Peregrine Turbine Technologies, LLC

Developer: Peregrine Turbine Technologies, LLC

Technology Type: Supercritical CO2 Brayton

EPRI Participation: None

Thermal Resource: Coal/Natural Gas

Development Status: Active

Application: New

Current TRL: 4

Technology Class: Standalone Power Plant

Last Updated: 11/7/2018

Introduction

Peregrine Turbine Technologies, LLC (PTT) is a turbo-machinery research and development company with proprietary technology in power conversion cycles. PTT was founded in 2012 for commercializing a proprietary thermodynamic cycle referred to as the partially recuperated or Stapp cycle, making use of a supercritical CO_2 (sCO_2) working fluid to achieve high efficiencies. PTT's thermodynamic cycle is specifically targeted for optimized performance using air-combustible fuels such as fossil fuels, biomass, municipal waste, and the like.

PTT is teamed with Sandia National Laboratories (SNL) under a Combined Research and Development Agreement where PTT's new turbo-machinery designs and heat exchangers are being tested for performance. PTT has also been partially funded by the Air Force Research Lab (AFRL) and the Navy's Office of Naval Research (ONR) to develop a high pressure ratio sCO_2 turbo-pump, which is now being tested at Sandia. These components will be employed in the partially recuperated system to demonstrate the performance and controllability in early 2020.

Process Description

The earliest variant of the PTT cycle, shown in **Figure 1**, is characterized by a symbiotic interaction between an air-Brayton cycle and a sCO_2 Brayton cycle. The air discharged by the air-cycle compressor serves as a recuperation medium and is pre-heated by the low-pressure (LP) heat exchanger via the heat rejected from the sCO_2 loop. Heat is added to the air stream via combustion and heat is then provided back to the sCO_2 cycle via the high-pressure (HP) heat exchanger. PTT refers to the back-and-forth transmission of heat in this circular fashion as a "thermal flywheel" and it is a principal reason for the high net efficiency of the system, which exceeds 50% lower heating value (LHV) for a turbine inlet temperature of 1382°F (750°C) and a pressure ratio of 3.5:1. This performance was predicted analytically using Numerical Propulsion System Simulation (NPSS) thermodynamic cycle analysis software models.

The heat-rejection LP heat exchanger for the sCO_2 loop suffers from the common pinch-point problem associated with supercritical fluids like sCO_2, where the specific heat of the fluid spikes near the critical point resulting in significant mismatches between the heat capacity rate of the source and sink heat transfer fluids. The result is that it is difficult to manufacture a cost-effective heat exchanger that will achieve effectiveness numbers significantly >80%.

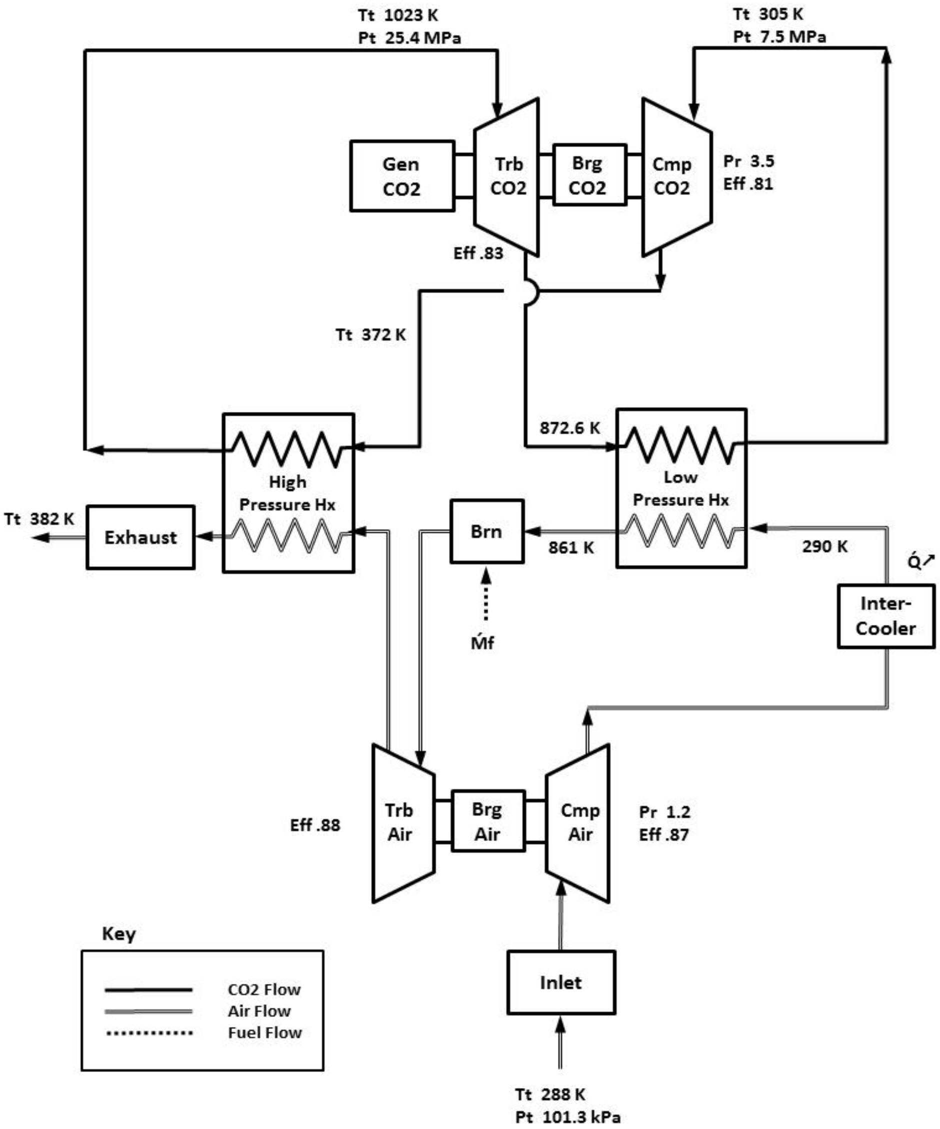

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Figure 1 – Process Flow Diagaram for the PTT sCO_2 Power Cycle

The partially recuperated cycle, which is currently being manufactured as a system, was subsequently developed to alleviate the pinch-point problem by intentionally mismatching the heat capacity rates between the two flows and storing sufficient heat by creating very high approach temperatures. This has the effect of both reducing the amount of surface area required by the heat exchanger, because of the large log mean temperature difference, as well as reducing the overall size of the heat exchangers. All the PTT cycles depicted call for operation entirely above the CO_2 critical point and with compressor inlet conditions near the critical point. Analyses were conducted based on compressor inlet conditions of 89.3°F (31.9°C) and 1131.3 psia (7.8 MPa).

The change in topology to the partially recuperated system, as depicted in **Figure 2**, resulted in a reduction of efficiency compared to the first cycle variant, but a dramatic improvement in cost to manufacture the system due to the reduction in the size of the heat exchangers.

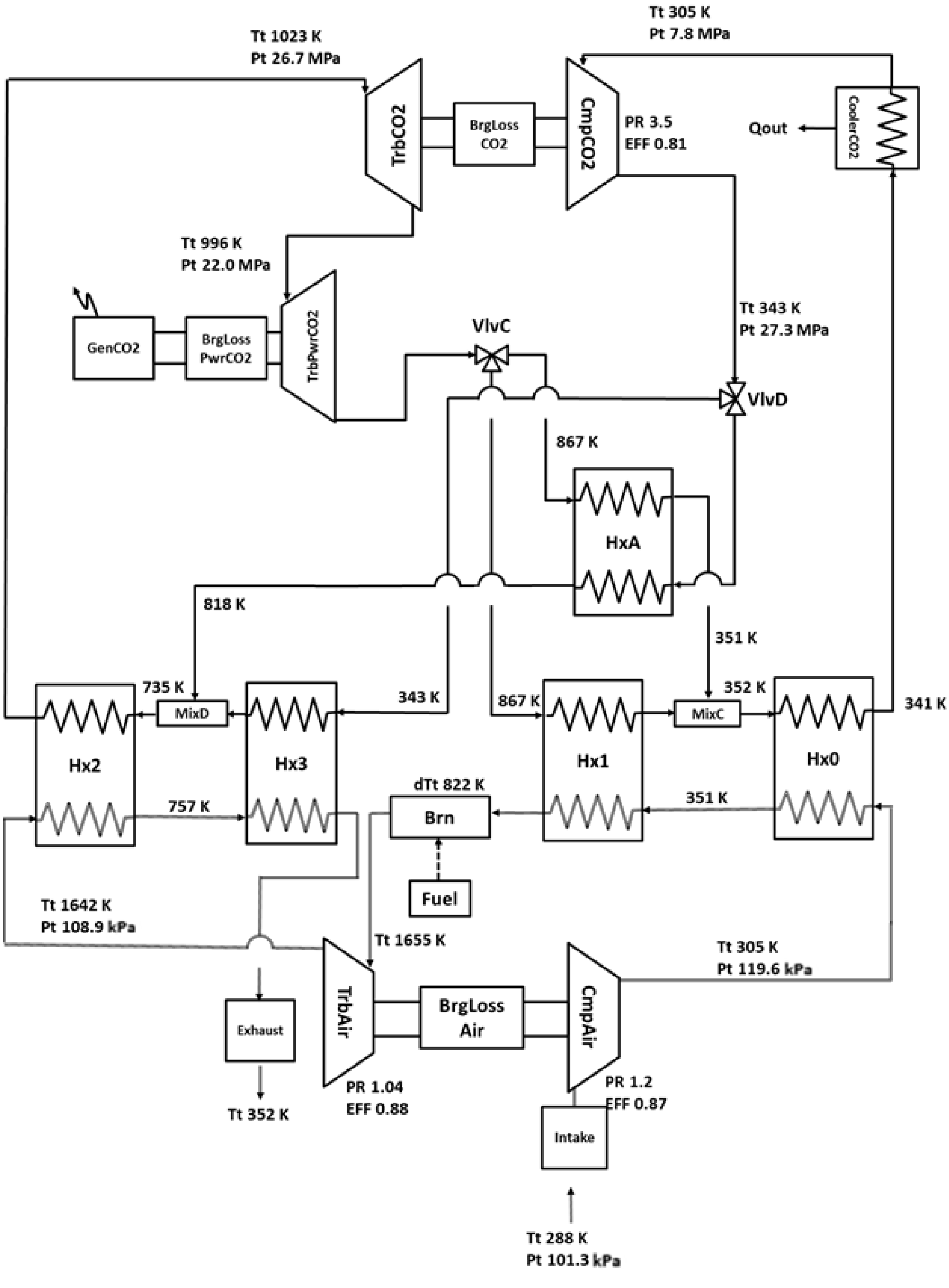

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Figure 2 – Process Flow Diagram for the PTT Partially Recuperated (Stapp) Cycle

The system depicted has a lower compressor pressure ratio of 3.5:1. Supercritical cycles generally demonstrate better performance when pressure ratios are above about 5:1 [1]. PTT examined the optimal pressure ratio as limited by American Society of Mechanical Engineers B31.1 pressure-rated piping, etc. and settled on a product pressure ratio of 5.5:1, which, combined with a turbine inlet temperature of 1382°F (750°C), yields a thermal efficiency of 45% LHV. This performance was also predicted analytically using NPSS thermo-dynamic cycle analysis software models.

It should be noted that due to the fuel-agnostic nature of the cycle, it may be advisable to create a sub-atmospheric combustion chamber to facilitate solid fuels like coal, biomass, or municipal waste. In that case, the air-side turbo-machinery may be replaced by induced-draft and forced-draft fans as is commonly the practice in coal-fired applications. The 1-MW natural gas-fired demonstrator engine will employ a forced-draft fan without the induced-draft fan for simplicity.

The main differentiating factor between the partially recuperated cycle and the PTT cycle is the addition of a recuperator and the splitting of the flows exiting the compressor and the turbine. Most of the flow passes through the recuperator effecting large amounts of heat transfer, while remaining heat is “recuperated’ via the airstream as before. But by judicious choices of where to split and remix the flows, PTT could capture more of the airstream heat before rejection to atmosphere, improving efficiency.

Technology Status

The PTT sCO_2 cycle was first conceived in 2011 by founder David Stapp. Highly recuperated cycles such as those utilizing sCO_2 pose a challenge to the use of air-combustible fuels due to the high temperature of the sCO_2 entering the primary heat exchanger. Because of the heat lost to flue gas, Stapp found that none of the existing cycle definitions delivered high enough thermal efficiency to yield an acceptable improvement in performance over existing turbine solutions.

The PTT cycle was first analyzed using simple spreadsheet calculations and thermodynamic state point data from an online calculator based on the Spann-Wagner equation of state. Having found that the thermal performance for this configuration was quite high, PTT employed Wolverine Ventures to perform an independent assessment. Results from the Wolverine Ventures modeling showed similar high-performance results using the same assumptions for turbo-machinery and heat exchanger performance, validating PTT’s projections for thermal efficiency [2].

Further work on sizing the heat exchangers required to achieve the high effectiveness numbers desired showed that this cycle variant without recuperation was probably not economical to produce, because heat exchangers were too large and costly. At this point, it became clear that a partially recuperated cycle could yield much better economics with only a slight reduction in thermal performance. The partially recuperated (Stapp) cycle was conceived in 2013 and subsequently was analyzed by Wolverine Ventures. It was found to achieve 45% LHV thermal efficiency, which was still above what was possible with other sCO_2 cycles when using air-combustible fuels. This variant also resulted in a 75% reduction in the size, weight, and cost of the heat exchangers required; a significant advantage over the previous cycle. Patents for both of PTT’s thermodynamic cycles were issued in early 2017 [3]. Additional patents for a dual-core variant of the system and for fatigue compliant heat exchangers was awarded in 2018.

Once the benefits of the cycle were understood, PTT reached out to SNL, whose work to that point in sCO_2 power cycle testing had set the stage for commercialization of the technology. SNL expressed an interest in understanding the cycle better and eventually conducted an analysis, which corroborated the Wolverine Ventures findings. Since then, SNL has signed a Combined Research and Development Agreement for testing and further commercialization work with PTT. The scope of SNL CRADA work began with testing and characterization of a thermal-mechanical-fatigue compliant recuperator in 2017. In addition, SNL purchased a Peregrine Turbopump capable of 1382^0F (750^0C) turbine inlet temperature to advance testing of sCO_2 high performance components including bearings and seals. Testing of the turbopump began in August of 2018 and is ongoing. The CRADA has since been expanded to include integration and testing of the components of a full engine in stepwise fashion, resulting ultimately in an electric power producing prototype at a 1MWe power rating.

In 2013, PTT applied for and was awarded a Small Business Innovation Research contract from the U.S. AFRL to study the utilization of the cycles in an aircraft propulsion application; namely, propulsion for heavy, unmanned aerial vehicles where 72-hour mission durations were desirable [4]. The studies conducted in Phase I of that project showed that for mission durations greater than 12 hours, the weight of the PTT turbine, plus the required mission fuel, would be lower than the current propulsion systems together with their respective fuel amount. This highlighted that the PTT technology warranted further development work for propulsion systems of all kinds where fuel efficiency is a logistics, life-cycle cost, or mission-capability enhancer.

In 2015, PTT applied for and was awarded a Phase III award under the same topic as a continuation of the previous work [5]. The scope of work for this effort was to design and build a turbo-pump for sCO_2 capable of delivering a pressure ratio of 5.5:1 and a turbine inlet temperature of 1382°F (750°C) at a mass flow rate of 12.1 lb/sec (5.5 kg/sec). These parameters are sufficient to provide thermodynamic power for a 1-MW engine. This contract was jointly funded by ONR, owing to the potential benefit for the Navy's future surface vessel fleet, which is slated to be powered by electric hybrid drives. PTT's calculations show that the novel turbine design can provide a 40% reduction in fuel burn over the marine-adapted turbofan engines currently used in the next-generation vessels such as the DDG-1000 Zumwalt-class ships. The design and build of the turbo-pump has been completed and started testing at SNL in August 2018. A picture of the core installed in the SNL sCO_2 loop is shown below in **Figure 3**.

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Figure 3 – PTT's Turbo-Pump Under Teat at SNL

Photos of various parts from the turbo-pump are shown in **Figure 4**.

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Figure 4 – Parts from PTT's Turbo-Pump

Through the course of these efforts, PTT developed proprietary heat exchanger analysis code named SciHex to analytically determine the anticipated pressure drops and heat exchanger effectiveness for design variants that were then under consideration. This tool proved to be useful in doing cost/performance studies given that about 70% of the engine cost for the PTT turbine is allocated to the heat exchangers, making for strong leverage between the two. The accuracy of SciHex has recently been verified by test data using supercritical Carbon Dioxide in a test loop using multiple Peregrine proprietary heat exchangers and the proprietary propane-fired heater.

The 1-MW version of the PTT turbine makes use of eight heat exchanger trains, in a FlatPak® arrangement of four on each side feeding radially into the turbo-pump on the horizontal centerline, which then feeds the power turbine driving the 1-MW electric generator as shown in **Figure 5**.

PTT built and tested the heat exchanger/combustor compliments, together with the turbo-pump, beginning in the last months of 2018. Thereafter, the power turbine assembly and generators will be added for a full machine test by late-2020. This first machine will be fired by propane fuel initially as a rig, then up-fitted for natural gas burners for the 1-MW demonstration. In parallel, PTT is working with a biomass combustor vendor to integrate the system for biomass fuel applications.

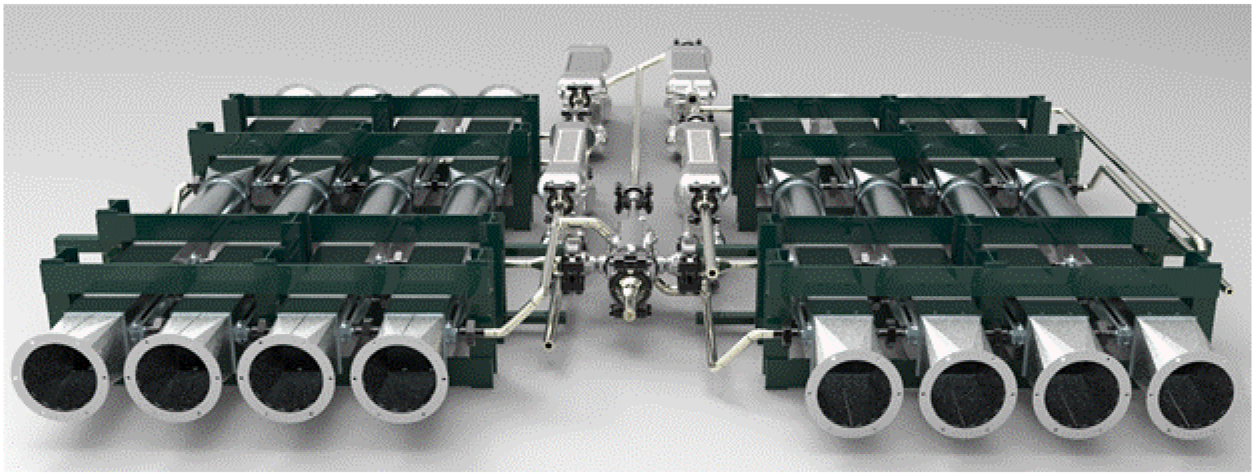

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Figure 5 – Depiction of PTT's 1-MW FlatPak®

The 1-MW FlatPak® can be deployed in 1–5-MW blocks, stacked on top of each other. This avoids the complexity of developing a separate machine and at the same time permits better application matching. Using the same modular components also simplifies manufacturing since only the single machine is being built and not until the final assembly process is it tailored to the customers requirement by stacking the appropriate number of 1-MW modules. A 3-MW FlatPak® arrangement is shown in **Figure 6**.

Benefits and Costs

Internal studies show that the patented, closed-loop sCO_2 Brayton cycle employed in the PTT turbine generator has a levelized cost of electricity (LCOE) like a natural gas combined cycle, does not consume water, achieves efficiencies approaching 50% LHV electrical, and because it is externally fired at atmospheric pressure, is fuel agnostic. Its modular, thermally-compliant heat exchangers are unique amongst power generation technologies and recuperate heat from both the air side and the sCO_2 side of the cycle. Unlike conventional turbine systems, the rotating equipment, both HP and LP systems, occupies only a small volume of the system and accounts for around 10% of the uninstalled system cost. The power-dense sCO_2 turbo-machinery enables the rotating groups to be housed in cartridges that slide into housings that have the hard connections to the heat exchanger systems, permitting fast removal and replacement during overalls and repair, leading to a projected mean-time to repair (MTTR) of around 4 hours. The low repair time together with the reliability of rotating engines combine to produce the potential high availability. In its current form, the system is conducive to systems ranging from 1–30 MW, with multiples used to achieve higher site ratings with extraordinary turndown capabilities.

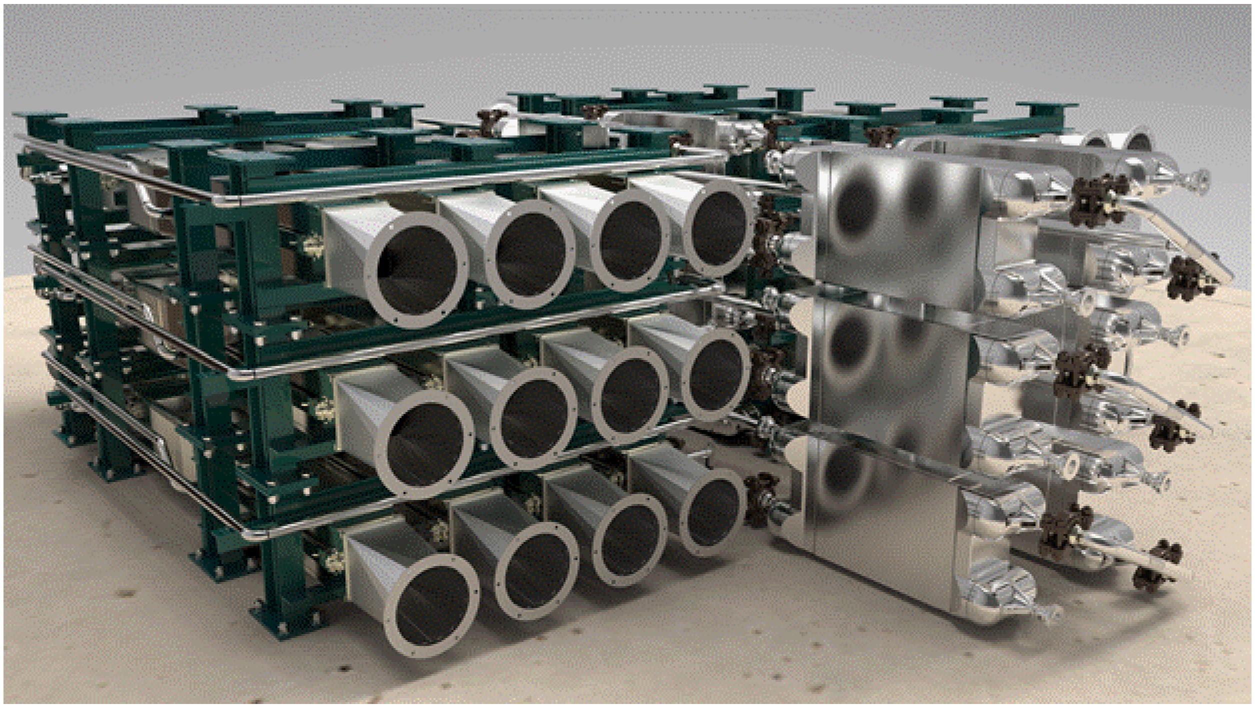

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Figure 6 – PTT's FlatPak® 3-MW Configuration

Purported benefits include:

- 50% LHV electric efficiency in simple-cycle mode
- Does not consume water
- Fuel agnostic

- High availability and reliability
- Load following with integral peaker capability
- Low LCOE with optimization based on externalities
- Low maintenance cost
- Low MTTR
- Modular construction
- Power block capital costs <$1000/kW
- Suited for combined heat and power applications.

The low LCOE is a combination of a low capital costs, high efficiency, and low maintenance costs. However, LCOE is not a static number; it is affected by two external variables: the price of fuel and the cost of money. Normally for a given technology, these are considered during the technology selection phase. The PTT system affords another level of selection that permits the LCOE to be optimized. While the power rating is established by the size of the turbomachinery and the combustion system, the efficiency is a function of the heat exchanger complement, which represents most of the cost of the system (over 60% of the cost). Thus, for a given power output, the efficiency can be set by simply changing the heat exchanger complement—more heat exchangers, higher efficiency and cost; less heat exchangers, lower efficiency and cost.

Water scarcity in some regions can put a limit on the use of water for power generation. The PTT system employs dry cooling and does not consume water. The power density of the sCO_2 leads to compact heat exchangers for the rejection of heat from the cycle, to return the power turbine exhaust to the initial compressor inlet temperature. This heat can either be rejected from the cycle or can be employed in a waste heat recovery system. The temperature and high specific heat capacity of the sCO_2 entering the cooler is ideal for district heating or another combined heat and power scheme. Its inherent scaling properties make it a good fit for both distributed and central plant power generation. This is especially relevant since unlike conventional systems, the efficiency of the system does not vary greatly with size.

While the cycle itself has benefits, its fuel agnosticism presents its own opportunities. The externally fired nature of the system employs near atmospheric combustion and so anything with a reasonable Btu content can be used as fuel. This is not just limited to normal carbon-based fuels, but a host of renewable and opportunity fuels, including biomass and high-grade waste heat. The range of acceptable Btu content is extended over conventional power generation by the elimination of fuel pressurization. The combustor system is also modular and external to the turbine system. For gaseous and liquid fuels, the differences to the engine would not be significant, requiring only a fuel nozzle change. For opportunity fuels and waste heat applications, the heat exchanger system is integrated into the plant. The modular heat exchanger systems permit integration with both direct-fired combustion and pyrolytic gasifier systems.

Closed-loop cycles benefit from the recirculation of a clean working fluid throughout the cycle. Because there are no products of combustion passing through the engine, many of the typical hot-end degradation mechanisms are avoided leading to potentially higher reliability. The unique properties of sCO_2 also permit high efficiencies with only modest turbine inlet temperatures and very low tip speed, approximately 50% of that which is typical of turbomachinery. The combination of both low temperature and tip speed leads to low stresses and potentially longer life using readily available turbine materials. It follows that these same factors could also enhance reliability: elimination of the hot-end erosion, corrosion, fatigue and creep failures from the turbine section. The hottest section of the engine is the high-temperature heat exchanger. This is positioned immediately after the combustor on the air side, and before the turbine inlet on the sCO_2 side. They are connected to the turbine housing by Grayloc™ connectors, and due to their modular nature and positioning, can be easily accessed for replacement.

There are several sets of heat exchangers that transfer heat between air and sCO_2, a recuperator that exchanges heat between hot and cold sCO_2 streams, and a cooler that rejects heat from the cycle to return it to inlet conditions. These heat exchange elements are thermally compliant and largely free of thermal strain at design-point operation. This permits rapid transient operation for load flowing without inducing thermal strain and reduces the potential for spallation. The heat exchangers are produced using the same sequence of manufacturing steps, making them well-suited to mass production. Because the sCO_2 turbine is smaller than an equivalent steam or gas turbine, its cost is also less.

The heat exchangers therefore constitute the greatest portion of overall cost. While still in the early phase of producibility, they have already seen a significant evolution of cost reductions from design iterations, which have dramatically reduced the material input. This bodes well for future cost reductions, where 80% of manufactured cost of high-volume components is the raw material input.

Barriers and Challenges

Industry has considered the development of bearings and seals as being a significant barrier to commercialization of sCO_2 cycles. Seals are always a challenging aspect of optimizing the performance of gas turbines. This is particularly true of sCO_2 cycles because the working fluid has such a high density. This has the desirable effect of shrinking turbo-machinery size, which reduces the annular area of a particular seal type by reducing the cord length. However, small seal gaps can pass substantially more mass flow, particularly because of the low viscosity. The net effect is a high sensitivity of seal flow to gap size. PTT has addressed this issue with a proprietary seal design not previously seen in gas turbines, but a variant of which has been employed in certain pump applications. Analysis shows that these seals will outperform alternatives. The performance of these seals is currently being tested in the context of turbopump tests at SNL. Early indications are that the seals perform well.

Previous testing of sCO_2 turbomachinery employed gas foil bearings for both radial and thrust bearings. Radial bearings have proven to be a reliable and trouble-free in airborne environmental control units and have been used for decades in that rigorous application. Capstone has also used them for some time in land-based gas turbines. Any problems seen in sCO_2 applications have been attributed to rotor-dynamic problems. The PTT turbine employs a modified version of the gas foil bearing that was designed specifically for the application. These bearings will also be tested in the last part of 2017.

With respect to thrust bearings, gas foil bearings in sCO_2 systems have proven to be very problematic. The load capability of these bearings is very limited. Because of that and to reduce windage losses associated with that bearing, the PTT turbine employs a gas static bearing with substantially more thrust capability, about an order of magnitude higher.

Another barrier to commercialization has been a cost effective and durable heat exchanger design that can withstand the very high pressures and temperatures associated with sCO_2 cycles. Work done at the University of Seville has shown that most sCO_2 cycles achieve peak efficiencies at a compressor discharge pressure above 5800 psia (40 MPa) [6]. Laboratory experiments by SNL and Knolls Atomic Power Laboratory have been limited to below 2900 psia (20 MPa) to mitigate costs and challenges of a higher-pressure system. PTT has developed a turbo-pump that is designed to provide compressor discharge at 6237 psia (43 MPa). This turbo-pump is designed for 1382°F (750°C) turbine inlet temperature and has design margins for still higher temperatures when heat exchanger technology advances to exploit it. Since the commercial market for heat exchangers was not capable of meeting those performance parameters, PTT undertook the design of proprietary heat exchangers. By employing practices in turbine hot-section design, PTT developed recuperators and air-to-sCO_2 heat exchangers that are purported to be more compliant and less susceptible to thermo-mechanical fatigue. The recuperator has been tested in conjunction with SNL and the heat exchangers were tested in Q3 2019. An example of an air-to-sCO_2 heat exchange module is shown in **Figure 8**.

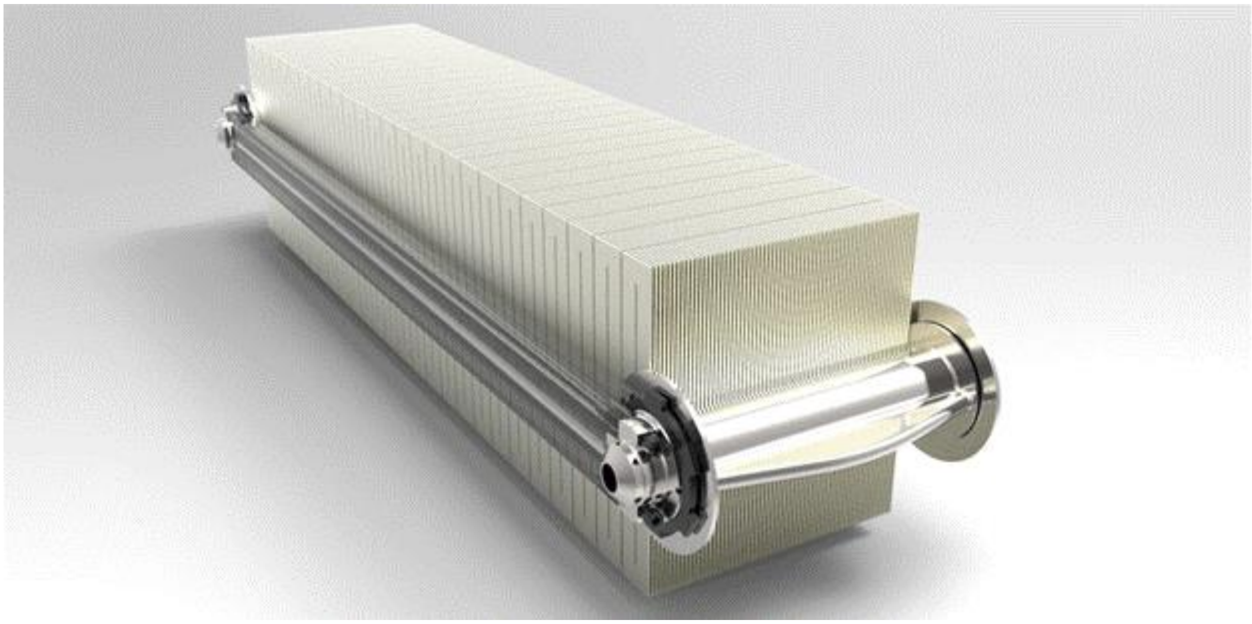

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Figure 8 – PTT's Heat Exchanger

PTT's power turbine section drives three independent PM generators, the power from which is combined using active rectification and power conversion to 60 Hz or other required power types depending on the application. Turbomachinery for the power turbine section consists of three radial inflow turbines in series. These are currently in the design phase and will be manufactured early in 2020. The controls and power electronics are still in development and will be tested in mid-2020.

System controls are perceived to be relatively straightforward since off-the-shelf valves and fuel supply systems are employed. It should be noted though that close-system controls development is not trivial and is still under development. Early versions of this control algorithm have been tested in rig tests in 2018-19. Expected refinements thereafter will be tested in engine tests slated for mid-2020.

References

[1] "A Novel SCO_2 Primary Cycle for Air-Combustible Fuels," D. Stapp, Proc. of the Supercritical CO_2 Power Cycle Symposium, September 2014.

[2] "Wolverine Ventures, Inc. Validation of Peregrine Turbine Cycle Design Only Simulation," E. Butzin, President, Wolverine Ventures, Inc., February 2012.

[3] "Power Generation System and Method with Partially Recuperated Flow Path," U.S. Patent 20150240665 A1, 2017.

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[6] "Analysis of the Thermodynamic Potential of Supercritical Carbon Dioxide Cycles: A Systematic Approach," F. Crespi, G. Gavagnin, D. Sanchez, and G. Martinez, Proc. of the ASME Turbo Expo, June 2017.