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Additive Manufacture and the Gas Turbine Combustor: Challenges and Opportunities to Enable Low-Carbon Fuel Flexibility

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Disclaimer

The work described herein was undertaken prior to the presenter's employment at Uniper. Credited organisations are given below. All data and figures are derived from publicly-available sources cited here or in the accompanying paper.

Credited Organisations:

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

GTRC
GAS TURBINE RESEARCH CENTRE

HiETA technologies

Background and Aims

- Gas turbine OEMs are increasingly using AM for ***new product development***, ***on-engine components***, and ***repair*** of in-service equipment.
- GTs will need to operate on ***low/zero-carbon fuels*** in the future (e.g., hydrogen, ammonia, biofuels).
- New designs of the GT combustor are needed ***quickly***, combining AM and computational methods to reduce time to market, increase fuel flexibility, and reduce costs.

<u>Aim #1</u>:

Conduct a thorough review of the current state-of-the-art in AM for ***academic combustion research***, ***micro-GT***, and ***industrial GT*** development and commercial applications

<u>Aim #2</u>:

Identify the ***challenges*** and ***research needs*** associated with AM in the GT combustion context

Setting the Scene

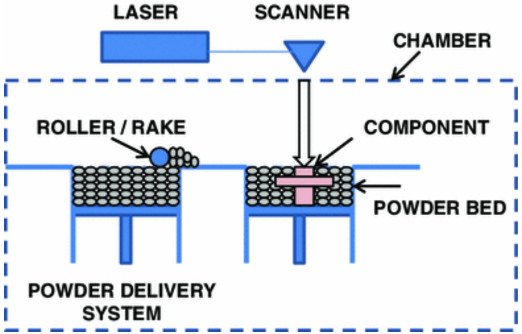
- AM is a global growth industry, predicted to expand 3x from 2019 to 2024 ($30B)

AM projects increased from ~50 (FP7) to >400 (Horizon 2020)

AM funding increased from £15M (2012) to >£180M (2020)

Government investment in AM exceeds $400M (2020)

- Powder bed fusion (PBF) by selective laser melting (SLM) represents 80% of global metal AM installations



- Other emerging AM technologies relevant to GT combustion:
  - Direct energy deposition (DED)
  - Laser metal deposition (LMD)
  - Ceramics
  - Compositionally-graded materials

Setting the Scene

Why use AM for GT combustors?

- Unlock the design space with increased design freedom (but new design constraints introduced)
- Cost-effective against traditional manufacturing for small batch, prototype, and complex parts
- Multi-component integration, reduced number of components/assemblies, eliminate welds, increased reliability
- Expanding availability of materials to match requirements (e.g., high-temperature materials)
- Reduced product development times (in combination with CAD/CAE/CFD)
- Reduced manufacturing waste
- Reduced need to holding stock of spare components ("spare parts on-demand")
- Production of obsolete parts

Increasing investment in AM for Gas Turbines

- Investments by GT OEMs in the use of AM:

GE

- $1.4B investment to purchase Arcam and SLM Solutions
- $50M for new industrial AM production facility
- Serialised production of AM fuel nozzles for GE LEAP engine

Siemens Energy

- >€30M investment in AM technology for combustor design, retrofit, repair
- Acquisition of Materials Solutions Ltd (UK)
- Reduced blade and combustor development time

Solar Turbines – A Caterpillar Company

- Using in-house PBF and LMD for new components and repairs
- AM partnerships with Penn State University and ORNL
- AM identified as H_2 technology enabler

Mitsubishi Power

- Opened AM-Zone in Japan in September 2020

Baker Hughes

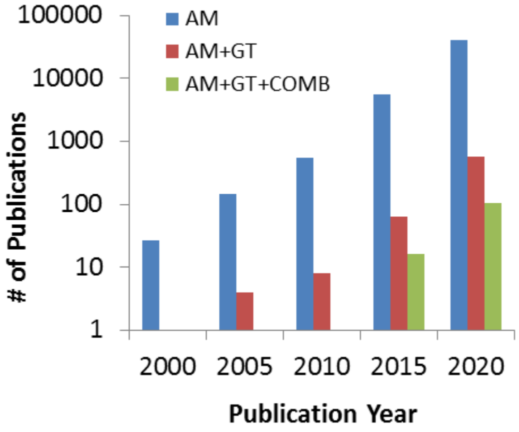
- Produced more than 25,000 AM parts and qualified more than 450 individual parts

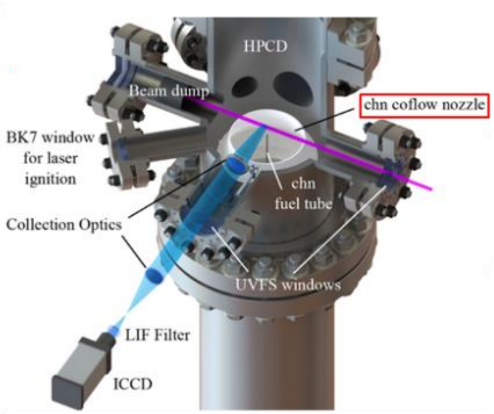
MAN Energy Solutions

- Invested €2.6M in the MAN Centre for Additive Manufacturing

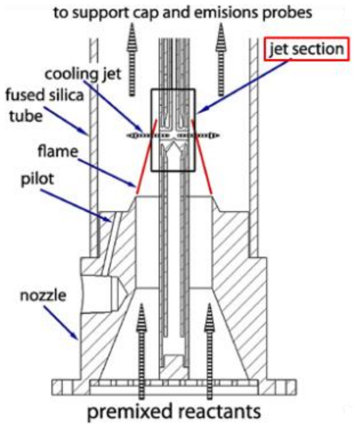
AM in Academic Combustion Research

- Large investments made in academic AM research centres.
- Systematic literature search reveals exponential growth in AM research output – GT combustion lags behind by ~15 years.
- 3 main focus areas:
    - Novel components to enable fundamental combustion research

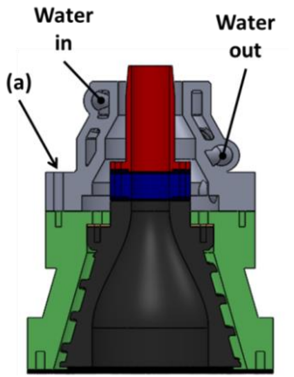




KAUST – Axisymmetric Co-Flow Nozzle



University of Melbourne – Cold Flow Jet Outlet Section



Cardiff University – Cooling Nozzle for Counterflow Burner

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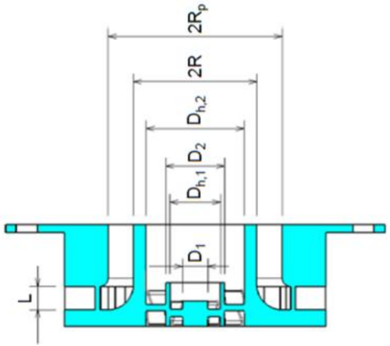
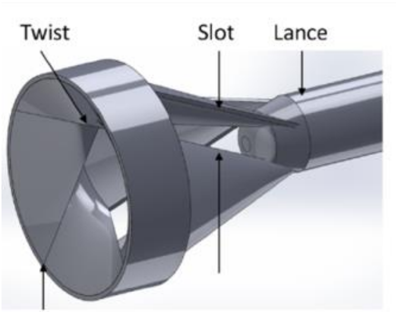
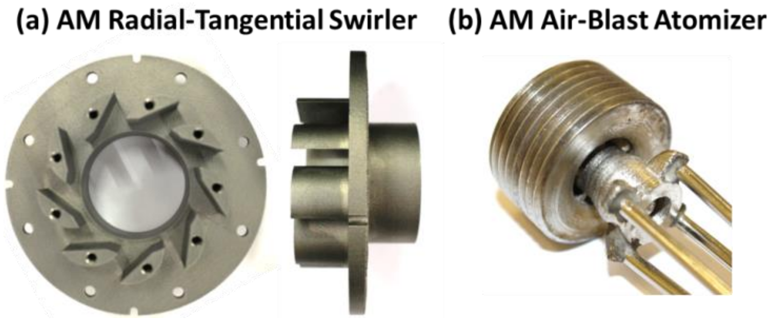
  - Low-TRL components (e.g., swirlers, fuel injectors)



Chongbuk National University –
Twin annular premixed swirler



Lund University –
CeCOST Swirl Burner



Cardiff University –
Swirler and Fuel Injector

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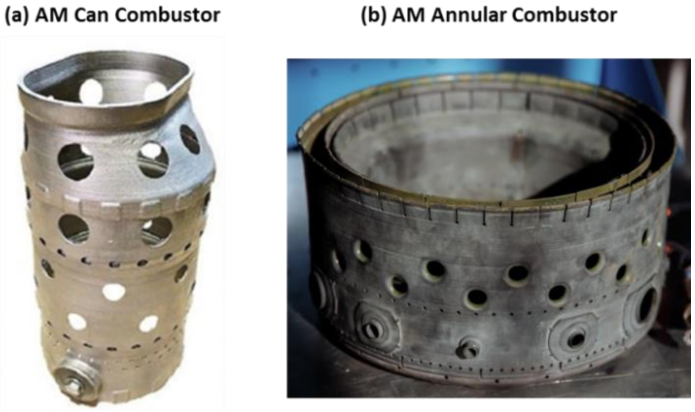
  - Low-TRL components (e.g., swirlers, fuel injectors)
  - High-TRL prototype components and assemblies

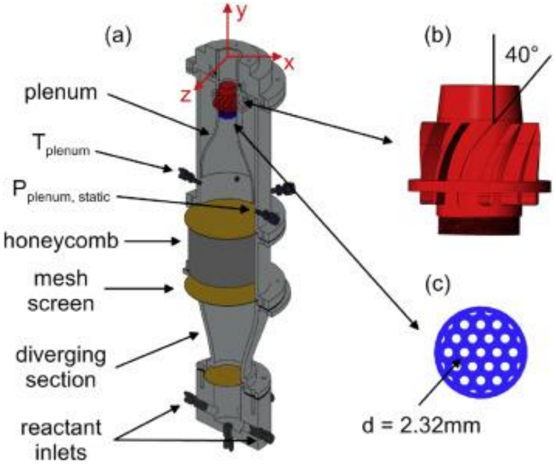


Samara University – Can and Annular Combustors

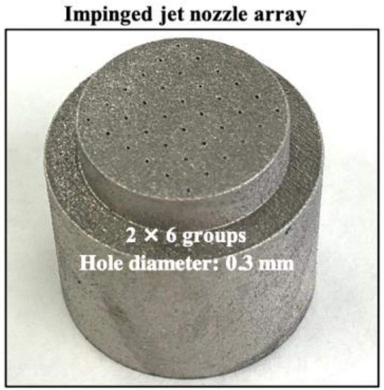

Monash University – AM Jet Engine

AM in Academic Combustion Research

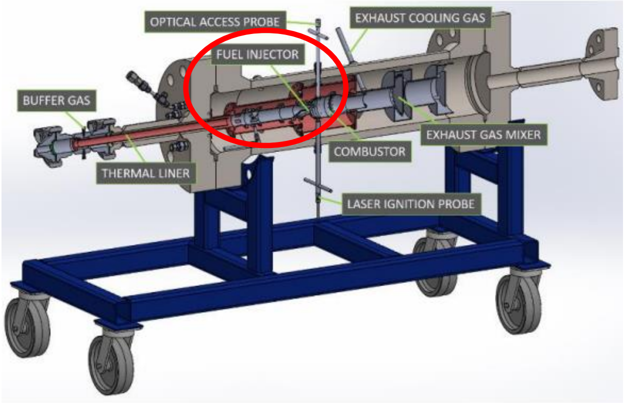
- AM enabling research into low-carbon fuels and cycles:
  - An et al. (2021) – AM low swirl injector designed to study flame/flow interactions in CH_4-H_2 blends
  - Fan et al. (2021) – AM multi-cluster injector for H_2-O_2 combustion diluted with H_2O.
  - Southwest Research Institute (Delimont et al., 2021) – optimised fuel injector design for AM (DfAM) to deliver complex swirling and mixing geometry in a 1 MW direct-fired supercritical CO_2 power cycle



An et al. (2021)



Fan et al. (2021)



Delimont et al. (2021)

AM for Micro-GT Combustion (< 1 MW)

“AM enabled a rethinking of fuel spray and flame shape in our combustion chamber”
– Roger Smith, CEO, Sierra Turbines

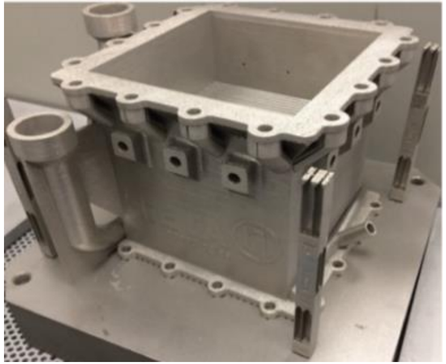
- Design for AM (DfAM):
  - Topology optimisation (360° fuel injection)
  - Multi-component integration (61 → 1)
  - High-temperature materials (Hastelloy X)
  - Reduced print time and cost (support-free printing)

https://www.additivemanufacturing.media/articles/one-3d-printed-turbine-replaced-61-parts-with-1-here-is-what-that-means
https://www.3dnatives.com/en/advanced-metal-am-enables-microturbines-to-be-40x-more-efficient-030920204/

AM for Micro-GT Combustion

- The size of MGTs makes components suitable for the build volumes of current AM platforms (<0.2 m^3).
- AM enables new designs of the high-temperature heat exchangers (HTHX) and recuperators for improved efficiency.
  - Topology optimisation of heat transfer surfaces, geometries unachievable with conventional methods, significant reduction in brazing/welding.
- Integration of AM porous media burners (PMB) and catalytic combustion systems under investigation.

Euro-K / EOS / Bilfinger –
MGT Combustion Can



HiETA Technologies –
AM waste heat HTHX (left), recuperator (centre), combustor-recuperator (right)

AM for Micro-GT Combustion

Challenges

- Effective business case development (large capital expense for machine, powder expense, post-processing)
- Powder removal and post-processing
- Build repeatability (tolerances, surface roughness, hole roundness)
  - Decrease in combustion performance (hot spots, clogging, increased pressure drop)
- Development of small-scale flame stabilisation mechanisms (e.g., micromixing, porous media for H_2)
- Sizing and design of HTHX and efficient distribution of outlet air into combustion chamber
- Differential expansion of monolithic designs with temperature gradients

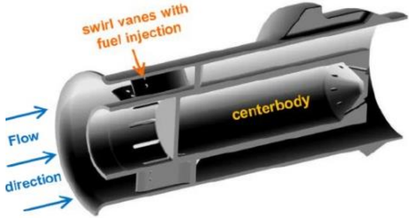
Research Needs

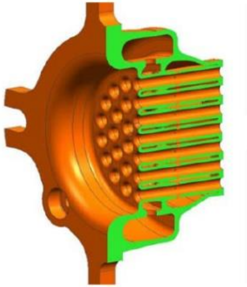
- Enhance data acquisition and control of build process
- Increase geometrical accuracy and improve surface finish
- Advanced process modelling tools to predict thermo-mechanical properties and surface finish
- Improve understanding of AM surface roughness and its interaction with heat transfer microstructures using CFD
- New high-temperature metallic and ceramic materials
- MGT research platform for qualification of new combustion components and configurations to improve modularity, reduce development time, and improve fuel flexibility

AM for Industrial GT Combustion

AM being used by nearly all industrial GT OEMs, with a significant focus on the combustion system (e.g., fuel injectors, fuel/air mixing, combustion cans, etc.)

- New H_2 swirler and micromix injector design prototyping (30+)
- HA-class fuel/air mixing nozzle (eliminate 1000s brazed joints)
- GT26 HE upgrade – fuel injectors and pulsation dampeners



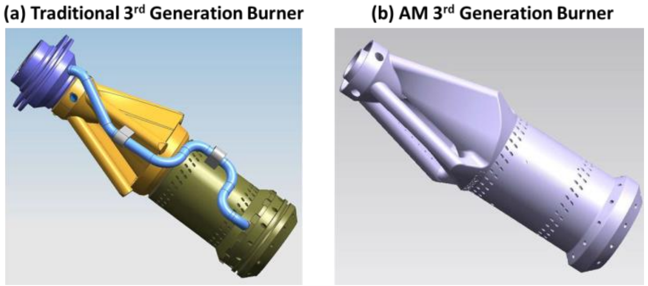


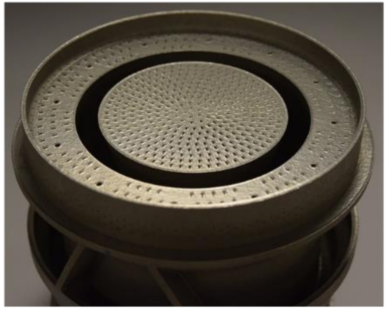
Baker Hughes

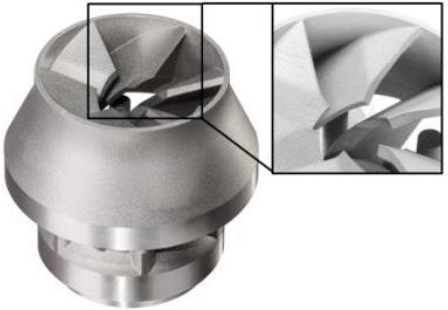
- AM swirler for O&G applications
- AM fuel burner for NovaLT16

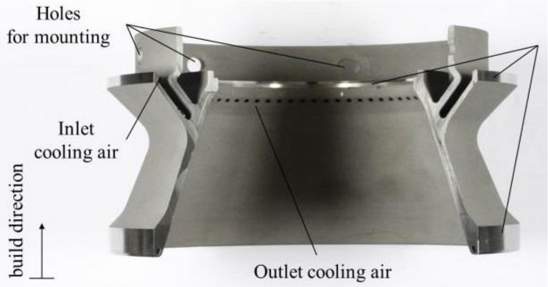
AM for Industrial GT Combustion

- Full AM burner for SGT-600/700/800 (13 parts → 1)
- SGT-A05 Premixer
- SGT-1000F Swirler (>12,000 hours operation)
- Burner nozzle pilot cone
- Burner tip repair (reduce repair time by 10x)









SIEMENS energy

Solar Turbines
A Caterpillar Company

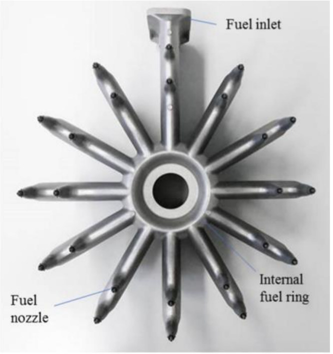
- Alloy X fuel nozzle

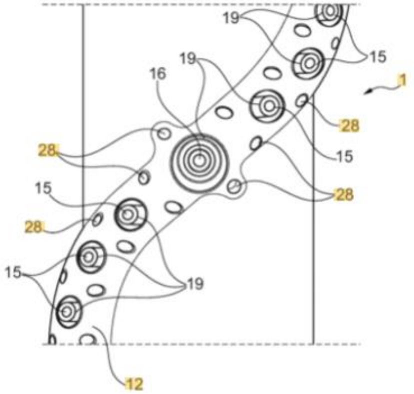
AM for Industrial GT Combustion

Looking ahead…new designs and methods for improved operation and fuel flexibilty

ANSALDO ENERGIA

- AM center body burner (CBB)
  - 100 parts/50 welds → 1 part
- AM sequential fuel injector





MITSUBISHI POWER

- Direct metal deposition (DMD) combustion chamber

AM for Industrial GT Combustion

Challenges

- Standardisation and quality control of AM machine processes
- AM process, materials, and workflows not well perceived by designers leading to ineffective designs
- Moving from validated design into serial production
- Powder availability, health and safety, characterisation
- Geometric limitations of current AM platforms
- Long-term product risk management, understanding failure mechanisms
- New cooling, fuel/air mixing, fuel/air injection, vaporisation methods for biofuels, H_2, and NH_3

Research Needs

- Upskilling GT designers on AM design methodologies, processes and materials
- Topology optimisation and machine learning for wide design parameter space (materials, heat transfer, aerodynamics, acoustics, chemistry)
- Cost optimisation versus traditional manufacturing, including AM build and powder cost estimation
- Integrating AM design tools with other computational methods (e.g., CFD) for reduced development time
- Integrated engineering approach to use AM across multiple subsystems and GTs
- Longitudinal AM product and material reliability studies, including data feedback from the entire value chain

Summary and Conclusions

Academic Combustion Research

- Large-scale investments globally in academic AM research centres
- AM-related research output increasing exponentially
- Metal AM widely used with increasing access to SLM machines
- AM mainly used for fundamental combustion components and low-TRL research
- Low-carbon AM burner designs investigated through industry-academic partnerships

Micro-GT Combustion

- Geometric scale ideal for current AM platforms
- Improved MGT recuperator design through topology optimisation and high-temperature materials
- AM may be useful for H_2, NH_3, and liquid biofuels using new fuel injectors (e.g., micro-mix), porous media or catalytic combustion.
- Challenges: cost, build consistency, powder removal, and surface finish
- Research needs: AM process modelling, CFD with conjugate heat transfer, MGT testing platform

Industrial GT Combustion

- OEMs using AM for fuel injection, fuel/air mixing, and cooling.
- OEMs active in fundamental and applied low-carbon research and using AM to increase H_2 capability.
- AM identified as key technology for reducing development time and cost.
- Challenges: AM design knowledge, moving into serial production, novel cooling and mixing designs for low-carbon applications.
- Research needs: Training in AM design, digital design tools, new materials, long-term component reliability.

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- Andrew Jones (HiETA Technologies Head of Innovation)

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Thank you for your attention!

For more information please feel free to contact me:

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