The International Journal of Advanced Manufacturing
https://doi.org/10.1007/s00170-023-11396-z

CRITICAL REVIEW

Improving efficiency of micro gas turbine systems by integration of combustor and recuperator using additive manufacturing techniques

Hossein Sheykhpoor[1] · Hamidreza Gohari Darabkhani[1] · Abdul Waheed Awan[1]

Received: 30 June 2022 / Accepted: 3 April 2023

Abstract
World energy consumption is rapidly increasing, and global rising patterns show a higher consumption increase in residential and commercial buildings. Combined heat and power (CHP) systems have been developed and commercialised to distribute and decentralise electricity generation for domestic applications to reduce energy consumption and gas emissions. The use of a micro gas turbine (MGT) shows a number of advantages over other CHP systems including smaller size, ease of operation, and competitive maintenance cost. The low efficiency of the current MGT units in the market combined with the urgent requirement for highly efficient and low-emission energy conversion systems are the motivations for the development of new MGTs using additive manufacturing (AM) techniques. In this study, the current metal-AM systems are reviewed, the development of the MGT combustor and heat exchanger is presented, and the challenges and opportunities toward manufacturing more efficient MGT for domestic applications are discussed. The integration of the combustor and recuperator of the hot section of a MGT is proposed to achieve up to 5% improvement in efficiency with a significant reduction in the weight and size of the system.

Keywords Micro gas turbine · Additive manufacturing · Combustor · Recuperator · Part integration

1 Introduction

Global economic growth has improved the quality of life, increased life expectancy, and raised income in much of the world at the expense of pollution and environmental degradation. Climate change and global warming will cause irreversible and long-term changes in human life and the whole natural system, with detrimental effects seen on rising sea levels and land and ocean ecosystems. In 2015, in response to the concern raised by scientists and institutions, the world leaders agreed to limit global warming to below 2 °C above the pre-industrial era (1850–1900). To reduce the effects of climate change, they set plans to further limit the temperature to 1.5 °C above pre-industrial levels [1]. Achieving this target implies a tight restriction on greenhouse gas emissions, stabilising the current level, and reducing the net addition of gas mainly carbon diox- ide (CO_2), to zero. Although studies show that half of the emitted gas is removed by the natural cycle, a substantial amount of produced gas has remained in the atmosphere for several millennia [2]. When greenhouse gas concen- trations increase in the atmosphere, the temperature rises on the Earth's surface, with the higher warming over the lands than in the oceans [3]. 24% of direct CO_2 emissions are sourced in land, agriculture, and forestry and 21% of the emitted CO_2 is from industry [4–7]. World energy con- sumption is rapidly increasing, and global rising patterns show a higher consumption increase in the residential and commercial sectors because of the growth in income and population [8–11].

Fossil fuels including coal, natural gas, petroleum, and oil are the primary energy sources. In addition to carbon, hydrogen, and oxygen these fuels contain other materials including sulphur, metal, and nitrogen compounds. The combustion of fossil fuels in the energy generation process results in emitting sulphur oxide, nitrogen oxide (NO_x), carbon monoxide (CO) and carbon dioxide, which is one of the by-products of the combination of carbon and oxygen in the

Hamidreza Gohari Darabkhani
h.g.darabkhani@staffs.ac.uk

[1] Department of Engineering, Staffordshire University, Stoke-On-Trent ST4 2DE, UK

combustion process [12]. One pathway towards the net-zero target is the average annual reduction of fossil fuel production by about 6% between 2020 and 2030, which means the global production of coal, oil, and gas has to be decreased by about 4%, 3%, and 11% per year, respectively [13]. Reducing the extraction and production of fossil fuels, and reducing energy requirements worldwide are already behind the plan (Fig. 1) [14]. On the other hand, building up the required capacity of renewable energy and nuclear power plants will take time. Enhancing the efficiency of the energy conversion systems is a shortcut toward reduction of greenhouse gas emissions and it should be the priority for global policymakers. In this regard, applying cogeneration and regeneration plant is one key solution to increase efficiency.

The cogeneration system also referred to as CHP [15], generate electricity and heat from a single fuel type simultaneously. Collecting the waste heat from the electricity production process to generate the required thermal energy for space heating will result in higher energy efficiency than the independent generation of thermal and electrical power. Other than that, CHP systems have some exclusive advantages, such as.

- Lower long term operating costs
- Reduced energy waste in power transmission and distribution
- Less greenhouse gas production
- The potential to design as a miniaturised unit
- Fewer grid system breakdowns

Many of the existing CHP plants are of multi-Megawatt size and are mainly large and industrial plant-related. In recent years, micro-CHP units have been developed and commercialised to reduce the residential and commercial sectors' energy consumption and gas emissions by generating both heat and power. A range of technologies can generate both commodities simultaneously including Reciprocating Engines, Stirling Engines, the Organic Rankine Cycle, Fuel Cells, Gas Turbines, and MGT.

Although the energy source structure varies in different countries, natural gas supplies the primary energy demand. According to the Balancing Mechanism Reporting Service (BMRS), 39.5% of the electricity demand in the UK in 2021 was generated using natural gas. Also, in the USA, 8% of the total cogeneration sites (more than 360 sites) use MGT to generate electricity with a capacity of 92 MW [16]. This is the special motivation for the choice of MGT as the technology for heat and decentralised electricity for residential and commercial buildings. It means each house or commercial unit can build up its supply network, which can still be supplemented by the grid when needed [17]. The other vital factors are small size, low noise, ease of operation, and low maintenance costs which are fulfilled

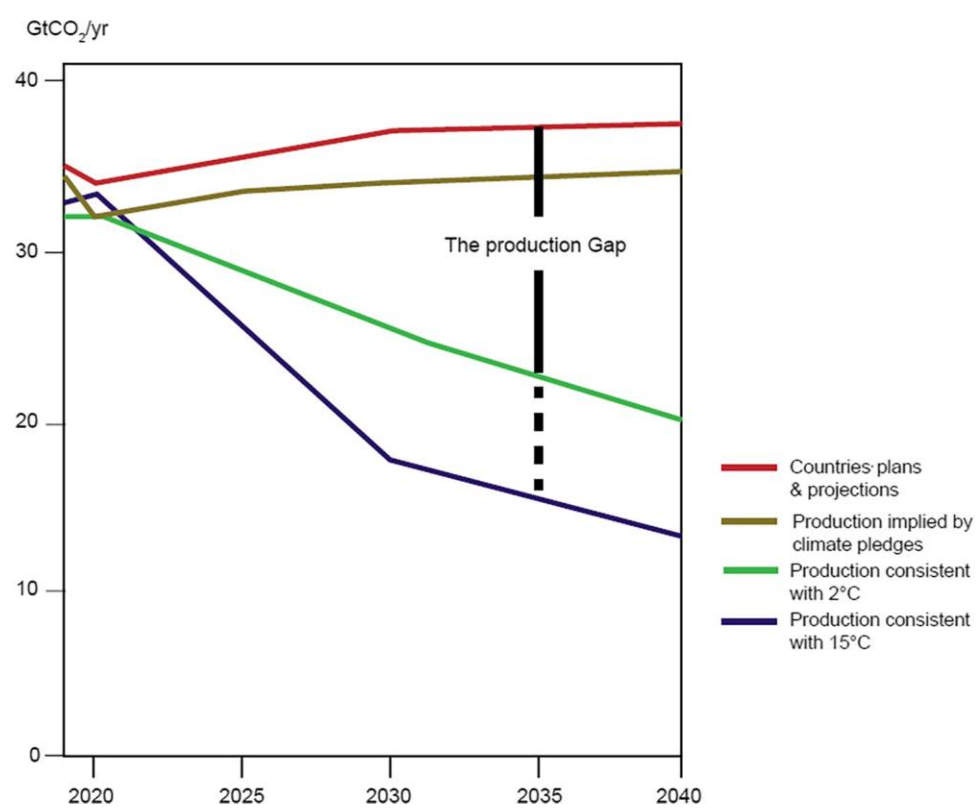


Fig. 1 Adopted from [14]; global fossil fuel production

by the use of a MGT and make it the best choice for small off-grid power generation and micro-cogeneration method.

1.1 Micro gas turbine

The gas turbine is the most rapidly developed cogeneration system [18], with a range of electricity output from 250 kW to 200 MW. The gas turbine system produces high temperature and high-pressure gas in the combustion system, and this gas will rotate the turbine blade to produce mechanical energy that drives the generator. The MGT principle comes from open-cycle gas turbines and can be driven by various fuels such as natural gas, gasoline, diesel, and kerosene and provide thermal and electrical power on a smaller scale. However, they present several typical features which distinguish it from other technologies, such as compact size, simple operability, easy installation, low maintenance, low-pressure ratio (3 to 1), air bearings and low NO_x emissions.

They operate under the Brayton cycle by assembling a compressor, a combustion chamber, a recuperative heat exchanger, and a turbine as shown in the simplified schematic in Fig. 2. The compressed air exits the compressor and enters the recuperator to heat before entering the combustor. In the combustor chamber, the heated air is mixed with fuel to ignite and produce high temperature and high-pressure gas. As the gas exits the combustor it rotates the turbine blades. The high-speed rotation of the turbine blade rotates the shaft and generates electricity through the high-speed generator. The turbine exhaust passes through the recuperator to increase the combustor inlet temperature. This improves the electrical efficiency to over 30%, while without heat recovery it drops to below 20% [19].

There is no strict definition of a MGT, but typically gas turbines with an electrical power output of less than 100 kW are classified as a MGT [20]. However, it should be mentioned that only a few of these turbines have been developed and are commercially available (Table 1).

Table 1 List of available MGT units

Model	Manufacturer	Power output (KW)	Electrical efficiency (%)
IHI Dynajet	Nissan	2.6	12
EnerTwin	MTT	3.2	16
MG12[1]	Bladon	12	25
C30	Capston	30	26
C65[2]	Capston	65	29
AE-T100NG[3]	Ansaldo Energia	100	30
AE-T100B[4]	Ansaldo Energia	105	30

[1]https://www.bladonmt.com/

[2]https://www.capstonegreenenergy.com/products/energy-generation-technologies/capstone-microturbines/c65

[3]https://www.ansaldoenergia.com/business-lines/new-units/microturbines/ae-t100ng

[4]https://www.ansaldoenergia.com/business-lines/new-units/microturbines/ae-t100b

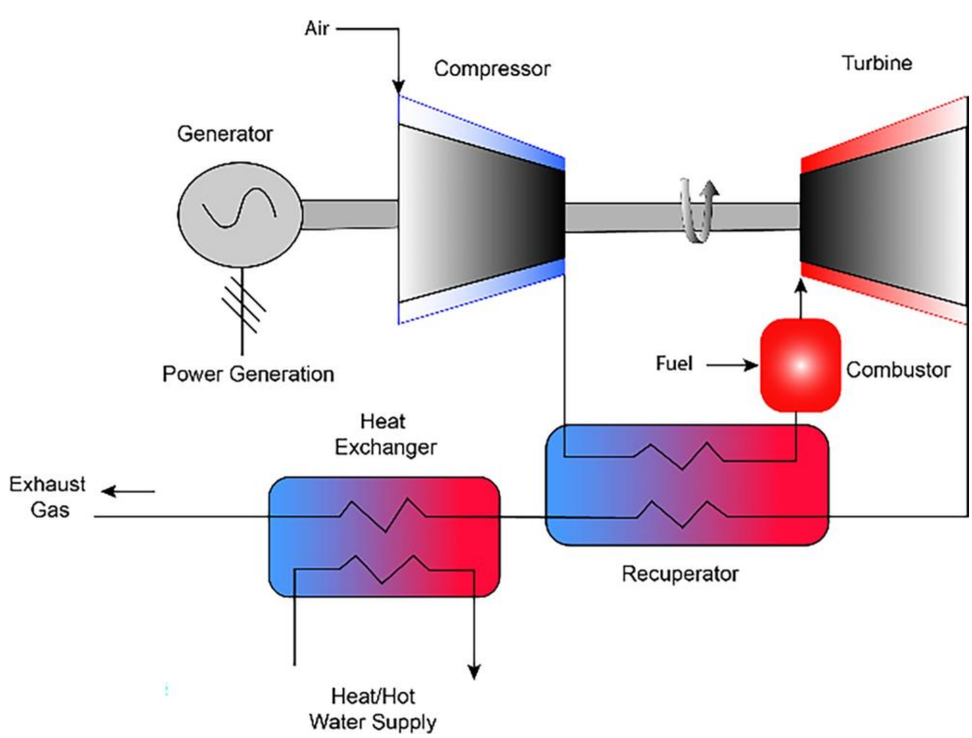


Fig. 2 Schematic diagram of MGT

Capstone Green Energy (formerly Capstone Turbine Corporation) built and tested a prototype of a 24 kW microturbine in 1994 and 2 years later, in 1996, undertook a project consisting of 37 prototypes for field testing. Today, they have two commercial recuperated MGTs, C30, and C65 (Fig. 3), with 30 kW and 65 kW electrical power output, respectively, and NO_x emission below 9 ppm. The C30, with an electrical efficiency of 26%, uses different types of fuel including natural gas, propane and biogas, while the C65 is designed for natural gas only and delivers electricity with 29% efficiency.

The most miniature single-shaft gas turbine, called Daynajet 2.6 was developed by IHI Aerospace Co., Ltd. in 2003, with the power output of 2.6 kW and a rotational frequency of 100,000 rpm (Fig. 4). The system was designed to be fuelled with kerosene and was made of a single-stage centrifugal compressor and turbine, a single CAN combustor, and a counterflow heat exchanger. With the dimensions of 825 (L) × 420 (W) × 455 (H) mm and a weight of 67 kg, its size and weight were between one-half and one-third of the conventional diesel engine generators of the same capacity [22].

The CAN combustor and single-stage centrifugal compressor were also used by Ansaldo Energia SpA, the Italian power generation company. They designed two commercial recuperated systems including a 105 kW microturbines (AE-T100B model) (Fig. 5) and 100 kW (AE-T100NG) which

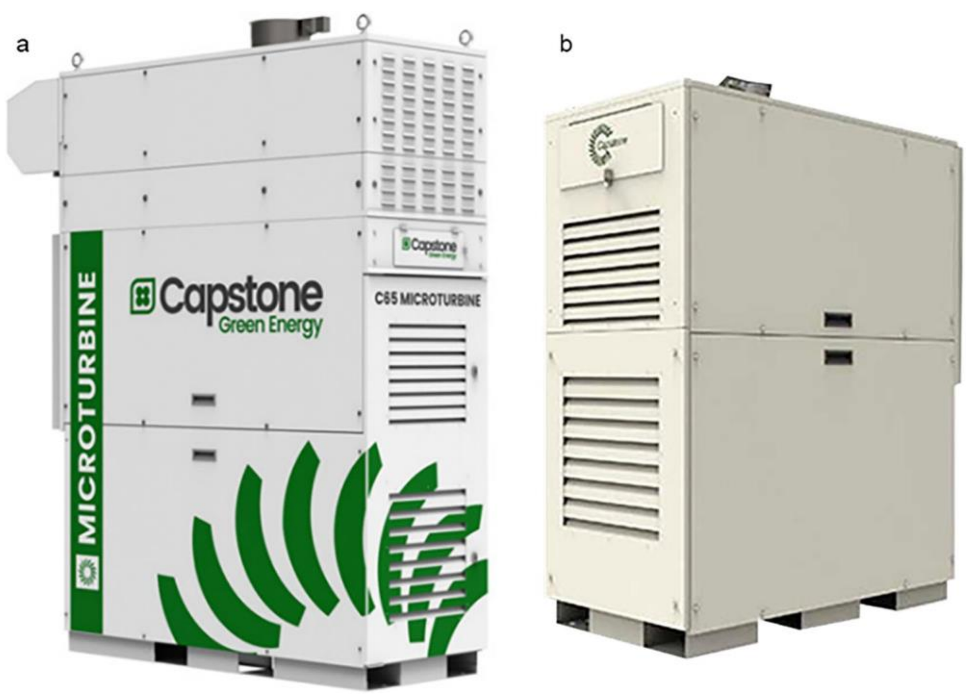


Fig. 3 **a** Capston C65 MGT. **b** Capstone C30 MGT [21]

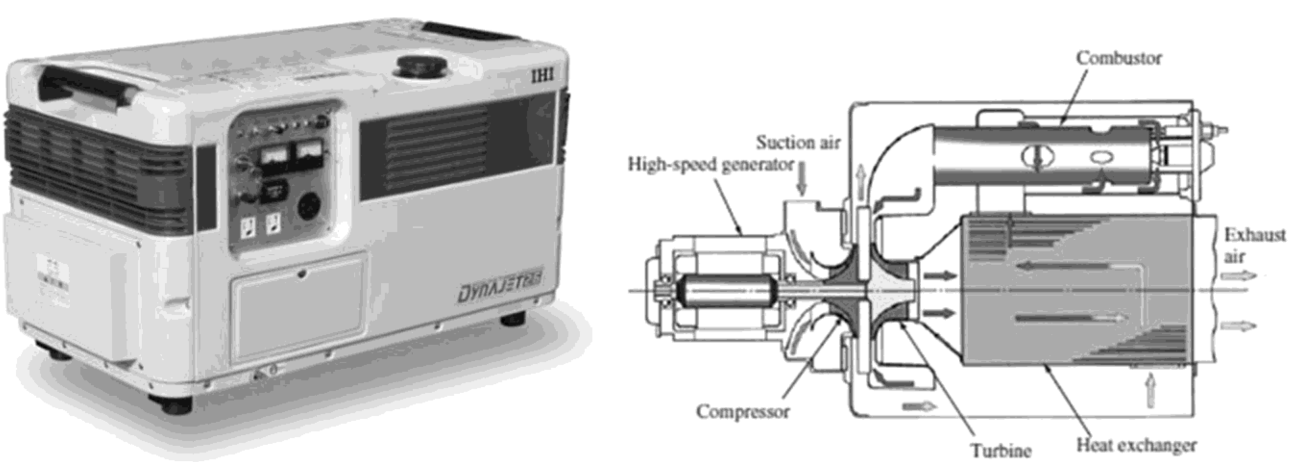


Fig. 4 General view and schematic diagram of Dynajet 2.6 [22]

Fig. 5 Ansaldo Energia SpA T100B model [23]

generate electricity at 400 V (AC). They operate with an efficiency of 30%, with NO_x and CO emissions of less than 15 ppm. The T100B model is designed to operate with biogas, while the T100NG uses natural gas for heat and power generation.

The efforts in developing a heat demand-driven micro-CHP system for domestic applications were followed by Micro Turbine Technology (MTT), located in Eindhoven, Netherlands. They started developing Enertwin MGT in May 2008 and after two phases of field tests in 2013 and 2014, launched the 3 kW micro gas turbine in mid-2015. The system is equipped with a recuperator that recovers heat from the gas turbine exhaust gas, which results in fuel saving and improves the system's electrical efficiency to 12% [24].

Bladon, a UK-based engineering company, expanded the application of MGTs to the telecommunication industry and launched its first commercial product, a 12 kW microturbine generator set (genset) called the Bladon MTG12 in October 2018 to power up the telecoms towers globally. The turbine is recuperated and works with various fuel types such as diesel, kerosene or both, and Bladon-approved paraffin. Other manufacturers were Honeywell (Parallon 75), Ingersoll Rand (Powerworks Microturbine MT70), and Bowman Power Systems (Turbogen-35 and Turbogen-80) which abandoned the MGT industry.

Two essential parameters for having a highly efficient MGT are a high turbine inlet temperature (TIT) and an increased effectiveness recuperator. Although the studies show that exhaust heat utilisation in a recuperative system leads to considerably higher efficiency [24, 25], the efficiency of the available MGTs equipped with heat exchangers still does not exceed 30% (Table 1), which explains their low market penetration.

Next to shifting toward more innovative cycles to enhance the performance and flexibility of MGTs [26, 27], improving the efficiency of the components should also be considered. The advantages of emerging manufacturing techniques such as additive manufacturing (AM) open great opportunities to redesign the gas turbine's hot section parts to enhance the systems' electrical and total efficiency.

AM is the method of fabricating complex structures layer by layer directly from a 3D model, as opposed to the subtractive method, in various sizes from micro to macro scale [28]. AM processes can be classified into seven distinct methods including Vat Polymerisation (VP), Material Extrusion (ME), Material Jetting (MJ), Powder Bed Fusion (PBF) [29], Binder Jetting (BJ) [30], Directed Energy Deposition (DED) [31], Cold Spray (CS) [32], and Sheet Lamination (SL) [33] where BJ, DED, CS, and PBF are being used for printing metals. 80% of the metal printing machines commissioned globally are powder-based [34]. Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are the most developed and widely used powder-based technologies. AM's advantages over conventional manufacturing techniques (i.e. subtractive or casting) include design freedom, light-weighting, part simplification, reducing the part storage time, improving the components' durability and efficiency, and a short development cycle for new and improved design. The other benefits of AM techniques are the integration of components (part consolidation) and thin wall thickness which will reduce turbine weight, and size and improve energy loss during operation, which is essential for using the MGT in residential and small commercial buildings [34–42].

To date, many studies reviewed the application of AM in the gas turbine industry focusing on the materials, microstructure, or components [43–50]. Nevertheless, a study of the additively manufactured components of the hot section of MGT, including the combustor and heat exchanger, is still absent. Therefore, this research is conducted to summarise the existing research and industrial parts of MGTs manufactured on PBF systems. In Sect. 2 available PBF systems in the market are introduced, and the additively manufactured parts for industrial gas turbine are discussed. In Sect. 3 AM of the MGT components including combustor (3.1) and heat exchanger (3.2) are presented and compared with conventional parts wherever possible. Finally, In Sect. 4, the inherent limitations of using AM for MGT components and the future opportunities are discussed. Based on the advantages and capabilities of metal AM, integration of the recuperator and combustor of MGT is proposed and the challenges and opportunities toward the development of compact MGT are elaborated.

2 Additive manufacturing of industrial gas turbine components

In 1996, the patent of laser-PBF (LPBF) was filed by Fockele and Schwarze (F&S) and the Fraunhofer Institute of Laser Technology. It was then commercialised by the German company MCP Realizer with Realizer250 machine in 2004 [51]. In the PBF processes, a layer of metal powder is deposited on the bed under partial vacuum or inert gas atmosphere. Then the laser, as an energy source, scans the powder bed and fully melts the metal powder particles layer upon layer according to the 3D model [52]. In the other PBF process the electron beam is used instead of laser. The high-energy electrons emitted by the heated tungsten filament or LaB6 crystal are used as the energy source to melt the metal powder and fabricate the parts additively. In collaboration with the Chalmers University of Technology in Gothenburg, Arcam from Sweden filed a patent on EBM principles and then commercialised the first EBM machine in 1997.

Along with the extensive applications in other industries such as defence [53], aerospace [47, 54], oil and gas [55], healthcare [56, 57], and automotive [58], in the energy sector, the interest in AM also grows [59]. The majority of gas turbine manufacturers have invested in the AM industry to exploit this manufacturing method's capabilities in optimising the current designs and producing new components. In October 2016, general electric (GE) invested $1.5B to acquire AM equipment suppliers Arcam AB of Sweden and concept laser GmbH of Germany [60]. In 2018, Siemens made another investment of £26 m in the expansion of materials solution, a British company specialising in using AM technology for various gas and aviation turbine applications [61]. Furthermore, AM opened new doors to Honeywell [62], MAN Diesel and Turbo [63], Ansaldo Energia [64], Mitsubishi Power [65] and Solar Turbines [66, 67] to develop new turbine components and repair the equipment whilst it is in service.

Research is also being conducted in all aspects of the PBF methods to overcome the challenges like controlling the scanning parameters [40, 41, 68, 69], surface finish [70–73], limited component size, build time, discontinuous production process, process monitoring [74–76] and multi-materials printing [77]. This led to emerging of new technologies and more than 40 manufacturers globally [78]. Table 2 and Table 3 show the main PBF systems in the market where most laser-based systems use continuous wavelength or long-pulsed fibre laser of 100 W to 1.2 kW, and EBM systems are operating with the output power of 3 to 6 kW.

The key characteristic of AM that makes it particularly attractive for a turbine engine is the potential equal or inverse relationship between complexity and cost. Hague et al. [79] suggest the addition of complexity to the design can be carried out at no extra cost. It means complexity can reduce the final cost of the part by decoupling the complexity from the cost of the manufacturing process [80]. Siemens (Munich, Germany) additively manufactured the burner of GT-700/800 to integrate 13 machined parts with 18 welds to 1 consolidated part, which led to a reduction of lead time from 23 to 3 weeks and a 20% reduction in weight (Fig. 6) [81]. Fu et al. [82] reported a 75% reduction in the production cycle of SGT-4000F turbine blades, including validating multiple cooling concepts. They have also used the advantages of AM for other gas turbines components, including redesigned aero-derivative gas turbine transition duct (Fig. 7a) [83] and dry low emission (DLE) pre-mixer for SGT-A05 to mix air and fuel more efficiently and reduce the CO emission (Fig. 7b) [61]. The SGT-750 combustion swirlers [83], SGT-1000F burner head (Fig. 7c) [82], SGT-400 turbine stage one blade (Fig. 7d) [84], SGT5/6-8000H DfAM swirler (Fig. 7e) [85], burner nozzle pilot cone [82] and SGT-9000HL combustion system (Fig. 7f) [86] were designed according to design for AM (DfAM) rules and fabricated on LPBF systems in a shorter manufacturing cycle.

GE processed TiAl powder to build a 40 cm long blade for the GE9X engine on the EBM system and achieved a 50% weight reduction and an expected 40% reduction in fuel consumption [87]. They have also printed 25,000 redesigned fuel nozzles of the GE LEAP aero engine with a 25% weight reduction (Fig. 8) [88].

Sierra turbine, an American company founded in California in 2017, has also used the capabilities of AM to design compact power generation units for unmanned aerial vehicles, both for jet propulsion and hybrid-electric drive-trains. They have developed a thin airfoil and smooth lattice that help the combustor effectively atomise fuel before combustion. Compared to the existing microturbines by consolidating 61 single parts to only 1, a more compact design was achieved, the manufacturing cost was reduced, and the time between overhauls improved by 40 times [89]. MAN Diesel and Turbo exploit the considerable potential of AM to design the vane segments incorporated into their MGT6100 gas turbine and other components like compressor impeller and fuel nozzle [90].

Table 2 Current LPBF systems in the market

Company	Machine model	Laser power (W)	Build volume (L × W × H) (mm)	Layer thickness (µm)	Laser spot size (µm)
3D Systems[5]	DMP factory 500 solution	3 × 500	500 × 500 × 500	N/A	N/A
	DMP flex 350 and 350 dual	(up to)2 × 350	275 × 275 × 420	N/A	N/A
	DMP factory 350 and 350 dual	(up to)2 × 350	275 × 275 × 420	N/A	N/A
	DMP flex 200	200	140 × 140 × 115	N/A	N/A
	DMP flex 100	100	100 × 100 × 90	N/A	N/A
Addup[6]	FormUp 350	(up to)4 × 500	350 × 350 × 350	20–120	N/A
Concept [7]Laser	M2 series 5	(up to)2 × 400/ 1000	245 × 245 × 350	25–120	N/A
	X line 2000R	(up to)2 × 1000	800 × 400 × 500	30–150	100–500
	Mlab 200R	200	100 × 100 × 100	15–30	75
	Mlab R	100	50 × 50 × 80 90 × 90 × 80	15–30	50
DMG Mori[8]	LaserTec 30 dual	(up to)2 × 600/1000	300 × 300 × 350	20–100	50–300
	LaserTec 12	200/400	125 × 125 × 200	20–100	35
	LaserTec 65	2500/3000	735 × 650 × 560	N/A	1.2–3.6
EOS[9]	M400-4	4 × 400	400 × 400 × 400	N/A	100
	M400-4	1000	400 × 400 × 400	N/A	90
	M300	(up to)4 × 400/1000	300 × 300 × 400	40–80	100
	M290	(up to)2 × 400	250 × 250 × 325	20–80	100
	M100	200	Ø100 × 95	N/A	40
Renishaw[10]	RenAM 500Q	4 × 500	250 × 250 × 350	N/A	80
	RenAM 500S	500	250 × 250 × 350	N/A	N/A
	RenAM 500 flex	1/4 × 500	250 × 250 × 350	N/A	N/A
SLM Solutions[11]	NXG XII 600	12 × 1000	600 × 600 × 600	N/A	80–160
	SLM 800	4 × 400/700	500 × 280 × 875	20–90	80–115
	SLM 500	(up to)4 × 400/700	500 × 280 × 365	20–90	80–115
	SLM 280 PS	(up to)2 × 400/700	280 × 280 × 365	20–90	80–115
	SLM 280 2	(up to)2 × 400/700	280 × 280 × 365	20–90	80–115
	SLM 125	400	125 × 125 × 125	20–75	70–100
Trumpf[12]	TruPrint 5000	3 × 500	Ø300 × 400	30–150	100–500
	TruPrint 3000	2 × 500	Ø300 × 400	20–150	80
	TruPrint 2000	2 × 300	Ø200 × 200	20–100	55
	TruPrint 1000	200	Ø98 × 100	10–50	30–55
	TruPrint 1000 green edition	500	Ø97 × 100	10–50	200
Aconity3D[13]	Aconity 2	(up to)4 × 400–1200	Ø400 × 400	10	80
	Aconity MIDI +	(up to)4 × 400–1000	Ø250 × 250	10	80
	Aconity MIDI	(up to)2 × 400–1000	Ø170 × 200	10	80
	Aconity MINI	200–1000	Ø140 × 150	10	80
	Aconity MICRO	200	Ø100 × 150	5–100	40
Sisma[14]	MYSINT 300	500	Ø300 × 400	30–60	100–500
	MYSINT 200	(up to)2 × 300	Ø200 × 200	20–40	55
	MYSINT100	200	Ø100 × 100	20–40	55
	MYSINT100 RM	200	Ø100 × 100	20–40	55
	MYSINT100 PM	200	Ø100 × 100	20–40	30
	MYSINT100 PM/RM	200	Ø100 × 100	20–40	30
	MYSINT 100 dual laser	2 × 200	Ø100 × 100	20–40	55
	MYSINT100 RM DUAL LASER	2 × 200	Ø100 × 100	20–40	55
Matsuura[15]	LUMEX Avance-25	500/1000	256 × 256 × 300	N/A	N/A
	LUMEX Avance-60	1000	600 × 600 × 500	N/A	N/A

Table 2 (continued)

Company	Machine model	Laser power (W)	Build volume (L × W × H) (mm)	Layer thickness (µm)	Laser spot size (µm)
Velo3D[16]	Saphire/ Saphire 1Mz	2 × 1000	Ø315 × 400/Ø315 × 1000	N/A	N/A
	Saphire XC	8 × 1000	Ø600 × 550	N/A	N/A
Aurora Lab[17]	RMP-1	4 × 1500		N/A	N/A
	S-Titanium Pro			N/A	N/A
Sharebot[18]	MetalONE	250	65 × 65 × 100	5–200	45
Xact Metal[19]	XM300C	2–4 × 100/200	254 × 330 × 330	N/A	min. 20
	XM200C	100/200	127 × 127 × 127	20–100	min. 20
	XM200G	100/200/400	150 × 150 × 150	20–100	50/100
	XM200G2	2 × 100/200/400	150 × 150 × 150	20–100	50/100
Farsoon[20]	FS721M	2/4 × 500	720 × 420 × 420	20–100	70–200
	FS421M	(up to)2 × 500	425 × 425 × 420	20–100	70–200
	FS301M	(up to)2 × 500	305 × 305 × 400	20–100	75–200
	FS273M	(up to)2 × 500	275 × 275 × 355	20–100	80–200
	FS121M	200	120 × 120 × 100	20–80	40–100

[5] https://www.3dsystems.com/3d-printers/metal

[6] https://addupsolutions.com/machines/pbf/formup-350/

[7] https://www.ge.com/additive/additive-manufacturing/machines/m2series5

[8] https://uk.dmgmori.com/products/machines/additive-manufacturing

[9] https://www.eos.info/en/industrial-3d-printing/additive-manufacturing-how-it-works/dmls-metal-3d-printing

[10] https://www.renishaw.com/en/--32084

[11] https://www.slm-solutions.com/products-and-solutions/machines/

[12] https://www.trumpf.com/en_GB/products/machines-systems/additive-production-systems/

[13] https://aconity3d.com/machines

[14] https://www.sisma.com/en/professional-3d-printers/lmf-fashion/

[15] https://www.matsuura.co.uk/additive-manufacturing/

[16] https://velo3d.com/products/

[17] https://www.auroralabs3d.com/

[18] https://www.sharebot.it/en/sharebot-metalone-dmls/

[19] https://xactmetal.com/

[20] http://en.farsoon.com/main.html

3 Additive manufacturing of micro gas turbine components

3.1 Combustor

The primary objective of designing a combustion chamber in developing a MGT system is to achieve smooth and reliable ignition, wide flame stability limit, and reduce fuel consumption which reduces greenhouse gas emissions and improves system efficiency [91, 92]. The small size of MGT combustion chambers, their complexity, and the range of required materials limit the significant improvements based on conventional manufacturing techniques [46]. AM is a suitable manufacturing method to overcome these limitations by offering freedom of design of the combustor parts and combustor chamber to fit the size of the engine and multiple components consolidation reducing the production tooling cost and lead time.

Giuliani et al. [93] printed a new swirls design on Farsoon FS121M machine using In718 powder. They found the as-built surface finish of the 3D-printed part an inherent risk that can cause pressure loss if the air is not pure or if the flow contains a reactive mixture. In this study, S-shaped swirls showed a better performance than the X-shaped with lower pressure loss (Fig. 9). This study was followed by Moosbrugger et al. [94] which exploited the design freedom of AM to combine an advanced liquid fuel injection with a monolithic premixed burner (mixing air and fuel before injection) for low-emission combustion. They presented a new method of a fuel ramp disconnected from the burner in the first approach, which combines the injection and pre-heating of the fuel. The results showed a fidelity problem in

Table 3 Current electron beam melting systems in the market

Manufacturer	Country	Machine model	Electron beam power (kW)	Build volume (L × W × H) (mm)
Jeol[21]	Japan	JAM-5200EBM	6	Ø250 × 400
Wyland Additive[22]	UK	Calibur3	5	300 × 300 × 450/450 × 450 × 450
Freemelt[23]	Sweden	ONE	6	Ø100 × 100
Arcam[24]	Sweden	Spectra H	6	Ø250 × 430
		Q10plus	3	200 × 200 × 200
		Spectra L	4.5	Ø350 × 430
		Q20plus	3	Ø350 × 380
		A2X	3	200 × 200 × 380
Qbeam[25]	China	Abeam Aero	3	350 × 350 × 400
		QbeamMed	3	200 × 200 × 240
		QbeamLab200	3	200 × 200 × 240
Sailong Metal[26]	China	S200	3	200 × 200 × 200
		Y150	3	150 × 150 × 180
Tada Electric[27]	Japan	EZ300	6	220 × 220 × 300
		TRAFAM	6	500 × 500 × 600

[21] https://www.jeol.co.jp/en/products/am/JAM-5200EBM.html

[22] https://www.waylandadditive.com/

[23] https://freemelt.com/

[24] https://www.ge.com/additive/additive-manufacturing/machines/ebm-machines/arcam-ebm-spectra-h

[25] http://en.qbeam-3d.com/

[26] http://www.slmetal.com/en/index.php?m=Product&a=show&id=6

[27] http://www.tadadenki.jp/english/welding_machines/metal_3d_printer/ez300.html

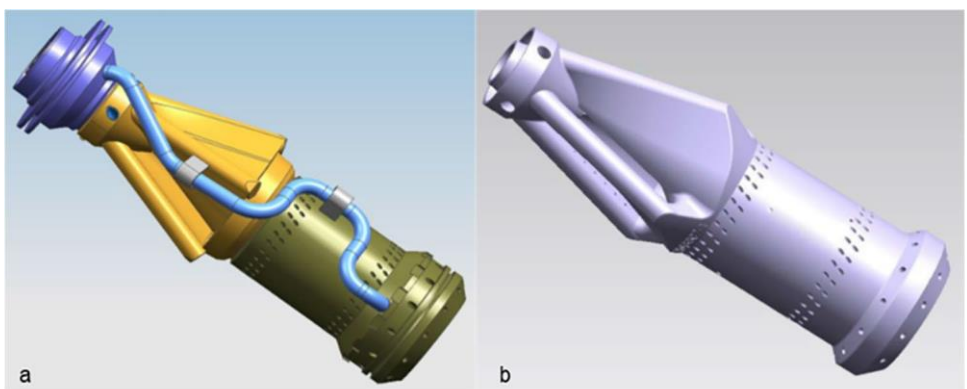


Fig. 6 **a** Traditionally manufactured burner. **b** AM adapted burner [80]

manufacturing when getting down to the injection surface near 0.2 mm^2 but integrating the parts and manufacturing of the burner was successful. Adamou et al. [95] compared an AM injector with two other injectors manufactured using the CNC machining method. The objective was to optimise the injector design to achieve better vaporisation of fuel before injection into the CAN-type combustor of the MGT. It was found that the 3 and 8 holes machined injectors could not produce stable combustion at the desired operating condition of 4 Bar and 630 °C. However, the additively manufactured injector with 8 holes could create more stable combustion at the design point. Umbricht et al. [96] compared two conventional pressure swirl nozzles with the novel AM nozzle and reported a 10% performance improvement at the higher pressure. Runyon et al. [97] investigated the influence of surface roughness on the performance of additively manufactured swirlers of MGT combustors. They tested the swirlers in as build condition and after grit blasting and compared it with the performance of machined swirler. As the surface finish changes, notable differences in flame stability and changes in the near-wall turbulence intensity were observed. The increased NO_x emissions of the machined swirler for the flame temperature above 2000 K highlights one of the advantages of AM for MGT manufacturing, where

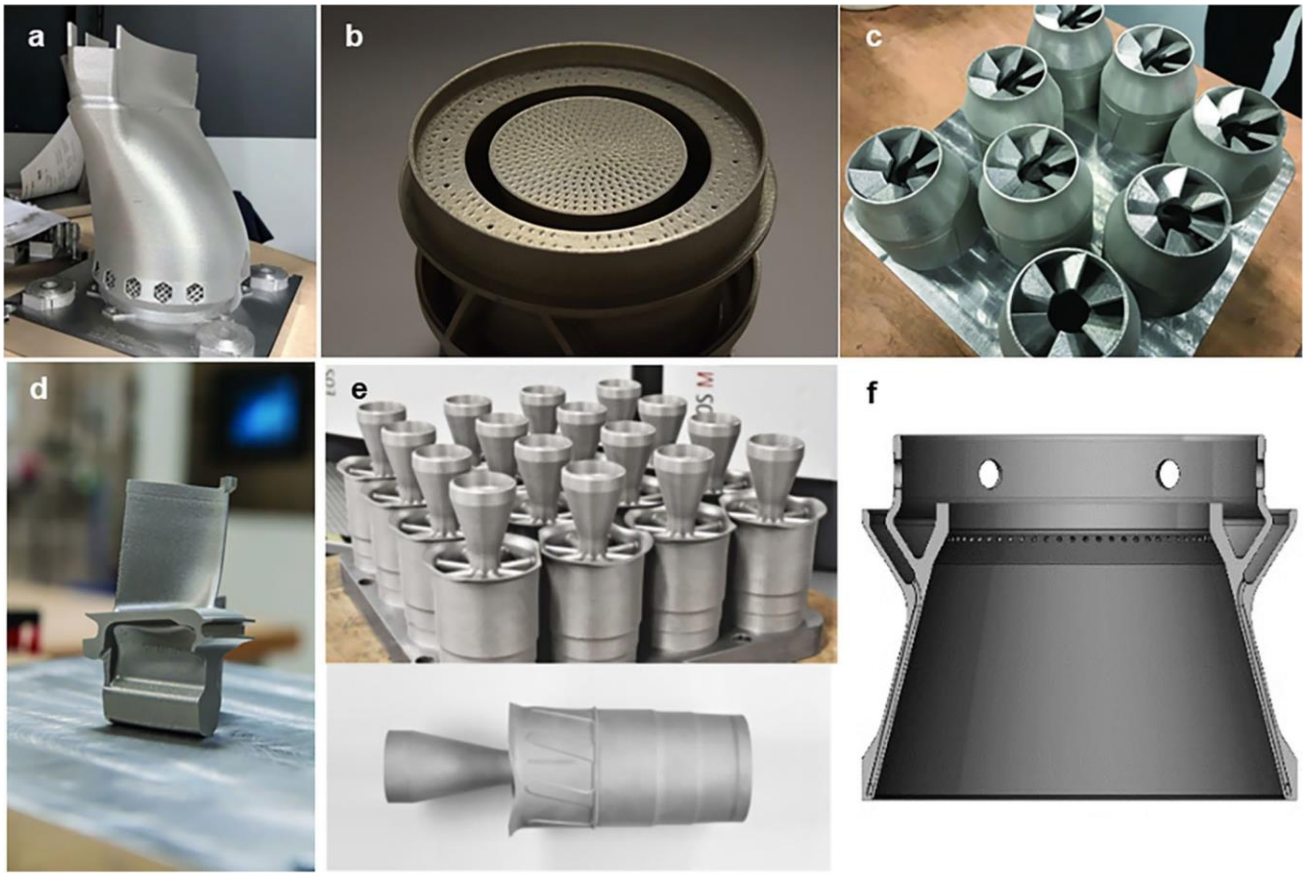


Fig. 7 **a** Aeroderivative GT transition duct [83]. **b** SGT-A05 pre- mixer [61]. **c** SGT-1000F burner head. **d** SGT-400 stage one turbine blade printed using CM247 Nickel-based superalloy [84]. **e** SGT 5/6-8000H swirler and burners printed in an array of sixteen parts on a LPBF machine [85], SGT-9000HL combustion system [86]

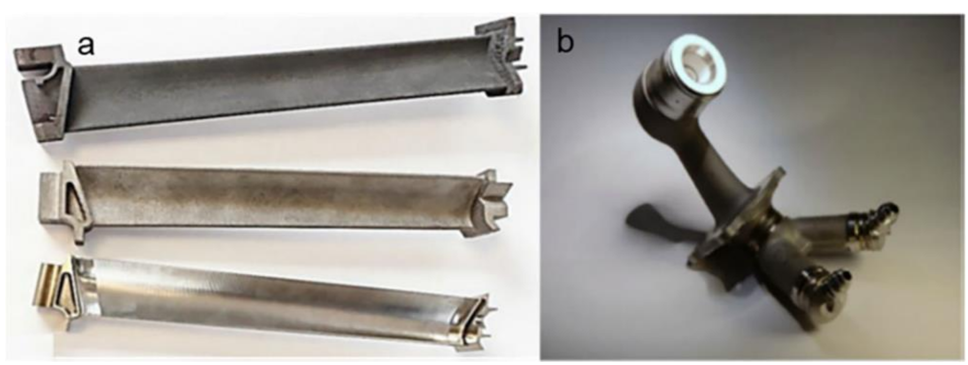


Fig. 8 **a** GE9X blade EBMed with TiAl [87]. **b** Laser melted GE LEAP fuel nozzle [88]

artificial roughness can apply to the surface, to improve the NO_x emission of the combustor due to the residence time effects.

Sotov et al. [98] investigated the short-term strength of laser-melted In738 cylindrical samples at room temperature, and 900 °C to be used for manufacturing of nozzle guide vane. They also studied the effects of hot isostatic press- ing (HIP), and heat treatment on the microstructural and mechanical properties of the samples. They found that for both as build and heat-treated samples, the tensile strength and plastic properties increased by increasing the sloping angle from 0 to 90°, despite the increase in the number of layers. This is because the net-shape tensile test specimens need more support at the gauge length for the horizontal samples and it has an adverse effect on the mechanical properties. In a collaborative project with HiETA technologies,

Fig. 9 Swirler modules of additively manufactured In718 [93]

the University of Bath's Institute of Advanced Automo- tive Propulsion Systems (IAAPS) used a validated reacting computational fluid dynamics (CFD) model to design and additively manufacture a novel conical radial swirl stabi- lised tubular combustor with internal vane fuel injection on Renishaw 500Q LPBF system using In625 nickel-based superalloy (Fig. 10a). The CFD simulation presented an immediate 20% increase in air and fuel mixing quality using the new upstream fuelling design and the three-row lattice downstream of the fuel injector to create turbulence and encourage better mixing. They used the capabilities of AM to design the curved fin surface to increase the cool- ing surface area and precondition the flow to achieve bet- ter alignment at the inlet of the swirler. The experimental results showed a 49–75% reduction in NO_x and 22–40% in CO emissions compared to the flat swirler made by the con- ventional manufacturing method. Adamou and Copeland [100] tested two AM liner cooling geometries with offset strip fin and curved fin (Fig. 10b) for a 10 kW MGT and reported a successful reduction of combustor liner wall temperature with minimum pressure loss. Most recently, they have recommended using AM advantages to design an increased efficiency combustor with a combination of the curved fin upstream liner and AM radial swirler (Fig. 10c) for different operation conditions with minimum modi- fications required. In their study, the effect of combustor

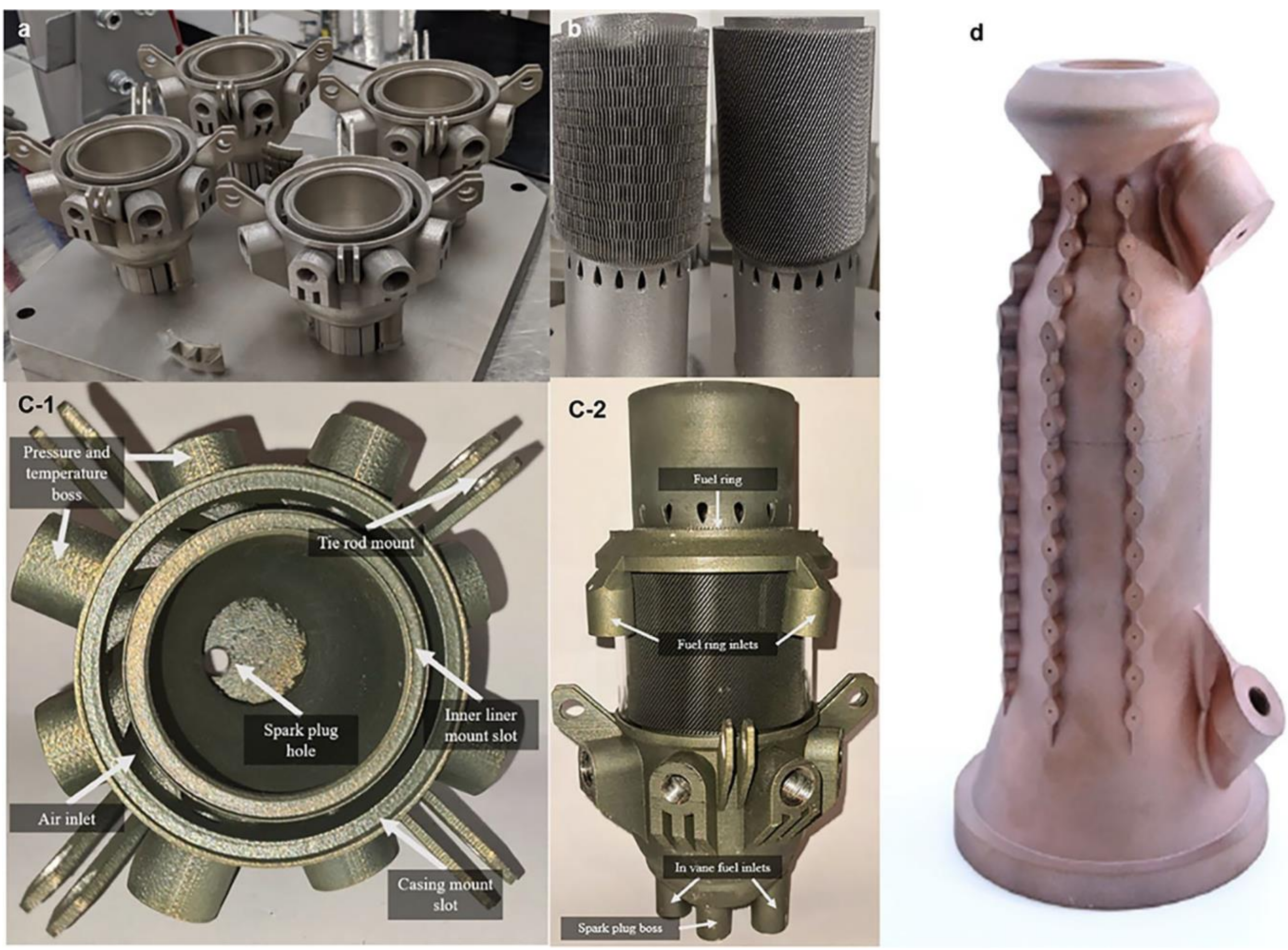


Fig. 10 **a** As printed swirler [99]. **b** Printed backside cooled combustor [100]. **c-1** AM radial swirler printed using In625. **c-2** In625 combustor assembly [101]. **d** CuCrZr combustion chamber after printing liner [102] design modification on emission and system efficiency is investigated [101]. The use of AM for combustion chambers is not limited to the gas turbine industry. Research has also been conducted on developing combustion chambers for rocket engines. As part of the UKSA Pathfinder funded programme, Waugh et al. manufactured two rocket combustors on the Renishaw 500Q machine with In718 and the recently developed ABD-900AM alloy [103] and a copper alloy (CuCrZr) [102] (Fig. 10d).

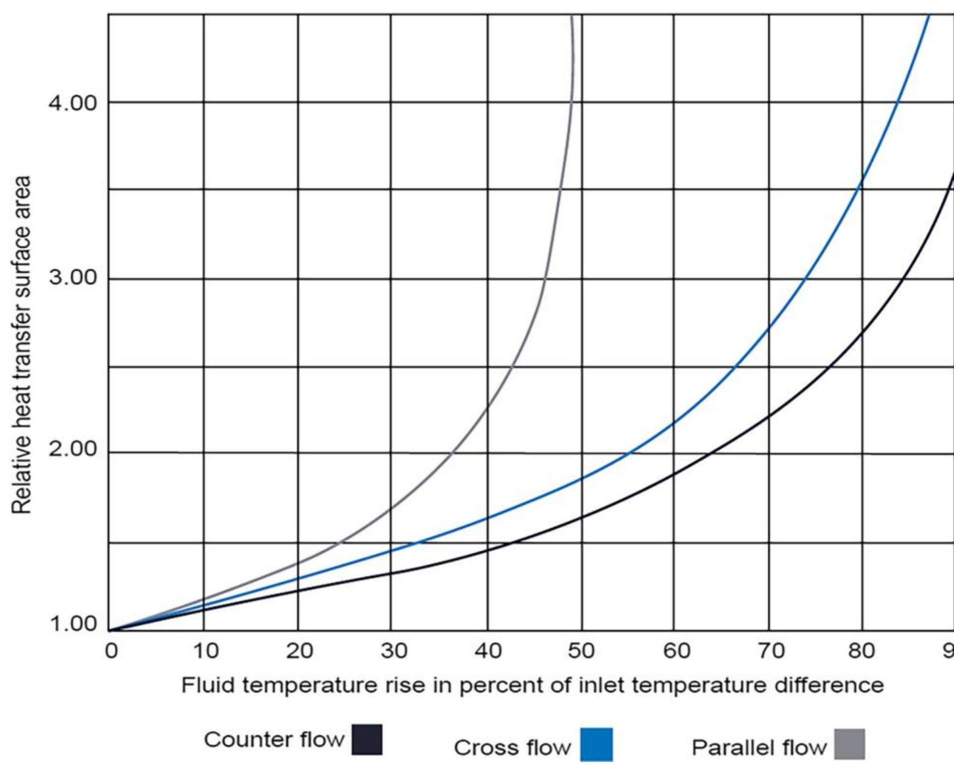
3.2 Heat exchanger

MGTs offer the advantages of compact size, fuel flexibility, high reliability, low emissions, and relatively low noise. However, their low electrical efficiency and high cost are the main challenges that need to be addressed for widespread utilisation and to improve competitiveness in the market. Adding a heat exchanger to the system, which transfers the turbine exhaust heat to the high-pressure compressed air before entering the combustor, can reduce fuel consumption and improve the electrical and thermal efficiency of the cycle.

According to the transfer process classification, there are two types of heat exchanger. The first is direct heat transfer, where the heat transfer in the heat exchanger takes place through the separating wall, and the fluids do not mix or leak. This type of heat exchanger is called a "recuperator". The second type is indirect heat transfer, where heat exchange is between fluids via thermal energy storage and released through the exchanger surface or matrix. This type of heat exchanger is called a "regenerator". A typical MGT system mainly uses a "recuperator" to transfer the heat of the exhaust gas to the compressed air. Based on the flow path configurations, heat exchangers are classified as counterflow/countercurrent, parallel flow, or concurrent and cross-flow. In the counterflow pattern, the fluids flow in opposite directions. In the parallel flow, the fluids enter the heat exchanger together from one side and exit together on the other side. One fluid passes through the heat exchanger core in the cross-flow, perpendicular to the other fluid. The main difference between these configurations is the required heat transfer surface area to transfer heat from the hot to the cold fluid. As shown in Fig. 11 counterflow pattern is the only type in which the temperature change in one or both fluids is close to the entering temperature; therefore, it needs the least surface area [104].

According to construction, heat exchangers are classified into tubular, primary surface, and plate-fin. The commonly used tubular heat exchanger design is called Shell and Tube, which is made of a series of parallel tubes surrounded by a cylindrical shell [104]. They can operate with a wide range of operating pressures and temperatures, and their superiority over the other types is reliability, relatively low cost, and ease of design and manufacturing. Still, they are typically large and bulky and not suitable for MGTs. The primary surface heat exchangers consist of parallel welded, brazed, or bolted plates

Fig. 11 Adopted from [104]; temperature change as a function of surface area for different flow patterns



to separate hot and cold fluids. The plates are either smooth or have a pattern of corrugation and have been designed for the MGT in three configurations; cross-corrugated (chevron pattern) [105, 106], corrugated-undulated, and cross-wavy [107] (Fig. 12). Plate-Fin heat exchangers are made by separating the plates by using louvred [108] or offset strip fins [109] which improves the compactness and efficiency of the system [104]. The compactness of a recuperator is characterised by the ratio of heat transfer area to the unit volume of the heat exchanger, called surface area density. The term micro heat exchanger is used if the surface area density of a gas–gas recuperator exceeds 700 m^2/m^3. Figure 13 shows the heat transfer surface area density spectrum of exchanger surfaces [110]. An efficient compact recuperator for MGTs requires thermal effectiveness (heat transfer performance) of over 90%, a pressure ratio below 3% and high-temperature resistance to creep and oxidation at high temperatures [19].

Also, as the cost of a recuperator in an MGT comprises 25–30% of the system's total cost [112], the production of a low cost, low volume and highly efficient recuperator is required to enter the market of decentralised power plants for households. AM has gained popularity in heat exchanger design and development as they provide freedom to test new and compact designs for heat exchangers that are not manufacturable with other methods. Klein et al. [113] presented a review of additively manufactured heat exchangers using LPBF processes as the most common method of production and studied various AM methods such as fused deposition modelling (FDM) and lithography-based ceramic manufacturing (LCM) for the production of polymer and ceramic heat exchangers. Zhang et al. [114] reviewed the additively manufactured components with internal fluid channels including heat exchangers and conformal cool- ing channels and highlighted the enhanced heat transfer

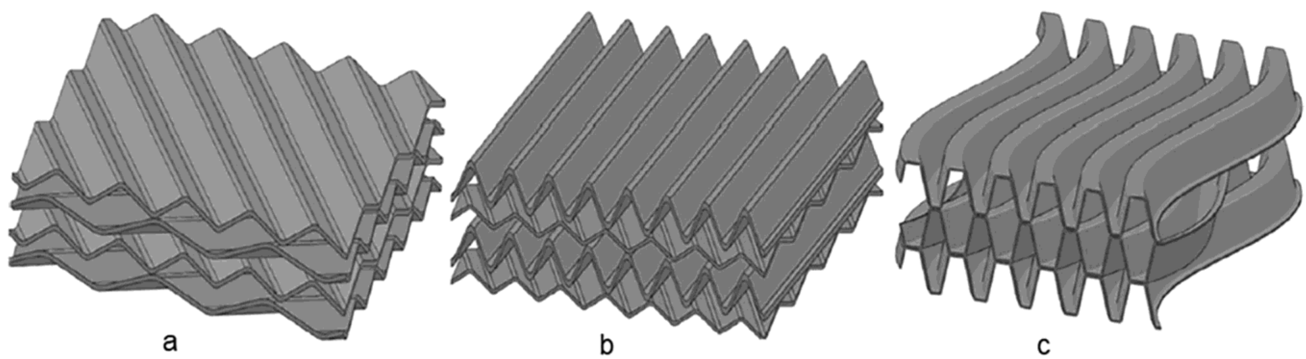


Fig. 12 **a** cross-corrugated (CC), **b** corrugated-undulated (CU), **c** cross-wavy (CW) [19]

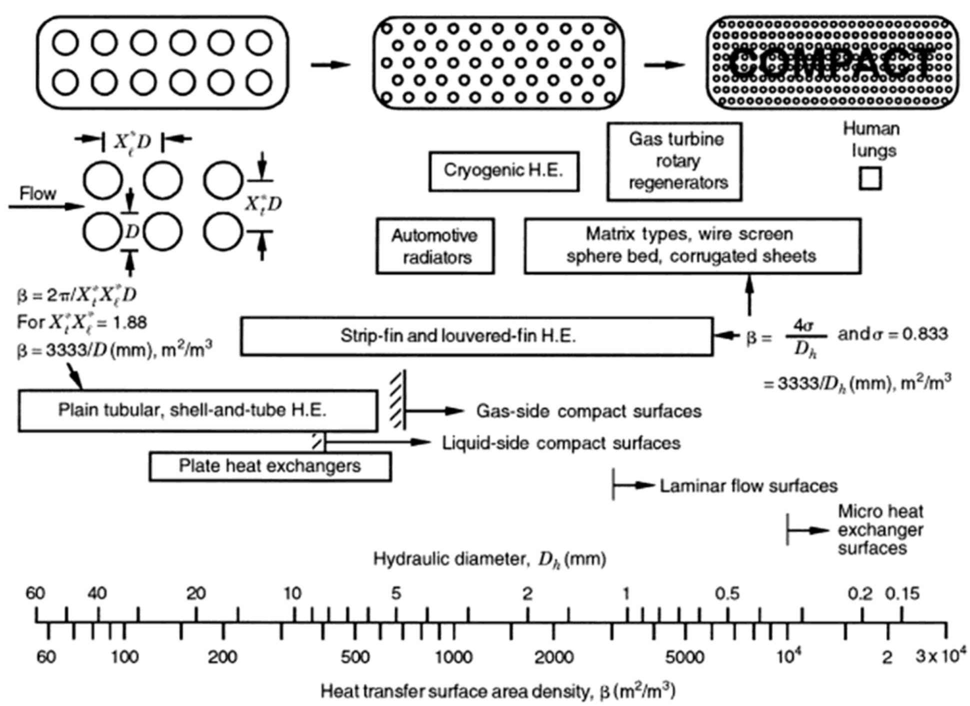


Fig. 13 Heat transfer surface area density spectrum of exchanger surfaces [111]

and cooling efficiency of the AM heat exchangers with new channel design. Niknam et al. [115] reviewed the AM of heat exchangers in terms of design, fabrication, and materials and reported the challenges and opportunities in heat exchangers' design and fabrication methods, including PBF and CS methods. Paraye et al. [116] focused on the benefits of AM in the context of heat transfer of heat exchangers and briefly discussed surface roughness, powder removal and wall thickness as the main challenging areas.

AM is used to optimise the design and enhance the performance of the heat exchangers in various applications. The use of AM in MGT recuperator manufacturing is limited by the difficulties of printing micro-internal channels, which are discussed in more detail in Sect. 4.

Zhang et al. [117] demonstrated a manifold-microchannel heat exchanger with a core size of 67 mm × 74 mm × 27 mm manufactured on an LPBF system using Inconel 718 superalloy for high-temperature gas–gas recuperators. The initial design [118] of the vertical fins and vertical manifolds on both hot and cold sides was modified to avoid overhangs and failure of the unsupported structure. The design of hot side fins and cold side manifold walls was optimised to be printed at an inclined angle of 45° (Fig. 14). In the experimental setup, the hot temperature (600 °C) nitrogen gas was used on the hot side to heat the air with a temperature of 38 °C on the cold side. The experiment showed a 25% improvement in the heat transfer density and superior overall thermal performance efficiency compared to the selected conventional plate-fin heat exchangers. The wall thickness of 180 µm was achieved for this manifold-microchannel heat exchanger, and despite the fabrication fidelity of 14%, the direct measurement of the internal microchannels is reported as one of the main challenges. The only non-destructive measurement method that can be used for measuring the dimensions of internal features is X-ray computed tomography (CT). CT has short measuring time and higher accuracy comparing to the tactile methods like coordinate measuring machine (CMM). It also has some limitations such as lack of clear standard for X-ray generation options and image settings and high cost which makes direct measurement of the internal channels a challenging task [119].

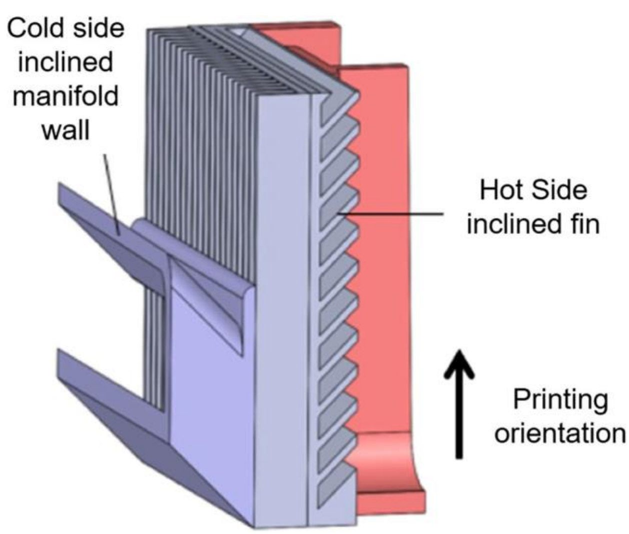


Fig. 14 The hot-side inclined fins and the cold-side inclined manifold wall [117]

As part of the design for additive manufacturing project, Fraunhofer Institute for Machine Tools and Forming Technology IWU manufactured a counterflow recuperator (Fig. 15) using nickel-based superalloy for a feasibility study to improve the efficiency of the MGT system. In this novel design, 18 layers of channels and fins were highly integrated with the inlets and outlets within a limited given space (156 mm × 83 mm × 54 mm). The internal waved shape channels were designed with a thickness of 3 mm to maximise the surface-to-volume ratio and optimise heat exchanger performance. Although there was no data to compare the novel design with the conventional heat exchanger, the measured efficiency of 93% shows the excellent heat transfer performance of the system [120].

Ivanov [121] modified an existing design of a MGT recuperator, which was designed by the Lappeenranta University of Technology according to the design for AM rules, and replaced the wavy fold geometry with rectangular corrugated fins. As a result, with almost the same compactness coefficient (surface to volume ratio) and equal heat transfer,

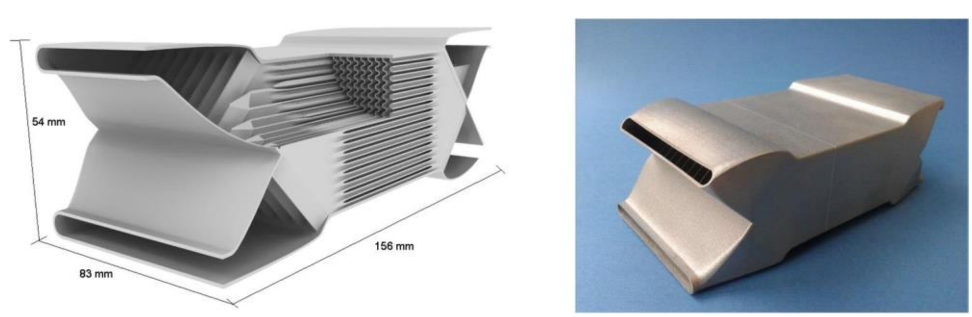


Fig. 15 Counterflow heat exchanger manufactured by the use of AM [120]

the length and weight of the additively manufactured recuperator were reduced by 110% and 139%, respectively.

Hieta Technologies were granted a UK patent [122] on the integrated cylindrical combustion chamber and recuperator with the counterflow arrangement. As the hot gas is typically less dense than the cold gas, the diameter of the hot gas conduits is greater than the cold gas channels. The system also includes the indirect preheating of fuel by absorbing the heat from the body of the heat exchanger before injecting it into the combustion chamber. The heat transfer performance and pressure ratio of the system in the real condition are not reported.

AM technologies facilitating the increase in heat transfer area by incorporating porous channels to the heat exchanger to reduce the size and improve efficiency; however, there are challenges and difficulties in manufacturing integrated combustor and recuperator for the MGT, which is discussed in the next section. Figure 16 shows the applications of AM in manufacturing MGT combustor and recuperator to date.

4 Challenges and opportunities

MGTs are set to play a prominent role in the future of decentralised power generation for residential and small commercial buildings. As discussed in Sect. 1.1, increasing the TIT and improving the efficiency of the recuperator are the main methods to enhance the electrical and total efficiency of the system. Galanti [123] highlighted that incorporating a recuperator into a MGT might improve efficiency; however, it increases the number of parts, complexity and capital cost of the unit. McDonald [124] introduced a material cost factor to consider the influence of using high-temperature alloys on the product's final price. For instance, increasing the TIT to over 900 °C requires using high-temperature alloys such as nickel-based superalloys or stainless steel 347 at the hot side of the recuperator to withstand the high temperature of the turbine exhaust. Recent studies [125] also show that in AM, the type of material significantly affects the manufacturing time and cost. The higher price of high-temperature alloys causes an increase in the price of the recuperator, the MGT, and the generated electricity.

Furthermore, as the traditional design of the recuperators cannot achieve high heat transfer efficiency, in this regard, using the capabilities of AM to optimise the design to reduce the size and improve the efficiency of a MGT is essential. The AM technique is paving the way for the production of MGTs with a small footprint and compact volume. This technique's potential for functional integration provides the opportunity to integrate the heat exchanger and combustor into one single component to reduce the number of parts, simplify the unit's structure, remove the assembly time, and reduce the materials required which results in decreasing the cost of the production of an MGT system. Also, some studies [126–128] show that part integration without compromising functionality leads to more sustainable production with less carbon footprint.

Despite the advantages of part consolidation, reducing the size of the whole system might increase the heat transfer between the hot section, including the combustor, recuperator and turbine, and the compressor as the cold section. This can have an adverse effect on the efficiency of the system.

The ability of AM to make 3D structures with novel geometries and internal complexities opens new doors, especially in the field of heat transfer, to build heat exchangers with lattice structure cores [129]. According to Gibson and Ashby [130], the lattice structure is a 2D or 3D component formed by an array of spatial periodic unit cells with edges and faces linked to a cellular solid. Lattice structures show superior mechanical properties e.g. high specific stiffness and strength, making them attractive for light-weighting applications. They also offer high heat transfer rate due to

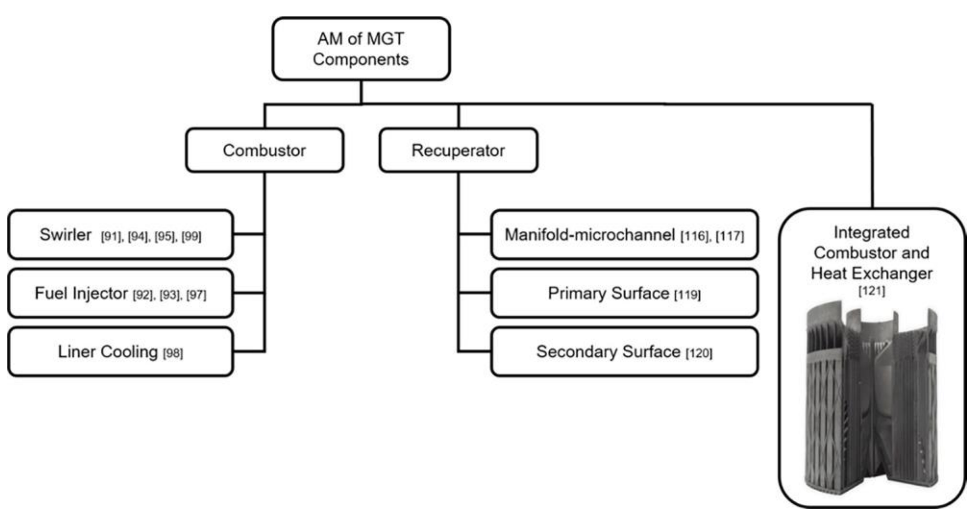


Fig. 16 The application of AM in the MGT component

the extended surface area. Researchers have extensively reviewed the mechanical properties [131] and the viability of these structures for heat exchanger applications [132]. A relatively new class of mathematically defined lattice structures known as triply periodic minimal surface (TPMS) exhibits minimum possible surface area and zero mean curvature within a specific volume [133], which leads to increased heat transfer [134] and high surface to volume ratio. Also, the zero mean curvature at each point in the TPMS structure provides the free movement of the fluid in any direction, which can reduce the hydrodynamic resistance and reduce the pressure drop consequently [135]. Some common TPMS structures are Gyroid, Schwarz Diamond, Schwarz Primitive, and SplitP where the given volume is divided into two regions that are identical in form but separated to avoid the mixture of fluids (Fig. 17).

The TPMS structure's thermal conductivity and heat transfer performance in the recuperator's design process depends on the sample's porosity, controlled by wall thickness and the unit cell size. An optimised value of these parameters defines the structure's optimum porosity and surface area and potentially enhances the heat transfer properties. Using the lattice structure results in reduced materials consumption, improvement in the compactness factor of the recuperator, and the cost of the final product. How- ever, the role of inherent defects of additively manufactured small parts with thin cross-sections on the heat dissipation and pressure drop needs a thorough investigation to the widespread use of this manufacturing technique for MGT components.

The major existing challenge that needs to be addressed for manufacturing heat exchangers with internal microchannels is surface roughness. The rough surface finish has a measurable adverse effect on the flow, friction coefficient, and pressure drop [136]. However, higher surface roughness leads to transition to turbulence flow by disturbing the boundary layers [137] and increases the surface area which improves the heat transfer rate [133, 134]. Kirsch et al. [138] reported good heat transfer performance and an acceptable pressure loss for additively manufactured wavy microchannels with a long wavelength. However, increasing the efficiency without sacrificing the fluid flow rate is challenging for the MGT recuperator.

In the laser melting method, the laser parameters including hatch distance, scanning speed, and laser power are optimised to achieve penetration of laser power for partial remelting of the previous layer and provide bonding between layers. The applied power semi sinters the powder particles adjacent to the metal melt pool. As a result of the rapid solidification and the interaction between laser power, the melt pool, and the powder bed the affected powder particles in the heat affected zone (HAZ) adhere to the outer layer of the printed part and deteriorate the surface finish. The balling effect which forms discontinued tracks, and unstable melt flow are the other laser-related reasons for the poor surface finish of AM parts in as-printed conditions [136, 137].

The other limitation of laser melting of metal powder is printing the downward-facing or overhang which is not printed on the solid metal but on the loose powder. Applying excess energy causes the melting of the metal powder, induces porosity, and delamination between layers and results in poor surface quality and deviation from the nominal dimensions. It is challenging to print the parts with interior features like the wavy/curved internal chan- nels of the recuperator [139], fuel injector, and swirler of the MGT, where the support structure and post surface treatment are not possible. Moving from conventional manufacturing of MGT parts to AM necessitates a deep understanding of the design requirements for MGT compo- nents and the AM constraints for effectively incorporating this novel material processing technique into MGT manu- facturing. Moreover, the material selection is expanding

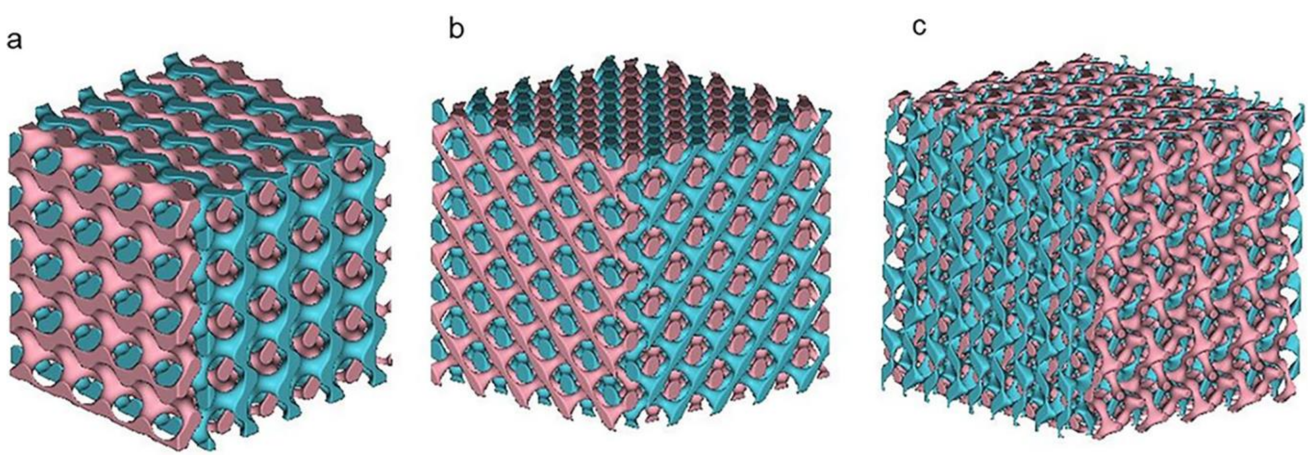


Fig. 17 TPMS structures: **a** Gyroid, **b** Schwarz diamond, **c** SplitP

and new high-temperature alloys including nickel-based superalloys such as ABD900 and intermetallic alloys like Oxide Dispersion Strengthening (ODS) [140], are real- ised to be used in gas turbine hot section components. Therefore, research is required to understand the effects of laser parameters on the fluid dynamics and melt pool behaviour to overcome this barrier and improve the surface finish of AM integrated combustor and recuperator [141]. Other than new metal alloys, progress has already been achieved in the AM of advanced ceramic materials for heat transfer applications [142]. There are opportunities to explore the potential of ceramics such as silicon carbides [143] and titanium aluminides [144] for integrated MGT components. Because of the very high melting point, low ductility, high brittleness and poor thermal shock resistance processing od ceramics in a molten liquid form is extremely challenging [145]. On the other hand, ceramic matrix composite (CMC) materials with advanced thermo structural performance and higher thermal shock resist- ance show potential to be used in the hot section of the next generation of MGT combustors. To improve the effi- ciency of the combustor and exploit the advantages of inte- gration with a recuperator, the heat loss through the wall of the combustor must be minimised, which is opposed to the recuperator core, where high heat conductivity is required. For instance, in the core of the counterflow recuperator, the high-temperature alloy is required for the hot side of the recuperator where the turbine exhaust gas enters, and the heated compressed air leaves the recuperator to enter the combustor. While at the exhaust of the recuperator, where the compressed air enter, alloys with higher thermal conductivity are needed.

The recent advancements in the LPBF process allows designers and engineers to process multi-materials in one build where distributed functional properties such as high temperature and corrosion resistance are required in one area while providing high thermal conductivity and maintaining the production cost and structural properties in other areas [142, 143]. Although this opportunity has yet to be exploited for the hot section of MGTs, it creates the opportunity to improve the efficiency of the system by using high-temperature alloys for combustors to provide thermal isolation. In contrast, cost-effective and high thermal conductive alloys are used for the target regions of the recuperator. The high surface roughness of the laser melting process is an advantage in processing multi-materials because it can increase the contact between two dissimilar materials and strengthen the bonding between the alloys [146]. The considerable difference in the melting points of dissimilar alloys and variation in laser absorptivity will cause metallurgical defects like forming brittle intermetallic phases [147, 148], elemental segregation, phase separation [149, 150], and lack of fusion of the powder particles of the alloy with a higher melting point which has an adverse effect on the mechanical and thermal properties of the parts.

5 Conclusion and future work

The rise in global demand for clean energy and reducing greenhouse gas emissions creates opportunities for research and development in decentralised power generation systems for domestic sectors. Natural gas is still the primary energy source for generating heat and electricity in energy conversion systems, but the efficiency of the current MGT systems developed for residential applications is not acceptable. This is a special motivation to develop new high-efficiency and low-emission MGT in a short time frame, using rapid manufacturing techniques like AM. In this work, an overview of the specification of the existing metal AM systems was carried out, and the state of the art in using AM for the hot section of the gas turbines, including combustor and recuperator, was discussed. Considering AM capabilities, the integration of the combustor and heat exchanger of a MGT is proposed to improve the system's efficiency and reduce the weight and volume of a MGT unit. It was revealed that the key challenges are improving the surface finish and dimensional accuracy of the AM compact recuperator and small scales combustor components like fuel injector and swirler. Comprehensive research is required to understand the metal behaviour in molten status and optimise the laser processing parameters. The ineffective use of AM during MGT component design is another challenge which requires understanding the AM limitations and MGT properties (i.e. heat transfer, pressure drop, and friction factor). Therefore, training the MGT designers to apply the AM design principles and rules is required to fully exploit this manufacturing method's capabilities, like integrating the various components into one single part and increasing the system's compactness. Advances in laser and electron beam powder bed fusion systems provide opportunities to develop new high temperature alloys and ceramics and process multi-materials in a single part which has an obvious benefit for performance improvement of the complex gas turbine system. Also, developing new post-processing methods like electrochemical and Suspension Plasma Spray (SPS) ceramic coating for the internal microchannels can be seen as a choice for future MGT technology.

In conclusion, the AM of MGT components offers great potential for enhancing the cycles' performance, compactness, and market penetration. Further research is necessary to overcome the limitations and use the potential of this manufacturing method to make the technology cost-effective and economically viable. This review is part of an ongoing project where an advanced compact recuperator with low-pressure drop and high heat transfer rate will be designed to integrate with the highly efficient and ultra-low emitting combustor. PBF of a highly conductive, high-temperature corrosion and oxidation-resistant ceramic powder will be evaluated as the fabrication method.

Acknowledgements We thank Daniel Nicklin, PhD researcher at Staffordshire University, for his editing help and insightful comments that have improved this study.

Author contribution Hossein Sheykhpoor: conceptualisation, data collection, analysis, and writing of the first draft.

Hamidreza Gohari Darabkhani: methodology, revision of the first draft, project supervision, and funding acquisition.

Abdul Waheed Awan: review and edit the original manuscript, project co-supervision.

Funding The authors gratefully acknowledge the support received from Staffordshire Advanced Manufacturing, Prototyping, and Innovation Demonstrator (SAMPID) that is part funded through the European Regional Development Fund 2014–2020, project reference No: 32R19P03142.

Data availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not

applicable.

Conflict of interest The authors declare no competing of interests.

References

1. Ki-moon B (2015) Adoption of the Paris agreement. Proposal by the President, Paris
2. Matthews HD, Caldeira K (2008) Stabilizing climate requires near-zero emissions 35:1–5. https://doi.org/10.1029/2007GL032388
3. Syukuro M (2019) Role of greenhouse gas in climate change**. Tellus A Dyn Meteorol Oceanogr 71:1–13. https://doi.org/10.1080/16000870.2019.1620078
4. Cassia R, Nocioni M, Correa-aragunde N, Lamattina L (2018) Climate change and the impact of greenhouse gasses : CO 2 and NO , friends and foes of plant oxidative stress. 9:1–11. https://doi.org/10.3389/fpls.2018.00273
5. Santamouris M (2019) Energy consumption and environmental quality of the building sector. Minimizing Energy Consum Energy Poverty Glob Local Clim Chang Built Environ Innov to Zero 29–64. https://doi.org/10.1016/B978-0-12-811417-9.00002-7
6. Amirkhanian S, Xiao F, Li J (2021) Civil engineering applications. Tire Waste Recycl 297–481. https://doi.org/10.1016/B978-0-12-820685-0.00015-6
7. Morawicki RO, Hager T (2014) Energy and greenhouse gases footprint of food processing. Encycl Agric Food Syst 82–99. https://doi.org/10.1016/B978-0-444-52512-3.00057-7
8. Chua KJ, Chou SK, Yang WM, Yan J (2013) Achieving better energy-efficient air conditioning – a review of technologies and strategies. Appl Energy 104:87–104. https://doi.org/10.1016/j.apenergy.2012.10.037

9. Sourmehi C (2021) Use of electricity in houses to grow more quickly in developing economies - Today in Energy - U.S. Energy Information Administration (EIA). In: US Energy Information Administration. EIA. https://www.eia.gov/todayinenergy/detail.php?id=50256. Accessed 11 Feb 2022
10. Dong Z, Liu J, Liu B, et al (2021) Hourly energy consumption prediction of an office building based on ensemble learning and energy consumption pattern classification. Energy Build 241:110929. https://doi.org/10.1016/J.ENBUILD.2021.110929
11. Ye Y, Zuo W, Wang G (2019) A comprehensive review of energy-related data for U.S. commercial buildings. Energy Build 186:126–137. https://doi.org/10.1016/J.ENBUILD.2019.01.020
12. Perera F (2018). Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity : solutions exist. https://doi.org/10.3390/ijerph15010016
13. SEI, IISD, ODI, et al (2020) The production gap report: 2020 Special Report
14. SEI, IISD, ODI, E3G U (2021) The Production Gap
15. Maghanki MM, Ghobadian B, Najafi G, Galogah RJ (2013) Micro combined heat and power (MCHP) technologies and applications. Renew Sustain Energy Rev 28:510–524. https://doi.org/10.1016/J.RSER.2013.07.053
16. Ren L, Zhu R, Liao L, Zhou Y (2021) Analysis on the development of micro gas turbine generation technology. J Phys Conf Ser 1983:. https://doi.org/10.1088/1742-6596/1983/1/012006
17. Beith R (2011) Small and micro combined heat and power (CHP) systems. Woodhead Publishing
18. Bhatia SC (2014) Cogeneration. Adv Renew Energy Syst 490–508. https://doi.org/10.1016/B978-1-78242-269-3.50019-X
19. Xiao G, Yang T, Liu H et al (2017) Recuperators for micro gas turbines: a review. Appl Energy 197:83–99. https://doi.org/10.1016/j.apenergy.2017.03.095
20. Bohn D (2005) Micro gas turbine and fuel cell – A hybrid energy conversion system with high potential. In: Micro gas turbines: papers presented during the AVT/VKI lecture series held at the von Kármán Institute, Rhode-St-Genèse, Belgium, 14 - 18 May 2004 = Micro turbines à gaz / NATO Research & Technology OrganisationReport number: RTO-EN-AVT-131. NATO Research & Technology Organisation, Rhode-St-Genèse, Belgium
21. C65 :: Capstone Green Energy Corporation (CGRN). https://www.capstonegreenenergy.com/products/energy-generation-technologies/capstone-microturbines/c65. Accessed 30 Mar 2022
22. Hirotaka K (2004) Development of portable gas turbine generator "Dynajet 2.6." IHI Eng Rev 37:113–114
23. Biogas. https://www.ansaldoenergia.com/business-lines/new-units/microturbines/ae-t100b. Accessed 30 Mar 2022
24. Bauwens P (2015) Gas path analysis for the MTT micro turbine. Delft University of Technology
25. Rodgers C (2001) Microturbine cycle options. Turbo Expo Power Land, Sea Air. https://doi.org/10.1115/2001-GT-0552
26. De Paepe W, Carrero MM, Bram S, et al (2018) Toward higher micro gas turbine efficiency and flexibility-humidified micro gas turbines: a review. J Eng Gas Turbines Power 140:. https://doi.org/10.1115/1.4038365
27. Sadeghi E, Khaledi H, Ghofrani MB (2006) Thermodynamic analysis of different configurations for microturbine cycles in simple and cogeneration systems. In: Proceedings of the ASME Turbo Expo: Power for Land, Sea, and Air. Volume 5: Marine; Microturbines and Small Turbomachinery; Oil and Gas Applications; Structures and Dynamics, Parts A and B. Barcelona, Spain, pp 247–255. ASME. https://doi.org/10.1115/GT2006-90237
28. Shamsaei N, Yadollahi A, Bian L, Thompson SM (2015) An overview of direct laser deposition for additive manufacturing; part II: mechanical behavior, process parameter optimization and control. Addit Manuf 8:12–35. https://doi.org/10.1016/j.addma.2015.07.002

29. Ladani L, Sadeghilaridjani M (2021) Review of powder bed fusion additive manufacturing for metals. Metals (Basel) 11:. https://doi.org/10.3390/met11091391
30. Li M, Du W, Elwany A, Pei Z, Ma C (2020) Metal binder jetting additive manufacturing: a literature review. J Manuf Sci Eng 142:090801. https://doi.org/10.1115/1.4047430
31. Thompson SM, Bian L, Shamsaei N, Yadollahi A (2015) An overview of direct laser deposition for additive manufacturing; part I: transport phenomena, modeling and diagnostics. Addit Manuf 8:36–62. https://doi.org/10.1016/j.addma.2015.07.001
32. Yin S, Cavaliere P, Aldwell B et al (2018) Cold spray additive manufacturing and repair: fundamentals and applications. Addit Manuf 21:628–650. https://doi.org/10.1016/j.addma.2018.04.017
33. ISO/TC 261 Additive manufacturing (2021) ISO/ASTM 52900:2021(en), Additive manufacturing — general principles — fundamentals and vocabulary. In: Int. Organ. Stand. https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-2:v1:en. Accessed 1 Mar 2022
34. (2019) SmarTech Analysis Issues Latest Report on Metal Additive. https://www.globenewswire.com/news-release/2019/06/05/1864873/0/en/SmarTech-Analysis-Issues-Latest-Report-on-Metal-Additive-Manufacturing-Market.html. Accessed 1 Mar 2022
35. Ngo TD, Kashani A, Imbalzano G et al (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos Part B Eng 143:172–196. https://doi.org/10.1016/J.COMPOSITESB.2018.02.012
36. Gao W, Zhang Y, Ramanujan D et al (2015) The status, challenges, and future of additive manufacturing in engineering. Comput Des 69:65–89. https://doi.org/10.1016/J.CAD.2015.04.001
37. Simpson J, Haley J, Cramer C et al (2019) Considerations for application of additive manufacturing to nuclear reactor core components. www.osti.gov. Accessed 6 Nov 2021
38. Frazier WE (2014) (2014) Metal additive manufacturing: a review. J Mater Eng Perform 236(23):1917–1928. https://doi.org/10.1007/S11665-014-0958-Z
39. Herzog D, Seyda V, Wycisk E, Emmelmann C (2016) Additive manufacturing of metals. Acta Mater 117:371–392. https://doi.org/10.1016/J.ACTAMAT.2016.07.019
40. Wimpenny DI, Pandey PM, Jyothish Kumar L (2016) Advances in 3D printing & additive manufacturing technologies. Springer, Singapore. https:// doi. org/ 10. 1007/ 978-981-10-0812-2
41. Dutta B, Babu S, Jared B (2019) Science, technology and applications of metal in additive manufacturing. Elsevier. https://doi.org/10.1016/C2017-0-04707-9
42. Milewski JO (2017) Additive manufacturing of metals. 258:. https://doi.org/10.1007/978-3-319-58205-4
43. Srinivasan D, Ananth K (2022) Recent advances in alloy development for metal additive manufacturing in gas turbine/aerospace applications: a review. J Indian Inst Sci 2022:1–39. https://doi.org/10.1007/S41745-022-00290-4
44. Tshephe TS, Akinwamide SO, Olevsky E, Olubambi PA (2022) Additive manufacturing of titanium-based alloys- a review of methods, properties, challenges, and prospects. Heliyon 8:e09041. https://doi.org/10.1016/j.heliyon.2022.e09041
45. Li Y, Liang X, Yu Y et al (2022) Review on additive manufacturing of single-crystal nickel-based superalloys. Chinese J Mech Eng Addit Manuf Front 1:100019. https://doi.org/10.1016/j.cjmeam.2022.100019
46. Runyon J, Psomoglou I, Kahraman R, Jones A (2021) Additive manufacture and the gas turbine combustor: challenges and opportunities to enable low-carbon fuel flexibility. Paper presented at 10th International Gas Turbine Conference: Gas Turbines in a Carbon-Neutral Society, Brussels, Belgium, 11–15 October 2021
47. Liu R, Wang Z, Sparks T, et al (2017) Aerospace applications of laser additive manufacturing. Laser Addit Manuf Mater Des Technol Appl 351–371. https://doi.org/10.1016/B978-0-08-100433-3.00013-0
48. Tan C, Weng F, Sui S et al (2021) Progress and perspectives in laser additive manufacturing of key aeroengine materials. Int J Mach Tools Manuf 170:103804. https://doi.org/10.1016/j.ijmachtools.2021.103804
49. Prashar G, Vasudev H (2021) A comprehensive review on sustainable cold spray additive manufacturing: state of the art, challenges and future challenges. J Clean Prod 310:127606. https://doi.org/10.1016/j.jclepro.2021.127606
50. Gibson I, Rosen DW, Stucker B (2010) Development of additive manufacturing technology. Addit Manuf Technol 36–58. https://doi.org/10.1007/978-1-4419-1120-9_2
51. Thomas D (2009) The development of design rules for selective laser melting. Thesis, Cardiff Metropolitan University. https://doi.org/10.25401/cardiffmet.20974597.v1
52. Kaserer L, Bergmueller S, Braun J, Leichtfried G (2020) Vacuum laser powder bed fusion—track consolidation, powder denudation, and future potential. Int J Adv Manuf Technol 110:3339–3346. https://doi.org/10.1007/s00170-020-06071-6
53. Panneerselvam P (2018) Additive manufacturing in aerospace and defence sector. Def Stud 12:39–60. https://doi.org/10.1007/978-1-349-95321-9_151
54. Mohd Yusuf S, Cutler S, Gao N (2019) Review: the impact of metal additive manufacturing on the aerospace industry. Metals 9(12):1286. https://doi.org/10.3390/met9121286
55. Sireesha M, Lee J, Kranthi Kiran AS et al (2018) A review on additive manufacturing and its way into the oil and gas industry. RSC Adv 8:22460–22468. https://doi.org/10.1039/c8ra03194k
56. Calignano F, Galati M, Iuliano L, Minetola P (2019) Design of additively manufactured structures for biomedical applications: a review of the additive manufacturing processes applied to the biomedical sector. J Healthc Eng. https://doi.org/10.1155/2019/9748212
57. Adugna YW, Akessa AD, Lemu HG (2021) Overview study on challenges of additive manufacturing for a healthcare application. IOP Conf Ser Mater Sci Eng 1201:012041. https://doi.org/10.1088/1757-899x/1201/1/012041
58. Charles A, Hofer A, Elkaseer A, Scholz SG (2022) Additive manufacturing in the automotive industry and the potential for driving the green and electric transition. Smart Innov Syst Technol (SIST) 262:339–346. https://doi.org/10.1007/978-981-16-6128-0_32
59. Sun C, Wang Y, McMurtrey MD, et al (2021) Additive manufacturing for energy: a review. Appl Energy 282:. https://doi.org/10.1016/j.apenergy.2020.116041
60. GE Press Release (2016) Aquisition of Concept Laser | GE Additive. https://www.ge.com/additive/press-releases/ge-makes-significant-progress-investments-additive-equipment-companies. Accessed 22 Mar 2022
61. (2018) Siemens achieves breakthrough with 3D-printed combustion component for SGT-A05 | Press | Company | Siemens. In: Siemense AG. https://press.siemens.com/global/en/feature/siemens-achieves-breakthrough-3d-printed-combustion-component-sgt-a05. Accessed 3 Mar 2022
62. Godfrey D, Morristown N, Morris MC et al (2014) Gas turbine engine components and methods for their manufacture using additive manufacturing techniques. https://register.epo.org/application?number=EP13197834
63. MAN News (2017) MAN Diesel & Turbo: 3D printing becomes a standard. https://brazil.man-es.com/home/news-details/2017/04/

19/man-diesel-turbo-3d-printing-becomes-a-standard. Accessed 22 Mar 2022
64. Stytsenko A, Mylnikov S, Baibuzenko I, Maurer M (2018) Nested article by additive manufacturing with non-removable internal supporting structure. https://www.freepatentsonline.com/y2018/0142894.html
65. Prodcuts Mitsubishi Power | Additive Manufacturing. https://power.mhi.com/products/additivemanufacturing. Accessed 22 Mar 2022
66. Sadek Tadros DAA, Ritter DGW, Drews CD, Ryan D (2017) Additive manufacturing of fuel injectors. Final Tech Report, EWI. https://doi.org/10.2172/1406179
67. Solar Turbines (2019) Additive manufacturing at solar turbines. www.Youtube.com, United States
68. Marrey M, Malekipour E, El-Mounayri H, Faierson EJ (2019) A framework for optimizing process parameters in powder bed fusion (PBF) process using artificial neural network (ANN). Procedia Manuf 34:505–515. https://doi.org/10.1016/j.promfg.2019.06.214
69. Arısoy YM, Criales LE, Özel T, et al Influence of scan strategy and process parameters on microstructure and its optimization in additively manufactured nickel alloy 625 via laser powder bed fusion. https://doi.org/10.1007/s00170-016-9429-z
70. Galati M, Minetola P, Rizza G (2019) Surface roughness characterisation and analysis of the electron beam melting (EBM) process. Materials (Basel) 12:. https://doi.org/10.3390/MA12132211
71. Snyder JC, Thole KA (2020) Understanding laser powder bed fusion surface roughness. J Manuf Sci Eng Trans ASME 142. https://doi.org/10.1115/1.4046504/1074958
72. Lou S, Jiang X, Sun W et al (2019) Characterisation methods for powder bed fusion processed surface topography. Precis Eng 57:1–15. https://doi.org/10.1016/J.PRECISIONENG.2018.09.007
73. Qiu C, Panwisawas C, Ward M et al (2015) On the role of melt flow into the surface structure and porosity development during selective laser melting. Acta Mater 96:72–79. https://doi.org/10.1016/j.actamat.2015.06.004
74. Imani F, Gaikwad A, Montazeri M, et al (2018) Process mapping and in-process monitoring of porosity in laser powder bed fusion using layerwise optical imaging. J Manuf Sci Eng Trans ASME 140:. https://doi.org/10.1115/1.4040615/366215
75. Clijsters S, Craeghs T, Buls S et al (2014) In situ quality control of the selective laser melting process using a high-speed, real-time melt pool monitoring system. Int J Adv Manuf Technol 75:1089–1101. https://doi.org/10.1007/S00170-014-6214-8
76. Fischer FG, Birk N, Rooney L et al (2021) Optical process monitoring in laser powder bed fusion using a recoater-based line camera. Addit Manuf 47:102218. https://doi.org/10.1016/J.ADDMA.2021.102218
77. Binder M, Anstaett C, Horn M et al (2020) Potentials and challenges of multi-material processing by laser-based powder bed fusion. In: Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference. SFF 2018, pp 376–387. https://doi.org/10.26153/tsw/17025
78. A comprehensive list of all the metal 3D printer manufactur- ers - 3Dnatives. https://www.3dnatives.com/en/metal-3d-print er-manufacturers/. Accessed 2 Mar 2022
79. Hague R, Campbell I, Dickens P (2003) Implications on design of rapid manufacturing. Proc Inst Mech Eng Part C J Mech Eng Sci 217:25–30. https://doi.org/10.1243/095440603762554587
80. Tuck CJ, Hague RJM, Ruffo M et al (2008) Rapid manufacturing facilitated customization. Int J Comput Integr Manuf 21:245–258. https://doi.org/10.1080/09511920701216238
81. J. Larfeldt (2017) Hydrogen co-firing in Siemens Low NOX industrial gas turbines. Siemens AG, Berlin, Germany
82. Fu W, Klapdor EV, Rule D, Piegert S (2017) Streamlined frameworks for advancing metal based additive manufacturing technologies in gas turbine industry Wentao. In: Proceedings of the 1st Global Power and Propulsion Forum. GPPF, Zurich, pp 1–8
83. Siemens Energy (2021) Additive manufacturing; Siemens Energy. https://doi.org/10.1080/02670836.2016.1197523
84. Varley J (2019) Additive manufacturing: there's no going back - Modern Power Systems. In: Mod. Power Syst. https://www.modernpowersystems.com/features/featureadditive-manufacturing-theres-no-going-back-7060286/. Accessed 3 Mar 2022
85. Huff R (2019) Redesigned for additive manufacturing: serial production of a new fuel swirler for Siemens gas turbine. Met AM 5:169–172
86. Burke J (2018) New HL-class gas turbines grow in the market - diesel & gas turbine worldwide. https://www.dieselgasturbine.com/7006283.article. Accessed 3 Mar 2022
87. Sinha A, Swain B, Behera A, et al (2022) A review on the processing of aero-turbine blade using 3D print techniques. J Manuf Mater Process 6:. https://doi.org/10.3390/jmmp6010016
88. Appleyard D (2015) Powering up on powder technology. Met Powder Rep 70:285–289. https://doi.org/10.1016/j.mprp.2015.08.075
89. (2020) This 3D printed turbine replaced 61 parts with 1: here is what that means | additive manufacturing. https://www.additivemanufacturing.media/articles/one-3d-printed-turbine-replaced-61-parts-with-1-here-is-what-that-means. Accessed 7 Nov 2021
90. (2017) MAN Diesel & Turbo: 3D printing becomes a standard. https://primeserv.man-es.com/home/news-details/2017/04/19/man-diesel-turbo-3d-printing-becomes-a-standard. Accessed 7 Nov 2021
91. Lefebvre AH (2010) Gas Turbine combustion. CRC Press Taylor & Francis Group, New York
92. Tuccillo R, Cameretti MC (2005) Combustion and combustors for MGT applications. NATO Res Technol Organ 1–56
93. Giuliani F, Paulitsch N, Cozzi D et al (2018) An assessment on the benefits of additive manufacturing regarding new swirler geometries for gas turbine burners. Proc ASME Turbo Expo 4A–2018:1–12. https://doi.org/10.1115/GT201875165
94. Moosbrugger V, Giuliani F, Paulitsch N, Andracher L (2019) Progress in burner design using additive manufacturing with a monolithic approach and added features. Proc ASME Turbo Expo 4A-2019:. https://doi.org/10.1115/GT2019-90720
95. Adamou A, Kennedy I, Farmer B, et al (2019) Experimental and computational analysis of an additive manufactured vaporization injector for a micro-gas turbine. Proc ASME Turbo Expo 4A-2019:. https://doi.org/10.1115/GT2019-90245
96. Umbricht M, Löffel K, Huber M, et al (2020) Novel pressure swirl nozzle design enabled by additive manufacturing. Ind Addit Manuf 399–414. https://doi.org/10.1007/978-3-030-54334-1_28
97. Runyon J, Giles A, Marsh R et al (2020) Characterization of additive layer manufacturing swirl burner surface roughness and its effects on flame stability using high-speed diagnostics. J Eng Gas Turbines Power 142:1–11. https://doi.org/10.1115/1.4044950
98. Sotov AV, Agapovichev AV, Smelov VG et al (2020) Investigation of the IN-738 superalloy microstructure and mechanical properties for the manufacturing of gas turbine engine nozzle guide vane by selective laser melting. Int J Adv Manuf Technol 107:2525–2535. https://doi.org/10.1007/s00170-020-05197-x
99. Adamou A, Turner J, Costall A et al (2021) Design, simulation, and validation of additively manufactured high-temperature combustion chambers for micro gas turbines. Energy Convers Manag 248:114805. https://doi.org/10.1016/j.enconman.2021.114805
100. Adamou A, Copeland C (2021) Experimental and computational analysis of additive manufactured augmented backside liner

cooling surfaces for use in micro-gas turbines. J Turbomach 143:. https://doi.org/10.1115/1.4050363
101. Adamou A, Costall A, Turner JWG, et al (2022) Experimental performance and emissions of additively manufactured high-temperature combustion chambers for micro-gas turbines. Int J Engine Res 146808742210826. https://doi.org/10.1177/14680874221082636
102. Iain Waugh (2021) Additive manufacture of rocket engine combustion chambers from CuCrZr (C-18150) using the DMLS process. In: Space Propulsion 2020+1. Virtual Conference
103. Waugh I, Moore E, Macfarlane J, et al (2021) Additive manufacture of rocket engine combustion chambers using the Abd R -900Am nickel superalloy. SP2020 Virtual Conf 17–19 March 1–9
104. Zohuri B (2016) Compact heat exchangers: selection, application, design and evaluation. Compact Heat Exch Sel Appl Des Eval 1–559. https://doi.org/10.1007/978-3-319-29835-1
105. Utriainen E, Sundén B (2002) Evaluation of the cross corrugated and some other candidate heat transfer surfaces for microturbine recuperators. J Eng Gas Turbines Power 124:550–560. https://doi.org/10.1115/1.1456093
106. Lagerström G, Xie M (2009) High performance and cost effective recuperator for micro-gas turbines. Am Soc Mech Eng Int Gas Turbine Institute, Turbo Expo IGTI 1:1003–1007. https://doi.org/10.1115/GT2002-30402
107. Wang QW, Liang HX, Luo LQ, et al (2008) Experimental investigation on heat transfer and pressure drop in a microtubine recuperator with cross-wavy primary surface channels. Proc ASME Turbo Expo 3 PART A:293–298. https://doi.org/10.1115/GT2005-68255
108. Bichnevicius M, Saltzman D, Lynch S (2020) Comparison of additively manufactured louvered plate-fin heat exchangers. J Therm Sci Eng Appl 12:. https://doi.org/10.1115/1.4044348
109. Do KH, Il CB, Han YS, Kim T (2016) Experimental investigation on the pressure drop and heat transfer characteristics of a recuperator with offset strip fins for a micro gas turbine. Int J Heat Mass Transf 103:457–467. https://doi.org/10.1016/j.ijheatmasstransfer.2016.07.071
110. Shah RK (2003) Shah, Sekulić 2003 - Fundamentals of heat exchanger design. In: Fundamentals of heat exchanger design. John Wiley & Sons, Inc., New Jersey
111. Ranganayakulu C (2018) Compact heat exchangers – analysis, design and optimization using FEM and CFD approach. John Wiley & Sons Ltd
112. Shah R (2005) Compact heat exchangers for microturbines. Micro Gas Turbines Educationa:1–18
113. Klein E, Ling J, Aute V et al (2018) A review of recent advances in additively manufactured heat exchangers. Int Refrig Air Cond Conf 1–10. https://docs.lib.purdue.edu/iracc
114. Zhang C, Wang S, Li J et al (2020) Additive manufacturing of products with functional fluid channels: a review. Addit Manuf 36:101490. https://doi.org/10.1016/j.addma.2020.101490
115. Niknam SA, Mortazavi M, Li D (2021) Additively manufactured heat exchangers: a review on opportunities and challenges. Int J Adv Manuf Technol 112:601–618. https://doi.org/10.1007/s00170-020-06372-w
116. Paraye P, Sarviya RM (2021) Review of efficient design of heat exchanger by additive manufacturing. SSRN Electron J 1–11. https://doi.org/10.2139/ssrn.3808984
117. Zhang X, Tiwari R, Shooshtari AH, Ohadi MM (2018) An additively manufactured metallic manifold-microchannel heat exchanger for high temperature applications. Appl Therm Eng 143:899–908. https://doi.org/10.1016/j.applthermaleng.2018.08.032
118. Zhang X, Arie M, Deisenroth D et al (2015) Impact of additive manufacturing on performance enhancement of heat exchangers: a case study on an air-to-air heat exchanger for high temperature applications. In: IX Minsk International Seminar on Heat Pipes, Heat Pumps, Refrigerators, Power Sources. National Academy of Sciences of Belarus Luikov Heat & Mass Transfer Institute NIS Scientific Association "Heat Pipes" Belarusian National Technical University, Minsk, Belarus
119. Jansson A, Zekavat A, Pejryd L (2015) Measurement of internal features in additive manufactured components by the use of computed tomography. Digital Industrial Radiology and Computed Tomography (DIR 2015), 22-25 June 2015, Belgium, Ghent. e-J Nondestruct Test 20(8). https://www.ndt.net/?id=18035
120. Torsten Schnabel, Markus Oettel DBM (2017) Guidelines and case studies for metal applications. In: The Cutting Edge. CMTS 2017, Dresden. https://doi.org/10.24406/publica-fhg-399168
121. Ivanov N (2020) Small-scale gas turbine integrated heat exchanger. MSc Thesis, LAPPEENRANTA-LAHTI Univ Technol LUT. https://lutpub.lut.fi/bitstream/handle/10024/161801/mastersthesis_Ivanov_Nikita_SSGTIHE.pdf?sequence=1. Accessed 5 Feb 2023
122. lloyds Jone S, Smith C (2018) Combustion chamber and heat exchanger. UK Patent. https://patents.google.com/patent/GB2554384A/en. Access 8 Mar 2022
123. Galanti L, Massardo AF (2011) Micro gas turbine thermodynamic and economic analysis up to 500 kWe size. Appl Energy 88:4795–4802. https://doi.org/10.1016/j.apenergy.2011.06.022
124. McDonald CF (2003) Recuperator considerations for future higher efficiency microturbines. Appl Therm Eng 23:1463–1487. https://doi.org/10.1016/S1359-4311(03)00083-8
125. Flores I, Kretzschmar N, Azman AH et al (2020) Implications of lattice structures on economics and productivity of metal powder bed fusion. Addit Manuf 31:100947. https://doi.org/10.1016/j.addma.2019.100947
126. Tang Y, Yang S, Zhao YF (2016) Sustainable design for additive manufacturing through functionality integration and part consolidation. Environ Footprints Eco-Design Prod Process 101–144. https://doi.org/10.1007/978-981-10-0549-7_6
127. Diegel O, Kristav P, Motte D, Kianian B (2016) Additive manufacturing and its effect on sustainable design. Environ Footprints Eco-Design Prod Process 73–99. https://doi.org/10.1007/978-981-10-0549-7_5/COVER
128. Javaid M, Haleem A, Singh RP et al (2021) Role of additive manufacturing applications towards environmental sustainability. Adv Ind Eng Polym Res 4:312–322. https://doi.org/10.1016/j.aiepr.2021.07.005
129. Liang D, He G, Chen W et al (2022) Fluid flow and heat transfer performance for micro-lattice structures fabricated by Selective Laser Melting. Int J Therm Sci 172:107312. https://doi.org/10.1016/j.ijthermalsci.2021.107312
130. Gibson LJ, Ashby MF, Wolcott MP (1999) Cellular solids: structure and properties, first pape. Cambridge University Press
131. Hanks B, Berthel J, Frecker M, Simpson TW (2020) Mechanical properties of additively manufactured metal lattice structures: data review and design interface. Addit Manuf 35:101301. https://doi.org/10.1016/j.addma.2020.101301
132. Kaur I, Singh P (2021) Critical evaluation of additively manufactured metal lattices for viability in advanced heat exchangers. Int J Heat Mass Transf 168:. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120858
133. Kaur I, Singh P (2021) State-of-the-art in heat exchanger additive manufacturing. Int J Heat Mass Transf 178:121600. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121600
134. Peng H, Gao F, Hu W (2019) Design, modeling and characterization of triply periodic minimal surface heat exchangers with additive manufacturing. In: Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference. ISFFS, pp 2325–2337. https://doi.org/10.26153/tsw/17483

135. Attarzadeh R, Rovira M, Duwig C (2021) Design analysis of the ”Schwartz D” based heat exchanger: a numerical study. Int J Heat Mass Transf 177:121415. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121415
136. Stimpson CK, Snyder JC, Thole KA, Mongillo D (2016) Roughness effects on flow and heat transfer for additively manufactured channels. J Turbomach 138:. https://doi.org/10.1115/1.4032167
137. Rhodes MJ, Taylor MR, Monroe JG, Thompson SM (2015) Experimental investigation of a flat-plate oscillating heat pipe with modified evaporator and condenser. ASME Int Mech Eng Congr Expo Proc 8A: https://doi.org/10.1115/IMECE 2014-39188
138. Kirsch KL, Thole KA (2017) Heat transfer and pressure loss measurements in additively manufactured wavy microchannels. J Turbomach 139:. https://doi.org/10.1115/1.4034342/378744
139. Arie MA, Shooshtari AH, Ohadi MM (2018) Experimental characterization of an additively manufactured heat exchanger for dry cooling of power plants. Appl Therm Eng 129:187–198. https://doi.org/10.1016/j.applthermaleng.2017.09.140
140. Xu R, Geng Z, Wu Y et al (2022) Microstructure and mechanical properties of in-situ oxide-dispersion-strengthened NiCrFeY alloy produced by laser powder bed fusion. Adv Powder Mater 1:100056. https://doi.org/10.1016/j.apmate.2022.100056
141. Tian Y, Tomus D, Rometsch P, Wu X (2017) Influences of processing parameters on surface roughness of Hastelloy X produced by selective laser melting. Addit Manuf 13:103–112. https://doi.org/10.1016/j.addma.2016.10.010
142. Shulman H, Ross N (2015) Additive manufacturing for cost efficient production of compact ceramic heat exchangers and recuperators. United States. https://doi.org/10.2172/1234436. https://www.osti.gov/servlets/purl/1234436
143. Pelanconi M, Zavattoni S, Cornolti L, Puragliesi R, Arrivabeni E, Ferrari L, Gianella S, Barbato M, Ortona A (2021) Application of ceramic lattice structures to design compact, high temperature heat exchangers: material and architecture selection. Materials 14(12):3225. https://doi.org/10.3390/ma14123225
144. Teschke M, Moritz J, Telgheder L et al (2022) Characterization of the high-temperature behavior of PBF-EB/M manufactured γ titanium aluminides. Prog Addit Manuf 7:471–480. https://doi.org/10.1007/s40964-022-00274-x
145. Lakhdar Y, Tuck C, Binner J et al (2021) Additive manufacturing of advanced ceramic materials. Prog Mater Sci 116:100736. https://doi.org/10.1016/j.pmatsci.2020.100736
146. Koopmann J, Voigt J (2019) Niendorf T (2019) Additive manufacturing of a steel–ceramic multi-material by selective laser melting. Metall Mater Trans B 502(50):1042–1051. https://doi.org/10.1007/S11663-019-01523-1
147. Rock C, Tarafder P, Ives L, Horn T (2021) Characterization of copper & stainless steel interface produced by electron beam powder bed fusion. Mater Des 212:110278. https://doi.org/10.1016/j.matdes.2021.110278
148. Liu ZH, Zhang DQ, Sing SL et al (2014) Interfacial characterization of SLM parts in multi-material processing: metallurgical diffusion between 316L stainless steel and C18400 copper alloy. Mater Charact 94:116–125. https://doi.org/10.1016/j.matchar.2014.05.001
149. Wei C, Li L (2021) Recent progress and scientific challenges in multi-material additive manufacturing via laser-based powder bed fusion. Virtual Phys Prototyp 16:347–371. https://doi.org/10.1080/17452759.2021.1928520
150. Aydogan B, O’Neil A, Sahasrabudhe H (2021) Microstruc- tural and mechanical characterization of stainless steel 420 and Inconel 718 multi-material structures fabricated using laser directed energy deposition. J Manuf Process 68:1224–1235. https://doi.org/10.1016/j.jmapro.2021.06.031