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REVIEW OF HIGH TEMPERATURE HEAT EX-CHANGERS

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ABSTRACT
Heat exchangers are essential components in most power conversion systems, and several industrial sectors stand to gain significantly from high-temperature heat exchangers. Key examples include traditional aerospace applications, advanced nuclear power generation systems, and high-efficiency stationary and mobile modular fossil fuel-to-shaft power/electricity conversion systems. This paper provides a comprehensive review of high-temperature heat exchangers, focusing on build materials, general design, manufacturing techniques, and operating parameters specific to these applications. It also discusses the challenges related to both conventional and advanced fabrication technologies for high-temperature heat exchangers. Lastly, the paper highlights the future research needs for the development and improvement of high-temperature heat exchangers.
Keywords - Heat Exchangers, plate fin heat exchanger,Manifold-microchannel Heat Exchanger

INTRODUCTION:
High-temperature heat exchangers (HTHXs) are typically defined as those operating above 500°C. The development of these exchangers was initially driven by the energy crisis in 1973, which created a need for more energy-efficient technologies. Since then, various types of HTHXs have been developed and used in applications such as gas turbine engines, aerospace, hydrogen production, waste heat recovery, supercritical CO2 power cycles, and high-temperature fuel cell systems.HTHXs operating at high temperatures face unique material challenges, including issues like creep, reduced strength at elevated temperatures, oxidation, corrosion, and thermal shock. To address these challenges, expensive alloys that maintain strength at high temperatures are typically used. However, these alloys tend to have low thermal conductivity and are difficult to manufacture, creating additional challenges in heat exchanger design and fabrication. Moreover, these alloys lose strength at higher operating pressures, requiring thicker walls to maintain structural integrity. This increased wall thickness leads to higher material costs, making HTHXs made from these alloys expensive, particularly in power cycle applications.One way to offset these costs is by developing compact heat exchangers with a higher surface area-to-volume ratio, reducing the amount of material needed. In recent decades, there has been a growing interest in the development of compact, cost-effective HTHXs. Advances in manufacturing techniques, particularly additive manufacturing of metals, have shown promise in creating compact HTHXs with innovative heat transfer surface designs.
This paper discusses the challenges encountered in developing HTHXs, including material selection, and highlights recent advancements in the design and application of HTHXs.

TYPES OF HIGH TEMPERATURE HEAT EXCHANGERS:
As mentioned earlier, the cost of high-temperature heat exchangers (HTHXs) increases significantly with higher operating temperatures, especially above 600°C. This is primarily due to the high material and manufacturing costs associated with superalloy and ceramic heat exchangers. The situation becomes even more complex for higher-pressure applications, such as those in power cycles. Traditional heat exchanger designs, typically used in lower temperature applications, become economically unfeasible at these high temperatures. The high cost of exchangers used in power plant applications, such as supercritical CO2 Brayton cycles, remains a major challenge to making these cycles cost-effective (Chordia et al., 2017). In response to this issue, new heat exchanger designs that

make more efficient use of materials are being developed. These designs often feature a higher surface area-to-volume ratio, utilizing microchannels and fin geometries to achieve this increased surface area. Smaller channel sizes in these designs enhance heat transfer, as the heat transfer rate is significantly higher in these miniature geometries (Arie et al., 2017; Kandlikar et al., 2005). Moreover, advancements in manufacturing techniques, such as 3D printing, have enabled engineers to create designs that would otherwise be difficult or impossible to fabricate (Arie et al., 2016; Gerstler and Erno, 2017).This section reviews various types and designs of heat exchangers, including traditional designs used in high-temperature applications.

Plate-fin Heat Exchanger (PFHX):

Plate-fin heat exchangers (PFHXs) are widely used in various industrial sectors, particularly for gas-to-gas heat transfer applications. The main components of a PFHX include side bars, fins, and parting sheets, The fins are typically manufactured using a stamping process and are then brazed together with the base plates. A brazed PFHX can withstand pressures up to 90 bar, while diffusion-bonded PFHXs are capable of operating at pressures as high as 200 bar.

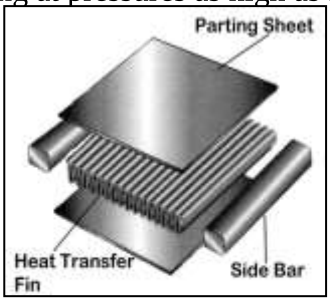

Fig No 1 : components of PFHX

Plate-and-frame Heat Exchanger :

Plate-and-frame heat exchangers are often used to transfer heat between two liquids or two gases. The fluid-separating plates of these heat exchangers are typically manufactured by compression processing of a thin metal sheet, and they come in several patterns such as wavy, chevron, washboard, herringbone, cross-corrugated, cross-undulated, or cross-wavy (Utriainen and Sundén, 2002; Stasiek, 1998; McDonald, 2000;Foerster and Kleemann, 1978). Two such heat transfer plates are then stacked to produce a single cell, and this process is repeated to manufacture the required number of cells. The structural strength of the core is achieved through the connection of the end plates once all the cells are stacked, For high pressure applications, the plates can be welded or brazed together to ensure operation up to 200 bar pressure and 815°C temperature (Shah and Sekulic, 1998). Two layouts are typically used for plate-and-frame heat exchangers in recuperators in microturbine systems: 1) rectangular designs, which are installed behind the rotating machinery, and 2) annular designs, which are wrapped around the turbine

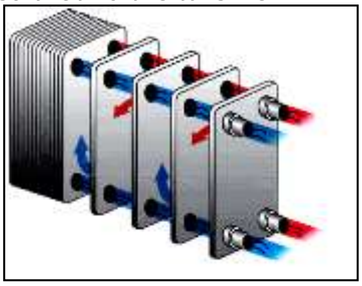

Fig No 2 : Plate-and-frame Heat Exchanger

Shell-and-tube Heat Exchangers :

Shell-and-tube heat exchangers (shown in Fig) are among the most commonly used types in industry. In conventional designs, the tube diameters typically range from 0.625” to 1.5” (~16 mm to 38 mm).

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These exchangers generally have a low surface area-to-volume ratio, making them less economical for high-temperature and high-pressure applications. However, Chordia et al. (2017) developed a shell-and-tube heat exchanger featuring a large number of smaller tubes with diameters close to 1 mm. This design helps achieve a thinner wall and a significantly higher surface area-to-volume ratio. Since the channels are on the order of millimeters or less, this type of heat exchanger benefits from enhanced heat transfer. It can handle more demanding conditions, including higher pressures and temperatures, making it suitable for applications like gas turbine systems, provided there is no space limitation. Additionally, it can be utilized as a high-temperature gas-cooled reactor for nuclear heat applications.

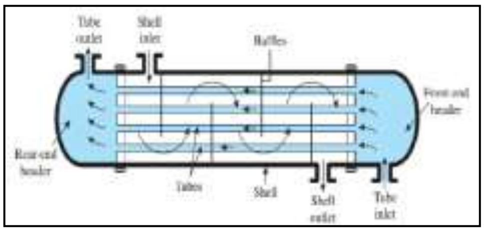

Fig No 3 : Shell-and-tube Heat Exchangers structure

Special High Tempearature Heat Exchnagers :

Working with superalloys through processes like machining, welding, brazing, and processing is challenging due to their high toughness, low thermal conductivity, and tendency to crack during welding. Additionally, suitable brazing materials are often unavailable, making the process even more complicated (Marlin Steel, 2016; Continental Steel & Tube Company, 2015; David et al., 2015). These materials typically require specialized equipment and highly skilled operators. However, emerging advanced manufacturing techniques, including 3D printing (additive manufacturing) and photo-chemical etching, offer promising solutions to these issues. These new methods are increasingly being used to manufacture heat exchanger (HTHX) components, providing effective alternatives to traditional manufacturing processes.

Manifold-microchannel Heat Exchanger:

The manifold-microchannel heat exchanger (M2HX) is an innovative design that leverages the high heat transfer rates of microchannels while minimizing the associated high pressure drops by shortening the flow length within the microchannel. However, with shorter flow lengths, the assumption of negligible spreading in the fluid-separating wall (base plate) may no longer hold true, meaning conventional heat exchanger correlations cannot be applied to determine heat exchanger effectiveness. In the case of very short flow lengths, spreading dominates, and it becomes feasible to assume a constant base plate temperature. This approach has been used by previous researchers to calculate the effectiveness of a cross-flow M2HX currently being developed for enhanced gas-to-gas heat transfer applications. In a manifold-microchannel heat exchanger, a manifold is positioned on top of the microchannels, as depicted in Fig. The inlet gas is distributed into the microchannels via the manifold and travels a short distance within each microchannel before being directed out.

THE KEY ADVANTAGES OF THE MANIFOLD-MICROCHANNEL HEAT EXCHANGER ARE AS FOLLOWS:

Reduced Pressure Drop: The pressure drop in the M2HX can be reduced by a factor proportional to the square of the number of divisions, thanks to the reduction in both flow length and flow rate (Cetegen, 2010; Ohadi et al., 2013). This allows for smaller hydraulic diameters compared to straight microchannels, leading to higher heat transfer coefficients and a reduced mass/volume ratio.

Improved Heat Transfer: The short flow lengths in the microchannels cause thermally developing flow, which enhances heat transfer performance compared to fully developed flow.

High Surface Area: The small fin size (less than 0.3 mm in width) results in an extremely high heat transfer surface area per unit volume (1000 to 2000 m^2/m^3), making the manifold-microchannel heat exchangers more compact than most current heat exchanger technologies.

Increased Effectiveness: By using a multi-pass manifold configuration, the effectiveness of the M2HX can be further enhanced by minimizing heat spreading in the separating wall between the fluid streams.

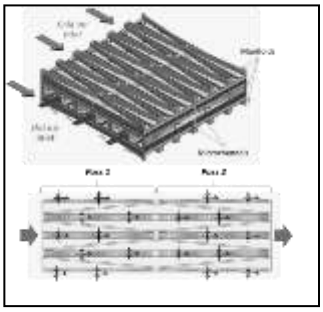

Fig No 04: Manifold-microchannel concept

Several studies in the literature highlight the superior performance of manifold-microchannel heat exchanger (M2HX) technology compared to conventional heat exchanger designs in various applications (Arie et al., 2018; Arie et al., 2016; Ohadi et al., 2013). These studies report a heat transfer improvement of 50% or more for the same pressure drop when compared to state-of-the-art fins, such as wavy fins, louver fins, and plain plate fins. A recent study conducted at the Advanced Heat Exchangers and Process Intensification Laboratory at the University of Maryland (Zhang et al., 2018) demonstrated that a manifold-microchannel heat exchanger made from Inconel 718 can achieve 25% less weight while maintaining the same heat transfer and pressure drop performance compared to several commercially available plate-fin heat exchangers (PFHXs). This improvement was specifically observed in pre-cooling applications at 600°C for aircraft applications.

Multi-furcating Heat Exchanger :

A different type of 3D printed heat exchanger (HTHX) was developed by Gerstler and Erno (2017) from General Electric Global Research. They successfully fabricated multi-furcating heat exchangers using Selective Laser Melting (SLM) for fuel-cooled oil cooler applications, The heat exchanger surfaces were made using four different materials: aluminum, titanium alloy (Ti64), cobalt chrome, and Inconel 718. Test results revealed that the 3D printed heat exchangers met the pressure drop and heat transfer design requirements while offering 66% lower weight and 50% lower volume compared to conventional heat exchangers.

Fig no 05 : Multi-furcating heat exchange

Printed circuit heat exchanger:

Photo-chemical etching is a manufacturing process that employs a photoresist and etching agents to remove specific areas of a metal plate. Initially developed for creating printed circuit boards, this method is now used for etching a variety of metals, such as titanium, nickel superalloy, and copper superalloy, due to its high precision. This capability has made it an effective technique for fabricating printed circuit heat exchangers. The process begins with the application of a photoresist layer on the metal surface. The photoresist is then exposed to ultraviolet (UV) light through a photo-tool. The exposed metal areas are then etched away to form semi-circular channels, typically ranging from 0.5 to 2 mm in width (Mylavarapu et al., 2012). After etching, the photoresist is removed using an alkaline solution. Depending on the exposure pattern of the photo-tool, the process is termed "positive-working photoresist" if the UV light targets the areas to be removed, or "negative-working photoresist" if it targets the areas to be preserved.

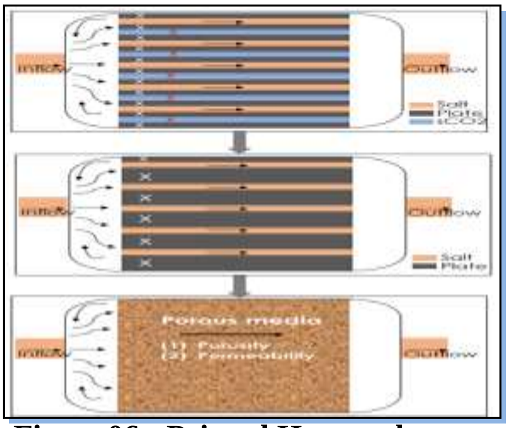

Fig no 06 : Printed Heat exchanger

Photo-chemical etching is widely used in the production of printed circuit heat exchangers (PCHEs). The design typically features stacked plates, each containing finely etched grooves, These stacked plates are often joined together using a diffusion bonding process. Common flow configurations for PCHEs include counter-flow, cross-flow, and cross-counter-flow. Some PCHEs are capable of withstanding design pressures up to 900 bars and temperatures as high as 980°C (Heatric, 2018). Heatric (2018) has successfully marketed a printed circuit heat exchanger manufactured through photo-chemical etching and diffusion bonding. PCHEs offer excellent thermal performance and compactness due to their small channel geometries. However, they also experience higher pressure drops because of the long, straight microchannels. Additionally, the chemical etching process can be costly for high-temperature materials, as these materials are challenging to etch. As a result, these heat exchangers tend to be relatively expensive, particularly for applications involving high temperatures. The low mass-based heat removal efficiency (kW/kg) and the high cost of these heat exchangers have posed challenges for their use in high-temperature (>600°C) and high-pressure (>100 bar) environments.

Ceramic Heat Exchanger:

A variety of ceramic heat exchangers have been developed and tested, such as ceramic plate-fin heat exchangers (PFHXs), plate-and-frame heat exchangers, and ceramic shell-and-tube heat exchangers (Ferrato and Thonon, 1997; Federzoni et al., 2007; Alm et al., 2005; Schmidt et al., 2011). Some of these exchangers are designed to operate at temperatures as high as 1370°C (Ferrato and Thonon, 1997).

Fig no 07 : Ceramic Heat Exchanger

The fabrication of ceramic heat transfer surfaces typically involves methods such as slip casting, tape casting, throwing, injection molding, and dry pressing. For example, Federzoni et al. (2007) used injection molding to create a plate-and-frame heat exchanger made from alumina, with a channel size of 0.5 mm x 0.5 mm. Similarly, shape molding was used by Schmidt et al. (2011) to produce a plate-and-frame heat exchanger, while slip casting was employed to manufacture a finned ceramic shell heat exchanger (Strumpf et al., 1982). In another example, Alm et al. (2005) combined stereolithography, additive manufacturing, and injection molding to fabricate a plate-and-frame heat exchanger, all with feature sizes as small as 250 microns. The bonding of ceramic heat exchangers can be classified into two types: non-monolithic bonds (temporary) and monolithic bonds (permanent). A non-monolithic bond is a temporary bond that can be easily separated or de-bonded. Mechanical joints and seals are examples of non-monolithic bonds. If a heat exchanger with a non-permanent bond gets damaged, it can be repaired by replacing the broken part. However, these bonds are generally weaker than monolithic bonds, making them unsuitable for high-pressure heat exchanger applications. Additionally, the mismatch in coefficient of thermal expansion (CTE) between two different materials can pose a challenge for non-monolithic bonding. In contrast, a monolithic bond is a permanent bond that cannot be separated once formed. Monolithic bonds provide a stronger connection compared to non-monolithic bonds. Techniques for monolithic bonding include polymer infiltration and pyrolysis (PIP), tape bonding, firing, and laser brazing. Ceramic heat exchangers have also been produced using additive manufacturing (AM). Ross et al. (Shulman and Ross, 2015) worked on fabricating a compact 4 cubic inch ceramic heat exchanger from zirconia-toughened mullite (ZTM) using the LOM (Laminated Object Manufacturing) process. They overcame initial issues with layer delamination by reducing the binder burnout rate and introducing a tape cleaning step. The heat exchanger was successfully tested at 700°C, although fabricating larger sizes proved difficult due to cracks caused by defects. In a separate study, Alm et al. (2005) developed a ceramic heat exchanger using a combination of AM techniques (stereolithography) and injection molding. The AM process was employed to create the injection molding mold, allowing for the fabrication of molds with feature sizes as small as 0.25 mm, highlighting the potential of AM in the production of ceramic heat exchangers.

Applications of High temperature Heat Exchnagers :

High-temperature heat exchangers have a wide range of applications, including aerospace, waste heat recovery, nuclear heat utilization, exhaust gas recuperation, and as primary heaters and recuperators in advanced high-efficiency power cycles like the supercritical CO2 Brayton cycle. This section provides an overview of some of the applications of high-power heat exchangers that are currently in use or under development.

POWER GENERATION :

Gas turbines have been widely used in power plants and aircraft propulsion for over fifty years, with heat exchangers playing a vital role in their efficiency. The heat exchanger acts as a recuperator, preheating compressed air before it enters the combustor by recovering heat from the exhaust gases. This process increases the gas turbine cycle's efficiency and reduces fuel consumption (Franco and Casarosa, 2004). In these systems, the temperature of the compressor exit gas can reach up to 725°C, which requires a high-temperature heat exchanger (HTHX) to function as the recuperator (Min et al., 2009). The three main types of recuperators used in gas turbine systems are plate-fin heat exchangers (PFHXs), plate-and-frame heat exchangers, and shell-and-tube heat exchangers.

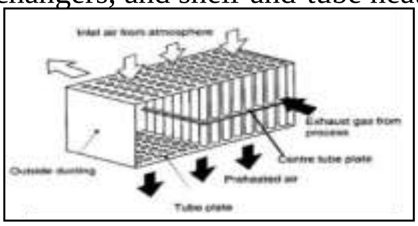

Fig no 08 : HE as recuperator

To optimize the gas turbine cycle, with an inlet gas/air temperature of 825°C/521°C and a pressure ratio of 24.3, Aquaro (2007) proposed a plate-fin heat exchanger (PFHX) made from superalloy, featuring an increased fin thickness of 0.15 mm on the air side to withstand the pressure at these high operating temperatures. Figure shows a PFHX designed by Toyo (Takase et al., 2002), which was used as a recuperator with an effectiveness of approximately 90% in intercooled and recuperated micro gas turbines operating at around 650°C, with an inlet pressure of about 400 kPa. Similarly, Ingersoll-Rand (Kesseli et al., 2003) developed a plate-fin recuperator with offset fins in the heat transfer area, designed to operate at 700°C with about 90% effectiveness and a cycle pressure ratio of up to 14. AlliedSignal (Honeywell's predecessor) (Parker K, 1979; McDonald, 1996) produced a compact plate-fin ceramic recuperator for cruise-missile propulsion and an industrial gas-turbine plate-fin recuperator (with 84-89% effectiveness), operating at 510-575°C and having a pressure ratio of 10.Rekuperator Svenska AB (RSAB) developed a plate-and-frame type recuperator with an effectiveness of around 90% and an operating temperature of 650°C for use in micro gas turbine power plants that generate both electricity and heat, Honeywell also developed a welded plate-and-frame counter-flow recuperator (Muley and Sundén, 2003). Additionally, Wilson et al. (2005) designed a plate-and-frame recuperator with 90% effectiveness using silicon carbide, which significantly increased the overall thermal efficiency from 27% to over 40%, due to the material's ability to withstand inlet hot gas temperatures up to 955°C.

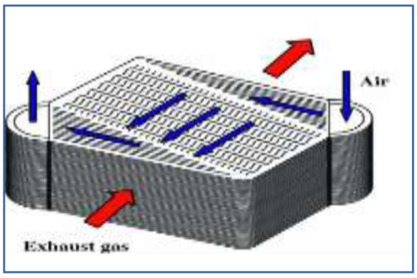

Fig no 09 : HE as plate recuperator

Intermediate Heat Exchanger for Nuclear Heat Utilization :

Another use of high-temperature heat exchangers (HTHXs) is in nuclear heat utilization. In nuclear power plants, these heat exchangers must be economically viable while also meeting strict safety standards. High-temperature gas-cooled reactors (HTGRs) offer excellent safety due to their high heat capacity from the graphite core and the chemical stability of helium as the coolant (Aquaro and Pieve, 2007). To transfer the nuclear heat to end-user facilities, such as hydrogen production or steam reforming systems, a high-temperature intermediate heat exchanger (IHX) is required. This IHX, which may use helium as the working fluid on both sides, must operate at temperatures above 900°C (Crosbie and Chapin, 2003). In the 1980s, a shell-and-tube He/He IHX with a heat duty of 10 MW was designed and built in Germany, successfully undergoing tests at temperatures up to 950°C for several months (Cook et al., 1989; McDonald, 1996). A similar 10 MW He/He IHX, based on the shell-and-tube design, was developed in Japan to operate above 900°C (Hada et al., 1991). The IHX consists of a vertical, helically coiled counter-flow heat exchanger. Primary helium enters at the bottom at 950°C and 4 MPa, while secondary helium enters at the top at 200°C and 4.1 MPa. To minimize the impact of axial and radial thermal expansions on the tubes, a floating hot header with a central hot gas duct running through the core of the helical bundle was used.

HE IN AIRCRAFT ENVIRONMENTAL CONTROL SYSTEM :

The environmental control system in aircraft is designed to maintain a comfortable and controlled environment by keeping the temperature within safe limits. To achieve this, hot bleed air from the engine compressor, which can reach temperatures between 500 and 750°C, is precooled using high-temperature heat exchangers (HTHXs) before being circulated to various aircraft systems for other purposes (Martinez, 2018; Bombardier Inc., 2012; Tsuji, 2003). These pre-coolers are typically compact plate-fin heat exchangers (PFHXs) that offer a high heat transfer surface area relative to their volume. Since weight is a crucial consideration in aircraft design, Stevenson et al. (1999) developed a plate-fin carbon-carbon heat exchanger operating at 650°C, achieving a 40% reduction in mass compared to standard metallic heat exchangers. However, to prevent oxidation at this temperature, multi-component coatings were necessary for the carbon-carbon heat exchanger. More recently, a manifold-microchannel high-temperature pre-cooler heat exchanger was developed and tested at the Advanced Heat Exchanger Laboratory at the University of Maryland (Zhang et al., 2015). The pre-cooler core, measuring about 7.5 cm x 7.5 cm x 2.5 cm, was fabricated using Direct Metal Laser Sintering (DMLS) with Inconel 718, The inlet and outlet manifolds were also created through additive manufacturing and welded to the pre-cooler core. This 3D-printed manifold-microchannel pre-cooler was tested at 600°C with an inlet pressure of 448 kPa. Test results demonstrated an overall heat transfer coefficient of up to 1000 $W/m^2 \cdot K$ for gas-to-gas applications and a heat transfer density of around 10 kW/kg, which is 25% higher than typical PFHXs (Zhang et al., 2018). Additionally, a larger 10 cm x 10 cm x 10 cm M2HX was successfully fabricated.

CONCLUSION:

Cost-effective high-temperature heat exchangers are essential for the success of emerging high-temperature, high-efficiency modular power cycles, which are critical for a range of energy conversion, power generation, and energy/waste heat recovery applications. Currently, the most common types of heat exchangers in use are plate-fin, plate-and-frame, and shell-and-tube designs. The ideal high-temperature heat exchanger would strike the perfect balance between heat transfer efficiency, pressure drop, size, weight (which indirectly affects cost), and the necessary longevity and reliability.For high-temperature applications, many heat-resistant superalloys that can withstand these extreme conditions tend to have low thermal conductivity and come at a high cost. Therefore, innovative approaches in design, materials, and manufacturing methods are key to successfully developing these heat exchangers. Although additive manufacturing (AM) of superalloys for high-temperature uses presents several challenges, continued research in this field is expected to overcome many of these hurdles. Recent advancements show promise in the use of AM for fabricating high-temperature heat exchangers. Some studies have investigated hybrid approaches that combine AM with traditional manufacturing techniques, offering a practical solution for certain applications.
Investing in the development of next-generation AM machines could help address current limitations such as build volume constraints, while also improving printer parameter optimization and the quality of the final product. Additional research opportunities lie in creating feedback loop controls for printers, ensuring better quality control throughout the printing process. Furthermore, the materials used in additively manufactured components for high-temperature applications need further research and development. For example, utilizing high-temperature and high-pressure Haynes alloys could represent a major advancement for next-generation high-temperature heat exchangers. Additionally, incorporating ceramic materials with two-dimensional reinforcement could improve the mechanical properties and pressure tolerance of ceramic heat exchangers.

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