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Constant volume combustion: the ultimate gas turbine cycle

Guest Feature

Constant volume combustion: the ultimate gas turbine cycle

Also in this section

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Pulse detonation combustion holds the key to 45% simple cycle and close to 65% combined cycle efficiencies at today's 1400-1500°C gas turbine firing temperatures.

The Kelvin-Planck statement of the Second Law of Thermodynamics leaves no room for doubt: the maximum efficiency of a heat engine operating in a thermodynamic cycle cannot exceed the efficiency of a Carnot cycle operating between the same hot and cold temperature reservoirs.

All practical heat engine cycles are attempts to approximate the ideal Carnot cycle within limits imposed by materials, mechanical considerations, size and cost. The operating principles of such engines are described by idealized "closed" cycles with a pure "working fluid" as detailed in the Thermodynamics section of this article (page 00),

Combustion engine cycles

Based on combustion process, the engine cycles are classified as internal combustion engine cycles such as Otto, Diesel, Atkinson and Brayton (vehicular engines and gas turbines) or external combustion engine cycles such as Ericsson, Stirling and Rankine (Stirling engines and steam turbines).

The internal combustion engine cycles are further classified according to their heat addition process based on constant pressure heat addition (such as Brayton gas turbine cycle) or constant volume heat addition (Otto and Diesel car and truck engines).

In the remainder of the main body of this article, the academic term "heat addition" will be replaced by the technical term for its practical implementation in actual engines, namely fuel-air combustion.

While **constant volume combustion** is presently limited to reciprocating (piston-cylinder) engines, the "first economically practical" gas turbine – as declared by none other than Aurel Stodola – was in fact a *bona fide* constant volume combustion (CVC) gas turbine invented and developed by Hans Holzwarth around the turn of the 19th century.

Subsequently however, starting in the early 1930s, gas turbine development has centered almost exclusively on **constant pressure combustion** (CPC) technology for aircraft propulsion and land-based power generation, This article is intended to provide a glimpse into the potential benefits of a return "back to the future" that CVC technology has to offer.

Why constant volume combustion?

In a modern gas turbine with an approximately constant pressure combustor, the compressor section consumes close to 50% of gas turbine power output.

Assume one could devise a combustion system where energy added to the working fluid (i.e. air) via chemical reaction with fuel would simultaneously increase the enthalpy (temperature) and pressure of the product gas. For that same amount of air and fuel, the resultant saving in power spent for air compression would result in an increase in net cycle output and efficiency.

Ultimate Gas Turbine Cycle Acronyms

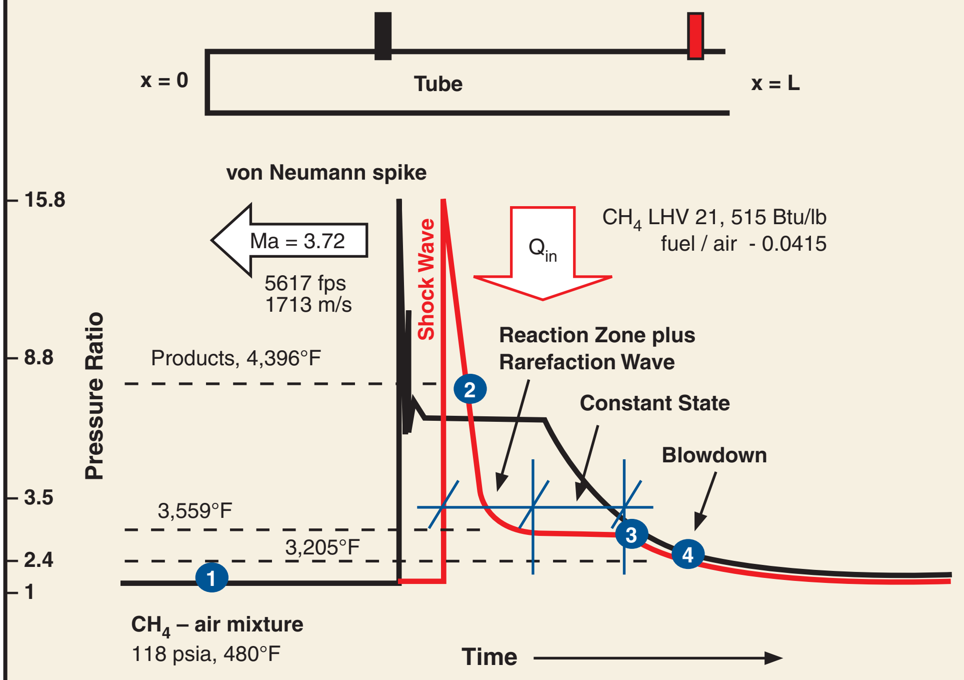
CPC	constant pressure combustion (current GT designs)
CPHA	constant pressure heat addition
CVC	constant volume combustion (pressure gain)
CVC-GT	constant volume combustion gas turbine (the ultimate)
CVHA	constant volume heat addition
GT	gas turbine
GTCC	gas turbine combined cycle
METH	mean-effective temperature (high)
METL	mean-effective temperature (low)
PDC	pulse detonation combustion
PDE	pulse detonation engine
PR	pressure ratio
PR'	precompression pressure ratio
RF	realization factor
R-G	Reynst-Gülen cycle
SSSF	steady state steady flow
TIT	turbine inlet temperature
USUF	uniform state uniform flow

In layman's terms, this is the simplest explanation of the benefit afforded by what is frequently referred to as **pressure-gain combustion** vis-à-vis the steady-flow combustion process in gas turbine combustors. (It must be pointed out that in practice, just as the former is not exactly a constant volume process, the latter is not a constant pressure process.)

Constant volume heat addition is the ideal cycle proxy for pressure gain combustion whereas constant pressure heat addition is the proxy for steady-flow combustion.

The ideal air-standard cycle analysis provides the thermodynamic explanation for the fundamental difference between the two processes without resorting to a highly complex thermochemical treatment of the actual combustion phenomena in their practical embodiments (i.e., combustion chambers or combustors).

Figure 1. Computed state points (1-2-3-4) apply to a conceptual Chapman-Jouguet detonation taking place in a semi-closed detonation tube fed with a stoichiometric CH_4 air mixture at 118 psia (P_1) and 480°F (T_1). Exit conditions: pressure ratio (P_4/P_1) = 2.4 and T_4 = 3205°F. Not shown is state 5, where combustion products mix with purge air before entering the turbine.



A very brief introduction of the thermodynamic principle behind the superiority of constant volume combustion vis-à-vis its constant pressure counterpart appears in the Thermodynamic section of this article. The reader not satisfied by the simplified explanation (above) is encouraged to examine the more rigorous albeit brief thermodynamic explanation.

The cited references and any textbook can be consulted for a more in-depth understanding; the remainder of this article is focused on the more practical aspects of constant volume combustion.

Why detonation?

From a purely theoretical perspective, constant volume combustion is clearly the superior process. By the same token, its practical, non-ideal embodiment (pressure-gain combustion) is superior to steady-flow quasi constant pressure combustion.

Indirect proof for this assertion can be found in efficiency comparison of reciprocating piston-cylinder engines (over 45% efficiency) and heavy duty industrial gas turbines (37-40% efficiency). Recip efficiencies are only matched by aeroderivative gas turbines with extremely high pressure ratios of 40 to 1 and higher.

Theoretically, comparison with other air-standard cycles (see Thermodynamics section) shows CVC to be the ultimate, i.e. highest efficiency approach to reaching the ideal Carnot cycle. The difficulty is in designing (conceptually as well as physically) a steady-flow device that can accomplish combustion with simultaneous temperature and pressure rise.

Constant volume or pressure-gain combustion in an otherwise steady flow system is characterized by intermittency or pulsation (in other words, *unsteadiness*). In fact, unsteady or intermittent flow approximating the ideal constant-volume combustion has been the main characteristic of historical machines and their modern-day descendants, gas-fired reciprocating engines.

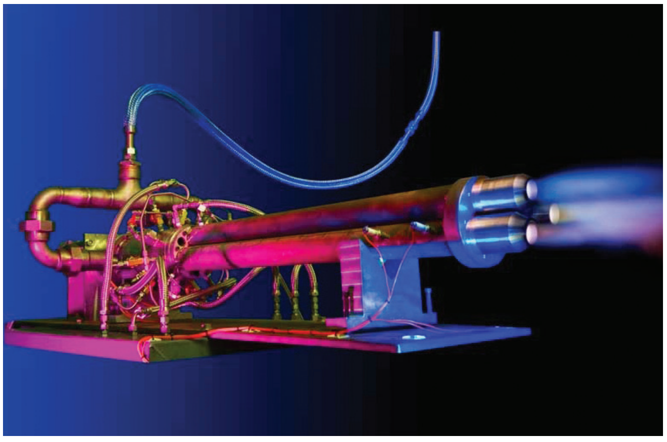


Figure 2. General Electric R&D 3-tube pulse detonation combustion test rig used to gather data on performance, operation and noise levels.

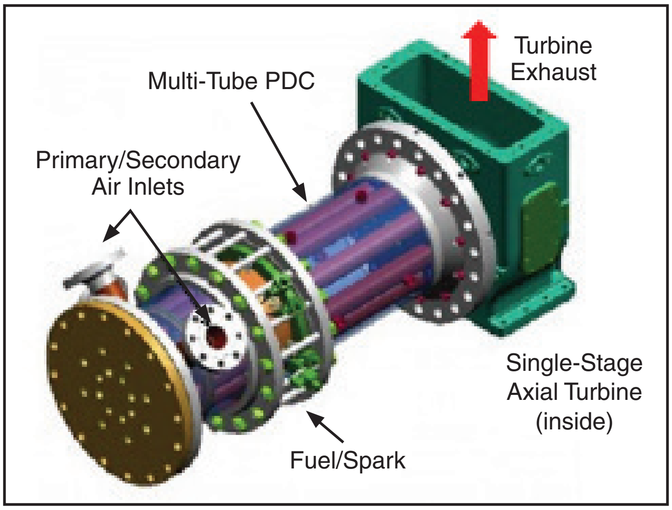


Figure 3. GE-NASA multi-tube pulse detonation combustion with 1000 hp single-stage power turbine.

From a practical perspective, reciprocating (piston-cylinder) engines or gas turbines with piston-cylinder engines as combustors are rather poor candidates for utility-scale electric power generation. Modern frame machines are pushing the 400 MW unit rating limit (in 50 Hz) with airflows close to 2,000 lb/s that are difficult to achieve in a piston-cylinder configuration of comparable power density.

This is where detonation combustion enters the picture. The only possibility for an adiabatic and steady flow process, with pressure rise, is a supersonic flow with a standing **shock wave** (idealized as a discontinuity in the flow field). Similarly, the only possibility for a steady flow process with pressure rise and heat addition is a supersonic flow with a standing **detonation wave**.

Detonation is a "rapid and violent form of combustion" that differs from other modes (flames) in that the main energy transfer mechanism is mass flow in a strong compression wave, i.e. a shock wave, with negligible contribution from other mechanisms (e.g. heat conduction in flames).

In other words, detonation is a "composite" wave made up of two parts: an ordinary shock wave, which raises the temperature and pressure of a mixture of reactants, followed by a thicker reaction zone in which the chemical reaction (ideally but not necessarily) goes to completion.

Note that detonation is not a constant volume process per se (specific volume ratio is about 0.6 for a typical γ of 1.3). Strictly speaking, detonation combustion is a form of pressure-gain combustion that is a reasonably close approximation of constant volume combustion.

Why pulse(d) detonation?

Achieving a standing detonation wave in a steady flow device is practically impossible – at least it is for land-based (stationary) power generation applications. Conceptually, it can be envisioned as a special *ramjet* where supersonic flow of fuel-air mixture created in a converging-diverging nozzle (fuel injected at the nozzle throat) leads to a shock wave.

With precise control of pressure, temperature and mixture composition, ignition and energy release occurs behind the shock wave. Almost all practical manifestations of detonation combustion in laboratory experiments (as well as in test engines) have been achieved in semi-closed tubes as successive *Chapman-Jouguet* detonations with a given frequency (Figure 1), hence the name *pulse(d) detonation*.

Thus, just like turbo-compound and pulse jet engines, the pulse detonation combustion gas turbine is also an approximation of the ultimate steady-state, steady flow constant volume combustion/heat addition cycle.

Nevertheless, pulse detonation combustion gas turbines or, more concisely **pulse detonation engines** (PDE), have the potential to lead to high power density designs comparable to modern frame gas turbine units, but with higher efficiency and (possibly) lower emissions.

A brief history of pulse detonation

The idea of using intermittent or pulsed detonation combustion for aircraft gas turbine engines goes back before the 1950s. Research engineers in Germany reportedly considered it as early as 1940 [4]. And today, continuing PDC development is devoted almost exclusively to military aircraft gas turbine propulsion applications.

Decades-long research and development recently culminated in the first flight of a PDE powered aircraft in 2008. An experimental pulse detonation engine built for US Air Force Research Laboratory (AFRL) had four detonation tubes firing at 20 Hz (the shock waves were at about Mach 5). The engine produced a peak thrust of about 200 lbs to power a small aircraft (Burt Rutan's Long-EZ) to just over 100 knots flying at less than 100 ft of altitude.

While it is difficult to see that the public will board airliners powered by pulse detonation engines anytime soon (if ever), PDEs recently piqued the interest of major OEMs for land-based power generation applications. General Electric,

Figure 4. China flight research 6-tube pulse detonation test engine used for demonstration and performance evaluation.

for example, has reported on a three-tube PDE research rig (Figure 2) in a movie on its Global Research Center internet site.

In cooperation with NASA, General Electric has also tested a multi-tube **pulse detonation combustor** and turbine hybrid system (Figure 3) in which the PDC tubes were arranged in a circumferential fashion (like a Gatling gun) "firing" into a single-stage axial turbine (nominal 1,000 hp rating at 25,000 rpm).

As reported by GE, the system operated at frequencies up to 30 Hz (per tube) in different firing patterns using stoichiometric ethylene-air mixtures to achieve 750 hp at 22,000 rpm.

In the US, R&D projects on pulse detonation engines have been funded by NASA, the Air Force Research Lab (AFRL) and Defense Advanced Research Projects Agency (DARPA).

These projects were carried out by leading aircraft OEMs (GE, Pratt & Whitney and Rolls-Royce) as well as by various universities and government R&D agencies.

Work also included research and engineering development on other variants of pressure-gain combustion, e.g. resonant pulse, wave rotor, and rotating detonation combustion.

Back in 2008 DARPA announced a multi-phase classified program named Vulcan for hypersonic propulsion that involved the development of a constant volume combustion engine that would operate in combination with advanced turbo jet engines to transition from supersonic to hypersonic flight.

Although the primary purpose of the Vulcan program was for propulsion, the US Navy also became interested in potential application of CVC technology under development for shipboard power generation.

About that same time period, China set up a Jet Propulsion Technology Laboratory for high speed propulsion R&D focused on development of advanced technologies for space vehicle propulsion that included scramjet engines, hypersonic turbine-based combined engines and pulse detonation engines.

Figure 5. Simple cycle efficiency of ideal constant volume heat addition (CVHA) cycles is about 20 percentage points higher than today's constant pressure heat addition (CPHA) GTs at the same turbine inlet temperature. Realization factors (RF) cuts down the efficiency improvement to 8-10 points. Note that today's J-class efficiency (>40%) can be achieved with pre E-class temperatures and materials. Note: Frame machine data from 2013 GTW Handbook

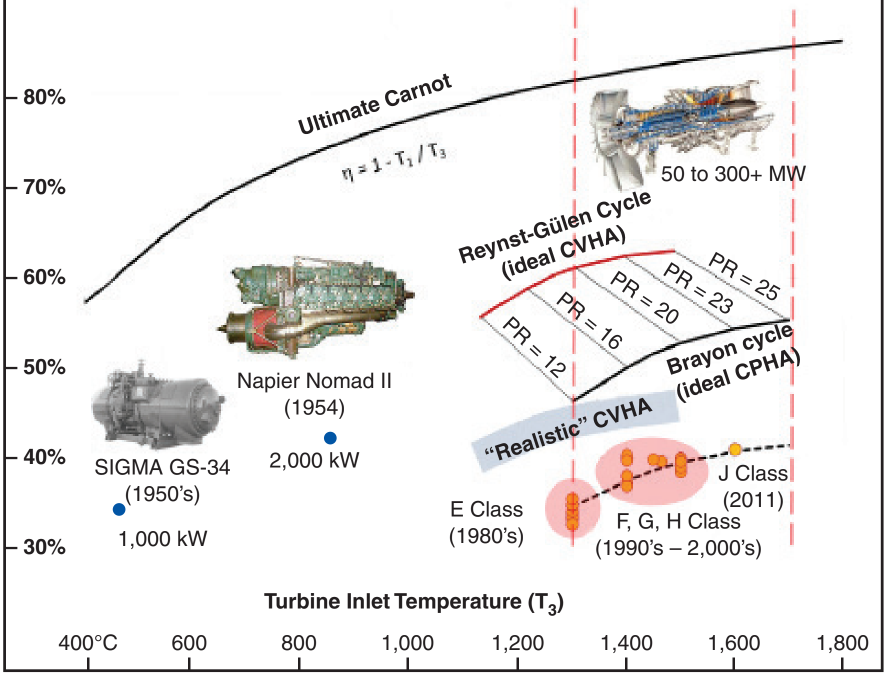
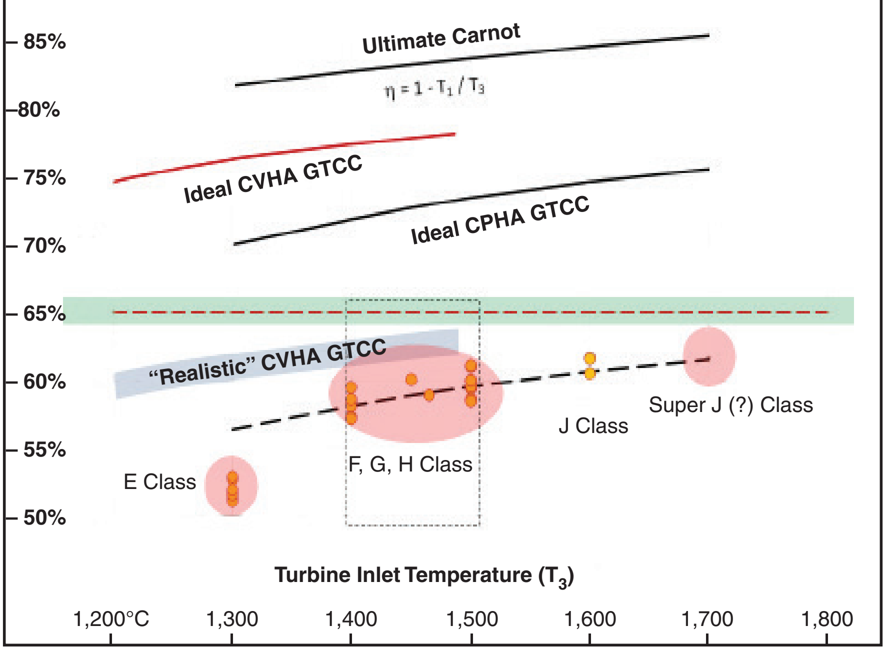


Figure 6. Combined cycle efficiency of an ideal constant volume heat addition GTCC plant comes within 5 percentage points of the ultimate Carnot cycle, i.e., over 80%. Efficiencies of a realistic CVHA-GTCC plant is about 5 percentage points higher than today's GTCC plants at the same turbine inlet temperature. Note: Frame machine data from 2013 GTW Handbook



Status and future of pulse detonation engines

As evidenced, pulse detonation engines are actively being investigated for airborne, marine and land based power generation. To the best of the author's knowledge, however, we have yet to see a commercial design or application.

From an electric power generation perspective, heavy duty industrial gas turbines with PDC or another constant volume or pressure-gain combustion process (CVC-GT) offers a potentially intriguing alternative to today's technology (see simple and combined cycle efficiency plots in Figure 5 and Figure 6).

The ideal Reynst-Gülen and Brayton cycles in Figure 5 are constructed by relaxing the air-standard cycle assumptions to account for the working fluid change before and after heat addition (i.e., γ=1.39 before and γ=1.29 after).

In effect, the ideal Brayton cycle efficiency thus calculated is the same that one would get from a heat balance tool (e.g., Thermoflex by Thermoflow, Inc.) with 100% component efficiencies, 100% CH_4 fuel and no pressure losses.

This efficiency is the true theoretical maximum for given T_3 and pressure ratio. It is the same as the efficiency of the *equivalent Carnot cycle* operating between the Brayton cycle's high and low mean-effective temperatures (METH and METL). These are the effective high and low temperatures between which a power cycle operates, and which are used to compute theoretical efficiency.

DARPA Contracts for CVC Engine Technology Development

In July 2010 the US Defense Advanced Research Projects Agency (DARPA) awarded Pratt & Whitney and General Electric separate R&D contracts valued at about $33 million each to develop Constant Volume Combustion (CVC) engine technology under Phase II of the Vulcan advanced propulsion program.

CVC engine cycles that burn fuel at a constant volume are significantly more efficient than conventional Brayton cycle engines that burn fuel at a constant pressure. With this potential in mind, the ultimate goal of the Vulcan program was to design, build and ground test a CVC technology system that could demonstrate a 20% fuel burn reduction for a ship-based power generation turbine.

CVC, when combined with jet turbine engines, offers the ability to design a new class of hybrid turbine power engines for naval ships and air-breathing aircraft engines for flight propulsion. Under Phase II, a CVC module was to be developed, fabricated, tested and fully characterized through analytical models as well as component and subsystem testing prior to final integration into a turbine engine for US naval surface vessels.

The application goal was on retrofitting 3 to 5MW class gas turbine generators (similar to those used on U.S. Navy surface vessels) with CVC technology that would reduce fuel consumption and airflow with an increase in overall operational capability.

This was to be a two-year effort including the design of a CVC module and associated components in addition to demonstration testing of key components to enable the design and test of a complete CVC turbine engine in Phase III.

Unlike conventional (Brayton cycle) gas turbine engines, which burn fuel in a steady constant pressure process and operate on rapidly expanding volume to produce power, CVC engines are characterized by an unsteady pulse-type process. As a result CVC engine designs typically require multiple combustors and unique valve sequencing to regulate the unsteady combustion process.

Key challenges for design and development include high efficiency detonation, low total pressure-loss initiation devices and valves, thermal management control systems, low turbulence flow nozzles, etc. Even more basic is choosing the most appropriate CVC engine configuration such as pulsed detonation engines (aka DLE), continuous detonation (aka CDE) or other "unsteady" detonation or combustion approach.

Technical details of the Vulcan program are classified. However, Pratt & Whitney announced last year that it had successfully completed its Phase II project and observed that CVC technology "has the potential to significantly reduce the fuel consumption of propulsion systems over a wide range of applications."

Further, that CVC capability developed under the Vulcan program can help achieve substantially higher cycle efficiency and lower specific fuel consumption when compared to Brayton cycle gas turbine engines operating at similar compression pressure ratios.

As stated by Jimmy Reed, director of the company's Advanced Engine Programs, DARPA was very pleased with their program results and commended the Pratt & Whitney-led team for a job exceptionally well done. "Our efforts extended the state of the art well beyond customer expectations."

At publication time, GTW calls to DARPA for further information on the status of the Vulcan propulsion program and plans for CVC technology have not been returned. Our understanding, however, is that Phase III continuation of the program has been put on hold, if not cancelled.

Comparison with actual large-frame gas turbine performance data (from GTW 2013 Handbook) reveals the interesting observation that actual cycle efficiencies (dotted curve, Fig. 5) are well represented by applying a factor ranging from 0.75 to 0.80 to this ideal efficiency curve.

The ideal R-G efficiency is obtained from the equation in the Thermodynamics section with a composite γ and c_p to reflect the change in the working fluid (1.345 and 0.264 Btu/lb-R, respectively).

It is only logical that, with existing technology, a similar realization factor (RF) with appropriate conservatism should apply to the ideal R-G efficiency to estimate actual gas turbine performance based on constant volume heat addition (CVHA).

Thus, the band in Figure 5 is constructed by applying a factor of 0.70-0.75 to the ideal R-G efficiency. (In passing, the realization factor for Nomad II vis-à-vis ideal CVC turbo-compound cycle is 0.66 at the same precompression pressure ratio.)

The combined cycle efficiency is a composite of the gas turbine or CVC-GT efficiency with the bottoming (Rankine steam) cycle efficiency. The latter can be evaluated in a similar fashion, i.e., by multiplying the ideal bottoming cycle efficiency, $\eta_{BC} = 1 - T_1/\text{METL}$, by a realization factor.

Interestingly (but not surprisingly), steam turbine data from GTW 2013 Handbook indicates that this factor, RF′, is also 0.75. (The author can be contacted for the plot confirming this assertion.) Thus, the combined cycle net efficiency, with an auxiliary load factor, α, of 1.6% is given by

$$\eta_{CC} = \left(RF \cdot \eta_{GT} + \left(1 - RF \cdot \eta_{GT}\right) \cdot RF' \cdot \eta_{BC}\right) \cdot \left(1 - \alpha\right)$$

The clear superiority of the constant volume combustion over the Brayton cycle (with constant pressure combustion) for simple cycle gas turbines is not that clear-cut on a combined cycle basis. This is directly tied to the lower exhaust temperature of the CVC-GT at the same pressure ratio and heat input (because $T_{3'}$ is lower than T_3) which limits the bottoming cycle contribution.

Nevertheless, within the turbine inlet temperature window of 1,400-1,500°C constant volume combustion (via PDC or another pressure-gain combustion technology) is potentially 2.5 to 3.0 percentage points better than the Brayton gas turbine combined cycle. (The advantage can be as low as 0.5 to 1.25 points if the pessimistic view is taken.)

Breaking the 65% combined cycle efficiency barrier is another matter. Constant volume combustion would definitely help in reaching 65% combine cycle efficiency – as a part of a comprehensive technology *toolbox* - but unlikely to be "the" technology for doing it *solo*.

There is, however, a silver lining to the story. The CVC-GT combined cycle can attain the same efficiency as a standard GTCC at nearly 200°C (~350°F) lower turbine inlet temperature (T_3) and about 62–63% combined cycle efficiency at 1,400°C (2,550°F) turbine inlet temperature instead of 1,600°C (2,900°F).

The ramifications with respect to NOx emissions can be significant. Current dry low NOx combustion technology is approximately at its limit near 3,000°F. While the temperature downstream of the shock front within the reaction zone can reach over 4,000°F (see Figure 1), the residence time is very small so that detonation combustion might result in lower NOx emission levels.

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Digging into the thermodynamics of alternative air-standard cycles

Some basic thermodynamic principles that will facilitate the qualitative analysis of alternative power cycles and evaluation of complex power generation systems.

At the very basic level, **air-standard cycles** are characterized by three major assumptions: 1) a pure working fluid (air) modeled as a calorically perfect gas, 2) external heat addition, and 3) internally reversible processes.

With the notable exceptions of the three-process Lenoir cycle and five-process dual cycles, practically all air-standard cycles of engineering interest have four key processes, i.e. compression, heat addition, expansion, and heat rejection in common. It has been demonstrated that:

- For a given cycle heat addition, if no limit is imposed on cycle pressure ratio (PR), the **constant volume heat addition** (CVHA) cycle is the most efficient air-standard cycle; specifically, the **Atkinson** cycle [1].
- For a given cycle pressure ratio and cycle heat addition, however, the most efficient air-standard cycle is the **constant pressure heat addition** (CPHA) cycle; specifically, the Brayton cycle [1]. Note that the efficiency of an air-standard **Brayton** cycle is <u>only</u> a function of the cycle pressure ratio, i.e.,

$$\eta = 1 - PR^{\frac{1-\gamma}{\gamma}}$$

The practical ramifications of these fundamental thermodynamic assertions based on ideal air-standard cycles can be seen in the comparative performances of gas-fired reciprocating gensets, aeroderivative gas turbines with very high pressure ratios, and heavy-frame industrial gas turbines with very high turbine inlet temperatures.

While these assertions are not incorrect per se, they are incomplete. In effect, the CVHA process in the cylinder of a Diesel engine or the explosion chamber of the Holzwarth turbine is a **Uniform State Uniform Flow** (USUF) process in a <u>closed</u> system (i.e., no working fluid mass flow crosses the control volume boundaries).

In contrast, all processes in a gas turbine, including the CPHA process, are **Steady State Steady Flow** (SSSF) processes in an open system (i.e., working fluid mass flow *does cross* the control volume boundaries).

Constant volume heat addition

Interestingly, the four-process air-standard cycle with steady state steady flow CVHA has been conspicuously absent from the literature. As far as we can tell, it only appeared (implicitly) in papers by the Dutch engineer/scientist François Henri Reynst in 1950s [2]. The author formulated it first in his 2010 paper and called it Reynst-Gülen or R-G cycle [3].

It can be shown that, at the same cycle heat input <u>and</u> overall cycle pressure ratio, i.e., either at the end of the compression process for the Brayton cycle with CPHA, or at the end of the heat addition process for the Atkinson and R-G cycles with constant volume heat addition, the R-G cycle is more efficient than the Brayton cycle, which is more efficient than the Atkinson cycle.

The Atkinson cycle is more efficient than the Brayton cycle at the same heat input only when the Brayton cycle pressure ratio is the same as the precompression pressure ratio of the Atkinson cycle. In essence**, the R-G cycle is the ultimate gas turbine cycle.**

Reynst cycle efficiency

The R-G cycle is a theoretical construction with no information regarding its practical implementation. Reynst envisioned a hybrid or turbo-compound cycle where the combustor of the gas turbine is replaced by a two-stroke reciprocating engine, based on the three-process **Lenoir** cycle (missing the isentropic compression process), whose shaft drove a compressor.

Reynst calculated the efficiency of that ideal constant volume combustion cycle as a function of its precompression pressure ratio, PR′, and T_1 as follows:

$$\eta = 1 - \frac{1}{\theta} \cdot \left[\left(\frac{A \cdot \theta}{PR'^{k}} + 1 \right)^{\frac{1}{\gamma}} - 1 \right], \quad \theta = \frac{q_{in}}{c_p T_1}$$

You can find the equation Reynst used for calculating efficiency on page 151 of Reference [2] where $k = 1 - 1/\gamma$; $A = \gamma$; and $q_{in} = f \cdot LHV$ (where $\gamma = 1.4$; $c_p = 0.24$ Btu/lb-R; and f is the stoichiometric fuel-air ratio). For his turbo-compound cycle, Reynst assumed a liquid fuel LHV of 18,900 Btu/lb and f = 0.067. (T_3 and P_3 at the turbine inlet were determined by the excess air factor.)

Note however, the ideal compound cycle efficiency is not affected by the amount of excess air and, as expected, the type of fuel has a negligible effect. For instance, 100% CH_4 with an LHV of 21,515 Btu/lb and f = 0.058 barely moves the needle.

Atkinson and R-G cycle efficiencies as a function of PR′ and cycle heat addition, i.e., $q_{in} = c_v \cdot (T_{3''} - T_{2'})$ for the Atkinson cycle and $q_{in} = c_p \cdot (T_{3'} - T_{2'})$ for the R-G cycle, are also given by the same equation, where A = 1 for the R-G cycle and A = γ for the Atkinson cycle [3].

In fact, Atkinson and Reynst's ideal constant volume combustion cycles are identical for the same non-dimensional heat input parameter, θ.

However, whereas θ is about 10 for the compound cycle of Reynst with CVC, Atkinson cycle θ for comparable pressure ratios and/or heat inputs as the base Brayton and R-G cycles is 2.4 to 4.2.

Making cycle comparisons

From a true engineering perspective, the correct comparison between *any* two gas turbine cycles can only be made at the <u>same</u> PR and heat input (q_{in}) basis. The efficiency hierarchy of the cycles is shown in Figure 7.

The cycles have different mean-effective heat rejection temperatures (METL) controlled by the temperature of cycle state point 4. However, in order to not complicate the chart, only METL corresponding to T_4 is shown and the variation in METL for the other cycles is ignored.

Thus, for each cycle the efficiency is dictated by their respective mean-effective heat addition temperature (METH), The reader can easily confirm (e.g., by visually comparing state points 4′, 4, 4′′ and 4′′′) that accounting for the METL further reinforces the hierarchy of the cycles.

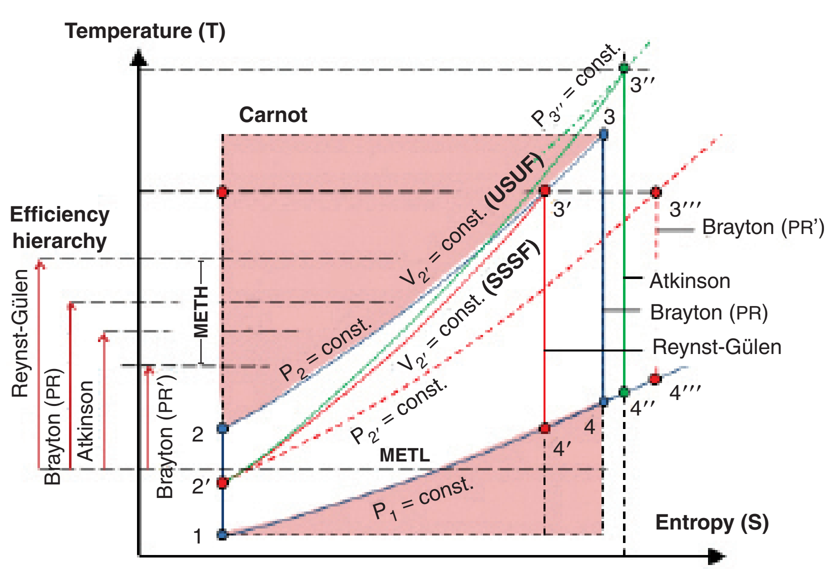
The objective here is to compare CVHA and CPHA cycles on an "apples-to-apples" basis. This is illustrated by the Brayton cycle {1-2-3-4-1} and Reynst-Gülen cycle {1-2′-3′-4′-1} in Figure 7.

The constant pressure SSSF heat addition process {2-3} is replaced by the constant volume steady-state steady-flow (<u>not</u> USUF) heat addition process {2′-3′} <u>without changing the amount of heat transferred</u>.

The R-G cycle's mean-effective heat addition temperature is higher than that of the base Brayton cycle and thus closer to T_3 at the same pressure ratio (i.e., $P_{3'} = P_3$) but at a lower cycle maximum temperature (i.e., $T_{3'} < T_3$). **In effect, a portion of the heat energy added to the cycle went to raising the pressure instead of raising the temperature.**

Furthermore, the R-G cycle is also more efficient than the Atkinson cycle with the same precompression pressure ratio (i.e., same $P_{2'}$) and heat input.

Figure 7. Temperature-entropy (T-S) diagrams for "apples-to-apples" comparison of air-standard cycles all having the same initial state and heat input. (METL shown corresponds to T_4). Cycle efficiencies are mainly dictated by respective mean-effective heat addition temperatures (METH). The R-G cycle (1-2′-3′-4′-1) is seen to have highest value of METH in spite of a lower peak temperature than the Brayton base-case (1-2-3-4-1).



Building on a history of pressure-gain combustion concepts and applications

The first half of the last century witnessed a number of pioneering and landmark (albeit short-lived) applications of pressure-gain combustion in a turbine framework for power generation, airborne, marine and vehicular propulsion.

Early attempts during the first half of the last century to develop pressure-gain combustion turbines for power generation and aircraft propulsion can be classified into three groups: 1) explosion combustion turbine, 2) pulsating combustion or pulse jet, and 3) compound cycle (or turbo-compound) engines.

First combined cycle

Holzwarth's "explosion combustion turbine" went through a reasonably successful operational period and several generations during the first quarter of the 20th century (as a bona fide combined cycle with a steam turbine nonetheless).

Ultimately it proved too complicated and expensive to be a viable product. Today, an early Holzwarth turbine can be seen in Deutsches Museum in Munich, Germany (Figure 8).

Eventually, Brown Boveri Company (BBC), who had taken over its design and manufacture, decided first to turn it into a forced-circulation boiler (referred to as **Velox** derived from the word velocity) and then replacing the explosion chamber with a constant pressure combustor.

The development chain finally ended in 1939 with the world's first commercial industrial gas turbine in Neuchâtel, Switzerland (now an ASME historical landmark).

Figure 8. First Holzwarth experimental gas turbine, 1908 (Deutsches Museum).

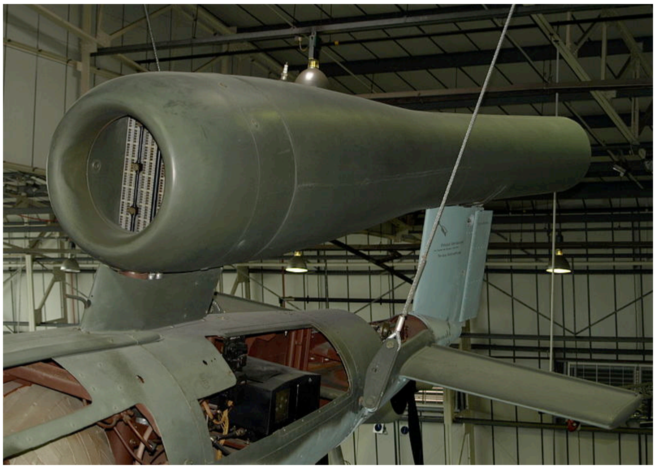


Figure 9. Propulsive pulse jet engine for V-1 missile (RAF Museum, London).

Pulsating combustion

Pulsating combustion found life in the "buzz bomb" Argus V-1, the German cruise missile invented by Paul Schmidt and extensively deployed during WWII (Figure 9).

The pressure gain inside the combustion chamber was created (without precompression by a compressor or other mechanical device) by successive explosions of the combustible air-fuel mixture (hence the name) *via acoustic resonance*.

In other words, the rising pressure of the explosion and the oscillation of the gas column inside the tube between the chamber and the exhaust nozzle, when in phase, led to the amplification of the said oscillations.

The modest PR of ~1.2 was created by the oscillating gas mass, which stored energy during expansion and discharged it during compression. (Animations and movies of pulse jet operation are widely available on the internet, e.g., Wikipedia.)

The pulse-jet engine was attractive to material-poor and overextended German war industry thanks to its very simple and cheap construction. It was not a contender in post-war modern aircraft propulsion due to its low efficiency (low pressure ratio) and its annoyingly high noise created by acoustic resonance (at ~50 Hz).

While turbojet engines eventually won the race (thanks to high thrust-to-weight ratios and relatively simple construction), another pressure-gain combustion system made a wave (no pun intended) in the immediate postwar years.

Turbo-compound engine

This was the turbo-compound engine, essentially a Brayton cycle gas turbine with the combustor replaced by a two-stroke Diesel or free-piston **Pescara** gas generator (i.e., constant volume combustion).

In order to avoid confusion, it must be stated up front that this is different from a *turbocharged* Diesel engine which involves a scheme to "squeeze" more air (i.e., more power output) into the engine cylinders (up to about 50% more) by compressing the intake air (known as *forced air induction*).

The low pressure ratio (~1.5) turbo-compressor is driven by an exhaust gas turbine (in effect, the combined system is a miniature gas turbine) whereas, in the turbo-compound engine, the gas turbine is a major cycle component and not an accessory.

The two practical turbo-compound cycle/engine examples of interest are the French Alsthom-SIGMA (Société Industrielle Générale de Mécanique Appliquée) **GS-34 turbine** (Pescara free-piston gas generator with power turbine shown in Figure 10) and **Nomad** aircraft engine designed and manufactured by the British company D. Napier and Son (a gas turbine engine with two-stroke Diesel generator).

Free-piston engine

The former, developed by the Swiss engineer Robert Huber (a student of Stodola) based on patents by the Argentinian engineer cum inventor Raul Pescara, had actually a quite successful run during the 1950s with installations for power generation (in multi-engine configurations up to 24 MW total in 1959) and ship propulsion in France.

Figure 11. General Motors XP-500 Firebird powered by a free-piston gas turbine engine.

It found some fame on this side of the Atlantic as well. In 1956, as a SIGMA licensee, General Motors installed a free-piston gas turbine engine in a futuristic car, **XP-500 Firebird** (Figure 11). Apparently, the car was conceived as an advertising gimmick rather than a serious commercial product since *"advertisements that generated the same attention would have been much more expensive."*

By all accounts, Napier's Nomad (Figure 12) was ahead of its time in terms of its achieved efficiency, about 0.325 lb/hr of fuel per shp at cruising speed and altitude (equivalent to around 40% efficiency).

The second generation Nomad II had a 12-cylinder two-stroke Diesel engine in two six-cylinder blocks, which served as a gas generator for the gas turbine (12-stage axial compressor with a pressure ratio of 8.25). Both the Diesel engine and the gas turbine contributed shaft power to the single propeller via a complicated gear arrangement.

At the end of the day, however, the low thrust-to-weight ratio (as a result of low airflow, heavy engine and gearbox) and immense complexity (mechanics referred to it as "parts recovery engine") doomed the Nomad by 1955. ■

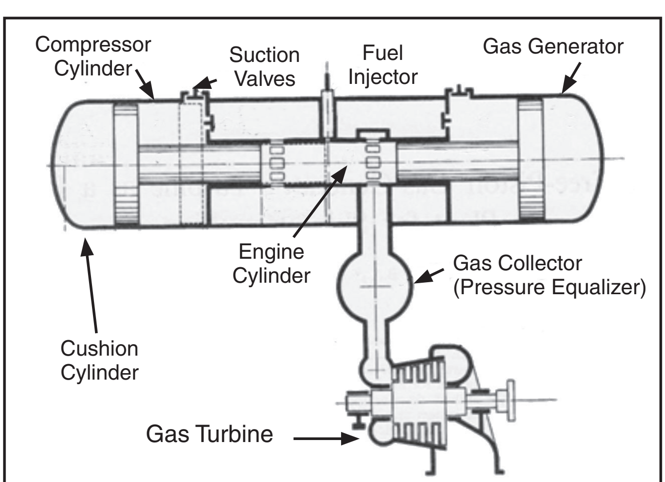


Figure 10. Diagram of a free-piston gas generator and gas turbine. (Animated videos of free-piston engines are widely available on Wikipedia and YouTube.)

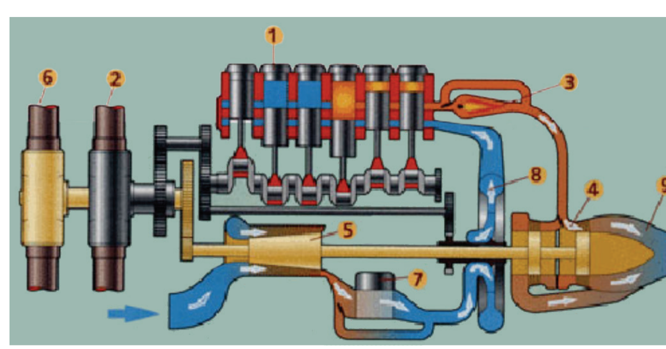


Figure 12 Layout of the original Nomad I flight engine with intercooled axial-centrifugal compressor and twin propellers (one driven by the gas turbine (6) and the other by the Diesel engine (2). Note the auxiliary combustor (3) and auxiliary turbine, activated by the flap valve to the left of (4), for extra power during take-off. In the final Nomad II variant, there was only one propeller, one 3-stage turbine and a single-spool 12-stage axial compressor without any intercooler (7).