Fuel Flowrate Control for Aeroengine and Fuel Thermal Management for Airborne System of Aircraft—An Overview

Dong Li ¹, Jie Hang ² , Yunhua Li ^{2,*} and Sujun Dong ¹

¹ School of Aeronautic Science and Engineering, Beihang University, 37 Xueyuan Road, Beijing 100191, China; ld890107@126.com (D.L.); dsj@buaa.edu.cn (S.D.)

² School of Automation Science and Electrical Engineering, Beihang University, 37 Xueyuan Road, Beijing 100191, China; hangyizhen@buaa.edu.cn

* Correspondence: yhli@buaa.edu.cn; Tel.: +86-010-82339038

Abstract: Fuel flowrate control system and fuel thermal management are very important for aero-engine and the overall aircraft, and it has been researched for several decades. This survey paper makes a comprehensive and systematic overview on the exiting fuel flowrate regulation methods, thermal load of fuel metering units, fuel-based thermal management, and the fuel tank's thermal management topology network with drain and recirculation. This paper firstly reviews the mechanism, technical advantages, and technical challenges of the fuel metering unit with flowrate control valve and constant pressure difference valve compensator, flowrate control valve and variable displacement pump-based pressure difference compensator, and motor-based flowrate regulation. Then, the technical characteristics of above fuel flowrate control methods related to thermal management are discussed and compared. Meanwhile, the behaviors of recirculated fuel flow within single tank system and dual tank system are explored. Thirdly, the paper discusses the future directions of fuel flowrate control and thermal management. The survey is significant to the fuel flowrate control and fuel thermal management of the aircraft.

Keywords: fuel flowrate control; metering control; motor-based flowrate control; heat sink; thermal management system

Citation: Li, D.; Hang, J.; Li, Y.; Dong, S. Fuel Flowrate Control for Aeroengine and Fuel Thermal Management for Airborne System of Aircraft—An Overview. *Appl. Sci.* **2022**, *12*, 279. <https://doi.org/10.3390/app12010279>

Academic Editors: Mathijs de Weerd and Kambiz Vafai

Received: 21 November 2021

Accepted: 23 December 2021

Published: 28 December 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Aeroengine is the power and heart of the aircraft. Fuel is used as fuel for aeroengine to produce the power of aircraft flight and heat sink to absorb thermal load in aircraft airborne system, and fuel flowrate control and fuel thermal management are always the key technologies of the aircraft. Therefore, to overview the relative technology status and development are very important. This section briefly presents the related technologies to fuel flowrate control and fuel thermal management.

1.1. Fuel Metering Unit

The functions of fuel control system (FCS) include fuel storage, fuel supply, and fuel thermal management [1,2]. FCS is located in the middle and rear outer circumference of the aeroengine and between the accessory gearbox (AGB) and the combustor. According to the established control law, the electronic control unit calculates the required fuel flowrate, and determines a signal to the fuel metering unit (FMU), which is used to transmit fuel to combustor [3].

Due to large weight and poor reliability, hydraulic and mechanical FCS with complex and numerous components, hydraulic and mechanical FCS, have been replaced by electronic FCS [4,5] since 1980. To meet the requirements of FMU, such as stability, performance, tracking, regulation, disturbance rejection, and robustness, there are three categories of the current flowrate metering methods and associated pressure-difference compensation mechanisms:

1. Metering-based flowrate control: The constant pressure difference compensated valve (CPDCV) is used to maintain the pressure difference across metering valve constant, and the discharge flowrate is regulated by fuel metering valve [6]. Although its response speed is fast, the application of FCS with metering-based flowrate control is limited due to the high power loss.
2. Pump controlled flowrate control: In this method, the pressure difference can be kept constant through CPDCV and variable displacement pump, so as to reduce the recirculation and throttling loss of excess fuel [7]. Nevertheless, its application is mainly limited to gas turbines because of the high cost and nonlinear characteristics [8].
3. Motor-based flowrate control: This method replaces hydraulic regulating mechanism with electro actuators [9]; hence, it can simplify structure and improves efficiency [10]. However, the application in electric engine system is limited due to the low control accuracy in the small flowrate range [11].

1.2. Thermal Management

Aircraft thermal management is very important for reliable operation of the aircraft [12]. Problems related to aircraft thermal management of FCS not only affect the operational performance at high Mach number because of the surface friction heating [13] but also have impact on the modern aircraft at low Mach number due to the internal heat. Airborne avionics, hydraulic control system, lubricating oil system, aircraft environmental control system, and other systems produce a large amount of waste heat load which should be managed, as well [14]. Meanwhile, low thermal conductivity of the composite skin on new aircraft also leads to worse heat management [15]. Moreover, transient peak thermal load generated by the high energy weapon should be temporarily stored in the phase change energy storage materials and then be released to the fuel [16].

Taking the fuel as heat sink to absorb waste heat energy from airplane mechanical-electronic system has the following advantages [17]: One is that the fuel can absorb the thermal load with the lowest heat-sink cost and the fuel to be preheated to a suitable temperature range before entering to combustor is helpful to the combustion. The other is that traditional air cycle system cannot meet the cooling exchange need of the airplane. Taking the fuel as heat sink can significantly improve the cooling capacity of aeroengine. However, the thermal management of FCS also confronts some issues to be addressed [18]. Firstly, the variation of fuel consumption and temperature always results in the dynamically change of the cooling capacity of the heat sink. Secondly, the maximum fuel temperature at the inlet of the combustor must be less than 135 °C to prevent fuel coking [19,20]. To solve these problems, research on aircraft integrated thermal management system (TMS) is very necessary.

One method of TMS is to increase the efficiency of FMU and to research and development more effective designs [21]. Variable displacement vane pump (VDVP) [22] used in pump-controlled flowrate control system and variable speed pump (VSP) [23] used in motor-based flowrate control system provide a promising approach to reduce the specific fuel consumption (SFC). VDVP is superior to the legacy system in the pollution resistance, fast response, and high thermal efficiency. VSP not only can reduce the thermal load of the conventional cooling accessories, such as fuel cooled ram air cooler (FCAC) and the absorptive capacity of the heat exchangers (HXs), such as hydraulic oil cooled fuel cooler (HCFC), oil cooled fuel cooler (OCFC), and PAO cooled fuel cooler (PAO-CFC) arranged between LP and HP, but also make contributions to the SFC and CO₂ reduction [24,25]. That is to say, the variable pump system can not only improve the performances of the aeroengine but also be more environmentally friendly.

The other approach of TMS is to actively dissipate thermal loads [25]. Through equipping heater exchangers and cooler exchanger in the aircraft, we can actively manage the thermal loads. The heater exchangers transfer thermal load to fuel in the feed line, and, meanwhile, to control the temperature of the fuel to flow into the high pressure pump (HP), part of the fuel returns to the fuel tank through return line with recirculation cooler.

If the thermal load transferred to atmosphere is less than the thermal load of the fuel to be absorbed in the cooler, the fuel to enter into the tank will increase the temperature of the fuel in the tank, and the serious case will result in aircraft failure [26].

This review article mainly deals with fuel flowrate control and fuel thermal management. We will mainly overview the present status of fuel flowrate control-, pump-, or motor control-based FMU, such as VSP and VDVP, the influence FMU on thermal management, the control strategy for thermal topology network, and the method to extend thermal endurance by controlling the flowrate of fuel and scheduling heat sinks in the aircraft.

2. Basic Description

FCS consists of several parts: a fuel pump for supplying required fuel, an electronic control unit (ECU) for receiving the command signal, and a FMU for transferring required fuel to combustor and returning the excess fuel to tank. The typical FCS is shown in Figure 1. The chemical energy generated by combustion can be converted into kinetic energy to generate thrust of the aeroengine, and mechanical energy to drive airborne accessories and fuel pump to operate through accessory gearbox (AGB). The heat transfer conduction of high temperature fuel gas in the jet pipe and the power loss of airborne accessories and fuel pump will be dissipated by the fuel system.

Figure 1. Typical aeroengine control system.

Taking fuel as a heat sink to absorb the thermal loads in the airborne electro-mechanical system is an important aspect of airplane thermal management. However, the fuel control system usually recirculates the hot fuel to the return tank, thus increasing the fuel temperature in the tank [27]. Thus, the control of the fuel-based thermal topology network, including valves, pumps, heat exchangers, and coolers, and planning of aircraft trajectories for optimal thermal performance have become the present challenging issues [28]. The schematic of fuel thermal management system is shown in Figure 2.

The dissipating thermal load of hydraulic system is realized by the immersed heat exchanger in the fuel tank or the hydraulic oil-fuel forced-convection heat exchanger in the fuel feed line. In order to restrain the temperature rise of the fuel in the tank caused by the recirculated fuel, a cooler of fuel-ram air is used to absorb the thermal load of the fuel and control the outlet temperature of cooler [29]. At the same time, the corresponding heat exchangers also dissipate the waste heat energy generated by the lubrication system and environment control system. The main layout approaches of heat dissipation of the hydraulic control system are as follows [30,31]:

1. The first approach is to make return line of hydraulic control system across the fuel tank, thus, produces the convective heat exchange through the area of heat transfer.
2. The second approach is to arrange a fuel-hydraulic heat exchanger on the return circuit of fuel pump housing. The heat exchanger can be immersed in fuel tank or connected in series with the fuel supply circuit of aeroengine.

3. The third arrange method is to set a fuel-hydraulic heat exchanger on the main hydraulic return pipe. The fuel after heat exchanging can be transmitted into a combustor or fuel tank.
4. The fourth method is to set a hydraulic-ram air heat exchanger on the return circuit of hydraulic pump housing and a hydraulic-fuel heat exchanger on the bypass line to be connected in parallel with the fuel supply line. Note that the cold side of the heat exchanger should be arranged on the stamping air channel after the diffusion of the stamping air inlet. In these two heat exchangers, priority is given to operation hydraulic-ram air heat exchanger. When the heat exchange capacity of hydraulic-ram air heat exchanger is insufficient, both operate at the same time.
5. The fifth method is to arrange the heat exchanger in the hydraulic booster tank so as to absorb the dissipating thermal loads through the ram air, cold air, fuel, or other heat sinks.

Figure 2. Fuel-based thermal management system.

3. Hydraulic-Based Fuel Flow Control

3.1. Metering-Based Flowrate Control

3.1.1. Mechanism and Technical Characteristic

The FCS with the metering-based flowrate control is mainly composed of two essential subcomponents [32]: the metering valve and the CPDCV. The fuel flowrate can be controlled by regulating the flow area of metering valve through an electro hydraulic servo valve. The function of the constant pressure-difference valve is to maintain the pressure-difference across the metering valve constant under both steady state and dynamic operation condition, and to transmit the required fuel flowrate to combustor. Particularly, a two-stage CPDCV in FCS should be used in large flowrate operation condition to maintain the pressure difference constant [3]. A novel flowrate control valve with two-stage CPDCV for afterburner system is shown in Figure 3 [3].

In the FADEC (full authority digital electronic control) system, the flow area of directly driven valve (DDV), i.e., metering valve, is proportional to the linear displacement of voice coil actuator (VCA), and the pressure compensated valve can maintain the pressure-difference across DDV constant [33,34]. Thus, fuel flowrate of FCS can be regulated by the DDV. The flowrate control system with DDV driven by VCA is shown in Figure 4. The problem of poor reliability caused by oil contamination in servo valve can be solved by employing the FCS with DDV. However, due to the fluctuation in scavenge oil flowrate, the spool displacement of pressure compensated valve will be changed frequently, which results in the fluctuation of discharge fuel flowrate.

Figure 3. Metering-based fuel flowrate control system: (1) Fuel pump, (2) safety valve, (3) pressure reducing valve, (4) servo valve, (5) metering valve, (6) directed constant pressure difference valve, (7) dynamic damping orifice, (8) main valve, (9) damping piston, (10) combustor.

Figure 4. Flowrate control system with DDV driven by VCA.

3.1.2. Evolution of FMU

In the past few decades, a large number of research studies on the performance improvement of FMU have been made. Carrese et al. [34] presented a simple FMU which only included a metering valve regulated by control unit. However, its control accuracy was low due to the lack of CPDCV. In order to solve this issue, Georgantas et al. [35] investigated a novel electronic FMU with a diaphragm valve to maintain the pressure-difference constant. Moreover, in order to simplify structure and improve efficiency of FMU, Krepec et al. proposed a novel FMU with bypass valve [36]. Moreover, Georgantas et al. researched a gas turbine engine with a double control unit [37]. The novel FMU not only could transmit the fuel to combustor but also return the superfluous flow to tank. In 1999, Mohtasab [38] presented a new metering valve. The key merit was the simple structure and low cost. Today, with the development of aeroengine, the function of hydro mechanical fuel system has been gradually improved. Engine speed and engine inlet temperature have been introduced into the control system to complete the specific operation tasks. Several research studies on FCS concentrates on the structure simplification and performance improvement. Agh et al. [5,6] proposed a new rotary FMU. The innovations were valve shape design and the direct drive actuation, but it was limited due to complex manufacture and high cost. Tudosie [39,40] studied the complex fuel control system with hydro mechanical type and researched the mechanism of the model. In addition, due to the high control accuracy and wide range, the variable pressure-drop fuel metering device [41]

has been researched. Conversely, the drawbacks are the complex manufacturing, repairing, and maintenance costs.

3.1.3. Influence Factors

The flowrate control accuracy of FMU is mainly subject to the following factors: metering valve opening control [3], CPDCV pressure difference regulation, and fuel temperature change. Some research concentrates on the cavitation [42]. Den et al. [43] researched a numerical tool combined with the cavitation model to forecast the flowrate. Jin et al. [44] studied the influences of spool shapes on cavitation. The result presented vapor mainly appeared in the gap between the sleeve and the valve core surface. Meanwhile, related research focuses on the numerical calculation [45] of the steady-state flow forces on the spool [46] and concentrates on the nonlinear dynamic friction compensation [47]. Yuan et al. [48] researched the flow-pressure characteristic of the flow valve. The results showed the flow area of triangular openings could be enhanced by approximately 40% than that of the rectangle one. Lisowski et al. [49] researched the flow coefficient of the hydraulic proportional directional valve. The results indicated the coefficient value was linked to spool position.

As the most expensive hydraulic control component, electro-hydraulic servo control valve [50] has an impact on the performance of FCS. Chen et al. [51] investigated that the factors influencing the property of FMU were the input current, servo fuel pressure, and direction of movement of fuel metering valve. Meanwhile, the effects of back pressure and other nonlinear factors on pressure difference across metering valve have been researched. Yuan et al. [52] researched the effect of the back pressure on the differential pressure. Chen et al. [53] proposed the differential pressure fluctuation was the result of the dead zone in the zone-relay link. Masuda et al. [54] investigated a method to decrease the frequency properties of the pressure change waveform when the fuel pump mode was changed. Note that fuel temperature shall be limited within the range from $-40\text{ }^{\circ}\text{C}$ to $135\text{ }^{\circ}\text{C}$ to achieve high efficiency and safety operation. [3]. Zhang et al. [30] deduced a mathematical model of temperature sensitive operating force for servo valve, which could explain the blockage caused by temperature change.

3.2. Pump-Controlled Flowrate Control

3.2.1. Mechanism of Fuel Flowrate Control

Compared with the legacy systems, the FCSs with VDVPs are characterized by excellent thermal efficiency, anti-pollution, and fast response [55]. Therefore, the VDVP with high control accuracy was used as a metering pump [56]. The schematic of pump-based flowrate control system is shown in Figure 5.

Figure 5. Schematic of pump-based flowrate control system.

When the hydraulic force on the pressure compensated valve of the variable-displacement mechanism of the VDVP is balanced with the spring force, the pressure-difference can be kept constant [10]. Under such circumstances, the fuel oil circuits of both

chambers can be closed off by the spool shoulder, and the spool of the slave piston can be maintained in a certain position, which means the displacement of the fuel pump remains unchanged. The pressure difference regulation principle of FCS with pump-based flowrate control is as follows: the inlet pressure of FCS increases with the increasing of fuel pump rotation speed, causing the pressure compensated valve spool move to the direction of increasing flow area of the fuel pipes to the two chambers of the slave piston. Then, the slave valve will be moved toward to the direction decreasing the displacement of the fuel pump, thus decreasing the inlet pressure of the FMU. Consequently, the pressure difference will be maintained constant, and the fluctuation of the fuel flowrate to flow through the metering opening of FMU can be effectively restrained without the cost of the orifice power loss of CPDCV.

3.2.2. Problems and Technical Challenges

In the FCS, the fuel pump used in metering-based flowrate control system is VDVP, and the change of output pressure is roughly proportional to the driving speed and combustor pressure [57]. Therefore, the fuel flowrate supplied must meet the requirement of the aeroengine in wide rotational speed range, especially while starting an aeroengine below engine idle speed. In this case, VDVP needs to regulate the variable displacement mechanism of the fuel pump to a large displacement and, in the meantime, can bypass the heat exchanger because the airborne system needs to heat dissipation when temperature rise is established, and the thermal load accumulates for a certain time. The great attraction of the VDVP is to realize the control of the fuel flowrate at a constant speed and allow the aeroengine to regulate the fuel flowrate without saturation and the overflow loss.

For the variable-displacement pump-based FCS, the following technology changes must be addressed [58]:

1. Reliability of FCS: Typical system reliabilities for FCS with VDVP are achieving mean time between failures of 175,000 h, with mean time between unscheduled removals of 75,000 h. These criteria are also being steadily improved by pump design technology, which requires meeting higher fuel system temperature and higher working pressure.
2. Minimizing the cost increase: The FCS with VDVP should comply with the simplification and control capability of FADEC without having an impact on the system cost. The novel VDVP should be able to integrate into the FCS while furthering the performance improvement.
3. Minimum weight increase: Because the structural composition of pump control-based FCS is more complex than that of valve compensation-based FCS, to minimize the weight increase is necessary because FCS must be ensured.

Moreover, the pressure control and control strategy of the fuel pump are also very important, but there are few fuel pump-related papers and hydraulic pump control-related papers; see references [59,60].

4. Motor-Driven Pump Flowrate Control

As the potential flowrate control approach, motor-driven pump flowrate control must regulate the FCS (hydro mechanical type) of the aeroengine in case of flight altitude increase. Increase of the control accuracy and the resolution of the fuel flow control system for the case of the sharp decrease in engine fuel consumption at high flight altitudes has been one of the challenges of the aeroengine.

4.1. Mechanism

Today, fuel metering system (MEE-FMS) in the more electric engine (MEE) has attracted great attention in the aeroengine. The MEE-FMS adopts motor-based FMS and reduces engine fuel consumption and CO₂ emissions. The MEE-FMS is an advanced FCS, which employs the latest innovations of motor and power electronic technology to replace the traditional engine accessories with electric motor driven pumps and electro-mechanical actuators.

Figure 6 shows a schematic of one kind of MEE-FMS with metering valve, where the fuel flowrate is regulated by the opening and differential pressure of FMV, and the FADEC can collect Δp from the pressure-difference sensor and control Δp to track the desired pressure-difference by regulating the speed of the motor. The fuel flow feedback can compensate the performance degradation of fuel pump by increasing the pump speed.

Figure 6. Schematic of MEE system.

The schematic of a higher efficiency novel MEE-FMS without the metering valve is shown in Figure 7. The expression among outlet flowrate of fuel pump, outlet pressure of fuel pump, fuel pump speed, fuel temperature, and other physical quantities can be acquired through the off-line calibration method. Then, by comparing the flowrate by online calculation with desired flowrate, the output flowrate of fuel pump can track the desired value by regulating the motor speed. Due to the elimination of the throttling loss, the novel FCS is superior to other fuel control schemes in the ability to absorb external heat loads [22,23]. Motor-based FMS, which consists of a motor-based pressure difference compensator and distributed metering valve, is the development tendency of FMS.

Figure 7. Schematic of a novel FCS with motor-based flowrate control.

4.2. Technical Advantages

MEE-FCS is no longer driven by the AGB accessories, but by the electric motor. While it cancels the metering valve [61], it also increases the burden of the aircraft generator. MEE-FMS eliminates the fuel flow bypass loss, and the pump can exactly output the fuel flow required by the engine. The advantages of the proposed integrated electric fuel system are as follows [22,23]:

1. The energy consumption for fuel regulation is reduced.
2. The number of components of FCS is decreased, and the constitution of AGB is simplified.

3. Improvement of maintainability of the FCS is important because of the reduction of the number of FCS components, the accessibility and the maintainability of FCS are improved.

In reference [23], Morioka and Oyori proposed an integrated fuel control system based on multi-motor-driven pumps distributed in the aircraft tanks, it cancels the cross connecting valve among the tanks; therefore, the pilot is no longer required to make any adjustments to the tank balance.

4.3. Technical Challenges

In the Motor-based FMS, the electric gear pump is employed as a metering device. MEE-FCS is expected to be simplified; however, there are still some technical issues to be addressed [11]:

1. Ensure the control accuracy of fuel flowrate through motor speed control [62]: To address the control accuracy issue for the MEE-FCS, studies on fuel flowrate feedback systems are needed.
2. Ensure that the gear pump operates in wide speed range [63]: Operation at low speed is significantly harmful to the pressurizing capability and bearing film lubrication of the gear pump; therefore, the rotational speed control of the pump in wide range is a challenge.
3. Ensure the power supply of the pump motor during aeroengine start-up [64]: Ensure that the generator can normally supply power at low speed (10% rated speed).

5. Fuel Flowrate Control Related to Thermal Management

In FCSs, the mechanism of the fuel metering directly determines the efficiency of FMS. The efficiency of FMS which is composed of constant pressure variable displacement pump and fuel metering valve is the lowest, and the efficiency of FMS which is composed of load sensing variable displacement pump and fuel metering valve is higher, and the efficiency of FMS which is composed of variable speed motor-driven pump without metering valve is highest. The high efficiency of FMS means the low power loss and self-thermal load, so that the fuel heat sink can dissipate the more airborne thermal load. Therefore, a great attention is being paid to the fuel flowrate control related to thermal management.

5.1. Causes of Temperature Rise

The fuel system should firstly satisfy the functions in all engine operational conditions and then absorb the thermal load of the engine and airborne electric-mechanical system as heat sink [65]. When the fuel temperature is lower than the cocking temperature, the fuel is the best heat sink from TMS operation cost. However, kerosene-type aviation fuel has the tendency to degrade at the temperature higher than its cocking temperature and forms solid deposits [66]. Decreasing the power loss of the fuel metering and supplying will help the fuel to absorb more thermal load in airborne mechatronic systems. The absorbed thermal load by the fuel and the power loss of the fuel itself result in the fuel temperature rise. In addition to the power losses caused by the fuel pump and HX, there are two main power losses in the fuel system, which lead to the temperature rise [67].

1. The first power loss is the by-pass power loss, which mainly occurs in FMS flowrate control with fixed displacement HP (high pressure pump) pump. Moreover, for the fuel supplying circuit from LP to HP, the speed of the LP is determined by AGB driven by the aeroengine, and the rest flowrate in which LP exceeds HP also causes by-pass power loss because the fuel pump must ensure that the aeroengine can work normally in all flight profiles. This type of the power loss will have an impact on the temperature of the fuel in HP inlet and fuel-recycling port of the fuel tank.
2. The second power loss is the throttling loss of metering valve and the pressure compensated valve in the fuel system, and load sensing pump-based FMS motor variable speed pump-based FMS can cancel the pressure loss of the pressure difference

compensator. The rise in temperature caused by throttling takes up a large proportion in the total temperature.

5.2. Measures to Decrease Temperature Rise

The factors on the rise of fuel temperature are the existence of the bypass fuel flow because of the mismatch of the required fuel flowrate and the pump discharge flowrate, and the throttling loss in the metering valve. To address the issue, the FCSs with variable displacement pump with the pressure compensation or pressure-difference and variable speed motor-driven pump with electric pressure-difference compensation in high pressure supplying circuit are good solutions [68,69]. In addition to cancelling the by-pass loss, FCS with pressure-difference compensation pump can effectively decrease the pressure loss in the compensator of the pressure-difference compensator, and variable speed motor-driven pump with electric pressure-difference compensation has only the metering loss of the metering valve.

5.3. Comparison

Each fuel system has advantages and disadvantages, and all the FCSs can be evaluated from the following three aspects:

1. Efficiency and temperature rise of fuel control system.
2. Power extraction from engine and the price of the attached fuel consumption of FCS.
3. Response characteristic.

5.3.1. Efficiency and Temperature Rise of Fuel Control System

The comparison of the efficiency of three kinds of fuel FCSs is illustrated in Table 1 [22].

Table 1. Efficiency of fuel flowrate control system under different flight mission conditions.

Fuel Control System	Efficiency of Fuel Control System (%)		
	Grounding	Cruise	Descent
Metering-based	20.4	4.4	1.4
Pump-Controlled	42.5	13.8	2.3
Motor-based	42.7	21.5	7.5

It is found that the performance of FCS with motor-driven pump flowrate control is the best [22,61]. By reducing amount of conventional cooling accessories, the FCS with motor-driven pump flowrate control can improve thermal management. The result of increased fuel temperature is shown in Table 2 [22].

Table 2. Temperature rise of fuel control system under different flight mission conditions.

Fuel Control System	Temperature Rise of Fuel Control System (°C)		
	Grounding	Cruise	Descent
Metering-based	9.6	28.6	98.2
Pump-Controlled	3.3	8.2	59.4
Motor-based	3.5	5.4	19.4

5.3.2. Saving Input Shaft Power

The calculated aeroengine power reductions are shown in Table 3 [22]. Compared with the traditional system, the extracted power of the FCSs with pump-controlled and motor-based flowrate control can be reduced by about 70% during the cruise mission [70].

Table 3. Comparison of aeroengine power reduction under different flight mission conditions.

Fuel Flowrate Control System	Reduction of Power Extraction from Aeroengine (%)		
	Grounding	Cruise	Descent
Metering-based	0	0	0
Pump-Controlled	52	68	68
Motor-based	49	77	79

5.3.3. Response Characteristic

The result of the fuel metering accuracy and response characteristic is shown in Table 4 [66]. For metering-based FCS and pump-controlled FCS, the property of the fuel flowrate control depends on that of the opening regulation of the fuel metering valve and the pressure difference compensation, and the property of the fuel flowrate control depends on the property of the flowrate metering device and metering formula for motor-based flowrate control system [70]. Meanwhile, the response characteristic of the metering-based FCS is faster than that of motor-based flowrate control and pump-controlled flowrate control.

Table 4. Fuel metering accuracy and response characteristic.

Fuel Flowrate Control System	Fuel Metering Accuracy and Response Characteristic		
	Fuel Metering Schemes	Fuel Metering Accuracy	Response Characteristic
Metering-based	Δp -control	standard	higher
Pump-controlled	Δp -control	standard	standard
Motor-based	Metering device and metering formula	standard	higher

6. Tank with Drain and Recirculation Related Fuel Thermal Management

Fuel is the lowest cost heat-sink in the aircraft. The goal of the fuel thermal management is to absorb the thermal load of aircraft airborne system to the greatest extent on the premise of meeting the effects of engine thrust and accessory power on fuel flow and allowable fuel temperature of high-pressure fuel pump. The fuel thermal management deals with the layout of the heat exchanger, regulating valve, the dissipation of the fuel self-thermal load, thermal topology design, and control strategy. This section reviews fuel thermal management-related technological status and development tendency.

6.1. Single Tank with Independent Recirculation through a HX

Single tank with independent recirculation loop through a HX is shown in Figure 8 [14]. This FCS stands for the majority situations of that use fuel as heat sink. The draining fuel represents the fuel transmitted to combustor. The heat exchanger in the recirculation loop as the heater transferred the total heat load to the fuel when the fuel is as heat sink or as the cooler to decrease the temperature of the fuel in the tank by using the ram air or other cooled medium [14].

Figure 8. Simplified block diagram of draining tank with a heat exchanger in recirculation.

6.2. Single Tank with Recirculation through Split HX

Single tank with partial recirculation is through split HX. In this method, fuel is transmitted from reservoir tanks to a feed tank and then absorbs the waste heat energy from airborne electromechanical systems through HX, before parts of fuel will be transferred to combustor. The portion of not burned fuel can be cooled by the ram air or third stream cooler exchanger (CX) before returning to the tank. Note that the CX temperature must be lower than the temperature of the recirculated fuel. Figure 9 shows the schematic diagram of the single tank with recirculation through a split heat exchanger [14]. This configuration is called a split heat exchanger-drain-recirculation (SHEDR) loop [24,25].

Figure 9. Simplified block diagram of tank with recirculation loop with drain between heat exchanger.

As shown in Figure 9, the HX adds waste heat energy at the rate of $\dot{Q}_h$ to the total fuel that supplied by fuel tank. One part of fuel ejected from recirculation loop is transmitted to combustor; meanwhile, after passing through CX that extracts heat load at a rate of $\dot{Q}_c$, the other part of unburned fuel will return to the fuel tank.

6.3. Dual Tank with Cooler Bypass

The concept of TMS based on dual tank was proposed in Reference [24]. In order to maximize thermal endurance, operation at a feasible trim point is beneficial. For enlarging the space of feasible trim points, a servo controlled valve is placed at the entrance to the cooler in order to control the fraction of fuel recirculated through the cooler and a bypass loop [25].

Figure 10 shows the schematic block diagram of a dual tank system with a continuously variable wye valve, which divides the recirculation flow into two branches: through the cooler branch and bypass cooler branch. In this method, when the temperature of the heat sink in the cooler is higher than the fuel temperature, a bypass valve is employed to directly transmit the fuel to reservoir tank. This condition is likely to occur under the procedure of takeoff in hot summer because the cold fuel is initially loaded into the aircraft tanks, and the temperature of the ram air is higher in this situation. Meanwhile, the continuously variable bypass valve can expand the operation range of the dual tank system, in which the total fuel will be cooled through CX, thus ensuring the fuel temperature at the outlet of drain and HX does not exceed the limit temperature. The opening of the bypass valve is increased in the flight condition of high mass flowrate. Further, Doman also studied the planning and control strategy by using the optimization method and modern control theory [71,72].

Figure 10. Dual tank topology with three inputs: feed line mixing valve (α), feed line flow rate ($\dot{m}_f$), cooler bypass wye valve (β) [71].

6.4. Hot/Cold Dual Tanks Recirculation with Tank Drains

It is well known that large heat flux electronic equipment, such as directed energy weapon system and large power IGBT device, needs a separate fuel system to absorb the peak thermal load [71,72]. Figure 11 shows a schematic diagram of laser recirculation circuit TMS with hot/cold dual tanks [14]. In the following analysis, the hot and cold tanks are connected by HX and CX, and drainage rate of the two tanks must be the same.

Figure 11. Simplified block diagram laser coolant recirculation loop.

The regulation process of TMS is as follows:

The laser weapon device can be cooled through TMS with dual tanks thermal topology network. The thermal load of the laser weapon is firstly transferred to the heater in the TMS through VCS, and then TMS can transfer the thermal load to the recirculated fuel between hot and cold reservoir tanks. Note that the fuel tanks are separated from the SHEDR circuit. When the valves remain closed, the peak thermal load will be managed by the recirculation fuel circuit. Thus, the TMS is isolated from the SHEDR loop, i.e., the fuel cannot be delivered to the SHEDR loop until the weapon is finished operating. After the operation of the laser device is ended, the pulsed thermal load stored in dual tank can be transferred to the SHEDR loop when the valve opens. When the fuel in the laser loop is sufficiently cooled and no longer needed hot/cold tanks loop, the hot and cold tanks in the laser loop can be drained to a feed tank. Thus, the fuel from the hot/cold tanks can be mixed with fuel from a main tank, prior to entering the SHEDR loop [14].

All in all, the dual-tank system has shown the great potential in greater thermal endurance, closer thermal limits, and higher rate of heat dissipation. The results also show that, under thermally stressing conditions, with the decrease of the volume of the recirculation tank, the performance and thermal endurance ratio of dual tank increases. However, a disadvantage of this scheme is that it increases the thermal load on the hot side of the heat exchanger in the fuel feed line, which will require more power to operate. Meanwhile, the temperature of the refrigerant will have to reach higher temperatures in order to provide sufficient temperature differences at the inlet and outlet, thus providing the required heat transfer rates for internal aircraft systems.

7. Conclusions and Future Directions

7.1. Conclusions

After the fuel control systems have been introduced and reviewed, difference flowrate regulation methods and related thermal management are researched. The results show that, although these FCS are independently researched by scholars, the basic flowrate regulation mechanisms are very similar, namely constant pressure difference regulation mechanism.

FCSs with pump-controlled and motor-driven pump flowrate control are superior to the conventional system with metering-based flowrate control in high efficiency, low temperature rise, and lower energy consumption. However, the response characteristic of the metering-based FCS is faster than one of motor-based flowrate control and pump-controlled flowrate control. Moreover, FCSs with pump-controlled and motor-driven pump flowrate control can reduce the cooling request on the heat exchanger. MEE system can reduce the bypass fuel and improve thermal management, and it is expected that the MEE will have more and more applications. Although MEE is still at its early stage, with the efforts of scholars researching in this field, we believe that the MEE will become more and more mature and gradually become one of the main stream FCSs.

Meanwhile, the dual-tank system has shown great potential in larger thermal endurance, closer thermal limits, and higher rate of heat dissipation. A continuous two-variable control system to regulate feed line mass flow rate and mixing valve position could obtain better performance than the simple switching controller. The fuel cost of using fuel as heat sink to absorb heat load is lower than that of using ram air as heat sink to absorb heat load.

7.2. Future Directions

Despite all of the progress and applications, MEE system and dual-tank system related thermal management are still far from mature. Although a large number of applications show the potential of these methods, more discussions are still needed to realize the advantages and shortcomings. Some topics that required further research in this area are as follows:

1. To improve the accuracy of metering flowrate controlled by motor: In MEE system, the motor controlled gear pump replaced the metering valve and CPDCV, and the accuracy of fuel flowrate control is affected by internal leakage, fuel temperature, and operating time range. The fuel flow feedback can compensate the performance degradation of fuel pump by increasing the pump speed. Moreover, the improvement of low-speed control characteristics of the motor is also important. In order to solve this problem, a digital servo control system with variable sampling time will be introduced. With the decrease or increase of motor speed, the sampling time will be shortened or extended.
2. To strengthen the modeling algorithm of the output fuel flowrate of electric motor-based fuel pump by using machine learning and big data and to develop the flowrate meter with high response and high accuracy, thus, the FCS of more electric aeroengine will be put into practical application as soon as possible.
3. To enhance the studies on heat-sink scheduling of multi-heat-sink, including fuel oil, ram air, and variable cycle engine 3rd bypass air, the synergetic combination of

a multi-heat exchange loop with different working fluids, high efficient heat load collection, and heat transfer technology, advanced control theory and control method, sensor network and control network, data fusion, and health management for thermal topology, thus the performance of fuel thermal system can be improved.

Author Contributions: Design of the research supervision: Y.L. and S.D.; Performing of the articles overview and writing of the manuscript: D.L. and J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Science and Technology Major Project (2017-V-0015-0067) and the National Key Basic Research Program of China (No. 2014CB046403).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No statement.

Conflicts of Interest: The authors declare no conflict of interest with other researchers.

Nomenclature

Notations

α	Mixing valve position.
β	Wye valve position, and $1 - \beta$ is the bypass ratio.
c_p	Specific heat of fuel.
E	Total instantaneous energy.
$E_1(t), E_2(t)$	Fuel energy in recirculation array and tank array.
E_C	Internal energy in the cold tank.
E_H	Internal energy in the hot tank.
$m, m(t)$	Mass of fuel in the tank.
m_0	Mass of fuel in the tank at $t = 0$.
$m_1(t), m_2(t)$	Fuel mass in recirculation array and tank array.
$\dot{m}_{1o}, \dot{m}_{2o}$	Mass flowrate leaving recirculation array and tank array, respectively.
m_C	Fuel mass in the cold tank.
$\dot{m}_d$	Derivative of fuel mass in the tank.
$\dot{m}_{di}$	Derivative of mass through each tank drain.
$\dot{m}_e$	Derivative of mass leaving the loop by way of the engine.
$\dot{m}_f$	Derivative of total mass flow in the dual tank case.
m_H	Fuel mass in the hot tank.
m_r	Arbitrary reference mass.
$\dot{m}_{rl}$	Derivative of mass through heat exchanger.
$\dot{Q}_{1o}, \dot{Q}_{2o}$	Derivative of internal energy flowing from recirculation array and tank array.
$\dot{Q}_c$	Derivative of internal energy through cooler exchangers.
$\dot{Q}_{Cd}$	Derivative of energy leaving the cold tanks to drains.
$\dot{Q}_{Ci}$	Derivative of energy entering the cold tanks.
$\dot{Q}_{Co}$	Derivative of energy leaving the cold tanks.
$\dot{Q}_d$	Derivative of internal energy flow leaving the system through the drain to the engine.
$\dot{Q}_e$	Derivative of energy leaving the loop by way of the engine.
$\dot{Q}_H$	Derivative of internal energy flow after passing the heat exchanger operating.
$\dot{Q}_{HD}$	Derivative of the energy flow at the heat exchanger output.
$\dot{Q}_{Hd}$	Derivative of energy leaving the hot tanks to drains.
$\dot{Q}_{Hi}$	Derivative of energy entering the hot tanks.
$\dot{Q}_{Ho}$	Derivative of energy leaving the hot tanks.
$\dot{Q}_h$	Derivative of fuel energy passing through heat exchangers.
$\dot{Q}_i$	Derivative of internal energy flow rate into the tank.
$\dot{Q}_o$	Derivative of internal energy exits through the tank outlet.
$\dot{Q}_{RD}$	Derivative of energy flowing through the recirculation loop and entering the cooler.

$\dot{Q}_r$	Derivative of internal energy flow leaving the tank through a recirculation loop.
$T, T(t)$	Fuel temperature.
$T_1(t), T_2(t)$	Fuel temperature in recirculation array and tank array.
t	Time.
T_C	Fuel temperature in cold tank.
T_{fD}	Feed line temperature for the dual tank system.
T_H	Fuel temperature in hot tank.
T_r	Arbitrary reference fuel temperature.
Abbreviation	
3D	Three-dimensional.
ACOC	Air cooled oil cooler.
AGB	Accessory gearbox.
CPDCV	Constant pressure difference compensated valve.
CX	Cool exchange.
DDV	Directly driven valve.
FADEC	Full authority digital electronic control.
FCAC	Fuel cooled ram air cooler.
FCS	Fuel control system.
FMS	Fuel metering system.
FMU	Fuel metering unit.
FMV	Fuel metering valve.
HCFC	Hydraulic oil cooled fuel cooler.
HP	High-pressure pump.
HX	Heat exchanger.
LP	Low-pressure pump.
MEE	More electric engine.
OCFC	Oil cooled fuel cooler.
PAO	Polyalphaolefin.
PAO-CFC	PAO cooled fuel cooler.
SFC	Specific fuel consumption.
SHEDR	Split heat exchanger-drain-recirculation.
TMS	Thermal management system
VCA	Voice coil actuator.
VDVP	Variable displacement vane pump.
VSP	Variable speed pump.

References

- Wang, B.; Ji, H.Y.; Ye, Z.F. Simulation and semi physical verification of fuel metering unit model for turbo shaft aeroengine. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2020**, *234*, 1866–1882. [\[CrossRef\]](#)
- Matveev, I.B.; Serbin, S.I.; Vilkul, V.V.; Goncharova, N.A. Synthesis gas afterburner based on an injector type plasma-assisted combustion system. *IEEE Trans. Plasma Sci.* **2015**, *43*, 3974–3978. [\[CrossRef\]](#)
- Hang, J.; Li, Y.H.; Yang, L.M. A novel low pressure-difference fluctuation electro-hydraulic large flowrate control valve for fuel flowrate control of aeroengine afterburner system. *Chin. J. Aeronaut.* **2021**, in press. [\[CrossRef\]](#)
- Wang, B.; Zhao, H.C.; Yu, L.; Ye, Z.F. Study of temperature effect on servo valve-controlled fuel metering unit. *J. Eng. Gas Turbines Power* **2015**, *137*, 061503. [\[CrossRef\]](#)
- Agh, S.M.; Pirkandi, J.; Mahmoodi, M.; Jahromi, M. Development of a novel rotary flow control valve with an electronic actuator and a pressure compensator valve for a gas turbine engine fuel control system. *Flow Meas. Instrum.* **2020**, *74*, 101759. [\[CrossRef\]](#)
- Agh, S.M.; Pirkandi, J.; Mahmoodi, M.; Jahromi, M. Optimum design, simulation and test of a new flow control valve with an electronic actuator for turbine engine fuel control system. *Flow Meas. Instrum.* **2018**, *65*, 65–77.
- Gaudet, T.J. Hydro mechanical control for a variable delivery positive displacement fuel pump. In Proceedings of the International Gas Turbine and Aeroengine Congress and Exhibition 1999, Indianapolis, IA, USA, 7–10 June 1999; pp. 1–11. [\[CrossRef\]](#)
- Hang, J.; Li, Y.; Zhang, P.; Yang, L. Nonlinear dynamic modeling and analysis for aviation axial piston pump in center spring return mechanism. *J. Low Freq. Noise Vib. Act. Control* **2021**, *40*, 169–180. [\[CrossRef\]](#)
- Borghei, M.; Ghassemi, M. Insulation materials and systems for more and all-electric aircraft: A review identifying challenges and future research needs. *IEEE Trans. Transp. Electrification* **2021**, *7*, 1930–1953. [\[CrossRef\]](#)
- Sarlioglu, B.; Morris, C.T. More electric aircraft: Review, challenges, and opportunities for commercial transport aircraft. *Transp. Electr.* **2015**, *1*, 54–64. [\[CrossRef\]](#)

11. Morioka, N.; Oyori, H. Fuel system design for the more electric engine. In Proceedings of the Turbine Technical Conference and Exposition 2012, Copenhagen, Denmark, 11–15 June 2012; Volume 1, pp. 767–774. [\[CrossRef\]](#)
12. Jafari, S.; Nikoladis, T. Thermal Management Systems for Civil Aircraft Engines: Review, Challenges and Exploring the Future. *Appl. Sci.* **2020**, *8*, 2044. [\[CrossRef\]](#)
13. Bergholz, R.F.; Hitch, B.D. Thermal Management Systems for High Mach Air breathing Propulsion Systems. In Proceedings of the AIAA Guidance, Navigation, and Control Conference 1992, Reno, NV, USA, 6–9 January 1992. AIAA-92-0515.
14. Doman, D.B. Rapid mission planning for aircraft thermal management. In Proceedings of the AIAA Guidance, Navigation, and Control Conference 2015, Kissimmee, FL, USA, 5–9 January 2015; p. 1076.
15. Bodie, M.; Wolff, M. Robust optimization of aircraft power thermal management system. In Proceedings of the AIAA Guidance, Navigation, and Control Conference 2010, Nashville, TN, USA, 25–28 July 2010; p. 7086.
16. Corbett, M.W. Large-scale transient loading of a three stream variable cycle engine. In Proceedings of the AIAA Guidance, Navigation, and Control Conference 2012, Atlanta, GA, USA, 30 July–1 August 2012. AIAA 2012-4142.
17. Qian, S.; Nan, C.S.; Yu, Y.S. Analysis of aircraft integrated thermal management using fuel as heat sink. In Proceedings of the IEEE International Conference on Aircraft Utility Systems 2016, Beijing, China, 10–12 October 2016; pp. 774–779.
18. Wickham, D.T.; Engel, J.R.; Rooney, S.; Hitch, B.D. Additives to improve fuel heat sink capacity in air/fuel heat exchangers. *J. Propuls. Power* **2008**, *24*, 55–63. [\[CrossRef\]](#)
19. Roland, J.; Rumpfheil, M.P. Wing fuel-Tank heat-sink calculation for conceptual aircraft design. *J. Aircr.* **2017**, *54*, 1172–1188. [\[CrossRef\]](#)
20. Butzin, E.; Johnson, P.; Creekmore, R. Airframe thermal management system modeling in NPSS. In Proceedings of the AIAA Guidance, Navigation, and Control Conference 2007, Cincinnati, OH, USA, 8–11 July 2007. AIAA 2007-5048.
21. Paluszewski, P.J.; Desai, M.C. Transient response and thermal performance of a variable displacement vane pump-based actuation system for turbo jet and turbofan aircraft engines. In Proceedings of the ASME Turbo Expo: Power for Land, Sea, and Air, Berlin, Germany, 9–13 June 2008; pp. 337–347.
22. Oba, D.; Gonda, Y. Fuel system with variable speed pump to improve thermal management ability for aircraft engines. In Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, Düsseldorf, Germany, 16–20 June 2014; p. V006T06A025.
23. Morioka, N.; Oyori, H.; Ozawa, K. More electric architecture for engine and aircraft fuel system. In Proceedings of the ASME Technical Turbo Expo, Vancouver, Canada, 6–10 June 2011; pp. GT 2011-46765.
24. Doman, D.B. Fuel flow control for extending aircraft thermal endurance part I: Underlying principles. In Proceedings of the AIAA Guidance, Navigation, and Control Conference 2016, San Diego, CA, USA, 4–8 January 2016. AIAA 2016-1621.
25. Doman, D.B. Fuel flow control for extending aircraft thermal endurance part II: Closed loop control. In Proceedings of the AIAA Guidance, Navigation, and Control Conference 2016, San Diego, CA, USA, 4–8 January 2016. AIAA 2016-1622.
26. German, B.J. A tank heating model for aircraft fuel thermal systems with recirculation. *J. Propuls. Power* **2012**, *28*, 204–210. [\[CrossRef\]](#)
27. Doman, D.B. Optimal cruise altitude for aircraft thermal management. *J. Guid. Control Dyn.* **2015**, *38*, 2084–2095. [\[CrossRef\]](#)
28. Wang, M.X.; Jiao, Z.X.; Xu, Y.Z. Analytical method of thermal-fluid transients in aero-hydraulic systems. In Proceedings of the International Conference on Fluid Power & Mechatronics 2015, Harbin, China, 5–7 August 2015; pp. 63–67.
29. Saleem, A.; Kim, M.H. Air-side thermal hydraulic performance of micro channel heat exchangers with different fin configurations. *Appl. Therm. Eng.* **2017**, *125*, 780–789. [\[CrossRef\]](#)
30. Zhang, Y.; Wang, S.; Shi, J.; Wang, X. Evaluation of thermal effects on temperature-sensitive operating force of flow servo valve for fuel metering unit. *Chin. J. Aeronaut.* **2020**, *33*, 1812–1823. [\[CrossRef\]](#)
31. Han, Z.X.; Guo, J.F.; Zhang, H.Y. Experimental and numerical studies on novel airfoil fins heat exchanger in flue gas heat recovery system. *Appl. Therm. Eng.* **2021**, *192*, 116939. [\[CrossRef\]](#)
32. Hang, J.; Li, Y.Y.; Yang, L.M.; Li, Y. Design and simulation of large flowrate fuel metering valve of are engine based on AMESim. In Proceedings of the IEEE Conference on Industrial Electronics and Applications, Kristiansand, Norway, 9–13 November 2020; pp. 1932–1937.
33. Zeng, W.; Tong, Z.Z.; Li, S.J. Thermodynamic characteristic study of a high-temperature flow-rate control valve for fuel supply of scramjet engines. *Chin. J. Aeronaut.* **2012**, *25*, 559–565. [\[CrossRef\]](#)
34. Carrese, G.; Krepec, T.; To, C. Simulation, testing and optimization of a new low cost electronic fuel control unit for small gas turbine engines. *J. Aerosp.* **1990**, *99*, 199–207. [\[CrossRef\]](#)
35. Georgantas, A.I.; Krepec, T.; Carrese, G. Computer aided development of a simple electronic fuel control unit for remotely piloted flying vehicles. In Proceedings of the International Computers in Engineering Conference and Exhibition 1990, Boston, MA, USA, 5–9 August 1990; pp. 631–637.
36. Krepec, T.; Hong, H.; Georgantas, A. Optimization of a diaphragm type differential pressure valve using CAD Techniques. In Proceedings of the Eighth World Congress on the Theory of Machines and Mechanisms 1991, editors M. Okrouhlik, L. Pust, Prague, Czech Republic, 26–31 August 1991.
37. Georgantas, A.; Krepec, T.; Cheng, R. Design optimization of an electronic fuel control unit featuring two digital actuators. In Proceedings of the AIAA Guidance, Navigation, and Control Conference, Sacramento, CA, USA, 24–26 June 1991.

38. Mohtasebi, S.S.; Hong, H. *Low Cost Electronically Controlled Fuel Metering System for Small Gas Turbine Engines*; 1999-03-01; SAE International: Warrendale, PA, USA, 1999; SAE paper number 1999-01-0545.
39. Tudosie, A.N. Aircraft single-jet engine with hydro-mechanical fuel flow controller. In Proceedings of the 18th IEEE Carpathian Control Conference, Sinaia, Romania, 28–31 May 2017; pp. 375–380.
40. Tudosie, A.N. Aircraft single-jet engine with hydro-mechanical thrust augmentation system based on coolant injection into the compressor. In Proceedings of the Carpathian Control Conference, Krakow-Wieliczka, Poland, 26–29 May 2019. [\[CrossRef\]](#)
41. Wang, Y.; Fan, D.; Zhang, C.K.; Shi, D.Y. Design and analysis of the variable pressure-drop fuel metering device. In Proceedings of the Chinese Control Conference, Dalian, China, 26–28 July 2017; pp. 6434–6439. [\[CrossRef\]](#)
42. Hang, J.; Gao, D.R.; Li, Y.H. Multi-objective optimization for axial flow fan based on BP neural network and genetic algorithm. *J. Chin. Soc. Mech. Eng.* **2018**, *39*, 433–442.
43. Deng, J.; Pan, D.Y.; Xie, F.F.; Shao, X.M. Numerical investigation of cavitation flow inside spool valve with large pressure drop. In *Journal of Physics: Conference Series, 9th International Symposium on Cavitation (CAV2015), Lausanne, Switzerland, 6–10 December 2015*; IOP Publishing: Bristol, UK, 2015; Volume 656, pp. 6–10.
44. Jin, Z.J.; Qiu, C.; Jiang, C.H.; Wu, J.Y.; Qian, J.Y. Effect of valve core shapes on cavitation flow through a sleeve regulating valve. *J. Zhejiang Univ. Sci. A* **2021**, *21*, 1–14. [\[CrossRef\]](#)
45. Lisowski, E.; Filo, G. CFD analysis of the characteristics of a proportional flow control valve with an innovative opening shape. *Energy Convers. Manag.* **2016**, *123*, 15–28. [\[CrossRef\]](#)
46. Lisowski, E.; Filo, G. Analysis of a proportional control valve flow coefficient with the usage of a CFD method. *Flow Meas. Instrum.* **2017**, *53*, 269–278.
47. Li, Y.; Wang, S.P.; Tomovic, M.M.; Zhang, C. Erosion degradation characteristics of a linear electro-hydrostatic actuator under a high-frequency turbulent flow field. *Chin. J. Aeronaut.* **2018**, *31*, 914–926. [\[CrossRef\]](#)
48. Yuan, Y.; Zhang, T.H.; Zhang, J.M. An investigation into factors determining the metering performance of a fuel control unit in an aero engine. *Flow Meas. Instrum.* **2020**, *71*, 101672. [\[CrossRef\]](#)
49. Lisowski, E.; Czyżycki, W.; Rajda, J. Three dimensional CFD analysis and experimental test of flow force acting on the spool of solenoid operated directional control valve. *Energy Convers. Manag.* **2013**, *70*, 220–229. [\[CrossRef\]](#)
50. Chen, B.; Gao, D.; Li, Y.; Chen, C.; Wang, Z.; Zhong, Q.; Sun, P.; Wang, Z.; Wu, S.; Zhao, J. Experimental analysis of spray behavior and lubrication performance under twin-fluid atomization. *J. Manuf. Process.* **2021**, *61*, 561–573. [\[CrossRef\]](#)
51. Chen, B.; Gao, D.; Li, Y.; Chen, C.; Wang, Z.; Zhong, Q.; Sun, P.; Wu, S.; Wang, Z.; Liang, Y. Influence of atomizing core on droplet dynamic behavior and machining characteristics under synergic ally enhanced twin-fluid spray. *Int. J. Adv. Manuf. Technol.* **2020**, *785*, 2269–2282. [\[CrossRef\]](#)
52. Yuan, Y.; Zhao, Z.; Zhang, T. A mimicking technique of back pressure in the hardware in the loop simulation of a fuel control unit. *Simulation* **2020**, *96*, 375–385. [\[CrossRef\]](#)
53. Chen, J.W.; Li, J.X.; Sun, S.N.; Zhang, H. Effect of nonlinear characteristic of the gas turbine engine fuel system with hardware in the loop. In Proceedings of the ASME International Mechanical Engineering Congress Exposition, Pittsburgh, PA, USA, 9–15 November 2018; p. V06AT08A059. [\[CrossRef\]](#)
54. Masuda, S.F.; Fuchiwaki, M.; Tanaka, K. Modelling and reducing fuel flow pulsation of a fuel-metering system during pump mode switching in a turbofan engine. In *IOP Conference Series: Earth Environmental Science*; IOP Publishing: Bristol, UK, 2019; Volume 240, p. 052030. [\[CrossRef\]](#)
55. Nyzen, R.; Clements, M.A. Hydromechanical Pressure Compensation Control of a Variable Displacement Pump in Centrifugal Pumping and Metering System and Associated Method. U.S. Patent US 0075634 A1, 19 March 2015.
56. Bennett, G.L.; Dalton, W.H.; Zagrankki, R.D. Constant Bypass Flow Controller for a Variable Displacement Pump. U.S. Patent US 0200459 A1, 14 October 2004.
57. Reuter, C.E.; Conn, G.; Gaudet, T.J. Hydrometrical Control for a Variable Delivery, Positive Displacement Fuel Pump. U.S. Patent US 5715674, 10 February 1998.
58. Hansen, L.D.; Kucera, G.D.; Clemons, J.S.; Lee, J. Aircraft gas turbine engine fuel pumping systems in the 21st Century. In Proceedings of the International Gas Turbine and Aeroengine Congress and Exhibition, Birmingham, UK, 10–13 June 1996; p. V005T15A018.
59. Liu, W.; Li, Y.H.; Li, D. Review on Inlet/Outlet Oil Coordinated Control for Electro-Hydraulic Power Mechanism under Sustained Negative Load. *Appl. Sci.* **2018**, *8*, 886. [\[CrossRef\]](#)
60. Zhang, P.; Li, Y.H. Research on Control Method for Pressure Continuous Regulation Electrohydraulic Proportional Axial Piston Pump of Aircraft Hydraulic System. *Appl. Sci.* **2019**, *9*, 13376. [\[CrossRef\]](#)
61. Noriko, M.; Hitoshi, O. Fuel pump system configuration for the more electric engine. In Proceedings of the ASME Turbo Expo: Turbine Technical Conference and Exposition, Düsseldorf, Germany, 16–20 June 2014; SAE 2011-01-2563. [\[CrossRef\]](#)
62. Mohamed, E.S. Experimental study on the effect of active engine thermal management on a bi-fuel engine performance, combustion and exhaust emissions. *Appl. Therm. Eng.* **2016**, *106*, 1352–1365. [\[CrossRef\]](#)
63. Morioka, N.; Oyori, H.; Gonda, Y.; Takamiya, K.; Yamamoto, Y. Development of the electric fuel system for the more electric engine. In Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, Düsseldorf, Germany, 16–20 June 2014.

64. Seki, N.; Morioka, N.; Oyori, H.; Yamamoto, Y. Development of fuel control system for more electric engine. In Proceedings of the ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, Montreal, QC, Canada, 15–19 June 2015.
65. Oyori, H.; Morioka, N.; Seta, M.; Shimomura, Y.; Saito, H. *A Motor Control Design for the More Electric Aero Engine Fuel System*; 2011-01-2619; SAE International: Warrendale, PA, USA, 2011. [[CrossRef](#)]
66. Hazlett, R.N. *Thermal Oxidation Stability of Aviation Turbine Fuels*; American Society for Testing and Materials: Philadelphia, PA, USA, 1991.
67. Roberts, R.A.; Decker, D.D. Control architecture study focused on energy savings of an aircraft thermal management system. *J. Dyn. Syst. Meas. Control.* **2014**, *136*, 041003-1. [[CrossRef](#)]
68. Turner, H.G.; Shube, E.E. The spill control and recovery valve-a new concept for reducing fuel temperatures and the cost of ownership of gas turbine control systems. In Proceedings of the Gas Turbine Conference and Products Show, Philadelphia, PA, USA, 27–31 March 1977.
69. Paluszewski, P.J.; Desal, M. Variable displacement vane pump for turbine engine applications. In Proceedings of the GT2007 ASME Turbo Expo 2007: Power for Land, Sea and Air, Montreal, QC, Canada, 14–17 May 2007; Paper No: GT2007-27948, pp. 777–784.
70. Matsunaga, Y.; Morioka, N.; Masuda, S.; Kurosaki, M. Development of double gear fuel pump for heat management Improvement. *J. Eng. Gas Turbines Power* **2010**, *132*, 081601. [[CrossRef](#)]
71. Doman, D.B. Fuel flow topology and control for extending aircraft thermal endurance. *J. Thermophys. Heat Transf.* **2018**, *3*, 35–50. [[CrossRef](#)]
72. Huang, G.P.; Doman, D.B.; DeSimio, M.P.; Tipton, A.; Sigthorsson, D.O. Dimensional analysis, modeling, and experimental validation of an aircraft fuel thermal management system. *J. Thermophys. Heat Transf.* **2019**, *33*, 983–993. [[CrossRef](#)]