Energy optimization analysis of the more electric aircraft

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Abstract. The More Electric Aircraft (MEA) underlines the utilization of the electrical power to drive the non-propulsive aircraft systems. The critical features of the MEA including no-bleed engine architecture and advanced electrical system are introduced. Energy and exergy analysis is conducted for the MEA, and comparison of the effectiveness and efficiency of the energy usage between conventional aircraft and the MEA is conducted. The results indicate that one of the advantages of the MEA architecture is the greater efficiency gained in terms of reduced fuel consumption.

1. Introduction
Driven by the demand to optimize aircraft performance, decrease operating and maintenance costs, increase dispatch reliability, and reduce fuel consumption and gas emissions, the aviation industry push toward the concept of More Electric Aircraft (MEA), and ultimately an all electric aircraft. Specifically, the MEA concept provides for the utilization of electrical power for all non-propulsive systems. Traditionally these non-propulsive systems are driven by a combination of different secondary power sources such as hydraulic, pneumatic, mechanical and electrical [1].

The move towards a MEA therefore involves replacing the hydraulic and pneumatic systems equipping current aircraft with electrical systems, and requires a significant increase in the power of the electricity generation and distribution systems. Progress in research in this area and the experience acquired in the most recent civil airliners, particularly the A380, A350 and B787, make it possible to foresee for future generations a radically transformed on-board energy chain, mainly based on electrical systems. This major technological breakthrough will consist of replacing the current multimodal circuits (mechanical, hydraulic and pneumatic) with electrical circuits controlling all functions of the aircraft, both on the ground and in flight [1-2].

In order to give a measurable way to quantify whether the MEA is energy optimized, this paper conducts exergy analysis to analyze the energy efficiency of each module of the MEA. Using this method, the MEA is divided into serval modules, including propulsive system, electrical system, hydraulic system, and environmental control system. In addition, the exergy destruction and efficiency of systems are calculated during the complete flight profile. Moreover, the comparison of overall aircraft level energy efficiency for conventional aircraft and the MEA is conducted. The result indicates that the MEA systems architecture is the greater efficiency gained in terms of reduced fuel consumption.

2. Description of the MEA
The concept of More Electric Aircraft (MEA) has been proposed as early as 1970s, when it was called the all electric aircraft. Since 1940s, the secondary power sources on the aircraft have adopted 3 hybrid powers: hydraulic, pneumatic and electrical sources. A centralized hydraulic power system consisting of engine driven pump is mainly used to actuate the control surfaces, drive the landing gear and doors, and control the engine reverser mechanism. High-pressure and high-temperature air bled from engine compressor is mainly used for anti-icing and environment control system. A variety of secondary power sources on the aircraft complicate the design of aircraft and engine, reduce energy efficiency, decrease dispatch reliability and increase maintenance costs. More electric aircraft emphasizes the use of electrical power in place of centralized hydraulic and pneumatic power.

The integration of all secondary power sources into one, the electrical power source, not only reduces the hydraulic pipes and gas ducts in the aircraft, simplifies the internal structure of the aircraft, but also simplifies the engine buildup. The engine of the MEA no longer extracts compressed air from the compressor, simplifies or eliminates the accessory drive gearbox, and uses pneumatic or magnetic suspension bearing without lubricating oil system. A starter generator is used to start the engine. After the engine works normally, the starter generator shifts to electric generator, supplying power to the electrical equipments [3].

2.1. Engines
The engine uses a compressor and turbine to compress ambient air, heat it, and then expand it through a turbine resulting in a hot gas used for thrust to push the aircraft through the air. Thrust produced from high-temperature and high-speed air is the primary purpose of the engine, but the engine provides a source of secondary power for the non-propulsive aircraft systems.

In the traditional architecture, the engines provide the majority of secondary aircraft systems power needs in pneumatic form; in the MEA architecture, the engines (no-bleed) provide the majority of aircraft systems power needs in electrical form via shaft driven generators. The traditional aircraft pneumatic bleed system architecture results in less than optimum engine efficiency. Eliminating the pneumatic bleed results in a more efficient engine operation due to reduced overall aircraft level power requirements, so it doesn’t burn as much fuel.

Moreover, the no-bleed architecture allows significant simplification in engine buildup due to the elimination of the pneumatic system and associated pre-coolers, control valves, and required pneumatic ducting.

The no-bleed engine architecture of the MEA is shown in Figure 1. In this architecture, bleed air is only used for engine cowl ice protection and pressurization of hydraulic reservoirs. The electrified functions are wing deicing protection, engine starting, driving the high-capacity hydraulic pumps, and powering the cabin environmental control system.

![Figure 1. No-bleed engine architecture of the MEA.](image-url)
2.2. **Electrical system**

The primary differentiating factor in the systems architecture of the MEA is its emphasis on electrical systems, which replace most of the pneumatic systems found on traditional commercial aircrafts.

Figure 2 shows the electrical system architecture of the B787. The B787 uses an electrical system that is a hybrid voltage system consisting of the following voltage types: 230 volts alternating current (VAC), 115 VAC, 28 volts direct current (VDC), and ±270 VDC. The 115 VAC and 28 VDC voltage types are traditional, while the 230 VAC and the ±270 VDC voltage types are the consequence of the no-bleed electrical architecture that results in a greatly expanded electrical system generating twice as much electricity as previous Boeing aircraft models. The system includes six generators, two per engine and two per APU, operating at 230 VAC for reduced generator feeder weight. The system also includes ground power receptacles for aircraft servicing on the ground without the use of the APU.

![Figure 2. Electrical system architecture of the B787.](image)

The generators are directly connected to the engine gearboxes and therefore operate at a variable frequency (360 to 800 hertz) proportional to the engine speed. This type of generator is the simplest and the most efficient generation method because it does not include the complex constant speed drive, which is the key component of an integrated drive generator (IDG). As a result, the generators are expected to be more reliable, require less maintenance, and have lower spare costs than the traditional IDGs.

The ±270 VDC system is supplied by four auto-transformer-rectifier units that convert 230 VAC power to ±270 VDC. The ±270 VDC system supports a handful of large-rated adjustable speed motors required for the no-bleed architecture. These include cabin pressurization compressor motors, ram air fan motors, the nitrogen generation system compressor used for fuel tank inerting, and large hydraulic pump motors.

3. **Energy and exergy analysis**

Only in case of emergency, such as both engines failures, the battery and ram air turbine provide a temporary limited power source for the aircraft. Normally in flight all forms of energy on an aircraft are based on one source which is the chemical energy stored in jet fuel. Chemical energy of jet fuel is burned in the engine combustor as part of a Brayon power cycle that produces heat (thermal energy potential). Most of this energy is transformed into thrust produced from the high-speed exhausting gas. The secondary energy/power is extracted from the engine to drive the non-propulsive systems.
The exergy $[\text{Ex}]$, or the maximum amount of useful work that may be extracted from a system, when it reaches equilibrium with its environment, can be expressed with the flowing general equation [4]:

$$\text{Ex} = U - U_{eq} + p_0(V - V_{eq}) - T_0(S - S_{eq}) + \sum n_i(\mu_{eq} - \mu_{io})$$  \hspace{1cm} (1)

where the subscript $eq$ denotes equilibrium with environment. $U$, $V$, $S$, and $n_i$ denote the extensive parameters of the system (internal energy, volume, entropy, and the number of moles of different chemical elements). $T_0$, $p_0$, and $\mu_{io}$ denote intensive parameters of the environment (temperature, pressure and the chemical potential of the component $i$ in its standard state, i.e. in equilibrium with environment).

For the open system in steady state, the general exergy balance can be expressed as:

$$\dot{\text{Ex}}_{in} = \dot{\text{Ex}}_{out} + \dot{\text{Ex}}_{dest}$$  \hspace{1cm} (2)

Eq. (2) includes three terms: the exergy flowing in, the exergy flowing out, and the exergy destroyed due to the irreversibility.

The MEA’s no-bleed systems architecture replaces the traditional pneumatic system and the bleed manifold with a high-power electrical system that, in addition to the traditional electrical system functions, supports a majority of the aircraft functions that were traditionally performed via bleed air. In this architecture, electrically driven compressors provide the cabin pressurization function, with fresh air brought onboard via dedicated cabin air inlets. The output of the cabin pressurization compressors flows through air-conditioning packs, using heat exchangers and air cycle machines to cool down the hot air. Excessive air discharges overboard for pressurization control.

Figure 3 shows the exergy flows in the MEA, which is divided into five modules, including engine, aircraft frame, electrical system, hydraulic system, and environmental control system.

Using Eq. (2) and considering the work rate flow, the rate form of the exergy balance for the engine can be written as [5]:

$$\dot{\text{Ex}}_{fuel} + \dot{\text{Ex}}_{air} = \dot{W}_{thrust} + \dot{W}_{ele} + \dot{\text{Ex}}_{gas} + \dot{\text{Ex}}_{dest-engine}$$  \hspace{1cm} (3)

Similarly, for the aircraft frame, electrical system, hydraulic system, environmental control system and the overall aircraft, their exergy balances can also be written respectively as:

$$\dot{W}_{thrust} = \dot{W}_{drag} + \dot{\text{Ex}}_{dest-frame}$$  \hspace{1cm} (4)

$$\dot{W}_{ele} = \dot{W}_{equipment} + \dot{W}_{hyd} + \dot{W}_{ECS} + \dot{\text{Ex}}_{dest-ele}$$  \hspace{1cm} (5)
In order to determine how well the desired effect of the system is accomplished, the efficiency is calculated as the ratio of the output (net produced) exergy to the input (net supplied) exergy or as a fraction of the input (net supplied) exergy used by the system to perform its function [6]:

\[
\eta = \frac{E_x_{\text{dest}}}{E_x_{\text{in}}} = 1 - \frac{E_x_{\text{dest}}}{E_x_{\text{in}}}
\]  

(9)

4. Results and discussion

As chemical energy of the fuel changes into a variety of sources, it provides a direct energy usage by something else, or it produces waste heat. So when discussing an energy optimized aircraft we should be focusing on (1) effectiveness, which means how to transition chemical energy into other forms that are the most useful, and (2) efficiency, which means how to reduce the waste heat produced while making the transition. Efforts in the past usually focus on reducing waste heat, which increases the efficiency of a system.

4.1. Effectiveness

Effectiveness is evaluating alternatives to determine if the most energy conserving form of energy usage is being employed. As previously mentioned a new no-bleed systems architecture in the MEA eliminates the traditional pneumatic system and bleed manifold and converts the power source of most functions formerly powered by bleed air to electric power (for example, the air-conditioning packs and wing anti-ice systems). Comparison of typical power levels between conventional aircraft and the MEA is given in Table 1. The result indicates that the total non-thrust power of conventional aircraft is approximately 1.74MW, 74% higher than that of the MEA, while both thrust power equals to 40MW.

| Power user | Thrust (MW) | Electrical (kW) | Pneumatic (kW) | Hydraulic (kW) | Mechanical (kW) |
|------------|-------------|----------------|---------------|----------------|----------------|
| Conventional | 40          | 200            | 1200          | 240            | 100            |
| MEA        | 40          | 1000           | 0             | 0              | 0              |

Table 1. Comparison of typical power levels between conventional aircraft and the MEA.

We can see that the MEA’s no-bleed systems architecture offers operators a number of benefits, including:

(1) Improved fuel consumption, due to a more efficient secondary power extraction, transfer, and usage.

(2) Reduced maintenance costs, due to elimination of the maintenance-intensive bleed system.

(3) Improved reliability due to the use of modern power electronics and fewer components in the engine installation.

(4) Expanded range and reduced fuel consumption due to lower overall weight.

(5) Reduced maintenance costs and improved reliability because the architecture uses fewer parts than previous systems.

The no-bleed systems architecture will allow the aircraft’s engines to produce thrust more efficiently — all of the high-speed air produced by the engines goes to thrust. Pneumatic systems that divert high-speed air from the engines rob conventional aircrafts of some thrust and increase the engine’s fuel consumption.
The ducting used to pass the pressurized air around the aircraft employs check valves and pre-coolers, and is itself made of titanium, which adds hundreds of pounds of weight to the aircraft. The electric system is also inherently easier to monitor and control, and produces only enough power as needed. The power, which comes off the generators at variable frequencies, is conditioned in the electronics bay before being distributed to the appropriate systems.

Boeing believes that using electrical power is more efficient than engine-generated pneumatic power, and expects the new architecture to extract as much as 35 percent less power from the engines. Conventional pneumatic systems generally develop more power than is needed in most conditions, causing excess energy to be dumped overboard.

4.2. Efficiency
Since the goal of an energy optimized aircraft is to optimize energy usage to reduce fuel needed to conduct flights then overall aircraft level assessments need to be conducted. Assessments should reflect how design decisions for selecting architectures, systems, and components impact/benefit the overall fuel needs for a flight.

Using the Eq. (1) - (9) and flight data of a complete profile, the fuel efficiency for conventional aircraft and the MEA can be estimated, respectively. The result indicates that the MEA systems architecture is the greater efficiency gained in terms of reduced fuel burn, accounting for fuel savings of about 3 percent.

In the B787 electrical architecture, the output of the cabin pressurization compressors flows through low-pressure air-conditioning packs for improved efficiency. The adjustable speed feature of electrical motors will allow further optimization of aircraft energy usage by not requiring excessive energy from the supplied compressed air and later regulating it down through modulating valves resulting in energy loss.

5. Conclusion
Replacing the conventional non-propulsive aircraft power, hydraulic and pneumatic with single electric power is known as the More Electric Aircraft (MEA). A key benefit expected from the MEA's no-bleed architecture is improved fuel consumption as a result of more efficient engine cycle and more efficient secondary power extraction, power transfer, and energy usage.

Eliminating the maintenance-intensive bleed system is also expected to reduce aircraft maintenance needs and improve aircraft reliability because there are fewer components on the engine installation; there are no IDGs, pneumatic ducts, pre-coolers, valves, duct burst protection, and over-temperature protection; and there is no compressed air from the APU, resulting in a simplified and more reliable APU.

The MEA's no-bleed architecture also features modern power electronics and motors that will provide increased overall reliability, decreased costs, and improved performance. Finally, the architecture means reduced aircraft weight, reduced part count, and simpler systems installation.

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