Effects of Equivalence Ratio on the Fire Characteristics of Hydroprocessed Esters and Fatty Acids derived Sustainable Aviation Fuel for Aeronautical Application

Abdulwasiu Muhammed Raji*, Brady Manescau, Khaled Chetehouna, and Ludovic Lamoot.

INSA Centre Val de Loire Campus de Bourges 88 Bd Lahitolle, University of Orléans, PRISME EA 4229, F-18022 Bourges, France.

Abstract

This study investigates the effects of the equivalence ratio (**φ**) on the fire characteristics of Hydroprocessed Esters and Fatty Acids-derived Sustainable Aviation Fuel (HEFA-SAF) using a NexGen burner setup for aeronautical applications. Results demonstrate a non-linear relationship between **φ** and heat flux density, with peak values observed under fuel-rich conditions (**φ** = 1.25). HEFA-SAF exhibits heat flux densities slightly lower than standard Jet A-1 fuel, with a peak value of 1689.3 W/m² compared to 1750 W/m² for Jet A-1. This variation is attributed to HEFA-SAF's higher oxygenated compound content, influencing combustion dynamics. HEFA-SAF shows lower heat flux due to its cleaner combustion, reduced soot formation, and lower aromatic content compared to Jet A-1. These factors reduce radiative heat transfer. Differences in molecular structure contribute to lower peak heat flux in HEFA-SAF despite similar trends in response to **φ**. In addition, HEFA-SAF demonstrates improved thermal efficiency under fuel-rich conditions, compensating for its lower laminar flame speed compared to Jet A-1. These findings align with prior studies and emphasize the critical role of **φ** in optimizing SAF combustion performance. The results support the viability of HEFA-SAF as a sustainable alternative in aviation, balancing efficiency and reduced environmental impact.

1. Introduction

The aviation sector is a major contributor to greenhouse gas emissions (GHG), accountable for nearly 2.8% of world carbon dioxide (CO_2) emissions. As the demand for air travel continues to grow, achieving significant reductions in aviation-related emissions is an urgent priority [1]. In response, the use of sustainable aviation fuels (SAFs) is a critical strategy to address this challenge. Among different production method, the hydroprocessed esters and fatty acids derived sustainable aviation fuel (HEFA-SAF) has the largest production volume. Ascribed to its compatibility with existing jet engines and infrastructure (as drop-in fuel), and potential to lower lifecycle GHG by up to 80% compared to fossil-based jet fuels [2,3]. To be certified as drop-in fuel, it must meet both the American society of testing materials (ASTM) D1655 [4]

Correspondence to: abdulwasiu.muhammed_raji@insa-cvl.fr

and the ASTM D7566 standards [5]. HEFA is a consolidated pathway for producing jet biofuels, involving processes such as hydrodeoxygenation, hydrocracking, and hydroisomerization, which are known refining processes [6]. The process is approved by the ASTM for producing Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) and is being used in commercial flights [7]. Despite these advantages, the full integration of HEFA-SAF into aviation transport still has some technical challenges. One of it being understanding it combustion characteristics and fire behaviour, especially under varying equivalence ratios (**φ**). **φ** is an important parameter that influences flame stability, combustion efficiency, and emission characteristics. These properties have been studied extensively for fossil jet fuels such as JET A-1 [8,9]. However, limited research has been conducted on the effect of equivalence ratio variations on the fire characteristics of HEFA-SAF under simulated aeronautical conditions. Previous studies focused on the flame characteristics of SAFs derived through the catalytic hydroprocessing method using waste cooking oil, such as the work by Abi Nurazaq *et al*. [10] and Xu *et al*. [11] which examined the burning characteristics of renewable aviation fuel produced via the catalytic hydrodeoxygenation using corn stover lignin. However, these studies often neglect vital properties such as flame temperature across vertical and horizontal thermocouples positions and heat flux measurement. Therefore, this study examines these properties using HEFA-SAF at different equivalence ratios (0.75, 0.83, 0.91, 1.0, 1.08, 1.16 and 1.25), filling a gap in understanding their relative fire performance in practical scenarios.

2. Materials and Methods

The tests were conducted using the Next Generation (NexGen) burner **(Fig. 1a)**, developed by the FAA for fire testing. The impinging flame condition for the set-up must maintain a heat flux of 116 kW/m² ± 10 kW/m² and an average temperature of 1100 °C ± 80 °C. The burner simulate the fire conditions outlined in ISO 2685:1998 and AC 20-135) [12]. It is a gun-type device that uses a pressurized fuel spray and a controlled air supply to produce a consistent and reproducible flame. Major components of the burner; an interchangeable fuel nozzle for precise control of fuel flow, a regulated sonic orifice for air supply management, and a turbulator to enhance flame stability and uniformity. The burner is designed to meet specific temperature and heat flux requirements, ensuring accurate simulation of fire conditions encountered in aviation scenarios. Fig. **1c (left)** was used to measure the total heat flux of the flame generated and **Fig. 1c (right)** is to determine heat flux measurement precision**. Fig. 1d** provides air to the burner, enabling the adjustment of air pressure through a compressor. The burner features a cone with dimensions of 16 cm (height) and 28 cm (width). K-type thermocouples were strategically placed in the XY plane at intervals of 2.5 cm, with 15 thermocouples positioned along the horizontal X-axis and 15 along the vertical Y-axis, resulting in a total of 30 thermocouples. The thermocouple located at the origin (X0, Y0) is positioned 10 cm from the cone's centre (O) to comply with the FAA standards. The methodology adhered to the FAA's fire test standards for the NexGen burner, ensuring compliance with industry procedures. Pure fuel sample of HEFA-SAF were prepared and tested across equivalence ratios (**φ**) of 0.75 to 1.25 to assess their combustion characteristics. The burner was calibrated to achieve the desired flame temperature and heat flux parameters, as specified in the FAA guidelines. Major combustion metrics such flame temperature, and heat flux were measured and recorded. Data acquisition systems captured real-time measurements, facilitating analysis of the impact of **φ** variations on the fire behaviour of the fuel sample.

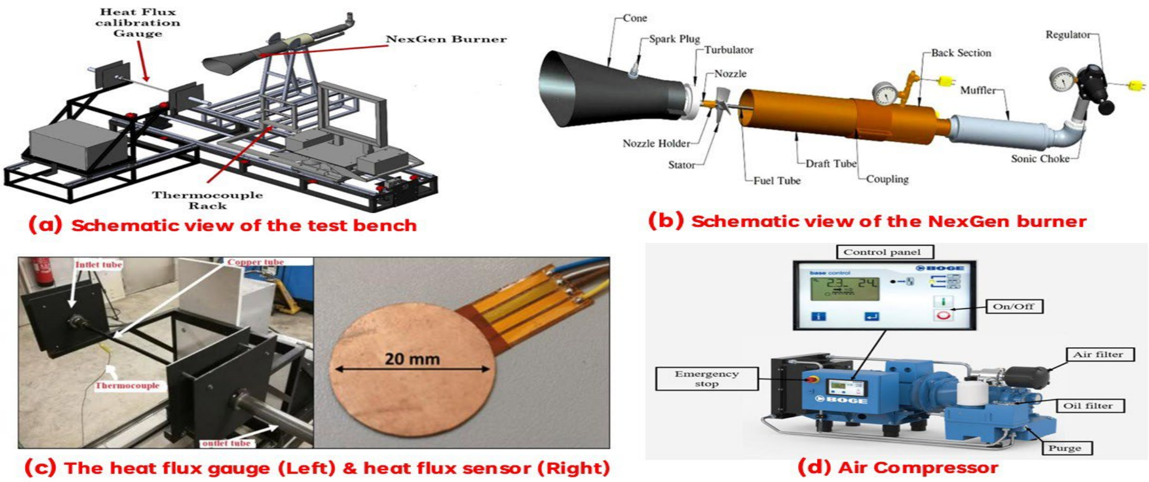
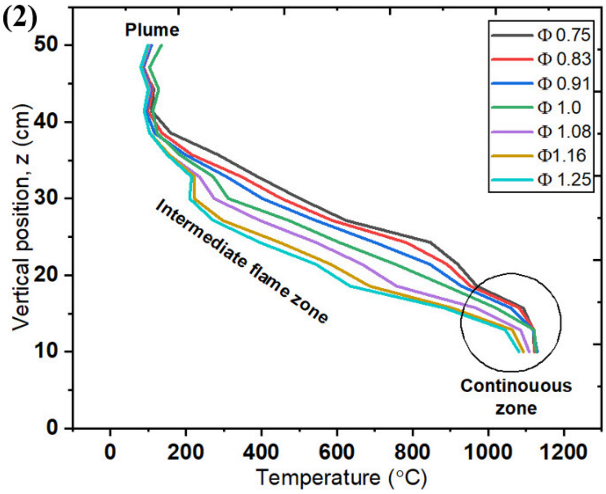


Figure 1: Set-up for the experiment

3. Results and Discussion

3.1 Effect of equivalence ratio on the flame temperature

The effect of the equivalence ratio (**φ**) on flame temperature for different thermocouple positions, both vertical and horizontal, was analysed as shown in **Figures 2 and 3**. The influence of Φ on flame temperature, the plume, intermediate flame zone, and continuous zone were examined. These zones exhibit distinct temperature distribution patterns, critical for understanding combustion efficiency and flame behaviour of biofuel. In the vertical direction, as shown in **Figure 2**, the flame temperature decreases with increasing distance from the burner, transitioning from the plume zone to the continuous zone. For example, in the intermediate flame zone at approximately 30 cm above the burner, the flame temperatures for Φ = 0.75,1.0, and 1.25 are 850°C, 950°C, and 1150°C, respectively. This demonstrates that higher **φ** lead to greater heat release and more robust combustion. The results align with findings from prior studies, which have shown that the stoichiometric or slightly rich mixtures (Φ≈1.1) produce the highest temperatures due to optimal mixing of fuel and oxidizer, ensuring complete combustion. For example, Dekhatawala et al. [13] observed similar results in jet fuel combustion, where the peak temperature occurred near the stoichiometric ratio, indicating efficient energy utilization. However, in lean (Φ<1) or excessively rich (Φ>1.25) mixtures, the temperature decreases due to limited fuel availability or incomplete combustion, respectively. In the continuous zone, the temperature profiles converge, indicating thermal equilibrium as the chemical reactions subside. This observation is consistent with previous literature suggesting that, beyond a certain height, the effects of the equivalence ratio diminish due to heat dissipation and mixing with ambient air [14]. From **Figure 3** (the horizontal direction), the flame temperature exhibited dependence on the equivalence ratio. At Φ =1.0, the maximum temperature in the plume zone at 35 cm from the burner is around 1100°C, while at Φ=0.75, it is approximately 900°C. The difference highlights the effect of fuel richness in stabilizing the flame and distributing heat across the combustion zone. Interestingly, the flame temperature at higher equivalence ratios (Φ=1.08, 1.16 and 1.25) show fewer steep slopes in the horizontal direction compared to lean mixtures. This may be attributed to the enhanced radiative heat transfer and reduced sensitivity to buoyancy effects at higher fuel richness, as discussed by [15]. In addition, the reduced flame flickering observed under rich conditions could contribute to the more uniform temperature profiles. The findings also show that the horizontal temperature distributions in the plume zone are lower than those observed in the vertical direction for equivalent heights. This observation supports previous studies that highlight the gravitational influence on flame dynamics, particularly in the buoyant plume zone, where vertical heat transfer dominates [16].



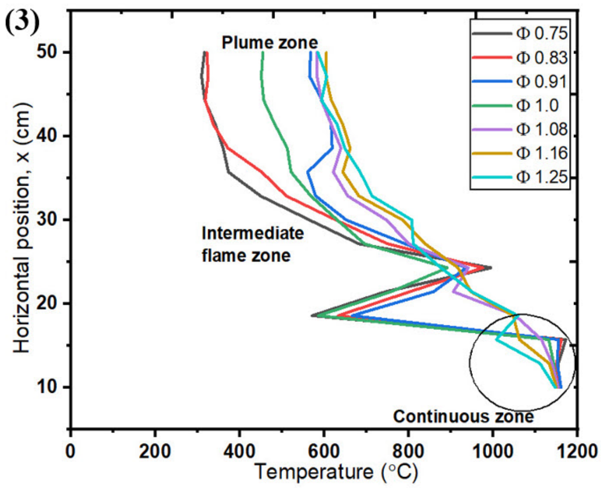


Figure 2: Effect of the vertical thermocouple's positions above the burner on the flame temperature for various equivalence ratio. **Figure 3**: Effect of the horizontal thermocouple's positions from the burner on the flame temperature for various equivalence ratios.

3.2 Effect of equivalence ratio on the heat flux density

Table 1 highlights critical insights into the effect of the equivalence ratio on the heat flux density of HEFA-SAF derived from the NexGen burner set up. The results show a non-linear relationship between the **φ** and the average heat flux, with peak heat flux observed at **φ** greater than stoichiometric values. These findings are compared with studies on bio-aviation fuels and standard Jet A-1 fuels highlighting their relevance to SAF applications. The study reveals that increasing the **φ** leads to higher heat flux densities, a trend consistent with previous research [11], attributed to enhanced molecular diffusion and higher energy density in fuel-rich biofuels. This highlights the role of **φ** in optimizing combustion performance. In addition, the study on laminar flame speed of SAF [17] emphasizes that SAF exhibits lower flame speeds than standard Jet A-1 fuel but compensates with improved thermal efficiency under fuel-rich conditions. This finding is consistent with our results, where HEFA-SAF exhibits a steady increase in heat flux densities with richer **φ**, peaking at **φ** = 1.25. Compared to Jet A-1 fuel, as reported by [18] in their study on kerosene/air flames produced by NexGen burner, HEFA-SAF demonstrates similar trends in heat flux response to **φ**. However, the heat flux densities for HEFA-SAF are lower than those of Jet A-1 at comparable conditions. For instance, Jet A-1 exhibited peak heat flux values closer to 1750 W/m² at φ = 1.25 [18], slightly higher than the 1689.3 W/m² for HEFA-SAF. Ascribed to differences in their chemical composition and energy density, HEFA-SAF contains higher oxygenated compounds that may influence combustion dynamics and thermal feedback. In addition, Jet A-1 produce more soot [19], enhancing thermal radiation and leading to higher heat flux. In contrast, HEFA-SAF burns cleaner with reduced particulate emissions (PM) [20], which lowers radiative heat transfer despite similar trends in flame behaviour with **φ**.

Table 1: Effect of equivalence ratio on heat flux density.

S/N	Equivalence ratio (**φ**)	Air Pressure (atm)	Average Heat Flux (W/m^2)
1	1.0	3.03	1250.3
2	0.91	3.45	1105.7
3	0.83	3.85	985.2
4	0.75	4.30	870.6
5	1.08	2.75	1402.4
6	1.16	2.45	1550.8
7	1.25	2.15	1689.3

4.0 Conclusion and future perspectives

The study demonstrates that the equivalence ratio significantly influences flame temperature in vertical and horizontal directions. Peak temperatures occurred at or near stoichiometric conditions, underscoring the significance of precise fuel-air mixing in optimizing combustion systems. Our results are consistent with prior literature and provide valuable insights for improving energy efficiency. The effect of **φ** on the heat flux density of HEFA-SAF in a NexGen burner set-up revealed a non-linear relationship, with peak heat flux observed at rich conditions (**φ** = 1.25), consistent with trends in bio-aviation and Jet A-1 fuels. While HEFA-SAF shows lower peak heat flux compared to Jet A-1, it compensates with improved thermal efficiency under fuel-rich conditions due to its oxygenated compounds and lower PM. These findings underscore the importance of optimizing **φ** for SAF combustion performance, contributing to the development of efficient and sustainable aviation fuel technologies. Our study has significant implications for optimizing combustion processes. Achieving the appropriate **φ** is critical for balancing combustion efficiency and minimizing pollutant formation. For instance, while rich mixtures (Φ>1.1) maximize heat release, it may lead to increased soot and incomplete combustion products. Lean mixtures (Φ<1) are less efficient in terms of energy output but may produce fewer emissions. Future studies could explore the effects of transient flame behavior and burner configurations to build on these findings. In addition, examine the fire characteristics of biofuels blends.

References

[1] Capaz RS, Guida E, Seabra JEA, Osseweijer P, Posada JA (2021). Mitigating carbon emissions through sustainable aviation fuels: costs and potential. Biofuels, Bioprod Biorefining. 15:502–24.[1] Capaz RS, Guida E, Seabra JEA, Osseweijer P, Posada JA. Mitigating carbon emissions through sustainable aviation fuels: costs and potential. Biofuels, Bioprod Biorefining 2021;15:502–24. https://doi.org/10.1002/bbb.2168.

[2] Shahriar MF, Khanal A. The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). Fuel 2022;325:124905. https://doi.org/10.1016/j.fuel.2022.124905.

[3] Raji AM, Manescau B, Chetehouna K, Ekomy Ango S, Ogabi R. Performance and spray characteristics of fossil JET A-1 and bioJET fuel: A comprehensive review. Renew Sustain Energy Rev 2025;207:114970. https://doi.org/10.1016/j.rser.2024.114970.

[4] ASTM D1655. D1655 Standard Specification for Aviation Turbine Fuels n.d. https://www.astm.org/d1655-22.html (accessed October 1, 2023).

[5] ASTM D7566. D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons n.d. https://www.astm.org/standards/d7566 (accessed November 6, 2023).

[6] Monteiro RRC, dos Santos IA, Arcanjo MRA, Cavalcante CL, de Luna FMT, Fernandez-Lafuente R, et al. Production of Jet Biofuels by Catalytic Hydroprocessing of Esters and Fatty Acids: A Review. Catalysts 2022;12:237. https://doi.org/10.3390/catal12020237.

[7] Song M, Zhang X, Chen Y, Zhang Q, Chen L, Liu J, et al. Hydroprocessing of lipids: An effective production process for sustainable aviation fuel. Energy 2023;283:129107. https://doi.org/10.1016/j.energy.2023.129107.

[8] Oni BA, Sanni SE, Ibegbu AJ, Tomomewo OS. Evaluation of engine characteristics of a micro-gas turbine powered with JETA1 fuel mixed with Afzelia biodiesel and dimethyl ether (DME). Renew Energy 2023;216:119134. https://doi.org/10.1016/j.renene.2023.119134.

[9] Reksowardojo IK, Duong LH, Zain R, Hartono F, Marno S, Rustyawan W, et al. Performance and Exhaust Emissions of a Gas-Turbine Engine Fueled with Biojet/Jet A-1 Blends for the Development of Aviation Biofuel in Tropical Regions. Energies 2020;13:6570. https://doi.org/10.3390/en13246570.

[10] Abi Nurazaq W, Wang W-C, Lin J-K. The properties of sustainable aviation fuel II: Laminar flame speed. Energy 2024;294:130946. https://doi.org/10.1016/j.energy.2024.130946.

[11] Xu C, Liu K, Song Y, Cui D, Li X, Wang Q, et al. Laminar burning characteristics of bio-aviation fuel candidate derived from lignocellulosic biomass. Fuel 2023;334:126719. https://doi.org/10.1016/j.fuel.2022.126719.

[12] Le Neve S (DGA AS. AC 20-135 / ISO 2685 Fire tests on components used in fire zones . Comparison of gas burner to oil burner. 2010.

[13] Dekhatawala A, Bhale P V., Shah R. Effect of Equivalence Ratio on Flame Morphology, Thermal and Emissions Characteristics of Inverse Diffusion Porous Burner. J Appl Fluid Mech 2024;17:1217–29. https://doi.org/10.47176/jafm.17.6.2419.

[14] Le Dortz R, Julien S, Strozzi C, Le Dortz R, Bellenoue M, Bonneau L, et al. Laminar Burning Velocities and Markstein Lengths of Jet Fuel Surrogate/Air Mixtures in a Spherical Chamber

2017.

[15] Paramasivam P, Obaid S Al, Balasubramanian A. Flame stabilization and emission reduction: a comprehensive study on the influence of swirl velocity in hydrogen fuel-based burner design. Aircr Eng Aerosp Technol 2024;96:1045–52. https://doi.org/10.1108/AEAT-05-2024-0137.

[16] Arai M, Sato H, Amagai K. Gravity effects on stability and flickering motion of diffusion flames. Combust Flame 1999;118:293–300. https://doi.org/10.1016/S0010-2180(98)00159-X.

[17] Masoud SM, Attia AMA, Salem H, El-Zoheiry RM. Investigation of jet A-1 and waste cooking oil biodiesel fuel blend flame characteristics stabilized by radial swirler in lean pre-vaporized premixed combustor. Energy 2023;263. https://doi.org/10.1016/j.energy.2022.125830.

[18] Ogabi R, Manescau B, Chetehouna K, Obame E, Senave S. The impact of equivalence ratio on the fire characteristics of Kerosene/air flame produced by NexGen burner for aeronautic application. Case Stud Therm Eng 2024;54:104004. https://doi.org/10.1016/j.csite.2024.104004.

[19] Raji AM, Manescau B, Chetehouna K, Lamoot L, Ogabi R. Comparative analysis of the combustion and emission characteristics of biojet and conventional Jet A-1 fuel: a review. Biofuels, Bioprod Biorefining 2024;18:2177–95. https://doi.org/10.1002/bbb.2682.

[20] Xu Z, Wang M, Chang L, Pan K, Shen X, Zhong S, et al. Assessing the particulate matter emission reduction characteristics of small turbofan engine fueled with 100 % HEFA sustainable aviation fuel. Sci Total Environ 2024;945:174128. https://doi.org/10.1016/j.scitotenv.2024.174128.