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Design and Development of High-Performance Heat Exchangers for Aerospace Applications

Raghubeer Singh Bangari
Asst. Professor, Department of Mechanical Engineering, Graphic Era Hill University, Dehradun Uttarakhand India,

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Abstract

When two bodies have different temperatures, heat, a type of energy, is transmitted between them. While weight and volume restrictions are either unchanged or even decreasing, thermal management requirements in the realm of aircraft applications are rising. Aerospace systems frequently have high heat flux requirements and necessitate small, light equipment that can function in environments with little or no air pressure. Efficient heat transfer is essential in these systems.Conduction, convection, and radiation are the three main ways in which heat transmission can take place. Understanding the fundamental mechanics of thermal convection and radiation in space applications remains a problem, despite the extensive experimentation and computational techniques used to govern heat transfer in aerospace systems.The heat exchanger, which is a crucial part of thermal management and is important in aeronautical systems, is one example. Heat exchangers are necessary for maintaining the ideal operating temperatures because they make the transfer of heat between fluids possible. This study examines a number of common uses for heat exchangers in aerospace systems and provides several hypothetical designs that have been used or may be useful in the field.Aerospace systems may effectively control and manage heat by using efficient heat exchanger designs, resulting in maximum performance and dependability. To advance thermal management skills in the sector, cutting-edge heat exchanger ideas that are specifically suited to the needs of aerospace applications must be created.

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Introduction

Due to their great efficiency, power output, and fuel flexibility, gas turbine engines are essential in many different industries, including power generation, aviation, and marine propulsion. For gas turbine engines to operate efficiently, reduce emissions, and work reliably, it is crucial to understand their combustion characteristics. Numerous methods, including numerical simulations and experimental research, are used to study the intricate combustion processes taking place inside these engines.The combustion characteristics of gas turbine engines can be simulated and studied using numerical analysis techniques like computational fluid dynamics (CFD) [4]. The flow patterns, temperature distributions, species concentrations, and combustion efficiency within the combustor can all be predicted using CFD models by solving the governing equations of fluid flow, heat transfer, and chemical reactions. The intricate fluid dynamics, turbulence, and chemical reactions that take place during combustion are better understood thanks to these models. Additionally, CFD simulations provide parametric analyses and design parameter optimisation to improve combustion performance [1].

In order to provide real-world data, validate numerical models, and ensure simulation accuracy, experimental analysis is essential. The direct assessment of combustion parameters, such as temperature profiles, species concentrations, pollutant emissions, and combustion stability, is made possible by experimental techniques like laser diagnostics, emission measurements, and thermocouple arrays. These measurements offer important information for assessing and enhancing the precision of numerical models. Furthermore, experimental analysis enables the exploration of transient events, flame dynamics, and igniting properties that may be difficult to accurately portray in numerical simulations[2].A thorough understanding of the combustion properties of gas turbine engines can be gained through the combination of computational and experimental studies. The accuracy and dependability of the numerical models can be evaluated and enhanced by comparing and connecting numerical predictions with experimental data. This repeated method makes it easier to improve numerical simulations, producing predictions that are more precise and new insights into the physics of combustion processes[3].

The goal of this study is to conduct an experimental and numerical examination of the gas turbine engines' combustion characteristics. To accurately represent the complicated combustion phenomena, numerical simulations will be carried out utilising cutting-edge CFD models that incorporate turbulence models, chemical kinetics models, and radiation models. The flow patterns, temperature profiles, species distributions, and other details will all be thoroughly explained by these models.Modern diagnostic methods, including as laser-based diagnostics, emission analysers, and thermocouple arrays, will be used to conduct the experimental measurements. Important combustion properties, including as temperature distributions, pollutant emissions, combustion stability, and ignition characteristics, may all be directly quantified thanks to these data[6]. To verify the correctness of the numerical models and gauge their capacity to accurately represent the combustion behaviour in the real world, the experimental results will be compared with the numerical predictions.

I. Heat Exchanger Applications In Aerospace

1. Cycles For Gas Turbines

In order to increase the thermal efficiency of gas turbine cycles, heat exchangers are essential. The overall pressure ratio and the turbine inlet temperature have the most effects on a typical gas turbine cycle's efficiency. The ratio of compressor exit pressure to compressor inlet pressure is known as the overall pressure ratio. The maximum pressure and temperature thresholds that the turbine blades can tolerate, however, limit both the overall pressure ratio and the temperature at the inlet of the turbine.The use of heat exchangers is essential to overcoming these restrictions and improving the effectiveness of gas turbine cycles. Heat exchangers make it possible for heat energy to be transferred between various fluid streams, enabling heat recovery and better thermal control within the system[10-13].

The high-temperature exhaust gases can be used to pre-heat the incoming air before it enters the combustion chamber by including heat exchangers into the gas turbine cycle. The air entering the combustion chamber is heated by this preheating procedure, which also raises the temperature of the air entering the turbine inlet. As a result, more heat energy is transformed into productive work, increasing the cycle's thermal efficiency.Higher overall pressure ratios and turbine intake temperatures are also made possible by material advances and creative cooling methods for crucial components like turbine blades[8]. By enabling gas turbines to run at higher temperatures and pressures without compromising the integrity and robustness of the turbine blades, these developments improve gas turbine performance.

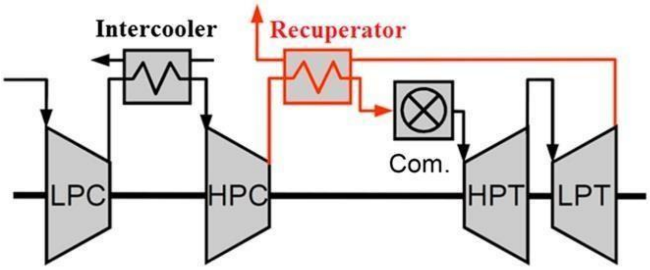

Figure 1: Gas turbine cycle with recuperation and intercooling. Low-pressure compressor, or LPC
For gas turbine engines to work at their best, high overall pressure ratios are crucial in the aerospace sector. [15]Implementing multistage compression with intercooling is one way to raise the total pressure ratio while retaining effective compression work. With an intercooler positioned in between the low pressure compressor (LPC) and high pressure compressor (HPC), the compressor is split into two stages in this method.A gas turbine cycle with intercooling and recuperation is shown visually in Figure 1. Both an intercooler and a recuperator are integrated into the gas turbine system in this design. The recuperator enables heat transfer between the heated exhaust gases and the entering compressed air, while the intercooler cools compressed air in between stages. [16] The combined system increases the gas turbine cycle's overall thermal efficiency and maximises the use of waste heat.

Between the LPC and HPC stages, the intercooler functions as a heat exchanger to cool the compressed gas. The intercooler lowers the temperature of the compressed gas before it enters the HPC. By lowering the specific volume of the compressed air, this cooling process aids in raising the total pressure ratio.A crossflow or counterflow air-to-air heat exchanger is frequently used to achieve effective cooling. In this setup, low-temperature ram air flows on one side of the heat exchanger and compressed air on the other. [18] As the temperature gradient between the two air streams encourages cooling of the compressed air, this design enables efficient heat transmission.
The specific volume of the air reduces by chilling the compressed air before it enters the HPC. For a particular compression work, this decrease in specific volume results in a greater pressure ratio. The gas turbine engine's total pressure ratio can be raised as a result, improving both its performance and efficiency[19].

The installation of an intercooler in gas turbine engines has a number of advantages in terms of increasing the effectiveness of the thermodynamic cycle. The intercooler improves cycle efficiency by lowering the specific volume of air by lowering the temperature of the compressed air.In addition, compared to the air leaving the high pressure compressor (HPC), the exhaust gases exiting the turbine in gas turbine engines frequently have much greater temperatures. A regenerator or recuperate, a type of heat exchanger, can be added to the system to further maximise efficiency [20]. This heat exchanger makes it easier for heat to be transferred from hot exhaust gases to compressed air.

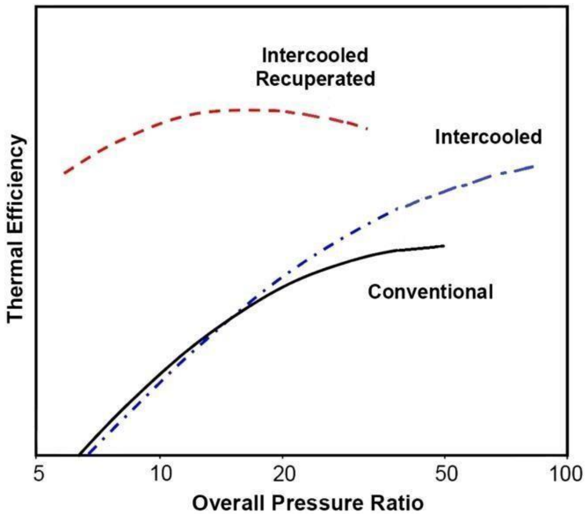

Figure 2: Different gas turbine cycles' thermal efficiency in relation to total pressure ratio

In regard to their overall pressure ratios, Figure 2 conceptually compares the thermal efficiency of several gas turbine cycles. It illustrates that for relatively low overall pressure ratios, often below 30, the intercooled and recuperated gas turbine cycle is particularly efficient. On the other hand, the intercooled gas turbine cycle without recuperation operates at very high overall pressure ratios and is therefore most effective.

2. The temperature cooling system

The necessity for effective and portable thermal management systems has increased with the demand for power-hungry electronic components in aerospace and military platforms. It is essential to control the heat produced by these components and keep their temperatures below those that cause performance to degrade in order to retain peak performance. Air cooling works well for components with modest heat flow, but as heat flux rises, it becomes less effective, requiring larger and more intricate forced air heat sinks[12]. As opposed to air cooling, liquid cooling delivers better thermal performance and energy efficiency.

Liquid cooling includes moving the liquid around to remove heat from the components, which raises the liquid's temperature. A liquid-to-air heat exchanger, such as a plate-fin heat exchanger (PFHE), is then used to transfer the heated liquid to the air.

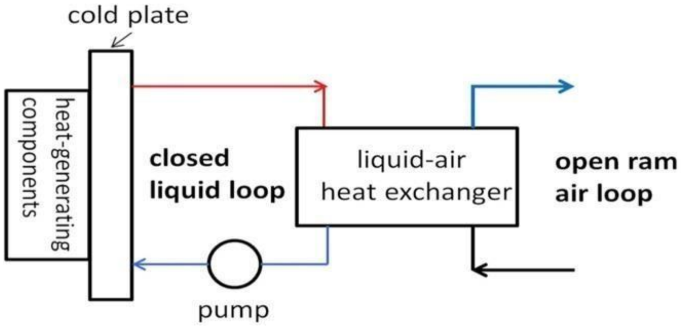

Figure 3: a hypothetical liquid cooling system.

Examples of cold plates are shown in Figure 4, including the tube liquid cold plate and the powdered metal cold plate, which show various layouts and strategies for efficient heat dissipation. These cold plates are essential for keeping electronic component temperatures within acceptable working ranges and ensuring that thermal management systems operate at peak efficiency [22].

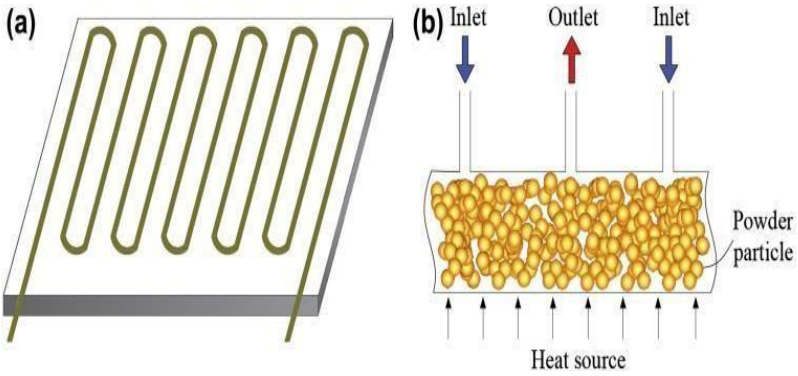

Figure 4. Diagram of cold plates are (a) a tube liquid cold plate and (b) a cold plate made of metal powder.

The [21] excessive heat produced by friction in gearboxes and compressors raises the temperature of the lubricating oil, causing a drop in viscosity and significant performance problems. Fuel or ambient ram air can be used as the working fluid in fuel-cooled or air-cooled oil coolers to regulate the oil temperature. These cooling techniques support optimal lubricant viscosity maintenance and shield against lubrication-related issues.

II. Different Types of Heat Exchange

1. Heat Exchangers With Plate-Fins

PFHEs, which are small heat exchangers used in aerospace applications, include finned chambers and flat plates that effectively transfer heat between fluids. PFHEs made of aluminium alloy are frequently used due to their small size and light weight. They use different fin shapes, such as triangular, rectangular, wavy, louvred, perforated, serrated, or offset strip fins, primarily for gas-to-gas heat exchange. Fin heights typically range from 2 to 20 mm, and fin thickness typically falls between 0.046 and 0.20 mm. PFHEs are useful for applications requiring high heat transfer surface area to volume ratio due to these properties [6].

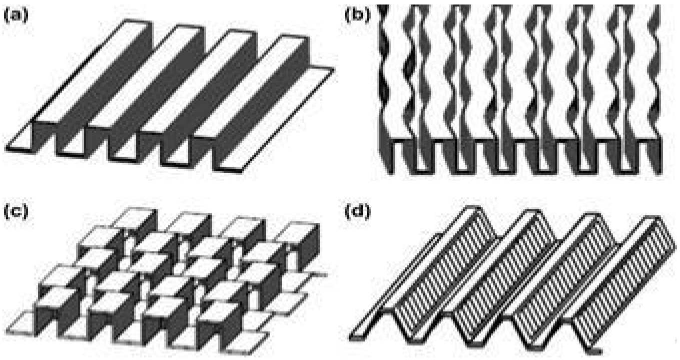

Figure 5. (a) Rectangular fin, (b)Wavy fin, (c) An offset strip fin, (d) A loured fin are examples of different fin shapes.

2. Printed Circuit Heat Exchangers

Printed Circuit Heat Exchangers were created at the University of Sydney in the early 1980s and have been produced commercially by Heatric Ltd since 1985. PCHEs are built from plates that have fluid flow channels made using chemical milling, a method that is similar to that used to make printed circuit boards. Due to the semicircular cross-sections that PCHEs commonly have for their fluid flow passageways, this design allows for flexibility in flow passage geometry. Regarding the effectiveness of heat exchange and design flexibility, using PCHEs has various benefits [16].

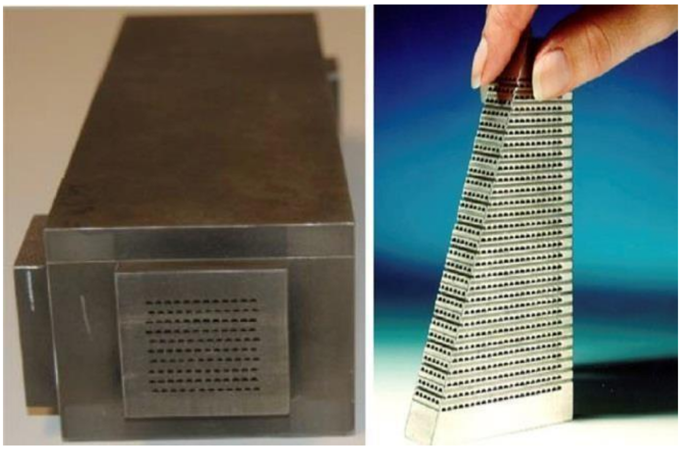

Figure 6: Printed Circuit Heat Exchangers diagram

PCHEs typically have channel diameters of 0.5 to 2.0 mm in depth and 0.5 to 5.0 mm in width, while greater dimensions may be possible for specific applications. PCHEs are extremely compact, with surface area-to-volume ratios surpassing 2500 m2/m3. A PCHE is often four to six times smaller and lighter than an equivalent-performing shell-and-tube heat exchanger in terms of size and weight [15].

III. Other forms of Aerospace Heat Exchangers

1. Exchangers For Primary Surface Heat

The walls separating the two media serve as the main heat conductors in primary surface heat exchangers, which are made of plates or sheets. Heat transfer takes place directly between the plates and the fluid in these heat exchangers because they lack internal fins or any separate internal elements. In contrast, fins are an extra component of secondary surface heat exchangers like PFHE and micro heat exchangers. Primary surface heat exchangers' top features include their 100% effective surface geometry (i.e., the absence of fins) and the capacity to be sealed via welding, which eliminates the need for pricey and time-consuming high-temperature furnace brazing. In the aerospace sector, primary surface heat exchangers are used as intercoolers and recuperators.

2. Heat exchanger for heat pipes

Due to their light weight, maintenance-free operation, and dependability, heat pipes with various capillary wick designs are extremely beneficial for spaceship cooling and temperature stabilisation. An evaporation zone, an adiabatic zone, and a condensation zone make up a conventional heat pipe. The liquid is heated in the evaporation zone, which turns it into vapour. The vapour then moves up the heat pipe to the condensation zone, where it condenses back into liquid and releases the latent heat. The liquid is then moved by capillary forces or outside forces back to the evaporation zone. For cooling applications, loop heat pipes and micro/miniature heat pipes hold great promise. Miniature heat pipes and micro heat pipes with a height of less than 1 mm can dissipate large heat fluxes.

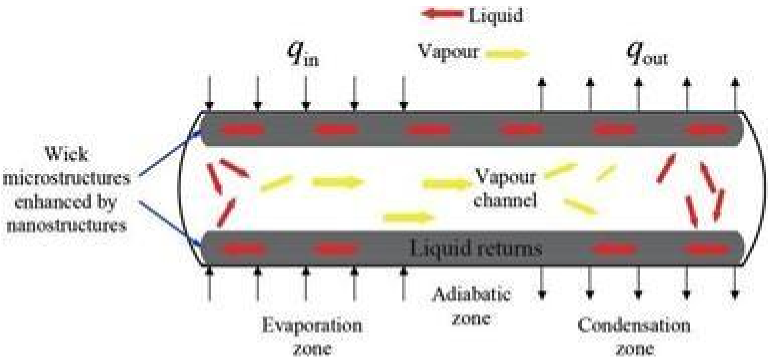

Figure 7:Micro flat heat pipe

The important benefit of heat pipes is that they don't require any external power to function. However, it is crucial to take into account the available area for transferring heat from the condensation zone to the surrounding environment when working with large heat fluxes, which can be constrained in aerospace applications. Compact designs can use micro heat pipes with a depth of less than 1.0 mm. Depending on the particular form factor of the electrical components, the width and length of the evaporation zone can be customised. Similar to this, the length of the condensation zone can be chosen based on the amount of heat that needs to be dissipated as well as the external heat sink's cooling configuration.

IV. Conclusion

For effective thermal management in contemporary aircraft and spacecraft, high-performance heat exchanger design and development are essential. Advanced heat transfer systems that are small, light, and able to function in harsh environments are required due to the rising power requirements and heat production of electronic components.Utilising intercoolers and recuperators in gas turbine cycles is a crucial strategy. These elements, like plate-fin heat exchangers (PFHEs), efficiently raise turbine inlet temperatures and overall pressure ratios, which increases thermal efficiency. Effective heat transfer and energy recovery are made possible by the integration of intercooling and recuperation techniques, especially at lower overall pressure ratios.Furthermore, main surface heat exchangers benefit from 100% effective surface geometry and a more straightforward welding sealing process, which makes them appropriate for intercooling and recuperation applications. They are perfect for aircraft conditions because to their lightweight design and compatibility with welding techniques.Additionally, tiny and micro heat pipes offer spacecraft cooling options that are portable and dependable. These heat pipes don't need an external power source because they transfer heat through capillary forces. They are ideal for dissipating high heat fluxes in small places due to their small size and great heat dissipation capabilities.The development of heat exchangers for aerospace applications has improved thermal management, raised efficiency, and improved the performance of the systems aboard aeroplanes and spacecraft. The ongoing search for small, light, and effective heat transfer technologies will develop aerospace thermal management and make it possible for power-hungry electronic equipment to operate successfully in difficult conditions.

Future work on the integration of intelligent and adaptive thermal management systems, including active control mechanisms and cutting-edge sensor technologies, will make it possible for heat exchange processes in aerospace applications to be more dependable and efficient. High-performance heat exchangers have a bright future in aerospace, with improvements in efficiency, compactness, and sophisticated thermal management techniques.

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