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The Application of Digital Technology in the Field of Civil Aircraft Fireproof †

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Abstract: Civil aviation flight safety has always been a core concern of the air transport industry, with aircraft fire prevention technology being crucial for ensuring the safety of passengers and crew members. This paper reviews the types of aircraft fires and the historical lessons learned from past incidents, emphasizing the importance and urgency of advancing aircraft fire prevention technology. It details the development process and current application of fire prevention technologies, with a particular focus on the role of digital twin technology, numerical simulation techniques, and multi-objective optimization algorithms in enhancing aircraft fire safety. Finally, the paper explores the future prospects of aircraft fire protection technology, suggesting that as digital technologies continue to evolve and expand, they are expected to play an increasingly vital role in building smarter civil aviation systems, thereby contributing to the high-quality development of aircraft fire prevention.

Keywords: digital technology; aircraft; fireproof

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1. Introduction

Civil aviation flight safety has always been the primary focus of the air transport industry. Fire poses a significant threat to the safety of aircraft operations and endangers the lives of passengers. Recent aviation accident investigations and data analyses indicate that aircraft fires are a critical cause of air accidents and fatalities [1]. The primary goal of aircraft fire prevention technology is to reduce the likelihood of fire incidents and mitigate the damage they cause. Given its importance to the safety of passengers, crew members, and the stable operation of civil airliners, fire prevention technology is integrated throughout various stages of the aircraft industry chain, including design, research and development, manufacturing, and airworthiness certification. It is widely applied across different compartments of the aircraft, such as the powerplant, cockpit, cabin, cargo hold, and systems, including fuel, lubrication, control, and electrical systems [2]. Therefore, aircraft fire protection technology plays a crucial role in ensuring the safety, stability, and continuous operation of aircraft, making it a major concern for stakeholders like airworthiness certification bodies, aircraft manufacturers, and aviation operators [3]. Currently, the field of aircraft fire protection is undergoing a pivotal phase of digital transformation. The rapid advancement of digital technologies, known for their efficiency, cost-effectiveness, and intelligence, has introduced new opportunities for the enhancement of aircraft fire protection systems. As science and technology continue to evolve, it is particularly important to deeply understand the current applications of these technologies in the field and to grasp the overall development trends to facilitate the smooth upgrading and sustainable development of aircraft fire prevention technology [4].

2. Aircraft Fireproof Technology

Aircraft fires can be classified into three categories based on their occurrence scenarios and characteristics: ramp fires, in-flight fires, and postcrash fires [5]. Ramp fires primarily occur when aircraft are parked or unattended. Although such fires can cause damage to the aircraft itself, they rarely pose a direct threat to the lives of those on board, as there are typically no passengers or crew members present at that time. In-flight fires mostly occur in hidden areas such as cargo holds and electronic bays, which are difficult for personnel to access. If not effectively controlled, these fires can spread to areas where passengers and crew are active, such as kitchens and lavatories. Even though fire suppression systems in these areas are designed to quickly contain fires, and the fires are usually detected and managed in time, they still pose a potential threat to the safety of those on board. During such incidents, passengers and crew may face challenges such as smoke, panic, and evacuation difficulties, and in severe cases, these fires could lead to an air disaster. Postcrash fires are the deadliest type, typically occurring during abnormal landings or when an aircraft collides with the ground or ground objects during takeoff or landing. Such collisions can rupture fuel tanks, leading to fuel leaks and large-scale fuel-fed fires. These fires are intense, spread rapidly, and are accompanied by thick smoke and toxic gases, posing a severe threat to the safety of everyone on board.

The development and application of aircraft fire protection technology have gradually advanced, driven by the profound lessons and experiences accumulated from past air accidents. Between 1965 and 2005, the global aviation industry witnessed numerous major air accidents, which not only exposed significant issues in aviation safety but also underscored the critical importance of continuously enhancing aircraft fire safety measures. In November 1965, United Airlines Flight 227, a Boeing 727, crashed while attempting to land at Salt Lake City Airport after the captain failed to recognize and stop a rapid descent, resulting in the loss of 43 lives. In May 1973, a fire broke out on Varig Flight 820, a Boeing 707, which made an emergency landing at Paris Orly Airport, killing 123 people. In August 1980, a fire on Saudi Arabian Airlines Flight 163, a Lockheed L-1011, following an emergency landing at Riyadh Airport, led to the death of all 301 people on board. In June 1983, Air Canada Flight 797, a McDonnell Douglas DC-9, caught fire after making an emergency landing in Cincinnati, resulting in 23 fatalities. In August 1985, a fire on British Airtours Flight 28M, a Boeing 737, during takeoff from Manchester Airport claimed 48 lives. In September 1998, Swissair Flight 111, a McDonnell Douglas MD-11, crashed near Halifax, Canada, killing all 229 people on board. In August 2005, Air France Flight 358, an Airbus A340, veered off the runway and caught fire while landing at Toronto Pearson International Airport; fortunately, all 115 people on board were evacuated with only minor injuries. These disaster accidents not only highlighted numerous challenges in aviation safety but also spurred the global aviation industry to increase investment in crash and fire prevention research, with the goal of reducing future accidents and improving passenger survival rates through technological innovation and enhanced emergency procedures [6].

Since the 1970s, the Federal Aviation Administration (FAA) has conducted a series of full-scale fire tests on aircraft such as the DC-7, B737, COMET 4B, and C-133 to effectively study factors that pose significant threats to the life safety of cabin occupants during aircraft fires, including heat release, smoke toxicity, and smoke concentration [7–11]. The research encompassed a wide range of topics, including chemical reaction combustion, complex turbulent flow, heat and mass transfer, and phase change due to evaporation. These studies involve the analysis of mass, momentum, energy, and chemical components within a complex environment characterized by three-dimensional, nonlinear, unsteady, and non-equilibrium kinetic processes.

In the 1980s, the FAA developed a comprehensive Aircraft Fire Protection research program that encompassed fire management, material management, and personnel management [12]. The program aimed to address the cabin hazards of transport aircraft caused by external fuel fires or in-flight fires, with a particular focus on the effects of the combustion of interior materials. The FAA sought to improve the survivability and safety of

occupants in the event of cabin fires by developing fire test methods and standards for interior materials, promoting the use of materials that could better withstand fire hazards.

The program also reviewed and recommended effective fire management methods, fire suppression systems, and evacuation aids. Based on the research findings, the FAA provided guidance on the design, development, manufacturing, and airworthiness of aircraft. For example, in FAA AC 20-135 [13], clear requirements were established for the fire performance and fire resistance of aircraft materials, leading to the development of standard test methods for airborne materials [14]. These include tests such as the heat release test, vertical combustion test, horizontal combustion test, seat cushion combustion test, smoke toxicity test, and smoke concentration test.

3. Digital Technology Application

3.1. Digital Twin Technology

With the continuous advancement of electronic computer technology and the ongoing improvements in numerical computing science, research methods in aircraft fire prevention technology are increasingly developing in the realm of full three-dimensional digital simulation.

Digital twin technology, a simulation analysis system based on measured data and physical models, integrates multidisciplinary, multi-scale, and multi-physical field characteristics. Through this system, the entire life cycle of physical equipment can be mapped in a virtual space. The digital twin system operates on multiple levels of synergy, which includes data assurance, simulation optimization, digital capabilities, user experience, and more. The data protection layer's primary functions involve data collection, transmission, operation, and management. The simulation optimization layer focuses on scientifically processing and analyzing data through numerical simulation and artificial intelligence technologies. The digital functional layer is responsible for making practical use of the processed results, while the experience layer provides a more direct sensory experience for users.

In recent years, digital twin technology has been widely applied across various fields. For instance, the U.S. Air Force Research Laboratory (AFRL) introduced the concept of "aircraft digital twins" to simulate and analyze the aircraft design and development process [15]. GE plans to implement real-time monitoring, timely inspection, and predictive maintenance of aero engines using digital twin technology, and Rolls-Royce uses digital twins to fine-tune engines and simulate performance under various conditions, further improving engine performance and reliability [16]. Furthermore, Gartner has recognized digital twin technology as one of the top ten strategic technologies for the future, highlighting its significant role in the industry. Siemens developed the MindSphere open IoT operating system to connect physical objects to the digital world, driving a closed-loop innovation model. Dassault applied its 3D Experience platform to the design and development of the Rafale fighter and Falcon business jets [17]. Lockheed Martin has utilized digital twin technology in the manufacturing process of the F-35 fighter jet, enhancing production efficiency and reducing costs [18]. Northrop Grumman leveraged digital twin technology to shorten the F-35 airframe development cycle and optimize the production process. Boeing has enhanced the first-pass yield of parts using digital twin technology, which has improved manufacturing quality. Boeing also employs rigorous data standards, networks with other plants via the cloud, and uses advanced artificial intelligence to build systems more simply and efficiently, allowing for flexible, scalable production to meet rapid development, deployment, or changes in customer needs and requirements.

3.2. Numerical Simulation Technique

Computational fluid dynamics (CFD) is a significant branch of fluid mechanics that uses numerical methods to solve mathematical equations describing fluid motion with the aid of computers, thereby uncovering the physical laws governing fluid behavior. This field not only investigates the spatial physical characteristics of stationary flow bodies but also

explores the spatiotemporal physical characteristics of unsteady flow bodies. For problems that are challenging to solve through theoretical analysis and experimentation, CFD offers an effective means of obtaining comprehensive and quantitative information about the entire flow field. The finite element method (FEM) is a widely used numerical approximation method for solving problems in mathematical physics. Its basic principle is rooted in the variational principle and the weighted residual method [19]. By dividing a continuous system into a finite number of non-overlapping elements and selecting appropriate nodes within each element as interpolation points for the solving function, the variables in the differential equations are transformed into linear expressions. These expressions are composed of the node values of each variable or its derivatives and the interpolation functions. Through this process of discretization, complex differential equations can be solved.

The finite element method is primarily employed to solve the relationship between force and displacement in structures. In practical applications, when fluid interacts with a solid, the fluid's motion may generate a stress load on the solid, potentially causing deformation. This deformation, in turn, affects the flow field, creating a complex system of fluid–structure interaction. This interaction becomes even more intricate in the physicochemical scenarios of an aircraft fire. The solid materials in an aircraft may experience physical phenomena such as thermal deformation, thermal fatigue, and thermal failure, as well as chemical phenomena like pyrolysis, carbonization, and coking under the influence of high back wind speeds and elevated flame temperatures.

As a result, the numerical simulation of aircraft fire prevention is a complex process involving computational fluid dynamics, computational combustion, numerical heat transfer, computational solid mechanics, and composite mechanics. This process requires multi-field coupling calculations of fluid, heat, and solid interactions, which necessitates the integration of CFD and FEM.

3.2.1. Full-Scale Fire Simulation

Since the 1990s, researchers have started using numerical simulation methods to simulate aircraft fire scenarios. However, due to the limitations of early aircraft fire prediction models and the restricted computing power of electronic computers at that time, simulations often relied on thermal boundary conditions or volumetric heat sources to represent the fire source. This approach could not effectively replicate the flame spread process, leading to limitations in the accuracy of the simulations. Consequently, this simulation method had limited guiding significance for aircraft fire prevention and control [20]. With the continuous development of numerical simulation technology, it has been possible to carry out simulation calculation research for local area and full-scale aircraft [21,22].

The University of Greenwich in the United Kingdom has combined data from the FAA's full-scale aircraft fire tests with historical real-world accidents to use numerical simulation methods to recreate the fire scenarios for C-133 and B-737 models. During the simulation process, various numerical models were applied, including flame propagation models, vortex dissipation models, toxicity models, and multi-ray radiation models [23–27]. By analyzing the simulation data, research efforts were made to improve cabin structure and material design, evaluate the survival probability of passengers, and establish airworthiness regulations. The research team also utilized fire simulation technology to assist the Transportation Safety Board of Canada (TSB) in investigating the in-flight fire of a Swissair MD-11, aiding in fire tracing efforts.

The Civil Aviation University of China has carried out numerical simulation studies on full-scale fire scenarios for aircraft models such as the A-380 and B-737 [28,29]. Through this research, the Fire Simulation Curve proposed by Barnett [30] in 2002 was revised to better apply to aircraft fire simulations. The revised calculation results showed good agreement with NASA's test data [31]. The study also identified that the temperature and concentration of carbon monoxide produced by aircraft fires are the primary factors threatening the life and health of escapees. Based on these findings, an optimized fire emergency rescue and evacuation plan was proposed.

3.2.2. Full-Scale Fire Simulation

According to AC20-135, the component or material under test must withstand the standard flame environment generated by the specified burner, thereby demonstrating compliance with the engine fire airworthiness requirements. A study conducted by the Sarov Engineering Center in Russia introduced a computational fluid dynamics/finite element method to predict component behavior under the local influence of a burner jet, using a real gas turbine tank as an example. In this model, heat and mass transfer are considered, and a unidirectional fluid–solid coupling method is employed to solve both the transfer and strength problems [32]. The research indicates that, at the current level, numerical simulation techniques are sufficiently mature to accurately predict the behavior of complex components under intense thermal conditions. Furthermore, the results show good agreement between numerical simulations and experimental data, particularly in terms of temperature and time, confirming the reliability of existing aero engine assessments.

3.2.3. Material Fire Simulation

The study of aviation materials' performance in fire environments is a critical field. Numerical simulation has emerged as a key research tool to investigate the behavior of these materials under extreme conditions. This method has been extensively used to analyze the heat transfer behavior of aviation composite materials in fire conditions. By establishing heat transfer models, key parameters such as temperature distribution and heat flux within the materials can be accurately predicted, providing a strong foundation for the optimal design of these materials. Additionally, numerical simulation is employed to evaluate the performance of thermal insulation materials in high-speed aircraft operating under thermal environments. By creating fluid dynamics models, the thermal response of materials under high-temperature and high-pressure conditions can be simulated, offering crucial reference information for material selection. Moreover, numerical simulation is utilized to simulate liquid diffusion and fire processes following aircraft impact accidents. Through the establishment of multiphase flow models, the development of fuel leakage and subsequent fires can be predicted, providing valuable insights for the formulation of accident emergency plans. Further applications of numerical simulation include studying the explosion characteristics of flammable gas mixtures within explosion-proof enclosures. By developing chemical reaction kinetic models, the pressure and temperature generated by explosions can be predicted, offering important guidance for the design of explosion-proof enclosures. In summary, numerical simulation is a vital tool for studying the performance of aviation materials in fire environments. It is widely applied in material design, structural analysis, and performance evaluation, making significant contributions to enhancing aircraft safety [33].

3.3. Multi-Objective Optimization Algorithm

The multi-objective parameter optimization technique is a method used to find the best balance between multiple objectives that may conflict or be interdependent. This technology is widely employed in engineering design, economics, operations research, computer science, and other fields. The core challenge lies in managing the trade-offs between multiple goals, as in practical applications, these goals often cannot be optimized simultaneously. The improvement of one objective often necessitates the sacrifice of another. Therefore, the goal of multi-objective optimization is to identify a set of "Pareto optimal solutions", in which no single solution is superior to others across all objectives. To achieve this, researchers have developed various algorithms, such as genetic algorithms, particle swarm optimization, simulated annealing, and the Non-dominated Sorting Genetic Algorithm II (NSGA-II) [34]. Each algorithm has its own characteristics and is suited to different types of optimization problems. These algorithms effectively approach the Pareto frontier in complex solution spaces while maintaining population diversity, providing decision-makers with a range of solutions to choose from. Despite challenges such as com-

putational complexity and dynamic environments, multi-objective optimization technology is expected to play an increasingly important role in various fields as research deepens and technology evolves [35]. This will provide powerful tools for solving practical problems and assist decision-makers in making more informed and reasonable choices among competing objectives. In the aviation field, optimizing fire safety design is a crucial area of research, encompassing the fire protection systems in passenger cabins, cargo holds, and engine compartments. Choi et al. have conducted a series of significant studies in this domain. In 2016, Choi and colleagues proposed a multi-objective optimization method for cabin fire safety design, which comprehensively considers key indicators such as temperature, pressure, and weight. This method optimizes the layout and material parameters of the cabin to significantly enhance its fire safety performance [36]. In 2017, Choi and his team extended their research to the optimization of cargo hold fire protection systems. They employed a multi-objective optimization design method, taking into account factors like temperature, pressure, and weight, to finely tune the layout and parameters of the fire extinguishing system in the cargo hold, achieving safer and more reliable fire protection performance [37]. In 2018, Choi et al. proposed another innovative multi-objective optimization method for engine compartment fire protection systems. They conducted a comprehensive optimization of the fire protection system in the engine compartment, optimizing several key indicators such as temperature, pressure, and weight to ensure safer and more effective fire protection [38]. In 2019, Choi and colleagues introduced advanced machine learning techniques to improve the optimization efficiency of engine compartment fire protection systems. They continued to use a multi-objective optimization approach, simultaneously optimizing system layout and parameters while employing machine learning models to accelerate the optimization process significantly [39]. In their 2020 and 2021 research, Choi et al. explored fire protection optimization for composite structures. They comprehensively considered key performance indicators such as temperature, pressure, and weight, optimizing the fire protection design of aircraft composite structures to enhance overall fire safety [40].

4. Discussion and Conclusions

Safety is the lifeline of the civil aviation industry, and innovation is the guiding force. Aircraft fire prevention, as a crucial technology for ensuring the safety of passengers and crew, plays a key role in the digital transformation of the industry. Compared to traditional testing methods, digital approaches offer numerous advantages, including improved design optimization efficiency, reduced research and development costs, enhanced safety, and the promotion of green environmental practices. In the future, digital technology will continue to play a significant role in aircraft fire protection. It will provide robust support for various aspects such as the digital management of the entire aircraft fire testing process, full-scale aircraft fire parameter prediction, aircraft component fire vulnerability assessment, and the analysis and summary of airborne material test data. As technology continues to advance and its applications expand, digital technology is expected to play an even more vital role in building a smarter civil aviation industry and contributing to the high-quality development of aircraft fire prevention.

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