



Reaching 90 sec runtime, throttling, and turbine operation with a hydrogen-based rotating detonation combustor

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Abstract

Rotating detonation combustors (RDC) promise superior efficiency and specific impulse compared to gas turbines and rocket engines. Their potential lies in using a fluid mechanical instability – detonation waves – rather than mechanical means – turbo pumps or compressors – to create the high pressures necessary for efficient combustion. However, the combustor experiences extreme conditions of periodic heat release and pressure peaks that travel around the annular combustor at frequencies of several thousand Hertz imposing challenging mechanical and thermal stresses. Reliably reaching and controlling quasi steady-state conditions is a prerequisite for both sustained RDC operation and to ensure reproducible boundary conditions for numerical simulations. Here, we report on the activities at the Institute for Thermal Energy Technology and Safety (ITES) at KIT Karlsruhe to develop a test bed, from early safety-related detonation experiments to design and operation of an RDC-based compressorless gas turbine that reaches quasi-steady state conditions with a turbine.

Keywords: *detonation, hydrogen, power, RDE, RDC*

1. Introduction

Pressure gain combustion realized in rotating detonation engines (RDE) promises a massive increase in efficiency for rockets [1] or gas turbine applications [2, 3]. Particularly for rotating detonation gas turbines (RDGT), an additional benefit is a simpler (and thus cheaper) system compared to gas turbines [4, 2, 5, 6]. Thermodynamically, in gas turbines (Brayton cycle), heat is added isobarically after the compressor stage, while the detonation cycle (Fickett-Jacobs) increases pressure beyond the compressor *while* adding heat. Figure 1 [4] compares the cycles and illustrates how detonation combustion even exceeds isochoric heat addition (Humphrey); the comparison is illustrative nonetheless: during detonation, heat is added at such a rate that the fluid has no time to expand, resulting in a substantial increase in pressure and temperature. Replacing a methane-fueled gas turbine with a hydrogen-fueled RDGT promises a theoretical efficiency gain of 89 %, see Table 1.

Table 1. Theoretical thermal efficiencies for variations of cycle and fuel with pressure ratio of 5. Going from a classical natural gas driven Brayton-Joule cycle (gas turbine) to a hydrogen based Fickett-Jacobs cycle (detonation combustor) yields a potential efficiency gain of 89% [4].

Fuel	Brayton-Joule	Fickett-Jacobs
Hydrogen / H ₂	0.369	0.593
Natural gas / CH ₄	0.314	0.532

How does pressure gain combustion work? Figure 2 shows the detonation wave system observed in a rotating detonation combustor (RDC) from in-house simulations using the GASFLOW-MPI solver [7]. Fuel and oxidizer are injected from reservoirs (A); they enter and mix in the combustion chamber (B);

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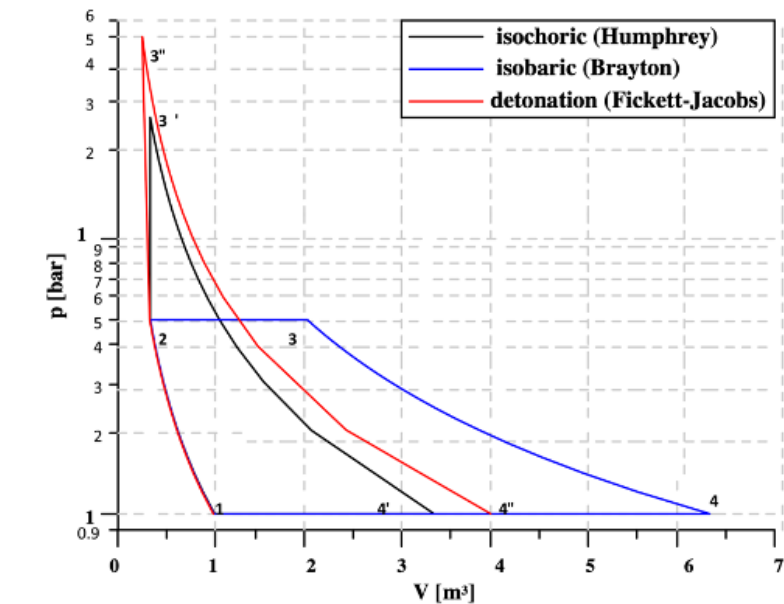


Fig 1. Comparison of thermodynamic cycles. The Fickett-Jacobs cycle exploits additional compression of the detonation wave after the compressor, resulting in superior efficiency, c.f. Table 1. From [4].

a detonation wave (C) moves (from left to right) through the unburnt mixture, leaving a high-pressure / high-temperature region in its wake which subsequently expands. The fresh incoming mixture acts as a ramp that pushes out the combustion products, which are deflected along the slip line (D), resulting in the formation of an oblique shock (E). With the detonation wave travelling into the fresh mixture around an annular combustor, this allows for a continuous, periodic operation. Interestingly, continuous detonation waves are closely related to nonlinear combustion instabilities with steep-fronted waves long known in rocket engines [8, 9, 10].

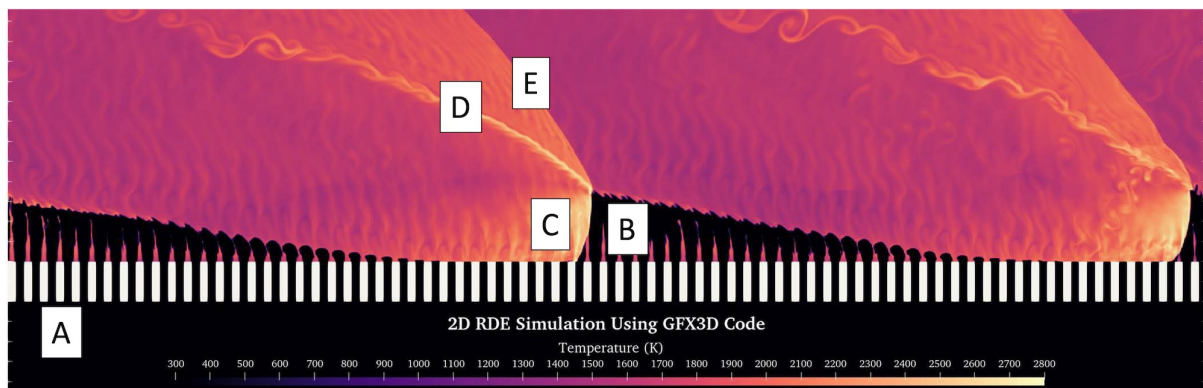


Fig 2. Simulation and structure of rotating detonation waves. A: reservoir; B: unburnt mixture; C: post-detonation; D: slip line; E: oblique shock. Simulation and image courtesy of Jianjun Xiao using the GASFLOW-MPI CFD solver [7], KIT-ITES.

Building a practical pressure gain combustor for a technical system is challenging because of the extreme and volatile thermal and mechanical conditions: both pressure and temperature peaks move with the detonation wave at supersonic speeds around the combustor. Integrating the combustor into a turbine-driven device holds the additional challenge of making exhaust and turbine compatible.

This paper discusses the activities at the Institute of Thermal Energy Technology and Safety that led to

the recent success of developing a compressorless rotating detonation gas turbine.

2. Hydrogen research at the Institute for Thermal Energy Technology and Safety (ITES)

Research into detonation at ITES started with a focus on hydrogen nuclear safety after the Chernobyl accident in 1986. Hydrogen safety remains an important core topic, extended towards more general applications in energy and mobility [11]. This includes work on hydrogen release [12], dispersion [13], and ignition [14]. The scenario to be avoided in the safety context is the deflagration-detonation transition (DDT), which thus warrants particular emphasis [15, 16].

Hydrogen safety research at ITES is both numerical [7, 13] and experimental [14, 15, 16]. Fig. 3 shows an external view of the HYKA Hydrogen Technology Center at KIT and an open air test area that is currently used for liquid hydrogen (LH₂) spill tests.

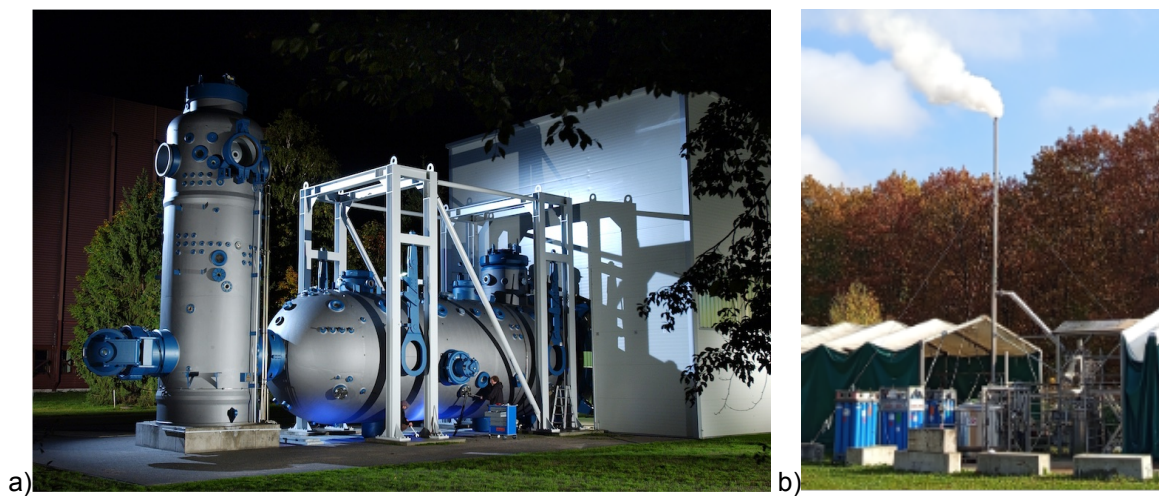


Fig 3. a: Hydrogen Technology Center HYKA at KIT external view; b: open air test area.

HYKA offers a number of pressure vessels for up to 160 bar pressure or 220 m³ of volume, allowing experiments in controlled and safe environments, even to the point of failure of the components to be tested. Figure 4 shows a schematic view of the different available vessels.

3. Rotating Detonation Combustor Development

The decades-long experience with detonation and power research made rotating detonation combustors and their application particularly attractive for ITES. Experience gained from studying how to avoid detonation could now be applied to the task of putting detonation waves to good use; safety studies about detonation waves in semi-confined air/H₂ atmospheres are remarkably close physically to the application in engines [17].

RDC tests are conducted in Test Cell TC160 in Fig. 4, which is originally for automotive tests and is equipped with suitable venting, gas supply, and measurement equipment.

Figure 5 shows the different generations of RDC developed at ITES since start of the program in September 2023, from an early demonstrator to an actively cooled version.

Hydrogen and air are injected individually into the combustor in stoichiometric ratio; mixing takes place in the combustor. Initiation of the detonation waves is performed through an ignition pipe that feeds tangentially into the combustor, filled with a hydrogen-air mixture and of sufficient length to ensure deflagration to detonation transition, which in turn is ignited by a spark plug. Operation of the combustor has been demonstrated stably for 40 s, across various mass flow rates corresponding to chemical power from 50 kW to more than 500 kW [17].

Ultimately, our goal at ITES is to enable sustained RDC operation with a turbine. To this end, we

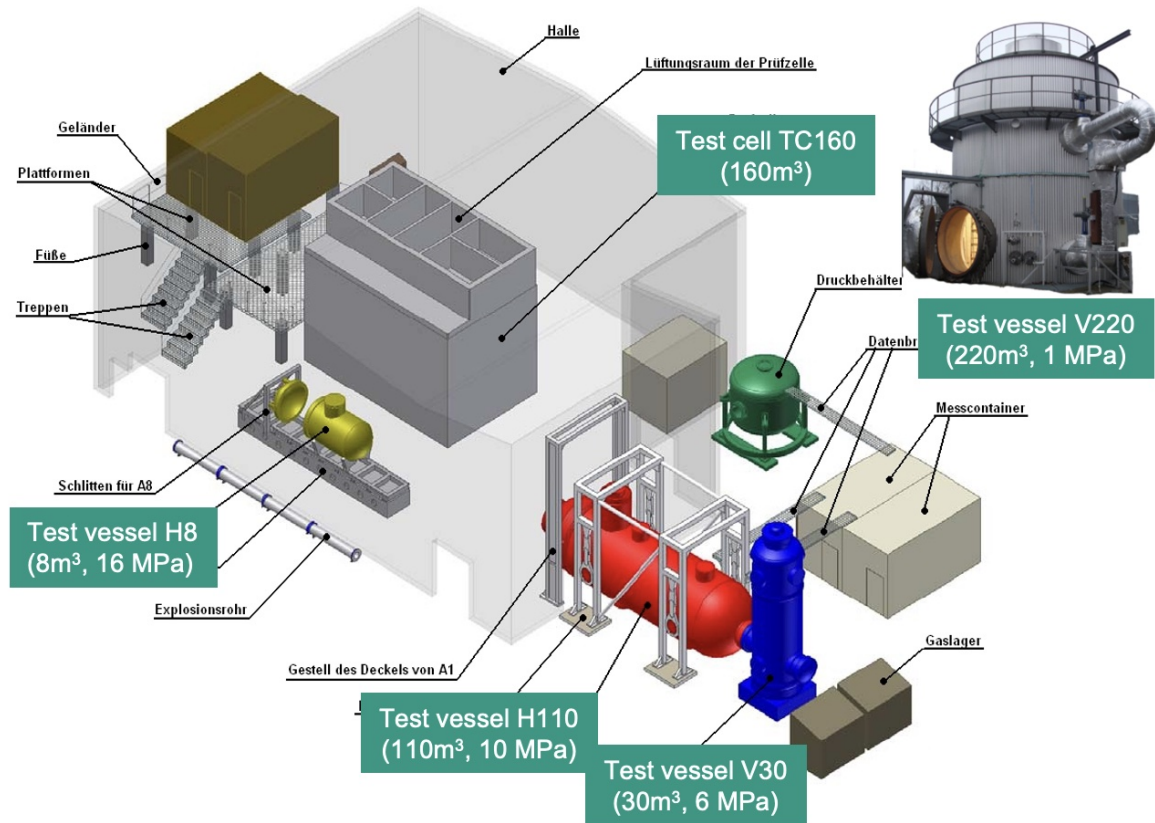


Fig 4. HYKA test vessels used in hydrogen safety research with volumes and pressures.

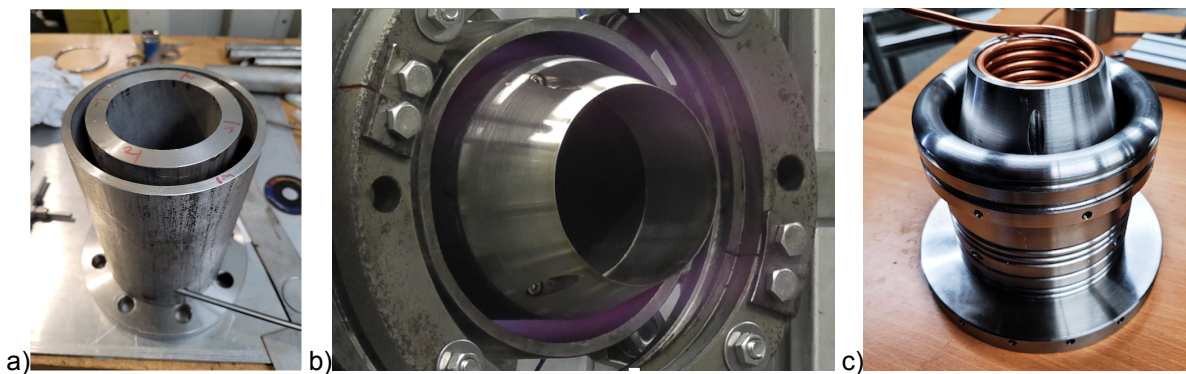


Fig 5. Generations 1, 2 and 3 (from left to right) of ITES RDC designs, illustrating the progression from an early demonstrator (a), to include a nozzle (b), to active cooling (c).

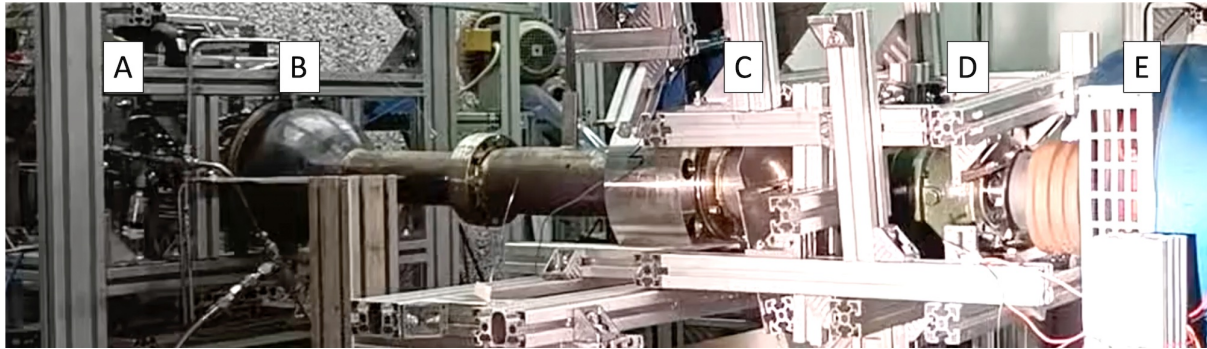


Fig 6. Compressorless rotating detonation gas turbine assembly. A: combustor; B: diffusor; C: turbine; D: gear box; E: generator.

extended the test stand as shown in Fig. 6. The actively cooled combustor (A), Fig. 5, exhausts into a diffusor (B), which feeds the turbine (C). Through gear box (D), the turbine is connected to generator (E). The generator in turn is connected to switchable electrical resistors.

Figure 7 shows the turbine shaft revolutions per minute for three different tests with turbine, turbine/generator, and turbine/generator/load. The turbine revolutions drop from a maximum when the shaft is connected to the generator. A maximum turbine runtime of 60s with a quasi-steady-state frequency of 20,000 U/min is achieved.

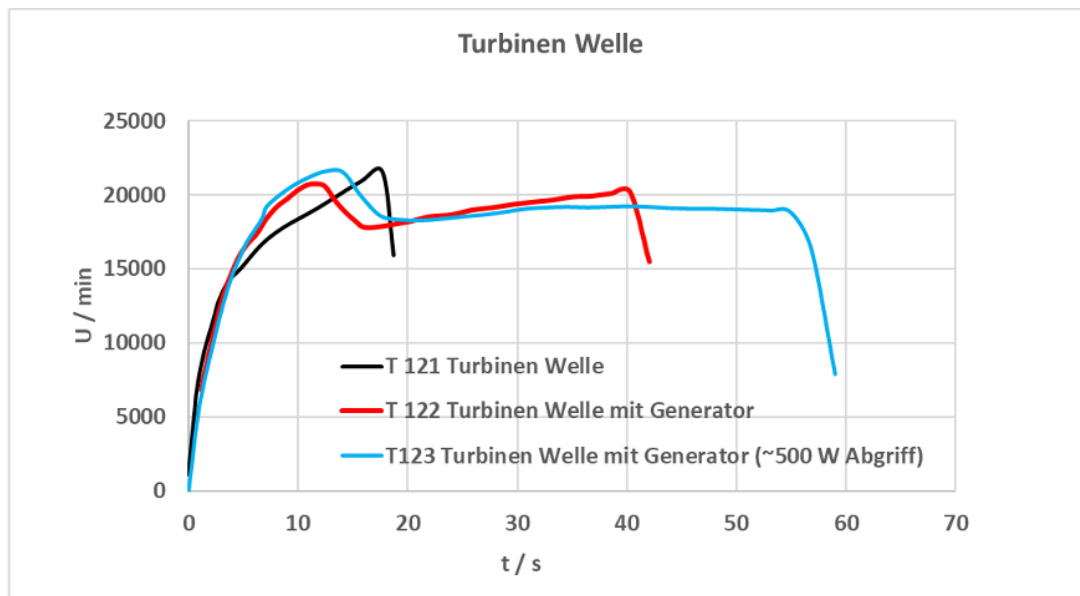


Fig 7. Turbine revolutions. Black: first test of turbine; Red: first test connected to generator; Blue: turbine with generator under electrical load. In test 123, a turbine runtime of 60s is achieved.

Figure 7 (blue) indicates that a quasi-steady-state is reached for operation with turbine/generator/load.

4. Summary and Conclusions

A rotating detonation combustor (RDC) - based compressorless gas turbine was developed at KIT-ITES over the last two years since September 2023 and successfully demonstrated in July 2025.

The RDC was integrated into a system allowing for active cooling, feeding a turbine that was connected to a generator. RDC runtimes of 90s and turbine runtimes of 60s have been achieved repeatedly; electrical power was generated.

Measured data indicate that a steady state was achieved. This is an important milestone towards a practical system as well as for comparison with numerical simulations.

The development shows how KIT-ITES experience in hydrogen safety research could be successfully leveraged towards RDC and RDGT development.

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