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EMS623U - Heat Exchange and Waste Minimisation

Individual Analysis Project – Aeronautical Electrical ECS

Abstract:

This study focuses on the viability of using an Electrical ECS as an alternative to bleed air ECS for helicopters with future adaptability to fixed winged aircrafts. The system operated using a refrigerant thermodynamic cycle using R-134a. Key components of the system are two heat exchanger (condenser and evaporator) , expansion valve and a 1 stoke compressor powered by the auxiliary gearbox (AGB). The proposed system outputs 1052 KW of work to the condenser while only requiring 103KW of work to be done by the compressor. Theoretical exergical efficient for this system is 48%, However by further heating the refrigerant to 80ºC a value of 57% can be obtained. The use of an E-ECS can possibly make aircraft more reliable and lighter. Future studies should focus on experimental forced convection for plate finned heat exchangers.

Part I:

Introduction:

When design any system the efficiency it is always a top priority. This is especially true in the aeronautical industry as all aircraft operate using a finite amount of fuel. Improving the efficiency of these systems can lead to more time in the air or lower emissions. Looking at most commercial aircraft there is a clear trend on using bleed air systems [1]. These however rely on the engine burning more fuel be able to allocate excess combusted hot air to run an Air cycle machine (ACM). These system can also fail catastrophically which can lead to sudden loss of cabin pressure which might lead to emergency landing on top of requiring excessive maintenance [1].

This study will dive into the possibility of using an Electrical Environmental Control System (E-ECS). This system works on the very common refrigeration heat cycle and uses a refrigerant as the working fluid. The specific focus for this study will be the analyse and propose a E-ECS like the one found in the Lockheed Martin S-92 helicopter (Fig. 1)[[2][3]. This aircraft was chosen to base this system on as its renowned for its versatility in a range of applications such as private aircraft, coastal guard and military use[4]. The use of E-ECS however should not be restricted to helicopters as it could adapted to fit airplane such as the Cessna mustang (Fig. 2)[5] which could potentially increase their range[3]. It could also be implemented as a back-up system for the current commercial airliner air circle machine based environmental control systems. This could help mitigate the need for emergency landing if the original system fails leading to less financial and reputation losses for airlines and manufacturers.

Fig 1 Lockheed Martin S-92 helicopter [2]

Fig.2 Cessna mustang (M2 gen 3) [5]

System configuration and Cycle:

The Electrical Environmental Control System (E-ECS) is based on a refrigeration cycle consisting of 4 main components (Fig. 5):

Compressor:

The compressor is responsible for compressing the low temperature low pressure refrigerant gas coming from the evaporator into a high temperature high pressure gas. This components behaves similarly to a 1 stroke engine and can be powered electronically [7].

Condenser:

The Condenser consists of a finned tube heat exchanger in this specific system and is what will be used to warm up and cool the air in the cabin of the aircraft. As well as helping the cabin electronics at operating temperatures which could mitigate equipment failure rates. This component takes the high-pressure high temperature gas and turns it into a lower temperature high pressure liquid.

Expansion valve:

The Expansion valve is used to lower the pressure of the fluid when in come out of the condenser this also lowers its temperature. This is due to the liquid going through a small diameter opening which increases its velocity. As its well-known faster fluid is cooler as there are less molecules interacting with each other. This produces a vapour liquid mixture.

Evaporator:

The Evaporator is the second Heat exchanger in the system which will be used to turn the vapour-liquid mixure into a gas. This will be done using the cold ram air from outside the cabin as air temperature increases with altitude.

Powering the proposed system:

While the ACM Based ECS used in comercial airliners rely on bleed air extracted after cumbustion Electrical Environmental Control System rely on Electrical power to run a compressor. This power can however be generated with already present system in most aircraft. This is due to the fact that they already need to provide current to all other onboard systems. This power is generated in the engine by introducing a gear right before the combustion chamber. This gear gets it rotational motion by being located the drive shaft that is connected to the low- and high-pressure turbines. This system is called the accessory gearbox (AGB). The output of that gear is then moved to the outer side of the engine using angled drive shafts to an accompanying gear box. This power is then converted into Electrical energy. The compressor could alternatively be powered directly by the (AGB) by using stepping gearbox to down the slow down the rotation and connecting it to the 1 stroke compressor's drive shaft.

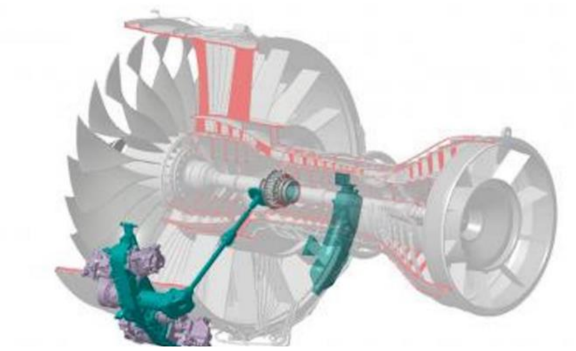

Fig. 3 AGB location in turbofan engine [8]

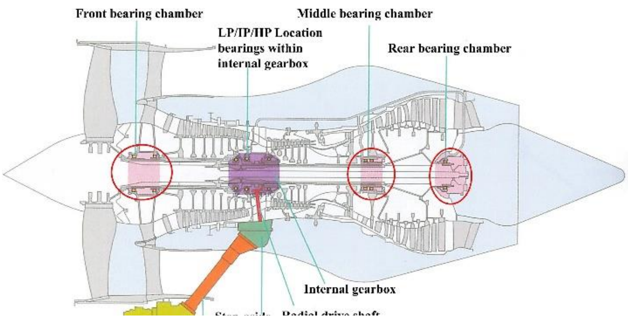

Fig. 4 AGB location in turbofan engine [9]
Side view

Given most aircraft already have an auxiliary gear box it is reasonable to assume that the system could be implemented for aircraft that have Turbofan/ Turboprop/ Turboshaft engines. As well as the potential for use in older naturally aspirated aircraft.

Refrigerant:

When picking a refrigerant for the proposed system it is emparical to pick one with low envatiomental impact , low boiling points , non flamable and low toxicity. With these specification we can narrow down to a few refrigerants such as a Hydrofluorocarbon Blend R-407C , CO_2 R -744 and 1,1,1,2-Tetrafluoroethane R-134a.

When comparing these refrigerant it can be noted that while Hydrofluorocarbon Blend R-407C is more ecofriendly that R-134a and has better thermal conductivity properties [10] it is harder to source as it requres precice mixture.

While CO_2 R -744 is the most ecofriendly of the ones highlighted at a global warming potencial of 1 and can adhere to the predefined standards [10]. It requires pressures in eccess of 1000 Psi. Having such a high pressure system on beard an aircraft is a safety hazzard.

For this study therefore 1,1,1,2-Tetrafluoroethane R-134a will be used as it has low to zero ozone depetion potencial [11]. It has a low boiling point of around -26 °C [12] making it idea for a refrieration cycle. R-134a is also non flamable [10] making it safe for use in the avaition industy. In case the refrigerant leaks into the cabin it is also non-toxic making it safe in case of the system failure. It was also choosen for a similar system currenly in use [13]

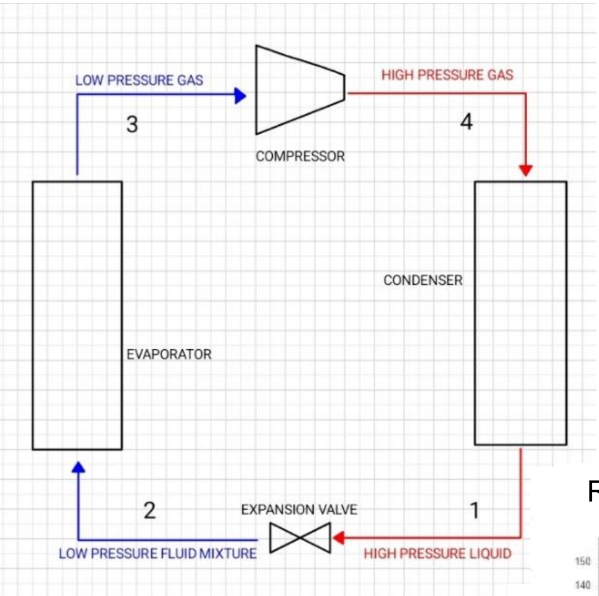

Fig. 5 (left) Cycle Components [14]

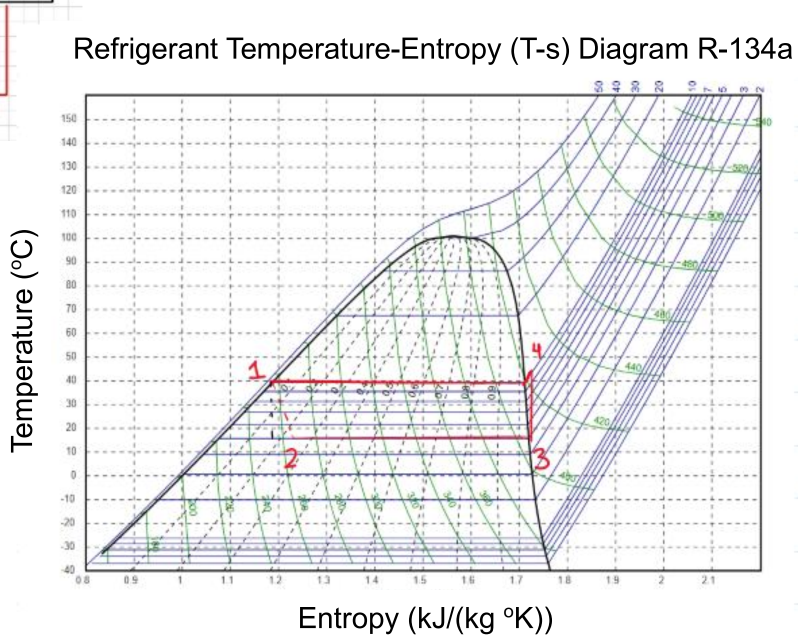

Fig. 6 (right) Thermodynamic cycle using R134a [15]

Heat exchangers:

In the system there are two heat exchangers that need to be addressed those being the condenser and the evaporator.

There are multiple types of heat exchangers that could be used for this application however due to the weight constraints both heat exchangers will use a compact Plate-fin configuration

Plate finned tube heat exchanger (PFHE):

Plate finned tube heat exchanger (Fig 7) combines the plate type heat exchanger and finned tube heat exchanger. This leads to an increase in efficiency due to the increased surface area [17].

The implication of this is that more heat can be conducted in a smaller footprint. A smaller footprint is also correlated with a

meaning that can transfer more hear in a smaller footprint which is ideal for this application as less material therefore less weight is required for the same amount heat transfer. A PFHE is classified as one type of compact heat exchangers having area density more than 700 m^2/m^3 [18]

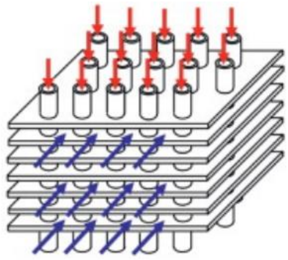

Fig. 7 Plate finned tube heat exchanger [16]

Structure and components:

Tubes:

This is what the working fluid travels through in this case a R-134a refrigerant this is usually made of a highly conductive metal such as copper aluminium or stainless steel.

Fins:

The second working fluid in this case air will interact with the thin metal fins which are attached to the tubes and be guided through the exchanger. These fins also have the benefit of increasing the surface area that the tube have as the fin surface since its directly connected to the tube becomes one structure. Fins in this type of heat exchanger do not necessarily have to be flat depending on the flow needs and over all heat transfer coefficient that need to be achieved, therefore they can be louvered or in a wave pattern.

Plates:

Plates are structure parallel to the tube and can be flat or corrugated. These are added to maintain an equidistant spacing between the fins and aid in the even distribution of the second working fluid, these however can be attached to the fins which increase their surface area of the heat exchanger. This increases the efficiency of the Heat exchanger.

Headers:

This is where the primary working fluid enters and exit the heat exchanger there are usually two placed on opposite sides of the heat exchanger and can be configures in multiple pass single tube or single pass multiple tubes (Fig 7). In this study a multi pass multi pass single tube configuration will be used due to its increase in heat transfer coefficient [19] and therefore lower weight. This is despite the fact that it will be significantly harder to manufacture hance will be more expensive

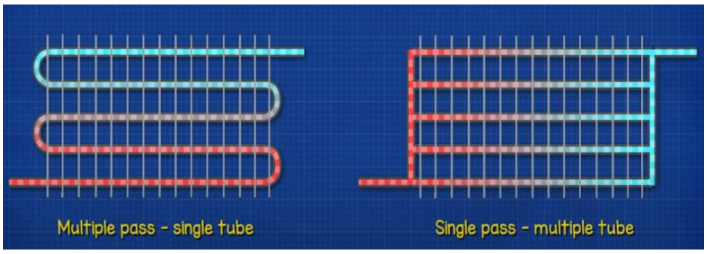

Fig. 8 Plate finned tube heat exchanger [20]

Fig. 9 Plate finned tube heat exchanger [21]

Applications:

This type of heat exchanger is highly used and can even be commonly found in car, namely the radiators used to dissipate heat from the engine coolant (Fig 9). Bigger heat exchangers and be used in industrial heat recovery systems.

Specification:

Table 1. Specification for condenser and evaporator heat exchangers

		Condenser	Evaporator
Length (mm)		400	400
Height (mm)		300	600
Fin thickness (mm)		0.15	0.15
Fin height (mm)		15	15
Tube diameter (mm)		19	19
Fin configuration		Regular	Regular
Header configuration [19]		Multiple pass single tube	
Inlet temperature (°C)	R-134a	45	15
Outlet temperature (°C)	R-134a	40	5
Mass flow rate (kg/s)	R-134a	6.34	6.28
Inlet temperature (°C)	Air	10	-5
Outlet temperature (°C)	Air	25	-4.5
Mass flow rate (kg/s)	Air	5	300
Theoretical Heat transfer coefficient (W/m^2 K)		1200	1500

Given that the system is being design for a helicopter it was necessary to have small heat exchangers therefore for this design both heat exchangers have a frontal surface area of less than 0.25 m^2 meaning they could be easy to integrate. The fin height , thickness and configuration were chosen based on currently used design [22]. The inlet and outlet temperatures for R-134a are based on the thermodynamic cycle presented in (Fig. 6). The inlet and outlet temperatures for the Air and its mass flow rate are reasonable assumption. The cabin temperature to be comfortable should be around 25 °C [24] hence the condenser air outlet temperature. At the cruising altitude of a helicopter around 1000m the inlet temperature for the evaporator going to be around -5 °C, on the same note at the cruising speed of a helicopter can be a reasonable assumption that the mass flow rate of the ram air (air taken in direction of travel) is around 300 kg/s. The Heat transfer coefficient (W/m^2 K) was based on the estimated provided in literature [22,23]. The header configuration was chosen based on literature [19].

To calculate the mass flow rate of the Refrigerant the energy balance equation is used:

$$\dot{Q}_{air} = \dot{Q}_{R-134a} (1) \qquad \dot{Q}_{air} = \dot{m}_{air} \cdot c_{p,air} \cdot \Delta T_{air} (2) \qquad \dot{Q}_{R-134a} = \dot{m}_{R-134a} \cdot \Delta h_{R-134a} (3)$$

Equation (3) was used due to the fluid being in a 2 states meaning there would be two densities

Part II

What is exergy?

Exergy can be defined as the maximum amount of useful work that can be produced by a system compared to its equilibrium state in the ambient environment. It can also be described as the amount of energy that can be converted into mechanical thermal chemical energy that can be used considering its surroundings.

It is therefore a just assumption that if the system is in equilibrium the useful exergy that can be extracted is 0 therefore a system in equilibrium has an exergy of 0.

Real systems are irreversible as can be affirmed by the second law of thermodynamics which states that the entropy or in simpler term the disorder of a system will always increase in any real physical system[25]. Exergy takes into account this fact as it denotes the energy that cannot be recovered in any useful process as destroyed Exergy.

The exergy of a system therefore gives an insight to the quality of energy a system produces.

Exergy can be categorized into:

Mechanical Exergy: Pressure or Kinetic energy differences

Chemical Exergy: Chemical reaction that produces energy

Electrical Exergy: generating a current creating electrical energy

Thermal Exergy: a change in temperature between the system and its environment where thermal energy can be converted useful work

Exergy analysis can help identify where systems lose energy by defining it as destroyed exergy. This can be used to make changes to the system to minimize the destroyed exergy which also increases its sustainability as less energy is wasted.

Formulas for Exergy analysis for proposed system:

$$\mathrm{W_{comp}} = \dot{m} \cdot (h_4 - h_3) \quad (4) \qquad \mathrm{Q_{in}} = \dot{m} \cdot (h_3 - h_2) \quad (5) \qquad \mathrm{Q_{out}} = \dot{m} \cdot (h_4 - h_1) \quad (6)$$

Formulas (4-6) evaluate all the work done by the system (4) compressor work (5) cooling effect (6) Heating effect.

$$\mathrm{COP} = \frac{\mathrm{Q_{in}}}{\mathrm{W_{comp}}} \quad (7)$$

The coefficient of performance (7) consists of the useful work divided by then work performed on the system.

$$\mathrm{Exergy_{in}} = \mathrm{W_{comp}} \quad (8) \qquad \mathrm{Exergy_{out}} = \mathrm{Q_{out}} \cdot \left(1 - \frac{T_0}{T_{condenser}}\right) \quad (9)$$

$$\mathrm{Exergy_{destoyed}} = \mathrm{Exergy_{in}} - \mathrm{Exergy_{out}} \quad (10) \qquad \eta_{\mathrm{Exergetic}} = \frac{\mathrm{Exergy_{out}}}{\mathrm{Exergy_{in}}} \quad (11)$$

Formula (8-11) are performed to find the exergetic efficiency of the system.

Exergy Analysis of proposed system:

The proposed system was simulated in python [26] using the Cool prop library [27] for the thermodynamic values of the refrigerant.

```python
import CoolProp.CoolProp as CP
massflowrate= 6.3 #kg/s
fluid = "R134a" #Refrigerant
T0 = 25 + 273.15 #Ambient Temperature(K)
P0 = 101325 #Ambient pressure(Pa)
T1 = 40 + 273.15 #temp condeser outlet
T2 = 15 + 273.15 #temp expansion valve oulet
T3 = T2 #temp expansion valve oulet
T4 = 45 + 273.15 #Temp compressor outlet
# s = entropy (J/kg.K) h = enthalpy (J/kg) P = pressure (Pa)
#condeser values
P1 = CP.PropsSI('P', 'T', T1, 'Q', 0, fluid)
h1 = CP.PropsSI('H', 'T', T1, 'Q', 0, fluid)
s1 = CP.PropsSI('S', 'T', T1, 'Q', 0, fluid)
#evaporator
P3 = CP.PropsSI('P', 'T', T3, 'Q', 1, fluid)
h3 = CP.PropsSI('H', 'T', T3, 'Q', 1, fluid)
s3 = CP.PropsSI('S', 'T', T3, 'Q', 1, fluid)
#Compressor outlet
s4 = s3
P4 = P1
h4 = CP.PropsSI('H', 'T', T4, 'S', s4, fluid)
#Expansion valve assuming no inefficiency
P2 = P3
s2 = s1
h2 = CP.PropsSI('H', 'T', T2, 'S', s2, fluid)
P1_bar = P1 / (10**5)
P3_bar = P3 / (10**5)
# Exergy analysis
Compressor_work = ((h4 - h3)/ 1000) * massflowrate #W_comp (KW)
Refrigeration_effect = ((h3 - h2)/ 1000) * massflowrate #Q_in (KW)
heating_effect = ((h4 - h1)/ 1000) * massflowrate #Q_out (KW)
COP = heating_effect / Compressor_work

Exergy_compressor = Compressor_work
Exergy_condeser = heating_effect * (1- (T0 / T1)) # exergy rejected by condenser
Exergy_Destruction = Exergy_compressor - Exergy_condeser
Exergetic_efficiency = (Exergy_condeser / Exergy_compressor) *100
```

Fig. 10 Python [26] code in VS Studio [28] simulating proposed system (Fig. 6)

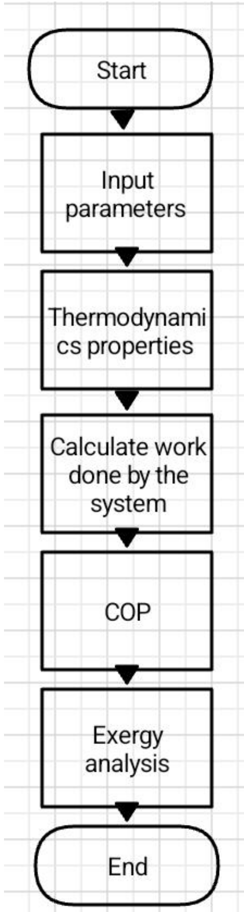

Fig. 11 Flow chart for the code/calculation [14]

```
Cycle Analysis for R134a:
Mass Flow Rate of refrigerant: 6.3  kg/s
Condeser Pressure (P1):  10.165930221206466  bar
Evaporator Pressure (P3):  4.883738643912942  bar

Exergy Analysis:
W_comp / Compressor_work:  103.55653041521991  KW
Q_in / Refrigeration effect :  961.243171226104  KW
Q_out /  heating effect:  1052.7385545850975  KW
COP / coefficient of performance :  10.165834548183883
Expergy input into compressor :  103.55653041521991  KW
Expergy rejected by condenser:  50.426563368278615  KW
Exergy destroyed by system :  53.129967046941296  KW
Exergetic efficiency:  48.69472081199364  %
```

Fig. 12 Python [26] output in VS Studio [28] simulating proposed system (Fig. 6)

The result of the calculation (Fig 12) seam promising as the system is able to output 1052 KW of heating energy which will be expelled using the condenser heat exchanger in (Table 1) which has a high heat transfer coefficient of 1200 (W/m^2 K) meaning the cabin of the helicopter will be warmed. This is while only requiring 103 KW of energy to power the compressor. This is due to the refrigerant high heat transfer coefficient. When performing the Exergy analysis it can be observed that 48% of the energy introduced to the system is being converted to usable thermal energy, this indicates that the cycle can be improved to yield a higher Exegetic efficiency.

Performance optimization:

As an area of improvement would be to increase the overall heat coefficient (W/m^2 K) of the condenser heat exchanger by adding forced convection. This would need to be run as an experiment since simulating it in software would correlate poorly to the real physical world. [29]

Another area exergy could be optimised would be to heat the refrigerant to a higher temperature. A calculation heating it to 80^0 C and setting the condenser outlet temperature to 75 80^0 C will be run using the code in (Figure 10).

```
Cycle Analysis for R134a:
Mass Flow Rate of refrigerant: 6.3  kg/s
Condeser Pressure (P1):  23.641199904466536  bar
Evaporator Pressure (P3):  4.883738643912942  bar

Exergy Analysis:
W_comp / Compressor_work:  199.6490435170804  KW
Q_in / Refrigeration effect :  657.064988079166  KW
Q_out /  heating effect:  791.5043134703773  KW
COP / coefficient of performance :  3.964478364268559
Expergy input into compressor :  199.6490435170804  KW
Expergy rejected by condenser:  113.67288718517557  KW
Exergy destroyed by system :  85.97615633190483  KW
Exergetic efficiency:  56.93635450622663  %
```

Fig. 13 Python [26] output in VS Studio [28] simulating proposed system but the refrigerant is heated to 80^0 C

This system requires more work to be preformed on the system however, it yield a higher exergetic Efficiency meaning more of the energy is being used to heat the helicopter cabin.

Conclusion:

This study aimed to explore the feasibility of using an electrical environmental control system (E-ECS) based on a refrigeration cycle to warm up the cabin of a helicopter, with possibilities of use on fixed winged aircrafts. The refrigerant the cycle is based on is the widely used R-134a which has a low boiling point , non-flammable , non-toxic and most importantly environmentally friendly as it does not react with ozone.

The Proposed an electrical environmental control system (E-ECS) has two heat exchangers the condenser and evaporator. It also has an expansion valve and a 1 stroke compressor to heat up the fluid. Using python [26] to run the calculation. It was determined that the system in (Fig. 6). Would output 1052W of energy through the condenser to the cabin while only requiring 103 KW of work to be performed by the compressor. The proposed Condenser would be capable of handing this through put as it has an overall heat transfer coefficient of 1200 (W/m^2 K).

The Exergy analysis revealed that roughly 48% of the energy in the system is being used to heat the system.

The condenser design can be improved by adding force conversion by adding a fan. While the Exergy of the system can be improved by heating the refrigerant up to 80ºC which increase the Exergy to 57%

The E-ECS could be potentially used an alternative for the traditional ECS that runs using a bleed air system reducing the amount of fuel used as it runs of the AGB that power all other electronic systems of the aircraft. Alternatively, it can be used as a back up system for aircraft that need to run operations where cabin temperature needs to stay constant.

In conclusion the E-ECS is a viable solution to current system while potentially being lighter weight and more sustainable. For future studies experiment should be run on the effect of forced convection on the overall heat transfer coefficient on plate fin heat exchangers. As well as further Exergy optimization of the system

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