Novel Thermal Energy Conversion Technologies for Advanced Electric Air Vehicles

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Future air vehicles will increasingly incorporate electrical powertrains that require very tight integration of power, propulsion, thermal, and airframe technologies. This paper provides an overview of a new category of thermal energy conversion technologies that can be used to provide highly efficient turbo-generation and electric propulsion, while synergistically managing and recycling both the low grade waste heat from electrical components and the high grade waste heat from engine components.

I. Nomenclature

TREES = Thermal Recovery Energy Efficient System – recycles waste heat
HEMM = High Efficiency Megawatt Motor – rotating superconducting coil and cryocooler
DELTA = Double-acting Extremely Light Thermo-acoustic engine – flight-weight UAM generator
STRAYTON = Stirling and Brayton Combined Engine – dual topping/bottoming cycle integration
Alpha-STREAM = Alpha Stirling Thermo-acoustically Resonated Electro-acoustically Modulated
Stretch = Length between cryocooler acceptor and rejector
ID = Inner Diameter of cryocooler regenerator
OD = Outer diameter of cryocooler regenerator
Porosity = Regenerator Open Volume Percentage
Dfiber = Diameter of the regenerator fiber
Inertance = Length of the cryocooler inertance tube
Qlift = Amount of heat lifted by cryocooler at 50K
TBTratio = Thermal Buffer Tube Ratio
G-M = Gifford-McMahon Cryocooler
J-T = Joule-Thompson Cryocooler

II. Introduction

Electric air vehicles range from small unmanned aerial systems (UAS) used for package delivery to urban air taxis for commuters to large single-aisle transport class aircraft for airlines. All these vehicles require tight integration of the power, propulsion, thermal, and airframe (PPTA) to reach their full potential fuel, emission, noise, and mobility benefits. Historically, these technologies were designed separately and optimized at the sub-component level. But after decades of development each component has nearly reached its full potential and only by integrating these traditional components together with new thermal energy conversion technologies is it possible to achieve a new level of aircraft architecture that synergistically combines PPTA. This paper will present several new thermal energy conversion technologies including the Strayton engine and High Efficiency Megawatt Motor (HEMM) for efficient turbo-generation, Double-acting Extremely Light-Weight Thermo-acoustic (DELTA) engine for flight-weight UAS power, and Thermal Recovery Energy Efficiency System (TREES) for recycling and managing all the low-grade waste heat on the aircraft. The Strayton engine merges a rotating Brayton cycle with an oscillating Stirling cycle and can provide high efficiency flight-weight turbo-generation and thrust; The TREES system combines acoustic mechanical energy distribution to pump heat to a high temperature and then recycles the waste heat throughout the aircraft via heat pipes while improving fuel efficiency; HEMM combines a rotating cryocooler with a superconducting rotor to provide high specific machine torque power for propulsion and power generation; DELTA technology allows for very high frequency operation in the lower power ranges and can provide very high specific electric power. All

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these technologies can be integrated to provide a unique electric aircraft configuration that improve system reliability and performance. This paper will provide an overview of these technologies.

III.   Strayton

First, a primary limit to the usefulness of all electric air vehicles is the amount of energy an air vehicle can fly with. This is true even for smaller light-weight UAS systems because flight endurance is often a key economic variable for profitability in many mission types. The highest specific power energy storage options by far are combustible fuels (a factor of 50 times or more than the best batteries). So the first key technology for achieving full performance is improving the conversion of fuel to useful power. In small air vehicles internal combustion engines are often used with an efficiency around 20% and in larger air vehicles high by-pass turbofans are used to achieve up to 50% efficiency. But for medium duty applications requiring 100kW to 1MW the efficiency of the turbine cycles drop significantly and the internal combustion engines don't scale well to high power due to their oscillating components and maintenance requirements. Moreover, many of the large single-aisle aircraft concepts are currently limited to about 1MW due to limits in SiC switching technology and therefore complicated power extraction from turbofan providing both thrust and power are employed to maintain overall high efficiency. Instead, a new kind of engine is proposed here that maintains the high efficiency of turbofans in the power range below 1MW while leveraging the advantages of an electric grid on aircraft. This engine is referred to as a Strayton Engine and it is a combined Stirling and Brayton (Strayton) engine in which the two cycles are combined to provide topping and bottoming cycles in a synergistic way.

Normally, Brayton rotating cycle engines lose efficiency at low power levels due to low Reynolds number effects and blade tip losses but are optimal at high power high Reynolds number applications as used in single-aisle transport jet aircraft. And the Stirling thermo-acoustic oscillating working fluid standing wave and traveling wave cycle engines normally have high efficiency at low power, but are limited in their higher power capacity due to the heat transfer limits of a sealed external combustion device. In addition, the practical implementation of either technology is often expensive because of the tight tolerances required for high speed rotating blade tips in Brayton rotating working fluid cycle machines and the tight tolerances around the piston seals in a Stirling/Brayton oscillating working fluid cycle machine. This technology combines both cycles in a synergistic way that overcomes their typical disadvantages. This combined cycle solution produces a new class of engine that is both efficient and capable of a wide range of power levels while achieving low cost manufacturing by reducing the tolerance requirements of both technologies through this integration. Each cycle can be made with lower efficiency components, because when integrated together they form a higher efficiency system at a higher power output than would otherwise be possible. Moreover, recent developments in low-cost turbo-chargers and quiet thermo-acoustic engines with no hot moving parts enables a system solution that is low cost and reliable. (United States of America Patent No. 9,163,581 B2, 2015) (MTT, 2016) (Electric)

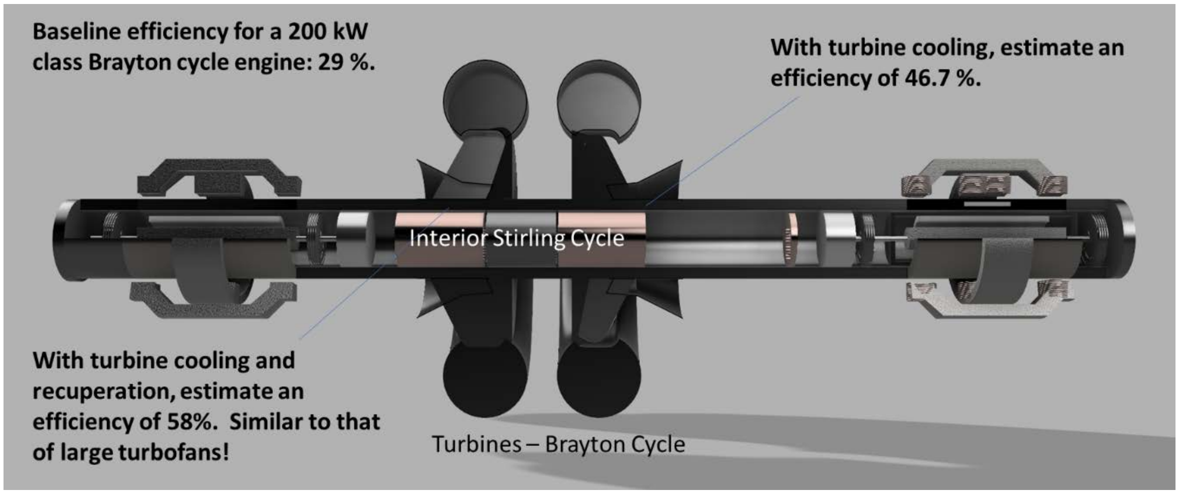


Figure 1. Strayton Engine Genset

As shown in Fig. 2 the rotating Brayton cycle energy and oscillating Stirling cycle energy are simultaneously converted to AC power with a rotary alternator and linear alternator respectively.

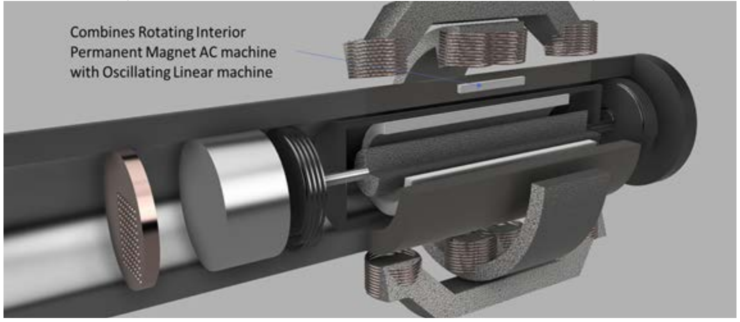


Figure 2. Rotoscillating Alternator

In Table 1 is shown a comparison of the Strayton engine estimated performance relative to the common alternatives:

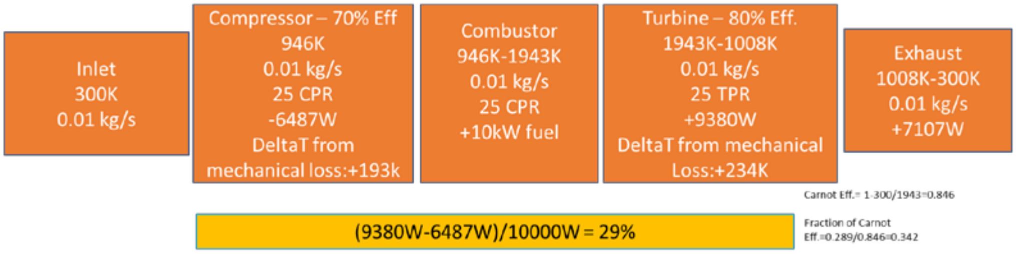
Table 1. Comparison of Power Generators

Technology	*Net System AC Power (kW)*	*Net Fuel LHV to AC Electric Power Conversion Efficiency*	*Full Production Equipment Manufacturing Cost $ per W*	*System Maintenance Cost $/kwh*	*System Availability Percent*	*System Life (yrs)*
Ideal	>100	>70	<0.9	0.02	>95	>20
SOFC-GT	>100	>70	<4	<1	>95	>5
Strayton	**>100**	**>50**	**<0.05**	**<0.02**	**>95**	**>20**
Fuel Cell	>100	>50	<5	<1	>95	<5
µ-Turbine	<300	>20	<1	<0.1	>95	<5
ICE OTTO	>100	>25	<0.05	<0.03	>95	<10
Gas Turbine	>1000	>40	<0.5	<0.1	>95	<5

Assumptions used include 60,000 hour bearing life (air bearings not included), 0.5% fuel cell degradation per 1000 hrs, hot turbine refurbish every 5 years, maximum turbine inlet temperature of 3100F, tubular solid oxide fuel cell used in SOFC-GT and TAFC, recuperator effectiveness 0.8, fuel utilization 0.9

A simple thermodynamic analysis of this engine is shown in Figs. 3-5. In fig. 3 is a typical unrecuperated small 3kW micro-turbine. For this analysis the simple adiabatic compressor and turbine equations are assumed and no recuperation is employed. Note the compressor ratio of 25 assumes two radial compressors and two radials turbines are employed. The net system thermal efficiency is approximately 29%. Note that the T4 turbine blade is not cooled and is likely too hot so this efficiency is likely not achievable but serves as a baseline for adding the Stirling recuperation system.

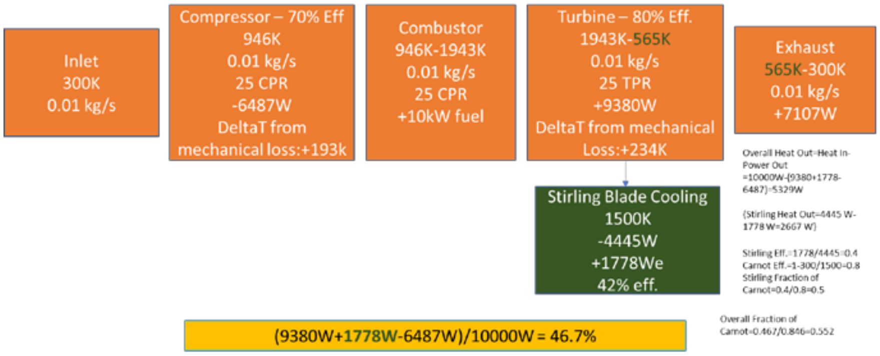
- Mdot 0.01 kg/s, Fuel in: 10 kW, CPR: 25, Comp. Eff. 70%, Turbine Eff. 80%
- Power Out 2892W, Eff. 29%, T2: 300K, T3: 946K, T4: 1943K, T5:1008K



Note too hot at T4 currently

Figure 3. Original Turboshaft Thermodynamics

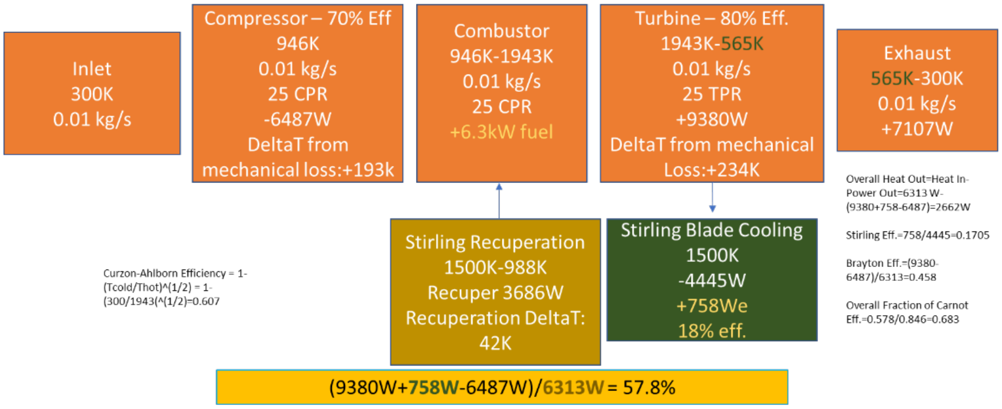
Next, if we add the Stirling thermo-acoustic cycle inside the rotor shaft we can cool the T4 turbine blade to 1500K using conductive cooling as shown in Fig. 4. Moreover, the high speed turbine blades are small enough that thermal conduction is effective. The waste heat from the Brayton cycle and the Stirling cycle is rejected to the ambient environment. Note the original micro-turbine system is now a Strayton engine without recuperation and achieves about 46% thermal efficiency as shown in Fig. 4.



Note T4 blade is conductively cooled to 1500K, waste heat rejected to environment (not recuperated)

Figure 4. Original Turboshaft Thermodynamics with T4 Blade Cooling (no Stirling recuperation) added

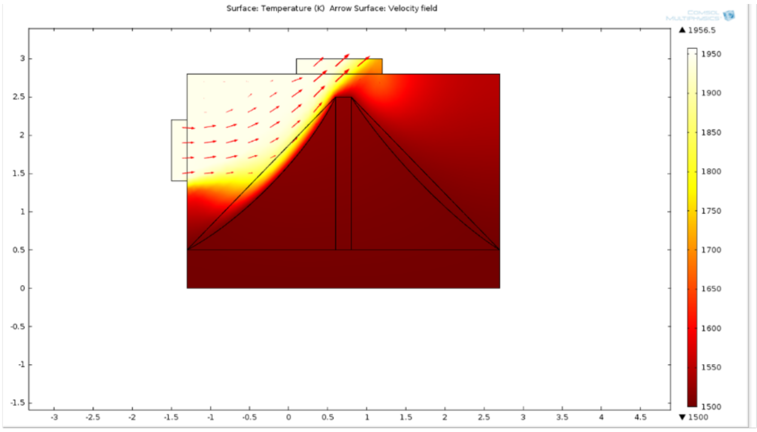
In Fig. 5 the same system is employed as in Fig. 4, but the waste heat from the embedded Stirling cycle is recuperated into the compressor exhaust. Note that even though the Stirling cycle efficiency dropped due to a higher reject temperature, the overall combined cycle efficiency climbed to 57%. This performance is close to the maximum possible according to the Chambadai-Novikov Efficiency limit (61%). Further improvement could be achieved by also adding traditional recuperation to the Brayton cycle exhaust in some circumstances.



Note T4 blade is conductively cooled to 1500K, waste heat recuperated drops fuel required by 3686W

Figure 5. Original Turboshaft Thermodynamics with T4 Blade Cooling (including Stirling recuperation)

In Fig. 6 an example turbine blade cooling conjugate heat transfer analysis was completed on a 4 inch diameter centrifugal turbine rotor to confirm the blade can be conductively cooled with the internal Stirling cycle. And in Fig. 7 is a separate analysis completed by Dr. Al Juhasz using a custom turbo-machinery code to predict the performance for a 100 kW Strayton engine while using more conservative compressor pressure ratio of 16 for a two-stage centrifugal compressor. Note it uses about 33 times more mass flow, but the overall performance is similar to the 3kW Strayton. His adiabatic efficiency was actually higher as well resulting in a baseline turbo-shaft efficiency of 32% vs. 29%.



Note radial turbine blade temperature kept below 1500K with 1943K tubine inlet temperature from gas
Can use additional non-working turbine blades to capture more heat as needed

Figure 6. Example Radial Turbine Conductive Cooling

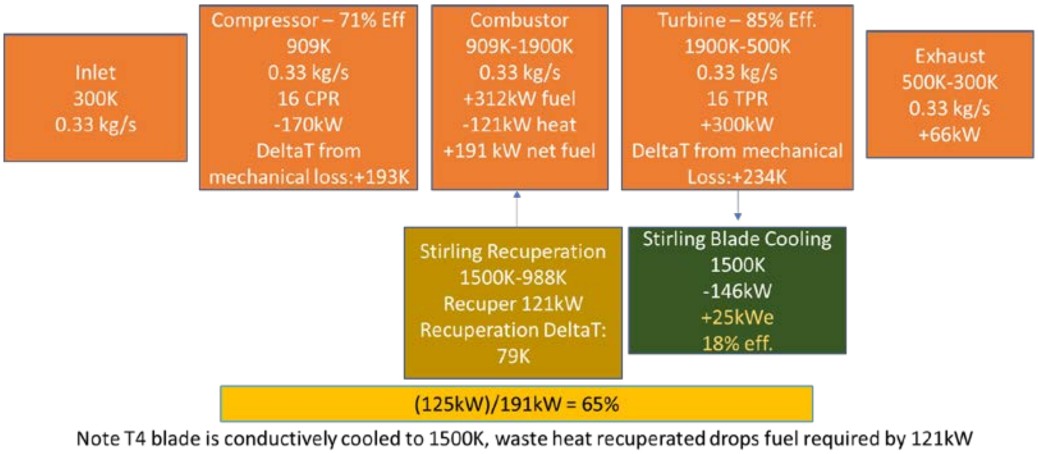


Figure 7. Strayton 100kW Thermodynamic Cycle

IV. HEMM Cryocooler

The high efficiency megawatt motor (HEMM) utilizes an embedded thermal energy conversion pulse-tube device to provide cryogenic cooling of the rotor to enable very high specific power motor at relatively low rotational speed to support direct drive of propulsors and minimize thermal management requirements (USA Patent No. LEW-19477-1 - Cryogen Free Partially Superconducting Electric Machine, 2015). Since the Strayton engine can provide some combination of electric power and thrust, some of the electric power can be distributed throughout the aircraft to drive additional HEMM propulsor motors to increase the effective fan by-pass ratio for thrust and for boundary layer ingestion aerodynamic drag reduction. The superconducting rotor, ambient stator, and embedded rotating cryocooler are shown in Fig. 8.

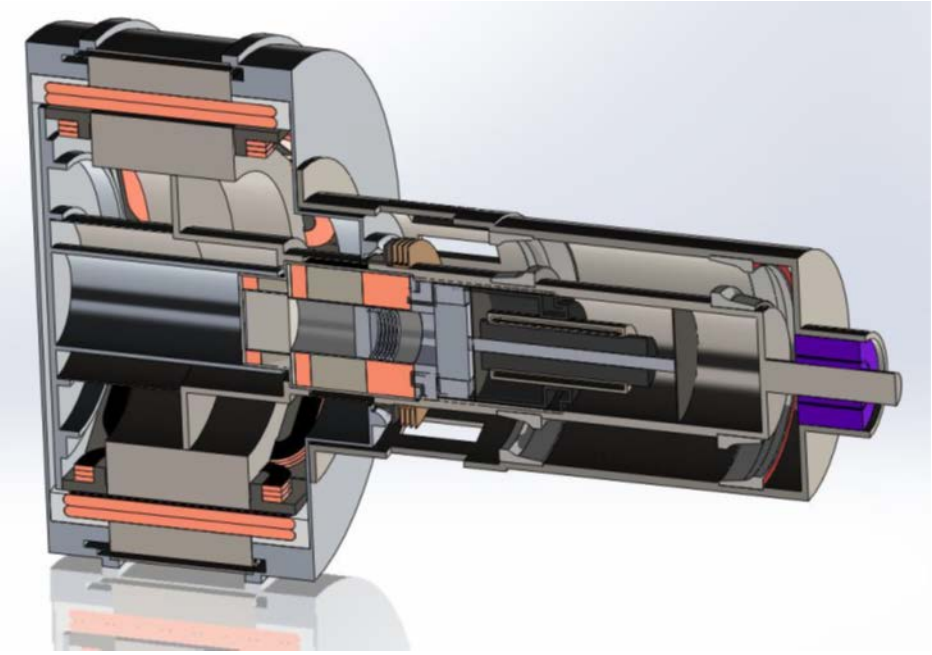
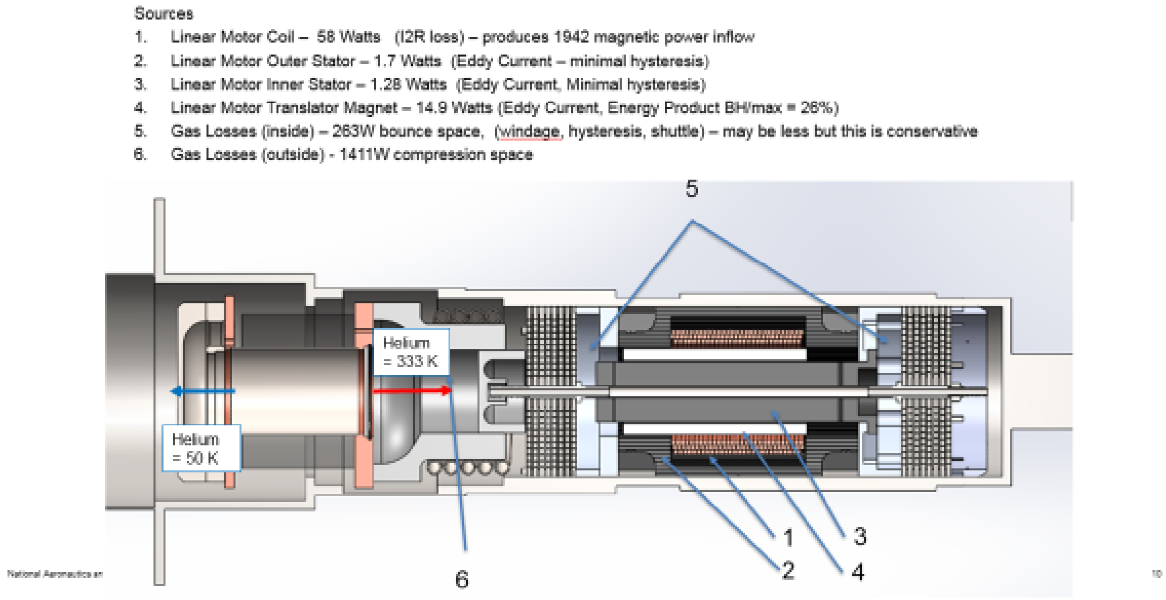


Figure 8. High Efficiency Megawatt Motor with Cryocooler Core

A cut-away view of the rotating cryocooler is shown in Fig. 9 along with expected thermal losses. It is designed to lift 50W of heat energy at 50K while rotating at 6800 RPM and fitting within a shaft of less than 90 mm diameter. The development of this cryocooler required designing a long and narrow linear motor capable of providing 2000 W of mechanical shaft power at 60 Hz and a pulse-tube cryocooler was selected to reduce moving part count on the cold-end. Numerous parametric redesigns such as shown in Table 2 were completed to allow for optimal integration with the balance of the machine.



Sources

1. Linear Motor Coil – 58 Watts (I2R loss) – produces 1942 magnetic power inflow
2. Linear Motor Outer Stator – 1.7 Watts (Eddy Current – minimal hysteresis)
3. Linear Motor Inner Stator – 1.28 Watts (Eddy Current, Minimal hysteresis)
4. Linear Motor Translator Magnet – 14.9 Watts (Eddy Current, Energy Product BH/max = 26%)
5. Gas Losses (inside) – 263W bounce space, (windage, hysteresis, shuttle) – may be less but this is conservative
6. Gas Losses (outside) - 1411W compression space

Figure 9. Linear Motor Thermal Heat Sources

Table 2. Parametric Variation

Stretch (cm)	ID (cm)	OD (cm)	Porosity (%)	Dfiber (micron)	Inertance Length (m)	Inertance Diameter (mm)	Qlift (W)	TBTratio
1	4.579	8	75	16.05	2	7.52	53.7	1.725268
2	4.65	8	75	16.93	2	7.758	50.3	1.913978
2	5.08	7.62	79.6	15.35	2	8	45.5	1.751969
2	3.81	7.62	77.2	16	2	8	37.6	2.335958
2	3.81	7.62	76.6	16.82	2.137	7.89	43.4	2.335958
4	4.592	8	75.19	18.02	1.982	8	44.56	2.373693
4.32	2.807	6.889	75	17.2	1.382	5.47	35	3.99715
8	4.035	7.097	79.4	17.97	1.765	7.524	32.6	3.692689

In Fig. 10, a 3D electromagnetic study was completed to confirm the forces acting along the entire magnet length. One interesting finding from this design work was the importance of keeping the full length of the magnet even though the Redlich style linear machine's stroke is much less than the length. If a portion of the magnet length is removed from the middle, the net force drops as indicated in the graph.

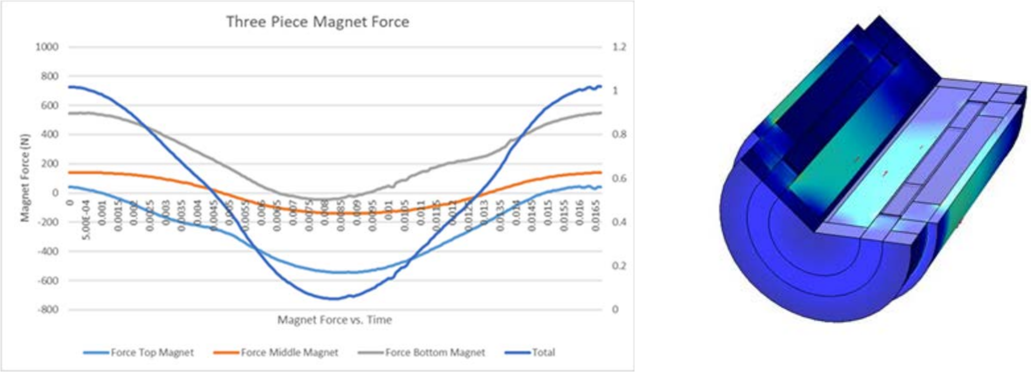


Figure 10. Linear Motor Electromagnetics

In Fig. 11 is the pulse-tube cryocooler that has no moving parts to minimize any rotational bearing risks and Fig. 12 shows a proposed test rig for rotating the cryocooler device:

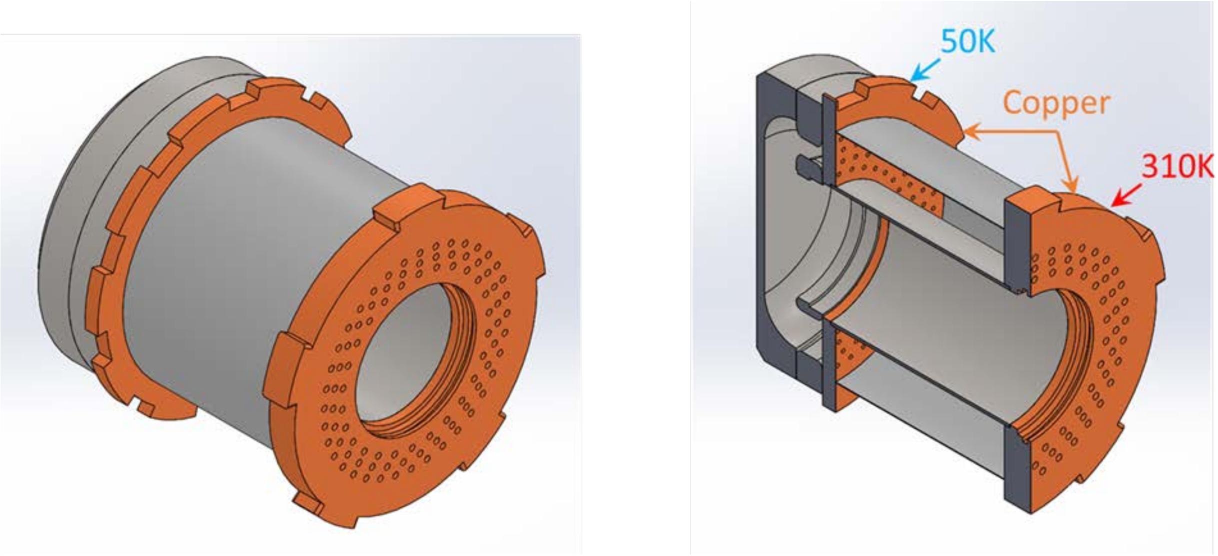


Figure 11. Pulse-Tube Cryocooler

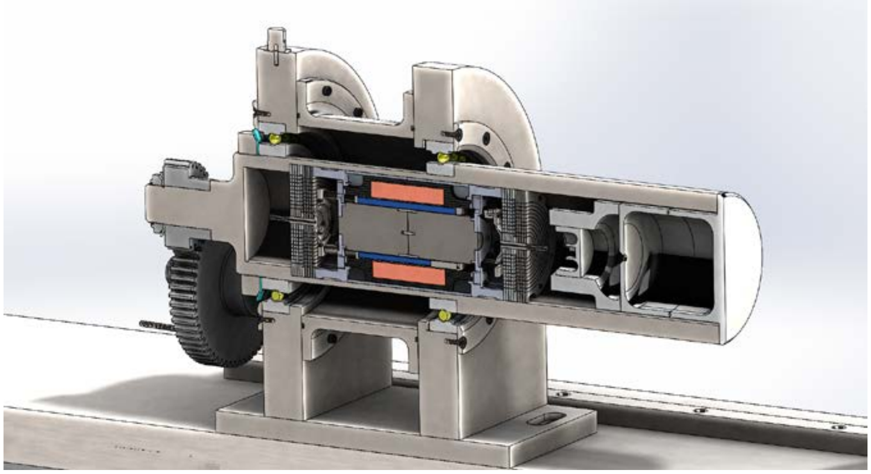


Figure 12. High Speed Rotation Test Rig

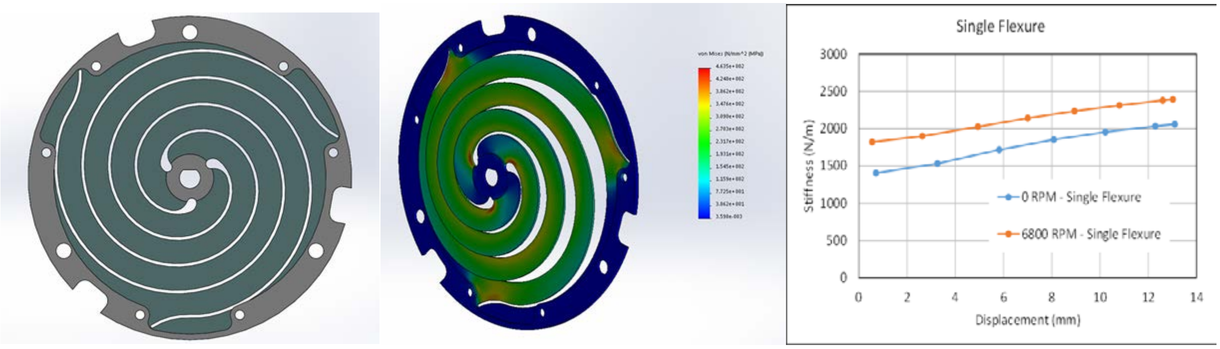


Figure 13. Linear Machine Flexure Design, Deflection, and Stiffness vs. Rotation Speed

One important difference in this cryocooler design is the requirement for high speed rotation. As shown in Fig. 13 this physically changes the effective axial stiffness as the rotational speed increases. This has the effect of changing the resonant frequency of the device. This is important because the cryocooler must operate when the motor is both stationary and spinning to maintain cryogenic temperatures for the superconducting rotor tape. This is accommodated by operating the cryocooler at two different frequencies. In addition, under a direct drive connection to the low-pressure spool the expected operating frequency will vary during take-off conditions and rejected take-off conditions so the crycooler must be able to support a range of rotating speeds.

V.   TREES Conceptual System

The TREES technology provides both thermal management for all the low grade heat sources in the aircraft and provides a means for advantageously redistributing that heat for de-icing, aerodynamic drag reduction, and combustor recuperation. This technology uses Alpha-STREAM related technology (United States of America Patent No. 9,163,581 B2, 2015) to distribute mechanical acoustic energy throughout the aircraft that then drives thermo-acoustic heat pumps to refrigerate the heat sources and then variable conductance heat pipes are used to move the high quality heat as is beneficial for the air vehicle.

A key problem with current ambient and cryogenic aircraft propulsion systems is the mass burden of cooling the high power electric motors and electronics. The anticipated significant mass addition required for thermal management can nullify the entire benefit of utilizing electric propulsion in aircraft due to the additional induced drag on the aircraft.

Moreover, the traditional method of cooling aircraft generators with standard jet fuel is not cold enough for use in future flight-weight cryogenic systems. Moreover, the much higher voltages required for flight-weight systems (4.5 kV vs. 270V) introduces additional spark ignition hazards associated with alternative cryogenic cooling fuels including liquid methane or liquid hydrogen. Instead, a thermoacoustic-based cooling system is proposed that would use the waste energy from turbogenerators to thermoacoustically create a pressure wave that is then delivered via routed embedded duct work to pulse-tube coolers located at all components requiring cooling in the aircraft. With this approach, both cryogenic and ambient electric aircraft can be cooled with minimal mass, fuel, and risk.

The complete power system including turbo-generator, distribution, protection, converters, and motors all generate heat that must be dissipated. A number of studies suggest that over half of the losses associated with a full electric power propulsion system is attributed to the thermal management system and as such is likely a key limiting factor to achieving economical flight. Moreover, as the operating temperature is reduced, the power and motor components become flight-weight and more efficient but often at the expense of increased thermal management system mass. In particular, the best system performance is predicted to occur at cryogenic temperatures. Ideally the aircraft thermal management system can lift 500kW or more of heat from 50K to 300K with a mass of 3 kg/kw or 1500 kg overall.

Today's aircraft generators are cooled convectively with jet fuel that is readily available at ambient temperatures. And this is safe because the aircraft bus voltage is below the Paschen curve at 270V. And so even if the insulation fails, a spark is not likely to form and ignite nearby jet fuel. However, future aircraft require a bus voltage of over 4500V to keep overall system mass and efficiency optimized for flight. At these high voltages a spark could ignite standard jet fuel as well as the alternative cryogenic fuels such as liquid methane/hydrogen. A second approach is to provide an inert cooling fluid such as liquid Nitrogen and utilize a heat pump such as reverse Brayton to refrigerate the fluid. But it is difficult to achieve flight-weight systems with that approach due to system complexity which includes coolant pumps, vacuum jacketed plumbing, size-able heat exchangers and recuperation mass. Further, such a system will deplete power from the turbo-generators to operate the turbo-alternators. And for cryogenic systems it is not likely possible to directly shaft connect the warm turbo-generator to the cryogenic turbo-alternator or other combinations in which an ambient component would be connected to a cryogenic component. And other approaches such as convective air cooling are inadequate for the amount of heat lift required in full-scale electric aircraft.

The key to making this technology light-weight and efficient is the creation of an acoustic wave to deliver cooling energy to distal locations through the aircraft. This eliminates the need to deliver energy with electrical, mechanical, or fluid flow- each of which adds mass and complexity. For example, electrical power distribution produces EMI, heating, and requires heavy cables. Mechanical distribution such as distributed torque shafts adds weight and requires lubrication. And pumping a cryogenic fluid requires a large volume of fluid, pumping mechanisms, extensive insulation, and heavy heat exchangers to transfer heat energy.

Instead, once the pressure wave is formed it is a simple matter to channel the wave in small tubes to anywhere in the aircraft. And since there are no moving parts in the cold region both the reliability and mass are suitable for aircraft. In addition, there are no hot moving parts either since the thermo-acoustic engine is used to create the pressure wave which eliminates the need for lubrication and maintenance. In comparison to reverse Brayton or Rankine systems, the thermo-acoustic engine pressure wave generator requires no lubrication and has no moving parts.

Based on existing thermo-acoustic devices we expect the performance of the system to be as follows. First, the Brayton jet engine is about 40% efficient. And with the exhaust temperature at 850C we expect the thermo-acoustic engine to be about 25% efficient. And at cryogenic temperatures of 50K rejecting heat to 300K we expect the cryogenic cooler to require 20W of energy input for every 1W of heat lifted. So to lift 500kW of heat would require 10MW of acoustic energy input from the pressure wave generator or about 40MW of thermal heat or mechanical energy from the turbo-generator. Delivering this much heat energy is difficult to deliver into a single unit externally. Instead multiple pipes would be used to reduce the transfer required per pressure wave generator and since each generator is essentially a hollow tube this is economical to do. And if the hot air is directly inserted under turbine pressure into the pressure wave generator the hot heat exchanger is not required.

This technology is useful for aircraft because it does not require extra fuel to operate it, is light-weight, and essentially maintenance-free. It could be used to provide cabin cooling, ambient/cryogenic cooling of converter, cables, and motors, and in addition it can be used to deliver power to remote locations on the aircraft without using wires.

Finally, as converters and motors become more efficient the expected heat load will reduce. Right now industry is trying to achieve a cryocooler with a capacity of 1000W at 50K and 30% of Carnot at 3kg/kW, and this invention can more easily meet that performance metric because of no moving parts and simple energy delivery to many distributed aircraft locations. The basic layout is a hot heat exchanger, regenerator, and cold heat exchanger on the hot side of the device located near the hot turbine exhaust. The cold heat exchanger is kept cold with jet fuel or air flowing over it. The hot side is heated either externally or internally with hot gases from the turbine. If the hot gases are channeled directly into the thermo-acoustic engine then the heat pump will also exhaust that air. Next, hollow tubes connect the heat engine pressure wave generator to the heat pumps that are located throughout the aircraft. And finally, each heat pump is at its simplest composed of a cold heat exchanger, regenerator, and ambient heat exchanger that utilizes the acoustic wave traveling through it to pump heat from the cold side to the warm side. The warm side can be made hot enough that the heat can be convectively rejected through connected fins to the environment. The delivered acoustic power can provide cooling using a range of acoustic cryocoolers including G-M, J-T, and pulse-tube-orifice-refrigeration. In addition, some or all of the acoustic power delivered throughout the aircraft can be converted to local electric power using a transducer such as a linear alternator or piezo-electrics. Shown in Fig. 14 is TREES applied to the STARC-ABL aircraft.

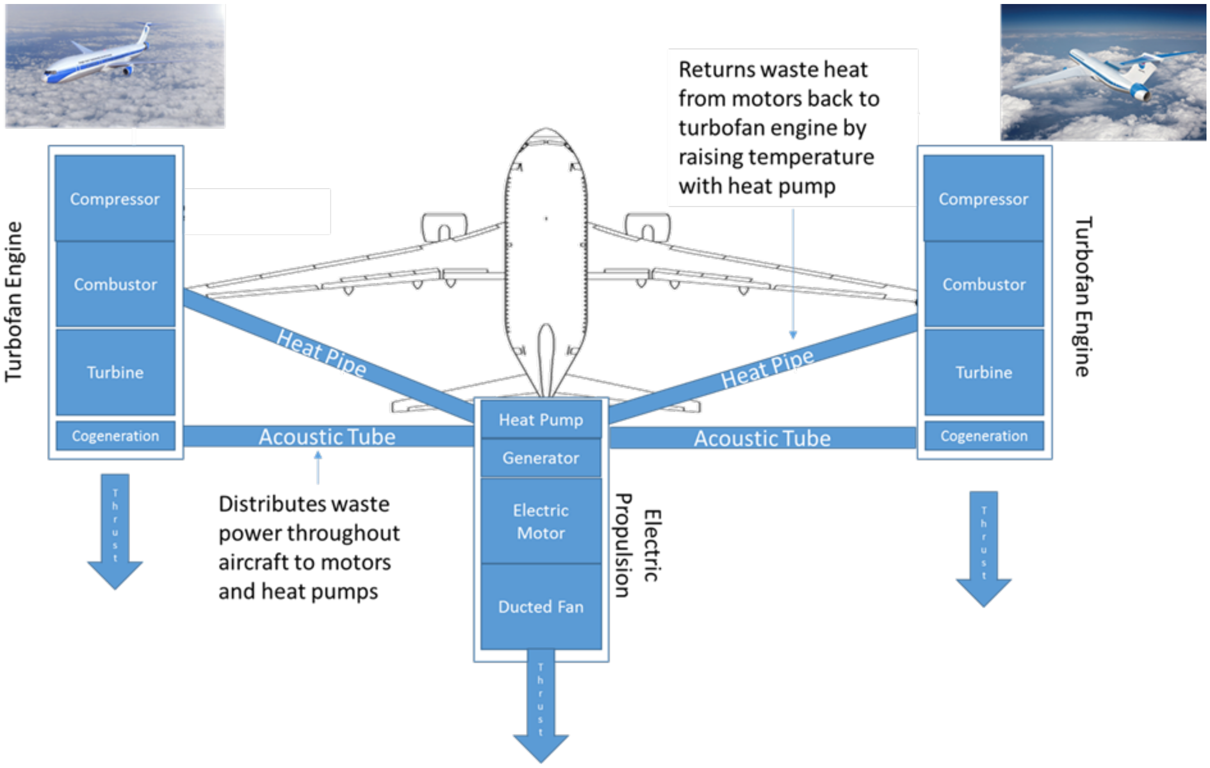


Figure 14. Thermal Recovery Energy Efficient System uses thermo-acoustic and heat pipe tubes embedded in the aircraft

VI. DELTA

And finally, a high specific power generator for smaller air vehicles in the 1-10kW range, a DELTA convertor that uses a double-acting high frequency piston driven by internal acoustic waves can be employed. This technology when combined with cryogenic fuels can provide maximum vehicle flight endurance.

Many power systems grow substantially in size and weight as their power level increases due to limitations in either their achievable current flow, required reactive force, or excessive centrifugal force. For example, solid-state energy conversion systems tend to be low voltage/high current devices and require many pairs in series for higher power. And while turbines and motors scale up to very high power, they are limited in their specific power by the high centrifugal forces as their rotational speed increases. And oscillating piston engines require exponentially growing reactive piston forces as the frequency increases; hence their power density is limited as well.

A new thermoacoustic engine technology is described herein that overcomes those limitations by operating at a much higher frequency than is conventionally achievable. It is based on a double-acting push/pull piston engine in which an acoustic wave pushes both sides of a single piston that eliminates the need for large springs while requiring only a single piston and engine to operate. This configuration enables an order of magnitude improvement in specific power compared to conventional engines.

Power generation from an external or internal heat source using thermal energy conversion technologies such as solid-state thermionics and thermoelectrics or dynamic conversion with Otto, Stirling, Brayton, or Rankine technologies are fundamentally limited in their maximum specific power due to either their low efficiency and/or operating frequency. The solid-state technologies are low voltage and hence produce a high DC current which restricts their minimum geometry to approximately 4 A/mm^2 to avoid over-heating. Hence, high power implementations of this technology class are both inefficient, large, and heavy.

And the dynamic technologies are limited to approximately 400 Hz because of two different reasons. First, the oscillating piston engines such as Stirling and Otto technologies require a force on the piston that grows exponentially with frequency which is difficult to achieve above 400 Hz with reactive springs or rods. Second, the rotating machines such as Brayton are also limited in frequency of operation because above 24000 RPM (400 Hz) the rotor tip speed either becomes supersonic or places too much stress on the rotor due to centrifugal forces. Hence today's space, terrestrial and proposed aircraft power systems are unnecessarily large and heavy for the power level they provide.

The DELTA Convertor is a Double-Acting Extremely Light Thermo-acoustic Converter that can achieve higher than 400 Hz operation. At that frequency the convertor can produce four times more power than conventional engines operating at 100 Hz. It is comprised of multiple thermo-acoustic stages in series that form a loop or delta-shaped triangle that also contains a single two-sided piston. The piston is located at the beginning and the end of the heat exchanger stages, but since the stages form a loop, this becomes a single double-acting piston in a push/pull arrangement. The multiple stages are designed such that when the piston moves it is simultaneously creating an acoustic wave on one side while receiving acoustic power on the opposite side. The pressure forces from the multi-staged engine push and pull on both sides of the piston which enables much higher forces on the piston than is possible if the typically one-sided power pistons are used with only a bounce space on the opposite side.

By using the engine's reactive forces on the single double-acting piston, eliminating the use of hot moving displacers, and using multiple stages for acoustic wave phase adjustment, the single piston can oscillate at over 400 Hz without using heavy springs. At this high frequency, the output current can be minimized and the specific power is maximized. Moreover, since the engine is essentially an empty tube filled with Helium, heat exchangers, regenerators, and a single non-contacting oscillating piston, the device does not require maintenance and is expected to be extremely reliable in addition to being low cost and light-weight.

A. A short summary of operation is as follows:

The piston moves to the left creating a sound wave. Then the sound wave travels through the heat exchanger and regenerator stages becoming amplified and phase adjusted. And next the high power acoustic wave pushes the other side of the piston where some of the power is used to create the next acoustic wave on the other side of the piston, and the rest of the power is extracted from the moving piston via a linear alternator or other transducer. The power output of the engine is controlled by managing the piston amplitude of motion.

While the use of a double-acting piston is not new to the heat engine field, the use of a high frequency double-acting piston via a thermo-acoustic push-pull configuration with a single engine driving both sides of the piston is very unique. Other double-acting piston engines require multiple pistons and are often connected via linkages and the piston speed is limited to below 400 Hz and their motion is driven by the linkages. And in other thermoacoustic push-pull configurations multiple engines are used to move the piston.

The DELTA Convertor uses a single engine to push and pull a single piston from both sides. This unique capability enables a high frequency motion while also forming a very compact footprint with a very simple control scheme. Moreover, unlike other thermoacoustic technologies that require electronic feedback, this technology mechanically provides feedback directly through the piston from expansion space to compression space. In addition, multiple stages can be employed to increase the power density further while still using a single piston regardless of the number of thermoacoustic heat exchanger stages employed.

The key to this technology is finding the proper heat exchanger and regenerator configuration so that acoustic wave pressure and velocity phases are matched properly on both sides of the single double-acting piston. The proper phasing achieves two things. First, the engine must amplify an acoustic wave by insuring the pressure and velocity are in phase within the regenerators while simultaneously extracting and inserting power into the engine from both sides of the same piston. Second, the piston dynamics must be matched so that the motion of the piston can be driven by the pressure waves on both sides of the piston coming from the engine. This enables tuning of the engine for maximum reactive power at the piston faces to achieve high frequency motion without requiring heavy springs. And since the engine itself has no hot moving parts it is straight-forward to generate high frequency acoustic waves throughout the tube.

A design demonstrating this technology has been completed using a conventionally accepted industrial design tool with a predicted system efficiency of 30% operating up to 400 Hz.

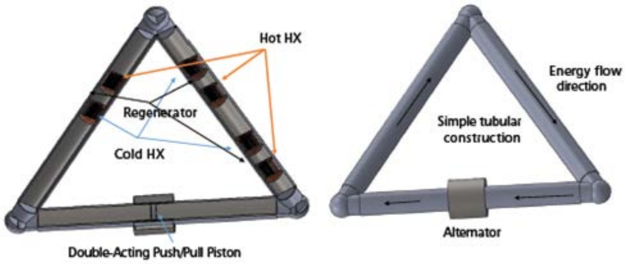


Figure 15. Double-acting Extremely Light-Weight Thermo-Acoustic Engine

VII. Conclusion

Electric aircraft based on traditional internal combustion engines, high by-pass ratio turbofans, vapor-compression thermal management, gearboxes, and battery technologies are past the optimization knee in the curve and significant jumps in performance are not likely without rethinking the basic technology used. This paper has shown how the Strayton generator can potentially provide propulsion and power more efficiently than Brayton cycle alone turbofan and turbo-generation, HEMM propulsion can effectively leverage this higher power generation efficiency to provide higher effective fan by-pass ratio and aerodynamic drag reduction with boundary layer ingestion, and TREES completes the energy cycle by providing thermal management with a net benefit in air vehicle performance. When fully integrated into the airframe of the aircraft these technologies can potentially provide fully integrated power, propulsion, thermal, and airframe systems that enable significant fuel, emission, noise, and mobility benefits.

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