The Supercritical CO_2 Closed Cycle Electric Turbofan
Specific Fuel Consumption of 0.357 lb/lbf/hr

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29th July 2014

ABSTRACT

Extensive research is currently being carried out by the electric power generation industry into the use of Supercritical Carbon Dioxide (S-CO_2) in a Closed Cycle turbine to generate electricity. Supercritical CO_2 presents many advantages as the working fluid over steam and gas in conventional turbines. A 50% improvement in thermal to electric power conversion efficiency is viewed as realistically achievable. According to the analysis presented here, if applied to aircraft propulsion an S-CO_2 closed cycle gas turbine could reduce fuel consumption over current state of the art turbofan engines by 30 – 40%.

Supercritical CO_2 also exhibits extremely high power density enabling the engine core to be packaged in a very small volume of low weight.

This paper presents an analysis of a geared ducted fan powered by an S-CO_2 core which would reduce the SFC of the current generation of turbofans from a range of 0.5 – 0.6 to 0.37 – 0.40 lb/lbf/hr.

In a further step this S-CO_2 core could form a separate electric main power generating unit (MPU) to power turboelectric propulsors in a series hybrid architecture, once electric motor technology has reached a suitable power density.

1. INTRODUCTION

Over the last decade research has been gathering momentum into the previously overlooked [1,2] Supercritical CO_2 power cycle to replace existing gas and steam turbines in electrical power generation plants. A number of test loops have been in operation since the mid-1990s. S-CO_2 is a leading candidate to replace steam in the next generation (GEN-IV) of nuclear power plants. Along with the Organic Rankine Cycle (ORC) which uses an organic refrigerant as the working fluid, S-CO_2 Rankine and Brayton cycles are also of great interest for a growing raft of renewable electrical power generation applications such as solar thermal, CHP, waste heat recovery and geothermal power plants. An increasing body of literature describes the many strengths and advantages of closed cycle thermodynamic cycles using Supercritical CO_2 as the working fluid [3,11].

However, the aerospace propulsion sector is almost entirely focused on the so called "Open Rotor" or Propfan/ Unducted Fan as its next step towards reducing fuel consumption. Although closed gas and vapour cycles are used in all stationary power plants, closed cycles or indeed open cycles that incorporate a recuperator to greatly increase thermal efficiency have never been adopted for aircraft propulsion due to the perceived weight and volume required for the recuperator in a gas turbine. The high density of the Supercritical CO_2 working fluid enables this problem to be overcome.

While Boeing, Airbus and the academic research community are starting to consider future hybrid turboelectric propulsion concepts, such as the Airbus E-Thrust and Boeing Voltair [4, 5], these concepts continue to use a conventional open cycle gas turbine as the electric power generating unit. The major efficiency advantages of closed cycles with high density working fluids and Supercritical CO_2 cycles in particular appear to have been overlooked. This paper explores the application of the high thermal efficiency closed S-CO_2 cycle to aircraft propulsion.

Supercritical CO_2 is in fact not a new working fluid for heat engines. Until 1940, 80% of refrigeration units in the world's shipping fleet used S-CO_2 [6]. This was progressively replaced by chlorofluorocarbon refrigerants (R12 and then R22) from the 1940s onwards. In hindsight, we now know this was a serious mistake.

The EU's Flightpath 2050 report [7] has set a goal for a 75% reduction in aviation CO_2 emissions by 2050. Bauhaus Luftfahrt [8] estimate that with improved airframe design providing 25% of the reduction and Air Traffic Management another 10%, 40% of the CO_2 reduction will be expected to come from powerplant improvements.

That figure of 40% is consistent with the SFC reduction that an S-CO_2 core could potentially provide.

As a first step, the turbine in an S-CO_2 closed-cycle core could be mechanically coupled to a ducted fan through a reduction gearbox. Further into the future, the S-CO_2 core could be used to generate electricity to power a distributed electric propulsor architecture, further reducing noise and improving transfer and propulsive efficiency.

Significant engine weight reduction may also be possible due to the greatly reduced number of turbomachinery stages required, although this will be offset to some extent by the requirement to carry CO_2 working fluid.

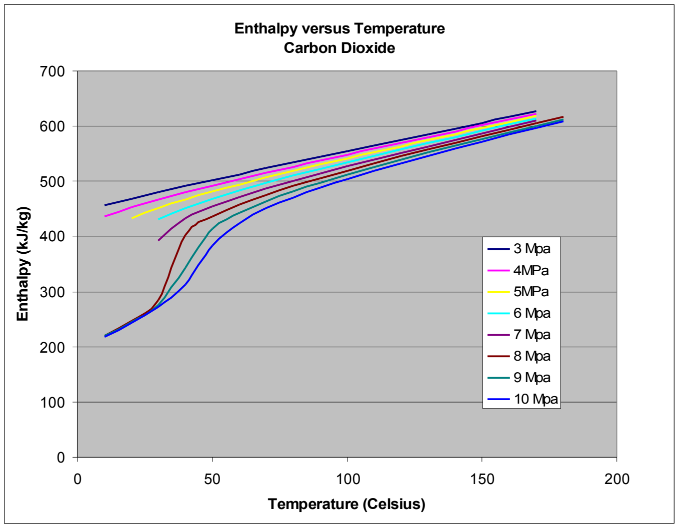
Instead of focusing on the problematic and arguably retrograde technology of Open Rotor, the engine manufacturers should instead be prioritising high efficiency closed cycles that provide improved fuel efficiency without the drawbacks of propfans and which can then be further integrated into future electric propulsion systems. Supercritical CO_2 provides a potentially highly effective pathway to achieve that transition to a series electric hybrid architecture.

2. EFFICIENCY

The S-CO_2 re-compression Brayton Cycle has a demonstrated thermal efficiency of over 47%, i.e. net turbine work to heat energy input, operating between T_H = 600 °C and T_C = 20 °C. This is an extremely low turbine inlet temperature by aerospace standards yet the thermal efficiency is still comparable to current state of the art turbofans. At T_H of 1000 °C, net efficiency would increase to 58% and to 68% at an upper temperature limit of 1480 °C (equivalent to GE90 turbine inlet temperatures of in the order of 2700 °F) and a T_C typical of that encountered at cruise altitude.

Carbon dioxide is thermally stable up to 1300 °C at atmospheric pressure. It would exhibit less than 0.2% decomposition at 1500 °C and at the operating pressures that would be used (20 MPa). This thermal stability is a major advantage of CO_2 for high temperature cycles as opposed to the organic refrigerants being investigated for electricity generation from low temperature heat sources.

Consider the following graph which plots the enthalpy of CO_2 against temperature for various pressures.



The critical pressure and temperature of CO_2 are P_{cr} = 7.38 MPa and T_{cr} = 31.1 °C.

At a pressure of 8 MPa and between 30 °C and 40 °C, H jumps from 284 to 403 kJ/kg. At the critical pressure of 7.38 MPa itself, the specific heat $C_p = (dH/dT)_p$ is a vertical line. This is not a latent heat phenomenon – if the temperature and pressure are increased from below, when the critical point is reached CO_2 transitions to the supercritical state immediately at constant temperature with no further heat input required, unlike a normal phase transition from solid to liquid or liquid to gas.

Therefore high efficiency can be obtained from a supercritical cycle heat engine by operating through the critical point to take advantage of the maximum dH/dT which occurs at that point (dT = 0).

3. PACKAGE SIZE

The main factor which governs the radial size of turbomachinery is the volumetric flow rate of the exhausted working fluid. With S-CO_2, the exhaust flow per unit power is 30 – 150 times less than that of steam [9]. This leads to extremely small turbomachinery with only 3 or 4 stages and tiny diameters being required compared to steam and gas turbines.

A machine [11] with a compressor of external diameter 6 inches (15 cm) and a turbine 11 inches in diameter, with a turbine pressure ratio r_p of only 3.3 and rotating at 25,000 rpm would produce 10 MW of electric power, sufficient for 9,300 lbs of thrust at M = 0.8.

Printed circuit heat exchangers (PCHE) have been developed with over 1000 m^2 of heat transfer area per cubic meter, even 2500 m^2/m^3. The new Marbond HE may offer even higher porosity. As a high density fluid (600-700 kg/m^3 at T_{cr} and 100 kg/ m^3 at typical power industry turbine inlet temperatures and pressures) S-CO_2 requires a very small heat exchange surface area compared to air or steam. This addresses one of the major limitations that has always hindered the adoption of recuperation on aircraft propulsion engines, i.e. the large volume of the recuperator required for a gas turbine system.

The weight of the recuperator is not insignificant. However this would be more than offset by the lower weight of the turbine/ compressor and the lower fuel load required, reduced by 30% – 40% for the same mission. Reference [10] compares the weight and volume of a stainless steel steam shell and tube HE to an equivalent PCHE. The conventional shell and tube device weighs 7.7 tonnes with a volume of 0.3 m^3. The PCHE unit weighs less than 1 tonne with a volume of 0.2 m^3. The weight would be further reduced for an aerospace application by using titanium, TiSiC or other lightweight alloy.

According to Wright [11] an S-CO_2 Brayton cycle turbine could generate 10 MW of electricity from a package with a volume of 4 to 6 cubic metres.

The small size of such a package is one of the enabling factors driving the proposed development of modular nuclear power plant (NPP) units that would be delivered in a standard container like conventional generator packages.

These characteristics have clear benefits for aircraft propulsion in terms of reduced volume, reduced weight and reduced manufacturing and maintenance costs. They also make Supercritical CO_2 an attractive option for future development of hybrid electric propulsion systems. Two S-CO_2 electrical power generation units (MPU) could be installed in suitable locations on the aircraft (such as the wing roots) to power multiple propulsion units and the nacelles would contain only the fan, drive system and electric motor.

4. THERMODYNAMIC CYCLE ANALYSIS

For a performance overview of six different S-CO_2 cycles operating between 550 °C and 32 °C at various turbine inlet pressures, see the analysis by Kulhánek and Dostál [12]. Their model predicts that the highest thermal efficiency is achieved with a recompression cycle, reaching over 46% for a TIP of 25 MPa and turbine pressure ratio of 3.2. A partial condensing cycle is not predicted to be more efficient, achieving the same efficiency at a higher turbine pressure ratio.

Gibbs et al. [13] state that the overall efficiency of the recompression S-CO_2 cycle can be related to the Carnot thermal efficiency by the function:

$$\eta_{SCO2} \approx \eta_{Carnot} - 0.19$$

where η_{Carnot} is the Carnot efficiency given by $1 - (T_C / T_H)$.

Kim et al. [14] describe a transcritical CO_2 (T-CO_2) simple Brayton cycle (i.e. non-recompression) operating between T_H = 600 °C and T_C = 20 °C with net efficiency (Q_{IN} / W_T out) of 42.1%. They also cite a partial condensation (Rankine) T-CO_2 cycle being physically operated at Tokyo Institute of Technology with η_{th} of 47.6%, operating between the same T_C and T_H values and the same P_H/P_L values of 200 bar and 57.3 bar. The first of these two cycles does not use recompression, only a regenerator. The partial condensation cycle in Tokyo does use a bypass compressor and low temperature recuperator in addition to the high temperature recuperator.

An S-CO_2 recompression Brayton cycle modelled by Kim [14] displays η_{th} of 46.4% with T_H = 600 °C, T_C = 32 °C, P_H = 200 bar and P_L = 77 bar. Net work output per kg of CO_2 is less than the two cycles referred to above at 99.9 kJ/kg compared to 134.9 kJ/kg for the partial condensation T-CO_2 cycle and 119.4 kJ/kg for Kim's T-CO_2 Brayton cycle which stays entirely out of the two phase (liquid/gas) subcritical region.

Bryant et al. [15] show efficiency of 46% for a simple Brayton cycle (without recompression) at a turbine inlet temperature of 750 °C and TIP in a range of 10 – 25 MPa.

With recompression, efficiency in Ref. [15] rises to between 52% and 53% possibly as high as 55% for the highest compressor and turbine inlet pressures (~ TIP= 25 MPa, CIP ~7.5 MPa) and T_H = 750 °C, T_C = 32 °C. Regenerator effectiveness is taken as 95%.

Another analysis [16] of a S-CO_2 Brayton cycle with recompression shows 49.2% thermal efficiency with T_H = 750 °C, T_C = 36 °C, P_H = 20 MPa and P_C = 8.4 MPa.

Finally Wright [17] obtained a cycle efficiency of 45.5% in his model for a recompression Brayton cycle between T_H = 810.9 K, P_H = 19.66 MPa, T_C = 305.4 K and P_C = 7.7 MPa. However, Wright finds that operating a "condensing Brayton" cycle with a heat rejection temperature 10K lower (295 K) increased modelled efficiency to 48.3%, or 3.7% higher than that predicted by the empirical equation relating η_{SCO2} to η_{Carnot}.

These results are summarised below.

T_H	T_C	P_H	P_C	η_{th} (model)	η_{th} (η_{Carnot} – 0.19)	Cycle Type
550 °C	32 °C	25 MPa		46.50%	43.90%	Recompression [12]
600 °C	20 °C	20 MPa	5.7 MPa	42.10%	47.40%	Simple Brayton [14]
600 °C	20 °C	20 MPa	5.7 MPa	47.60%	47.40%	Partial condensation recompression [14]
750 °C	32 °C	10-25 MPa		46.00%	51.20%	Simple Brayton [15]
750 °C	32 °C	25 MPa	7.5 MPa	55.00%	51.20%	Recompression [15]
750 °C	36 °C	20 MPa	8.4 MPa	49.20%	50.80%	Recompression [16]
538 °C	32.4 °C	19.7 MPa	7.7 MPa	45.50%	43.30%	Recompression [17]
538 °C	22.4 °C	19.7 MPa	7.7 MPa	48.30%	44.60%	Partial condensation recompression [17]

These results indicate that the simple S-CO_2 Brayton cycle is about 5% less efficient than given by the empirical formula for the recompression cycle:

$$\eta_{SCO2\_simple} \approx \eta_{Carnot} - 0.19 - 0.05$$

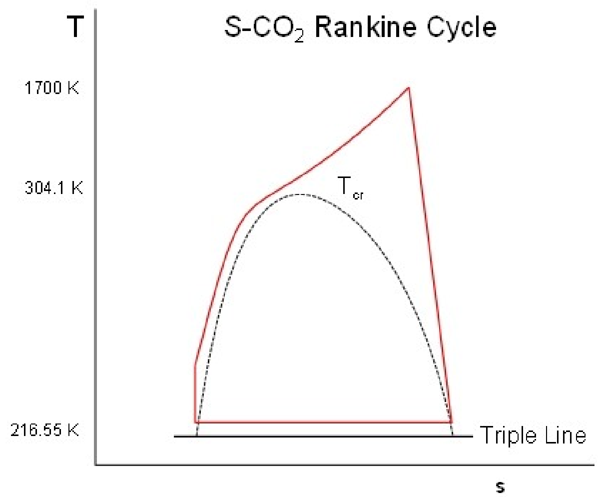
Therefore for an aerospace application, a simple S-CO_2 closed Brayton cycle using one recuperator without a recompression compressor, with a turbine inlet temperature of 1000 °C (1273 K) and an ISA T_C of 15 °C (288 K) we could expect a net thermal efficiency of

$$\eta_{SCO2} = 1 - (288 / 1273) - 0.19 - 0.05$$

$$= \mathbf{53.3\%}$$

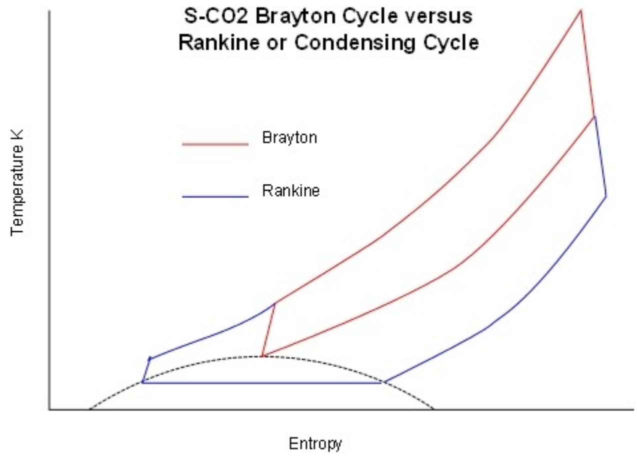
At cruise altitude with an OAT of 220 K thermal efficiency would increase to 58.7 %.

We now need to consider the fact that for aircraft propulsion, the condenser heat rejection temperature would vary between hot daytime ground-level temperatures (~50 °C) and ~220 K at high altitude. The S-CO_2 cycle will therefore vary between a Brayton cycle in which the CO_2 stays supercritical when OAT > 31.1 °C and a condensing Rankine cycle at cruise altitude. The aircraft propulsion application therefore enjoys the benefit of guaranteed condensing temperatures below the critical point and can use the more efficient condensing cycle. This option is denied to most stationary power applications since heat rejection temperatures of less than 31.1 °C cannot be guaranteed. In the rest of the analysis presented below, we have used the empirical S-CO_2 recompression Brayton cycle formula [13] which will therefore under-predict the actual efficiency that can be expected since it does not account for the additional efficiency gain of the condensing cycle, in which the cooled CO_2 will be recompressed as a liquid to the critical pressure, requiring very little compressor work, before being heated. Heating will be highly efficient due to the good thermal matching obtained from a working fluid which in this case is first in the liquid phase and then in the supercritical phase, as opposed to the gas phase in a gas turbine.



On the other hand, with the low heat rejection temperatures used in an aircraft propulsion condensing cycle, there is high internal irreversibility in the recuperator heat transfer between the hot fluid exhausted from the turbine and the cold fluid which has just left the pump or compressor. This is due to the fact that the turbine exhaust is gaseous with a low specific heat C_p and the compressor exhaust is a liquid with high specific heat C_p. Recompression of part of the turbine exhaust flow and the use of two recuperators – a high and low temperature device – was devised to overcome this pinch-point problem.

The diagram below shows the additional work that can be obtained from the "condensing Brayton" or Rankine cycle compared to a purely supercritical CO_2 recompression Brayton cycle.



According to Wright [17] compressors and gas coolers designed for the S-CO_2 Brayton cycle will perform satisfactorily in condensing (Rankine) mode due to the fact that the difference in density between CO_2 in the liquid and vapour phase is only a factor of 2 or 3. Therefore the CO_{2s} core components should be able to operate seamlessly in both S-CO_2 Brayton and T-CO_2 Rankine modes, i.e. at both high ambient air temperatures above T_{cr} and at low temperatures.

Research is ongoing into "tuning" the critical point by up to ±15 – 20 K by adding other gases such as SF_6. If T_{cr} could be raised to ~50 °C then condensing / Rankine mode would become possible under most take-off conditions to improve efficiency and power output.

Another potential issue is that of the CO_2 working fluid becoming frozen. 220 K is the lowest heat rejection temperature that could be used since the triple point of CO_2 is at T_{tp} = 216.55 K, P_{tp} = 517 kPa. This is 0.1 K below the ISA value for the temperature of the atmosphere above 37,000 feet. The temperature and pressure of the condenser and compressor inlet will have to be maintained above the triple point.

Therefore, no analyses have been published on a CO_2 supercritical Rankine cycle operating between the wide temperature limits required for aircraft propulsion. In particular, further analysis needs to be performed on the recuperator and efficient transfer of heat between the hot low pressure and cold high pressure fluid streams – for instance, will three recuperators and three compressors be required? We will investigate this in more detail in a future paper. For the purposes of this analysis, we will assume the empirical relations for the simple and recompression S-CO_2 Brayton cycles referred to above apply down to a T_C of 220 K, bearing in mind that a condensing Rankine cycle may display 5% higher thermal efficiency than the recompression Brayton cycle at least in the transcritical region, with efficiency down to 220 K being strongly dependent on recuperator effectiveness.

5. TSFC ESTIMATION

We consider two cases:

1. The S-CO_2 core is mechanically coupled to a geared ducted fan.
2. The S-CO_2 machine is an MPU comprising an integrated Turbo Alternator Compressor (TAC). The electricity generated by the MPU powers one or more electric motors driving geared ducted fans.

To show the potential of this system we will take a turbine inlet temperature consistent with that used on the latest generation of large turbofans of in the order of 2700 °F or 1480 °C (1750 K). (This would also be about the upper limit for thermal stability of the CO_2 working fluid). The cold sink temperature at cruise altitude (FL330) will be taken as 220 K.

The net thermal efficiency of the engine will therefore be

$$\eta_{SCO2} = \eta_{Carnot} - 0.19 - 0.05 \qquad \text{(Simple cycle, no recompression)}$$

$$\eta_{SCO2} = 1 - (220 / 1750) - 0.19 - 0.05$$

$$\mathbf{= 63.4\%}$$

1. Mechanically coupled to a geared fan

In a conventional turbofan, the overall efficiency equals the product of the thermal efficiency, transfer efficiency and propulsive efficiency:

$$\eta_O = \eta_{th} \times \eta_{tr} \times \eta_{pr}$$

For the current generation of turbofans the propulsive efficiency is about 0.79 and the product of the thermal and transfer efficiency is about 0.45 (made up of $\eta_{th} \approx 0.55$ and $\eta_{tr} \approx 0.85$), giving an overall efficiency of 35.6%. (Source: see reference [18]).

In the S-CO_2 directly coupled system, the net output work of the turbine will directly drive a geared ducted fan without a compressor.

For the geared fan, we can expect a propulsive efficiency η_{pr} of at least 90%.

For the transfer efficiency, we only have fan, nozzle and mechanical coupling loss without low pressure compressor loss. Therefore we will assume η_{tr} will also be 90%.

Therefore the overall efficiency that can be expected from an S-CO_2 direct drive geared ducted fan is:

$$\eta_O = 0.634 \times 0.9 \times 0.9$$

$$= 51.4\%$$

Therefore every unit of heat put into the carbon dioxide working fluid will generate 0.51 units of net work by the fan propelling the aircraft. (Efficiency of the heater is already taken into account in the empirical relation for thermal efficiency).

We take a flight velocity of 250 ms^{-1} or M 0.83 at cruise altitude, where a = 300 ms^{-1}.

With an S-CO_2 core and net 10 MW of turbine power we have:

$$\begin{aligned} \text{Thrust x } V_{acft} &= 10 \times 10^6 \\ T.250 &= 10 \times 10^6 \\ T &= 40{,}000 \text{ N} \\ &= 8992.8 \text{ lbf} \end{aligned}$$

LHV of Jet Fuel = 43.2 MJ/kg.

Therefore to generate 10 MW of net power at 51.4% overall efficiency we require:

(10 MW / 0.514) ÷ 43.2 X 10^6 kg of fuel per second

= 450 g of fuel per second.

Therefore SFC = 0.450 x 2.205 x 3600 / 8992.8

= **0.398 lb/lbf/hr**

If a recompression cycle was used, adding another 5% to the thermal efficiency, overall efficiency would rise to 55.4% and SFC would fall to:

SFC with recompression **= 0.370 lb/lbf/hr**

2. Hybrid Electric System

In the hybrid electric system, we will first assume propulsive efficiency remains the same at η_{pr} = 0.9. In other words, to enable a direct comparison, a distributed propulsion architecture using a larger number of smaller propulsors each with reduced jet exhaust velocity is not assumed.

The main benefit of electric drive is improved transfer efficiency. Now the only losses are in the conversion of mechanical work by the turbo-generator to electricity and reconversion of electrical power to mechanical work by the motor (plus fan-drive mechanical losses). We will assume the first efficiency is 98% and the second is 95%, giving an overall transfer efficiency in this case of 0.93. Overall efficiency with a recompression cycle will therefore be 57.3%.

This leads to an SFC of **0.357 lb/lbf/hr.**

If propulsive efficiency was boosted to 95% with multiple smaller propulsors, η_O would further increase to 60.4% and SFC would fall to **0.337 lb/lbf/hr.**

These figures compare to a range of 0.53 – 0.58 at FL330 and cruise Mach for the GE90, GEnx, Trent 800 and so on. Older engines such as the CF6 exceed an SFC of 0.61 at that altitude and speed.

Therefore in comparison to the latest generation of turbofan technology, with a Supercritical CO_2 propulsion system operating at a high cruise Mach setting of M 0.83 (250 ms^{-1}) SFC in the order of at least 0.34 to 0.40 lb/lbf/hr could be expected, versus 0.55 currently, a reduction of 33%.

(Note that our η_O figures of 51.4% - 60.4% imply a reduction in fuel consumption by 31% - 41% over the current baseline $\eta_O \approx 35.6\%$ estimated earlier).

Supercritical CO_2 technology therefore presents a major opportunity not just for the power generation sector but also for the aerospace propulsion sector of the gas turbine industry. At this juncture, the gas turbine industry has the opportunity to reduce the cost and risk of innovation by combining he development of S-CO_2 systems for both applications – stationary electric power generation and aircraft propulsion. Indeed it should also be applied to surface transportation, notably to upgrade diesel-electric locomotive powertrains and ship propulsion systems.

6. TAKE OFF THRUST CONSIDERATIONS

In a similar way as currently being proposed for gas turbine powered turboelectric systems, the S-CO_2 system could be sized for cruise thrust operation and a combined battery/super-capacitor bank used to provide the additional power required for take off and climb. The potential 40% reduction in required fuel load gained with an S-CO_2 MPU would provide payload capability and space for a battery bank.

Alternatively, a full power system could be installed, sized for the maximum thrust requirements (engine out performance on take-off, top-of-climb thrust). Wright [11] indicates for example that a 300 MWe S-CO_2 system would require a turbine with a diameter of 1 metre and only 3 stages of turbomachinery.

It would therefore seem feasible to size the system for maximum thrust requirements and still retain package size and weight benefits for aircraft installation.

7. OTHER CHARACTERISTICS OF AN S-CO_2 ENGINE

Supercritical CO_2 is probably the most suitable working fluid for an aircraft propulsion closed cycle application since it can withstand high temperatures and exhibits exceptional power density. We initially considered organic refrigerants which are undergoing extensive analysis for low temperature industrial heat recovery and geothermal / solar energy applications. In comparison to these organic working fluids, CO_2 has the following advantages:

- Thermal stability – stable up to 1500 °C at the operating pressures required.
- Safety – non-toxic, non-flammable.
- Cost – low cost, abundant.
- Global Warming Potential – non-ozone depleting, significantly lower GWP than organic refrigerants.
- Energy density – low specific volume in the supercritical state, high enthalpy increase at T_{cr} for Delta T = 0.
- Low back work ratio – compression of high density fluid (or liquid in condensing cycle).
- High power density – tiny turbine and compressor size. 3 or 4 stages of turbomachinery only. Weight, volume, manufacturing cost and maintenance cost reduction. Low pressure ratio – recompression cycle efficiency not improved by higher r_p.

- Compact recuperator size – high density fluid, excellent thermal matching, low heat exchange surface area required compared to organics/steam/air. Recuperator weight and volume saving.

The operating pressure of 20 MPa is seen as a drawback by some commentators. However the Japanese domestic "Ecocute" heat pump water heating unit uses S-CO_2 as its working fluid, pressurised up to 10 MPa. Millions of these units have been sold.

8. ELECTRIC MOTORS

The viability of aircraft electric propulsion is currently seen as being dependent on the development of high temperature superconducting (HTS) electric motors.

A number of researchers [19, 20] note that the specific power of a gas turbine core is in the range of 5 – 10 kW/kg compared to less than 0.5 kW/kg for electric motors.

The development of electric vehicles (EVs) is stimulating intensive research into improving the efficiency of electric traction motors. The electric motor designed by BMW for their new i3 electric car weighs 50 kg with a maximum rated power output of 125 kW – a peak power density of **2.5 kW/kg**. Smaller high speed EV motors have been developed [21] with a continuous rated power density of nearly 9 kW/kg (80 kW from a 9 kg motor). The figure of merit (goodness factor) for electrical machines increases with size. Axial flux motors have the potential to reduce motor diameter. Therefore electric propulsion may become achievable without the need for HTS, particularly if the weight of the motor can be offset by the small package weight of the S-CO_2 core. (Update April 2015: Siemens recently announced the development of an electric motor for light aircraft weighing **50 kg** with a continuous rated output of **260 kW**).

9. CONCLUSION

The aircraft engine manufacturers predict that a further 20% reduction in SFC represents the limit of what can be achieved with gas turbine propulsion systems. They do not appear to have considered the use of closed cycles using fluids of high specific heat in which the compressor operates on the liquid phase, despite the universal use of the closed Rankine steam cycle for electricity production and extensive research being applied to Organic Rankine Cycles and S-CO_2 cycles worldwide.

The Supercritical or Transcritical CO_2 closed cycle offers extremely high efficiency due to the well known thermodynamic properties of CO_2 in the trans- and supercritical regions. At a turbine inlet temperature of only 600 °C, less than half the temperatures found in an aircraft engine, the S-CO_2 cycle achieves equivalent efficiency to existing aeropropulsion gas turbines. If high turbine temperatures were used in an S-CO_2 core (with cooled turbine blades), SFC could be reduced by more than 30% compared to existing state of the art turbofans.

In addition, the very high power density of an S-CO_2 machine means that the turbomachinery required is physically very small and fewer stages are required. Although recuperators and condensers are notoriously heavy components, PCHE units are much lighter than conventional technology and their weight will be more than offset by reduced fuel load.

A Supercritical CO_2 core lends itself naturally to a future hybrid turboelectric architecture. The electric power generation sector is actively researching the adoption of S-CO_2 cycles for both new renewable and nuclear electric power generation. Therefore this work could be synergistically extended to aircraft on-board electrical power generation. Its small size and use of a closed cycle make it convenient for packaging in a suitable location in the aircraft remote from the propulsors themselves.

Therefore the S-CO_2 closed cycle provides a clear pathway for realising the Flightpath 2050 Vision which implies that direct aircraft-related CO_2 emissions must be reduced by 40% to achieve the overall 75% reduction target.

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