A Discourse of the “Bleedless” and “Bleed Air” Gas Turbine Engines

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This discourse is intended to describe, compare and analyze two distinct turbofan engine architectures. Discussed, will be the differences between the classic bleed-air turbofan engine and the bleedless/electric turbofan engine and the various advantages and disadvantages of each engine’s architecture.

Nomenclature

A_i	=	Inlet Area
C	=	Celsius
F_T	=	Thrust Force
k	=	Adiabatic Compression Coefficient
K	=	Kelvin
kg	=	Kilograms
m	=	Meters
$\dot{m}_c$	=	Mass Flowrate of Coolant Air
$\dot{m}_e$	=	Mass Flowrate of Air – Exiting Nozzle
$\dot{m}_i$	=	Mass Flowrate of Air – Entering Inlet
N	=	Newtons (force)
NS	=	Number of Stages
P	=	Power
$p1$	=	Initial Pressure
$p2$	=	Final Pressure
s	=	Seconds
V_{ac}	=	Aircraft Velocity
V_e	=	Air Velocity at Nozzle Exit
V_i	=	Air Velocity at Inlet Entrance
$\dot{V}$	=	Volumetric Flowrate
W	=	Watts
ρ	=	Density

I. Introduction

It is common practice in many modern aircraft engines to route air flow away from the compressor stage. This is known as “bleed air”. The bleed air system on an aircraft has a variety of different purposes, including (but not limited to) cooling turbine fan blades, pressurizing the aircraft’s cabin and lavatory water tanks, and heating various aircraft components as to keep them ice-free [1]. However, the use of bleed air detracts from the efficiency of the engine. In an attempt to improve upon engine efficiency, Boeing has introduced a bleedless/electric system for their 787 Dreamliner aircraft. Boeing claims that this new bleedless/electric system has several benefits, including improved fuel consumption, reduced maintenance costs, improved reliability, and an overall weight reduction [2]. This report aims to highlight the differences between these two system architectures as well as subjectively discuss the advantages and disadvantages of each.

II. Bleed Air System Overview

Most gas turbine aircraft engines incorporate a bleed air system. This architecture takes advantage of the relatively hot (200-250 degrees C), high-pressure air flowing through the compressor section of the engine. Air can be bled from any point within the compressor section, and its location varies depending on the particular engine. In some cases, air is bled from multiple compressor stages due to the variability in the pressure and temperature characteristics of the gas as the flow moves though each stage [1]. This air is then transported to various areas of the aircraft through a network of pipes, regulators and valves. As mentioned previously, this high pressure air has a wide variety of uses, which are detailed below.

Aircraft Pressurization

Perhaps the most important use of bleed air is providing pressure to sections of the aircraft fuselage. As an aircraft climbs to its cruising altitude, the surrounding environment changes drastically. The atmospheric pressure at cruise drops to nearly 20% of that at sea level (Wolfram Alpha, 11 km altitude); therefore, it becomes necessary to supplement the pressure in the cabin and cockpit.

Environmental Control

In addition to supplying pressure to many areas within the fuselage, it is also necessary that this pressurized environment is circulated so that the occupants of the cabin and cockpit have a fresh supply of air. The pressurized air flowing into these compartments must be introduced at a ‘comfortable’ temperature. Considering that this air is extracted from the compressor stage while it is hot (200-250 degrees C), a method of cooling the air is required [1]. This is typically accomplished by routing a portion of this air through the plane’s air-conditioning packs. The temperature of this air can then be adjusted by mixing it with the un-cooled bleed air [1].

Turbine Blade Cooling

Due to the trend of increase turbine entry temperatures in an attempt to increase an engines thermodynamic efficiency, cooling of the turbine blades has become a necessity. Most modern engines have turbine entry temperatures greater than the melting point of the turbine blade material. This fact has forced innovative ways of cooling the blades to prevent high stress and elongation of the blades. Many engines have utilized bleed air, fed through tiny passages within the turbine blades for cooling. This air typically exits the blade near the leading edge to create a film of cooler air around the blade.

De-icing

Warm, high pressure air can also be fed to areas of the aircraft where ice build-up is a concern. Bleed air can be used to heat the engine inlets to prevent ice from forming, detaching and being ingested into the engine. Similarly, this warm air can be used to prevent ice build-up on the leading edges of the wings.

Engine Start

Bleed air is also sometimes used for starting one of the aircraft's engines. This air is fed to a turbine starter motor, which provides the torque necessary to start the engine [1]. This can also be accomplished with an electric or hydraulic system; however, an air turbine starter motor is typically a smaller and lighter package then either of these systems [1].

Water System Pressurization

In addition to pressurizing the cabin of the aircraft, bleed air is also used to pressurize the plane's water system. This method provides a robust way of supplying potable water to the lavatories and the galley. Using bleed air for this purpose eliminates the need for a hydraulic pump and therefore eliminates a failure mode as well [1].

Improving Boundary Layer Separation

Although not commonly used on commercial aircraft, bleed air can be used to improve the aerodynamic flow characteristics over a wing or into an engine inlet. This system injects the high pressure air just before the leading edge of the wing flap, which delays the boundary layer separation. This can lower the stall speed due to reduced drag, which can decrease the landing speed of the aircraft [3]. It should be noted that this system is more often used in high-performance aircraft.

III. Bleed Air System Advantages and Concerns

The primary advantage of a traditional bleed air system is its high versatility. As demonstrated, this system accomplishes many different goals. Without this comprehensive system, many of these goals would require the addition of electric components. For example, the pressurization of the cabin and the environmental control system would require an electric air compressor (this could also be applied to boundary layer separation improvement). The heating of certain components would require addition of electro-resistive components and a power source. Finally, the pressurization of the water system would need to be replaced by a hydraulic pump, again requiring a power source. By eliminating the need for multiple electric components, the bleed air system is able to reduce the weight of the craft as well as reducing the required electrical power draw from the engines themselves.

A concern with the traditional bleed air system is the potential for air contamination. According to an expert panel on aircraft air quality, "Cabin air in commercial aircraft can be contaminated with hydraulic fluids, synthetic jet oils or the compounds released when these fluids are heated or pyrolysed. The incidence of contaminated air events and the nature of contaminants within the cabin air are difficult to determine as commercial aircraft do not have air quality monitoring systems on board and under-reporting is common amongst aircrew." [4]. Several other parameters present themselves as "concerns", but will be discussed as "advantages" for the bleedless/electric architecture.

IV. Bleed Air System Performance Considerations

Bleeding air from the compressor stage of a gas turbine engine negatively affects its performance. Although bleed air accounts for a small percentage of the mass flowrate of the air through the engine, it still directly affects the thrust output of the engine. Viewed from a thermodynamics standpoint, it is intuitive that engine performance would be adversely affected by bleeding air from the compressor. Work is done on the incoming air to pressurize it; however, work is not extracted from the bleed air for thrust. This can be viewed in terms of a reduction of thrust specific fuel consumption as well if thrust is held constant; however, for the purposes of this paper, thrust reduction will be the primary consideration. Equation 1, shown below, is the general thrust equation.

$$F_T = \dot{m}_e V_e - \dot{m}_i V_i \qquad (1)$$

It can be seen, that if the mass flowrate is not altered throughout the cycle due to the addition of fuel the same equation can be written as:

$$F_T = \dot{m}(V_e - V_i) \qquad (2)$$

This form of the equation clearly demonstrates that a reduction in the mass flowrate of air through the engine, due to bleed off, will also result in a reduction of thrust from what is theoretically possible.

To demonstrate this effect, an analysis was performed to determine the theoretical reduction of thrust resulting from a bleed air system. This analysis assumes that the large majority of the bleed air mass flow results from turbine blade cooling and cabin air pressurization/recirculation. In addition, this analysis assumes then engines are in cruise conditions.

Bleed Air Mass Flow Determination

In most cases, the large majority of air bled from the compressor gets routed to cooling turbine blades using a method called transpiration. As mentioned previously, this air is forced though the turbine blades themselves to create a cooling, protective film of air around the blade to prevent them from being subjected to very high turbine inlet temperatures. Previous analyses have been performed to determine what fraction of bleed air to exhaust air is required to cool turbine blades optimally. Shown below, is a chart generated in [5], which plots the above-mentioned bleed air percentage as a function of various turbine entry temperatures. The derivation of the equations used to generate this graph can be found in [6].

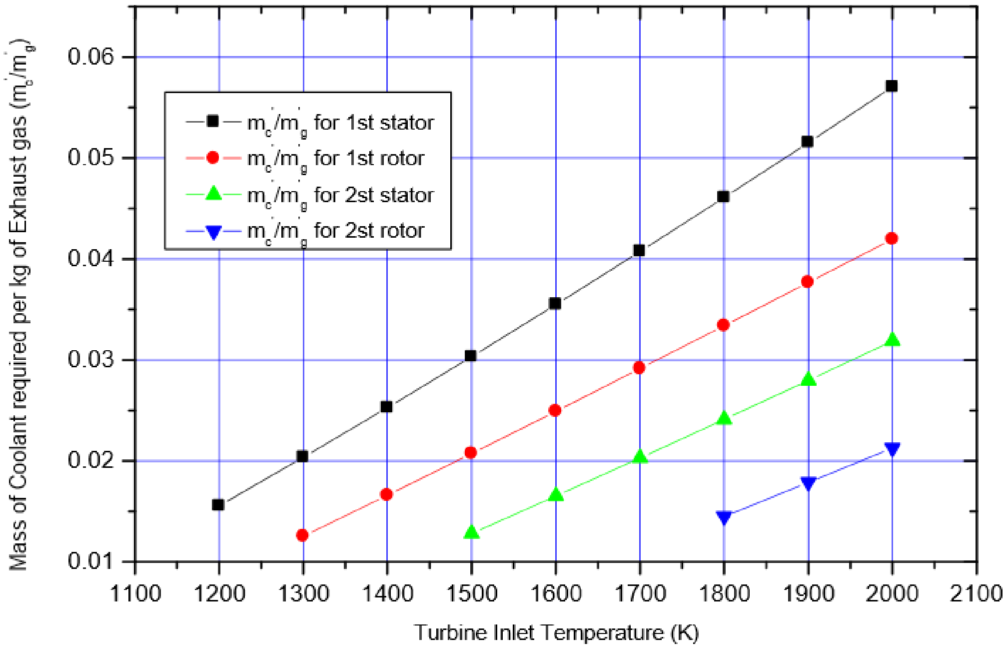

Figure 1: Coolant fraction required as a function of turbine entry temperature [5]

A baseline turbine entry temperature of 1600 K is selected for this discourse's analysis to determine the mass flowrate of air supplied to the turbine for cooling purposes. This selection leads to a summation of percentages for the first rotor and first two stators equal to 7.6%.

The second-most significant contribution to bleed air consumption is assumed to be cabin pressurization and air circulation. According to a US Department of Transportation advisory circular, a supply of 0.55 pounds per minute of fresh air per passenger is required. This translates to a value of 0.00416 kilograms per second. To calculate the total air supply required, a baseline of 400 passengers is assumed, leading to an air supply value of 1.66 kg/s.

Engine Airflow Determination

To continue with the analysis, a mass flowrate through the engine must either be assumed or calculated. It was decided that engine air mass flowrate would be calculated based on an engine that uses a bleed air system and is comparable to the GEnx engine (which uses the bleedless/electric system). The engine chosen for the analysis was the Rolls-Royce Trent XWB. Parameters for this engine, as well as the equation used to calculate mass flowrate are shown below.

$$\dot{m}_i = \rho V_{ac} A_i \qquad (3)$$

Table 1: Trent XWB and A350 Parameters

Inlet Cross Sectional Area	7.07 m^2
Cruise Speed	Mach 0.85
Resulting Air Mass Flowrate	750 kg/s

Determining Incoming and Outgoing Velocities

In order to solve for thrust in equations 1 or 2, it is necessary to determine the velocity of the air entering and exiting the engine. Incoming air velocity can be reasonably assumed as the equivalent of the cruise velocity of the aircraft. Next, to determine a baseline exhaust velocity, equation 2 was reworked using the engine manufacturer's provided value for SLS thrust and the mass flowrate calculated above. SLS thrust was scaled based on air density at altitude to provide a more accurate value. This yielded an exhaust velocity of roughly 450 m/s.

Performance Analysis

To determine the effects of bleed air on thrust, it was necessary to determine an approximate "worst-case" scenario for bleed air. This was accomplished assuming that the entirety of bleed air was used for two purposes: cabin air pressurization/circulation and cooling of turbine blades. A worst-case value for cabin air was determined using the US DOT minimum fresh air per passenger value multiplied by a baseline of 400 passengers. This parameter is considered worst-case because it does not consider cabin air re-circulation, meaning it is likely over stated. Similarly, turbine blade cooling air was determined using a graph developed for turbine blade transpiration cooling in [5]. This is considered worst-case because the air bled from the compressor does not actually leave the engine. Rather, it simply bypasses combustion, and is injected back into the airstream through the turbine blades. This means that, rather than not contributing to thrust at all (as this analysis assumes), it actually does provide momentum thrust. In addition, the assumptions made leading to this chart (i.e. blade material, turbine scale and type) are ambiguous. The values for both these scenarios were summed to determine the total worst-case bleed air mass flowrate. To determine the effects on thrust, bleed air was varied from 0 kg/s to the maximum of 58.6 kg/s, and deducted from the mass flowrate in the general thrust equation (2). Shown below are two graphs: the first displaying the resulting reduction in total thrust, and the second showing a reduction of thrust, normalized by the theoretical maximum thrust achievable in cruise conditions.

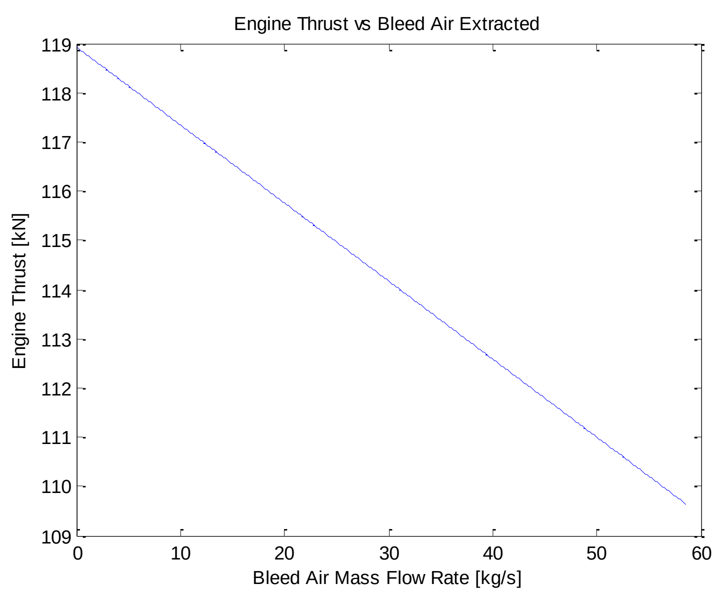

Figure 2: Engine thrust reduction resulting from bleed air

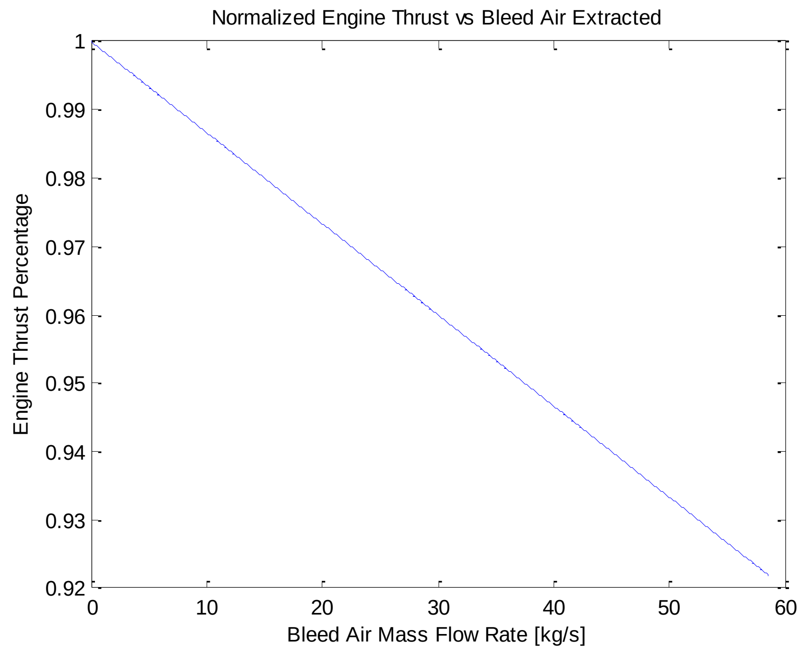

Figure 3: Normalized engine thrust reduction resulting from bleed air

It can be seen from the above plot, that if the maximum mass flowrate for bleed air is accurate, the thrust from the engine is reduced by roughly 9.5 kN. This is also shown as a percentage reduction in figure 3; which shows that almost 8% loss in thrust is possible with the maximum or "worst-case" value for bleed air flowrate. It should be restated that these plots likely grossly overestimate the reduction in thrust because they do not take into account that the air being used to cool the turbine blades is still being expelled from the nozzle thereby generating momentum thrust. The Matlab code used to calculate these parameters and generate these plots can be found in the appendix.

V. Bleedless/Electric System Overview

Somewhat recently, Boeing has introduced the GEnx engine which does not incorporate a traditional bleed air system. Instead, an electric air compressor, powered by either the engine's starter generators or the auxiliary power unit (APU), is utilized [2]. Boeing makes no mention of whether this electrically compressed air is used for turbine blade cooling. However, Boeing notes that this electric system does handle many of the functions that are typically achieved using bleed air. The electric system provided by Boeing is responsible for powering the hydraulic system, environmental control system (including cabin pressurization), and wing ice-protection system [2].

VI. Bleedless/Electric System Advantages and Concerns

There are multiple advantages to replacing a bleed air system with an electric compression system. The main advantage to the electric system is that, transporting power through electricity is significantly more efficient than a pneumatically driven power system. This results in less power drawn off the engine during cruise conditions. Boeing claims that the resulting improvement in fuel consumption due to this reduction in power draw could be anywhere from 1-2% [2]. Additionally, Boeing notes that pneumatic systems typically generate more power than is necessary, whereas the electric system can be utilized only when needed, resulting in up to a net 35% less power draw from the engine [2]. Another advantage of the electric system is the elimination of the bleed air pneumatic network. This means all of the high pressure lines, valves, and regulators can be removed from the aircraft. Removal of this complicated system may end up having a net improvement on weight, even though there is an addition of a large electric air compressor and other components to support the electrical system. Boeing claims that there is, in fact, a net weight reduction leading to improved aircraft range [2]. Also, with the removal of this pneumatic network, Boeing expects that maintenance costs will fall significantly, as the bleed air system is traditionally maintenance intensive [2]. It should be noted that, these claims come directly from the engine manufacturer, and should be taken with a grain of salt.

Similar to the bleed air system, there are concerns regarding the electric system. The primary concern is loss of pressure due to an electrical system malfunction. To provide a level of redundancy in this respect, the addition of batteries will likely be necessary. This will significantly increase the weight of the electric system. The overall weight of the system is also a concern; however, Boeing does claim the change from a traditional bleed air system to an electric/bleedless system results in a net weight improvement [2].

VII. Bleedless/Electric System Performance Considerations

Although it is not clear whether the electric/bleedless system is used to cool turbine blades, it likely is not. An excessively large compressor would be required to supply the flowrate required to cool the turbine blades sufficiently. This means that the main performance consideration should be whether or not the addition of larger generators and electric air compressors is worth the improvement in engine efficiency. In the analysis of the bleed air system above, cabin pressurization and circulation accounts for far less than 1% of the thrust reduction due to bleed air. Because Boeing does not provide the specifications of their electric system, it is difficult to determine whether the mass addition of the larger generators and electric compressor results in an overall benefit. For rough analysis, the power required to compress the air from the bled system is compared to the resultant power loss from thrust reduction. Because the bleed air used to cool the turbine blades is routed back into the engine, only the air used for environmental control is considered in the following analysis.

Power Loss from Thrust Loss

To determine the power loss resulting from a reduction of thrust, equation 4 (shown below) is used. This equation describes the power of an engine, given the trust force and the velocity of the aircraft.

$$P = F_t V_{ac} \qquad (4)$$

This calculation resulted in a thrust power loss of 77 kW under cruise conditions. This value is then compared to the power required to compress the bleed air. This comparison will demonstrate the discontinuity between the power-draw required to compress the air and the power lost due to removing that same air from the engine.

Power Required to Adiabatically Compress Bleed Air

The power required to adiabatically compress the air that is bled from then engine is calculated using equation 5. Following this calculation, it is assumed that a 15% increase in the baseline power is required to account for mechanical friction.

$$P = \left(\frac{NS\, p1\, \dot{V}\, k}{k-1}\right)\left(\frac{p2^{\left(\frac{k-1}{NS\, k}\right)}}{p1} - 1\right) \qquad (5)$$

This calculation resulted in a power of 64 kW. Comparing this value to the potential thrust power loss of 77 kW, it is clear that the bleed air is more efficiently used to produce thrust. An electric system should draw less power in compressing this air than is lost due to the resultant thrust lost in cruise conditions. The power calculations which yielded the above values can be seen in the appendix.

VII. Conclusion

In summary, the bleedless engine architecture has clear advantages over one that bleeds air from the compressor. There are, however, drawbacks to using the electric system. An electric system allows for efficient compression of air, while enabling the engine to operate at maximum air flow, thereby improving the engine efficiency. In addition, the maintenance costs of the electric system will likely be much less than that of the opposing architecture in the long run. The primary drawback to using a bleedless architecture over a traditional one is the increased mass resulting from the addition of larger generators and an electric air compressor. It is difficult to determine if the increased mass will outweigh the benefits of a more efficient system. Although Boeing claims that the electric system actually results in a net weight deduction as well as improved efficiency, it is difficult to determine the accuracy of this statement. The assumptions made by Boeing to make this statement are unknown; therefore, its degree of validity is uncertain. The fact remains that Airbus, for the time being, has decided against implementing a bleedless system, meaning the net benefits of this architecture are likely not significant. This may very well be due to other variables, such as the cost of implementing or retrofitting an electric system. A much more in depth analysis to determine or dispel the quantitative benefits of the bleedless/electric system should be performed if specifications regarding Boeing’s architecture become available.

Appendix

Determining the Maximum Amount of Bleed Air

```
baCoolingRatio = 0.076;          % ratio of bleed air to exhaust
pass = 400;                      % number of passengers
baCabinPP = 0.00416;             % [kg/s] per person air supply to cabin
baCabinTot = baCabinPP*pass      % [kg/s]
```

```
baCabinTot = 1.6640 [kg/s]
```

Determining the Mass Flow Rate of the Engine

```
cruiseAlt = 11000;                               % [m]
cruiseVel = 0.85*343                             % [m/s]
area_fan = pi*(3/2)^2                            % [m^2]
[~,~,airPress,airDens] = atmosisa(cruiseAlt)     % [kg/m^3]

massFlowE = airDens*cruiseVel*area_fan           % [kg/s] enngine air mass flow rate
```

```
cruiseVel = 291.5500 [m/s]

area_fan = 7.0686 [m^2]

airPress = 2.2632e+04 [Pa]

airDens = 0.3639 [kg/m^3]

massFlowE = 749.9789 [kg/s]
```

Analyzing Performance Loss Due to Bleed Air

```
baTurbine = baCoolingRatio*massFlow                         % [kg/s] bleed air to turbine

baMaxMassFlow = baTurbine + baCabinTot                      % [kg/s] maximum bleed air flow

thrustSLS = 400340;                                         % [N] SLS Engine Thrust (manufact.)
[~,~,~,airDens0] = atmosisa(0);                             % [kg/m^3]
densScaling = airDens/airDens0;                             % thrust scaling factor

exhaustVel = (thrustSLS*densScaling)/massFlowE + cruiseVel          % [m/s]

baVaried = 0:0.1:baMaxMassFlow;

thrust = ((massFlowE - baVaried)*(exhaustVel - cruiseVel))/1000;    % [kN]
thrustNorm = ((massFlowE - baVaried)*(exhaustVel - cruiseVel))/...
    ((massFlowE)*(exhaustVel - cruiseVel));

% Plotting thrust and normalized thrust by bleed air mass flowrate
figure(1)
plot(baVaried,thrust)
title('Engine Thrust vs Bleed Air Extracted')
xlabel('Bleed Air Mass Flow Rate [kg/s]')
ylabel('Engine Thrust [kN]')

figure(2)
plot(baVaried,thrustNorm)
title('Normalized Engine Thrust vs Bleed Air Extracted')
xlabel('Bleed Air Mass Flow Rate [kg/s]')
ylabel('Engine Thrust Percentage')
```

```
baTurbine = 56.9984 [kg/s]

baMaxMassFlow = 58.6624 [kg/s]

exhaustVel = 450.1297 [m/s]
```

Determining the Power Lost Due to Thrust Reduction

```
ft_loss = ((massFlowE)*(exhaustVel - cruiseVel))-...
    (massFlowE - baCabinTot)*(exhaustVel - cruiseVel)   % [N] thrust loss

p_loss = ft_loss*cruiseVel/1000                         % [kW] power loss
```

```
ft_loss = 263.8765 [N]

p_loss = 76.9332 [kW]
```

Determining Power Required to Compress Cabin Air

```
N = 3;                      % number of compression stages
frictMargin = 1.15;         % margin added for mechanical friction
k = 1.41;                   % adiabatic compression coefficient
p1 = 23000;                 % [Pa] initial air density (11000 m)
p_ba = 275790;              % [Pa] from 40 psi extraction baseline
R = 287.05;                 % Specific gas constant for dry air
T = 225 + 273.15;           % [K] temperature of bleed air extracted

rho = p_ba/(R*T);           % [kg/m^3] air density after compression
volFlow = baCabinTot/rho    % [m^3/s] volumetric flow of compressed air

Power_cmpr = (((N*p1*volFlow*k)/(k-1))*...
    ((p_ba/p1)^((k-1)/(N*k)) - 1))*frictMargin/1000     % [kW]
```

```
volFlow = 0.8628 [m^3/s]

Power_cmpr = 64.0956 [kW]
```

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