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An Engine-Level Safety Assessment Approach of Sustainable Aviation Fuel Based on a Multi-Fidelity Aerodynamic Model

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Abstract: Safety is essential for sustainable aviation fuels (SAFs). However, evaluating SAFs' impacts on aero-engine safety is challenging because it involves multiple space scales and the strongly coupled relationships of aero-engine components. Aiming at addressing this problem, a model-based approach is proposed to establish the relationship between the fuel-level physical properties and engine-level safety parameters. Firstly, a unified modeling criterion is proposed to consider the interrelations of aero-engine components. Under this criterion, aero-engine secondary air system (SAS) components are included in SAF safety assessment, since they have non-neglectable influences on aero-engine safety. Secondly, this paper proposes a surrogate-based iteration strategy to embed the combustor's high-dimensional computational fluid dynamics (CFD) model into the aero-engine flow network model. Then, the proposed model-based safety assessment approach is applied to a Fischer–Tropsch hydro-processed synthesized paraffinic kerosine (F-T SPK) safety assessment case. The effects of fuel flow and blending ratio are considered. The results indicate the necessity to evaluate SAFs' safety at the aero-engine level and consider the influences of SAS components. The proposed model-based approach may provide a preliminary screening before SAFs' certification tests. This convenience may be beneficial for reducing the cost and accelerating SAFs' application.

Keywords: sustainable aviation fuel; safety; aero-engine; multi-fidelity; model-based assessment

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1. Introduction

Because of climate change and the rapidly growing transport demand, it is urgent for the aviation industry to control its green-house gas (GHG) emissions [1]. Plenty of researchers have devoted their efforts to studies related to reducing aviation GHG emissions through various technical approaches, including optimizing operational strategies, developing advanced aircraft/engine designs, and finding sustainable energies [2]. The first two of these strategies could effectively slow down the growth rate of GHG emissions. It is also necessary to find sustainable energies to seek net-zero carbon emissions or carbon neutralization for the aviation industry. Sustainable energies are supposed to have low emissions, high safety, and high energy density. Several attempts have been made to employ hydrogen, electrical batteries, and sustainable aviation fuels (SAFs) in the aviation industry [3,4]. Represented by bio-fuels and other eco-friendly synthesized carbon-based fuels [5], SAFs have the most promising potential to achieve life-cycle net-zero or even negative carbon emissions [6,7], since the ingredients may sequestrate the carbon dioxide from the atmosphere. In addition, SAFs have better compatibility with the current propulsion systems and infrastructure [8] than other novel energies, requiring minimal changes in aero-engines and ground facilities. SAF's moderate energy density is also beneficial for widely applying them in various situations with different flying distances and passenger capacities [9]. Because of these advantages, SAFs are widely recognized as an effective solution to achieve carbon neutralization within the short and midterm.

SAFs' influence on aero-engines safety is the decisive factor in whether it has an acceptable application risk. With the growing numbers of novel feedstocks and refining pathways [10,11], SAFs may have diverse compositions and properties compared to fossil fuels, such as a higher heat value, fewer aromatics, and a more concentrated carbon distribution [12,13]. These differences may lead to different burning behaviors and result in non-neglectable influences on aero-engine operation. These influences are closely related to passenger safety, which should be thoroughly considered and carefully evaluated.

Technically, both experimental and numerical approaches can be used for SAF's engine-level safety assessment and certification. Industrial practice usually utilizes well-established component and engine tests [14] to validate whether the SAF can support the engine's safe operation. These tests provide a practical pathway for SAF safety assessment. They have guaranteed the safety application of several types of SAFs. However, these approaches may also be quite costly and time-consuming [15]. Numerical or model-based approaches are considered an effective supplement to these tests and a promising way to reduce the costs. They may also support researchers in quantifying SAFs' influences on aero-engine safety and reveal the underlying mechanisms. These advantages may be beneficial for SAF's development. Therefore, there is a great demand to establish a reliable model-based approach to evaluate SAF's impacts on aero-engine safety [16].

It is quite challenging to quantitively evaluate SAFs' influence on aero-engine safety via model-based approaches, since this involves multiple research levels and space scales. Published SAF research includes studies on the aero-engine system, component/subsystem, and fundamental process [17,18] levels. Analysis on each level is supported by the next level, as indicated in Figure 1. Engine-level safety researchers are usually concerned about SAFs' influences on the engine's safety-critical parameters (SCPs) [19], such as the rotor axial load safety margin and turbine entry temperature. Researchers prefer low-fidelity aerodynamic models [20] to rapidly acquire the entire engine's response and evaluate the SCPs' deviation. Meanwhile, component-level research pays close attention to component performances, such as the combustor efficiency. Researchers prefer to utilize high-fidelity computational fluid dynamics (CFD) models to closely observe the combustion process and detailed flow field in a combustor [21]. It is challenging to combine these models with different resolutions to establish the mapping relationship between SAFs' properties and the aero-engine's SCPs.

Moreover, engine models in published engine-level research may be insufficient for analyzing SAFs' influences on aero-engine safety. These models usually only consist of gas flow path (GFP) components (such as the compressor, combustor, and turbine), because researchers mainly focus on the engine's performance (such as thrust and specific fuel consumption) rather than safety. Nevertheless, evaluating the engine's SCPs involves massive secondary air system (SAS) components [22]. It is necessary to consider SAS components for SAFs' engine-level safety assessment. The importance is twofold. On the one hand, the characteristics of SAS components determine the air bleeds from the GFP, which may significantly deviate the co-work point of GFP components and the engine's operation state. Published research has shown that a 1% increase in air bleeds requires an increase of 11K in the turbine entry temperature to maintain the same thrust level [22]. In addition, the compressed air in modern gas turbines bleeds at a rate of up to 20% [23]. The effect of air bleeds through the SAS components on the SCPs is non-neglectable. On the other hand, the SAS components are also closely related to the integrity of the life-limited parts [24]. For instance, the turbine disk is immersed in the air flow within the SAS. The flow and heat transfer characteristics of SAS components directly affect the thermal load and fatigue life of the life-limited parts [25], which are vital to aero-engine safety and airworthiness. Therefore, it is also of great importance for SAF's engine-level safety assessment to introduce SAS component modeling techniques, solving both the GFP and SAS components simultaneously.

Fortunately, advanced aero-engine modeling techniques could be introduced into SAFs' engine-level safety assessment to address the abovementioned difficulties. Firstly, researchers proposed the integrated engine model [26] to calculate the coupling of the GFP and SAS components, which are strongly inter-related and co-determine the engine's working state. This model solves the GFP and SAS components via the component method and network method, respectively, and matches them with bleeding/returning modules. This method has been used to evaluate the aero-engine SCPs when adopting fossil fuels. It may also be applicable for evaluating SAF's influence on aero-engine safety, especially the load of life-limited parts. Secondly, the data-zooming method could embed high-fidelity component models into the low-fidelity engine system model [27,28] to effectively improve the engine model's resolution. This method may apply to the combustor to improve the engine model's compatibility with different fuels, thus evaluating SAFs' impact on engine-level SCPs. These aero-engine modeling techniques may support us in establishing model-based approaches for SAFs' engine-level safety assessment with necessary improvements.

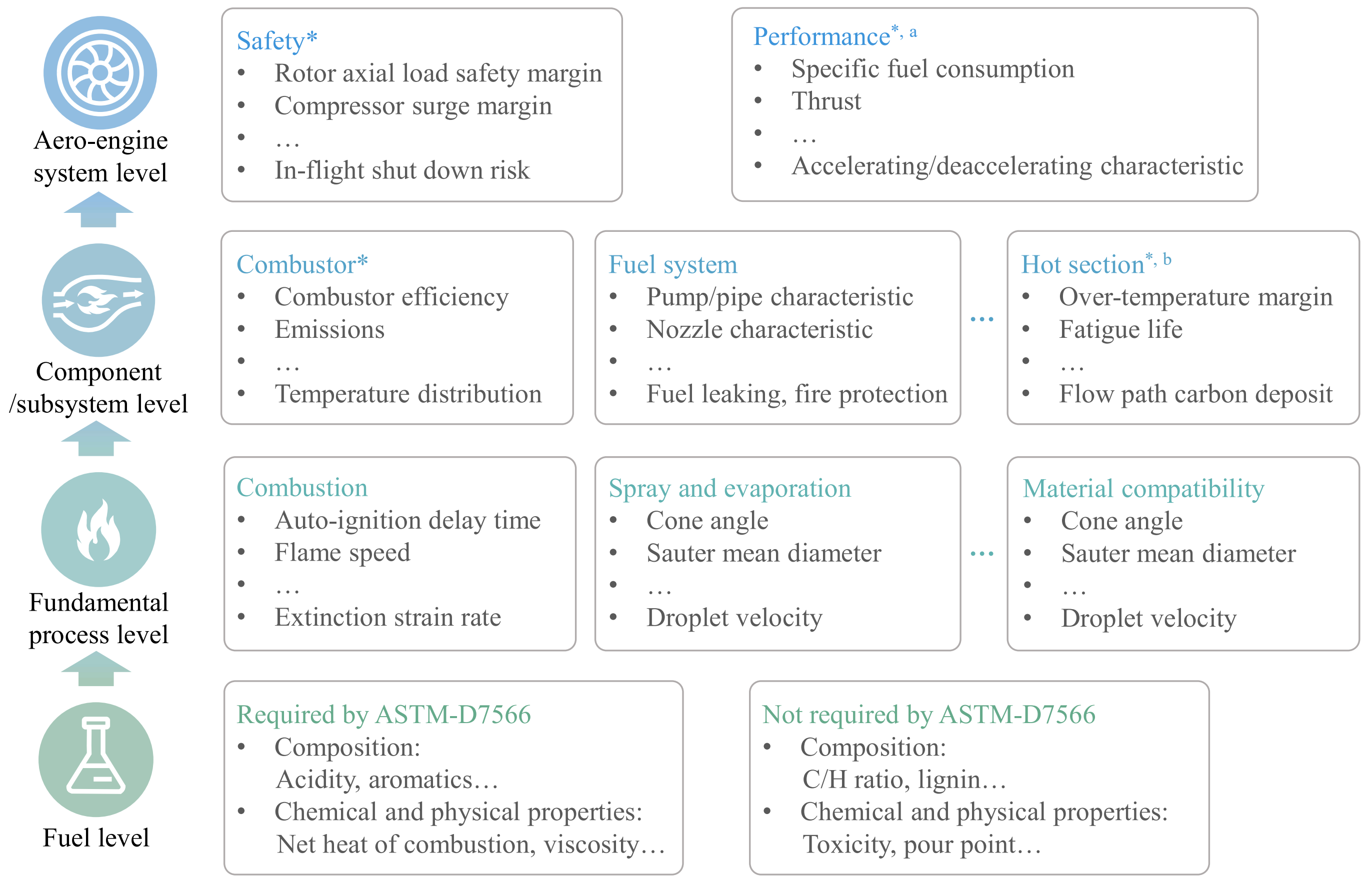

Figure 1. Different research levels of SAF's influences on aero-engine. * The scope of this paper. a. Performance parameters are generally considered as SCPs in this paper, since they may influence the aircraft's survivability when encountering dangerous. b. Some component-level effects are suggested to research within the aero-engine system environment, since the component's boundary conditions are determined by the co-work point.

In summary, there is very limited published research simulating and quantitively discussing SAFs' engine-level influences from a safety perspective. Published engine-level research [29–32] mainly focuses on SAFs' influence on aero-engine performance, and barely considers the conservation and coupling relationships between the combustor and the engine. The reason for this deficiency is the lack of effective approaches to achieve conservation throughout the engine flow field and to integrate simulation models with different fidelities.

Therefore, the main scope of this research work is to develop a model-based approach to evaluate SAF's influence on aero-engine safety. A multi-fidelity integrated engine model

(MF-IEM) is proposed to establish the mapping relationships between SAFs' properties and aero-engine SCPs. The MF-IEM solves unified aerodynamic conservation relationships for both GFP and SAS components. In addition, the combustor part of the MF-IEM was modified using a high-fidelity CFD model with a novel surrogate-based iteration strategy, achieving the conservation between the combustor and the engine model. The MF-IEM is proven to have sufficient resolution to discriminate SAFs' influences on aero-engine safety. There is also the promising potential to develop a comparative assessment approach for SAF's safety based on the MF-IEM.

The rest of this paper is organized as follows: Section 2 describes the modeling approaches and multi-fidelity iteration strategy, establishing the relationship between fuel-level properties and engine-level SCPs. Section 3 applies the proposed approach to a study case, evaluating SAF's influences on engine's safety quantitively. Section 4 discusses the potential of utilizing the model-based approach for SAF certification. Section 5 summarizes this paper and puts forward future research directions.

2. Materials and Methods

2.1. Integrated Engine Modelling

A low-fidelity integrated engine model (IEM) was first established to evaluate engine SCPs at the co-work point of massive engine components. The IEM was designed to have two categorized modules: the node and the component module. The former guarantees the global conservation of massive components, including the fluid and the mechanical nodes, while the latter describes the detailed behaviors of each component, including the GFP and SAS components.

As the connector of adjacent or related components, the node module solves various GFP and SAS components simultaneously with a unified conservation criterion. The fluid node ensures mass and energy conservations at each interface between adjacent components. The momentum transfer at the interface is neglected, assuming that the volumes between the components are sufficiently large. Under the steady states of aero-engines, the fluid nodes ensure conservation by solving Equations (1) and (2):

$$\sum_{i=1}^{n} \dot{m}_i = 0 \tag{1}$$

$$\sum_{i=1}^{n} \dot{H}_i = 0 \tag{2}$$

where the enthalpy flowrate is calculated as $\dot{H} = \dot{m} \cdot c_p \cdot T^*$ for related components.

It is also important for aero-engine spools to guarantee the power balance between power-generating (such as the turbine) and power-consuming components (such as the compressor). Under the steady states of aero-engines, the mechanical nodes ensure energy conservation by solving Equation (3):

$$\sum_{i=1}^{m} \dot{W}_i = 0 \tag{3}$$

where the power flowrate $\dot{W}$ equals the enthalpy flowrate rise over each related component.

For convergence consideration, it is preferred to solve these conservations using the time-marching method [33]. Therefore, Equations (1)–(3) could be transformed into the dynamic form by adding the term at the right side of the equations, indicated as Equations (4)–(6):

$$\sum_{i=0}^{n} \dot{m}_i = V \cdot \frac{\partial \rho}{\partial t} \tag{4}$$

$$\sum_{i=0}^{n} \dot{H}_i = V \cdot \frac{\partial(\rho \cdot c_v \cdot T)}{\partial t} \tag{5}$$

$$\sum_{i=0}^{m} \dot{W}_i = J \cdot \frac{\partial (0.5 \cdot \omega^2)}{\partial t} \quad (6)$$

where Equations (4) and (5) represent the aerodynamic conservations achieved by fluid nodes, and Equation (6) represents the rotor-dynamic conservation achieved by mechanical nodes. Under constant aero-engine boundary conditions and fuel flows, the solution of Equations (4)–(6) would converge with the solution of Equations (1)–(3) as the solving time t enlarges. These conservation relationships are generally applicable for both GFP and SAS components with great convergency.

The component module describes the nonlinear responses of mass, enthalpy, and power flowrate under the boundary conditions set by the node module, such as the total pressure P^*, total temperature T^*, and rotor speed n. Notably, the combustor's preliminary response is acquired by means of a semi-analytical model. Since the combustor is the stationary part of the aero-engine, it does not involve the power balance with the rotating parts or the spools. Therefore, the model mainly includes mass and energy change over the combustor, indicated as Equations (7)–(8):

$$\dot{m}_{out} = \dot{m}_{in,a} + \dot{m}_{in,f} \quad (7)$$

$$\dot{H}_{out} = \dot{H}_{in,a} + \dot{m}_{in,f} \cdot LHV \cdot \eta_c \quad (8)$$

where the fuel's enthalpy flow is neglected in Equation (8) since it is relatively small compared to its internal energy. The air flow at the combustor inlet $\dot{m}_{in,a}$ and the combustion efficiency η_c are dependent on aerodynamic parameters of the upstream and downstream fluid nodes. They can be interpolated by the combustor's characteristic map and modified by the experience coefficients Cw and $C\eta$.

This low-fidelity model can be solved by non-linear algorithms, such as the N+1 algorithm [34]. At each pseudo time step, the algorithm first guesses the boundary conditions on the fluid and mechanical nodes. Then, the algorithm may obtain the components' responses and calculate the residuals of Equations (4)–(6). Next, the algorithm modifies the guess values until the result reaches acceptable accuracy.

Compared to the conventional engine modeling approaches [26], the proposed integrated modeling approach with the unified criterion can achieve the conservation of GFP and SAS components without extra blending/returning modules. This convenience provides a better consistency between the model and the engine structure and simplifies the modeling complexity. In addition, the proposed model can solve the engine components simultaneously under the unified criterion without assigning different numerical solvers for GFP and SAS components, respectively. This may be beneficial for achieving better numerical efficiency for engine model calculation, which is important for the multi-fidelity iteration.

This low-fidelity IEM could effectively calculate the SCPs throughout the engine flow field, considering the GFP and SAS components' impacts on the aero-engine's operation state. It not only shows excellent numerical convergency, but also has the capacity to be modified by high-fidelity models. Therefore, the low-fidelity IEM can be recognized as an adjustable surrogate model for further detailed analysis.

2.2. Multi-Fidelity Iteration Strategy

This paper proposed a multi-fidelity iteration strategy to embed the combustor's high-fidelity CFD model into the engine's low-fidelity model, establishing the mapping relationship between SAFs' properties and the engine's SCPs through the combustor's performances.

The objective of this strategy was to seek accurate SCP values at the engine's co-work point influenced by SAF's properties. The multi-fidelity strategy is indicated in Figure 2. Firstly, the low-fidelity IEM provides rough aerodynamic boundary conditions to the combustor's CFD model, including combustor inlet total pressure P^*_{in}, total temperature T^*_{in}, outlet mass flowrate $\dot{m}_{out}$, and fuel flowrate $\dot{m}_{in,f}$. These boundary conditions may not be accurate enough until a few iterations have been made. The reason for this is that the low-fidelity IEM estimates the combustor's performances via the semi-analytical model, which may be insufficient for considering SAF properties and the combustor's structure.

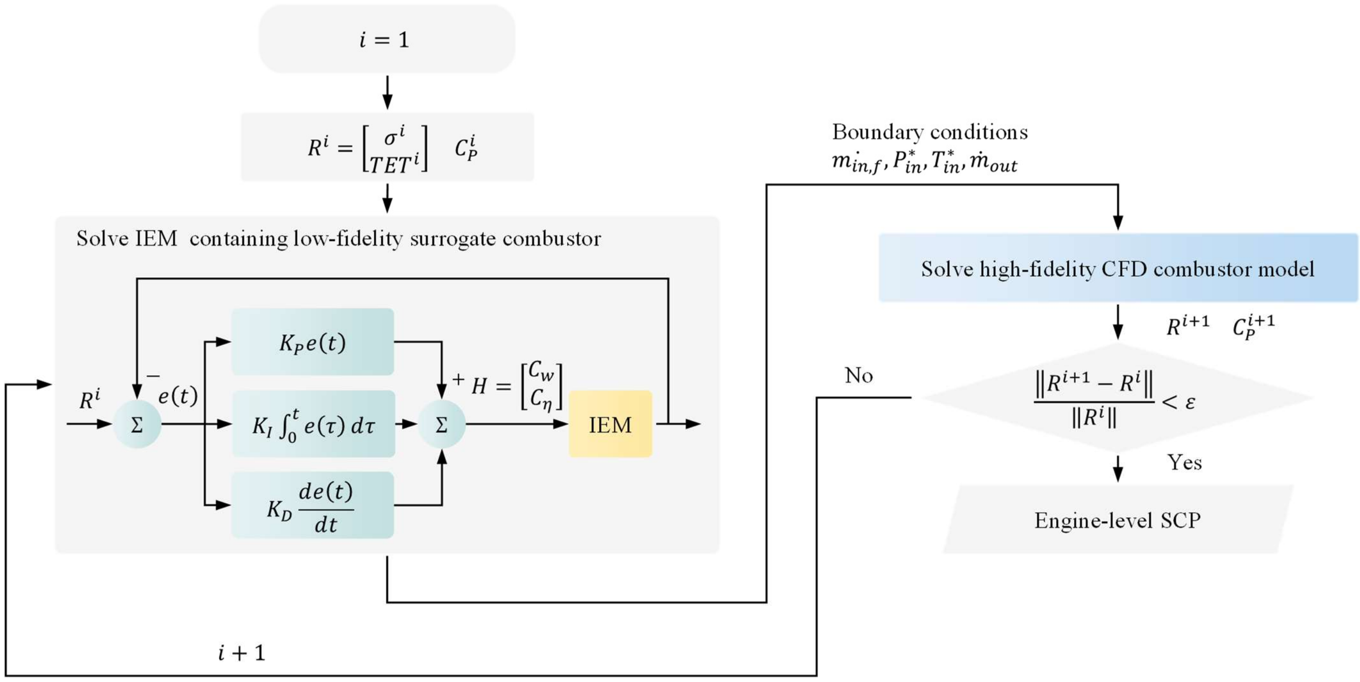

Figure 2. Surrogate-based, multi-fidelity iteration strategy.

Secondly, the CFD model may analyze the detailed combustion process, flow pattern, and combustor performances under the abovementioned boundary conditions calculated by the IEM. The impacts of SAF properties and combustor structure are considered. Concerned performance parameters in this paper include the combustor's pressure recovery coefficient σ, outlet temperature (also known as the turbine entry temperature) TET, and outlet pressure non-uniform coefficient C_P [35]. In other words, the CFD model outputs σ, TET, and C_P in each multi-fidelity iteration for further engine-level simulation.

Next, the CFD model returns the combustor's performance $R = [\sigma, TET]^T$ to modify the IEM's low-fidelity surrogate model by adjusting the coefficients $H = [C_w, C_\eta]^{\mathrm{T}}$. The outlet pressure non-uniform coefficient C_p is directly set to the high-pressure turbine, which is located adjacently downstream of the combustor, considering the influence of the pressure inlet non-uniformity on the turbine efficiency. After the modification, the low-fidelity model would be able to provide more accurate boundary conditions for the next iterations. Guided by the multi-fidelity iteration strategy, the engine-level SCPs at co-work points would converge to accurate values as the residual error of the combustor's performances reduces to an acceptable value ε.

Notably, this paper proposed a control-theory-analogy training algorithm when modifying the low-fidelity IEM. Governed by Equations (4)–(8), the IEM can be regarded as a non-linear system or an aerodynamic-conservative network model. The components can be regarded as the flow and power links between the nodes. The experience coefficient H can be regarded as an adjustable parameter to be trained by the algorithm. The training algorithm for the IEM regards the high-fidelity model's results R as the control targets. The error between the models is defined as Equation (9):

$$e(t) = R_{IEM}(t) - R_{CFD}^i \tag{9}$$

Analogized to the control theory [36], the adjustable coefficients can be modified by the proportional, integral, and derivative values of the error, as shown in Equation (10):

$$H(t+1) = H(t) + K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de(t)}{dt} \quad (10)$$

Under steady engine operating conditions and constant fuel flows, the adjustable coefficient H would converge to appropriate values. The error between the low-fidelity and high-fidelity models would approach acceptable accuracy at the same time, outputting the well-trained IEM. This control-theory-analogy training algorithm does not depend on the gradient calculation. It shows great convergence with appropriate values of the coefficients K_P, K_P, and K_D. This is beneficial for embedding the high-fidelity combustor model into the low-fidelity engine model.

The conventional approach to embedding the combustor's CFD model into the engine model has to acquire the combustor's characteristic map before the engine-level calculation. Obtaining the characteristic map requires massive CFD calculations over a wide range of the combustor's boundary conditions. The higher the accuracy required for the map and the engine-level matching calculation, the denser the sampling point of the combustor CFD calculation. The calculation time also increases according to the power law when considering the fuel properties as the independent variable of the combustor's characteristic map and the input of CFD simulation. The proposed multi-fidelity algorithm only needs to compute the combustor's CFD model near the engine-level matching state, attributed to the rough guess of boundary conditions provided by the engine model in each multi-fidelity iteration. The multi-fidelity algorithm shows great convergence, and it can usually obtain the co-work point within ten iterations and CFD calculations with appropriate initial values. This convenience is beneficial for reducing the computation resource costs when evaluating an SAF's engine-level safety impacts, achieving the same engine-level matching calculation accuracy as the conventional approach. In addition, the proposed approach is beneficial for considering the impact of the combustor's high-dimensional characteristics on aero-engines, such as the outlet pressure's non-uniformity or the aerodynamic parameters' distribution.

Combining the IEM and the multi-fidelity iteration strategy, the proposed MF-IEM could not only effectively evaluate the SCPs through the engine flow field, but also recognize the SAF's property differences in detail. It may be applicable for quantifying SAFs' influences on aero-engine safety.

3. Case Study

3.1. Model Setting and Validation

This section applies the proposed method to a Fischer–Tropsch, hydro-processed synthesized paraffinic kerosene (F-T SPK) [37] engine-level safety assessment compared to Jet A. The study is conducted on a two-spool, high-bypass engine, configurations of which are the utmost common in commercial use. The topology of the engine's flow path is indicated as Figure 3. The GFP components are shown in blue or yellow frames, and the SAS components are shown in green. Notably, the engine contains three safety-critical SAS flow paths, responding for turbine disk cooling, rotor axial load control, and gas ingestion prevention. Their flow and heat transfer conditions not only influence the engine's performance at the co-work point, but are also directly related to the turbine disk's load. Based on the aerodynamic parameters of SAS flow paths, the heat transfer condition in the turbine disk cavity could be further estimated through the experience formula [38].

Considering that the research's main objective is to validate the feasibility of the proposed engine-level safety assessment approach, a simplified combustor's CFD model is designed for further discussion. This model describes an axial-flow combustor, which is commonly used in high-bypass turbofan engines. Unstructured meshes are used for the fluid domain computations. For turbulence simulation, published articles tend to use large eddy simulation (LES), the Reynolds stress model (RSM), and the realizable k-ε model [39,40]. The LES and RSM can capture the flow details inside the combustion chamber with high computational accuracy but have high demands regarding computational resources. The realizable k-ε model shows satisfactory performance in calculating the combustors' performance, which is concerned by the engine's calculation. The realizable k-ε model also requires a lower computation time than the other abovementioned turbulence models. Considering the iteration calculation process between the CFD model and the engine model, it is necessary to obtain the CFD results in a short period of time with acceptable computational accuracy. Therefore, the realizable k-ε model is used for turbulence simulation, and the scalable wall function is used for wall treatment. The eddy-dissipation model [41] is used to calculate turbulence–chemistry interactions. This CFD model was validated through experimental data in [42]. This model shows satisfactory accuracy in calculating the turbulent flame's temperature profile, which is a typical process for turbulent mixing and chemical reactions in the combustor chamber. The grid independence and y^+ criterion have been verified. It is assumed that the fuels are heated to the combustor's inlet air temperature by the fuel–air heat exchanger before the injection.

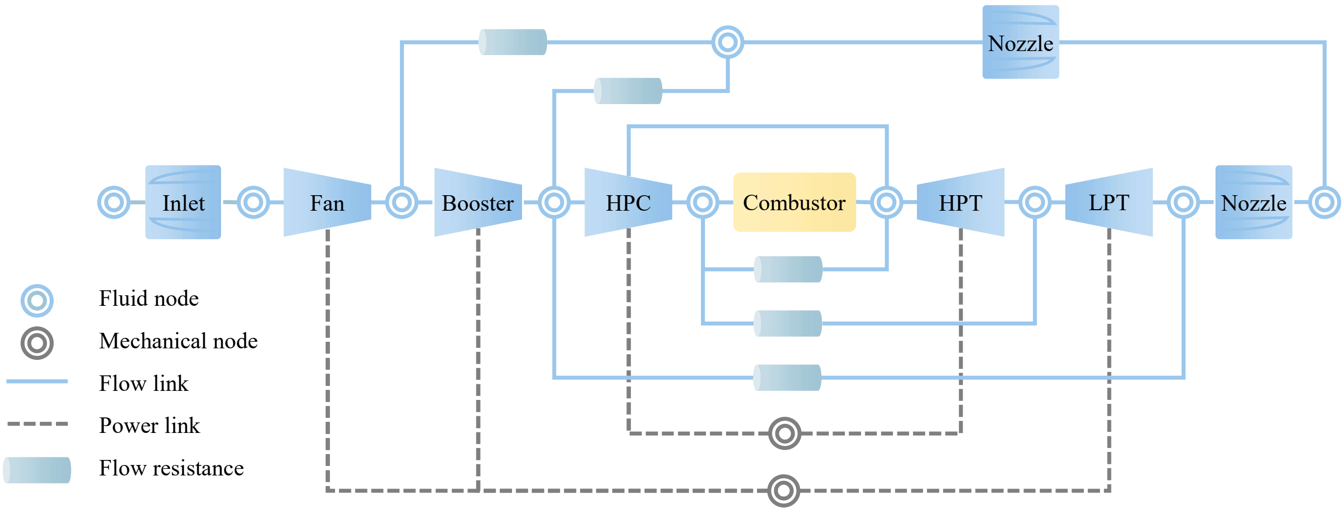

Figure 3. Aerodynamic-conservative network topology of the IEM.

Moreover, surrogate fuels are designed to evaluate LHV's influence on aero-engine SCPs. Published research has revealed that SAF's LHV is one of the most important properties for the engine-level safety impacts [43]. Therefore, this paper designs a surrogate fuel of F-T SPK to achieve 3.27% higher LHV than Jet A [44] by blending n-octane vapor (C_8H_{18}) with nitrogen.

The MF-IEM is validated at the engine's steady-state design point. The validation is conducted in a sea-level environment. The fuel flow, environmental pressure, and temperature are inputted into the MF-IEM according to the design value. Under these boundary conditions, the engine's network and the combustor's CFD models converge to the co-work point according to the surrogate-based iteration strategy. The convergence criterion for the IEM, the CFD model, and the multi-fidelity iterate algorithm are set to 10^{-6}, 10^{-6}, and 10^{-4}, respectively. Then, the MF-IEM outputs the aerodynamic parameters at the co-work point and they are then compared to the design value [45]. Table 1 lists the calculation results of the engine's aerodynamic parameters, such as the specific fuel consumption SFC, the specific thrust F_N, the bypass ratio BPR, the corrected speed of the high-pressure rotor $n_{cor,HPR}$, and the low-pressure rotor $n_{cor,LPR}$. The MF-IEM shows great accuracy for SAF safety assessment.

Table 1. Validation of the MF-IEM.

Performance	Design Value	MF-IEM	Error (%)
Altitude (km)	0	0	/
Mach Number	0	0	/
SFC	0.0368	0.0369	0.18
F_N	286.820	286.857	0.01
BPR	5.920	5.924	0.06
$n_{cor,HPR}$	87.330	87.270	−0.07
$n_{cor,LPR}$	29.310	29.261	−0.17

The effects of fuel flow and blending ratio are considered during the evaluation of SAF's engine-level influences. The fuel flow rate is one of the most important control parameters in the aero-engine [46], and it determines the engine's operating state. Based on the study case, a 1.0% deviation in fuel flow around the design value can result in a 0.7% change in the aero-engine's thrust, which is non-neglectable for engine operation. Therefore, F-T SPK and Jet A's engine-level safety influences are compared under the same fuel flow $\dot{m}_{in,f}$. The values of $\dot{m}_{in,f}$ are determined using different nominal engine thrust levels when adopting Jet A. This paper also considers the effect of the blending ratio of F-T SPK and Jet A, since this is one of the most important factors that is considered in SAF certification [16]. In the following research, the aero-engine consistently operates in a sea-level environment.

3.2. Results

The combustor's performance at the co-work point indicates the necessity of conducting the SAF's research within the aero-engine system environment. The F-T SPK has a higher LHV, resulting in a higher temperature rise within the combustor. For instance, the difference in temperature rise in the engine's 100% nominal thrust state is 7.6 K. This additional heat release would provide more turbine work and compressor work, thus resulting in a higher combustor inlet temperature of 3.8 K. This feature may be unbeneficial for the combustor's casing, which is usually regarded as a life-limited part in airworthiness certification and has vital impacts on aero-engines' safety. Considering the combustor's higher temperature rise and the increasing shaft work, the TET would increase by 11.4 K in total, which may also deteriorate the working condition of hot section parts such as turbine blades. Notably, simply assessing SAF's influences on TET on the component level would underestimate the severity by 33.3%, because it could not recognize the combustor's inlet boundary conditions changes. Therefore, it is necessary to evaluate SAF s' safety at the engine level.

The engine-level result shows that various SCPs may change following different trends, as shown in Figure 4. The F-T SPK has a higher LHV or energy density than Jet A, leading to higher specific thrust F_N under the same fuel flow. This influence becomes more evident at lower fuel flow or nominal thrust conditions. Affected by the increased F_N and inlet air flow, the aero-engine's specific fuel consumption SFC also decreases significantly. A higher blending ratio would result in more benefits. In other words, adopting an SAF could achieve the same engine thrust with lower fuel consumption. This is beneficial for reducing operations costs. From the environmental perspective, adopting an SAF may be beneficial for controlling GHG emissions. The contributions are twofold. On the production side, SAFs' ingredients, such as energy plants, may capture carbon dioxide from the atmosphere. On the utilization side, the aero-engine may consume less fuel and discharge fewer GHGs due to the high heat value. Combining these two factors, adopting SAFs may reduce GHG emissions more than fossil fuels throughout their life-cycle.

In addition, the results show that SAF's influences on the following SAS-related SCPs are equivalent in their severity compared to the abovementioned GFP-related SCPs. Adopting F-T SPK would lead to a higher rotating speed of the low-pressure rotor (LPR), which may impose a higher centrifugal load on the blades and disks. The Nusselt number

Nu around the side of the turbine disk also increases, providing stronger heat convection and cooling effects on the turbine disk. Adopting F-T SPK may also lead to a higher SAS air discharge. This may be beneficial for preventing the hot gas from being ingested into the turbine disk cavity. As the area-weighted and directed sum of GFP-nodes and SAS-nodes pressure, the rotor axial load F_{ax} is a vital SCP to protect the engine's bearing. Adopting the F-T SPK would increase the F_{ax}, which is beneficial for preventing load reverse, but may impose excessive load on the aero-engine's bearing. To ensure the safety of the F_{ax}, airlines are suggested to choose an appropriate blending ratio, aided by the MF-IEM.

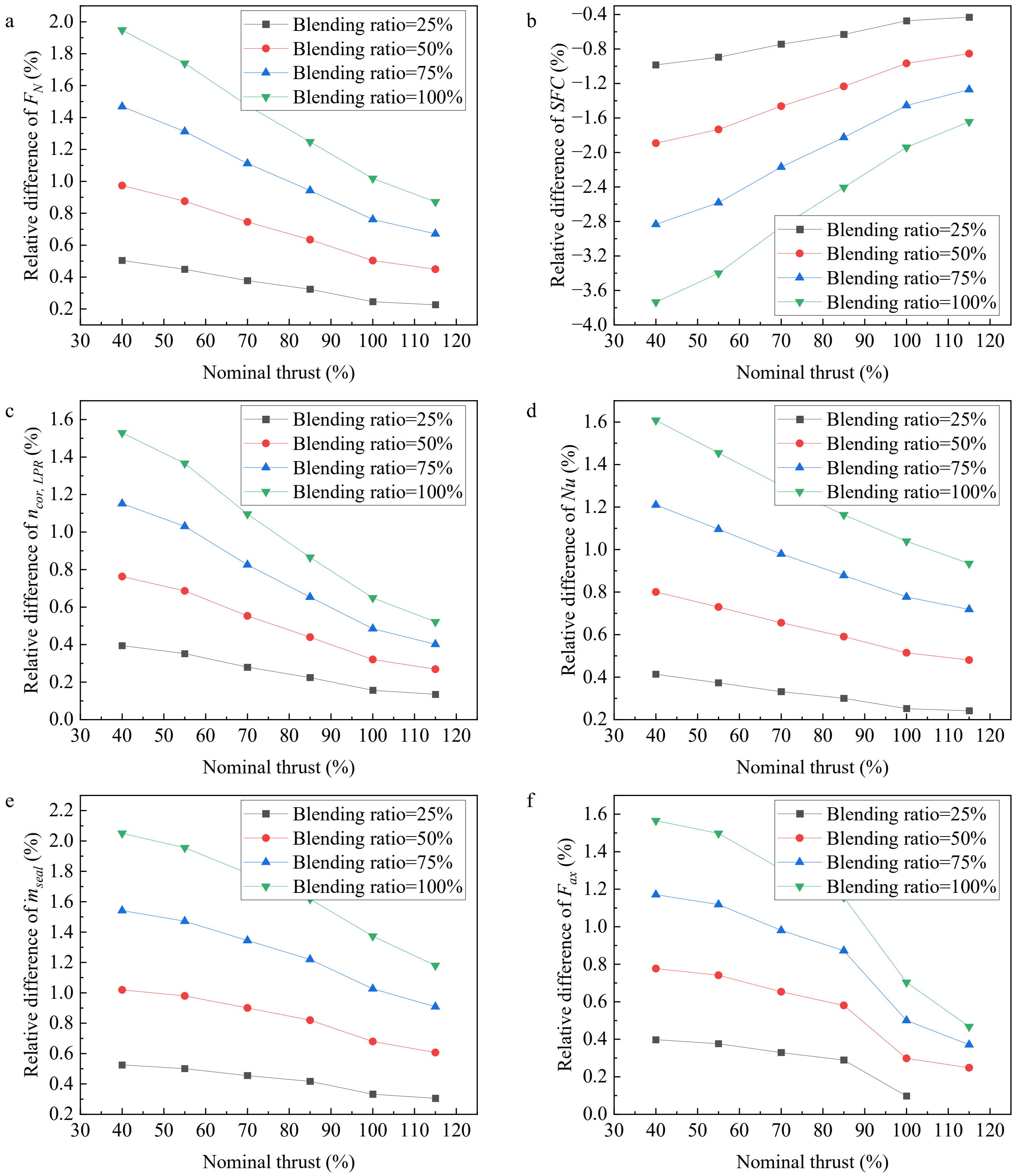

Figure 4. SAF's influence on (**a**) specific thrust; (**b**) specific fuel consumption; (**c**) turbine rotating speed; (**d**) turbine disk heat transfer; (**e**) cavity sealing air flow; (**f**) rotor axial load.

4. Discussion

The MF-IEM represents an engine-level scope and tool to evaluate SAF's safety. Based on the MF-IEM, an engine-level comparative safety criterion could be established for SAF safety assessment and airworthiness certification. Current SAF safety requirements, such as ASTM D7566 [47], impose fuel-level restrictions on SAFs' compositions and physical properties. These restrictions mainly refer to service experiences with fossil fuels. However, these fuel-level restrictions may be neither sufficient nor necessary for novel SAFs' safety assessment within the engine-level systematic scope. For instance, SAFs' lignin content may significantly influence carbon deposition on the gas flow path and deteriorate turbine blades' cooling. However, there is no corresponding requirement in published SAF safety standards, which may lead to safety risks in aero-engine operation. Meanwhile, ASTM D7566 clearly restricts SAFs' aromatic content, because it may influence rubber ring swelling and oil sealing performance [48]. However, recent research reveals that cycloparaffins may implement the same functionality [49]. Similar over-restrictions derived from experiences with fossil fuels may impose unnecessary limitations on developing SAFs with novel ingredients and refining pathways. This deficiency may lead to higher SAF prices and fewer applications. Engine-level evaluation has the potential to comprehensively consider the influences of SAFs' various physical properties and their interrelationships. It is suggested to evaluate SAFs' safety on the engine level.

Within the systematic scope, the criterion for SAF safety assessment is supposed to be the capacity to support the continuing operation of aero-engines. Aero-engine SCPs when adopting SAF should be safer than when adopting fossil fuels or other certificated fuels. As shown in Figure 5, the aero-engine SCPs based on certificated fuels are considered as the benchmark or the safety boundary. These boundaries can be obtained using databases of certificated fuels' properties and usage experiences. Thereby, fuel producers and aero-engine designers can evaluate SAF's engine-level safety comparatively. If SAF-based SCPs are similar enough or comparatively safe, the SAF may have the potential to achieve engine-level safety. Therefore, fuel producers and aero-engine designers are encouraged to expand their production and applications after further validations, such as engine and flight tests. Otherwise, they could conduct detailed research to judge whether the SCPs' deviation is acceptable. If the detailed research shows that the influence is acceptable for the aero-engine operation, the SAF could still be a candidate for further evaluation. Otherwise, fuel producers are supposed to make the necessary adjustments, such as blending the SAF with certificated fuels with an appropriate blending ratio or improving the refining process.

The proposed model-based approach provides a preliminary screening before costly tests, which may be beneficial to reduce the dependency on various tests and reducing the certification cost. Instead of carrying out engine-level tests that require a large amount of fuel for each certification trial, SAF producers only need to produce small volumes of the fuel sample to acquire the necessary properties required by the model's input, such as the heat value. Then, producers may obtain SAF's engine-level safety influences from the proposed model. The results may support producers in deciding whether to carry out further certification processes. The quantitative evaluation results may also guide SAF producers in making targeted adjustments. These conveniences may reduce trail-and-error costs when developing the novel SAF. In the future, as the models continue to be validated and become increasingly reliable, it is also promising that the certification authority may allow SAF producers to use an analysis approach supported by the simulation results to show compliance with the safety standards, substituting parts of the tests and reducing the certification cost.

In addition, the newly tested SAFs may also enlarge the safety boundary and renew the safety assessment benchmark. Since the proposed criterion focuses on SAF's influences on engine-level impacts rather than strictly imposing restrictions on fuels' physical properties, the proposed certification process may reduce the probability of failing the SAFs that exceed the current fuel-level restrictions yet would not degrade engine-level safety parameters. This convenience may allow SAFs with a broader range of fuel physical properties and blending ratios for further validation. If these validations show no deterioration in aero-engine safety, the results may support researchers in proposing amendment suggestions for fuel safety requirements, enlarging the fuel property restrictions or blending ratio limits referring to these SAFs.

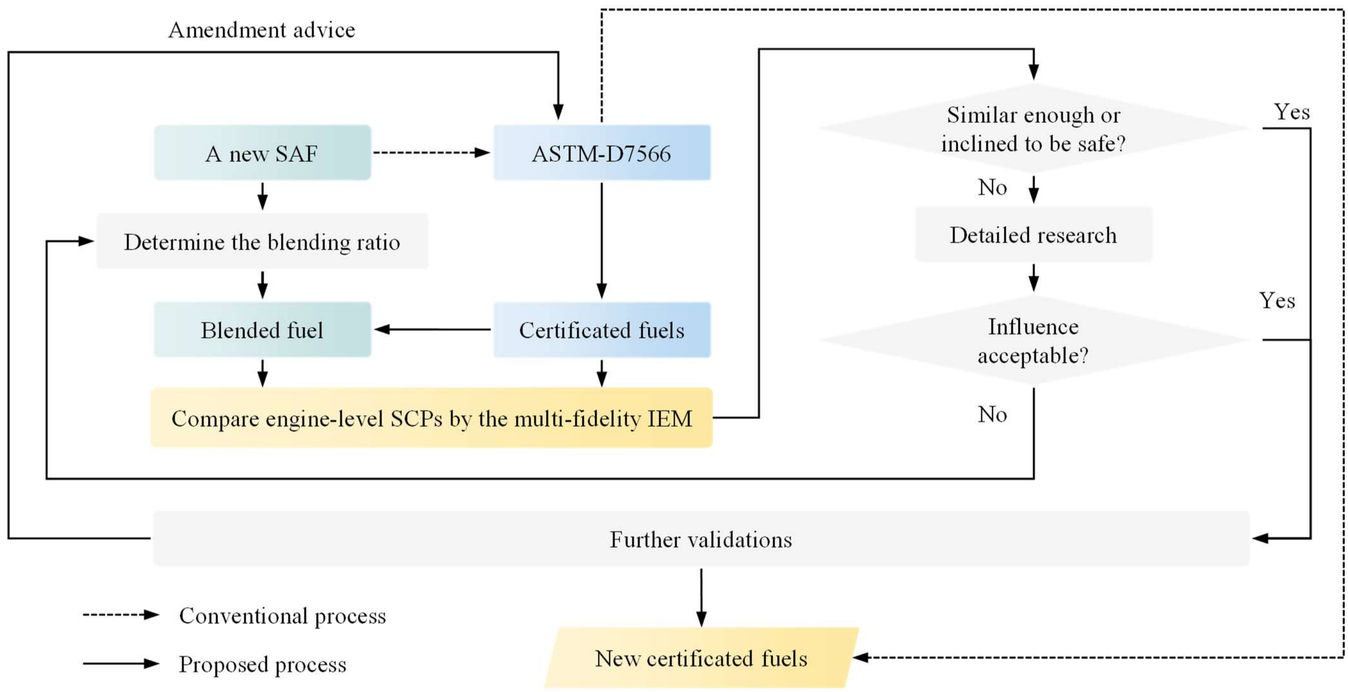

Figure 5. SAF's engine-level comparative safety assessment.

The proposed comparative safety criterion does not concern whether adopting SAFs can push aero-engines beyond their absolute safety boundary. Instead, this criterion examines the deviation in engine SCPs when using SAFs compared to fossil fuels or other certificated fuels. Under this criterion, the proposed model plays a role in providing a consistent platform or mapping relationships between fuel properties and engine SCPs for both SAFs and fossil fuels. The model's inherent uncertainties, such as the applicability to the novel SAF to be certificated, would not significantly influence the assessment conclusions in SCPs' deviation trends. As the model continues to be validated and improved, it will be able to assess the deviation magnitude more precisely.

5. Conclusions

This paper proposed a model-based approach to evaluate SAF's safety at the aero-engine level. The proposed MF-IEM could effectively establish the mapping relationship between the SAF's physical properties and the aero-engine's safety-critical parameters. The contributions of this paper can be summarized into the following two points.

First, the proposed MF-IEM can effectively evaluate SAF's influence on aero-engines' SCPs. The MF-IEM first establishes a unified criterion to ensure the aerodynamic conservations of both the GFP and SAS components of aero-engines. Thereby, SCPs throughout the engine flow field can be evaluated under the co-work point. A surrogate-based multi-fidelity iteration strategy is then proposed to embed the high-fidelity combustor model into the engine model. A control-theory-analogy training algorithm is used to train the aero-engine network model by regarding the high-fidelity model's results as the control targets and the low-fidelity models' adjustable coefficients as manipulated handlers. The proposed model-based approach shows great numerical convergence and sufficient accuracy for SAF safety assessment.

Second, the proposed approach is applied to an F-T SPK safety assessment case. The effects of fuel flow and the SAF's blending ratio with Jet A are discussed. The results prove the necessity to assess the SAF's safety on the engine level. The case study shows that only researching SAF's impact on the component level may underestimate the severity of the turbine entry temperature increase by 33.3%. In addition, the results show that adopting the F-T SPK will improve thrust and specific fuel consumption. However, it will also increase the turbine entry temperature, which may be detrimental for the hot-section and engine life-limited parts. Notably, the influences of SAFs on SAS-related SCPs show an equivalent severity compared to the GFP-related SCPs, which also need to be aware of for SAF safety assessment.

Based on the proposed MF-IEM, the SAF producers and aero-engine designers could effectively evaluate SAFs' influences on engine safety compared to fossil fuels. This may be beneficial for reducing certification costs and expanding SAF's application. In the future, we will extend our research to the transient modeling of MF-IEM and evaluate SAFs' safety influence during an engine's accelerating and decelerating process, such as take-off and landing. It is also of interest to evaluate SAFs' influence on the failure risk of aero-engine's life-limited parts corresponding to the airworthiness requirements, which requires investigating the SAF's properties uncertainty caused by product instability and conducting SCP probabilistic analysis.

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