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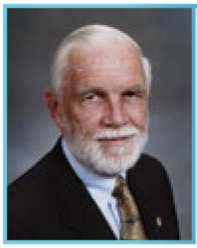
Gas Turbine Pumped Thermal Energy Storage



Lee S. Langston
Professor Emeritus, University of Connecticut
lee.langston@uconn.edu

In 2014, *The Economist* [1] published a short article, "Pumping heat--A reversible heat pump promises a cheap way to store renewable energy". It briefly summarized work going on in the UK to store energy in two heat reservoirs by a heat pump and then to recover the energy by a heat engine operating between them.

In 2017, Stanford University's Robert Laughlin [2], summarized subsequent work that had gone on with this pumped thermal energy storage (PTES) concept. He proposed the use of the thermodynamic Brayton cycle for both the heat pump and heat engine, calling the resulting PTES assembly a "Brayton Battery". (George Brayton invented the first such heat engine and Benjamin Franklin coined the word "battery".)

The Brayton Battery looks very attractive for at least two reasons: 1) It could be based on our well-known and successful gas turbine technology. 2) Heat reservoirs storing thermal energy can be of any appropriate size and constructed from insulated con-tainers filled with a suitable thermal storage medium (e.g., gravel, a packed bed of ceramic pebbles or water) at almost any location, rural or urban.

WHY ENERGY STORAGE?

In the distinctively titled text, *Sustainable Energy – without the hot air*, author David MacKay [3] of Cambridge University points out that we have an addiction to fossil fuels, which is not sustainable, for our future.

However, sustainable energy sources (a.k.a. renewables) such as wind and solar are available, for their conversion to our modern society's life blood, electrical energy. When the wind blows to turn wind turbines and the sun shines on arrays of silicon solar panels, electric power is produced, and life is good. However, the electricity grid transmits power, but it cannot store energy. Thus, when the wind diminishes and the sunlight fails, as MacKay relates, we currently must fall back on easily turn-off-and-onable fossil fuel electrical production (e.g., our efficient natural gas fueled gas turbine combined cycle plants) or nuclear power plants (which are not flexible for rapid start up or shut down).

The answer to this problem of intermittent sustainable energy is one of energy storage. Its unpredictability then calls for a system of wind and solar that will produce more electrical energy then the immediate electricity market calls for, and to store the surplus, to be used when wind and solar subside.

HOW MUCH IS NEEDED?

Just how much energy storage might be called for at given sites? One quick estimate is given by Laughlin in his discussion of the Brayton Battery (more on this to follow) [2]: The average electrical power delivered to say Los Angeles or New York is about 1.4 x10^{10} Watts. Storing this power for just one hour of electrical energy consumption comes to 5.04 x 10^{13} Joules (1.4 x 10^{7} kWh) – or about one Hiroshima-sized atomic bomb. Thus, energy storage sites could be large—and need to be safe.

On a smaller scale, we can estimate electrical energy storage size on a daily per capita level in the United States. For 2019, EIA data [4] show that the average daily electrical energy consumption in the US was about 33 kWh, per capita. (To put this in perspective, the US daily per capita food intake energy from food is about 2.54 kWh [5], placing per capita electrical energy consumption in the US at 13 times greater than the need for food intake energy.)

ELECTRICAL ENERGY STORAGE MEANS

Electrical energy storage here refers to the process of converting electrical energy to a form that can be stored and then converted back to its initial form when required. There is always some available energy loss in recovering the stored energy and converting it back to grid-ready electricity.

We are all well-aware of many ways that electrical energy can be stored. Many of these are reviewed by MacKay [3], who gives criteria by which each can be judged. One of the most prevalent forms of electrical energy storage worldwide, is pumped hydroelectric energy storage (PHES). Available water is pumped from a site at a lower elevation level using surplus electricity to a higher elevation reservoir, increasing the water's gravitational potential energy. When called upon, reservoir water is released to the lower elevation through hydro turbines to produce electrical power. However, PHES is limited to sites where water is in good supply and the terrain has adequate elevation variations. In practice, PHES generating periods are often less than half a day, with round-trip energy efficiencies varying between 70-80%. As Laughlin [2] has pointed out, if the stored energy is accomplished safely, the loss of available energy through round trip efficiency must be acceptable, since storage of electricity is fundamentally about value, not about conserving energy.

THE PTES GAS TURBINE BRAYTON BATTERY

Recently, overall features of the PTES Brayton Battery have been reviewed by Joseph Chiapperi and his co-authors at MIT [6] [7]. This was part of their detailed analysis of the actual Brayton cycle gas turbine turbomachinery that would be required.

Following [6], Fig. 1 shows a very simplified schematic of the PTES Brayton Battery system. The green path indicates operation of the Brayton cycle heat engine (the gas turbine) closed-cycle gas path (e.g., argon) when it runs to generate electricity from hot gas heated by the hot reservoir, via a heat

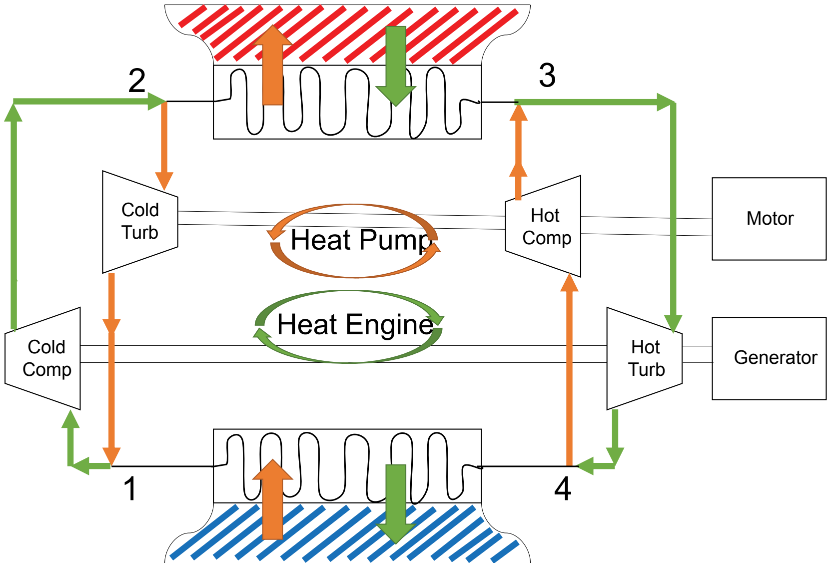


Figure 1. Simplified schematic of the PTES Brayton Battery system, from [6].

exchanger (red hatching and the upper broad green arrow). Green path exhaust heat is then rejected to the cold heat reservoir via a heat exchanger (blue hatching and the lower green arrow).

Similarly, the orange path in Fig. 1 indicates operation of the Brayton cycle heat pump closed-cycle gas path when it is powered by an electric motor, to transfer heat from the cold heat reservoir (blue hatching and the lower orange broad arrow) to the hot heat reservoir (red hatching and the upper orange broad arrow).

Figure 2 is a T-S, temperature-entropy diagram for the ideal Brayton cycles of the gas turbine heat engine and the heat pump shown for the PTES Brayton Battery of Fig. 1.

As Chiapperi [6] observes, the PTES Brayton Battery system in Fig. 1 has separate components for the energy storage and for the energy withdrawal processes. A set of turbomachinery runs as a heat pump while another set is idle. Then, when the energy is to be withdrawn, the idle turbomachinery is used in the heat engine, while the heat pump becomes idle. If a bi-directional turbomachine could be built to operate as a compressor in one direction and a turbine in the other however, there would be no components sitting idle, and the system would be potentially cheaper and less complex. Figure 3 shows a very simplified schematic of a PTES system with bi-directional turbomachines. The design of such turbomachines is the focus of [6] [7] and is a work in progress. ◆

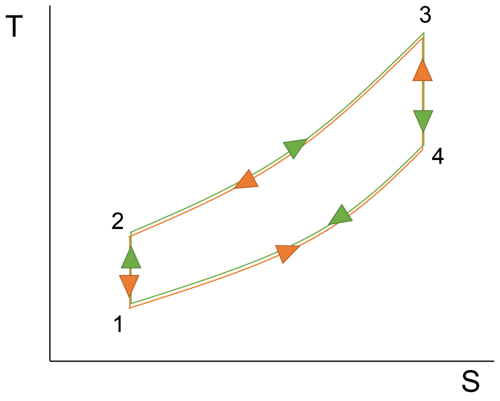


Figure 2. Ideal Brayton cycle gas turbine (green) and heat pump (orange) temperature (T)--entropy (S) diagram for the Brayton Battery system, from [6].

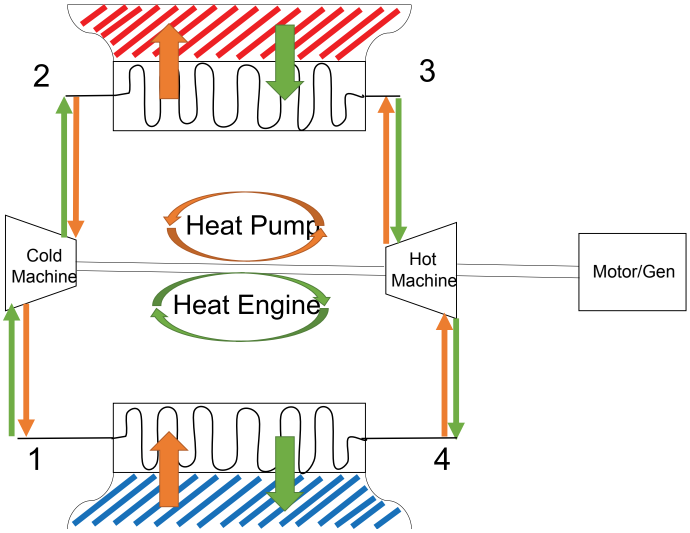


Figure 3. Simplified schematic of the PTES Brayton Battery system with bi-directional turbomachines, from [6].

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Additive Manufacturing Benefits and Challenges in Developing Turbine Technologies

Karen A. Thole and Scott Fishbone, Steady Thermal Aero Research Turbine (START) Lab, Pennsylvania State University

Given the high temperatures and demanding thermal stresses that gas turbine components must withstand, you might assume metal additive manufacturing (AM) has no place in the industry. However, to meet the aggressive goals for sustainability set by the U.S. Aviation Climate Action Plan [1] advancements in turbine components must happen at a rapid pace to improve thermal efficiencies while still ensuring today's aviation safety records. For such advancements, gas turbine companies are turning to additive manufacturing, also known as metal 3D printing. AM ranges from selective laser melting (laser powdered bed fusion) for high resolution parts to electron beam melting for large parts requiring less stringent tolerances.

AM components have been shown to aid in rapidly developing new designs that can quickly be manufactured and tested. In replacing legacy parts AM can reduce part number, weight, manufacturing waste, and sometimes even costs. For these reasons, the turbine industry is embracing metal printing technologies for rapid design prototyping, tooling, and even production parts.

OPPORTUNITIES IN USING AM

Single-crystal, cast blades, required to meet the extreme temperature and stress environments in a turbine, are still one of the most challenging components to manufacture. Only a handful of countries in the world can claim to have the capabilities to achieve such a manufacturing novelty. Even for those few companies who are adept at manufacturing single-crystal blades, significant time and effort is required to develop the magic needed to make parts that meet the design requirements. Metal additive manufacturing allows for the rapid fabrication of complex components relative to conventional casting methods that can more rapidly aid in the development and testing of advanced turbine cooling designs. While an AM blade or vane is not at the point of meeting harsh turbine environments in the first stages of a turbine, it does provide a pathway for faster development of turbine components including airfoil shapes and even cooling technologies. For example, metal AM allows such technologies to be assessed quickly prior to spending development time and money to make cast parts.

To illustrate the business opportunity for using AM, consider that the development time for a new cooling design manufactured into a traditional cast blade or vane requires multiple years with a typical yield rate of 1 in 25 airfoils, based on the experiences of the authors, to meet the design intent and specified flow tolerances. In contrast, a set of AM blades for a single stage may require on the order of a few months with a yield rate greater than 90%. While the yield rate is high for AM parts, post-machining is still required which can bring in additional challenges requiring further trials. Based on the

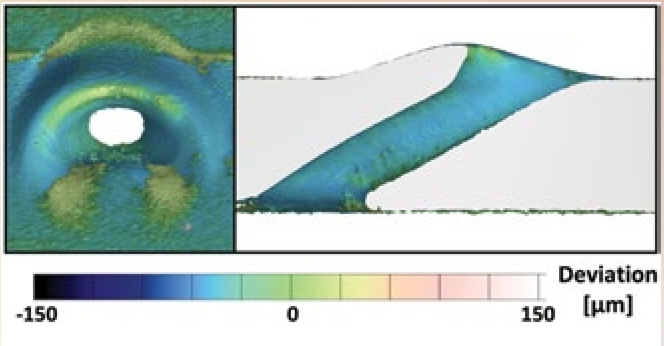

Figure 1. Illustration of an optimized film-cooling hole with contours of the deviation from the design intent [1, 2].

authors' experiences in several test campaigns working with industry, time is not the only cost savings using AM, actual hardware costs can be reduced from over a million dollars for set of cast blades to less than a few hundred thousands of dollars for an AM set.

Another opportunity that turbine companies are quickly realizing is using AM to more rapidly make the tooling needed for turbine blades and vanes. Currently, tooling dies for cast vanes and blades require high precision machining with tolerances within a thousandth of an inch. These tool dies for both the core and wax pattern, can cost well over a $100,000 and take over a year to build, which is an important cost factor for a small quantity of parts. Alternatively, AM can help with this issue in a couple of different ways. First, the tooling itself can be printed. While the tolerances or durability of the tool might not be as precise as the machined piece, it is faster and an order of magnitude cheaper. Second, AM can entirely eliminate the need for dies. Companies are using ceramic printing processes to AM the entire casting mold. By printing the mold, it removes the need for ceramic cores and wax patterns to cast an airfoil.

What continues to be an opportunity with much more to explore is to combine computational optimization methods for new designs, as illustrated by one example in Figure 2 for a film cooling hole showing the optimized design and deviation from the design intent [1, 2]. Also there exists opportunities to tailor surface roughness, for example, through AM processing parameters as shown in Figure 2 [3].

Also possible are AM-made stationary, production parts that can achieve complexity while reducing the number of parts and wasted material. The classic example is that of the GE fuel nozzle, which was introduced in 2015 and reached 100,000 manufactured in 2021 for the CFM LEAP engine [4]. AM is also making way for integrating complex cooling features in heat exchangers such as vortex generators and wavy channels, which do not exist in today's tube-and-shell designs to reduce weight while increasing performance.

AM VENDOR LANDSCAPE AND CHALLENGES

Although laser powdered bed fusion (LPBF) has advanced rapidly as a manufacturing method over the past few years, challenges still exist in manufacturing parts, particularly prototyping cooled turbine airfoils given the complexities and features sizes. First, to reap the benefits of using AM, the designs must differ from those of conventionally cast airfoils. Second, the manufacturing process depends on many variables: the type of metal powder, the build orientation, the layer size, the support structures needed for the build process, the AM machine, and the processing parameters including the contouring and the energy density. Just as in conventional manufacturing, multiple trial prints are required to hone in on the print with concessions being made on feature resolution and surface roughness, both of which are highly sensitive to the processing parameters and build direction.

AM is not without disadvantages in producing turbine parts. For instance, after several trial prints, airfoil shapes can be off by as much as 0.020 inches from the design intent. In addition, roughness levels can be as high as 200 microns and with variability from different vendors and with the same vendor. Small features are challenging with dovetails not meeting tolerances and cooling holes in a collapsed state. Figure 3 shows a printed vane that is highly cooled whereby the holes were printed. Evident from Figure 3 is a range of quality in terms of the holes. One vendor was able to get cooling holes

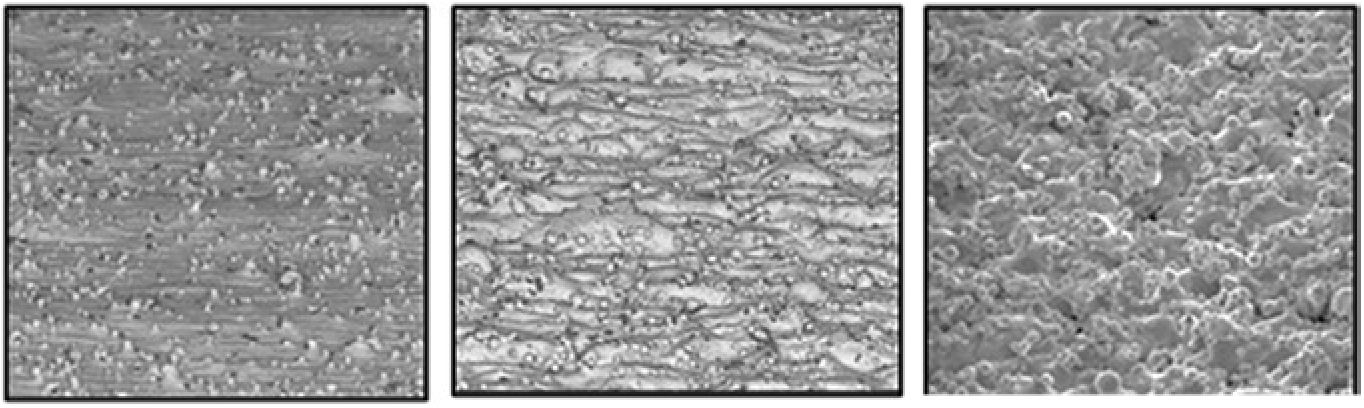

Figure 2. Range of surface roughness levels achieved through AM processing parameters [3].

to successfully print by changing the print parameters and build direction. While capabilities have improved over recent years, LPBF parts must still have post-manufacturing processes such as conventional electron beam machining of holes.

Probably the most interesting aspect of the AM industry is the entrepreneurial draw resulting in a rapid growth of small companies who claim to be able to print anything. However, such claims are not the case. Rather, those vendors who succeed are the ones with a base knowledge of component accuracy required for the turbine industry. In addition, because of the synergistic use of AM for turbines, the OEMs have begun to diversify their businesses. Some examples include Siemens Energy, who is making this a business strategy printing parts for other turbine companies; GE, who is manufacturing and selling LPBF machines; and Honeywell who is developing ceramic core printing processes.

Many challenges still remain in using the AM technology. Foremost is the quest for materials that can be 3D printed while still withstanding high temperatures and thermal stresses. The inherent roughness, which is always an important consideration in turbines, is important to be able to control and understand. Part-to-part variability, especially builds that span over time, often do not meet the tight controls necessary for turbine applications. Finally, to take the full advantage of AM, turbine designers need to think differently and continue learning about what is possible and what is not. ◆

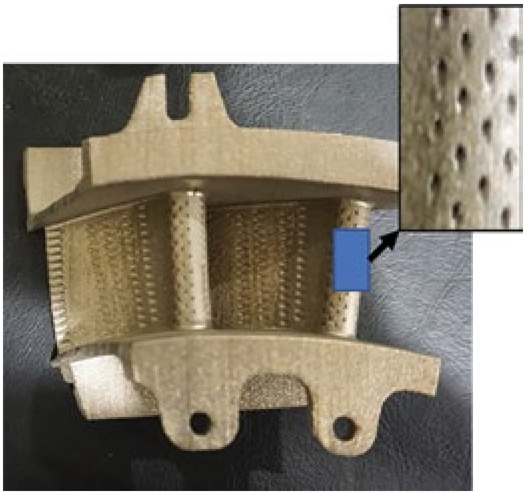

Figure 3. The same turbine vane design printed at two different vendors created variations in cooling hole performance due to changes in printing parameters. The top vane has cooling holes that are flowing while the bottom has minimal flow due to the cooling holes collapsing.

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Inspiring Pressure Gain Combustion Integration, Research and Education

A. Andreini (UNIFI), M. Bohon (TUB), T. Poinsot (CERFACS), M. Bellenoue (ENSMA), A. Sorce (UNIGE), S. Zurbach (SAFRAN), M. Mihaescu (KTH), S. Salvadori (POLITO)

The thermodynamic cycle used in a gas turbine (GT) has undergone little change since its early development. Over the last decades, effort has been put into increasing efficiency through reducing losses and raising overall pressure ratio and peak temperature. To break out of the current limits, a different cycle is required. One of the most promising is the case of Pressure Gain Combustion (PGC). The key objective of PGC is to achieve an increase in the thermal efficiency through a reduction in the entropy generated across the flame by no longer utilizing the isobaric heat release process of traditional devices and instead allowing for an increase in pressure. This is achieved by imposing some form of confinement during the heat release. This confinement is either a mechanical confinement as in a constant volume combustor or an aerodynamic confinement such as within a detonation wave.

In an effort to develop this technology, the EU MSCA Innovative Training Network INSPIRE – INSpiring Pressure gain combustion Integration Research and Education (inspire.cerfacs.fr/en/) has assembled a pan-European team to study the possibility of PGC solutions on an integrated level. This training network is composed of 8 research institutions as beneficiaries supported by 8 additional collaborative partners, hosting 15 Ph.D. students distributed across Europe. The research focus of the network focuses on two combustor technologies; incorporating the subsonic flames of Constant Volume Combustors (CVC) and supersonic flames in the form of detonations in a new combustor technology known as Rotating Detonation Combustion (RDC). One of the fundamental differences between PGC and traditional technologies is the inherent high level of unsteadiness in a PGC system which necessitates additional work areas

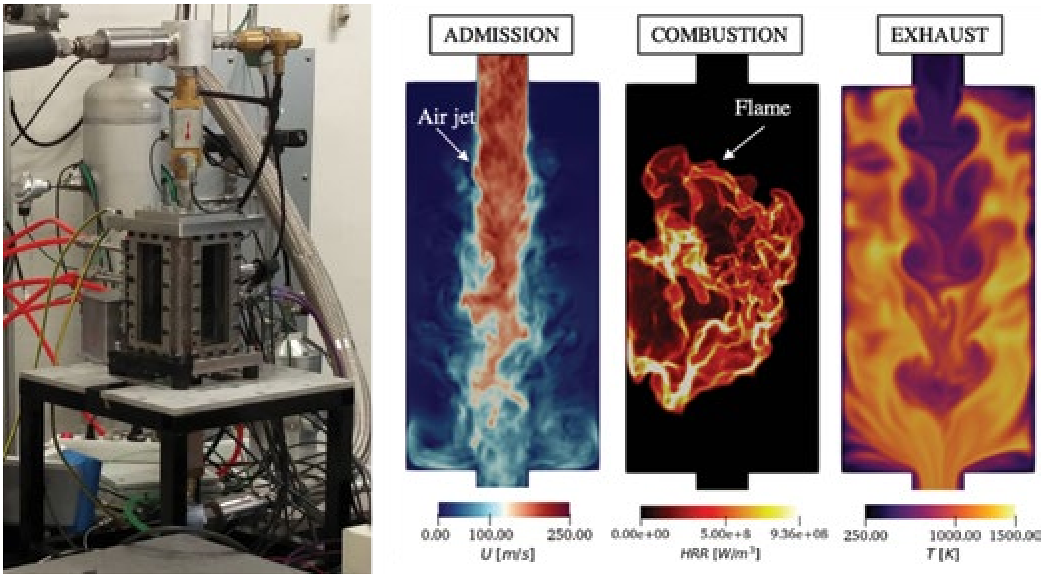

Figure 1. Experimental aparatus (left) and LES simulations (right) of the flow field of different phases within the constant volume combustor (CVC)

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[1] Marie Skłodowska-Curie Actions

[2] H2020-MSCA-ITN-2020, GA: 956803

within the network. These areas will aim at studying the main phenomena and technologies required to enable PGC solutions in actual GTs. Such topics include the heat transfer, unsteady components interaction, noise generation, and overall system performance in addition to the fundamental numerical and experimental investigations of the reactive processes occurring in the combustors. The objective of the INSPIRE network is to endeavour to develop PGC technologies further, better understand the practical implications of changing the combustor principles, and develop means and methods to handle the unsteadiness induced by the combustion.

In essence, it is the unsteadiness of the involved processes that motivates much of the work within the INSPIRE network. As shown in Figure 1, the laboratory-scale constant volume combustor is composed of a relatively simple geometry with valved inlets and outlets, the phased opening and closing of which results in a rigid volume that must undergo cyclic operation of reactant injection, combustion, and then exhaustion of burned products, typically in the range of 10’s-100’s of Hertz. The photo on the left highlights the configurable combustion vessel (approx. 0.65 L up to 20 bar) for characterizing the various stages of the cyclic process. LES simulations of these processes are shown in the three instantaneous snapshots on the right. The first snapshot shows the high velocity air jet during the reactant admission phase. While not visible in this image, the fuel is also injected during this phase and allowed to mix. The second image shows the heat release rate as the spark ignited flame expands within the fixed volume. The last image shows the temperature field as exhaust process is underway. Technically, these cyclic processes introduce many interesting challenges with respect to mixing and ignition as well as requiring a better understanding of the influence of residual burned gases and the effect of cycle-to-cycle variation. Current research is focused on better understanding the fundamental aspects of the in-chamber gas states (in terms of pressure, temperature, residual gas composition, velocity, and mixing quality) and their effect on the cyclic operation of the combustor, ignition, and combustion efficiency through both experimental and high-fidelity LES simulations.

Along a similar track, but with a fundamentally different combustion process, the unsteadiness in a RDC originates in the cyclical passage of a detonation wave propagating circumferentially in an annular combustion chamber. This combustion wave, typically propagating around Mach 4 or near 2000 m/s, traverses the perimeter of the combustor at a frequency in the range of several kHz and a thermal power density that is at least an order of magnitude higher than a constant pressure combustor. In the short period of time between successive wave passages, reactants are injected and mixed within the refill zone. The resultant operation results ideally in a quasi-steady flow field as shown in Figure 2. The photo on the left shows the 90 mm diameter, 2 MW thermal power, H2/Air laboratory burner at TU Berlin. This configuration runs at pre-detonation pressures up to approx. 3 bars and is configurable for various injector and outlet geometries including nozzle guide vanes or aerospike nozzles producing thrust up to about 1 kN. The middle image shows high fidelity LES of the mixing and detonation zone within the combustor. Here one can see an iso-contour of the pressure field highlighting the detonation wave surface and max pressures in excess of 10 bars. While the scale is difficult to interpret from this image, the height of the detonation wave is only approximate 40 mm within a thermal power of approximately 1.6 MW. The last image on the right shows a simplified “unwrapped” 2D solution of the temperature field where the thickness across the annulus radius is neglected. Here it is easier to see the characteristic flow field of the RDC, composed of a detonative reactive front propagating into the refill zone where fresh reactants are injected and mixed. The detonation products then expand into the downstream end of the combustion chamber where there are potentially processed again by an oblique shock attached to the detonation wave. This image demonstrates one of the major challenges where, despite the low residence times, the

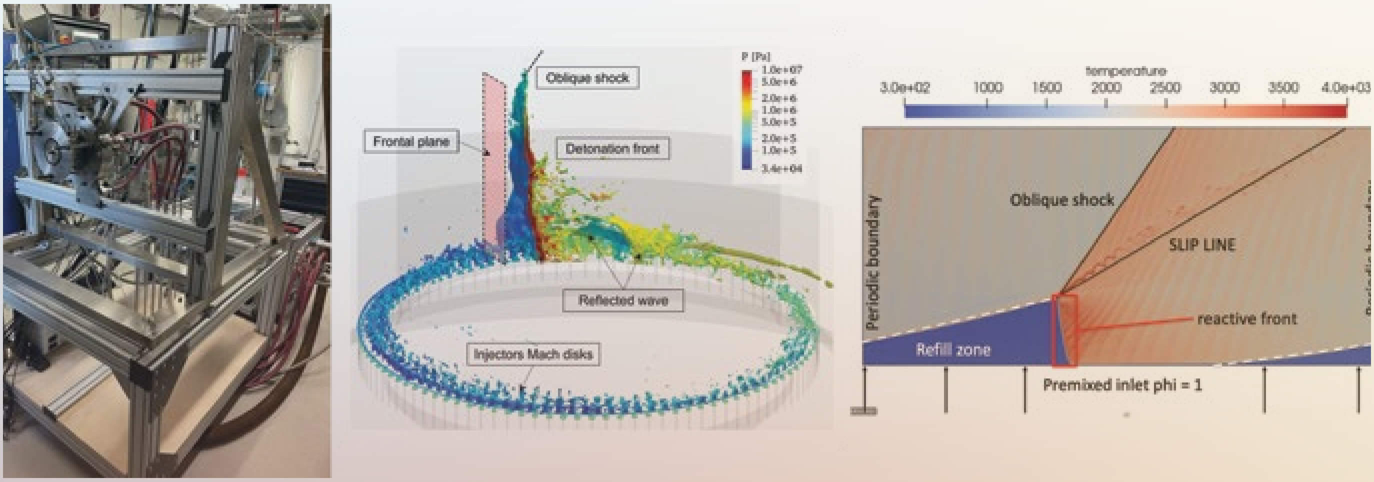

Figure 2. Experimental RDC (left) with LES illustrating the structure of the detonation wave (middle) and the unwrapped temperature field within the annulus (right).

high temperatures and mixture reactivity has the potential for significant deflagrative pre-burning at the interface between burned products and fresh reactants which must be avoided to maximize pressure gain as it represents a reduction in maximum performance. Additionally, achieving a sufficient mixture quality in the short mixing period is complicated by the very high reactant flow rates and the objective of minimizing the total pressure loss through the reactant injection while minimizing backflow following the detonation wave passage.

In both combustor technologies, the unsteady combustion results in a fluctuating outflow that then needs to be efficiently expanded. This process presents an additional area of focus within the INSPIRE network, in that efficiently extracting work from this fluctuating flow such that the hard-won efficiency gains in the pressure gain combustion process are not lost due to lower efficiencies in the high-pressure turbine or nozzle. Therefore, within the network, a major research focus is on interventions in terms of exhaust section designs that can efficiently attenuate fluctuations as well as turbine aerodynamic designs capable of handling higher fluctuations. These studies include the development of a co-flow mixer to reduce the combustor exhaust temperature and attenuate the oscillation amplitudes. The network will also focus on design optimization to efficiently attenuate these fluctuations while connecting to the high pressure turbine as well as the aerodynamics of the turbine blades in the unsteady flow. Lastly, this unsteadiness has implications for the cooling and thermal management within the combustion chamber and high-pressure turbine stage. The combination of the fluctuating flow with the higher power densities (especially in the case of the RDC) means that new cooling schemes are being investigated.

A final area of focus within the network is to predict and understand the expected efficiency gains and the integration of PGC devices in systems for power generation and propulsion. This requires the development of fast modelling tools that can incorporate the unsteady combustors for the purposes of system design and optimization. This requires developing lower order models of these complicated physics while maintaining a sufficient fidelity to yield accurate models for thermodynamic analysis and optimization.

The INSPIRE project, and the related 15 Ph.D. paths, will close by the end of 2024. The next two years will see the organization of several related events such as qualified training workshops for the Ph.D. students and dedicated dissemination actions. Additionally, research progress is already being published in the relevant journals and conferences. According to EU Open Science practices all the scientific papers produced on INSPIRE results will be open access and related data publicly disclosed. Therefore, we invite those who are interested to continue to follow this space. ◆

CONTACTS

Project Coordinator:
Prof. Antonio Andreini (antonio.andreini@unifi.it)
Project Email:
info@inspire-etn.eu

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The project INSPIRE has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956803

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Both the Aircraft Engine Technology Award and the Industrial Gas Turbine Technology Award have an application deadline of **October 15**. Applications may be emailed to igtiawards@asme.org.

Nominating letters should contain all information on the nominee's relevant qualifications. The Award Committee will not solicit or consider materials other than those described below. The selection committee will hold nominations active for a period of three years. A minimum of two supporting letters from individuals, other than the nominator, must accompany the nominating letter. Including a CV would be appreciated. Supporting letters should reflect peer recognition of the nominee's breadth of experience with various aspects of industrial gas turbine technology.

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- Nomination letter
- Two supporting letters
- Current resume of the nominee

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