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AERO ENGINE CONCEPTS BEYOND 2030:
PART 3 – EXPERIMENTAL DEMONSTRATION OF TECHNOLOGICAL FEASIBILITY

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ABSTRACT

Recognizing the attention currently devoted to the environmental impact of aviation, this three-part publication series introduces two new aircraft propulsion concepts for the timeframe beyond 2030. The first part focuses on the novel steam injecting and recovering aero engine concept. In the second part, the free-piston composite cycle engine concept is presented.

Complementary to the two technical publications, this third part describes the cooperative project, which was initiated by an interdisciplinary consortium, aiming at the demonstration and the proof of concept of both aforementioned aero engine concepts.

At the beginning of the project, simulations on propulsion, aircraft system, and test bench level will be conducted. On this basis, preliminary tests and fundamental experiments are planned in order to establish a solid basis for the demonstration. Finally, a system demonstration will be carried out at the laboratory level. Thus, the project allows for a final judgement on both the feasibility of the new concepts and the attainability of the requirements for future aircraft propulsion systems.

Keywords: CLIMATE NEUTRAL AVIATION, EXPERIMENT, DEMONSTRATION, REVOLUTIONARY AERO ENGINE, STEAM INJECTION, WATER CONDENSATION, WET COMBUSTION, COMPOSITE CYCLE ENGINE, FREE-PISTON, CLOSED VOLUME COMBUSTION

NOMENCLATURE

List of Symbols

$\dot{m}$	kg/s	Mass flow
p	kPa	Pressure
S	-	Saturation level
WRF	-	Water recovery factor
x	-	Molar fraction

List of Subscripts and Superscripts

i	Insertion of water into the system
r	Recovered liquid water from the exhaust flows

List of Acronyms

CCE	Composite cycle engine
CFD	Computational fluid dynamics
Claire	Clean air engine (MTU's technology agenda)
FADEC	Full authority digital engine control
FP-CCE	Free-piston composite cycle engine
HRSG	Heat recovery steam generator
M250	Rolls-Royce Model 250 gas turbine
SAF	Sustainable aviation fuel
SIRA	Steam injecting and recovering aero engine
TMC	Transport membrane condenser
TRL	Technology readiness level
WP	Work package

1 INTRODUCTION

In civil aviation, the conventional gas turbine prevails as the propulsion system for larger aircraft (>100 passengers). It has undergone enormous technological developments since its invention. The Strategic Research and Innovation Agenda (SRIA) targets further significant improvements on engine level: CO_2 emissions per passenger kilometer should decrease by 30 % by 2035 compared to the year 2000 technology standard [1]. At present, it seems possible that the Joule-Brayton cycle-based gas turbine will meet those targets through continuous but increasingly expensive technological improvements.

With an average growth rate of the worldwide air traffic of approximately 5.0 % per year and an overall aircraft efficiency improvement of approx. 1.5 % per year, the global aviation kerosene consumption increases by approximately 3.5 % annually [2].

The combustion of kerosene in the gas turbine produces carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), unburned hydrocarbons (UHC), carbon monoxide (CO), sulfur oxides (SO_x), aerosols, and soot particles. Although in 2015 civil aviation accounted for only 2.69 % [3] of the emitted anthropogenic CO_2 emissions, its climate impact, that is the radiative forcing, was estimated to be two to three times higher [4, 5]. Besides the commonly discussed CO_2 emissions, both H_2O and NO_x contribute to climate change. At typical flight altitudes and correspondingly low temperatures, condensation trails (contrails) form from the water vapor in the exhaust gases. NO_x contributes to the formation of ozone and the depletion of methane, both of which are green-house gases.

In order to avoid an excessive global temperature increase, aviation has defined challenging emission reduction goals for the year 2050 [1, 2, 6]. Considering the increasing growth in air traffic in combination with the approaching physical limits of the known gas turbine cycle, continuous development of today's gas turbine engine will not suffice and, thus, radical ideas for novel aero engine concepts are inevitable.

For this reason, in this three-part publication series, two innovative aero engine concepts are presented, each capable to significantly reduce climate-effective emissions. Part one [7] introduces the steam injecting and recovering aero engine concept (SIRA), which recovers exhaust heat by generating steam from condensed water. The concept promises considerable fuel burn reduction and almost complete avoidance of contrails and NO_x emissions. Part two [8] introduces the free-piston composite cycle engine (FP-CCE) concept, which combines the turbofan architecture with a free-piston engine in the high-pressure core. The piston engine leads to considerably improved thermal efficiency and, thus, reduced CO_2 and water emissions.

As contributors in international aerospace industry and research, MTU Aero Engines (MTU), the German Aerospace Center (DLR), the University of Stuttgart (UniS) and Bauhaus Luftfahrt (BHL) have jointly launched a cooperative project, named *DINA2030*$^+$, to experimentally demonstrate the proof-of-concept of major components of the two new aero engine concepts at a very early stage. In the current preliminary design phase, both concepts show the potential to achieve and even exceed the emission targets for 2050.

1.1 The steam injecting and recovering aero engine

In part one [7] of this publication series, based on consistent thermodynamic descriptions, preliminary designs, and initial performance studies, the steam injecting and recovering aero engine concept potentials are analyzed. Complementarily, a detailed discussion on concrete engineering solutions considers the implementation into aircraft. Finally, the impact on emissions is outlined.

As shown by the scheme in Figure 1, in the SIRA concept, exhaust heat generated steam is injected into the combustion chamber. By use of a condenser, which is installed behind the steam generator, the water is recovered from the exhaust gas-steam mixture. The humidified mass flow contains significantly more extractable energy than air. Furthermore, the pumping of liquid water up to the necessary pressure requires a magnitude less power than the compression of air, which reduces the internal power demand. Both lead to a notable increase in specific power compared to a conventional gas turbine and, foremost, to a significant increase of thermodynamic efficiency [7].

The proposed concept is expected to reduce fuel burn and CO_2 emissions by about 15 % and NO_x formation can be almost completely avoided compared to state-of-the-art engines of the same technology level. Moreover, the SIRA concept has the potential to drastically lower or even avoid the production of condensation trails. Operated with sustainable aviation fuels (SAF)

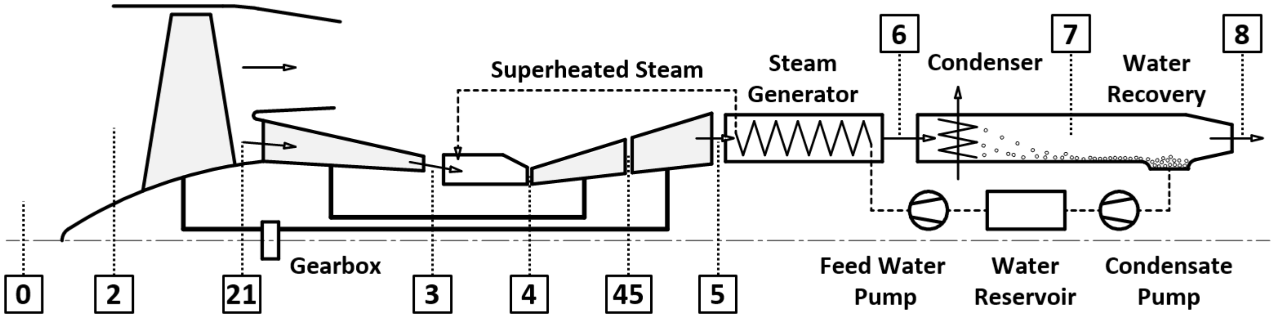

FIGURE 1: Scheme of a half side arrangement of the proposed steam injecting and recovering aero engine (SIRA) concept supplemented with international engine station nomenclature [9].

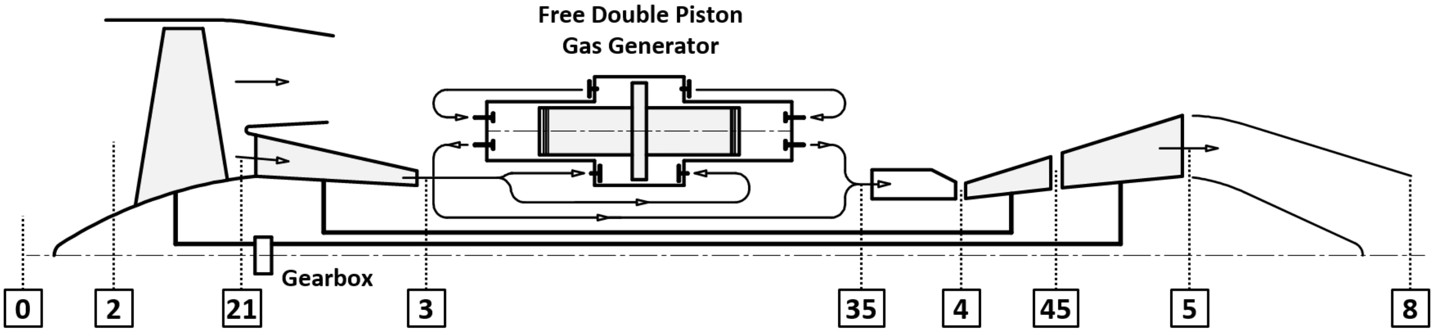

FIGURE 2: Scheme of a half side arrangement of the proposed free-piston composite cycle engine (FP-CCE) concept supplemented with international engine station nomenclature [9].

the novel concept offers the potential for climate-neutral aviation.

1.2 The free-piston composite cycle engine

In Part two [8] of this publication series, the proposed FP-CCE design is described in detail and thermodynamic benefits are as well as concrete engineering solutions are discussed.

The FP-CCE concept as schematically drawn in Figure 2 is composed of a gas turbine topped with a free-piston system. The latter is a self-powered gas generator, in which the internal combustion process drives an integrated air compressor. Here, several free-piston engines replace the high-pressure core of the gas turbine. Through the ability to work at much higher temperatures and pressures, the overall system efficiency can be increased significantly, and fuel burn, as well as CO_2 emissions, reduce by about 15 % [8].

The specific design enables lower weight and size, as no mechanical transmission and lubrication system is required. The absence of a crankshaft and connecting rods eliminates reactive forces and reduces mechanical losses and, thus, allows for higher mean piston velocities. Facilitated through air lubrication, higher cylinder temperatures are possible. The reduction of heat losses allows keeping the heat losses of the piston within the composite core engine. The use of a sequential combustion chamber offers the potential to enhance operability and to tailor the production of NO_x in low-altitude operation. A detailed discussion of environmentally-effective emissions shows the potential to reduce the climate-warming impact of aviation.

2 PROJECT DESCRIPTION

During the last decades, aviation technology reached an all-time high degree of maturity. This high standard has made it extremely challenging to further improve those systems without compromising their reliability. The development of new aero engines for large civil transport aircraft, today, is a significant effort in time and costs. In order to take this not least economic risk, the start of a development project will, therefore, be based on well-understood technology with a high technology readiness level (TRL). For example, it took decades from the begin of development of the gearbox for the geared turbofan (GTF) to its maiden flight. According to the International Air Transport Association (IATA) [10], TRL development for engine technologies from level two towards maturity typically takes ten to 20 years.

If the development of evolutionary and less radical technology for conventional aero engines is already as complex, how long will it take to industrialize any revolutionary, unknown and unconventional concepts, such as those introduced at the beginning of this paper?

To this end, the four-year project DINA2030$^+$ was initiated based on the idea either to prove the feasibility of two innovative propulsion concepts or to refute them scientifically correct as early and pragmatically as possible. DINA2030$^+$ is an acronym for the German project title "*Demonstration innovativer Antriebskonzepte für 2030+*". In English, this reads: "Demonstration of innovative propulsion concepts for 2030+". Within the scope of DINA2030$^+$ the two revolutionary aero engine concepts introduced in Section 1, SIRA [7] and FP-CCE [8], will not only be investigated numerically, but the technical feasibility of key systems (proof-of-concept) will also be demonstrated experimentally. The targeted TRL is three, which refers to an analytical and experimental critical proof-of-concept [11].

2.1 Interdisciplinary consortium

Both concepts, the SIRA and the FP-CCE, were invented and first evaluated by MTU. Based on initial potential studies, MTU decided to initiate the DINA2030$^+$ project to further detail the assessments towards an experimental demonstration and to identify possible show-stoppers at an early stage. Since both concept architectures and their technologies strongly differ from those of gas turbine engines, the necessary disciplines for a holistic and consistent investigation have been brought together and the following interdisciplinary consortium has been jointly formed.

MTU Aero Engines

MTU is Germany's leading aero engine manufacturer and has been a key player in the global engine industry for 85 years.

MTU excels in high-pressure compressors, low-pressure turbines, turbine center frames, as well as manufacturing and MRO services. The company invented and holds patents [1214] of the two revolutionary aero engine concepts presented in this paper and, beyond, has overall propulsion system design and evaluation competence based on its program experience.

DLR Institute of Combustion Technology

The DLR-VT[1] is focused on combustion research topics, ranging from fundamental chemical kinetics to the development of novel measurement technics and simulation tools to develop and test gas turbines combustion chambers. The institute operates combustion test benches from one to 40 bar pressure as well as several highly instrumented, customized micro gas turbine test rigs with electrical power outputs from one to 350 kW.

DLR Institute of Vehicle Concepts

The past research and development activities at the DLR-FK[2] include the conceptual design of different free-piston engine concepts. Two types of free-piston combustion chambers have been designed and tested with a multitude of additional research. Thereby, the institute has gathered experience in innovative combustion processes and alternative fuels.

Institute of Aerospace Thermodynamics

The ITLR[3] at the University of Stuttgart contributes with expertise in convective heat transfer and water condensation. It can further rely on strong expertise in the investigation of sprays and droplets. All of these will feed into the design of a generic experiment to investigate different methods of water recovery needed for the SIRA concept.

Bauhaus Luftfahrt

BHL focuses on the multi-disciplinary conceptual design and aircraft-level evaluation of advanced propulsion system architectures as well as tightly-coupled propulsion-airframe integration options. BHL's expertise covers alternative energy technologies as well as heat engines featuring novel thermodynamic cycles. As part of this, several studies on key aspects of the composite cycle engine concept [1518] have been conducted.

2.2 Timeframe and funding

DINA2030$^+$ was set up for a period of four years with a split into two funding phases. The first two-year funding phase started in December 2019 with a German grant from the 3rd call of the Federal Aviation Research Program V. The estimated overall project budget is several million euros, of which more than three million euros will be invested in the first two years. In addition to the federal grant, MTU and DLR add own resources into the cooperative project. The overall project budget covers fundamental research, numerical investigation, preliminary tests, and the purchase of the test rig gas turbine (see Section 2.4).

2.3 Work package structure and implementation

In line with the visualization shown in Figure 3, the tasks of the proposed DINA2030$^+$ project are structured into three main work packages (WPs), complemented by the project management. WP1 and WP2 comprise tasks related to the SIRA and the FP-CCE concepts, respectively, while WP3 contains the tasks related to design and set up of the final test rig demonstration. From a chronological point of view, the tasks within each WP are additionally aligned in three technical project phases: conceptual design, preliminary experiments, and experimental demonstration. In Chapters 3 to 5, fundamental tasks of the work packages within each phase as well as their targets are described in more detail.

Basically, WP1 and WP2 have a similar sub-work package structure. In both cases, the WP1.1 and WP2.1 in the first conceptual design phase focus on the integrated numerical assessment of each concept on engine level as well as on aircraft system level. Based thereon, the work packages in the second phase are dedicated to the preparation, design and construction of the concept-specific preliminary experiments.

In WP3, the first phase focuses on the numerical modeling and simulation of the test rig. Thereafter, the second phase of WP3 contains the modular setup and the instrumentation of the test rig to finally allow for the demonstration in phase three.

In many ways, the DINA2030$^+$ project is challenging. The most obvious challenge is that the particular technological feasibility of not only one but two new revolutionary concepts will be evaluated through demonstration. However, a parallel test rig demonstration of two new concepts is neither feasible under the budgetary and temporal conditions nor meaningful with respect to the very different concept architectures. Therefore, the implementation of the final rig test demonstration, that is WP3.4 and WP3.5 as shown in Figure 3, is in sequential order. In the first instance, a test rig that represents the steam injecting and recovering aero engine concept will be operated as part of WP3.4. Hence, the related preparation tasks within phase two of WP3 also focus on this specific arrangement.

A test rig demonstration of the second concept, that is the free-piston composite cycle engine, would be conducted afterwards. The preliminary experiments that are prepared and performed in WP2 lay the basis for subsequent testing of the free-piston aero concept in WP3.5.

2.4 Base test rig gas turbine

A major prerequisite for the underlying project is the base gas turbine of the test rig. A Rolls-Royce Model 250, formerly known as Allison M250 and in the following referred to as M250, serves as the base gas turbine for subsequent modifications towards the demonstration major elements of both revolutionary aero engine concepts.

The M250 engine has a special architecture compared to conventional aviation turboshaft engines. The combustion cham-

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[1] DLR-VT refers to the German name “Institut für Verbrennungstechnik”.

[2] DLR-FK refers to the German name “Institut für Fahrzeugkonzepte“.

[3] ITLR refers to the German name “Institut für Thermodynamik der Luft- und Raumfahrt“.

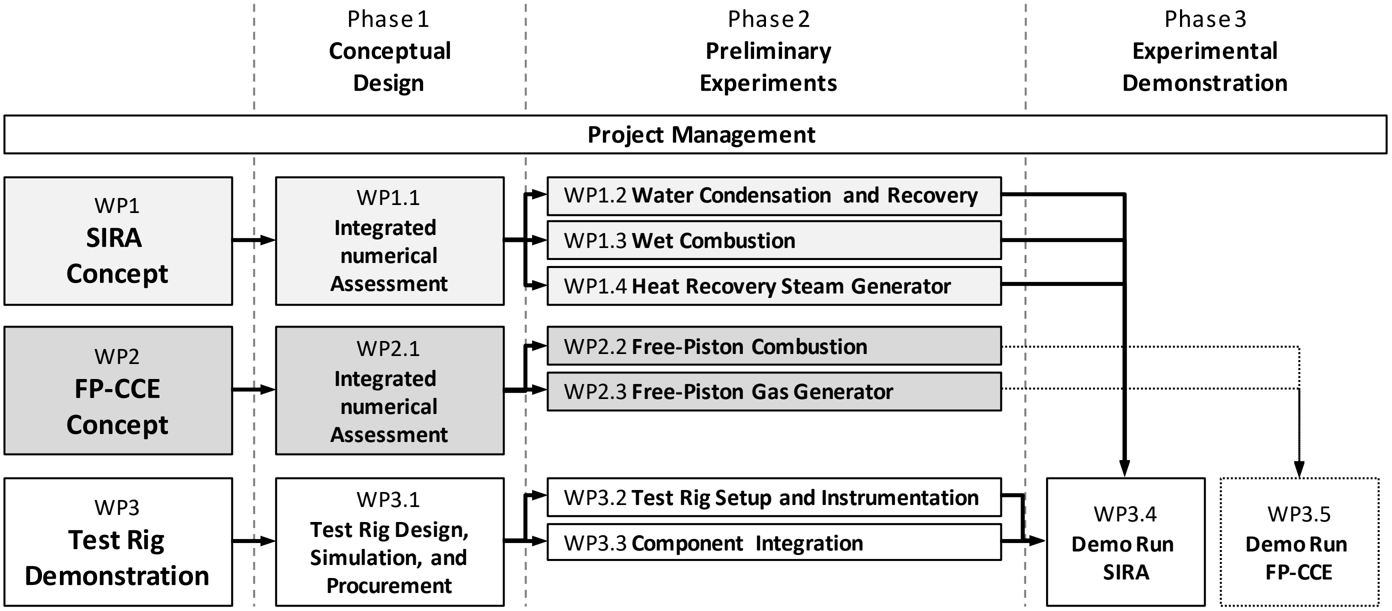

FIGURE 3: Work package structure of the DINA2030$^+$ project with a focus on the Steam Injecting and Recovering Aero engine (SIRA) and the Free-Piston Composite Cycle Engine (FP-CCE) concepts.

ber is designed as a counter-flow can combustor located outside of the rotating parts. Because of this arrangement (cp. Figure 5), the air from the compressor is guided to the combustor via two external tubes. This architecture allows for the decoupling of the mass flows downstream of the compressor and for the refeeding of external mass flows into the combustion chamber. This feature, combined with the easily accessible and replaceable combustion chamber, proves useful for the planned cycle demonstrations. Thus, the M250 gas turbine was chosen as the demonstration test rig for the DINA2030$^+$ project.

3 PHASE 1 – CONCEPTUAL DESIGN

In the first phase of the project, the primary focus lies on numerical assessments. The main target is to enable a statement on the fuel consumption (i.e. fuel burn) for a defined reference aircraft mission in particular and the emission production of each of the two concepts in general. Furthermore, the M250 test rig gas turbine, as well as the projected modifications, will be numerically mapped in order to allow for the design, construction and operation of required hardware and instrumentation.

To this end, in phase one, the major task lies within the development of numerical methods for mapping the new concept-specific components and underlying physics. Based on initial potential analyses, from the steam injecting and recovering aero engine concept point of view, methods related to steam injection, water vaporization, water condensation and recovery, as well as wet combustion are of most interest. The numerical mapping of the FP-CCE concept generally requires piston engine methods and, particularly, methods being capable of mapping the specific free-piston physics.

3.1 Initial potential analysis

Based on initial assessments, each concept has shown the potential to reduce fuel burn by about 15 % compared to an application of the same technology level. Further potential details may be found in part one and two of this paper series [7, 8].

The improvement potentials, however, dependent on the ability to overcome the expected technological limits. The newly implemented components are exposed to extreme aero conditions during operation, i.e. high pressures and temperatures, and need to provide low volumes and weights at the same time.

Both concepts, SIRA and FP-CCE, envisage the integration of technologies into aircraft, which are established and proven in ground-based applications today. The steam-enhanced concept utilizes heat exchangers, such as the heat recovery steam generator (HRSG) and the condenser, a steam-injected combustion chamber, and a novel water recovery system. The FP-CCE utilizes a novel free-piston gas generator (cp. [8], Figure 2).

During the project, the components will be scrutinized and the technology assumptions will be updated according to the findings in the subsequent experiments. Therefore, the improvement potential will be determined with increasing confidence during the project phases.

3.2 Development of methods

Firstly, the propulsion system conceptual design syntheses and performance simulations of both concepts have to be set up for the thrust requirements of predefined reference aircraft missions. Therefore, BHL uses its in-house software Aircraft Propulsion System Simulation (APSS) [19], in which a library of models for key aspects of the cycle and flow path design is available. The framework features high flexibility with regards to the synthesis and simulation of unconventional thermodynamic cycles and novel power plant system architectures. While a basis for the FP-CCE simulation and integration has been established already by conceptual design studies of different variants of the CCE concept in the past [15-18], numerical simulation of the steam injecting engine concept entails further efforts.

Indeed, the steam injecting engine concept requires the implementation of additional specific components like steam generator, condenser, liquid water recovery system and pump. Both design and off-design behavior need to be accounted for, as well as for phase change of the fluid, and for estimation of component volume and mass for integration and assessment at aircraft level. Moreover, potential new phenomena in existing components like fogging in the compressor, condensation in the turbine or in the nozzle have to be considered. Modification and extension of the current semi-ideal gas model have to be conducted in order to account for higher water-air-ratios as well as a phase changes.

Conceptual design studies will be conducted on both concepts in order to define an optimized propulsive system regarding fuel consumption, overall mass and volume.

Water condensation and vaporization

The key challenge of the steam-injected engine cycle is to recover the maximum possible amount of injected water from the exhaust gas in order to constantly supply fresh water for the cycle. Here, water may not only enter the gas turbine through artificial insertion but also through the engine intake as ambient humidity or as a fraction of turbine cooling flows. In addition, water is also supplied indirectly through its chemical creation as a result of fuel oxidation processes during the combustion.

The condensation and recovery of liquid water require further research on firstly how condensation affects the performance of the heat exchanger and on secondly how the water can be extracted from the exhaust gas. To the author's knowledge, so far only a little research has been published on these topics associated with gas turbines.

Condensation in heat exchangers has been addressed in the context of coal power plants to increase thermal efficiency by waste heat utilization by Wang et al. [20]. They demonstrated that 40 % of the exhaust gas water (at 16 % incident moisture content purely from the chemical reaction) could be recovered with an innovative heat exchanger design utilizing a transport membrane condenser (TMC). Even though this concept is promising, the size, weight and pressure drop might limit its applicability to an aircraft.

For a feasible aero application, the overall water recovery factor (WRF) needs to be increased beyond 40%, where

$$WRF = \frac{\dot{m}_{H20,r}}{\dot{m}_{H20,i}} \qquad (1)$$

is the quotient of the recovered water mass flow, $\dot{m}_{H20,r}$, divided by the total mass flow of water insertions, $\dot{m}_{H20,i}$, which directly or indirectly enter the gas turbine system.

Condensation and water separation has been further addressed in other areas, e.g. in charge air coolers, applied to prevent pre-ignition of turbocharged engines. Choi et al. showed that different types of vane separators efficiently isolate the condensate prior to combustion [21]. Moreover, Cash et al. argued that condensation can be reduced or even avoided by solely optimizing the geometry, for which they developed a validated simulation methodology [22]. However, the water content within such intercoolers is low compared to the present case and the results are thus difficult to transfer.

Condensation within the condenser might impede the overall heat transfer if a water wall film forms [23]. Thus, the ideal condenser for this application should exhibit flow properties that only allow water to collect at locations where it can be easily removed. Nevertheless, we aim to use an "off the shelf heat exchanger" for the demonstration purpose. If the demonstrator succeeds, a full-scale heat exchanger will be carefully designed that is optimized for the boundary conditions imposed by an aircraft engine. Even though a significant part of the water will be collected within the condenser, it is unlikely that the targeted WRF can be met. That is why an additional water separator is needed, which collects the water drops from the exhaust gas downstream of the heat exchanger.

Common water separators are usually based on the exploitation of inertial and centrifugal forces [24], for example, swirl generators [25] and vane-type separators [26]. Another promising concept is to enhance the droplet deposition and growth at the walls where the condensate can be directly collected, for example by the application of micro pin fins [27].

Thus, one of the main objectives of the present cooperative project is to investigate, which of these approaches is most suited for water recycling from the exhaust gas of the SIRA aero engine concept, that is preferably within a short distance, at high speed and with little pressure loss.

Wet combustion

Combustor development for the steam-injected engine concept is in many ways challenging since a lot of different aspects have to be investigated. Humid air combustion has been studied previously, however many of those studies are limited to mainly gaseous combustion and stationary energy system applications or low water loads. Overviews on studies dealing with wet conditions in gas turbines can be found in the literature [28, 29].

In the present project, a combustion system for kerosene fuel (e.g. Jet A-1) with high water loads is developed. The liquid-fueled system is embedded into the well-established FLOX® combustor technology. The main challenge in the development is the combination of spray processing of conventional kerosene alongside with high water loads and, at the same time, the integration into jet-and-recirculation stabilized combustion. However, several benefits are expected from this.

Combustion systems operating at wet conditions are promising since they feature drastically reduced NO_x and CO emissions with low water addition already [28]. This is an important aspect of the framework of liquid combustion since liquid fuel processes tend to show increased NO_x emissions.

Especially NO_x emissions are reduced in wet combustion since peak temperatures are decreasing. This is due to increased specific heat capacities. Reduced oxygen concentrations additionally lower NO_x formation processes [29]. Therefore, a shift in chemistry processes contributes to pollutant emissions decrease, besides the reduction of peak temperatures [28].

The embedding of the combustion process into the FLOX® technology intends the utilization of key benefits of this combustor type. Those are particularly stable combustion with at the same time very low risks of flame flashback and thermo-acoustics.

Free-piston engine

A main challenge in the FP-CCE concept is the free-piston gas generators. The aim of the project is to utilize an Atkinson-like, two-stroke cycle combustion unit. After a short compression phase, the fuel-air mixture ignites and the expansion takes place until the gas exchange is started by the valve-control. The gas exchange will take place under pressure conditions, which are unusual for any internal combustion engine. Therefore, evaluating the basics of the gas exchange and unsteady combustion under these conditions is an interesting challenge. Yet, the high pressure and thus high temperature during ignition is a cause for NO_x emissions, leading to the necessity of testing uncommon combustion strategies such as rich mixture combustion.

A further question is how the stability of the pistons' oscillation can be controlled. Intermittent combustion faces fuel mixing variations for each ignition. Depending on the system's internal balance between the two combustion chambers and the two compressor chambers, a control system needs to be implemented. Likewise, as the FP-CCE concept would integrate multiple free-piston units, an even phase-shift between the moving units is necessary to minimize the mass flow variation and vibrations for the core engine.

3.3 Integrated aircraft assessment

Besides a system demonstration at the laboratory scale, the project also aims at evaluating both the SIRA and the FP-CCE concepts at aircraft level. Aero engines are optimized conventionally for minimum fuel burn, which is the best compromise between improved overall engine efficiency, weight and volume. In addition to the conventional engine optimization parameters – such as overall pressure ratio, combustor exit temperature, specific thrust, compressor pressure ratio split – the new components of both concepts add a multitude of new simulation parameters, which will be investigated and used for optimization. For the assessment at aircraft level, a reference aircraft (e.g. Airbus A320-like) with thrust requirements between short-to-medium and long-range applications will be selected at the beginning of the project.

Retained conceptual designs will be integrated at aircraft level, with respect to mechanical, aerodynamic and thermal aspects. Previous studies featured a compact propulsion system with a relatively simple integration interface, such as the FP-CCE. In contrast, the integration aspects for the steam-enhanced engine are more challenging, especially considering additional equipment like vaporizer, condenser and water recovery systems. Indeed, those components are expected to have considerable volume, which has to be integrated into the cell and leads to a direct impact on drag and mass models. These effects have to be evaluated considering cascade effects.

In parallel, a numerical model at rig scale will enable to return the knowledge of experiments to both the propulsion system conceptual design synthesis and the performance simulation environment. This way the numerical component models of both the FP-CCE and the SIRA concepts can be validated.

4 PHASE 2 – PRELIMINARY EXPERIMENTS

In the second phase of the project, experiments are the focus of the work package tasks. Building upon the findings gained in phase one, the main target of phase two is to proof and to validate the numerical models. Furthermore, the implementation of experiments serves as testing of both the functionality as well as the construction and manufacturing process of preliminary component designs, which are required for the rig demonstration in phase three.

As drawn in the work package structure shown in Figure 3, the sub-work packages WP1.2 to WP1.3 are related to the steam injecting and recovering aero engine concept. In WP1.2, the condensation and recovery of water are fundamentally investigated. WP1.3 focuses on combustion with large amounts of steam. WP1.4 investigates initial aspects of a heat recovery steam generator. However, in the last sub-work package, no experiment is planned yet. The first two sub-work packages are described in detail as follows.

4.1 Condensation and water recovery (WP1.2)

Considering the SIRA concept, a small-scale water separation test rig is currently designed at ITLR to evaluate different methods that can be applied to recycle the remaining water downstream of the condenser. At this location (engine station 7, see Fig. 1), the condensation process is completed and the flow can be treated as adiabatic. Thus, the goal of these experiments is to investigate droplet growth and their deflection and accumulation.

Because no details on the condenser are available yet, these experiments will represent a "worst-case scenario" assuming that all water is evenly distributed as little droplets in the gas flow (fog). Therefore, ambient air will be saturated with water by an evaporator system and then strongly oversaturated to the desired set point with a number of fog nozzles before entering the test section.

Figure 4 shows a schematic of the test section. It consists of three symmetric modules that can be easily exchanged, redistributed or flipped: The first module allows investigation of the incident drop size (without swirl) or to add a swirl to the flow when equipped with a swirl generator. The second module has an exchangeable upper wall, where micro pin fins or separating walls can be added to the flow. The third module is equipped with three sloping channels to collect the condensate at its end.

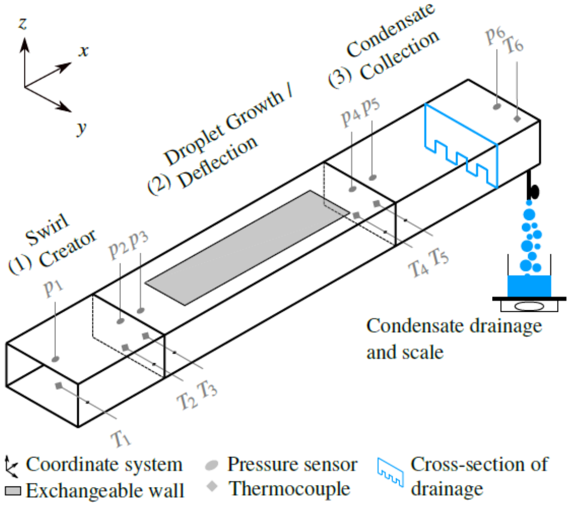

FIGURE 4: Schematic of the flow channel for basic water separation experiments at the ITLR.

All modules have a rectangular cross-section of approx. $4 \times 2.5\ cm^2$ and are fabricated from Plexiglas to allow for the application of optical measurement techniques. The maximum cross-section is limited by the capacity of the evaporator system and the maximum velocity to be investigated. All experiments will be run for two different operational points, which represent take-off and cruise conditions, as well as different flow Mach numbers. The results will be used to evaluate a numerical model and to validate 3D computational fluid dynamic (CFD) simulations of the two-phase flow that can be applied to design the full-scale water separator for the demonstrator test rig.

4.2 Wet combustion (WP1.3)

The goal of this subproject is to develop, integrate and test a combustion chamber for the M250 gas turbine, which can handle high contents of water vapor in the combustion air of the steam injecting and recovering aero engine concept. Due to its high combustion stability range and its low exhaust gas emissions, a FLOX-based combustor utilizing Jet A-1 will be designed for water vapor contents up to 20 % by mass. The novel liquid-fueled combustor will be based on the F400s.2 [30] micro gas turbine combustor of the DLR.

At first, a generic experiment will analyze the influence of increasing water vapor in the combustion air on the emissions and stability of a single nozzle FLOX-based combustor utilizing Jet A-1. Based on this knowledge a preliminary combustor design is set up for the steam-enhanced engine cycle including modification of the reaction mechanism, modification of the geometric parameters of the combustor taking into account the thermodynamic boundary conditions, a preliminary design of the fuel staging concept and the initial operating strategy as well as the selection of the spray injectors. Subsequently, a detailed CFD study will be conducted varying geometric parameters, load points and water vapor contents. Iterations will close the loop between preliminary design and CFD. The resulting design will be manufactured to fit into DLR's high pressure, single burner test rig (HBK-S) [31]. An external vaporizer will feed the water vapor into the air supply of the rig. By variations of fuel power, equivalence ratio, water vapor content and fuel staging split, the combustor will be characterized experimentally regarding combustion stability, flame shape and position as well as exhaust gas emissions. The results will be fed into the CFD in order to optimize the combustor design. Single burner rig tests will be conducted once again for the second optimized combustor at selected load points. This will lead to a derived combustor operating strategy, which can be applied to the M250 gas turbine rig. On the basis of the operating strategy, the secondary airflow will be designed by CFD. Finite element modeling will be used to calculate the structural integrity of the combustion chamber and optimize its design with respect to gas turbine integration. Then, the manufactured combustion chamber system will be integrated into the demonstration rig (cp. Chapter 5).

4.3 Free-piston combustion (WP2.2 and WP2.3)

No known test bench fulfils all the conditions for the intermittent combustion in the FP-CCE with high intake pressures and temperatures. Thus, a task of the DLR-FK is to analyze the conditions and to investigate how a test bench setup must be designed to represent them.

The most straightforward option is utilizing a common single-cylinder test bench, redesigning a crankshaft to demonstrate the two-stroke cycle, adding an external charging system to raise the pressure and supplying exhaust gas backpressure through nozzles or a turbine. The many uncertainties in such a test bench adaptation could make it necessary to focus on reproducing the conditions in the combustion unit at ignition and during the expansion. This would allow for important conclusions regarding the emissions of the free-piston combustion. To facilitate such a comparison, the development of the free-piston combustion unit will be supplemented by various 3D CFD simulations, which will likewise be validated by the result of the test bench. The aim is to create a basic understanding of the combustion under the special conditions, allowing the design of a free-piston engine that could be coupled with a gas turbine for the next steps of demonstration.

With the help of CFD simulations, the gas exchange under extremely high boost pressures has to be investigated in the first step since the in-cylinder flow motion, defined by the port geometry and timing, affects the combustion process in the high-pressure phase. However, the composite engine cycle presumably allows new combustion concepts since the exhaust gases flow towards the combustion chamber of the turbine instead of the exhaust after-treatment used in conventional engines.

The different operation strategies are to be investigated experimentally in the next step. The characterization of the engine performance also allows the validation of the simulation models. The experimental analysis contains exhaust gas measurements in order to understand the effects of NO_x formation during combustion.

5 PHASE 3 – EXPERIMENTAL DEMONSTRATION

As initially outlined in Section 2.2 and shown in Figure 3, in the demonstration phase three, the principles of the novel steam-enhanced aero engine concept will be installed and tested first, followed by the FP-CCE concept.

In this first phase, the development of all steam-related components will be stepwise integrated into the gas turbine rig and tested. In order to design a flexible rig that is suitable to demonstrate both cycle concepts, the setup and design of the rig is supported by numerical assessment tools. A key challenge is to connect the novel concept components to the M250 gas turbine flow path and to achieve and maintain a stable gas turbine operation. The major goals of the demonstration are to evaluate the feasibility of the technical realization, to identify further needs of component development, and to provide validation data and correlations for the numerical tools.

5.1 Design and process simulations (WP3.1)

Developing and modifying the demonstration test rig will be a joint effort of all partners. Numerical process simulations are closely integrated to support all design stages. The simulation tools used are described in detail in the literature [19, 32, 33]. First, cycle models of the M250 gas turbine are built up and verified based on data from the literature. On one side, they are used to derive boundary conditions for the development of the test rig infrastructure; on the other side, they are required for preliminary sensitivity studies in order to predict the impact of the M250 cycle modifications on system performance. As an example, the effects of pressure losses due to additional peripheral ducting can be investigated and the ability to operate the system under high load can be analyzed. In order to simulate the gas turbine operation under off-design conditions, compressor and turbine maps are needed. After the M250 is instrumented and characterized, the numerical models are optimized and validated accordingly. Among others, real values of pressure losses and air inlet conditions will be available after the first test rig experiments.

When further improved with data from detailed experiments, for example, pressure loss of the new combustor, the models will be used to support the design process of the additional components necessary to demonstrate the SIRA and the FP-CCE concepts. The former cycle benefits from experiments done by ITLR where condensation and separation of water are investigated. The latter cycle involves detailed CFD simulations run at the DLR-FK, leading to preliminary design parameters of the free-piston engine. Results from these experiments will allow for highly accurate models of the novel cycles. These models will further demonstrate the potential of the SIRA and the FP-CCE concepts.

5.2 Setup (WP3.2 and WP3.3)

The demonstration of the SIRA concept will be done stepwise. The first step is a baseline performance test to evaluate the influence of the laboratory infrastructure and ducting on the performance of the unmodified M250 gas turbine. In the following steps, the novel combustion chamber will be integrated followed by the installation of the heat exchanger and the water recovery system. The schematic of the complete steam-injected engine test rig is schematically outlined in Figure 5. The numbers of this schematic correspond to the stations in Figure 1.

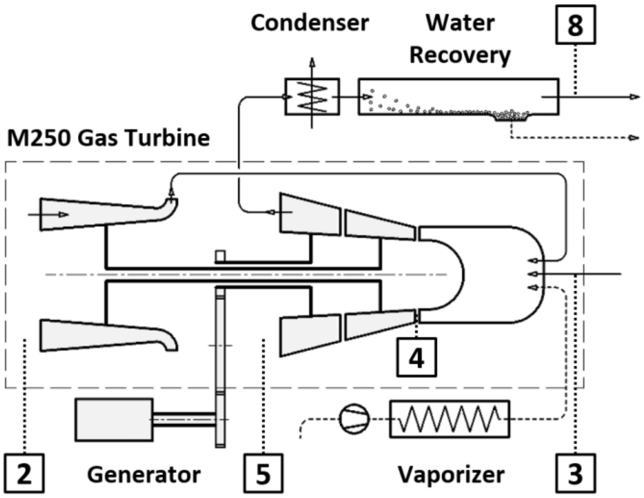

FIGURE 5: M250-based test rig modified for the steam injecting and recovering aero engine concept demonstration.

The M250 turboshaft engine will be equipped with a specially developed high power density electric generator with silicon carbide semiconductors based power electronics. This additional equipment will serve as a load unit converting the shaft power of the engine into electric power. The electric power will be fed into the electric grid of the site via a dc link. In contrast to the ideally closed steam injecting engine cycle introduced in Figure 5, the test rig cycle will not be fully closed. Instead of a directly connected water/steam line between the water recovery system, the heat exchanger, and the combustion chamber, the recovered water will then be measured and dumped. This rig design gives a higher degree of freedom for the tests, allowing independent operation of the combustion chamber from that of the heat exchanger and the water recovery system.

The heat exchanger will be mounted into the gas turbine exhaust duct to cool down the exhaust gas and to enable initial condensation of water. In the test rig, the cooling power for this task will be supplied by cooling water. Behind the heat exchanger, the water recovery system will be connected to the piping and will have the task of condensing the water and separating the forming droplets from the exhaust gas. The recovered water will then be extracted by a pump and measured by a mass flow meter. The WRF can, therefore, be determined from the recovered water mass flow and the injected one. Hence, all water mass flows into and out from the rig will be measured in detail. In order to evaluate all steam-enhanced engine components independently, the steam mass flow into the combustion chamber will be inserted by an external vaporizer system controlled by a mass flow controller. However, if the WRF (cp. Eq. 1) of the water recovery unit will be high enough, a closed water cycle could be emulated in combination with the steam injection into the combustor.

For the experimental analysis of the rig, detailed instrumentation will be installed in front of and behind each component, providing validation data for the cycle simulations. The air mass flow through the engine will be measured by a differential pressure nozzle attached to the inlet of the compressor. The differential pressure nozzle will be located in a settling chamber, which will be connected to an intake duct supplying the engine with ambient air from the outside of the laboratory. The hot exhaust gas will be passed to a stack via piping. Two probing positions for the exhaust gas will be installed. The first one will be placed directly behind the gas turbine exit and the second one will be set up behind the water recovery unit. This arrangement gives the further opportunity of evaluating the influence of this component on the exhaust gas emissions. Additionally, humidity sensors will be integrated into all flow channels of the rig.

For a flexible operation of the novel combustion system, it is essential to have full access to the gas turbine control system. Therefore, the hydro-mechanical fuel control unit of the M250 will be replaced by a novel full authority digital engine control (FADEC) system.

5.3 Demonstration (WP3.4)

In order to reduce the project's complexity the demonstration phase initially focusses on the SIRA concept. Therefore, in the demonstration phase all component analyses, developments, and system simulations of the SIRA concept culminate in the experiments. These should verify and evaluate both the feasibility of the steam injecting aero engine concept and the achievable water recovery factor. This means that the primary goal of the demonstration phase is the proof-of-concept of the cycle. Furthermore, the experiments are supposed to locate the technical issues in the system operation and to identify the needs for components and cycle layout development and modifications. Finally, the demonstration should evaluate the quality of prediction of the developed models.

The demonstration will be done in two steps. At first, the novel combustion chamber will be integrated into the M250 and tested without the additional installation of the heat exchanger and of the condenser. In the second step, all equipment for water recovery will be integrated and tested. While evaluating the novel combustion chamber, the main focus of the parameter variations will be on gas turbine load point from minimum to nominal load, on fuel split, and on water mass fraction. The key target figures of the experiments will be the combustion stability and the exhaust gas emissions in the complete gas turbine operating range, from the ignition, via ramp-up and minimum steady-state load, up to nominal load. At first, the stability limits with respect to fuel split and maximum water mass fraction will be determined. Based on this analysis, a design-of-experiments method will be used to define suitable measurement points of the three parameters matrix. Models for the two target figures and the three variation parameters will be derived from the resulting experiments and validated. Using these models, the results will be analyzed with a focus on the main factors, interdependencies of the parameters, as well as statistical quality. Furthermore, the derived models will be fed into the numerical cycle simulations to conduct more accurate parameter studies. With the help of these investigations, the novel combustion chamber system will be evaluated in the gas turbine system environment. Finally, the results of the demonstration rig will be compared to the results of the high-pressure burner test rig (see Section 4.2) and the CFD simulations.

The second demonstration step will be the implementation of the exhaust gas heat exchanger as well as of the condenser into the gas turbine rig. The key target parameters will be the WRF, system stability, heat exchanger and condenser system behavior and their effects on gas turbine operation. Because of the additional components (heat exchanger and condenser) into the M250 gas turbine exhaust gas duct, the margin to the turbine outlet temperature limit will decrease. This will narrow the feasible operating range of the M250 gas turbine. Thus, the stability limit of the gas turbine will be analyzed during the first experiments with regard to water mass fraction for different condenser configurations. Afterwards, a detailed study of gas turbine load points, water mass fraction, and geometric condenser configuration will be conducted in the feasible load range. Based on this study, correlations for the target parameters will be derived and implemented into the cycle simulation tool for further concept studies. Additionally, the measurements will help to identify components' critical locations and operating conditions as well as to evaluate the effects of the wet steam conditions on the gas turbine.

The combination of experimental demonstration and cycle simulations will contribute to evaluate the feasibility of the SIRA concept for aircraft applications, especially focusing on the water recovery factor as a major key parameter. Based on these analyses, further component and cycle development will be defined.

6 CONCLUSION AND OUTLOOK

This paper is part of a series of three publications. While the first two parts [7, 8] present two revolutionary concepts for future aircraft engines, this third part outlines the projected strategy for the experimental validation of critical technology assumptions.

To date, the presented concepts appear to be promising candidates to meet future emission reduction targets. Both concepts, the steam injecting and recovering aero engine and the free-piston composite cycle engine, address the economic and environmental needs of aircraft propulsion systems for the timeframe beyond 2030. In particular, each novel concept shows the potential to reduce fuel burn and, therefore, CO_2 emissions by about 15 % compared to conventional gas turbine engines of the same technology level. However, both revolutionary concepts require further detailing and the preliminary study results need to be validated.

To this end, MTU Aero Engines, the German Aerospace Center, the University of Stuttgart and Bauhaus Luftfahrt entered into a strategic research partnership. Initiated by MTU, the interdisciplinary consortium defined the DINA2030$^+$ project, that is described in this paper in detail. The project targets on the experimental demonstration of the technological feasibility of crucial functionalities and critical components of the two novel concepts.

Aiming at a functional demonstration of revolutionary aero engine concepts and with the subsequent technology maturation in view, the joint technology project DINA2030$^+$ will depend on national and European funding. The project will also provide near-term and mid-term benefits for industrial product improvement and development as well as scientific research.

The consortium's initial research work on revolutionary engine concepts has a clearly national marker. However, future work to achieve technological maturity will also integrate the capabilities of European and other partners where this is beneficial in a globalized supply chain.

The project partners are eager to support the realization of the Flightpath 2050 with new best-possible aero engine product standards in line with MTU’s technology agenda, Claire. The development of revolutionary aircraft engines is the responsibility of both the aviation industry and the research, to provide future generations with climate-friendly and socially accepted mobility.

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