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EVOLUTION AND MANUFACTURING TECHNIQUES OF HEAT EXCHANGERS FOR AEROSPACE APPLICATIONS: A REVIEW

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Abstract: *Heat exchangers (HXs) are crucial components in various industrial applications, including aerospace engineering, where they play a vital role in ensuring the proper functioning of ultra-high bypass ratio turbofan engines. Particularly, air to oil HXs are essential for cooling the oil that lubricates the internal rotating components of aeroengines, operating under high temperatures, severe corrosion, and wear conditions. Traditional manufacturing processes for aerospace HXs involve complex assembly methods such as brazing or diffusion bonding, which are time-consuming and require specialized equipment. However, innovative techniques like diffusion bonding offer opportunities for producing high-performance compact HXs more efficiently. Despite advancements in manufacturing, there remains a need for further improvements to meet evolving aerospace requirements. This review addresses this gap by exploring the evolution of HXs and manufacturing techniques necessary for the production of the new generation of HXs. It provides a detailed discussion on additive manufacturing (AM) techniques, particularly Laser-Powder Bed Fusion, and their advantages and limitations. Additionally, it examines a wide range of materials and postprocessing strategies, with a focus on advanced Aluminium alloys, to meet the stringent demands of the aerospace industry.*

Keywords: *Heat exchangers, aerospace applications, manufacturing techniques, diffusion bonding, additive manufacturing, Laser-Powder Bed Fusion, Aluminium alloys.*

I. INTRODUCTION

Heat exchangers (HXs) are indispensable in several applications. In general, a heat exchanger (HX) is used to transfer heat between fluids, usually in motion, to get rid of the excessive heat generated during a process or operation of a component. In particular, in aerospace applications, HXs are essential to ensure the proper functioning of ultra-high bypass ratio turbofan engines. In particular, air to oil HXs are often used to cool the oil that lubricates the internal rotating components of aeroengines. For this, HX is inserted in the front part of the aero-engine, typically on the fan-case, as expressed in Fig. 1 and must necessarily operate at high temperatures, severe corrosion and wear conditions, mostly for aircraft with longer standstill times in areas with ocean–atmosphere, dynamic vibrations and long periods of operation [1]. Due to the complex heat transfer surfaces within the external case, aerospace HXs are conventionally produced through a long process, by assembling thin plates by brazing or diffusion bonding. Brazing is a joining process that uses a filler metal with a lower melting point than the base materials being joined.

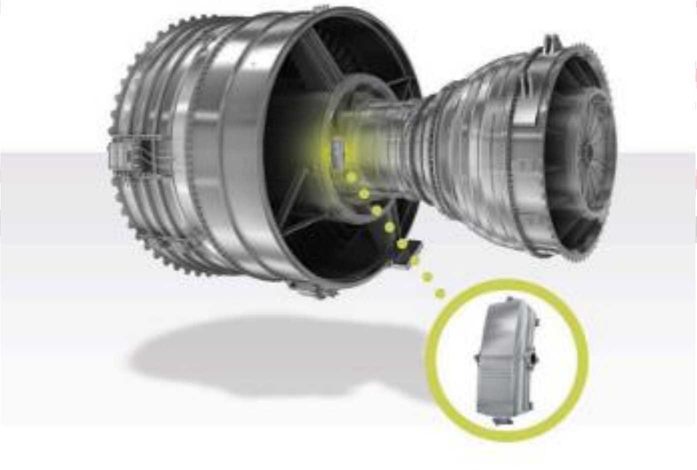

Figure 1. Conventional HX for an aero-engine (courtesy of Meggitt Plc.) [2].

The innovative diffusion bonding, allows a better and easier union between the metallic parts, leading to high-performance compact HXs. In particular, this process consists in applying high temperature and high pressure to bond the plates with no melting or deformation of the shape. However, the process requires specialised equipment and a long process time. Furthermore, the success of the joining relies on surface preparation and close contact between the surface, restricting the range of application for complex geometries. Over the years, the aerospace industry has achieved great technological improvements and nowadays the components of an HX are made more efficiently in order to minimise waste [3]. However, the development of new and more efficient HXs is still ongoing. It is of primary importance to reduce the final weight of the component, by acting on the size/weight, while the performance in terms of thermal efficiency must reach high levels [4]. Consequently, there are several main objectives during the design and manufacture of an HX that result in challenges from an engineering and production cost point of view. Today's requirements for the correct manufacture and operational life of all components used in the aerospace field, whether civil or military, together with the most stringent rules on environmental impact have forced the industry in the sector to a new vision of HXs, leading to the modelling of complex systems that very often cannot be achieved through conventional manufacturing techniques due to their limited versatility in modelling geometries with complex features. Furthermore, this new regulation has led to the consideration of new types of manufacturing technologies and, therefore, materials with a high density/strength ratio [5]. This study proposes to fill the gap in a description of the evolution of HXs and manufacturing techniques necessary for the correct production of the new generation of HXs. In particular, a detailed description of AM techniques, with particular attention to Laser-Powder Bed Fusion, and the advantages and limitations of these new manufacturing technologies are provided. In addition, the wide range of materials and postprocessing strategies currently used are also explored with particular interest in the advanced Aluminium alloys[6]–[9].

II. APPLICATION FOR HEAT EXCHANGERS

Heat exchangers are integral to a myriad of applications across industries, facilitating the efficient transfer of thermal energy between fluid streams. From the oil and gas sector, where they aid in refining processes and heat recovery, to electronics cooling, aviation, automotive systems, renewable energy applications, and building HVAC systems, heat exchangers play diverse and indispensable roles. Their versatility and effectiveness contribute significantly to enhancing energy efficiency, improving performance, and ensuring the reliability of processes and systems in modern society [10]–[13].

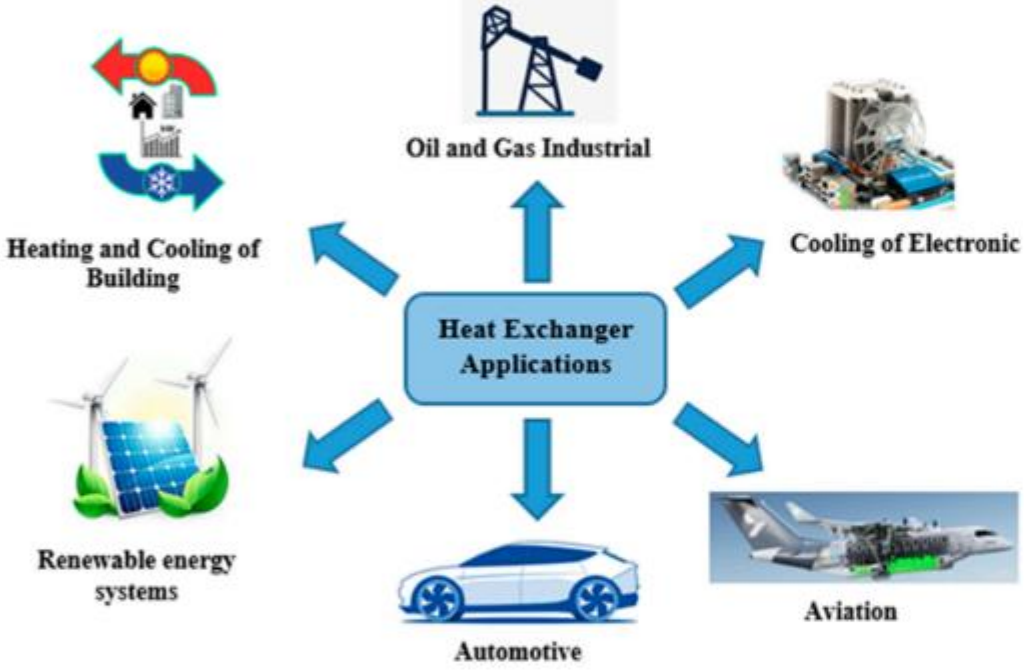

Figure 2 A few applications for heat exchanger

Oil and Gas Industry: In the oil and gas industry, heat exchangers are utilized for several purposes. They are commonly employed in refineries for processes such as crude oil distillation, where heat exchangers help in heating crude oil to separate it into various components like gasoline, diesel, and kerosene. Heat exchangers are also used for cooling purposes, such as cooling gases or condensing vapors in processes like natural gas liquefaction. Additionally, heat exchangers aid in heat recovery from various process streams, improving overall energy efficiency in oil and gas operations[14]–[17].

Cooling of Electronics: Heat exchangers play a crucial role in cooling electronic components and systems to maintain optimal operating temperatures. They are often integrated into electronic devices, such as computers, servers, and telecommunications equipment, to dissipate heat generated by electronic components like processors, transistors, and power supplies. Heat exchangers help prevent overheating and ensure the reliability and longevity of electronic devices by efficiently transferring heat away from sensitive components to the surrounding environment.

Aviation: Heat exchangers are essential components in aircraft systems for regulating temperatures and cooling various onboard systems. In aviation, heat exchangers are commonly used in aircraft engines for cooling purposes, helping to dissipate the immense heat generated during combustion. They also play a role in cooling hydraulic systems, air conditioning systems, and onboard electronics. Heat exchangers contribute to the safe and efficient operation of aircraft by maintaining critical temperatures and preventing system failures due to overheating.

Automotive: Heat exchangers are integral to automotive systems for managing engine temperature and providing climate control within vehicles. In automobiles, heat exchangers are primarily used as radiators to cool the engine coolant, preventing overheating and maintaining optimal operating conditions. Additionally, heat exchangers are employed in automotive air conditioning systems to cool and dehumidify air circulated within the vehicle cabin. They also play a role in cooling transmission fluids, engine oil, and turbochargers, contributing to the overall performance and reliability of automotive systems.

Renewable Energy Systems: Heat exchangers are essential components in various renewable energy systems, including solar thermal collectors, geothermal heat pumps, and biomass boilers. In solar thermal systems, heat exchangers facilitate the transfer of heat captured from sunlight to a working fluid, such as water or air, which can then be used for heating purposes in residential, commercial, or industrial applications. Similarly, in geothermal heat pumps, heat exchangers transfer heat between the ground and a heat pump system to provide space heating or hot water. Heat exchangers also play a role in biomass boilers by transferring heat from combustion gases to water, steam, or thermal oil for use in heating systems[18]–[23].

Heating and Cooling of Buildings: Heat exchangers are widely used in heating, ventilation, and air conditioning (HVAC) systems for buildings to regulate indoor temperatures and improve energy efficiency. In HVAC systems, heat exchangers facilitate the transfer of heat between air streams, allowing for efficient heating or cooling of indoor spaces. They are commonly found in air handling units, heat pumps, chillers, and rooftop units, where they help maintain comfortable indoor temperatures while minimizing energy consumption. Heat exchangers also play a role in heat recovery ventilation systems, where they recover heat from exhaust air to preheat incoming fresh air, reducing the energy required for heating or cooling[24]–[29].

III. LITERATURE REVIEW

Eswiasi & Mukhopadhyaya [6]: This review explores the rising utilization of ground source heat pumps (GSHPs) in heating and cooling applications, particularly in regions with diverse climates. It analyzes the impact of construction and operational parameters on the thermal efficiency of vertical ground heat exchangers (VGHEs) within GSHP setups. Key findings include the positive correlation between borehole diameter and thermal performance and strategies to enhance VGHE efficiency, emphasizing the importance of pipe configuration and grout materials.

Ajeeb & Murshed [7]: Focusing on compact heat exchangers, this review discusses the demand for enhanced energy efficiency and sustainability. It highlights nanofluids as a promising solution to improve heat transfer efficiency, stability, and minimal pressure drop. The review scrutinizes factors affecting nanofluid performance and emphasizes the importance of selecting appropriate geometries and nanofluid structures for sustainable thermal energy solutions.

Rashidi et al. [8]: This review delves into entropy generation and exergy analysis in shell and tube heat exchangers, emphasizing the significance of operating conditions and fluid properties. It discusses potential avenues for reducing entropy generation and enhancing exergy efficiency through modifications in fluid properties and operating conditions.

Swamee et al. [9]: Proposing a novel optimization approach, this paper addresses challenges in designing double pipe heat exchangers for industrial applications. It formulates the design optimization as a geometric programming problem, enabling engineers to streamline the design process, enhance system efficiency, and minimize costs.

Dizaji et al. [10]: Experimental investigations on double pipe heat exchangers with corrugated tubes reveal significant effects of outer tube corrugations and arrangement types on thermal and frictional characteristics. Findings emphasize the impact of tube corrugation on heat transfer and effectiveness.

Wang et al. [11]: Introducing a novel double-tube heat exchanger with staggered helical fins (DTHE-SHF), this study investigates thermal performance enhancements through numerical simulations. Results highlight reduced pressure drop and improved thermal performance compared to traditional designs, emphasizing optimization efforts for superior performance.

Vaisi et al. [12]: Experimental investigations on vapor flow in finned double-pipe heat exchangers with perforated tube inserts reveal consistent improvements in heat transfer coefficients compared to plain heat exchangers. Results underscore the impact of perforation configurations on heat transfer enhancement, with higher Reynolds numbers correlating with increased heat transfer performance.

IV. GROUND SOURCE HEAT PUMPS AND VERTICAL GROUND HEAT EXCHANGERS

Ground source heat pumps (GSHPs) represent a sustainable and efficient solution for heating and cooling residential and commercial spaces, particularly in regions with varying climate conditions. These systems capitalize on the stable thermal properties of the ground to regulate indoor temperatures effectively, offering significant environmental benefits by reducing carbon emissions. A key component of GSHP systems is the vertical ground heat exchanger (VGHE), which facilitates the exchange of heat between the ground and the heat pump fluid. Understanding the factors influencing the thermal efficiency of VGHEs is crucial for optimizing GSHP performance and promoting their widespread adoption.

Growing Utilization: The notable surge in the utilization of GSHPs stems from a global shift towards prioritizing energy efficiency and environmental sustainability in building design and operation. With increasing awareness of the environmental impact of traditional heating and cooling systems, stakeholders are turning to GSHPs as viable alternatives that offer significant reductions in energy consumption and greenhouse gas emissions. This trend is driven by both regulatory incentives and consumer preferences for environmentally friendly technologies.

Environmental Friendliness: GSHPs are celebrated for their exceptional environmental friendliness, characterized by a significantly lower carbon footprint compared to conventional heating and cooling systems. By harnessing renewable energy from the ground, GSHPs eliminate the need for fossil fuels in heating and cooling processes, thereby reducing reliance on non-renewable resources and mitigating harmful emissions. This environmental advantage makes GSHPs highly appealing to eco-conscious consumers and businesses striving to minimize their environmental impact and contribute to sustainability efforts.

Thermal Storage Capacity: One of the key strengths of GSHPs lies in their utilization of the ground's inherent thermal storage capacity. This unique feature allows GSHPs to effectively store and extract heat from the ground, enabling them to maintain consistent indoor temperatures year-round, regardless of fluctuations in external weather conditions. By leveraging the ground as a heat source or sink, GSHPs ensure reliable and efficient heating and cooling performance, offering occupants a comfortable indoor environment while minimizing energy consumption.

Role of VGHEs: Vertical ground heat exchangers (VGHEs) play a pivotal role in GSHP systems as they serve as the primary interface between the ground and the heat pump. VGHEs facilitate efficient heat exchange by transferring thermal energy between the circulating fluid within the heat pump system and the surrounding ground. This process enables GSHPs to extract heat from the ground during the heating season and reject heat to the ground during the cooling season, effectively regulating indoor temperatures and enhancing energy efficiency.

Influence of Parameters: Various construction and operational parameters significantly influence the thermal efficiency of VGHEs in GSHP systems. Factors such as pipe configuration, diameter, grout composition, heat injection rate, and flow rate play crucial roles in determining the effectiveness of heat transfer between the ground and the heat pump fluid. Understanding and optimizing these parameters are essential for maximizing the performance and efficiency of GSHP systems, ensuring optimal heating and cooling outcomes while minimizing energy consumption and operational costs.

Research Objectives: The primary objective of this study is to comprehensively analyze the influence of various construction and operational parameters on the performance of VGHEs within GSHP systems. By systematically investigating the impact of parameters such as pipe configuration, diameter, grout composition, and flow characteristics on thermal efficiency, the research aims to identify strategies for enhancing the overall performance and effectiveness of GSHP technology. Through rigorous analysis and experimentation, the study seeks to provide valuable insights and recommendations to stakeholders in the energy and building sectors, facilitating the wider adoption and implementation of GSHP systems for sustainable heating and cooling solutions.

V. CONCLUSION

Heat exchangers are indispensable components in aerospace applications, ensuring the efficient operation of critical systems in ultra-high bypass ratio turbofan engines. As the aerospace industry continues to evolve, there is a growing demand for HXs that offer high performance, reliability, and efficiency while meeting stringent weight and environmental requirements. Traditional manufacturing techniques have limitations in meeting these demands, necessitating the exploration of innovative manufacturing methods such as diffusion bonding and additive manufacturing. These techniques offer opportunities for producing HXs with complex geometries, improved performance, and reduced production costs. However, challenges remain in optimizing these techniques for aerospace applications and selecting suitable materials that offer the required strength-to-weight ratio and corrosion resistance. By addressing these challenges and leveraging advanced manufacturing technologies, the aerospace industry can continue to advance the development of next-generation heat exchangers, ensuring the continued safety, reliability, and efficiency of aerospace systems.

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