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Environmentally Friendly Structures and Promising Technologies in Hybrid Electric Aircraft

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Abstract. With the development of aircraft, the demand for energy-efficient and environmentally friendly aircraft is increasing. In this work, environmentally friendly structures and promising technologies in hybrid electric aircraft will be discussed, which include power system, thermal management, weight and structural design, ecology and environment and business model. To deal with the primary limitation----mass, some new components fabricated in composite materials can be considered to for use the body of the aircraft. Also, details such as the battery's model, material, lifespan, safety and endurance will be mentioned in this paper. As a result, carbon emissions and resource consumption are reduced significantly. However, basic infrastructures like maintenance and support measures still need to be improved.

Keywords: Hybrid Electric Aircraft, Energy-Efficient, Environmentally Friendly

1. Introduction

Since the 20th century, aircraft propulsion has evolved from piston engines to turbofans, enabling faster and longer-range flight but relying heavily on fossil fuels—it may cause energy scarcity and environmental pollution, such as overproduction of carbon dioxide and other toxic gases. Additionally, traditional propulsion systems face issues like complex mechanical structures, high maintenance costs, and noise pollution, limiting their application in urban air mobility and causing long-term environmental harm.

Against this drawback, electric propulsion aircraft (EPA) have emerged as a sustainable alternative, leveraging electric motors for lower emissions and simpler maintenance. However, EPAs confront critical challenges: the density of the engine is too high, which may increase significantly of aircraft's air weight; this may cause shaking when flying and may reduce the travelling comfort of the passengers.

To address these issues, our study mainly focuses on the structure of these core directions: energy control. This article may talk about the distribution of the energy in the engine and give some possible solutions on the recycling system of the aircraft. It will also mention that the heat management such as some thermal design. Then it will talk about the design on the structure of the

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aircraft to reduce the weight and increase the rigidity of the material. Then will mention the environmental problem to society and give some possible solutions.

2. Power systems

2.1. Energy management

Energy management strategy and energy recovery system will be discussed in this section. Energy management is important for the aircraft as it can reduce the mass and toxic emissions efficiently. Based on Control Architecture Complexity, this section will introduce Rule-based, Hierarchical MPC, Uncertainty MPC(CC-SMPC) and Multi-objective optimization.

2.1.1. Rule-based

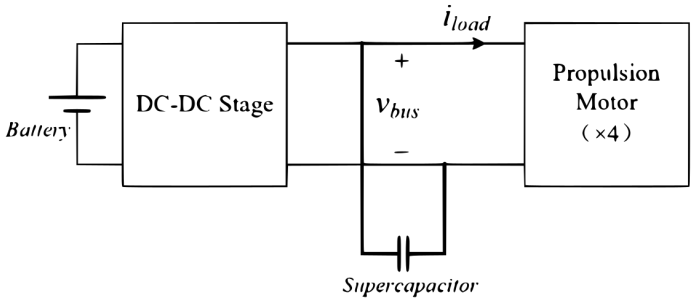


Figure 1. Schematic of the hybrid energy storage system (HESS) combining battery and supercapacitor [Xiang.Li et al./IFAC Papers Online 58-29(2024)31-36]

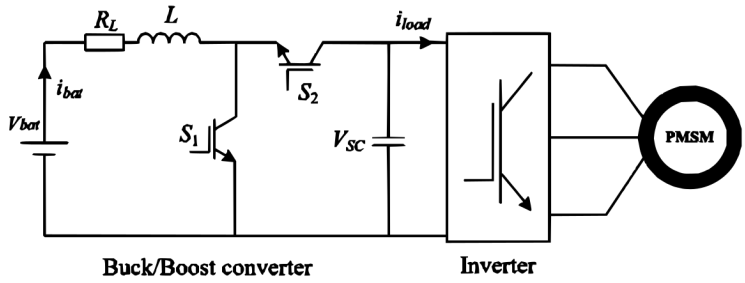


Figure 2. Equivalent circuit illustration of the HESS [Xiang.Li et al./IFAC Papers Online 58-29(2024)31-36]

The core of the lowest complexity is Rule-based, which has a low hierarchical structure, simple algorithm type, and few decision variables. Based on preset "hard rules" (if-else logic) or "finite state machines (FSM)", power distribution is realized through fixed thresholds (such as SOC ranges, load priorities) without the need for dynamic optimization calculations. Rule-based control is applicable to hybrid Energy Storage System(HESS) in electric aircraft, as Figures 1 and 2, more electric aircraft(MEA), more electric vehicles(MEV), and the terrestrial power grid. To be more precise, for HESS, when matched with a Finite-Control-Set MPC(FCS-MPC), optimizing the controller's sampling time Ts2, which means the computational burden will be reduced a lot, and improve the efficiency of the controller strategy greatly. As noted in [1], the power and current

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fluctuation of the battery in rule-based EMS are more obvious than those under advanced EMS, while advanced EMS can stabilize the power fluctuations of supercapacitors and avoid significant changes caused by load power variations. However, as we point out in [2], Rule-based is solely based on the current and the past information of the system and not able to forecast the possible adventure in the future.

2.1.2. Hierarchical MPC

Compared to Rule-based, Hierarchical MPC can consider the changes of the system in the future. MPC-based controller addresses an online optimization problem. It is able to analyse the optimal strategy according to the desired performance and the system constraints. For instance, the majority of the generator's output is allocated to two key purposes: supplying power to loads and charging the batteries. MPC-based controller reduces the total power output from the generator, which means a significant reduction in fuel consumption [2]. In [2], the work does not apply the concept of Hierarchical MPC directly, but it implicitly embodies the typical Hierarchical MPC logic. Hierarchical MPC has greater dynamic adaptability than Rule-based. As the former section mentioned, a Rule-based controller has fixed thresholds so that it does not require any complex calculation [1]. But for Hierarchical MPC, it determines the load shedding scheme on the low voltage(LV) and calculates the power reference values; second, it computes the power deviation between the recommended available input power on the high voltage(HV) side. Finally, considering the configuration of the Electric Power System (EPS) and the recommended power references, it calculates the remaining power capacity from battery cells to the LV bus [2].

2.1.3. CC-SMPC

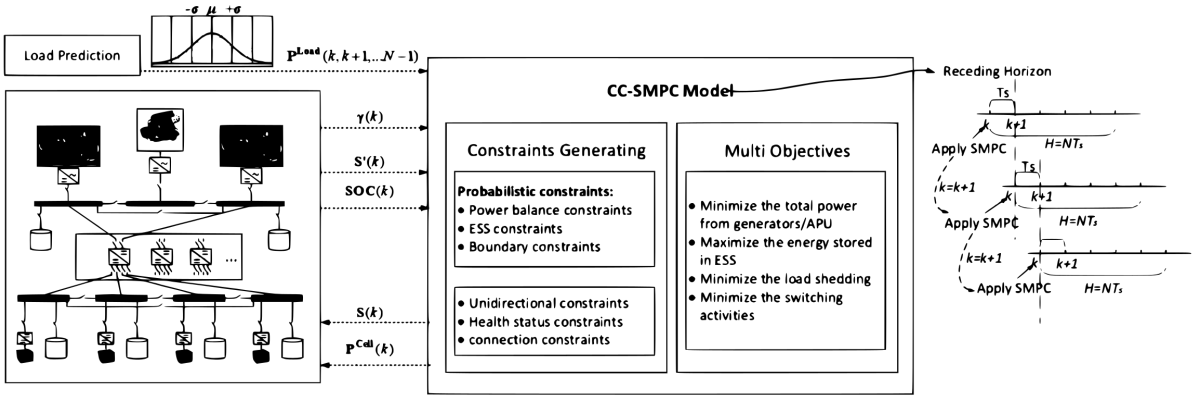


Figure 3. Online CC-SMPC optimization framework: flowchart [Xin.Wang et al. Journal of Energy Storage 55 (2022) 105629]

Load uncertainty and risk of component failure are two main problems for the electricity power system(EPS) of the more electric aircraft(MEA). The load power fluctuations of the high voltage(HV) and low voltage(LV) are modeled as Gaussian PDFs because, to counteract uncertainties, both generators and the APU are set to run in voltage control mode. Since generators and APU have uncertain power output, the deterministic boundary constraints for their power limitations need to be replaced with the two probabilistic constraints. The objective function of HL simultaneously minimizes total power from the generator to reduce the fuel consumption, the load

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shedding to ensure the power supply and minimizes the switching activities to extend component lifespan [3]. The detailed process is shown as Figure 3.

2.1.4. Multi-objective optimization(NSGA-II)

The EMS layer employs Non-dominated Sorting Genetic Algorithm II(NSGA-II) aims to solve the global optimal energy allocation strategy for Hybrid Electric Aircraft(HEA) with the goal of "minimizing the fuel consumption and total energy consumption", so as to balance multi-objective conflicts. These solutions cover a continuous performance spectrum: at one end(defined as S1), which has minimum energy consumption. At the other end(defined as S5) which has a minimum block fuel burn. For short-range missions with a flight range of 1000nmi, S5 solution achieves a 19.36% reduction in block fuel burn with a 7.83% increasing in energy cost. The scheme has been implemented in a standard narrow-body aircraft, which has a mechanically integrated hybrid electric parallel propulsion configuration [4].

2.2. Energy recovery system

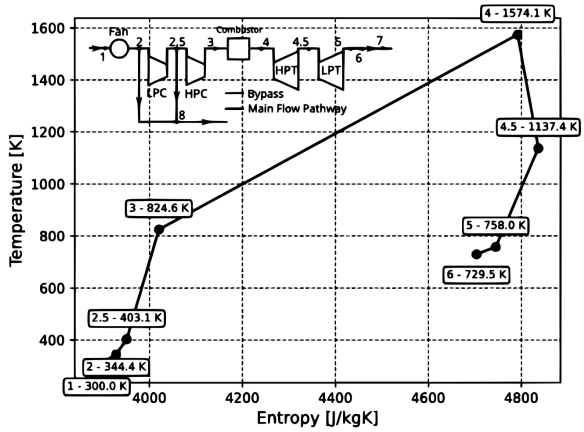


Figure 4. Stagnation Parameters of the main flow path for engine 1 under ground conditions: T-s and schematic diagrams [L. Vesely et al. International Journal of Thermo2uids 24 (2024) 100798]

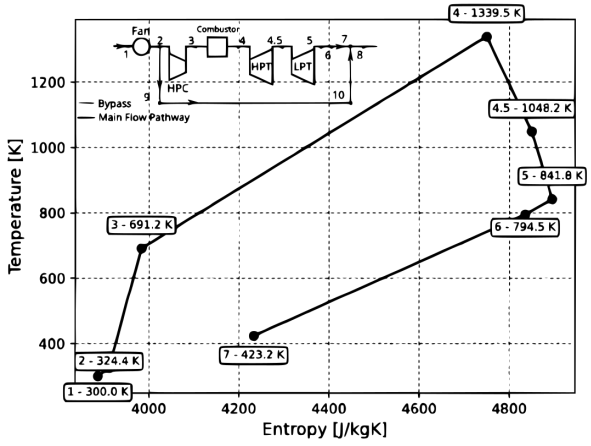


Figure 5.Agnation parameters of the main flow path for engine 2 in ground regime: T-s and schematic diagrams[L. Vesely et al. International Journal of Thermo2uids 24 (2024) 100798]

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The aim of the Energy Recovery System is to be eco-friendly. The emissions from the aviation industry occupy 4% of the total artificial emissions. Notably, only 40% of the energy in an aircraft is useful to support the power system, and the rest of the energy will be wasted in forms like heating. In other words, they face two main issues: they demand excessive installation space and add significant weight to the aircraft. The Organic Rankine Cycle (ORC)is one kind of power cycle, but even with various working mediums, it still has limited operating regimes. However, the supercritical carbon dioxide (sCO2) power cycle can be used in all operating regimes by using another type of working medium. Supercritical carbon dioxide (sCO2) waste heat recovery (WHR) systems exhibit a high degree of compactness, primarily attributed to the elevated density of sCO2 as the working fluid. The key advantage of these systems lies in their adaptability to fluctuations in turbine and compressor inlet temperatures, a characteristic that significantly enhances the net power a lot. As shown in Figures 4 and 5, the sCO2 Brayton cycle is suitable for the power levels of typical commercial aircraft. sCO2 WHR systems can be configured through various cycle layouts. Common layouts include the Simple Brayton cycle, the Recuperated cycle (RC), and the Recompression cycle (RCC). Regardless of the specific layout, each system comprises core components: a compressor(C), a turbine(T), a Cooler and a primary heat exchanger(PHX). However, for each aircraft, the system should consider the available space. In terms of thermodynamic modeling, the simulations and resulting data in this study are based on a centralized WHR configuration. The primary optimization constraints include reducing the WHR compressor inlet temperature(engine air stream temperature) and the temperature gap between the exhausted gas and the inlet temperatures of the sCO2 turbine. The turbomachinery efficiencies and recuperator effectiveness are fixed in the work, but for reality, these two will vary depending on the operating conditions and the sCO2 mass flow rate. In practical application, the sCO2 WHR unit demonstrates the capability to convert waste heat from aircraft engine exhaust streams into usable net power. For engine 1, the sCO2 WHR cycle thermal efficiency ranges from 25% for RC to 34% for RCC. And that for engine 2 are 31% and 39% respectively, which means the total emissions are reduced [5].

2.3. Electric drive system

In this section, the questions about "how to improve the battery endurance capability" will be discussed so that structural batteries, high energy density batteries will be introduced. And this section will also provide Hybrid Mode Optimization, which is about energy management strategy.

2.3.1. Battery endurance capability

Whatever kinds of batteries are used in the aircraft, the aircraft will be affected by the extra mass of the batteries, depending on traditional electric storage methods. As the Figure 6, extra mass from the batteries will increase the take-off weight of the aircraft. To address this problem, a novel solution emerges in the form of structural batteries: multifunctional structures that seamlessly integrate electrical energy storage capabilities with load-bearing functionality, eliminating the need for separate, weight-adding battery packs. For example, the maximum take-off weight of the aircraft is about 3710kg, the estimated fuel consumption to fulfil the design task is about 588kg, and the structural mass which is based on an all-aluminium alloy structure, is about 1122.5kg. The mass of the wing and the fuselage should be focused mostly in that they will serve as the structural batteries' vessels. This may reduce the extra mass of the batteries and improve the fuel efficiency [6]. The solid oxide fuel cell-gas turbine(SOFC-GT) is a hybrid system with high electrical efficiency. The system focuses more on thermodynamic performance and mass. By comparing the materials of the

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fuel(hydrogen, ethanol, alkanes), methane offers the best hydrogen production performance, maximizing SOFC efficiency. However, the SOFC-GT system will be affected by various factors. When it comes to non-hydrogen fuel options, n-decane stands out for its ability to deliver higher electrical efficiency, whereas methane offers the advantage of lower fuel consumption—each fuel thus presents distinct performance strengths. In the context of SOFC-GT (Solid Oxide Fuel Cell-Gas Turbine) aircraft, those powered by n-decane or n-octane demonstrate superior endurance compared to counterparts using other non-hydrogen fuels. Notably, integrating n-decane with the high-efficiency SOFC-GT hybrid system creates a synergistic effect: this combination not only leverages the fuel's electrical efficiency potential but also capitalizes on the hybrid system's energy utilization capabilities, ultimately leading to a significant reduction in carbon dioxide (CO_2) emissions [6].

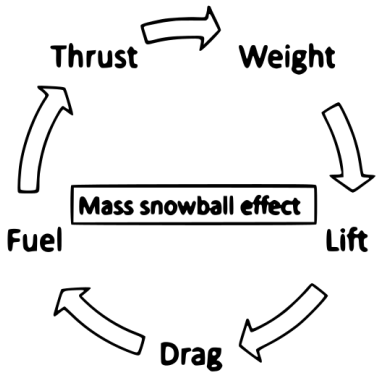


Figure 6. A diagram illustrating the snowball effect that impacts aircraft weight [Gennaro Di Mauro et al. Journal of Materials Engineering and Performance Volume 32(9) May 2023]

2.3.2. Hybrid mode optimization

In this section, the energy management strategies will be mentioned again, but for the electric drive system this time. As the Figure 7, it applies a new algorithm to extend the energy distribution and balance(EEDB), which considers the restriction of mass. The strategies of EEDB include night charging and fast charging during aircraft stops with series-hybrid power. There is no mechanical connection between the internal combustion engine and the propeller shaft, allowing the internal combustion engine to operate at its optimal working condition during all flight phases, thereby significantly reducing fuel consumption. Additionally, the structure is simple, and the internal combustion engine has higher flexibility in positioning. This is suitable for "short time, high power" energy demand. For example, an aircraft company called OFD, which is running the airlines between the islands of North Germany. The distances are short, but the interval between the two flights is also short. EEDB can improve the efficiency significantly. As for the electric motor, by considering the commercially off-the-shelf product and the ability to satisfy the baseline engine of 225KW or more, the series of CTSM242 motors have great robustness and high performance. This kind of motor has a 250 kW maximum power output with only 30kg mass, which is an ideal choice for the hybrid power system. Lastly, the selection criteria for battery energy density is state-of-the-art lithium-ion batteries used in automobile applications [7].

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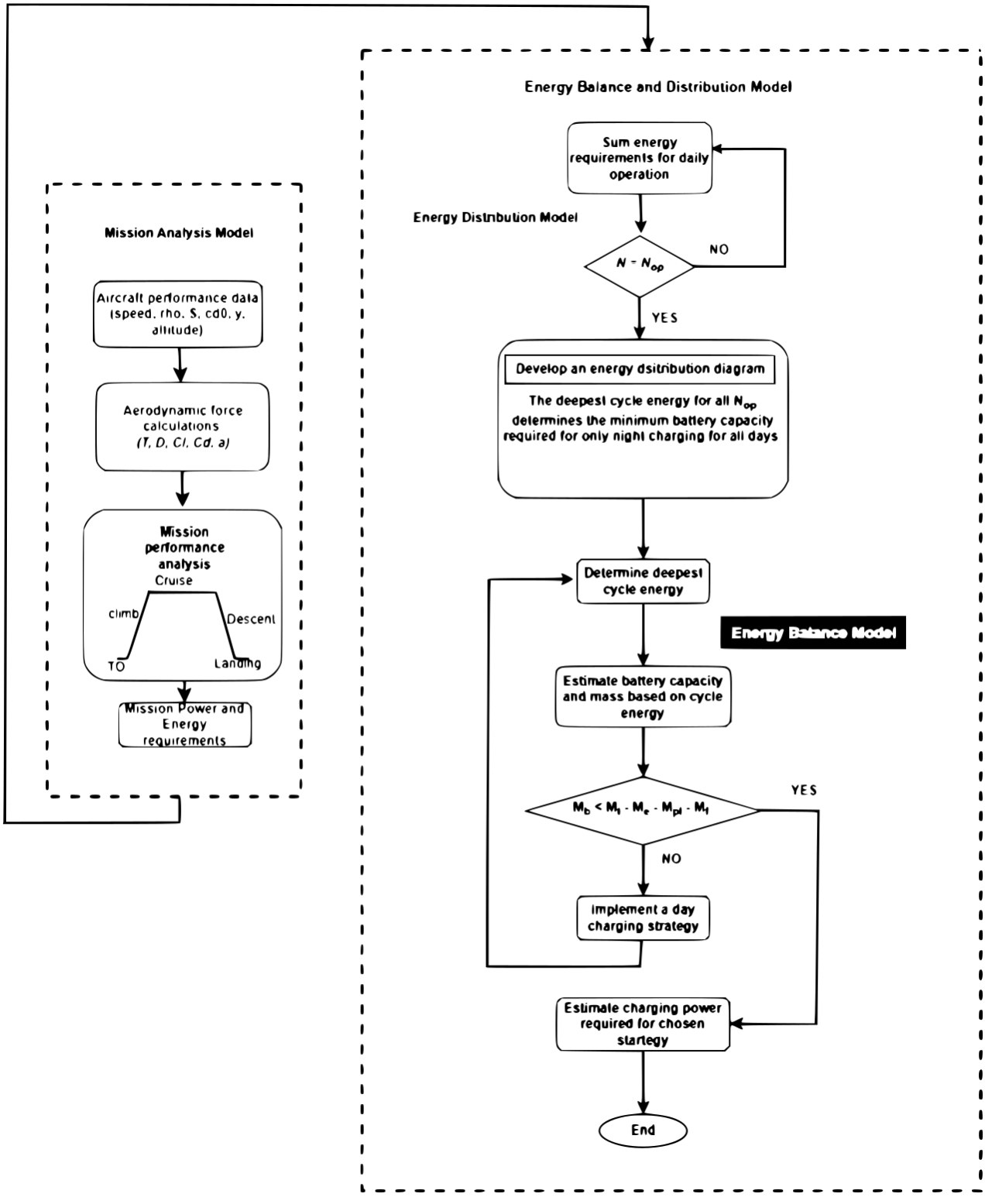


Figure 7. Simulation configuration implemented using the Extended Energy Balance and Distribution (EEBD) algorithm [B.A. Adu-Gyamfi et al. Transportation Engineering 21 (2025) 100380]

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3. Heat management

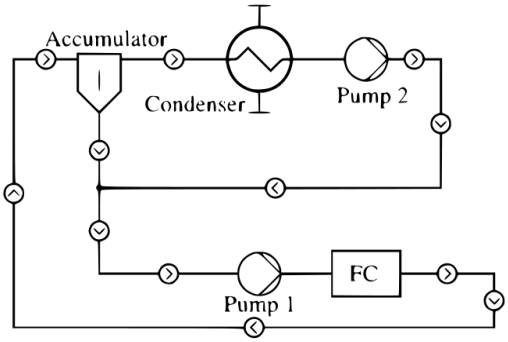


Figure 8. The "Baseline System"—a pumped two-phase cooling system that utilizes two pumps—with adaptation from Koschel et al. [J.F. Hellmuth et al.Applied Thermal Engineering xxx (xxxx) xxx]

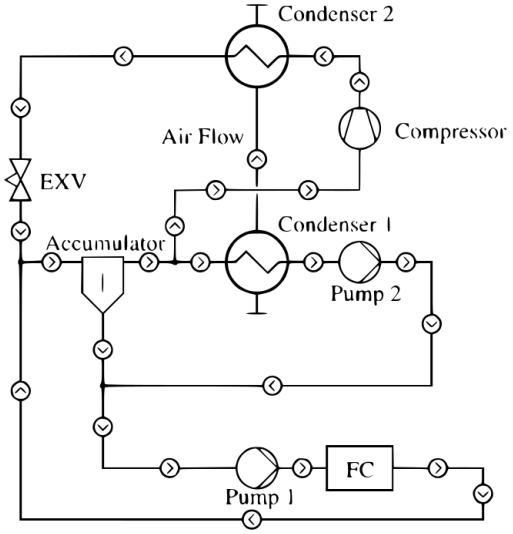


Figure 9. Pumped methanol circuit system, extended by high-temp refrigeration cycle (high-load cooling, higher-temp heat rejection in Condenser 2) [J.F. Hellmuth et al. Applied Thermal Engineering xxx (xxxx) xxx]

The battery supplies the required voltages and onboard avionics systems and provides propulsion energy to the electric motor so that heat management is very important for the aircraft to prevent thermal runaway [7]. In work [8], three operating modes are discussed. Under idle conditions, it can obtain a Lower Heating Value(LHV) of approximately 227W. Due to the frequent purging requirement of an anode, nearly 74% energy is wasted so the total efficiency is not ideal. During acceleration and climbing, the power output of the fuel cell power unit is close to its full-load capacity. The Lower Heating Value(LHV) of the hydrogen flow supplied is about 1197W, and the hydrogen utilization rate in the fuel cell exceeds 88%. The electric motor and electric controller have 74% efficiency and the propeller efficiency is 70%. However, the efficiency of the propeller is low because of the low speed of the aircraft and the low advance ratio. The total efficiency of the power system is only 14%. For the cruise mode, the propulsive power accounts for 84% of the maximum propulsive power. In the system of liquid hydrogen(LH2), modern integrated setups employ multi-

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layer insulation (MLI) and vapor-cooled shields tailored to different operational environments to minimize heat ingress. Additionally, Cryogenic compressed storage containers equipped with an integrated evaporation recovery system (including but not limited to heat exchangers) have been developed to enhance the operational efficiency of unmanned aerial vehicles, thereby achieving long-duration operation with minimal hydrogen consumption. Pressure swing adsorption technology further optimizes these systems — by regulating pressure fluctuations within storage containers, this technology helps reduce hydrogen loss [8].

In [9], the Baseline System has been mentioned, as Figure 8, this system comprises four key components: a fuel cell, a condenser block, an accumulator, and two dedicated pumps. The first pump (Pump 1) is installed upstream of the fuel cell, drawing liquid refrigerant from the reservoir and delivering it into the fuel cell. Within the fuel cell, the refrigerant absorbs the heat produced and undergoes partial evaporation. The speed of Pump 1 acts as the control variable, with the vapor quality at the fuel cell outlet(set to a fixed value 30%) serving as the regulated parameter. In the second branch, the second pump (Pump 2) is located downstream of the condenser. It extracts gaseous refrigerant from the reservoir, which then enters the condenser and is condensed into a liquid state. A critical control requirement for Pump 2 is to adjust the volume of refrigerant it delivers, ensuring that the condenser's outlet maintains a state of subcooling; this pump maintains a constant subcooling degree of 5K through control. The operating state of the system is shown in Figure 9. The advantages of this system are simple structures and the small required refrigerant mass flow rate. It can not only utilize the refrigerant's latent heat but also achieve a uniform temperature distribution throughout the entire fuel cell.

As Figure 9 shows, the extended system increases a high-temperature refrigeration process with a compressor based on the Baseline System. The compressor pulls in a portion of gaseous refrigerant, and they are compressed to a higher pressure level. The heat energy is dissipated into the surroundings by compressor 2. EXV makes the liquefied refrigerant expand to the lower pressure level and the refrigerant flows back to the accelerator, merging with that from the pumped circuit. The accumulator has a coupling. By doing so, the high-temperature refrigeration cycle effectively removes excess heat from the refrigerant, lowering the enthalpy of methanol (the refrigerant used) within the accumulator. This reduction in enthalpy not only enhances the cooling capacity of the refrigerant but also improves the overall energy efficiency of the cooling system— particularly under high-heat-load conditions such as aircraft takeoff.

4. Weight and structural design

The new energy aircraft design to reduce the weight by the advanced materials, first like carbon fiber components and aluminum-lithium. Both of them, compared to the classical mantel they have stronger rigidity and are lighter. In structure optimization techniques, such as topology optimization and additive manufacturing to let the craft have more strength and more stability [10]. However, it still faces some problems, the most significant is the expensive material in the cell. This will increase the cost of production significantly, and the weight also can not be ignored; the cell takes up a large amount of weight of 35 tons, which is also a challenge for aircraft to reduce it to make it easy to fly. implementing smart cooling systems, and leveraging AI-driven simulations for real-time optimization. Furthermore, because it has few real applications and the application in the aircraft filed. So we are now focusing more on the design to further enhance sustainability and performance to make it attachable.

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5. Ecological and environmental systems engineering

Sustainable developing solutions is combining ecological engineering with innovation. Concerned about the problem of carbon emission, hybrid-electric engine system such as Airbus E-Fan X) reduced CO2 by 40 percent, while sustainable aviation fuels (SAF) derived from algae can decrease the production of pollution up to 80%. Noise pollution through advanced engine designs like Rolls-Royce's UltraFan (to compare with the 1990s year, it has decreased 75% quieter) [11] and AI-optimized flight paths. Resource efficiency is stimulated by good real economy action, including Boeing using carbon fiber in 777X and Airbus's up to 10 percent [12]. Realization of 85% material recycling through PAMELA. Certification got to new technologies with FAA/EASA's Special Conditions, this strategy set by the company has the practicality of the whole economy and increases the sustainability systematically. In the near future, the propeller can be designed by more safety, such as hydrogen fuel and a hybrid system. Moreover, it can also combine with the Al to make it more attached. In the hand, the government can also make some regulations, such as setting the reward and level for the business. These significant problems should be supported by the whole society and put more effort into achieving this aim.

6. Discussion and results

This paper focuses on some new technologies for the hybrid-electric aircraft. Firstly, the Power System has been discussed. The four methods are Rule-based, Hierarchical MPC, CC-SMPC, and Multi-objective optimization(NSGA-II), respectively. Rule-based has simple logic and is easy to maintain. High response speed and low running costs are also its advantages. But it cannot deal with complicated conditions. Hierarchical MPC can efficiently handle large-scale or complex systems and flexibly adapt to multiple needs. The main drawback of it is the high difficulty in coordination between levels with complicated calculations. For CC-SMPC, it has distributed decision-making, reduces communication and computational pressure and robustly responds to random disturbances. But it highly depends on communication with weak anti-interference ability. As for NSGA-II, it can efficiently handle multiple conflicting objectives and has strong diversity of solutions and powerful global optimization capability. However, it has complicated calculations and poor real-time performance. The selection of Pareto solutions depends on the decision-maker's experience.

In heat management, heat dissipation design and high power demand is conflict. Stability and compatibility of Cooling Media need to be considered. Safety risks still exist in the batteries.

In weight and structural design, the balance between performance and the conflict between structural optimization and redundancy design are still problems that deserve to be solved in the future.

In business modes and infrastructure, the market demand is unknown and the running costs may be high. The modern aircraft keeps using fuel, so for the hybrid-electric aircraft, the energy supply and takeoff or landing support are insufficient.

As the demand for eco-friendly products increases quickly, the market size for the hybrid-electric will also increase. To run the whole airline system successfully, these problems need to be solved in the future.

7. Conclusion

Nowadays, the feasibility of implementation has been improved significantly. As the dependence and efficiency are improved. Many policies prefer to support the development of the electricity

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industry. Electric drive has moved from "technically feasible" to "engineering and commercially feasible". The goal of achieving full electrification of the aircraft is just around the corner.

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