three forms are shown in Fig. 1 as (a), (b) and (c), respectively.

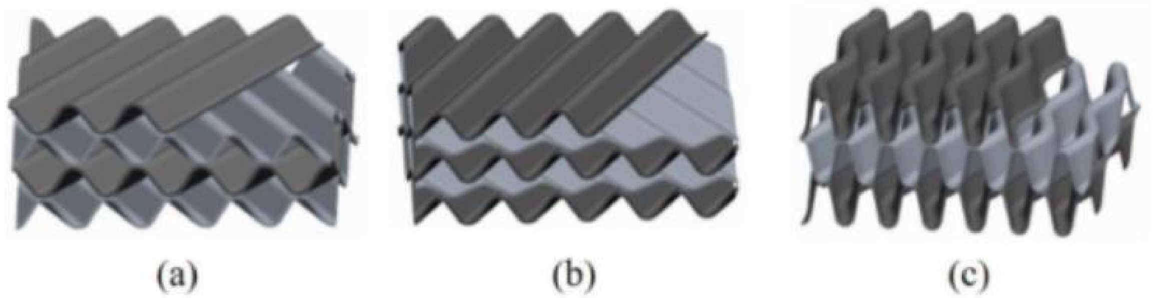


Figure 1: Surface structure of heat exchange plate

In the primary surface heat exchanger, the two fluid media are directly exchanging heat on the alternate metal thin layer, and the thickness of the thin layer is around 0.1 mm. The core of the CC type primary surface heat exchanger is assembled by a number of corrugated surface plates with different orientations stacked at a certain angle, and the stagger angle θ varies from 0° to 90°, and its compactness can reach more than 2000m2/m3 [2]. The CW type primary surface heat exchanger consists of a number of corrugated plates stacked on top of each other, with a corrugated phase difference of 180 degrees in the flow direction of adjacent heat exchanger plates and showing a corrugated shape in both the flow and cross-section directions.

The primary surface heat exchanger, also known as primary surface heat exchanger, has an equivalent diameter of about 1mm for the work material flow channel. The corrugated structure is designed with a short direct flow channel, which reduces the resistance in the flow process. In addition, the corrugated plate is made by stamping the whole metal plate, and there are no weld seams or weld joints inside the heat exchanger, so it has a strong resistance to thermal cycle fatigue and a long service life. Since all heat transfer surfaces are primary surfaces, the heat transfer efficiency is high, with a heat return of more than 85 per cent, and it is easy to produce and assemble [3].

Theoretical Study of Primary Surface Heat Exchanger

The Influence of Structural Parameters

The structural parameters of the corrugated plate have an important influence on the heat transfer performance of the primary surface heat exchanger. The key factors include Reynolds number, Nussel number, pressure loss, cross-section corrugated pitch P, height H, flow direction corrugated length L, amplitude A, channel radius R, friction coefficient f, heat transfer factor j, and plate crossing angle. Researchers both domestically and internationally have investigated the heat transfer performance of primary surface heat exchangers through experimental studies and numerical simulations. Three-dimensional numerical simulations are primarily conducted using CFD software based on non-orthogonal and boundary-fitted grid techniques to model the flow and heat transfer characteristics within primary surface channels. Comparative analyses of various computational models have been performed to reveal the suitability of different models for simulating various flow conditions. Additionally, the velocity and pressure fields of the working fluid in the heat exchanger have been thoroughly analyzed. Experimental studies have provided critical insights for optimizing the design, including analyses of flow and heat transfer characteristics using primary surface heat exchanger test platforms. Furthermore, field synergy theory calculations, based on the two-dimensional laminar boundary layer energy conservation equation, have been conducted for varying flow interlacing angles and aspect ratios of primary surface heat exchangers. These efforts aim to evaluate the impact of structural parameters on heat transfer performance.

Li Guojun et al [4] studied the effect of relative pitch (P/H) on flow heat transfer in a CC-type heat exchanger by numerical simulation. The results showed that the friction coefficient f increases with increasing P/H at $Re < 500$; at $Re > 1300$, f increases with increasing P/H at P/H between 1.5 and 2.2, and f decreases with increasing P/H at P/H between 2.2 and 4.

Liu Yinze et al [5] compared the heat transfer performance of 45° cross-flow type and straight channel counter-flow type heat exchanger through numerical simulation. The results show that the flow inside the 45° cross-flow type is complex, the vortex strengthens the heat transfer, the velocity and temperature distribution are not uniform, and the heat transfer performance is better than that of the straight channel counter-flow type, but the pressure drop on both sides of the hot and cold sides increases significantly.

Qu Zuoming et al [2] analysed the influence of corrugation geometry parameters on the flow heat exchanger performance of a staggered corrugated channel using the finite volume method and a low Reynolds number k-ω turbulence model. The results show that the corrugation geometry parameters significantly affect the drag coefficient, but have less effect on the Nussell number; the corrugation period has a greater effect on the overall performance in the flow and cross-section directions. The corrugation slope affects the temperature gradient near the trough, and an increase in the temperature gradient will cause the velocity boundary layer to become thinner.

Huang Yongkui et al [3] performed numerical simulations using a low Reynolds number k-ε model to explore the mechanism of heat transfer enhancement inside the channel. The results show that with the increase of Re, the average velocity inside the channel increases and the fluid disturbance is strengthened, which improves the heat exchange effect, but also leads to the increase of pressure loss. It was also found that the overall performance of the heat transfer unit cell is better when H/P is larger. At $Re < 300$, the heat transfer unit with $A/L = 0.109$ performed best, and at $Re > 300$, $A/L = 0.136$ performed best.

Zhang Shengbao et al [6] generated a titanium alloy heat exchanger by 3D printing technology and tested its heat transfer performance on the test bench. The results show that regardless of the channel size, the larger the cross-flow angle is, the stronger the heat transfer performance is; under the same 30° cross-flow angle, the heat transfer performance of the small channel is better than that of the large channel; the influence of the channel size on the heat transfer performance is greater than that of the cross-flow angle. Shi Xusheng et al [7] analysed the influence of corrugated plate structural parameters on heat transfer performance, and established a three-dimensional model of gas, air and solid wall coupling heat transfer. The effect of the structural parameters of the microchannels of the CW type heat exchanger on the entropy production was studied by numerical simulation.

Wang Wei et al [8] verified that the field synergy theory can be used to guide the heat transfer enhancement of the primary surface heat exchanger. The study was carried out by calculating the width-to-height ratio and different flow stagger angles with the central unit cell in a 7 × 7 multibody model as shown in Figure 2, where W and D are the inlet surfaces and E and U are the outlet surfaces. The field synergy analysis under laminar flow conditions introduces the field synergy number $F_c=\int U\cdot\nabla T dy=Nu/RePr$, the larger the average synergy angle β_m, F_c, the better the heat transfer effect; the smaller the field synergy angle, the better the heat transfer effect.

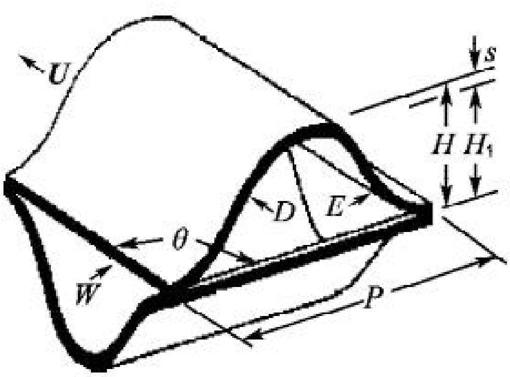


Figure 2: Unit control unit [8]

Wu Tianyao et al [9] used STAR-CD software to simulate and analyse the heat transfer performance of rectangular and circular cross sections in a CW type primary surface heat exchanger. The results showed that with the increase of Reynolds number, the average Nussel number increased and the equivalent friction coefficient decreased; the heat transfer performance of rectangular cross-section was better than that of circular cross-section at.

Zhu Xiaohua et al [10] investigated the characteristics of corrugated plate flow heat transfer in a CC type primary surface heat exchanger with different stagger angles and 90° stagger angle. The numerical simulation results show that the loss coefficient increases with the increase of the staggering angle when the Reynolds number is the same; when the staggering angle is less than 90°, the fluid in the channel forms a cross-flow and produces a secondary flow; the Nussle number on the corrugated plate varies significantly, and the maximum value occurs at the contact point of the upper and lower corrugated plates, which is larger at the peaks and smallest at the troughs.

Yin Jixiang et al [11] carried out a simulation analysis of a CC type primary surface heat exchanger, where the components between two plates and four contact points were selected as the units, and the calculation area was 7×7 unit channels. The results showed that the swirl intensity increased when the Reynolds number increased and decreased when P/H increased. The increase of vortex intensity improves the heat transfer efficiency, and the heat transfer enhancement originates from the strong mixing of fluids caused by the spiral-type unstable shear layer in the channel.

Liang Hongxia et al [12] analysed the effects of air inlet temperature, pressure and gas flow rate on heat transfer resistance and derived the fitted correlation equations for Nu-Re and f-Re: $Nu=0.0815(Re)^{0.62803}$, $f=84.10(Re)^{-0.7144}$. The results showed that the change of gas inlet temperature has little effect on the relative pressure drop. With the increase of air inlet pressure, both air outlet temperature and gas outlet temperature increase and heat exchange is enhanced, but the temperature difference on the gas side decreases and the regenerative degree decreases. The increase in air inlet pressure increases the air density, decreases the flow velocity and decreases the pressure drop, while the pressure drop on the gas side increases and the total relative pressure drop decreases.

For the primary surface heat exchanger corrugated plate, the structural differences mainly include the stagger angle between the two adjacent corrugated plates, the width-to-height ratio of the corrugated channel, and the relative pitch. There are channel structure differences in different structural parameters, and different channel structures will directly affect the degree of disturbance of the fluid flow. The larger the disturbance, the more complex the fluid flow in the channel, the more uneven the velocity and temperature distribution, and the better the heat exchange performance of the heat exchanger plate. In addition, the different parameters of the corrugated plate structure will also affect the Reynolds number and Nussel number. When the Reynolds number increases, the vortex strength increases, which increases the heat exchange efficiency of the heat exchanger plate.

The Approaches of Optimal Design

Uneven fluid distribution often occurs inside the heat exchanger, and the reasons include uneven flow in the header pipe, flow in the micro channel, cooling of the hot fluid, two-phase flow, and change in fluid temperature. In order to solve the uneven fluid distribution in the microchannel caused by the unreasonable inlet structure, an effective method is to add a deflector sheet in the inlet structure of the primary surface heat exchanger. Nie Sanxi et al [1] proposed to add horizontal and oblique flow deflector sheets, and the structural size and number of deflector sheets were used as variables to study the channel flow distribution and flow resistance characteristics. Figure 3 shows the diagram of the intake structure without the addition of deflector sheets, and Figure 4 shows the diagram of the intake structure with the addition of three deflector sheets, where H=10mm, L1=10mm, L2=10mm, and channel one, channel two, and channel three in order from the top to the bottom.

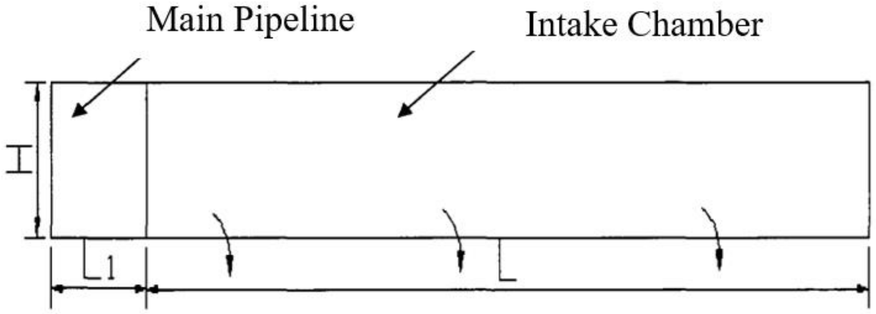


Figure 3: Schematic diagram of the box cavity intake structure

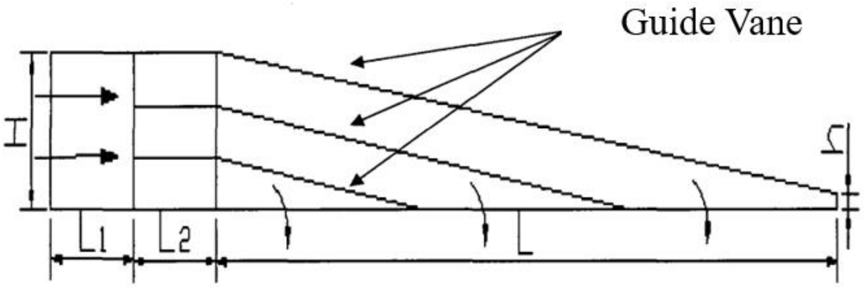


Figure 4: Air intake structure diagram with baffle

The simulation results show that the inlet structure with deflector sheets has a more uniform velocity distribution in the outlet cross-section and has a higher average outlet velocity than the structure without deflector sheets. This advantage is more obvious as Re increases. This indicates that the addition of the deflector sheet not only improves the flow distribution uniformity of the heat exchanger core, but also increases the flow rate.

Liang Hongxia et al [13] used genetic algorithm to optimise the design of the primary surface heat exchanger for micro gas turbine. Figure 5 shows the process of combining thermal performance design with genetic algorithm.

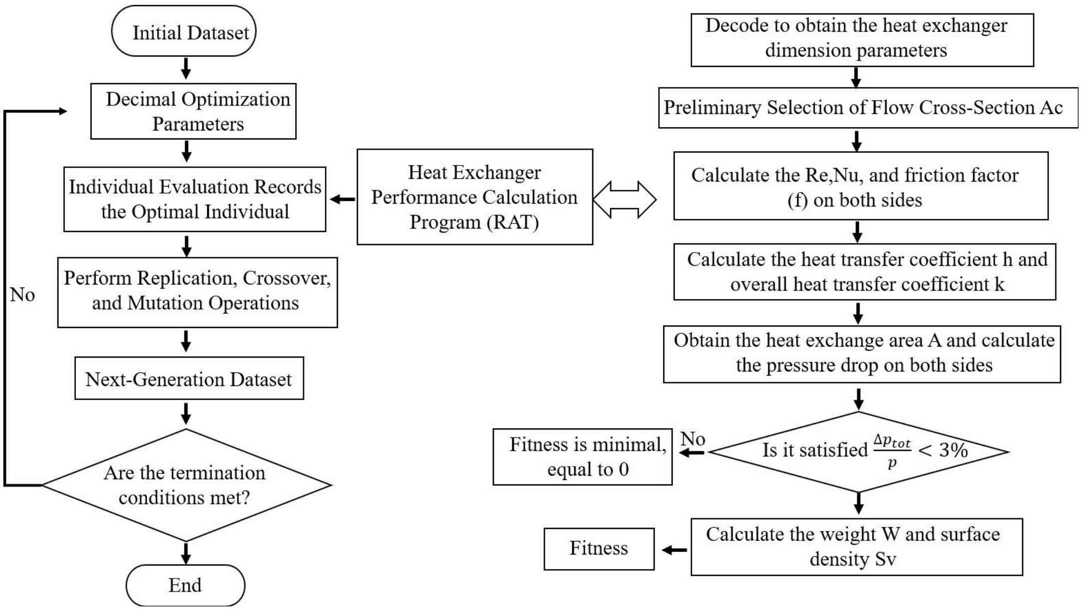


Figure 5: Thermal performance design and genetic algorithm combined process

This experiment was conducted to optimise the design of the chevron-type staggered corrugated heat transfer surface of the primary surface heat exchanger of a 100KW micro gas turbine. By comparing the objective function of lightest weight with maximum compactness/weight, it is found that when the objective function is maximum compactness/weight, the optimised weight is 3% lighter than the objective function of lightest weight.

When the corrugated plate size is used as an optimisation variable with the heat exchanger core parameters, the corrugated pitch P, the internal height of the channel H, and the channel corrugation radius R are reduced in size accordingly, which improves the compactness of the heat exchanger, reduces the weight of the heat exchanger, and reduces the total pressure drop on both sides.

Advances in Researches Related to Primary Surface Heat Exchanger

Kim et al [14] proposed an improved double-wave CC primary surface as shown in Fig. 6. Corrugations are added vertically to the conventional single-wave CC primary surface. The small-scale and large-scale vortices between the double-wave sheets work together to enhance the flow mixing. The vortex motion at the double-wave inflection point increases the heat transfer coefficient, and the additional corrugation enlarges the heat transfer area. Compared to single wave heat exchanger, the heat transfer performance of double wave heat exchanger is improved by about 50 per cent, but the pressure drop is increased by 30 per cent [15].

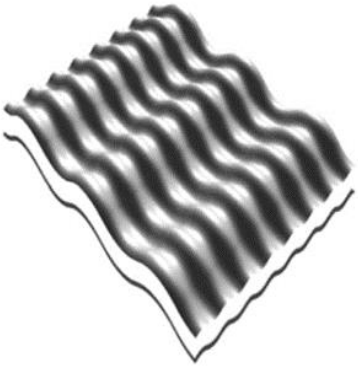


Figure 6: Double-wave surface

Liu et al [16] proposed to add small sinusoidal wave corrugations to the cross-section of the primary surface of a conventional CC in order to enhance the heat transfer performance of the swirling motion, as shown in Fig. 7. These additional corrugations increase the heat transfer area and reinforce the fluid disturbance and mixing near the wall surface. In the channel, the fluid forms a significant spiral secondary flow along the primary surface, especially in the peak area. The helical secondary flow carries more fluid from the main flow to the peak area, enhancing heat transfer. The heat transfer performance of the CC primary surface with small sinusoidal wave corrugations was improved by 10 per cent compared to the non-corrugated surface.

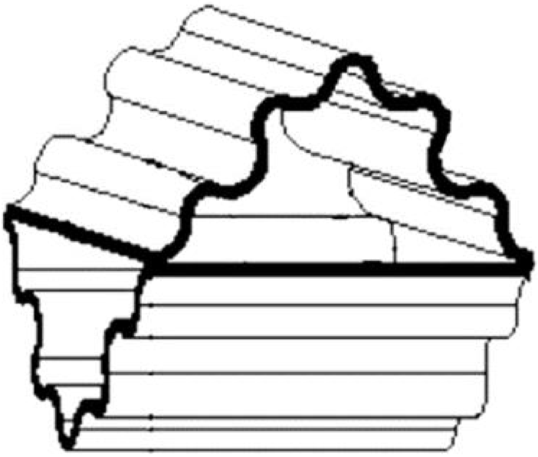


Figure 7: CC surface with corrugations

Luo and Ma et al [19, 20], inspired by the flow perturbation of the offset strip plate-fin channel, designed the CC primary surface channel with offset bubbles, as shown in Figure 8. Similar to the offset strip plate-fin channel, the fluid undergoes lateral bending in front of the offset bubbles. The additional lateral perturbation improves the heat transfer performance. In addition, all heat transfer surfaces are primary surfaces and there is no fin efficiency issue. Compared to the offset strip plate-fin channel and the CC3.1-60 channel (pitch ratio of 3.1 and oblique angle of 60°), the average area goodness coefficients were improved by 41% and 71%, respectively.

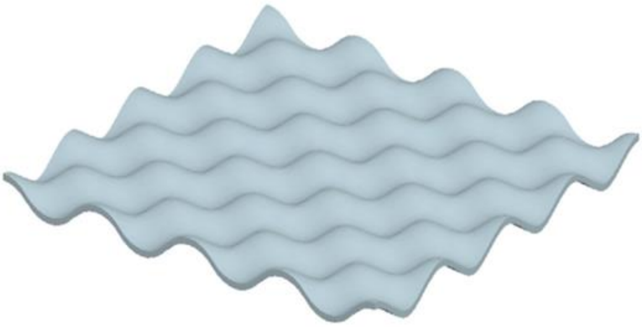
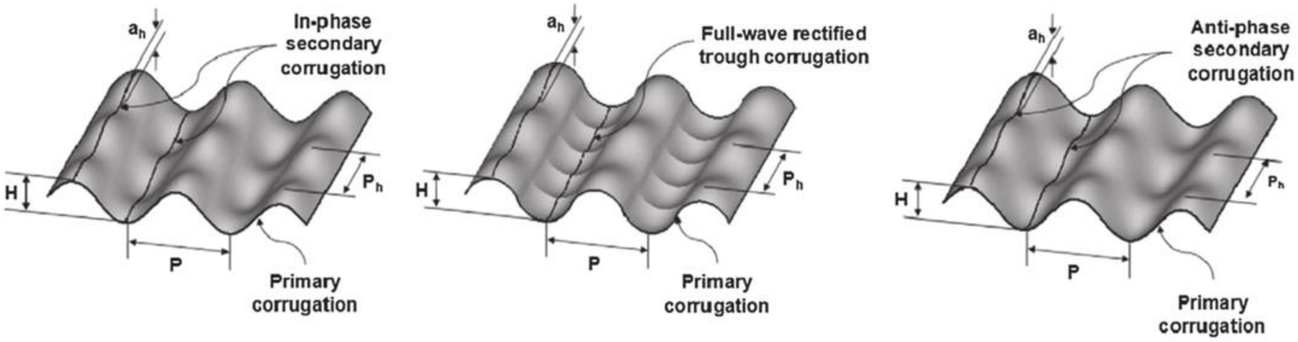


Figure 8: Offset-bubble surface

Blomerius and Mitra [19] developed a new three-dimensional CC primary surface with additional waves vertically stacked on the conventional CC primary surface waves with a corrugation degree of 45°. This three-dimensional structure generates extensive longitudinal vortices at the upper and lower wall surfaces and at the core of the channel, unlike the conventional CC primary surface which flows mainly along the grooves of the upper and lower plates. Comparison using Webb's VG1 criterion showed that the three-dimensional CC primary surface with a corrugation degree of 45° improved the heat transfer performance by about 10 per cent over the conventional CC primary surface at a Reynolds number of 1800.

The flow in the middle plane of the CC channel is a helical mixed flow pattern induced by the interaction of the upper and lower plates, but the flow near the trough is mainly along the corrugation direction [20]. As a result, the heat transfer performance in the trough area is lower than that in the peak area. In order to enhance the flow mixing and heat transfer in the trough, Doo et al [21,22] proposed three improved primary surfaces with different secondary corrugations, i.e., in-phase secondary corrugation, full-wave rectified trough corrugation, and anti-phase-secondary corrugation, as shown in Figure 9. CC primary corrugations are different from conventional straight corrugations by containing secondary corrugations at the peaks and troughs, which are classified as in-phase and anti-phase. Anti-phase secondary corrugations have the greatest potential to improve the compactness of the heat exchanger matrix. The larger primary surface of the anti-phase secondary corrugations will result in flow separation, recirculation, and collisions, allowing the fluid to flow more parallel in the downstream direction. This surface reduces the pressure drop by about 15 per cent compared to the conventional CC channel but the change in heat transfer ability is not significant.



(a) In-phase secondary corrugation (b) Full-wave rectified trough corrugation (c) Anti-phase-secondary corrugation

Figure 9: Three types of corrugated channels

In some advanced systems, such as intercooled cycle gas turbine engines, the operating pressure and pressure drop requirements are different on the hot and cold sides. To address these situations, Kim et al [23] proposed a novel primary surface channel with asymmetric profiles that can be adjusted to control the pressure drop on each side by adjusting the degree of asymmetry. As the degree of asymmetry increases, the flow separation and shock on the high-pressure side are more intense than on the low-pressure side. This design aims to balance the pressure drop on both sides, but may slightly affect the effectiveness.

The Russian Institute of Aeronautics and Technology proposed a Flenkley-type surface for aero-engine regenerator [24], which is similar in form to the primary surface. After strength tests, this surface with a flow diameter of 2.2 mm was able to resist a hydrostatic pressure of 5-6 MPa. Although it has been applied to the design of AL-34 turboshaft engine regenerator, the connection problem has not been solved, and related research is in progress [25].

Different aspects of performance optimisation exist for different corrugated channel configurations. Among them, the vertical corrugated, extra sinusoidal and offset bubble-shaped corrugated plates are effective in increasing heat transfer performance; the inverted secondary corrugated plate channel reduces the pressure drop in the channel; the pressure drop on each side of the new heat exchanger plate with an asymmetric profile can be controlled by adjusting the degree of asymmetry of the profile; and the Frenkeli type of heat exchanger surface resists a certain amount of hydrostatic pressure.

The Application of Primary Surface Heat Exchanger

The application of Primary Surface Heat Exchanger in Aero-Engine

The SABRE (synergetic air breathing rocket engine) designed by Reaction Engines (UK) is a new type of non-traditional aero-engine, which is mainly used in rockets. Figure 10 shows a physical model of the SABRE [26]. The fuel weight of an aero-engine accounts for 40-60% of the total take-off weight of transport and fighter aircraft, while its lifetime cost accounts for 20-40% of the entire aircraft [27], so the application of compact primary surface heat exchangers in aero-engine is the key to improving efficiency.

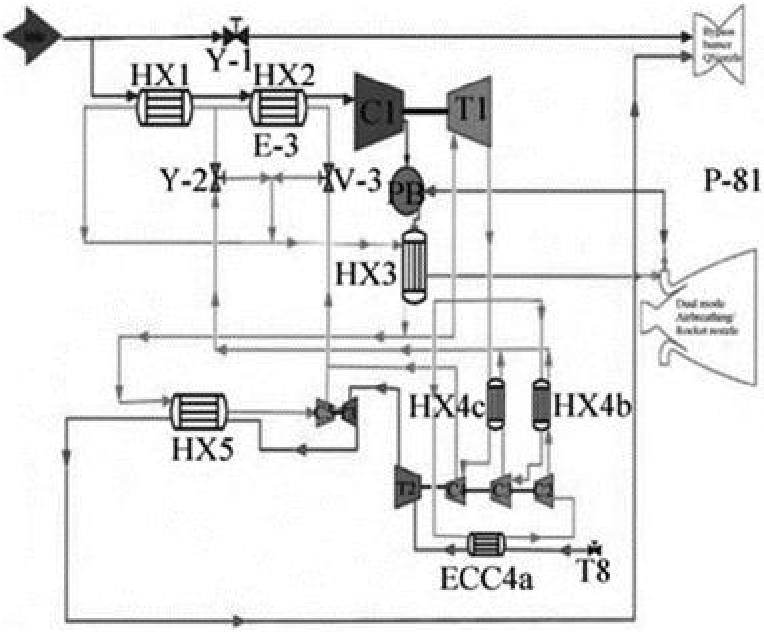


Figure 10: SABRE engine physical model

Currently, the latest concept is to place a heat exchanger in the engine's outer duct to cool the gas drawn from high pressure compressor, thus effectively cooling the turbine blades [28]. It has been shown that engines with thermal management systems have significant improvements in exhaust emissions, thermal efficiency and performance, and the application of heat exchangers has made higher pressure ratios (OPR=80) possible. The main objectives of the design of heat exchangers for aero-engines are to reduce the flow resistance pressure drop and increase the heat transfer efficiency, while ensuring that the heat exchanger is small, compact, safe and reliable, and has sufficient strength and lifetime at operating pressures and temperatures [29-31]. Researchers conducted an in-depth comparison of engine designs using a comprehensive analysis tool, TERA2000, and found that the implementation of thermal management through the heat exchanger can significantly improve engine efficiency, with an expected reduction in fuel consumption of an additional 5.56% [32-34].

The air cooler is a core component in the aero-engine system, which is used to cool the air drawn from the high pressure compressor before it is used to cool the hot side components [35]. The Russian AL-31F engine has successfully applied an air cooler in the outer duct to cool the cooling air by 125~210 K and effectively cool the turbine blades. The air cooler is characterised by high heat transfer efficiency, low pressure loss and compact structure [36].

There are many limitations in the application of intercooled reheat technology to aero-engines, but the reheat cycle is advantageous when thrust is low and the total pressure ratio is difficult to increase, as well as when the total pressure ratio is relatively low [24]. Walker et al [37] pointed out the presence of a radial drive shaft between the low-pressure compressor and the intercooler, and the presence of the radial shaft necessitates axially asymmetric geometry for the connecting channel. Camilleri et al [38] proposed an intercooled reverse flow core machine, where the air flow direction is changed by the low pressure compressor and then enters the reverse high pressure compressor and combustion chamber, and the gas is discharged from the outer duct, so the intercooler needs to be changed accordingly. Gong Hao et al [39] studied the parameter matching of intercooled reheat engine and pointed out that the higher the effectiveness of intercooler and reheater, the lower the fuel consumption, but the weight and pressure loss of heat exchanger need to be considered.

Application of Primary Surface Heat Exchanger In Intercooled Reheat Engine

Intercooled reheat technology has been successfully applied to gas turbines as it is highly effective in improving the performance of aero-engines and environmental protection. For example, the AGT1500 reheat gas turbine for M1A1 tanks developed by US Avcolet, the LMS100 intercooled reheat gas turbine developed by General Dynamics, and the WR-21 intercooled reheat gas turbine for Type 45 destroyers of the British Royal Navy jointly developed by Grumman and Rollo have all achieved good results [40].

The regenerator system of the Model WR-21 Intercooled Cycle Recuperated (ICR) marine gas turbine consists of two cores, including the air pipework from the combustion chamber to the regenerator, valves and pneumatic actuators. Each core module has four sections and is made of 14Cr4Mo stainless steel, a low-cost material with a good coefficient of thermal expansion and corrosion resistance comparable to that of Incoly 800. INCO 625 is more expensive but has excellent corrosion resistance and mechanical properties. The supply and bypass valves in the system share a common pneumatic actuator with a hydraulic pump for emergency manual operation. 40.6 cm return air check valves can isolate the system in case of regenerator damage. Short--term cleaning is operated via the bypass and long-term cleaning is carried out with a steam lance on top of the regenerator. During low temperature and low power operation, the system automatically maintains the HPC discharge temperature above 149°C to prevent condensation and corrosion of H_2SO_4 [41].

In recent years, large and medium-sized water surface warships have gradually adopted gas turbines and diesel engines and their combined power plants, and this combination has significantly improved the power performance of the ships. Gas turbines have shown a broad prospect in naval applications due to their high efficiency and reliability [42, 43]. Intercooled reheat cycle gas turbines not only have high thermal efficiency and high power under design conditions, but also solve the problem of poor economy of simple cycle gas turbines under low load conditions [44, 45]. The intercooler design of naval gas turbines needs to meet the requirement of high compactness due to limited installation space. At the same time, the design also needs to pay more attention to the pressure drop across the flow path and the heat transfer efficiency of the intercooler [46, 47].

The gas turbine intercooler includes the primary surface heat exchanger and the main focus of the design is on the temperature of the gas side and pressure changes. The increase of freshwater flow rate can reduce the gas-side outlet temperature of the intercooler, but too large freshwater flow rate will lead to the increase of freshwater pressure drop, which will increase the volume and operating cost of the freshwater supply system. In a gas-liquid heat transfer system such as an intercooler, the convective heat transfer coefficient on the gas side is much smaller than that on the liquid side. Therefore, from the point of view of improving heat transfer efficiency, subsequent studies should focus on how to improve the heat transfer coefficient of the gas side [48].

Summary and Outlook

Summary

The primary surface heat exchanger can meet the requirements of military, aerospace, transport and civil fields for high-temperature gas-gas heat exchange with small size, light mass and high compactness. Most of the papers take the heat exchanger unit as the research model, carry out numerical simulation and explore the influence of the structural parameters on the heat exchanger performance and the related optimisation design. The design and manufacture of high-efficiency compact primary surface heat exchanger has been broken through abroad, while there are still many design methods that are not complete domestically, such as: the matching relationship between heat transfer and resistance of the micro-channel is not clear, the calculation method of the structural rigidity and bearing capacity of the ultra-thin plate with multi-point support is not clear, and there is a lack of complex moulding and welding technology of the ultra-thin plate domestically. In-depth research is still needed in these aspects.

Outlook

As a highly efficient heat transfer device, the primary surface heat exchanger (PSHE) is designed to maximize the heat transfer surface area and optimize heat transfer performance, making it widely applicable in the energy, chemical, and HVAC sectors. In terms of environmental energy conservation, PSHE significantly enhances thermal energy utilization, reduces energy losses, and lowers waste heat emissions, contributing to resource efficiency and environmental protection.

Currently, Capstone integrates microturbine applications with environmental protection and sustainability goals. In combined heat and power (CHP) systems, microturbine-driven chillers are used to reduce exhaust emissions. Methane gas from domestic wastewater and other waste gases serve as fuels in CHP systems for power generation, effectively reducing CO_2 emissions. Additionally, methane waste gas from landfills is utilized for electricity generation via microturbines.

In the future, PSHEs can be integrated into these applications, particularly in microturbine systems. Their compact design not only improves heat exchange performance but also promotes the utilization of waste gases, reduces energy costs, and further lowers emissions of nitrogen oxides and carbon dioxide. PSHE provides vital technological support for advancing green development. Therefore, the application potential of PSHE in energy conservation, emissions reduction, and sustainable development is significant, representing a critical component for achieving sustainable development and environmentally friendly energy systems.

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