Technical Articles

Moving to an All-Electric Aircraft System

MORIOKA Noriko : General Manager, Control Systems Engineering Department, Research & Engineering Division, Aero-Engine & Space Operations
TAKEUCHI Michiya : General Manager, Control Systems Engineering Department, Research & Engineering Division, Aero-Engine & Space Operations
OYORI Hitoshi : Ph. D., General Manager, Electrical Technologies Office, Technologies Development Department, IHI AEROSPACE Co., Ltd.

The More Electric Architecture for Aircraft and Propulsion (MEAAP) project aims to improve safety, environmental friendliness, and economic benefits with innovations that integrate electrical power management and thermal management for aircraft. IHI is trying to develop an all-electric system for the engine and aircraft of the future within the next decade or two. This paper introduces an overview of the MEAAP concept and IHI all-electrical system innovations.

1. Introduction

In recent years, the aviation business has entered a major growth period, becoming a growth industry with increased air transportation demand projected for the future. On the other hand, the rising awareness of environmental issues on a global scale demands a reduction in substances of concern and decreased CO_2 emissions. Furthermore, as the international demand for fuel increases, fuel prices are rising, and the aviation business is urgently requesting better fuel efficiency for economic reasons as well, since reductions in fuel consumption directly lead to cost savings. These needs must be met, while we continue to provide technological developments related to safety and reliability that form the bedrock of aviation technology.

In conventional aircraft, the four power sources of hydraulic power, pneumatic power, mechanical power and electricity make up aircraft systems and subsystems, but whereas hydraulic, pneumatic and mechanical power have been used as the primary drivers of components owing to their long record of safety and reliability, the proportion of electrification has been small in scale. However, to utilize the advantages of electrified systems, which include excellent efficiency and advanced functionality, the promotion of electrified aircraft system (MEA: More Electric Aircraft) and the promotion of electrified aircraft engine system in which hydraulic and mechanical pumps and actuators in the engine are electrified (MEE: More Electric Engine) have taken root as an effort directed towards ① safety, ② environmental friendliness, and ③ cost effectiveness.[1] IHI is studying system concepts oriented towards the research and development of the next stage of this technology: All-Electric Aircraft (AEA) systems that consolidate the component systems. **Figure 1** illustrates the All-Electric Aircraft system.

The latest MEA is the state-of-the-art Boeing 787 from Boeing (USA). The Boeing 787 has a large starter generator capable of electrically starting the engine, as well as high voltage power distribution. By eliminating engine bleed via the adoption of an electric motor-driven compressor and switching to an electro-thermal anti-icing system, dramatic increases in efficiency and fuel economy are achieved. With even more advanced electrification designs, AEAs aim to electrify aircraft systems in which hydraulic, pneumatic, and mechanical actuators are used, while at the same time optimize aircraft energy and power management by consolidating power management and thermal management.

2. The concept of AEAs

Here we will summarize the concept of an all-electric system from an operational perspective by the phases of a flight, and we will introduce several specific research efforts by IHI in the sections denoted by angle brackets (< >).

2.1 Parking and boarding

The equipment that passengers first encounter when boarding a plane is already powered by an electrical power source on the ground, which allows the air conditioning to be run to maintain a comfortable environment inside the cabin.

Conventional aircraft use an Air Cycle System (ACS) that provides air conditioning by changing high-temperature and high-pressure compressed air from the engine or Auxiliary Power Unit (APU) into cool air with a heat exchanger and turbine/compressor. **Figure 2** illustrates the Air Cycle System.

In the latest MEA, the Boeing 787, outside air is compressed directly with an electric motor-driven compressor and supplied to the ACS, but since compression and expansion must also be conducted on the ground where the air pressure is high, neither system can achieve a high energy efficiency because of the need to pump heat out.

In an AEA, a vapor cycle system that works as a heat pump using the latent heat of vaporization promises to solve this problem, and since the Coefficient of Performance (COP) is approximately three times that of an ACS, the energy-saving potential is high. Currently, the challenge is

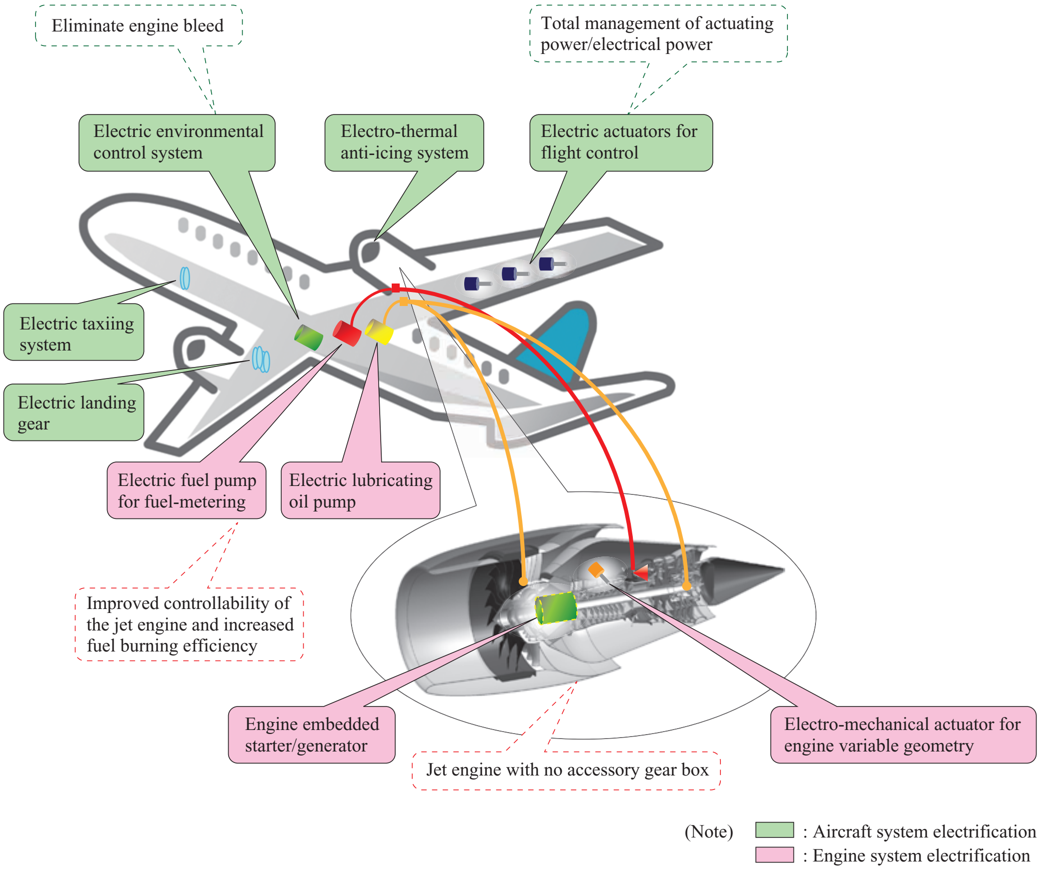


Fig. 1 Overview of the All-Electric Aircraft system

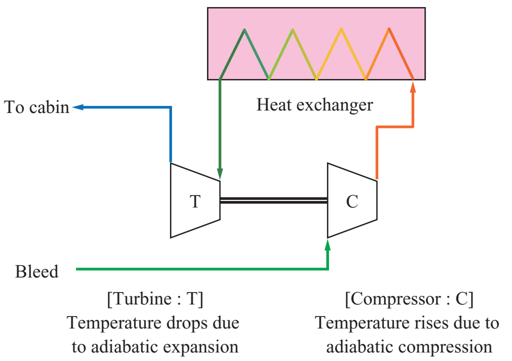


Fig. 2 Outline of air-conditioning using ACS

to switch to alternative Freon refrigerants with low global warming potential, and reduce the size and weight of the system.

2.2 Departure and taxiing

Once passengers finish boarding and pre-flight preparations are completed, the aircraft heads to the runway. Aircraft that disengage from a boarding bridge must back up in almost all cases, but since engine thrust is the only available means of locomotion, the aircraft is ordinarily pushed back with a towing car. Afterwards, the aircraft taxis to the runway, but since the aircraft advances with engine thrust during this time, in a busy airport the engine experiences repeated acceleration and deceleration.

In order to minimize unnecessary engine fuel consumption during this pushback and taxiing, electric taxiing enabling the aircraft to travel autonomously is being researched, and electric systems and mechanisms are being investigated including their structural safety and reliability. Electric taxiing is expected to yield even greater efficiency in the future thanks to fuel cells, and the realization of an on-board fuel cell system is being actively pursued.

< Regenerative Fuel Cell system >

Regenerative Fuel Cells (RFCs)[(2), (3)] hold promise as a way to apply fuel cells to AEAs. **Figure 3** illustrates an on-board RFC being installed into a Boeing 737. An RFC is an energy storage system made up of a fuel

(Image credit: Boeing)

Fig. 3 On-board RFC installed into Boeing 737 for test flight cell, an electrolyzer and a fuel tank. In this system, power is generated with the fuel cell when electric power is required, and when there is surplus power in the system, water generated by the fuel cell is regenerated (charged) by the electrolyzer to become fuel gas (hydrogen, oxygen) for the fuel cell. This system makes for a steadier power supply, resulting in a more efficient electric power system. **Figure 4** illustrates an RFC charge/discharge cycle.

As far as the general application of fuel cell systems is concerned, fuel reforming from jet fuel is being researched, but there are issues such as the need to maintain a high temperature for reforming as well as poisoning by carbon monoxide and other substances produced during fuel reforming. Additionally, when attempting to use pure hydrogen as fuel, the handling and maintenance of the high pressure hydrogen storage tank and ground-based infrastructure is challenging. As a potential solution, generating fuel from water with an RFC is advantageous as carbon monoxide is not produced, and no special infrastructure is required.

When this system is put into operation, pre-takeoff taxiing is conducted using hydrogen generated by ground electrical power, and hydrogen equal to the spent power is regenerated at high altitude with electric power from the engine generator. After landing, taxiing is conducted using the regenerated hydrogen. Another feature of an RFC is the fact that the charge terminal and the discharge terminal are mutually electrically insulated, enabling usage scenarios that are not possible with other types fuel cells, such as simultaneous charge and discharge while maintaining its insulation. For this reason RFC has the potential to be used as an uninterruptible power system. Furthermore, the emergency stop of fuel cell electrical power generation during an emergency is a safety feature not found in conventional batteries used as an aviation electrical power source. With these characteristics, RFCs also have the potential to be utilized as an emergency electrical power source.(4)

2.3 Takeoff and ascent

An aircraft heading to the runway by electric taxiing starts its engines several minutes before takeoff. The engine reaches its maximum engine speed during takeoff. Power

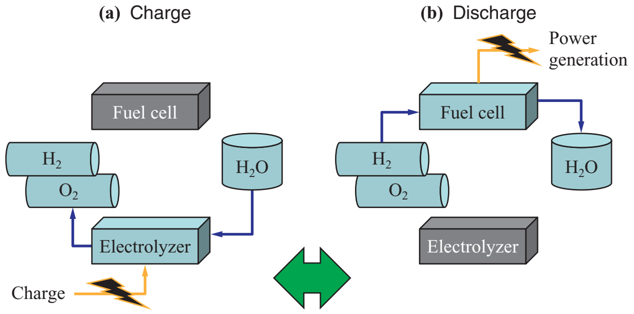


Fig. 4 Charge and discharge behavior of on-board RFC

consumption also reaches a maximum as the electrified aircraft simultaneously conducts the work of the high lift system (flaps and slats) and stows the landing gear using electro-mechanical actuators, prevents icing on the leading wing edges and engine inlets with the electro-thermal anti-icing system, activates the galley and other service equipment for the passengers, and runs the compressor to pressurize the cabin as the air pressure drops. In this situation, electrical load management (peak shift) is expected by using components such as the RFC.

Furthermore, a power source for attitude control repeatedly supplies and regenerates electrical power for the operation of the electro-mechanical actuators used for attitude control. Since the electric motor also functions as an electric generator, power generation and energy regeneration are conducted depending on load conditions. Energy regeneration sends current back to the power source, causing sudden voltage spikes to occur. With an electric train, such voltage spikes can be managed by sending them back into the overhead line, while in an electric vehicle or a hybrid vehicle, the on-board rechargeable battery or capacitor is charged or made to accumulate electricity, so voltage spikes do not particularly pose a problem.

However, in an aircraft, since electrical power is directly supplied by a generator, high-capacity rechargeable batteries or capacitors are not typically installed on board. For this reason, it is challenging to manage the regenerative current produced during deceleration while still ensuring the acceleration current required by the flight control actuators.

In conventional designs, the electrical power regenerated by electro-mechanical actuators is converted into heat by resistors installed specifically for this purpose, and the heat in turn is dissipated by a cooling device. The consequent heavy weight is a problem. One potential solution is a method that uses regenerated power to support the engine rotation via a starter generator.(5)

< Regenerated power absorption by engine >

In this system, a permanent magnet generator is used instead of the conventional electromagnet field winding generator, thereby causing it to easily and instantaneously function as an electric motor through the use of an inverter and to regenerate energy in the engine. This system also functions as an electric starter. This design of returning regenerated power back to the engine is superior as an aircraft system from a weight and cost perspective as no additional equipment is required.

2.4 Cruising

At an altitude of approximately 40 000 ft (approximately 12 000 m), the aircraft cruises on engine thrust balanced against air resistance. For long-distance flights, reduced fuel consumption during this period is particularly desired, and methods of reducing fuel consumption include reducing air resistance with Active Laminar Flow Control (ALFC), and improving system efficiency with an electric fuel system.

< Electric Active Laminar Flow Control system >

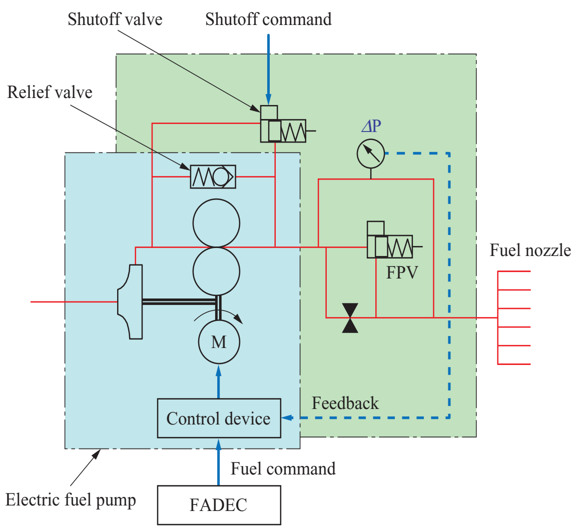
ALFC has been researched for many years as a method of reducing air resistance, and there exists both research and proven examples of laminar flow control on the main wing surface for the purpose of reducing resistance via the suction of laminar flow from the wing surface. Since the main wing has the function of producing lift and laminar flow control potentially exerts both good and bad effects, we thought the compound interference effect would be less for the vertical stabilizer, and conducted an investigation into the possibility of a distributed, highly efficient electric ALFC system in the vertical stabilizer using compact high-speed electric compressor technology.

For example, assuming a single-aisle passenger airplane, the mass flow rate of suctioned air for which a fuel consumption decrease of 1% may be expected is approximately 0.3 kg/s at 40 000 ft.[6] Assuming that 15 compact, 2 kW electric compressors are installed, this flow rate may be realized with a total weight of approximately 30 kg, and a required power output of approximately 45 kW.

< Electric fuel system >

An electric fuel system is a key technology in MEEs. In an electric fuel system, a geared fuel pump is driven by an electric motor, and since the fuel flow rate required by the engine is controlled by the motor speed, the circulation of surplus fuel in the conventional system is eliminated, enabling a reduction in engine power extraction.[7] **Figure 5** illustrates an electric fuel system. Preliminary calculation results of a better fuel consumption rate due to fuel system efficiency improvements for a small engine indicate an improvement of approximately 1% during cruising.[8]

The present system features a fuel metering function realized by rotational speed control of the electric fuel pump. In order to achieve high metering accuracy equal to a conventional metering system using a metering valve, a system that feeds back the flow rate from the pressure differential before and after a fuel pressurizing valve downstream of the pump is being developed. In addition, since the electric fuel pump is required to supply fuel in a rotational speed range that is much lower than that of a conventional fuel pump driven by an accessory gearbox, IHI aims to realize a single shaft pump that coaxially drives a low-pressure centrifugal pump and a high-pressure gear pump in this range, while also enabling miniaturization and simplification.[9]



(Note) FPV : Fuel pressurization valve
M : Electric motor
ΔP : Differential pressure gauge

Fig. 5 Schematic of electrical fuel system

With MEEs, the electrification of the engine fuel pump increases the degree of freedom in placing and outfitting the fuel pump, while AEA makes integration of the electric fuel system with the aircraft fuel system possible.[10] In addition to the reduction of fuel consumption through the system efficiency improvements brought about by electrification, the integrated aircraft electric fuel system also makes it possible to reduce the number of pieces of equipment within the fuel system. It is believed that elimination of equipment installed inside a conventional fuel tank, improvement of serviceability brought about by unitizing the electric fuel pump and cutoff valve, and reduction of pilot workload by making selector valve operations unnecessary, will all become possible.

Furthermore, since it is possible to use two electric fuel pumps to supply the maximum fuel flow rate for the engine during takeoff and then supply the required fuel flow rate with one electric fuel pump during cruising, it becomes possible to create a kind of redundancy that has been difficult to implement in conventional systems, which, if realized, would contribute to improved reliability and safety.

2.5 Descent

An aircraft approaching its destination lowers its altitude and prepares for landing. During descent, the engine rotational speed and thrust both lower, and thus the power generating performance of the engine generator also lowers. Meanwhile, the air conditioning and pressurization devices, which are the largest consumers of electricity, continue their work in a high load state, and anti-icing devices are also activated. At this point, the high lift system is also activated, and attitude control is crucial. As the engine thrust lowers and a higher proportion of the engine output becomes taken up by power extraction, the effects of power extraction on engine operation become greater. Integrated management of the engine and electrical power generation is a means of addressing the effects of increased electrical power generation on engine operation.

< Integrated management of engine and power generation >

If the generator running on the high-pressure shaft of the engine increases its power output, the power extracted from the high-pressure shaft increases, thereby lowering the rotational speed of the high-pressure shaft. At this point, in the case of ordinary control where the fan speed is kept constant, the supply of fuel is increased to maintain the fan speed and not let it drop as a result of the lowered rotational speed of the high-pressure shaft. However, since the rotational speed of the high-pressure shaft lowers, this leads to a situation where it is difficult for air to flow from the low-pressure compressor to the high-pressure compressor, decreasing the surge margin of the low-pressure compressor. If the low-pressure shaft is substituted for the high-pressure shaft as the shaft from which to extract power for electricity generation, the low pressure compressor operating line also moves with the amount of power extracted, and the direction of movement is opposite to that of high-pressure compressor extraction. With the increase in power extraction, the low-pressure compressor operating line moves away from the surge line, increasing the surge margin. However, a generator attached to the low-pressure shaft only has access to approximately 40% of the cruising engine speed during descent and idling, which means that the generator must be designed to be capable of supplying the necessary electrical power under such conditions. Also, if a starter generator is used, starting the engine requires the starter generator to turn the engine shaft and deliver compressed air to the combustion chamber with the starter function, but this becomes more difficult on the low-pressure shaft.

The solution to this system design issue is an electrical power generating system that extracts power from both the high-pressure shaft and the low-pressure shaft. With such a system, it becomes important to attempt to optimize electricity generation via management.(5) This system places inverters for adjusting the electrical power on the load side of each HP-spool generator and LP-spool generator, and controls the share of electrical power generation for each of them such that the inverters ensure that the surge margin of the engine is at least a certain level.(11)

2.6 Approach

The final approach demands the most delicate attitude and speed control. If full aircraft electrification is achieved, hydraulic and pneumatic pipes and mechanical mechanisms for energy supply would become unnecessary, and the improved layout and arrangement of energy distribution devices, which are electrification's strong point, would be easy. The resulting increase in the degree of design freedom would allow for easier system redundancy and diversification, making it possible to improve aircraft reliability and safety.

Furthermore, we believe that more stable and safer flights could be made possible by taking advantage of the electrification and constructing an integrated control system. Using this system to control the velocity vector of the aircraft, the effects of turbulence could be reduced and it could be used as an alternative means of flight control in the event of equipment failure.

One challenge to realizing these goals lies in improving the reliability of electro-mechanical actuators. Another challenge for safer systems lies in the integration of engine control and flight control.

< Improving electro-mechanical actuator reliability >

Electro-mechanical actuators are the most crucial component for providing control, and anti-jamming measures are the issue that must be overcome. The velocity summing method was selected as the redundancy mechanism for avoiding jamming in electro-mechanical actuators, and linear actuator ball screw velocity summing methods are being researched. By reversing the rotational method of the ball screw lead and nut to conduct rotary/linear conversion, the resulting method is simple and highly reliable, without having to use the differential gears used as a conventional velocity summing mechanism, and in addition, the effects of the gears jamming are completely avoided or isolated.

Also, for the control method of the free rotating mode of a motor, which is a problem with the velocity summing method, we are proving that it is possible to use velocity summing actuator control maintained with regenerative braking instead of using a typical mechanical braking method and are developing technologies such as automatic jamming diagnosis and gain control.(12)

< Integrated thrust flight control >

Methods of controlling aircraft attitude via thrust control during an emergency have been researched in the past, but improving engine thrust response has been challenging. Such high responsiveness could be obtained by increasing acceleration or deceleration rates, however in doing so, it is absolutely necessary that the surge and blowout margins, the allowable temperature, and the speed limits of the engine not be exceeded.

Ndot control is one of the control methods used in civil aircraft engines using FADEC (Full Authority Digital Engine Control). Ndot control reduces the thermal stress produced in high-temperature section components by controlling the engine acceleration and deceleration times, and in addition, equalizes the acceleration and deceleration across multiple engines, regardless of inconsistencies or degradation in their respective engine performance.

Ndot contributes to reducing operating costs and maintenance costs in this way, and now a technique is being considered in which acceleration/deceleration schedule control using the fuel-air ratio is applied to raise engine thrust responsiveness by making the acceleration and deceleration of the engine speed as fast as possible while keeping it within a range safe from surges or blowouts.(13) On the other hand, depending on the inconsistencies in engine performance or the degree of degradation, inconsistencies in the rate of temperature increase in high-temperature sections and the rate of engine speed increase may occur, and for this reason, care must be taken to select acceleration/deceleration schedule control only in an emergency, and even then maximally increase engine responsiveness while monitoring factors such as the temperature and engine speed. In other words, the aircraft control system and the electric fuel system must be coupled to provide engine control in accordance with the aircraft state. Electrification systems that aim to integrate flight control and engine control are expected to contribute to aircraft safety improvements by making such control an actuality.

2.7 Landing and taxiing

After landing, the aircraft decelerates with electrical thrust reversers and electrical brakes, and then heads to the terminal. Once again, electric taxiing is conducted without using the engine. Effective utilization of regenerated power by deceleration and acceleration during electric taxiing is anticipated. In order to realize such utilization, an accumulator function that accumulates electrical energy becomes necessary.

< Aircraft power accumulator >

Since aircraft power accumulators accumulate energy in severe temperature environments, the use of flywheel batteries is being investigated. A flywheel battery converts electrical energy into rotational energy, and energy accumulates by keeping the flywheel spinning. Compared to rechargeable batteries or capacitors, which have problematic lifetime and temperature characteristics due to chemical reactions, constructing an accumulator entirely with mechanical and electrical components provides long life and minimal maintenance.

Flywheel batteries are structurally resistant to the effects of temperature changes, and are thus usable over a wide range of temperatures. Weight and structure do pose engineering challenges, but composite rotors are becoming more widespread, and by adopting high-speed rotors, flywheel batteries are becoming more compact. In our system, which will supply energy for 10 s at an input/output of over 130 kW, is provisionally calculated to have a main body weight of approximately 55 kg.[(3)]

2.8 Arrival and maintenance

When the aircraft stops and a ground electrical line is connected to the arriving aircraft, the on-board power source is switched over to the ground power source, and the seatbelt sign turns off. The boarding bridge or ramp preparations are completed, and when the doors open, passengers disembark and are guided to the terminal. The aircraft then begins the preparations for the next safety flight.

One advantageous effect of electrification for maintenance work is that since hydraulic piping is exchanged for wiring (pipeless), improvements in serviceability are anticipated. Furthermore, electrification is also promising from the perspective of reducing substances of concern. For the hydraulic oil in hydraulic pressure systems, synthetic oils containing organophosphates are used because of their excellent physiochemical stability over a wide range of temperatures (−54°C to +135°C), resistance to fire, light weight, noncorrosiveness, and lubricating ability. However, such synthetic oils are also irritants.

For refrigerants, long-life coolants such as ethylene glycol and propylene glycol are being used. Propylene glycol is also used in cosmetics and is advantageous for its low toxicity, but is generally known to become aluminum-corrosive depending on the additives. For this reason, ample protection and safeguards to eliminate environmental effects are required during operation and maintenance. In order to solve these issues and raise serviceability, the challenge lies in eliminating hydraulic pressure systems in favor of an all-electric system, and switching to fluid-less designs by creating an air-cooled system.

< Autonomous distributed air cooling system >

In electrified aircraft as exemplified by the Boeing 787, heat generation is concentrated around the large electric motor controller, and thus a liquid cooling system using a refrigerant liquid is provided in order to carry away that heat. In other words, even if electrification is realized, pipeless and fluid-less designs cannot be attained unless fluids are eliminated from the cooling system. Attaining pipeless and fluid-less designs requires air cooling of electrical equipment, and the realization of an autonomous distributed air cooling system applying compact electric blowers is anticipated for this purpose.

3. Conclusion

An overview of the research related to All-Electric Aircraft and engine systems, as well as the technological features and challenges thereof, have been discussed primarily in terms of IHI's advanced technology efforts indicated below.

- Although the electrification of aircraft around the world today has mainly progressed by electrifying accessories, future challenges lie in propulsion, control, and power system integration. Integrated management of engine and electric power generation, regenerated power absorption by the engine, and integrated thrust flight control are the system concepts addressing these challenges.
- Realizing these system concepts will require new technology innovations. Regenerative Fuel Cell systems, electric fuel systems, aircraft power accumulators, and reliability improvements in electric actuators are examples of such crucial technology innovations, and their research and development is progressing.
- Electric Active Laminar Flow Control systems for contributing to further reductions in fuel consumption, and autonomous distributed air cooling systems for achieving serviceability improvements and reductions in substances of concern are also being considered.

The electrification of aircraft makes it possible to attain the global and societal demands for improved safety, environmental friendliness, and cost effectiveness, and holds promise as a next-generation aircraft system that will help to realize aircraft that are both people-friendly as well as environment-friendly. IHI is contributing its own technologies to the electrification of the world's aircraft, with a primary focus on engine electrification systems.

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