Recent Advances in Power Cycles Using Rotating Detonation Engines with Subcritical and Supercritical CO_2

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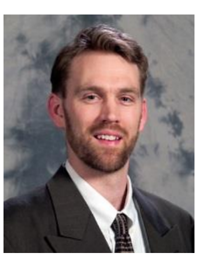

Jeffrey Stout has been an innovator of new propulsion and combustion systems for 17 years at Aerojet Rocketdyne. He has planned and executed over 1500 hot fire tests. He led the design, fabrication and test efforts for over a dozen programs involving ceramic matrix composite chambers and nozzles, including new tooling and processing methods. Since 2010, Jeff has led several projects on state-of-the-art rotating detonation combustion engines, participating in design, fabrication and test. He received his B.S. and M.S. degrees in mechanical engineering from Brigham Young University.

1. ABSTRACT

The present work deals with the modeling of a Recompression Brayton cycle (RCBC) with Sub-critical and Supercritical CO_2 (either pure or mixed with small impurities such as H_2O and Ar) as the working fluid for rotating detonation engine (RDE) pressure gain combustion based turbines in the power cycle. Results indicate that RDE-based sCO_2 power plants with CO_2 capture have about 14 percentage point higher efficiency than the conventional J Class natural gas combined cycle (NGCC) with CO_2 capture. The RDE-based RCBC has 25% lower levelized cost of electricity (LCOE) than J class NGCC. Although in early development stages, RDE-based combustion turbines provide a promising future for conventional air-fired NGCC as well as sCO_2 based power plants. As part of a series of internally and externally funded programs, Aerojet Rocketdyne has achieved significant technical breakthroughs in development of the RDE to increase the Technology Readiness Level. More work is needed to develop and test the RDE with architectures similar to J class and sCO2 turbines.

2. INTRODUCTION

The sCO_2-based Brayton cycle has primarily been investigated for nuclear applications, first during the 1960's and then more focused since the early 2000's. Although the Brayton cycle does not offer efficiency benefits at lower turbine inlet temperatures (<1,050°F or 839°K) over the steam Rankine cycle, the higher density of sCO_2 and its liquid-like behavior in the supercritical region reduces turbomachinery size and compression costs. Combining this with potential safety enhancements, and/or lower operating and maintenance costs, could lead to lower electricity costs. However, at higher turbine inlet temperatures of 1050 to 3500°F (839°K to 2200°K), the efficiency advantage of the supercritical and subcritical CO_2 Brayton cycle increases over that of the steam Rankine cycle significantly based on analysis. Combining this increased efficiency and lower turbomachinery cost will likely lead to a reduction in electricity costs. Furthermore, issues such as corrosion and hydrogen embrittlement are known to limit higher steam turbine inlet conditions - while for sCO_2 cycles, the work to date indicates the potential exists to operate at higher temperatures and pressures, without these limitations. The $_SCO_2$ cycle can also take advantage of multiple reheats for additional efficiency benefits.

Since the 1970's, Aerojet Rocketdyne has studied the application for super- and subcritical CO_2 cycles for various heat sources such as coal, natural gas, concentrated solar power and nuclear reactions. Oxy-combustion of natural gas produces a flue gas with mostly H_2O, CO_2 and some impurities. When the flue gases are mixed with recycled pure CO_2 stream, it produces CO_2-rich stream (volume percentage 90-98%) with minor impurities such as H_2O, Ar and N_2, depending upon the configuration selected. Similarly, in integrated gasification combined cycle (IGCC), the syngas (mixture of CO and H_2) produced from coal gasification can be burned in the same way as natural gas. These cycles thus can be configured operate at high efficiency (lower energy cost) with a pure CO_2 exhaust stream which can be sequestered (minimal emissions). Increasingly, the CO_2 emissions from power plants are getting similar treatment (e. g. proposing stringent regulations to reduce CO2 emissions from coal power plants as well as replacing some fraction of new plants by renewable energy such as wind and solar) by the Environmental Protection Agency (EPA) as SOx and NOx in the 1970 clean air act. Therefore, a higher efficiency plant which can provide CO_2 capture without significantly increasing cost of electricity are needed to address economic and regulatory issues. Inherently such a plant needs to have higher efficiency or lower capital cost.

Existing commercial natural gas combined cycle power plants (eg. J Class Turbine by Mitsubishi, H F Class Turbine by Siemens and General Electric) use compressed air and natural gas burned in a constant pressure heat addition mode – an adiabatic temperature rise. The flue gas is then passed through the turbine and exhaust from the turbine at about 1100°F (866°K) is passed through the heat recovery steam generator (HRSG) which runs a bottoming steam Rankine cycle. To improve the efficiency of this cycle, Aerojet Rocketdyne is investigating the replacement of the convention constant pressure combustor with a pressure gain combustor that utilized a rotating detonation wave to generate the pressure rise. By using the combustion system itself to assist in pressure gain, the oxidant (air/oxygen) or fuel (natural gas or syngas) does not need to be compressed to high pressures. For the same amount of heat added, the pressure gain combustion can be modeled as constant volume heat addition – an isochoric temperature rise.

Although the constant volume combustion process is unsteady by necessity, for the same ignition conditions and same heat added, the mass averaged state point at end of combustion or start of expansion is at a higher temperature, pressure and lower entropy than the Brayton cycle state point so more useful energy is available for expansion. An example comparison of pressure gain and constant pressure combustion is shown in Figure 1. The state points 1-2-3-4-5-1 represents a commercial J-class NGCC Brayton cycle (constant pressure heat addition, compressor work is from 4 to 5). The state points 1a-2a-3-4-5a-1a represents the approximation of rotating detonation engine pressure gain combustion (constant volume heat addition, compressor work is from 4 to 5a). Due to the gain in pressure, the compressor outlet pressure can be reduced to achieve the similar turbine inlet pressure.

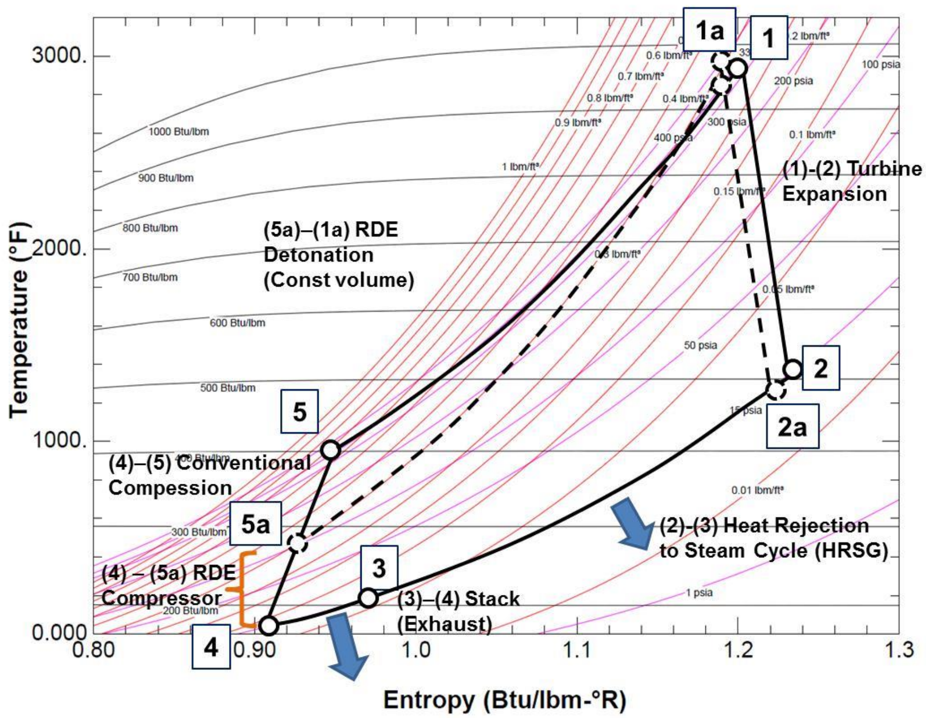

Figure 1. Mitsubishi Heavy Industries Commercial J Class turbine NGCC has been used as an example to compare conventional constant pressure adiabatic combustion turbine with pressure gain combustion using rotating detonation engine.

The desire to achieve constant volume combustion in a mechanically simple device has led to the development of pulse detonation and rotating detonation engines where the combustion reaction itself (detonation) causes the pressure gain. Because most implementations of pulse detonation engines require fast acting valves and consequent mechanical complexity and are limited to relatively low frequency operation, rotating detonation engines are being developed at Aerojet Rocketdyne for implementation in gas turbines.

3. ROTATING DETONATION ENGINE DEVELOPMENT FOR PRESSURE GAIN COMBUSTION

The rotating detonation engine or RDE (Figure 2) under development at Aerojet Rocketdyne eliminates the mechanical complexity of fast acting valves and maintains a far higher frequency than the pulse detonation engine, potentially achieving a cycle closer to true "single shot" detonative combustion. The RDE operates with one or more detonation waves continuously rotating around an annulus. In Figure 2 the propellants are injected at left, mixing rapidly upon injection. Behind the detonation wave the pressure rises, shutting off the propellant flow until such point behind the detonation wave that the propellant inflow pressure exceeds the downstream pressure. Behind this point the mass flow is approximately constant, yielding a triangular shape of the mixed, unburned propellants in the annulus. As part of a series of internally and externally funded programs, Aerojet Rocketdyne has achieved significant technical breakthroughs in development of the RDE. Figure 3 illustrates recent RDE development activities. Operability and sustainability of the detonation wave in hot fire testing have been demonstrated and significant risk reduction has been completed in the areas of fuel/oxidizer/air mixing, detonation initiation, inlet/fuel injection and wave directionality through past programs funded by Aerojet Rocketdyne internal funds and in collaboration with HyPerComp, Inc. As shown in Figure 4 with an aerospike nozzle attached (at top), Aerojet Rocketdyne rocket technology has succeeded in demonstrating an ignition system resulting in repeatable, sustained (indicated by the pressure traces in lower left), high quality, rotating (lower right shows the footprint of detonation waves rotating around the annulus) detonations with methane, hydrogen and ethane and liquid hydrocarbons with oxygen and oxygen diluted with nitrogen to near air-like conditions. Multiple injector, nozzle, and chamber configurations have been tested in 524 successful hot fire tests with instrumentation including high frequency pressure transducers, high speed cameras and calorimetry with water cooled hardware. Recent test series have achieved a consistency of rotation direction which is necessary for implementation of the RDE into gas turbines. Furthermore, in 2011, Aerojet Rocketdyne designed, built, and tested an airbreathing RDE combustor that incorporated transient plasma augmentation, in which

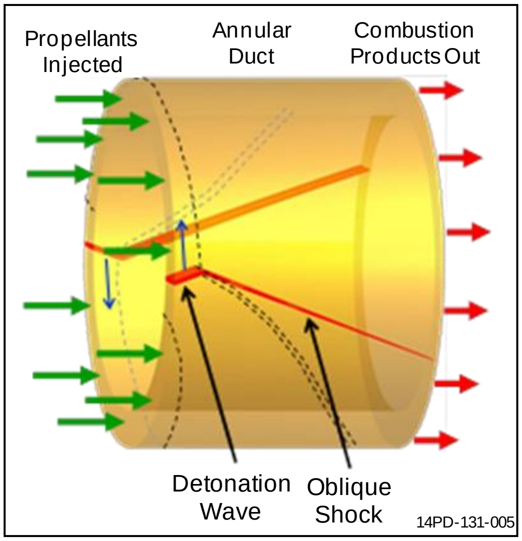

Figure 2. Schematic of a Rotating Detonation Engine

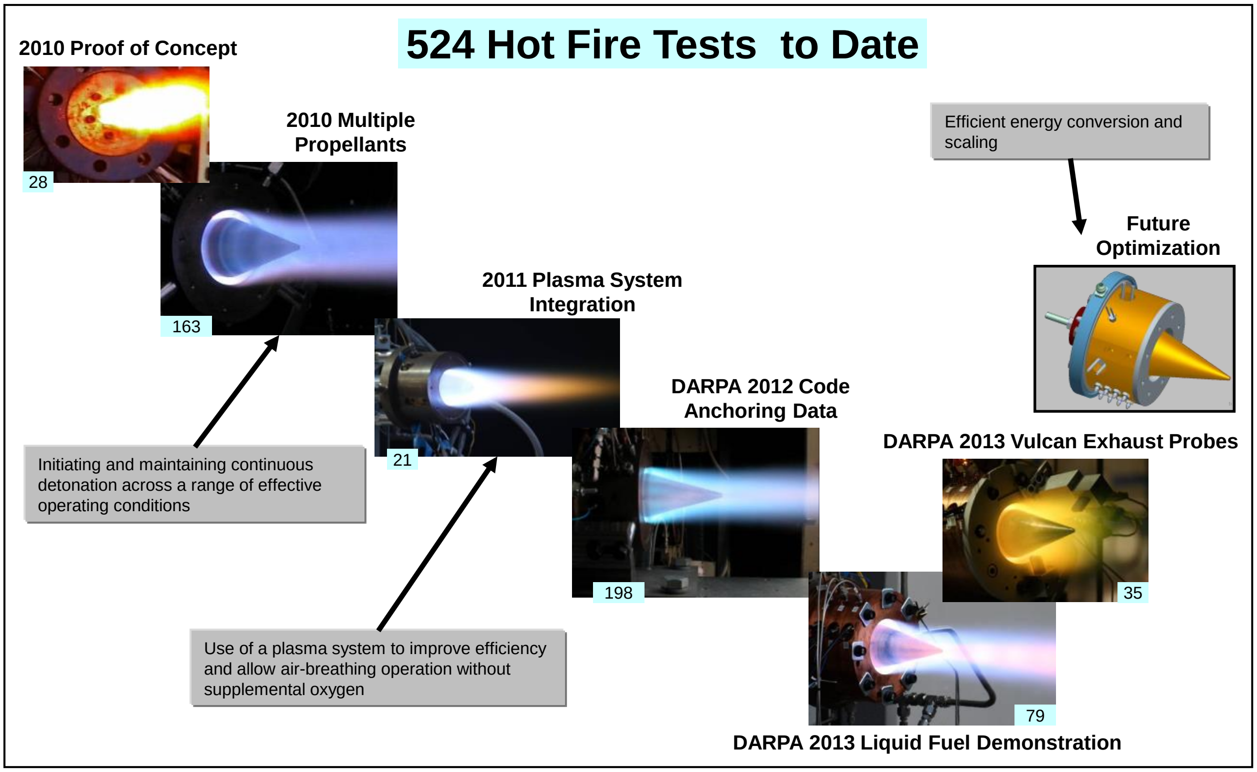

Figure 3. Aerojet Rocketdyne has Steadily Matured RDE Technology

high speed electrons create chemical radicals which facilitate the detonation process and eliminate the need for oxygen enrichment in air/natural gas combustors. This is a key step for application to gas turbines. Numerous tests have been conducted with high speed instrumentation including instream unsteady measurements of swirl and total pressure for use in Computational Fluid Dynamics (CFD) validation.

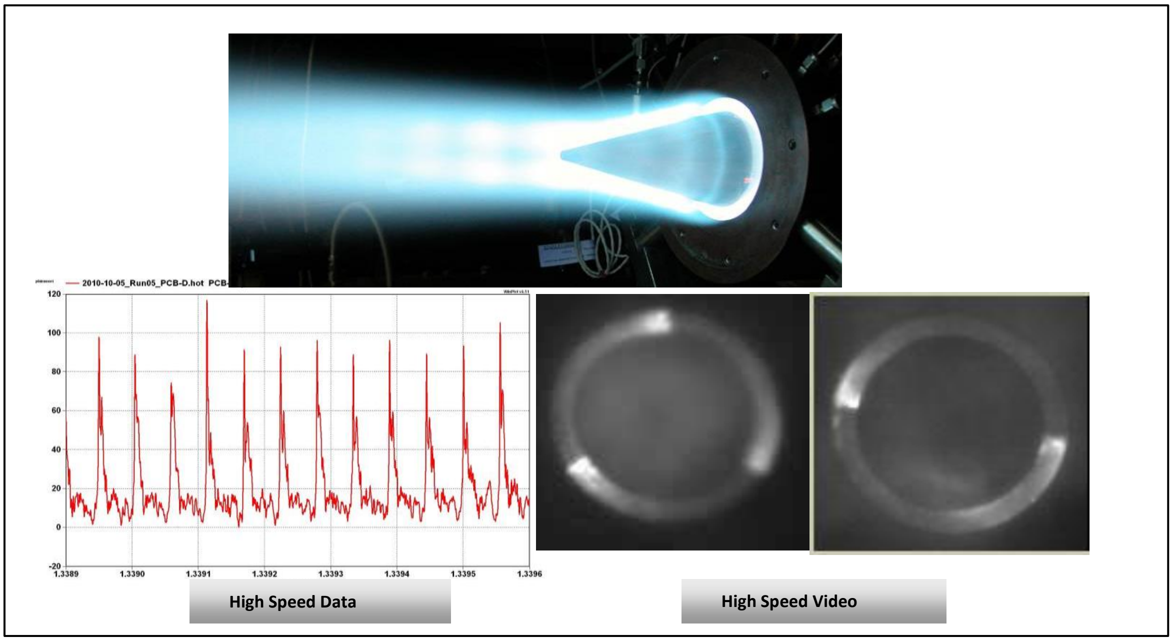

Figure 4. Aerojet Rocketdyne RDE Test Successes: RDE Operating with Aerospike Nozzle (Top), high frequency pressure signal indicates repeatable detonation waves achieved (bottom left), multiple rotating waves seen in flow visualization (bottom right)

Multicycle CFD computations of RDE's and RDE's integrated with turbines and ejectors have been carried out by Aerojet Rocketdyne with viscous, detailed mechanistic and global kinetics CFD using the PWRflow code (see Figure 5). Detonations were attained simply through deposition of energy at constant volume to simulate a spark using a special treatment of the chemical source term to inhibit predetonation whereby the source term is evaluated at its minimum value in the neighborhood of the detonation as described in Ton, Karagozian, Engquist, and Osher (1991). This enables capturing much of the essential physics needed for use in engineering design including the wave speed and detonation structure as well as the critical detonation energy on the relatively coarse grids needed for engineering analyses without inducing unphysical wave speeds as described in LeVeque and Yee (LeVeque, R. J. and H. C. Yee, J. Comp. Phys. 86:187-210 (1990)).

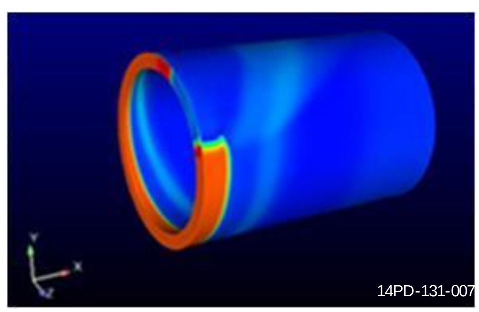

Figure 5. AR Annular RDECFD computation showing fuel behind detonation travelling upstream until propellant total pressure exceeds downstream pressure, upon which typical triangular profile emerges.

4. SUBCRITICAL AND SUPERCRITICAL CO_2 POWER CYCLES WITH PRESSURE GAIN COMBUSTION

Figure 6 shows the schematic of the sCO_2 recompression Brayton cycle that uses natural gas pressure gain combustion. The flue gases of natural gas combustion with oxygen are directly mixed with the recycled CO_2. An optional loop of indirect heating by coal combustion to use a low quality heat is also shown. The TS diagram of sCO_2 and subcritical CO_2 processes are shown in Figure 7.

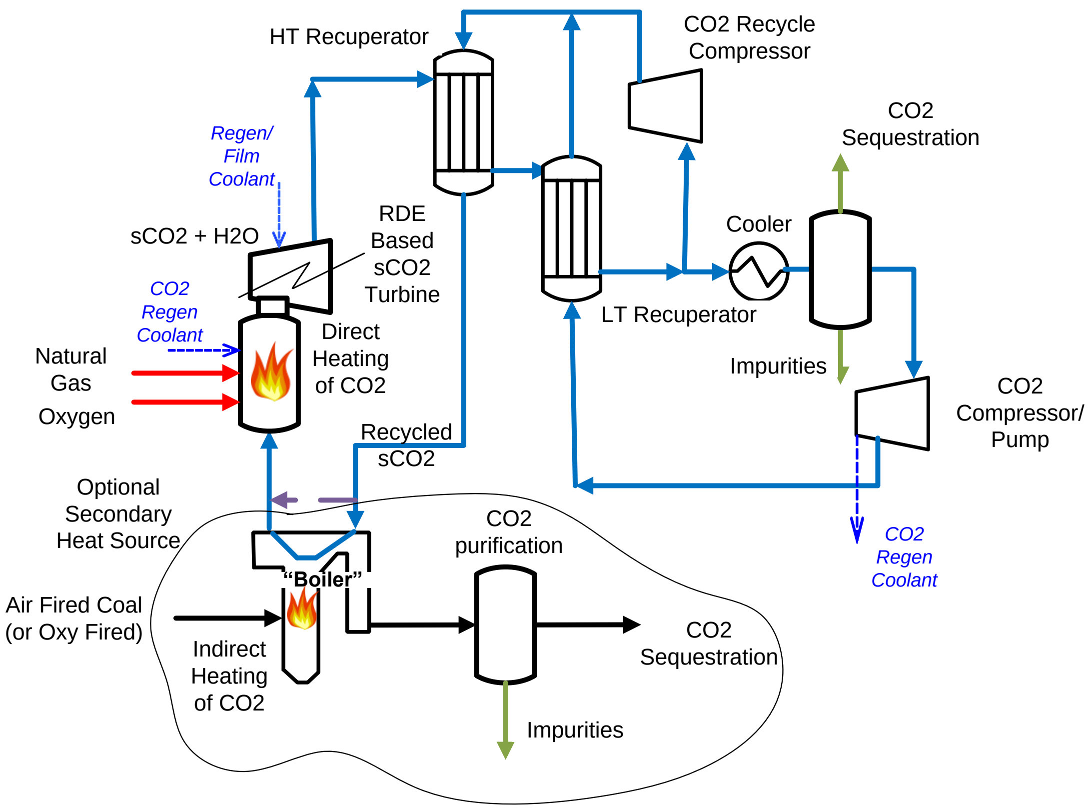

Figure 6. Schematic of a power plant with CO_2 capture incorporating pressure gain combustion in a supercritical CO_2 RCBC which uses natural gas oxy combustion with an optional coal combustion in a boiler with indirectly heating CO_2.

In a recompression Brayton cycle (RCBC), the hot CO_2 (or CO_2 flue gas) goes through the turbine on the same shaft as the two compressors to produce power. The hot flue gas at the exit of the turbine is then passed through a high temperature recuperator (HTR) followed by a low temperature recuperator (LTR), to pass that low quality heat to the compressed CO_2 used as recirculation fluid. The cold CO_2/water mixture is then split with one part sent to a compressor and HTR and other part sent to a cooler and filter for removal of impurities including water. The clean CO_2 is then compressed and sent through the LTR as shown in Figure 6. For the RDE based turbine, the compression required is significantly lower (nearly half) compared to a conventional RCBC with CO_2. As seen from Figure 7, both the cycles based on subcritical CO_2 as well as supercritical CO_2 require significantly less compression as compared to the conventional RCBC. The constant density lines and constant pressure lines are more diverging in case of supercritical CO_2 case as compared to subcritical CO_2 cycle.

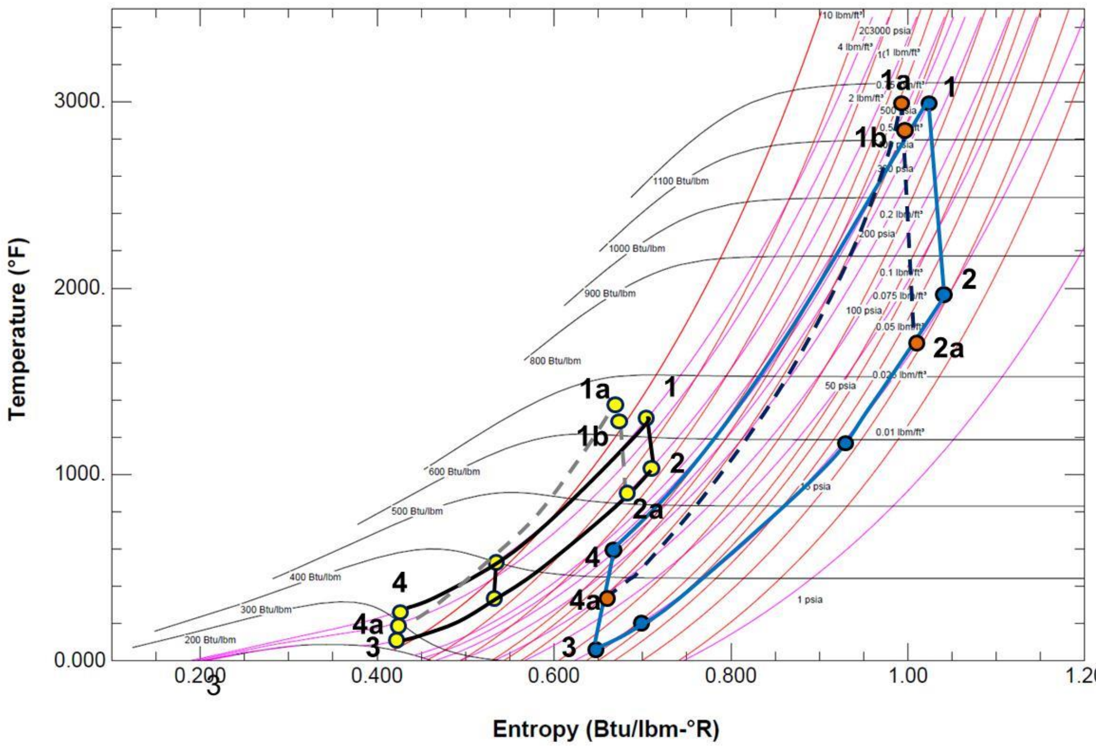

Figure 7. Temperature entropy diagram of a super and sub-critical recompression Brayton

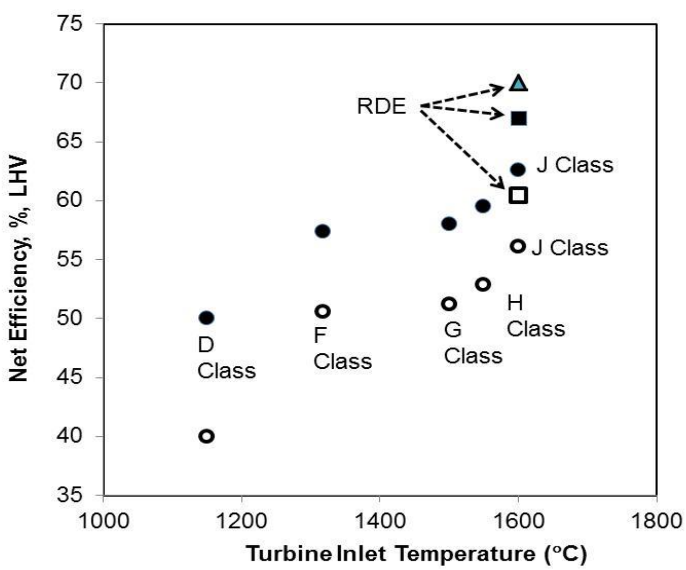

Figure 8. Net plant efficiency of various commercial combined cycle power plants without (filled circles) and with CO_2 capture (open circles) (Wally Shelton, DOE/NETL-341/061013). The RDE based J class NGCC plant with and without capture is shown with open-square and filled squares. The RDE based RCBC sCO_2 cycle is shown as filled triangle.

A comparison of efficiency of various power plants is shown in Figure 8. RDE-based J class turbine offers about 67% efficiency as compared to 62.6% offered by conventional combustor (Wally Shelton, DOE/NETL-341/061013). The analysis of RDE based sCO_2 cycle shows an efficiency of 70% LHV. The estimates of efficiency and T-S diagrams were obtained using AspenPlus (aspenONE V8.6) process modeling tool with REFPROP Version 9.1 Database 23 properties to develop process models. The methodology suggested by NETL/DOE in QGESS guidelines (DOE/NETL-2011/1455, April 2011; DOE/NETL-341/081911, January 2012) was used. The efficiency numbers for F, H and J Class turbines used in this report have been taken from DOE/NETL-341/061013.

The levelized cost of electricity plot for various commercial power plants (F, H and J Class NGCC) is shown in Figure 9. Also, shown is the LCOE of RDE based J Class NGCC and RDE-based sCO_2 RCBC cycle. The LCOE offered by RDE-based power plants is significantly lower than conventional natural gas based powerplants. The levelized cost of electricity was modeled using PSFM (Power Systems Financial Model) version 6.6. For the purpose of calculations, the material/equipment cost for RDE based J Class turbine was assumed to be 10% more than conventional adiabatic combustors. The labor cost was scaled proportionally.

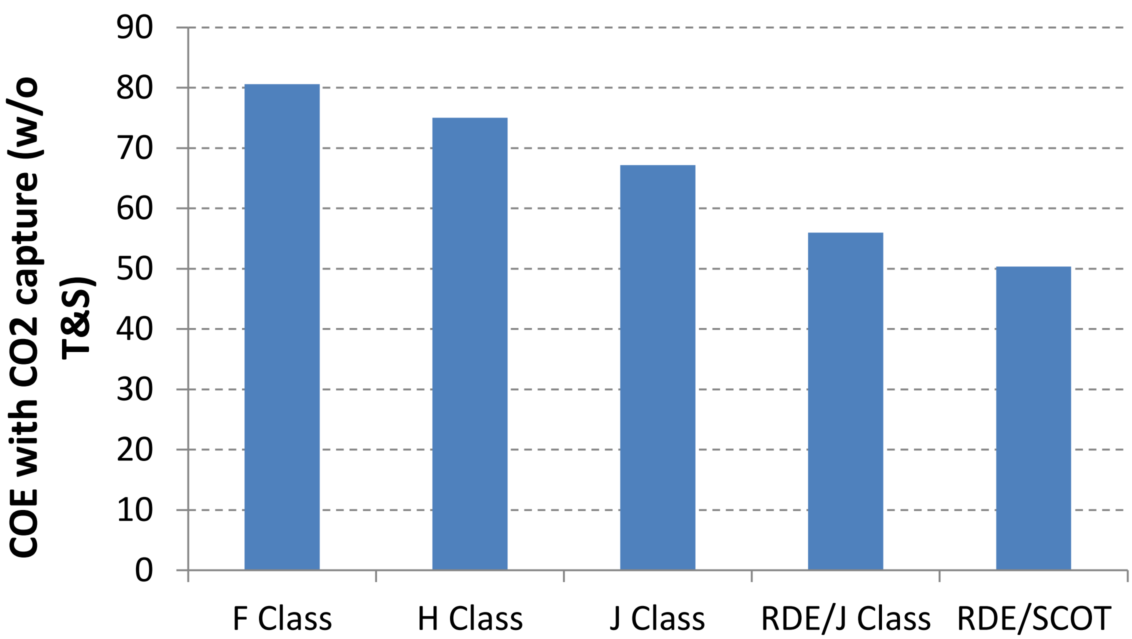

Figure 9. Levelized cost of electricity of various commercial power plants compared with RDE based power plants.

5. CONCLUSIONS

Pressure gain combustion with an RDE-based power cycle using natural gas combustion offer higher LHV efficiency and lower LCOE for both sCO_2 RCBC and J-Class based NGCC. The efficiency of an RDE-based sCO_2 plant is about 14 percentage points higher with 25% lower LCOE than corresponding commercial J Class NGCC. Although in early development stage, RDE-based combustion turbines provide a promising future for conventional air-fired NGCC as well as sCO_2 based power plants. As part of series of internally and externally funded programs, Aerojet Rocketdyne has achieved significant technical breakthroughs in development of the RDE to increase the Technology Readiness Level. More work is needed to develop and test the RDE with architectures similar to J class and sCO2 turbines.

NOMENCLATURE

CFD	=	Computational fluid dynamics
HRSG	=	Heat recovery steam generator
HTR	=	High temperature recuperator
IGCC	=	Integrated gasification combined cycle
LCOE	=	Levelized cost of electricity
LHV	=	Lower heating value
LTR	=	Low temperature recuperator
NGCC	=	Natural gas combined cycle
RCBC	=	Recompression Brayton cycle
RDE	=	Rotating detonation engine
sCO_2	=	Supercritical carbon dioxide

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